OPEN REPORT
SCK•CEN-BLG-1103

Fusion Programme SCK•CEN under the Contract of Association Euratom – Belgian State

Final Report FP7 2007-2013

Compiled by Vincent Massaut

March, 2015

SCK•CEN
Boeretang 200
BE-2400 MOL
BELGIUM

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Revision 0

OPEN REPORT OF THE BELGIAN NUCLEAR RESEARCH CENTRE
SCK•CEN-BLG-1103

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Studiecentrum voor Kernenergie
Centre d’Etude de l’Energie Nucléaire
Boeretang 200
BE-2400 MOL
BELGIUM

Phone +32 14 33 21 11
Fax +32 14 31 50 21

http://www.sckcen.be

Contact:
Knowledge Centre
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This report is a summary of the 7 annual reports that were compiled related to the Fusion Programme SCK•CEN under the Contract of Association.

These reports can be found on the enclosed CD-ROM and are also registered in the Knowledge Centre of SCK•CEN with following references:

1) 2007: SCK•CEN-BLG-1053
2) 2008: SCK•CEN-BLG-1063
3) 2009: SCK•CEN-BLG-1067
4) 2010: SCK•CEN-BLG-1073
5) 2011: SCK•CEN-BLG-1080
6) 2012: SCK•CEN-BLG-1090
7) 2013: SCK•CEN-BLG-1096

I. Executive summary for the period 2007 - 2013

A. The year 2007

Radiation effects on fusion materials

Vessel and in-vessel materials for ITER: beryllium, copper, tungsten

The vacuum vessel structure and first wall of a fusion reactor has to withstand not only neutrons, but also very high heat fluxes at some locations. Behind the first wall covered by beryllium, tungsten or CFC, an active cooling involves the use of copper ducts. Moreover, behind the blanket modules, attachment parts in inconel are also subject to severe environments. Beryllium is also used in the form of pebbles in the breeding test blanket module, to be installed in ITER.

The combined effect of radiation and thermal load are critical issues to study in order to ensure a high reliability and safety. SCK•CEN helps assessing these materials, in order to guarantee the challenging requirements of ITER. The activities involve:

- Related to plasma wall interaction, the effect of both neutron irradiation and thermal shockson the behaviour of the divertor armour materials such as beryllium, carbon and tungsten is been studied, in close collaboration with FZJ: this work is now embedded in the ITER-like Wall Project at JET;
- In the same context, work is performed to prepare the quality assurance testing of the tiles to be used for the ITER-like wall, and to perform specific spectroscopic measurements on sample tiles;
- A plasmatron testing machine has been installed with the view to make it available for plasma wall interaction studies in the future;
- SCK•CEN has become a partner of a training network on first wall materials;
- Concerning the copper ducts in the first wall modules, the in-situ assessment of themechanical performance and lifetime of copper alloys has been further studied, preparing anew series of tests with the unique in-situ test rig developed during the previous years;
- Analysing copper-steel and copper-beryllium joints under radiation for which the irradiations are on-going.

This work is complemented by studies on specific waste management issues related to these materials, and in particular to beryllium.

Reduced activation ferritic martensitic steel Eurofer97

Eurofer97 is the reference steel for the future fusion reactors. It is a reduced activation ferritic martensitic steel with 9% chromium. Assessing its mechanical performance under neutrons and in the presence of liquid metals are critical questions to answer. It is to be noted that SCK•CEN covers on this material a broad assessment scope, grouping in-house the irradiation testing, the mechanical and corrosion testing and the modelisation approaches.

The activities involve:

- The results of the post-irradiation examination of irradiated Eurofer97 joints, as well as of oxide dispersion strengthened (ODS) steels, have been integrated into a general overview of all
- available data on Eurofer97;
- The irradiation campaign of the new reference ODS steel has been completed and the postirradiation examination is on-going;
- A new irradiation campaign for Eurofer joints is being prepared;
- The corrosion tests for irradiated Eurofer97 joints in liquid lithium-lead is completed;
- Modelisation of irradiation effects is crucial to extrapolate the experimental data obtained with fission reactors: the binary alloy Fe-Cr is studied as a model alloy for Eurofer97, both theoretically (down to the atomic scale) and experimentally; Accent has been put on the effect of dislocations on the microstructural evolution of the alloy.

Radiation effects on instrumentation

Physics integration: Radiation effects on diagnostics systems

Diagnostics systems have been developed on existing tokamaks where no radiation constraints are present. ITER sets a particular challenge to these developments by requiring a high radiation tolerance in a severe environment.

SCK•CEN has focused its work on four items: optical fibres allowing optical diagnostics to become more flexible and performant, degradation effects on insulation ceramics, radiation tolerance of bolometers and radiation effects in mineral insulated cables. The activities involve:

- Evaluating the performance of optical fibres for infra-red thermography; this task is being completed in close collaboration with CEA;
- Following-up in-situ the resistance of radiation hardened bolometers: improvement of the design of the ITER-relevant bolometer is being studied in collaboration with IPP-Garching and CIEMAT; particular attention has been put on the ceramic-metal attachments, considered as the weak point of present bolometer design;
- An initial evaluation of current sensing using optical fibres has been successfully completed, the activity being now pursued with CEA to reach the prototype level;
- Evaluating the different radiation and thermal effects appearing in mineral insulated cables connecting diagnostics systems;
- The assessment of window assemblies under representative radiation and temperature is ongoing both experimentally with the foreseen test on six different window types, and theoretically on generic glass-metal bonding structures;
- A first phase of development of a database for the radiation effects on diagnostic components has been completed in close collaboration with UKAEA.

Vessel-In-Vessel: Radiation effects on remote handling sensing systems

The remote maintenance of ITER will require sufficiently long lifetimes for the different components of the handling units to be used inside the vessel. SCK•CEN coordinates the European efforts in this domain, maintains a database of the radiation tolerance information, and sets particular emphasis on multiplexing techniques to alleviate umbilical problems of the handling units. The activities involve:

- A large scale radiation assessment campaign has been launched for DC motors, solenoid and servo valves, pressure gauges and pre-amplifier modules for the Cassette Multifunctional over (DTP2 facility in Finland);
- The development of radiation hardened electronic integrated circuits for the signal processing of remote handling sensors;
- The design and manufacturing of specific remotely-operated components for the divertor refurbishment platform has been completed (task performed by Gradel in Luxemburg).

Waste management

Assessing the behaviour of materials under radiation must be complemented by studies on their management as nuclear waste. The fusion option is particularly attractive for its waste characteristics, but particular problems are to be solved for tritiated waste and special materials such as beryllium. SCK•CEN helps optimising the detritiation techniques and studies specific waste issues such as recycling, disposal criteria and conditioning performance. The activities involve:

- The detritiation of JET-type molecular sieve beds is being studied experimentally and the task is about to be completed, showing the efficiency of the proposed approach;
- The approach is also extended to a set of typical high heat flux components of ITER containing beryllium, tungsten and carbon;
- A critical review of the decontamination procedures foreseen for the neutral beam cell;
- The study of a large scale waste processing unit for JET has been started. Specific studies are on-going on the detritiation techniques to be used for organic liquids and molecular sieve beds;
- Recycling is a critical issue in fusion waste management, especially for high value materials such as beryllium. An assessment study has been completed for beryllium and for other fusion materials; different industrial recycling routes have been compared, and specific issues of the beryllium recycling scheme have been studied;
- Radiation protection optimisation using 3D modelisation tools has been reviewed and improved procedures have been suggested.

Socio-economics

The waste problem touches a sensitive aspect of energy production: its acceptation by the public. Socio-economics aspects are therefore important in this debate, and must be considered with great attention. As part of its social science programme, SCK•CEN evaluated communication aspects, related to the use of energy model argumentation and public perception to the ITER construction in the Cadarache area.

Scientific output

During the period October 2006 – October 2007, more than seventy documents were published: i.e. 42 papers in journals, 36 presentations at international conferences, 44 task reports, 4 BSc, 2 MSc and 2 PhD theses. SCK•CEN presented fusion related papers to several international conferences, with in particular a strong presence at SOFT (Warsaw, September 2006, 12 papers), PFMC (Greifswald, October 2006, 3 papers), ITER-LMJ (Aix en Provence, June 2007, 3 papers), Euromat (Nuremberg, September 2007, 2 papers), ISFNT (Heidelberg, September 2007, 2 papers), BEWS (Lisbon, December 2007, 3 papers), and ICFRM (Nice, December 2007, 7 papers). SCK•CEN attended also the ITPA on Diagnostics meetings in Princeton (March 2007).

SCK•CEN insures also a set of lectures on fusion in Belgian universities (in particular for the European Erasmus-Mundus Master in Nuclear Fusion Science and Engineering Physics) and organises in Mol the interuniversity "Master of Nuclear Engineering" teaching under the framework of the Belgian Nuclear Higher Education Network (BNEN), with fusion as part of the curriculum.

In 2007 a participation in the European fusion training scheme for young scientists has been launched, inside the consortium related to first wall components, together with CEA, FZJ, ENEA and IPP.

Collaborations

The EFDA Technology Tasks are in essence collaborative initiatives, where several associations are brought together to study different aspects of an overall problem. The following table (Table 1) shows where these collaborations are the most effective.

Field	Task	JET	CEA	CIEMAT	CH	FOM	FZJ	FZK	IPP	IPP-CR	IPPLM	MEdC	ÖAW	RISOE	TEKES	UKAEA	VR	RF-HT	US-HT
Physics Integration																			
	TW4-TPDC-IRRCER		X	X															
	TW5-TPDC-IRRCER		X		X				X									X	
	TW6-TPDC-IRRCER	X		X												X			
	UT-OF-2006				X						X								
Vessel-In Vessel																			
	TW1-TVV-BOLMAT					X													
	TW3-TVM-COFAT													X	X				
	TW4-TVM-COFAT2													X	X				
	TW4-TVM-CUSSIR													X	X				
	TW5-TVM-SITU2													X	X				
	TW5-TVR-RADTOL		X	X											X				
	TW5-TVR-RADVAL		X	X											X				
Tritium Breeding and Materials																			
	TW2-TTBB-005							X											
	TW5-TTMS-001				X	X		X											
	TW5-TTMS-003																		
	TW5-TTMS-006																		
	TW4-TTMS-007				X		X							X					
	TW5-TTMS-007							X						X	X	X	X		
	TW6-TTMS-007															X			X
	UT-MOD1-2006															X			
	UT-PWI-2006						X			X									
Safety and Environment																			
	TW5-TSW-001																		
	TW6-TSS-SEA																		
	UT-BER-2006																		
	TW5-TRE-FESO		X																
	TW5-TRE-FESS												X						
JET Technology																			
	JW4-FT	X														X			
	JW5-FT	X														X			
	JW6-FT	X	X				X									X			

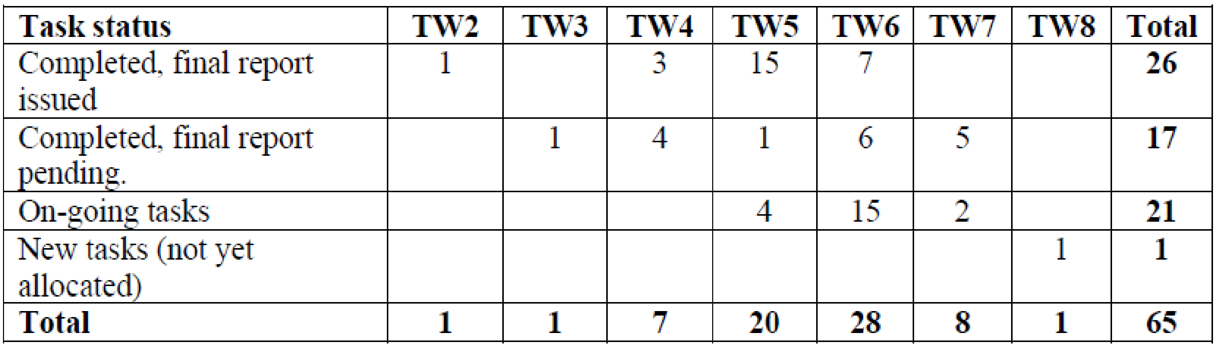
Table 1: Collaboration with other Associations

Overview of the tasks status

At the end of 2007, 65 tasks are active. Their status is given in Table 2:

- Twenty six tasks will be completed at the end of 2007;
- Twenty one tasks are still on-going at the end of 2007;
- Almost no new tasks have been negotiated for 2008. This situation is due to the long delay in establishment of the new ELE (future F4E) and EFDA structures.

A few tasks are in delay with respect to their original planning, essentially due to delivery problems of test samples or components.



Task status	**TW2**	**TW3**	**TW4**	**TW5**	**TW6**	**TW7**	**TW8**	**Total**
Completed, final report issued	1		3	15	7			**26**
Completed, final report pending.		1	4	1	6	5		**17**
On-going tasks				4	15	2		**21**
New tasks (not yet allocated)							1	**1**
Total	**1**	**1**	**7**	**20**	**28**	**8**	**1**	**65**

Table 2: Number of running tasks and their respective status

B. The year 2008

The year 2008 was a transition year in the fusion community.

It was thus also the case within SCK•CEN for the research activities on fusion technology. Moreover the SCK•CEN was reorganized in 2006-2007, and the management decided to focus the activities on some specific topics in which our skills and competences were recognized and which presented some synergies with the R&D in fission reactors developments.

The research activities of SCK•CEN are since several years focused around three main areas:

- the structural materials and the effects of neutron irradiation on their mechanical properties;
- the effects of radiation on diagnostics and remote handling components and the development of radiation resistant systems;
- the fusion waste management and recycling of materials.

With the new orientation and focus decided for 2008, the main areas of R&D at SCK•CEN concentrates on the radiation effects on Eurofer, ODS Eurofer and on Tungsten, which is currently recognized as one of the promising structural material for DEMO. Moreover, since several years, activities were started on plasma-wall interaction investigations, and the SCK•CEN recovered in 2007 the plasmatron from the former ETHEL lab in Ispra, which was refurbished during 2008.

The qualification of diagnostic and remote handling components remains an important focus of research and testing and the development of radiation hardened components is part of the SCK•CEN strategy. Optical diagnostic systems are certainly central in our activities and the current main developments are concerning a radiation hardened fibre optics current sensor (FOCS) able to measure steady state plasma currents.

For the waste management, particular attention is paid to the detritiation of solid materials and of effluents (liquid an gas), which will be increased thanks to the complete refurbishment of the SCK•CEN tritium lab.

The strategic focus were also supported by three main projects and installations which are considered as important milestones in the participation of SCK•CEN to the development of fusion power. These projects are the following ones :

- The plasmatron “VISION I” which will allow to enhance the plasma-wall interaction investigation by its unique features (being able to test irradiated and toxic material and to use tritium in the plasma). The installation was completely refurbished during 2008, and the first plasma in the installation was achieved very early in 2009. Further improvement in the diagnostics for the device will then be installed in 2009 to have a complete experimental system ready in 2010;
- The new refurbished tritium laboratory, with a large walk-in booth and a large oven (for tests on detritiation), which will also be licensed to work with up to 1g tritium (or about 370 TBq). This limit will place the lab as the second civilian one in Europe in terms of licensed tritium content;

- The intention to develop a new diagnostics system based on fibre optics current sensor (FOCS) and to perform mock-up testing up to a scale 1:1 (or approaching) test in the technology hall of SCK•CEN.

The SCK•CEN is also involved in the "Broader Approach" as implementing agency for the Belgian State, but also for some validation activities and design developments for the IFMIF/EVEDA[1] project.

The SCK•CEN will participate in the validation of the European (and maybe the Japanese) concept of the High Flux Test Module for IFMIF by irradiation in a high flux reactor. It will develop the design of the Low Flux Test Modules and of the High Flux start up module in collaboration with CIEMAT (Spain). These activities just started at the end of 2008.

The different activities and projects are carried out either under support of the European Fusion Development Agreement (EFDA) or with the specific support of the Belgian Government for developing prototypes for ITER and for the Broader Approach in fusion.

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[1] IFMIF states for International Fusion Material Irradiation Facility and EVEDA for Engineering Validation and Engineering Design Activities

C. The year 2009

The SCK•CEN has set up in 2008 several strategic lines for its activities oriented towards the development of fusion energy. These lines can be summarized as follows:

- studies on structural and first wall materials for ITER and DEMO with special focus on the neutron irradiation effects and on plasma-wall interactions;
- studies and testing on the radiation resistance of instruments and components for the diagnostics and remote handling, with a special focus on optical instruments and components;
- studies and development concerning fusion radioactive waste management and minimization, with a special focus on the detritiation of solids and effluents;
- development of irradiation devices and systems for the testing of fusion materials under representative environment, with a special focus, from 2008 onwards, on the development and testing of irradiation modules for the IFMIF facility within the Broader Approach agreement.

These main development lines are also supported by the decision to develop new facilities for the execution of the strategic objectives. These facilities are mainly:

- the refurbishment and license renewal (with higher T level) of the tritium laboratory, including the installation of the plasmatron within the lab for tritium plasma experiments;
- the preparation and setting in service of the plasmatron VISION I for studies on plasma wall interactions, using deuterium and tritium plasma and toxic or irradiated target material. This activity being proposed to be integrated in the Trilateral Euregio Cluster (TEC) agreement.
- the preparation of the plasma Fibre Optics Current Sensor (FOCS) development, including the possibility to test it and qualify it on a real scale mock up.

Most of the activities reported here are in line with these strategic objectives and developments. Some supplementary work is still carried out also on socio-economic studies of fusion energy development, in the follow-up of preceding activities based on the know-how and skills acquired within the fission studies.

For what concerns the research and development around materials for fusion, the SCK•CEN concentrated its efforts on three different materials, namely the Reduced Activation Ferritic Martensitic steel (Eurofer), the Oxide Dispersion Steel ODS Eurofer and the Tungsten as plasma facing material. The effects of irradiation are studied by irradiation and testing; modeling of the mechanisms implied should allow extrapolating the results towards high irradiation doses and potentially high energy neutrons, not available yet for qualifying the materials. Therefore important efforts are delivered for the modeling of the material behavior and neutron damage effects.

The plasma-wall interaction is also a topic requiring a lot of development to understand the mechanisms and the effects on the materials at this important interface. New materials, like tungsten and tungsten alloys are currently considered as first wall material for future fusion reactors. But tungsten is still a material not well known and it is thus one of the objectives of the strategic lines to acquire a better knowledge of this material and of the effects of neutron irradiation on its properties and behavior. Moreover, the plasma-wall interaction (PWI) mechanisms can be simulated in non-tokamak plasma facilities dedicated to the PWI studies.

The installation and commissioning of the plasmatron VISION I will allow determining the effects of deuterium and tritium plasmas on the blanket candidate materials. The year 2009 has seen the first plasma generated in the facility and the installations of the main diagnostics. The first actual experiments could start at the end of the year or early next year.

The qualification of components and instruments in radiation environment is a topic gaining more and more attention as ITER procurements are foreseen in the near future. The effects of radiations on dielectric materials and optical components (windows, mirrors, fibre optics,…) were analyzed for a long time at the SCK•CEN, and a strong experience has been built on the testing methods and the way to harden components towards radiation. The development of radhard sensors is thus also part of the main objectives of the research unit. Within these, the development, testing and qualifying of a fibre optics current sensor (FOCS) for the plasma current appears to be an interesting diagnostic component to deal with steady state or very long pulse durations.

The refurbishment of the tritium lab was already started last year. Now, it has been confirmed that the plasmatron VISION I will take place in one of the two main rooms of the new tritium lab. This room is also being refurbished and should lead to an available space for the plasmatron beginning of 2010. In the meantime the first experiments and use of the first room of the tritium lab could take place. The main objectives of the SCK•CEN remains the development of methods and processes for the detritiation of solids and effluents. The new capacity of the lab and the new installed equipment will allow to carry out prototype scale experiments in controlled atmosphere.

Finally the development and engineering of irradiation devices for the fusion materials and components, which is a skill used for years at SCK•CEN in its fusion programme, will be used further for the design and engineering of test facilities for the IFMIF facility within the Broader Approach.

D. The year 2010

The year 2010 has seen the consolidation of the focusing of the activities at SCK•CEN in fusion R&D towards its main skills and strategic objectives. Behind the completion of former technology tasks from the old EFDA, SCK•CEN centred his activities around four main poles:

- the studies of the first wall of future DEMO facility and plasma wall interactions, using the recently refurbished plasmatron VISIONI;
- the study of the radiation resistance of optical and specific diagnostic components and the development and prototyping of a Fiber Optics Current Sensor (FOCS) for measuring Tokamak plasma current for long plasma pulses and without embarked electronics;
- the further study, by irradiation and mechanical testing but also by modelling, of the future structural material for a fusion plant, the RAFM Eurofer and the development and characterization of ODS-Eurofer;
- specific fusion socio-economic studies on fusion, based on the specific developments carried out for fusion and radioactive waste management.

But, besides these activities, carried out in the framework of the Contract of Association with Euratom, and mostly within EFDA launched tasks on Emerging Technologies, SCK•CEN is also strongly involved in the Broader Approach agreement and plays here the role of the "Designated Institution" for the Belgian State, having a coordinating and managing role for all Belgian activities in this agreement.

For what concerns the four main activity domains of the SCK•CEN, all situated around fusion technology development, the year 2010 has seen the following main achievements. The plasmatron VISIONI has been moved to the tritium laboratory and is now in preparation for its tritium plasma licensing. In the meantime, some scientific experiments with Deuterium plasma on fuel retention in Tungsten have already been made and have delivered some first promising results. Further development of plasma diagnostics are on-going to better characterize the plasma behaviour and the conditions to which the samples are exposed. A Phd on the modeling of the plasma in the test chamber has also been started.

The development of the Fiber Optics Current Sensor has been pursued and a test stand for the analysis of susceptibility to vibrations and temperature has been set up. This test stand will also allow to assess the possibility of distributed measurement along the fiber length. Another fiber optics neutron flux sensor, based on the Cerenkov effect, is also developed for the IFMIF facility within the Broader Approach, but if successful will be interesting for DEMO and maybe for ITER.

On the other hand, the study of the radiation resistance of mirrors for all kinds of diagnostics would also bring important data for ITER where several mirrors, facing the plasma are used for diagnostic purposes. The radiation testing of bolometers, electrical contacts and even electronics components, is a long standing activity at SCK•CEN, which will be important for ITER as well as for the DEMO developments.

The development of suitable structural material for the future DEMO facility and power plants, is a very long lasting programme, requiring a lot of efforts and presenting several challenges for the resistance towards neutron radiations, heat flux, high temperature etc. Simulating the environment by neutronic irradiation in fission reactors is currently a necessity, although the neutron dose and neutron energy cannot be simulated easily. It is here that modelling brings promising forecasts on the possibilities (in the future) to determine the needed properties and behaviour of materials, based on some limited testing, used to assess or benchmark the modelling results. Nevertheless, the way is still long towards a full understanding and modelling of all the processes happening in complex materials under irradiation. It was decided, at SCK•CEN, to focus the testing and modelling on a few material types only: the Reduced Activity Ferritic Martensitic steel (Eurofer) and the newly developed ODS-Eurofer.

Finally a new potential huge source of energy like fusion can also dramatically change the political environment and public opinion. It is thus important to evaluate the impact of such a new technology on the society in advance. These aspects are analysed in the light of similar studies carried out for the fission development and the radioactive waste disposal societal approach.

E. The year 2011

During the year 2011, the SCK•CEN has concentrated his activities on the four main poles defined in the former years, i.e.:

- the studies of the first wall of future DEMO facility and plasma wall interactions, using the recently refurbished plasmatron VISIONI, and through the collaboration within the Trilateral Euregio Cluster (TEC) agreement;
- the study of the radiation resistance of optical and specific diagnostic components and the development and prototyping of a Fiber Optics Current Sensor (FOCS) for measuring Tokamak plasma current for long plasma pulses and without embarked electronics;
- the further study, by irradiation and mechanical testing but also by modelling, of the future structural material for a fusion plant, the RAFM Eurofer and the development and characterization of ODS-Eurofer;
- specific fusion socio-economic studies on fusion, focused on an integrated sustainability assessment study, based on a reflection group meeting held in 2011.

But, besides these activities, carried out in the framework of the Contract of Association with Euratom, and mostly within EFDA launched tasks on Emerging Technologies, SCK•CEN is also strongly involved in the Broader Approach agreement and plays here the role of the "Designated Institution" for the Belgian State, having a coordinating and managing role for all Belgian activities in this agreement. With the strong decrease of the European funding for the Contract of Association and EFDA proposed tasks, the main activities in fusion have been indeed performed either for these Broader Approach activities or in preparation of proposals for F4E and ITER, as several calls interesting the SCK•CEN have been launched by both institutions this year.

Nevertheless, in 2011 the plasmatron VISIONI (which was moved in 2010 to its final location in the tritium laboratory) has started actual experimental studies on plasma wall interactions with Hydrogen and Deuterium plasmas. Several interesting results have already been obtained and the comparison of hydrogen isotopes retention at different fluxes could be investigated thanks to the collaboration with FOM and the collaborative use of Pilot-PSI and VISION I.

The development of the Fiber Optics Current Sensor has been pursued and the test stand for the analysis of susceptibility to vibrations and temperature has been used. The first studies on the distributed sensing of magnetic flux along the fiber have been started. Another fiber optics neutron flux sensor, based on the Cerenkov effect, is also developed for the IFMIF facility within the Broader Approach, and a prototype will be irradiated in the BR2 reactor with the other components of IFMIF.

On the other hand, the study of the radiation resistance of mirrors for all kinds of diagnostics would also bring important data for ITER where several mirrors, facing the plasma are used for diagnostic purposes.

The development of suitable structural material for the future DEMO facility and power plants, is a very long lasting programme, requiring a lot of efforts and presenting several challenges for the resistance towards neutron radiations, heat flux, high temperature etc. Simulating the environment by neutronic irradiation in fission reactors is currently a necessity, although the neutron dose and neutron energy cannot be simulated easily.

It is here that modelling brings promising forecasts on the possibilities (in the future) to determine the needed properties and behaviour of materials, based on some limited testing, used to assess or benchmark the modelling results. Nevertheless, the way is still long towards a full understanding and modelling of all the processes happening in complex materials under irradiation. It was decided, at SCK•CEN, to focus the testing and modelling on a few material types only: the Reduced Activity Ferritic Martensitic steel (Eurofer) and the newly developed ODS-Eurofer. But most of these activities would be done under F4E Grants (call still pending) or within the Broader Approach agreement. Only the modelling is still a strong part of the EFDA program and will make use of the different available super computer at FZJ and in Japan.

The societal aspects of fusion energy production is approached through various tools and methods. This year the SCK•CEN started his ISAF project on Integrated Sustainability Assessment exercise in the interest of energy governance at European level. The main aspect of this study in 2011 was the organisation of a reflection group meeting with an in-depth analysis of the results of the discussion of the group.

F. The year 2012

Since more than 35 years the SCK•CEN is active in the technology aspects of fusion energy. We focus our activities mostly on four main areas:

- the study and development of materials (structural and first wall) for fusion and the influence of neutron irradiations on their physical and mechanical properties;
- the plasma-wall interaction studies, mostly oriented towards the materials of the Plasma Facing Components (PFC) and the fuel retention aspects;
- the diagnostics, mostly focused on optical based systems and on the radiation resistance of materials, components and systems;
- and finally the waste management and recycling, by using the return of experience from our developments and studies carried out for fission power.

We are also active within the Socio-Economical research on fusion power (SERF) with a particular focus on the Social aspects and the acceptance studies of the future fusion energy.

Moreover, since several years, Belgium is a voluntary contributor to the Broader Approach agreement for fusion, for which the SCK•CEN has been designated by the Belgian Government as the agency for the management of execution of the Belgian commitments. The SCK•CEN is also contributing to this agreement by delivering irradiation services and engineering design studies for parts of the future IFMIF installation (International Fusion Material Irradiation Facility).

For the material, we continued most of the work done on tungsten and tungsten alloys, with even the development of new W-alloys, based on the introduction of oxides powders used as grain growth inhibitors. The mechanical characterization of ODS ferritic steel will be pursued by an irradiation carried out in the framework of the Broader Approach, embarking some samples useful for this programme. We also started some literature review on SiC/SiC composites, as potential new area of future developments. However, the main activity remains concentrated around the physical modeling of Fe-Cr alloys using various scales and various techniques to approach the actual behavior of ternary and further multiple components alloys. The applied techniques and methods will be tentatively applied to other metals like tungsten and tungsten alloys, candidate as first wall and structural materials of future power reactors.

The plasma facing components analysis continued by analyzing JET exposed samples. But the main developments remain centered around the plasmatron VISION I with a view on its use with tritiated plasmas. Improvements in plasma diagnostics and overall instrumentation are also parts of the current activities.

The development of the Fiber Optics Current Sensor for ITER remains one of our major activities in the domain of optical diagnostics. This comprises the various aspects of such a process, including the radiation resistance of the sensor, the testing of the remote replacement of the fiber and the studies and development of distributed sensing along the fiber path.

For what concerns the Public Information and dissemination of the knowledge, the SCK•CEN, in collaboration with partners from the Trilateral Euregio Cluster, was this year the main organizer of the 27th SOFT (Symposium On Fusion Technology), which was held in Liège, on the banks of the River Meuse. It attracted more than 1000 researches, scientists, engineers and industrials to exchange information about the construction of ITER and the developments of future fusion power plants.

Finally, the socio-economic research on fusion was continued within the integrated sustainability assessment for energy governance and the implications for the fusion option, by organizing a specific dedicated workshop on the usability of computer assisted scientific foresight in the context of energy policy. This workshop was very positive and its outcomes gave interesting conclusions.

In parallel with all the developments and studies carried out under the Contract of Association, the SCK•CEN continued also his participation to the Belgian Contribution to the Broader Approach. It started also some works for ITER through F4E Grants and service contracts, mostly oriented towards irradiation of components or consultancy on radiation hardening of components and systems.

G. The year 2013

The SCK•CEN has reinforced, during the year 2013, its implication in the main research topics it had selected and focused since several years, i.e.:

- The studies of materials, and their behaviour under neutrons irradiation, as well for structural materials as for armour materials and even some functional materials. These studies are based on a very long experience in this domain and allow to combine the practical tests (using our reactors and labs for highly active material testing) with modelling at atomistic and molecular level in order to define the laws governing these effects and be able to predict the behaviour in several circumstances.
- The development of radiation hardened diagnostics systems, and in particular those based on fibre optics. The development of a Fibre Optics Current Sensor (FOCS) and its application on various tokamaks in Europe is also part of the work carried out.
- The studies of plasma-wall interactions (PWI), mostly oriented on the side of the Plasma Facing Materials (PFC), and the tests of these materials under radiation or under exposure to simulated plasmas.
- Our research on the socio-economic aspects of fusion is carried on with the organisation of a small workshop and a satellite meeting at the ISFNT conference.

Beyond the Contract of Association, the SCK•CEN is also actively participating to the Broader Approach agreement for fusion, being the so-called “Voluntary Contributor Designated Institution” in charge of coordinating the whole Belgian contribution to the Broader Approach. Moreover the SCK•CEN is also actively involved in the IFMIF validation and engineering design activities, and in DEMO design activities concerning the Small Samples Testing Technologies.

The SCK•CEN is also involved in several grants and procurement (directly or indirectly) for ITER through contracts with F4E (Fusion for Energy), the European Domestic Agency for the procurements of ITER.

The end of the year 2013 was also focused on the new fusion management system at European level for the framework programme H2020 (cancelling of the system of Associations) and its implication at Belgian and SCK•CEN levels. We took this opportunity to set up an internal roadmap for the research on fusion materials, including PFC, able to answer some of the main questions and issues raised at European level for the future DEMO reactor.

II. Detailed report of last results – Annual Report 2013

Extract from Full annual report of 2013

Reference SCK•CEN-BLG-1096

1. Provision of support to the advancement of the ITER and DEMO Physics Basis

1.1 Power and particle exhaust, plasma facing components

1.1.1 PFC and tritium in JET tokamak: dust sample analysis (SCK•CEN WP nr 1.4.1)

EFDA Task nr: *JW13-NFT-Belg-39, JW13-FT-1.22*
Principal Investigator: *I. Uytdenhouwen (iuytdenh@sckcen.be)*
Scientific Staff: *W. Broeckx, H. Van Eyck*

OBJECTIVES

The objective of this task was to perform a feasibility study related to the analysis of the dust particles from JET. During the 2009-2011 shutdown interventions, dust/flakes were vacuumed from various positions in the JET tokamak and stored in different pots. All dust particles (mainly graphite) are Beryllium and tritium contaminated. This task will check if it is possible to capture the dust on silicon targets. If successful, the surface morphology and chemical composition of the dust particles will be determined by SEM/EDX or EPMA (depending on dust size).

ACHIEVEMENTS

The dust samples has been shipped directly from JET to SCK•CEN. Table 1 shows the characteristics of the dust related to the total activity of the tritium per gram and the measured elements with their content.

Total amount (g)	**tritium** (GBq/g)	**Element**	**Dust Sample** (mg/g)
2.26	0.35	C	796
		Be	0.60
		BeO	0.52
		Cr	17.0
Sample ID: "H"		Fe	1.90
		Ni	74.0
		Mn	0.75
		Al	0.52

Table 1: Dust characteristics of the sample ID "H".

The proposed procedure by JET was to deposit the dust on a silicon wafer and to heat the sample in a vacuum furnace (100°C for 1 hour). The dust which contains mainly carbon particles is contaminated with beryllium and tritium. Therefore the setup to deposit the dust must have the necessary safety precautions to protect the operators from the contaminated dust.

The entire setup has been installed in a fume hood of the tritium laboratory at SCK•CEN and the preparatory safety documents were written and approved.

Description of the setup

A vacuum furnace (Type VT6025, fisher Scientific) was purchased, commissioned and installed in the fume hood present in the tritium laboratory. The outlet of the furnace passes through a HEPA filter before going to the vacuum pump to capture possible release of Beryllium contaminated dust. The vacuum pump is a dry scroll pump from Edwards (XDS10_XDS5) The outlet of the vacuum pump is directed back into the fume hood as schematically shown in Figure 1. Connections to and from the vacuum pump are through the sidewall of the cabinet. Roughly half of the cabinet is available as a work area to prepare the Si disks before placing them into the furnace. A balance is positioned on the work area to measure the amount of deposited dust.

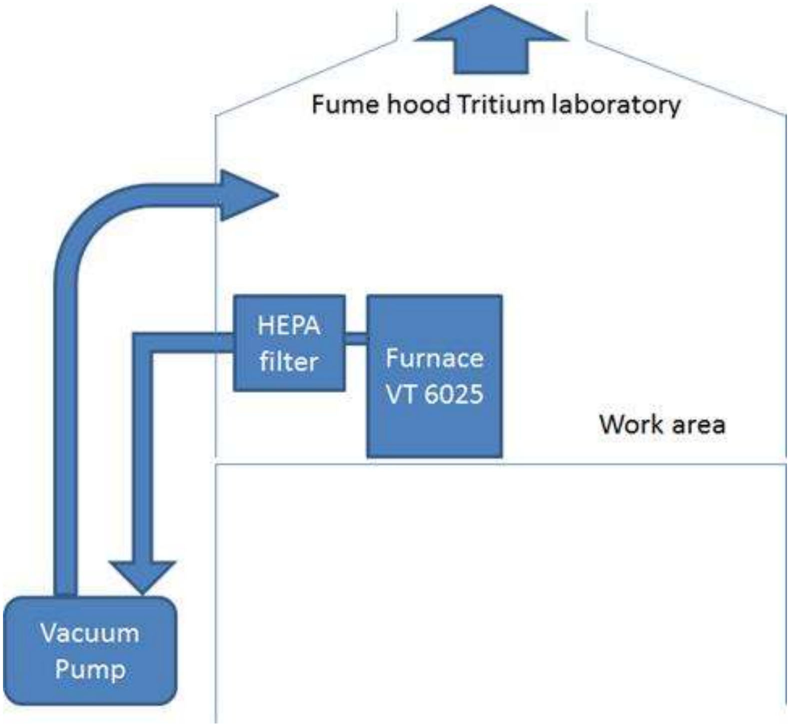


Figure 1: Schematic view of the installation of the furnace for the Be, T contaminated dust particles deposition on the Si sample in the tritium laboratory.

The proposed procedure was first validated with uncontaminated graphite dust. The chosen graphite dust had similar size characteristics as the dust sample retrieved from JET in order to simulate real dust behaviour. The first trial experiments were performed. The details of the trials with respect of sample temperature and time can be found in Table 2. Unfortunately, the graphite dust did not stick to the silicon wafers as expected independent on the temperature, time. Even when a small mechanical pressure was applied, the dust still did not stick to the Si surface. The reason for this should be checked and a new procedure should be proposed before future analysis on the surface morphology and chemical compositions can be made with SEM/EDS or EPMA.

Temp	Time	Result
100C	1hr	no sticking
200C	1hr	no sticking
200C	5hr	no sticking
200C	2hr (+ mechanical pressing)	no sticking
200C	2hr	no sticking

Table 2: Details of the furnace and results of the trial experiments on the sticking of the dust to the Si wafer.

PARTNERS

- EFDA-JET, Culham, UK

2. Development of plasma auxiliary systems

2.1 Plasma diagnostics

2.1.1 Radiation-induced Effects in Optic Fibres used for diagnostics (SCK•CEN WP nr 2.2.1)

EFDA Task nr:	*JW13-FT-4.33*
Principal Investigator:	*W. Leysen (wleysen@sckcen.be), A. Goussarov (agoussar@sckcen.be)*
Scientific Staff:	/

OBJECTIVES

The feasibility of performing radiation testing in JET was studied in the framework of JET Fusion Technology JW12-FT-5.47 task. The conclusion was that irradiation experiments in JET during the future D-T campaign are relevant with respect to the expected ITER radiation environment, when transient effects are of concern.

Optical fibres are an inherent part of the Fibre Optics Current Sensor (FOCS), which is considered for installation in ITER. The sensing fibre will be directly placed on the ITER vacuum vessel, where an intense nuclear radiation field will be present. Radiation hardness of optical fibres for FOCS was intensively studied and suitable fibres with respect to transmission preservation were identified. However, the effect of 14 MeV neutron radiation, in particular their influence on the Verdet constant, still requires due assessment. Therefore, the possibility to perform radiation hardness studies under relevant conditions is extremely appealing.

The objective is to install a FOCS system on JET to allow an assessment of the influence of the 14 MeV neutrons. Therefore, it is relevant to perform such measurement before the start of the D-T campaign to have reference measurements. During the DT campaign the influence of the 14 MeV neutrons can be assessed.

ACHIEVEMENTS

The goal this year was to install FOCS fibre around the JET Vacuum vessel to allow assessment of the influence of the JET environment on the performance parameters of the Fibre Optic Current Sensor (FOCS). Due to difficulties to procure a suitable fibre on time the JW13-FT need to be postponed. Now installation is planned in the next shutdown of JET planned in March 2014. For the installation of the FOCS fibre on the JET tokamak it was agreed to insert the FOCS fibre in a small stainless steel tube of 1,6 mm outer diameter.

PARTNERS

- JET, UK (P. Batistoni)

2.1.2 Radiation tolerance of optical sensors and equipment: design, system integration and testing - Design of a Fiber Optics Current Sensor (FOCS) (SCK•CEN WP nr 2.2.3)

EFDA Task nr:	*no EFDA task*
Principal Investigator:	*A. Goussarov (agoussarov@sckcen.be)*
Scientific Staff:	*W. Leysen, M. Aerssens*

OBJECTIVES

Precise measurements of the plasma current and vessel eddy currents are essential for operation of fusion devices since they allow the control of the plasma magnetic equilibrium. In the current ITER design the magnetic diagnostics comprise several subsystems, which have different designs but share one common feature: these are inductive sensors based on the generation of a voltage due to a change in the magnetic field. The current value is obtained by integrating voltage over time. In case of long term integration parasitic voltages induced by radiation, thermal gradients, etc., force the measurement drift away. Until now this wasn't a problem since realized plasma pulses are of (relatively) low power over short periods of time up to a few minutes during which the plasma current varies significantly. In case of longer discharges, like that obtained at Tore Supra, compensation techniques were developed to carry out precise measurements even with the presence of a relatively constant current. However the ultimate goal of future Burning Plasma eXperiments (BPX) is the operation in a quasi-stationary regime. The time-derivative sensors are have an inherent weakness for this latter. In addition, intense nuclear radiation with high-energy gamma rays and fast neutrons can significantly disturb the operation of inductive sensors by multiple irradiation effects such as radiation-induced voltages in the cables due to ionization (Radiation-Induced Electromotive Forces - RIEMF) and insulation degradation (Radiation induced conductivity - RIC).

At SCK•CEN an alternative to inductive sensors is being developed during a number of years. This system is the Fibre Optic Current Sensor (FOCS). FOCS uses optical fibres placed around the ITER Vacuum Vessel to measure the plasma current. Its operation is based on the detection of the Faraday rotation experienced by a polarized light beam in a fibre thanks to influence of magnetic field oriented along the fibre axis. FOCS allows a direct measurement of plasma current and therefore its sensitivity is independent on the plasma pulse duration. Theoretically, the system has many important advantages like a broad frequency bandwidth from DC up to MHz, low weight, small size, simple coupling with fibre-optic data links. It was also demonstrated that the radiation-induced absorption levels in radiation hard optical fibres are compatible with the requirements for signal transmission for the full ITER lifetime. In addition the same optical fibre which is used for the FOCS can potentially allow for distributed high-resolution measurement of other parameters, e.g. temperature, strain, or radiation dose. A distributed magnetic field measurement using the FOCS structure seems also possible. All these considerations resulted in the decision that FOCS should be a part of the ITER diagnostic system. In December 2011 the grant on the engineering design of FOCS was awarded to SCK•CEN. The end of the work is foreseen for 2014. A practical implementation of a FOCS in ITER requires consideration of various specific design issues with the account of the ITER harsh environment.

ACHIEVEMENTS

In 2013 a review of FOCS technical specifications and environmental constraints relevant to ITER implementation was performed. Nuclear radiation is an important part of the FOCS ITER environment. However available experimental and theoretical data allow assessment of the effect of nuclear radiation operation on the FOCS performance only from the point of view of transmission degradation. Data on the radiation effect on the Verdet constant are limited to one experiment with the total dose far too low to be relevant for the ITER environment. A theoretical assessment was performed. The conclusion is that the effect should not result in an unacceptable performance degradation.

The 2013 activity included preparation and participation in the FOCS Preliminary Design Review (PDR) for the front-end of the FOCS for ITER. This work was performed in collaboration with the IRFM of CEA, using their experience with the design of other diagnostic systems for ITER. The PDR took place at the ITER IO headquarter in Cadarache. Various aspects of the system integration were analysed, including design of the tube system on the Vacuum Vessel skin, penetration through the cryostat, the feed-through arrangement compatible with the ITER vacuum system requirements, installation procedures. The review panel identified a number of issues (Chits). Those issues must be resolved before the Final Design review, scheduled for January 2014.

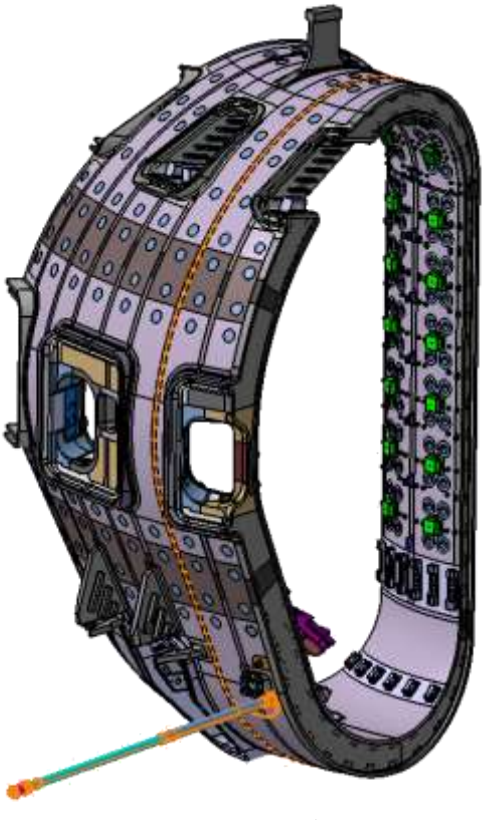


Figure 2: CAD model of the FOCS.

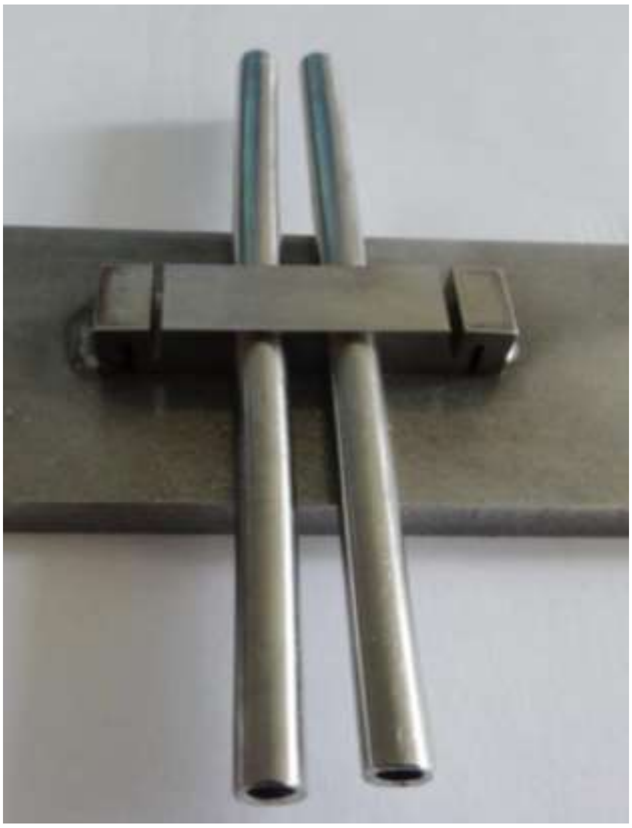


Figure 3: Mock-up of the FOCS tube clamp (SCK•CEN design).

PARTNERS

- University of Mons, Belgium (Prof. P. Mégret and Prof. M. Wuilpart)
- CEA Cadarache, France (P. Moreau, Institut de Recherche sur la Fusion Magnétique)

3. Development of concept improvements and advances in fundamental understanding of fusion plasmas

3.1 Theory and modelling

3.1.1 Characterization of the plasma behaviour in VISIONI (SCK•CEN WP nr 3.4.1)

EFDA Task nr:	*WP13-IPH-A01-P1-01*
Principal Investigator:	*O. Van Hoey (ovhoey@sckcen.be)*
Scientific Staff:	*J. Schuurmans, H. Van Eyck*

OBJECTIVES

Material migration and material mixture are crucial issues in tokamaks, strongly determining the lifetime of the reactor components. Therefore, one definitely has to make reliable predictions for these phenomena in the future ITER tokamak. Due to the complexity of the problem, this requires the combination of modelling with dedicated experiments.

A lot of modelling concerning local material migration has been performed already with the ERO code. In general this resulted in good agreement with experiments. A remaining issue is that of enhanced re-erosion of re-deposited layers. The local ^{13}C deposition efficiencies measured during $^{13}CH_4$ tracer experiments in TEXTOR, JET and AUG are very low. These low values can only be reproduced by the ERO code if one assumes an enhanced re-erosion of re-deposited carbon. This is not completely understood yet. However, it is an important topic because it influences strongly the local transport of material and net-erosion. Further studies are therefore necessary.

The objective of this project is to perform similar methane injection experiments in the VISIONI plasmatron (SCK•CEN) and model this with the ERO code. This will allow one to study the enhanced re-erosion of re-deposited layers in a different type of machine and check the general validity of this assumption.

ACHIEVEMENTS

ERO modelling for VISIONI requires detailed knowledge of the VISIONI plasma parameters. A study of the VISIONI plasma was performed by a combination of modelling and Langmuir probe measurements. A Monte-Carlo charged particle tracking code to simulate the VISIONI plasma has been written from scratch. A fluid simulation code was not possible for VISIONI because the low collisionality led us to believe that the energy distributions of the charged particles are not necessary Maxwellian as is assumed in fluid simulations. This was later demonstrated both by the simulations and the Langmuir probe measurements. Also directly solving the fundamental Boltzmann equation with a particle-in-cell Monte Carlo collision code (PIC-MCC) turned out to be impossible for VISIONI. The presence of the filaments and the magnets breaks the cylindrical symmetry of the device. Therefore, 3D simulations are needed.

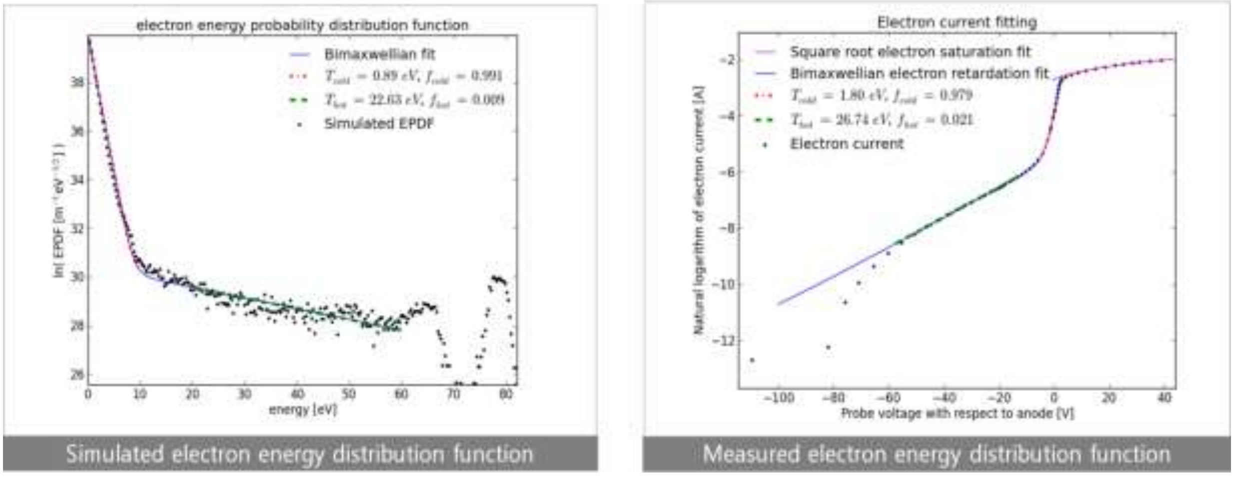
Furthermore, the scale of VISIONI is rather big in comparison with the typical Debye length in our plasma of about 0.1 mm. PIC-MCC would then require solving Poisson's equation on a huge spatial grid each time step to calculate the electric field self-consistently. As to our understanding this would lead to unrealistically long simulation times even for a massively parallelized code on the best HPC systems available these days. Hence, it was necessary to make approximations concerning the electromagnetic field: only the magnetic field of the permanent magnets and the tungsten filaments was taken into account, the width of the sheaths at the filaments and the vessel walls is assumed to be infinitely small and no electric field is taken into account in the bulk plasma. With these assumptions there is no need to solve Poisson's equation. Apart from these assumptions the code takes into account the most important physical phenomena occurring in the plasma. The tungsten filaments thermionically emit primary electrons, which are instantaneously acceleration in the sheath. The motion of the charged particles in the analytically calculated magnetic field is treated with the Boris-Leapfrog integrator. Both electrons and ions can undergo collisions with the neutral gas, which is treated as a constant homogeneous background. Some of the electron impact collisions lead to ionization and the release of new electrons and ions. Also recombination between electrons and ions is taken into account. All these collisions are treated with the very efficient Monte Carlo null collision method. Electrons can additionally undergo Coulomb collisions with each other.

These collisions are treated as a diffusive process in velocity space with the binary collision method from. The charged particles can also collide with the vessel walls. All ions colliding with the vessel walls are considered to be lost by absorption or neutralization. Electrons can only collide with the walls if their normal velocity is high enough to overcome the potential barrier of the sheath potential drop. This potential drop is determined by requiring charge neutrality in the plasma. If the electrons hit the wall, then reflection, absorption and secondary electron emission is treated with the model from Scholtz. The Boris-Leapfrog integrator is the most time consuming step. Therefore, this part of the code has been parallelized using the MPI standard. The output data files can be analysed automatically using a Python script. This results in a lot of interesting plots and numbers which allow studying the behaviour of the plasma in detail. Some of the output data is even not accessible experimentally.

In parallel with the development of the code a movable Langmuir probe has been fabricated and installed in VISIONI. It is located in the centre of the target plate at the top of the plasma chamber, at the location where normally the sample holder is installed. The probe is water cooled in order to withstand the harsh conditions during plasma exposure. The probe tip consists of a thin molybdenum cylinder with 1 mm diameter and an exposure length of 1 cm. The probe is fixed by a ceramic holder which is not in contact with the tip at the end of the holder in order to avoid uncontrolled increase of the effective probe surface area by deposition of conducting layers on the ceramic holder. The analysis of the Langmuir probe measurements can be done automatically with a python script. The analysis model used in this script is based on the most recent findings concerning Langmuir probe measurements.

Qualitatively the simulation results are in very good agreement with experimental findings. Most primary electrons are captured by magnetic mirrors close to the tungsten filaments. This leads to inhomogeneity of the plasma. The edges at the filaments have a much higher plasma density with an asymmetry caused by the gradient B drift. This was also observed in a picture of the light emission during an argon plasma. Further, H_3^+ appears to be the dominant ion in the simulations. This was also seen during measurements with the energy and mass quadrupole analyser. The electron energy distribution function turns out to be bimaxwellian both in the simulations and the Langmuir probe measurements, with a majority of the electrons belonging to a cold electron population with a temperature of about 2 eV and a minority of a few percent belonging to a hot electron population with a temperature of about 25 eV.

At the moment a more detailed parameter study is being performed with the code and the Langmuir probe with variations of neutral pressure, filament heating current and filament biasing. This is done with the aim to get a more quantitative comparison of the simulations and the Langmuir probe measurements.



Simulated electron energy distribution function

Measured electron energy distribution function

Figure 4: Left: Simulated electron energy distribution function, Right: Measured electron energy distrubution function.

Eventually, after benchmarking of the code results with the Langmuir probe measurements, the plasma parameters will be implemented in the ERO code together with the VISIONI geometry. In parallel we are already preparing the material migration experiments in VISIONI. Graphite samples will be exposed to the plasma. Different copper strips will attached at different locations to the plasma chamber walls. After the exposure the sample and the copper strips will be analysed with SEM, EDX, AES and profilometry to characterize the erosion in deposition of the carbon. The carbon samples have already been cut out. A cold finger is being manufactured to control the sample temperature because it greatly influences the chemical erosion of carbon.

With this study we hope, as the final objective of this work, to get a better understanding of the enhanced re-erosion issue described above.

PARTNERS

- FZJ (Forschungszentrum Jülich), Germany
- TEC (Trilateral Euregio Cluster)

4. Emerging technologies

4.1 Development of material science and advanced materials for DEMO

4.1.1 Neutron effects on first wall materials (microstructure, thermal shock resistance, mechanical properties): irradiation campaigns, microstructural analysis, mechanical testing, thermal heat load resistance - Tungsten and tungsten alloy development (material manufacturing, characterization, …) (SCK•CEN WP nr 4.1.1)

4.1.1.1 Understanding of intrinsic brittleness of W (dislocation movement by internal friction) (SCK•CEN WP nr 4.1.1)

EFDA Task nr:	*WP13-MAT-HHFM-01-01*
Principal Investigator:	*M. Konstantinovic (mkonstan@sckcen.be)*
Scientific Staff:	*H. Sheng, I. Uytdenhouwen*

OBJECTIVES

Understanding the intrinsic brittleness of W and its alloys and further embrittlement due to recrystallization by identifying the intrinsic defect evolution and by investigating the dislocation movement with internal friction. With respect to the understanding of brittleness in nuclear materials, the most important issue is to establish the link between the microstructural/nanostructural properties and macroscopic behaviour. This is essentially a mesoscale problem which can address by analysing the influence of various defects to the dislocation motion. Unfortunately, this field is the one with poorest possibility for comparison between calculations and experiments. The reason for this lies in the fact that the transmission electron microscopy (basic experiment for observation of dislocations) provides limited spatial information and is essentially a static experiment. In order to overcome these difficulties we propose to utilize the internal friction (IF) method to study dislocation dynamics. The IF technique provides, through the measurements of relaxation processes, various parameters characterizing dislocation motion such as activation energy, distribution of activation energies and dislocation density.

The main objective is to start with the basic characterization of the defects and dislocation movement on selection of standard deformed W and W alloys. For that purpose, IF spectra of the samples with several heat treatments on the various grades are measured and analysed. Since all alloys have undergone a strong deformation during the manufacturing process, the relaxation peaks that could be related to dislocation movement in the IF spectra are addressed.

ACHIEVEMENTS

High frequency setup

The dynamic Young's modulus and the damping were measured by the IMCE HTVP 1750 measurement technique which is equipped with a thermal controller. Typical heating and cooling rate were 3°C/min. The suspension of the sample is accomplished by carbon wire holding system. The mechanical excitation is achieved by a ceramic rod hitting automatically the specimen from below at the centre at a predefined interval (every min). An inserted alumina tube (from the top) close to the specimen surface, guides the acoustic wave from the specimen out of the furnace to the microphone, used to record the motion

Low frequency setup

The internal friction low frequency measurements are performed in an inverted torsion pendulum operating in free vibration at about 1.8 Hz in the temperature
range between 100 and 600 K. From the free decay signal, the resonance frequency and the internal friction coefficient are determined. The measurements have been performed at a strain amplitude of about 10−4, in a He atmosphere with a heating
rate of about 1.5 K/min, and no magnetic field is applied.

Results

The internal friction (damping) spectra of double forged tungsten specimen measured at low and high frequencies in the temperature range between 100 K and 1800 K are shown in Figure 5. The result of the fit including several relaxation peaks (Gaussian) is also presented. The features which are observed can be described as follows [42-44]:

(1) Double peak structure at about 200 K can be ascribed as thermally activated edge dislocation motion, also known in the literature as alpha-peaks.

(2) The 650 K peak corresponds to the Snoek-carbon relaxation.

(3) Broad peak at about 800 K originates from thermal activation of the screw dislocation motion, gamma-peak.

(4) Discontinuity at about 1200 K is typical for the phase transitions.

(5) The peak at about 1550 K visible as a hump in the high temperature background.

(6) Recrystallization peak at about 1680 K.

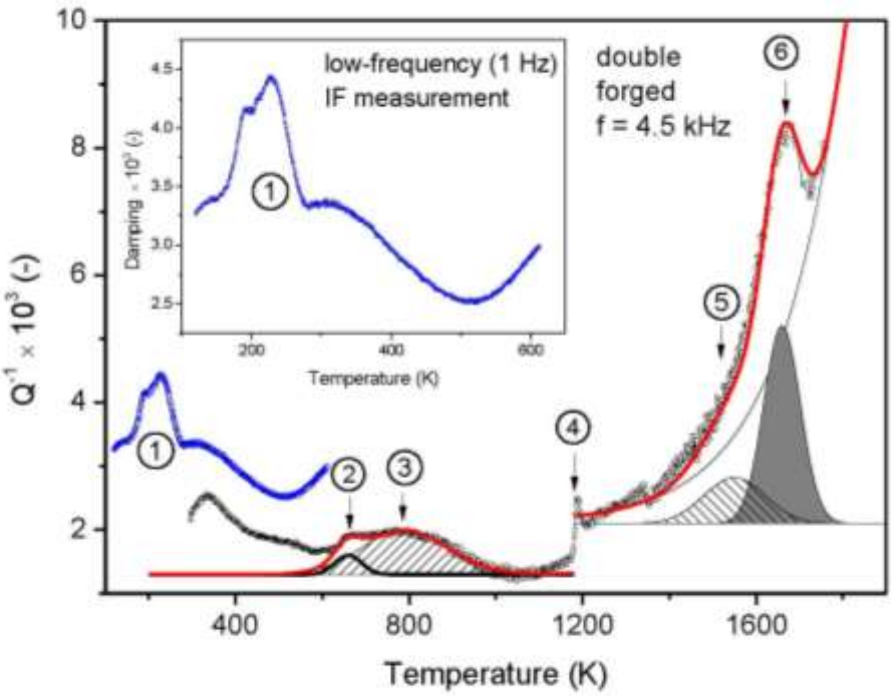


Figure 5: Internal friction spectra of double forged tungsten measured at 4.5 kHz. Inset: The spectra measured at 1 Hz.

In the following we focus our attention to the properties of the recrystallization peak (peak 6) and their correlation with tensile test results. In tungsten, as in all other metals, recrystallization affects the damping through evolution of the dislocation structure. Namely, internal friction coefficient is sensitive to the dislocation density and the mean dislocation loop length. During recrystallization an increase in internal friction can be interpreted as due to an increase in dislocation loop length / dislocation mobility which is required for the nucleation of the new grains. The subsequent decrease of the internal friction coefficient occurs due to decrease in dislocation density. Because of that the peak 6 is not a consequence of relaxation process, so it should not depend on frequency. This indeed confirmed by performing the measurements at different frequencies, see Figure 6.

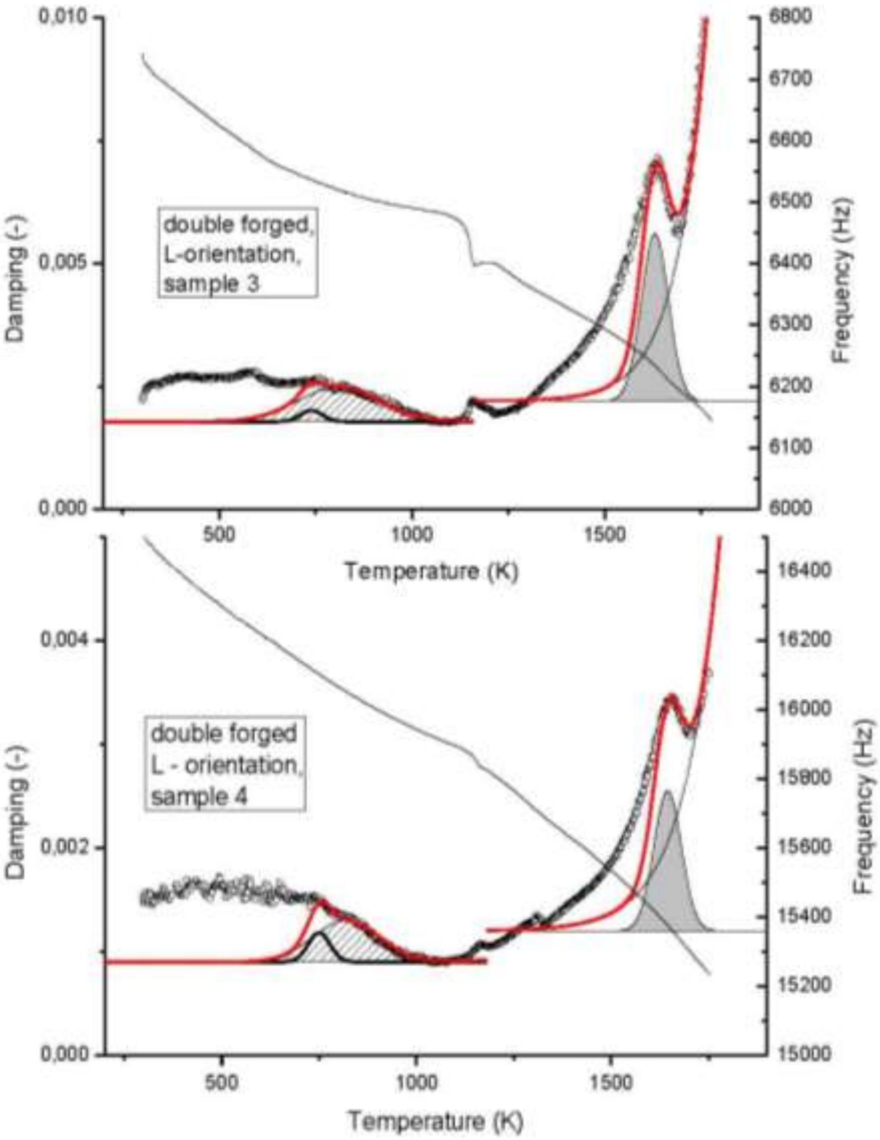


Figure 6: The damping of the double forged tungsten measured at two different frequencies.

The electron back scatter diffraction (EBSD) or orientation imaging microscopy (OIM) measurements are also performed and the results are presented in Figure 7. OIM allows assessing the grain boundary character in the microstructure, i.e. the angle of disorientation between neighbouring grains. In general, low angle grain boundaries (LAGB) with a disorientation angle 2-15° are differentiated from high angle grain boundaries (HAGB) with a disorientation angle > 15°. The measured grain boundary character distribution in both orientations is presented in Figure 7. We found that the majority of the grain boundaries are LAGB, and that their numbers in the L and T direction do not differ to each other by more than 10 % [45]. This is found to be in a very good agreement with the recrystallization peak intensities which are proportional to LAGB densities, see Figure 8.

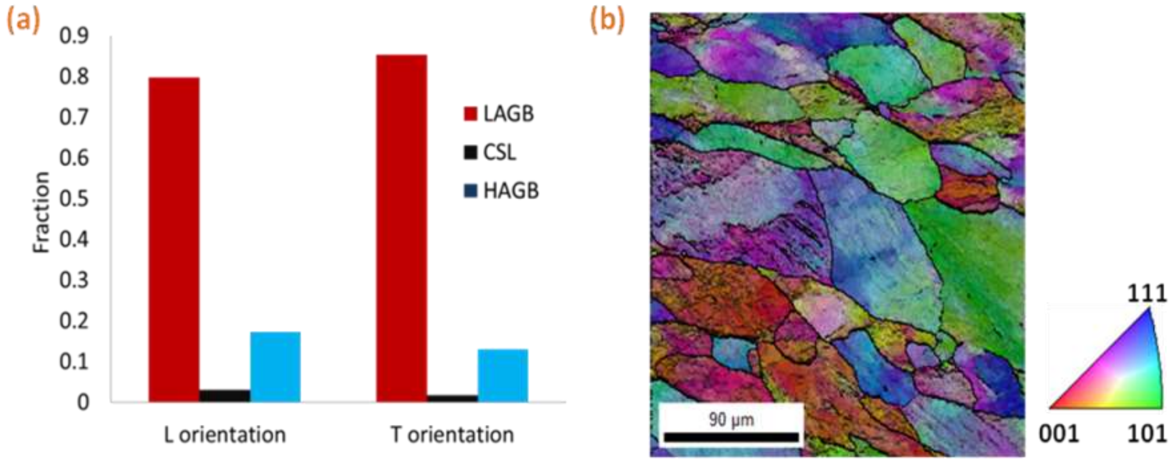


Figure 7: (a) Grain boundary distribution in the L and T directions of double forged tungsten. (b) Image quality and IPF map of double forged tungsten in the T orientation.

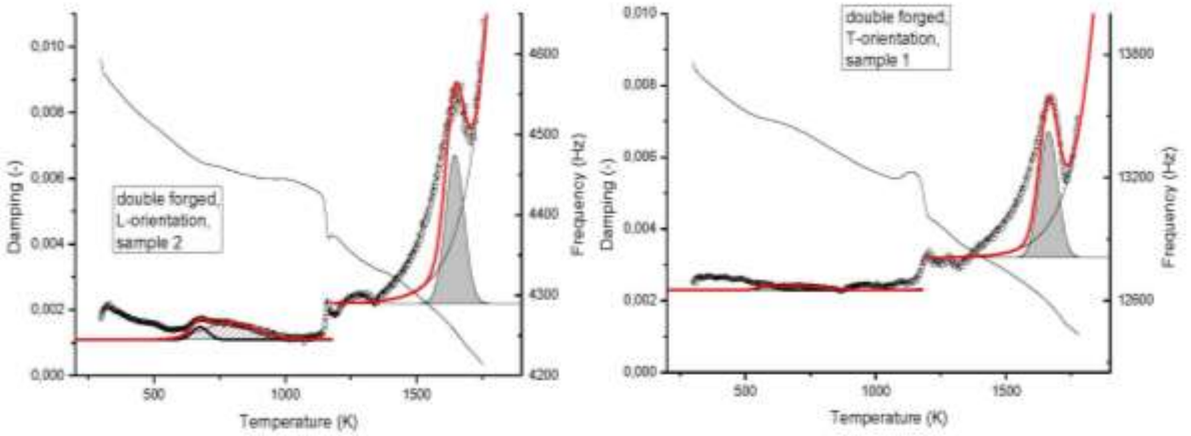


Figure 8: The internal friction spectra in tungsten for L and T orientations.

Interestingly, the internal friction spectra of potassium doped material do not exhibit the recrystallization peak, see Figure 9. Typically, due to brittleness of tungsten dopants such as potassium are used to increase the recrystallization temperature of the tungsten. Indeed, the recrystallization peak in the internal friction spectra is shifted towards higher temperatures, and becomes invisible due to high temperature background.

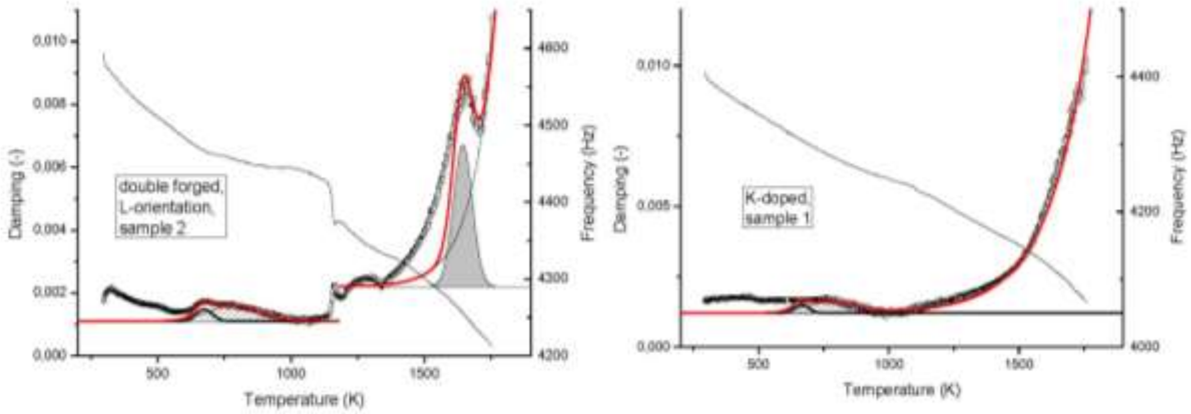


Figure 9: The internal friction spectra nominally pure tungsten and potassium doped tungsten.

The effect of potassium doping, regarding the increase of the recrystallization temperature, is correlated with macroscopic mechanical properties. The yield stress as a function of the temperature for nominally pure tungsten and potassium doped tungsten is shown in Figure 10. By increasing the temperature the yield stress decreases since thermal fluctuation help dislocations to overcome Peierls potential barrier. The sharp drop of the yield stress is observed in double forged tungsten at the temperature of about 1500 K. This temperature can be nicely correlated with recrystallization peak at about 1650 K. In potassium doped tungsten the sharp drop of the yield stress is not observed due to shift of the crystallization temperature towards higher temperatures.

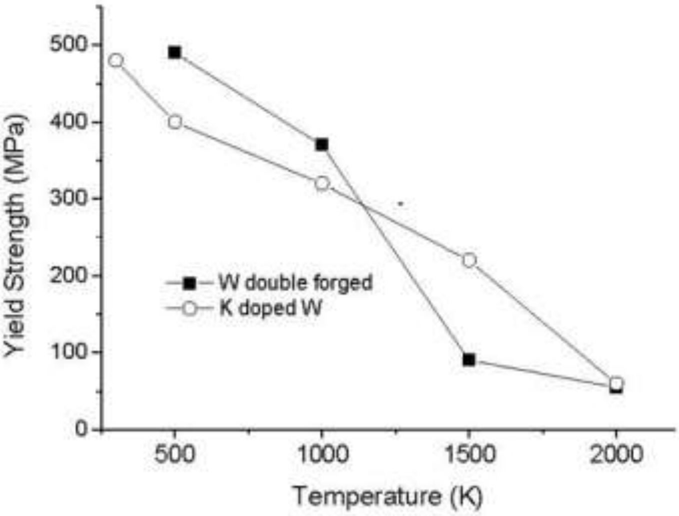


Figure 10: The temperature dependence of the yield stress in nominally pure and potassium doped tungsten.

CONCLUSIONS

Mechanical spectroscopy/ internal friction measurements provides useful data on dislocation dynamics, which can be linked to macroscopic mechanical behaviour of the W and W-alloys. Recrystallization peak, observed at about 1650 K in double forged W is shifted to higher temperature by doping with K. Consequently, thermal – athermal change of the mechanical behaviour shifts to higher T by K doping.

PARTNERS

- KUL (Catholic University Leuven), Belgium
- TEC (Trilateral Euregio Cluster)
- UGent, Belgium

4.1.1.2 W&W alloy detailed characterization (Development and Characterization of W-TiC alloys) (SCK•CEN WP nr 4.1.1)

EFDA Task nr:	*WP13-MAT-HHFM-01-02*
Principal Investigator:	*I. Uytdenhouwen (iuytdenh@sckcen.be)*
Scientific Staff:	*W. Broeckx, H. Van Eyck*

OBJECTIVES

The final objective is to develop a new and improved W-alloy with respect to their thermal shock resistance, high temperature strength, low temperature ductility and recrystallization behaviour.

- Verification of the effect of the TiC addition
- Specific qualification and characterization of the most promising grades by high temperature mechanical tests and e-beam heat loading

ACHIEVEMENTS

In a previous task, several W alloys with TiC, Ta and Re were successfully produced. It was found that oxidation of the powder should be avoided and that there was some contamination of the ZrO balls.

Three new different W-TiC grades were produced at KULeuven with pulsed electric current sintering (PECS) [46]. The powders were mechanically alloyed in a Retsch PM400 planetary mill in 2 stainless steel containers each filled with TZM milling balls in order to avoid the Zr contamination. The containers were filled in a glove box under an argon atmosphere. The preparation of the SPS moulds was also done in this glove box to avoid oxidation of the fine milled tungsten powder. The settings used for the milling and the PECS were similar to the previous manufactured discs and are described below.

Milling settings:

- 250 rpm
- 2 hours

Pulsed electric sintering settings:

- Sintering temperature 1800°C
- Sintering pressure 80MPa
- disc size Ø 40mm x 5mm

In Figure 11, a typical sintering graph is shown with the applied temperature and pressure profile during the PECS of the W-Ta-TiC (Starck) disc. During warm-up a force of 0.4MPa is applied on the mould. When a temperature of 1800°C is reached the force is increased up to 80Mpa, until the displacement (flow of the material) stabilizes. This indicates that the maximum density of the powder is reached.

The TiC power is supplied by H.C.Starck (powder: TiC STD 120) because the TiC powder from Ceramyg is no longer commercially available. Two W-Ta-TiC grades were made to discriminate between the effect of the TZM milling balls compared to previous ZrO and the different TiC sources. The density was measured by using Archimedes' principle in ethanol and results are shown in Table 3.

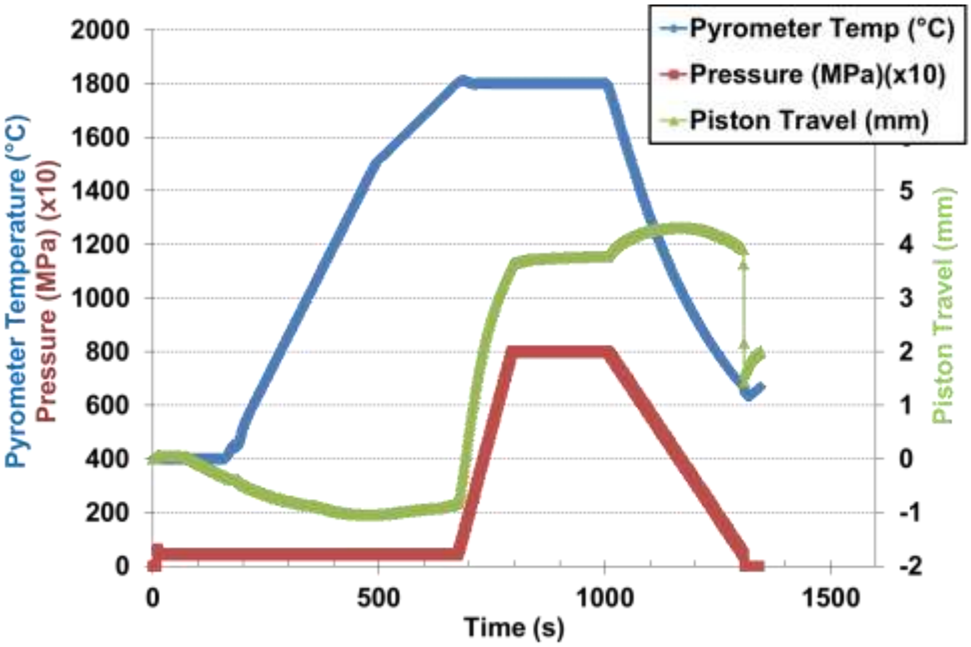


Figure 11: Temperature, pressure and displacement profile of a W-Ta-Tic disc (Stark) during PECS.

Grade	**Ta (wt %)**	**TiC (wt %)**	**TiC Supplier**	**Density (g/cm^3)**	**% of TD**
W-5Ta-0.5TiC	5	0.5	Ceramyg	17.812	94.6%
W-5Ta-0.5TiC	5	0.5	H.C. Starck	17.607	93.5%
W-0.5TiC	0	0.5	H.C. Starck	17.503	92.2%

Table 3: W-(Ta)-TiC grades and densities.

It can be seen from the densities that no full densification was reached. However the porosities are closed since the mass in the ethanol was stable.

PLANNED ACTIVITIES

The three obtained discs will be further characterized in detail. First the basic properties will be investigated:

- Characterization of the contamination from the milling balls and homogeneity of the added alloys with XRF;
- Grain size analysis of the final sintered materials by metallography (SEM);
- Hardness.

Several batches will be produced from the most promising batch. This is, the batch that has a microstructure without large Mo contaminations from the milling balls and if it is homogenous (no agglomerates of TiC or Ta). It should be checked if the density can be increased as well by additional treatment of the discs. Those should be investigated in future (outside the scope of this task) in terms of advanced mechanical properties such as low and high temperature tensile testing and bending. Finally thermal shock resistance and retention characteristics should be examined as well.

PARTNERS

- KUL (Catholic University Leuven), Belgium
- TEC (Trilateral Euregio Cluster)

4.1.1.3 Microstructural investigation of material degradation of different W grades under combined transient and steady-state heat loads (SCK•CEN WP nr 4.1.1)

EFDA Task nr: *WP12-IPH-A11-1-06/BS-01*

Principal Investigator: *I. Uytdenhouwen (iuytdenh@sckcen.be)*

Scientific Staff: *W. Van Renterghem (wvrenter@sckcen.be)*

OBJECTIVES

The objective of this task is to simulate the performance of plasma facing components under ITER relevant transient thermal loads and to improve the knowledge base for ELM-like transient heat loads with high cycle numbers. In order to identify the effect of the thermally induced material degradation on the microstructure, the material tested in the JUDITH I facility was sent to SCK•CEN for transmission electron microscopy (TEM) analyses to observe changes in the defect structure in the subsurface area, where the heat load is maximal.

ACHIEVEMENTS

Five samples of the reference double forged tungsten grade (as-received) were provided to SCK•CEN by FZ Jülich after thermal shock loading [47] with the JUDITH I electron beam. Five different exposure conditions were applied, simulating relevant ELMs in ITER without trespassing the cracking threshold in order to be able to investigate the damage in the microstructure only by the thermal stresses. The parameters differed in the heat flux factor (absorbed power density), in the steady state heat load (SSHL: base temperature of 200, 400 or 700 °C) and the number of pulses, as given in Table 4. Afterwards, the integrity of the tungsten surface was analysed with scanning electron microscopy (SEM). TEM was applied to visualize the defect structure in the region of the maximal heat load. The defect structure was compared to the microstructure from a part of the sample that was not affected by the electron exposure.

Sample ID	SSHL (MWm^{-2})	Surface base temp.	Heat flux factor ($MWm^{-2}s^{0.5}$)	Number of pulses
6_0_1E5	-	200°C	6	10^5
6_0_2.5E5	-	200°C	6	$2.5*10^5$
6_10_1E4	10	700°C	6	10^4
9_5_1E3	5	400°C	9	10^3
9_5_1E4	5	400°C	9	10^4

Table 4: Exposure conditions in JUDITH I.

The SEM investigation, shown in Figure 12, revealed that surface roughening occurred on all samples. A higher heat flux factor, a higher steady state heat load and an increased number of pulses resulted in an increase of the roughening. Moreover, micrometre sized cracks were found in all samples apart from sample 6_0_1E5.

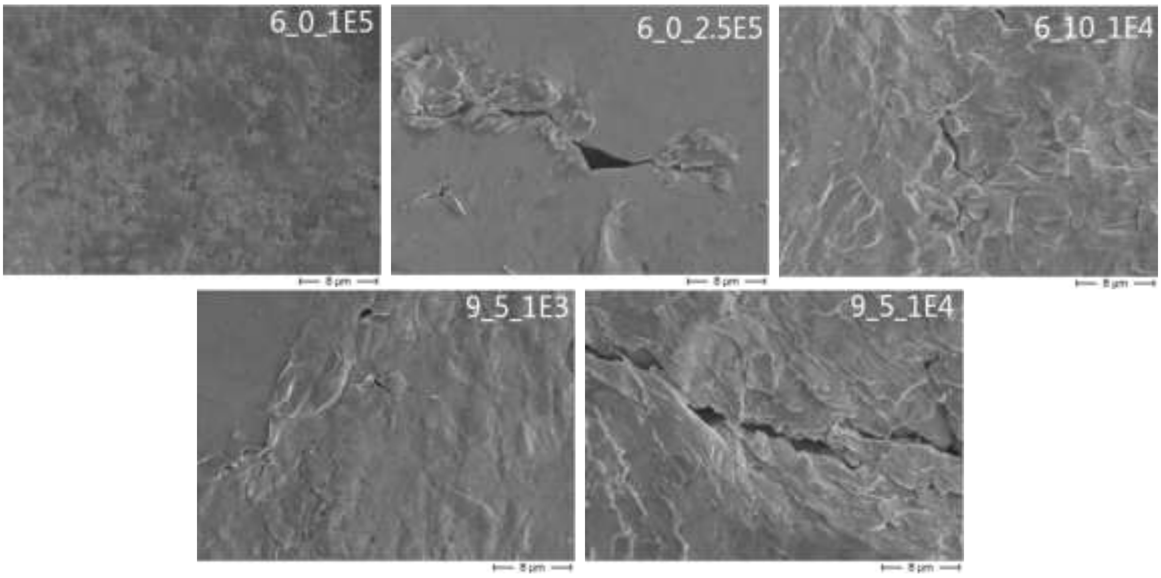


Figure 12: SEM images showing the surface modification after e-beam exposure.

The samples for TEM were prepared to analyse the material about 10 µm below the exposed surface. As a reference, the defect structure of a sample taken about 1.5 mm below the exposed surface was analysed as well. A large amount of small-angle grain boundaries, creating sub-grains with an average size of 2 – 3 µm, were found. In the interior of the sub-grains, a few isolated line dislocations were observed.

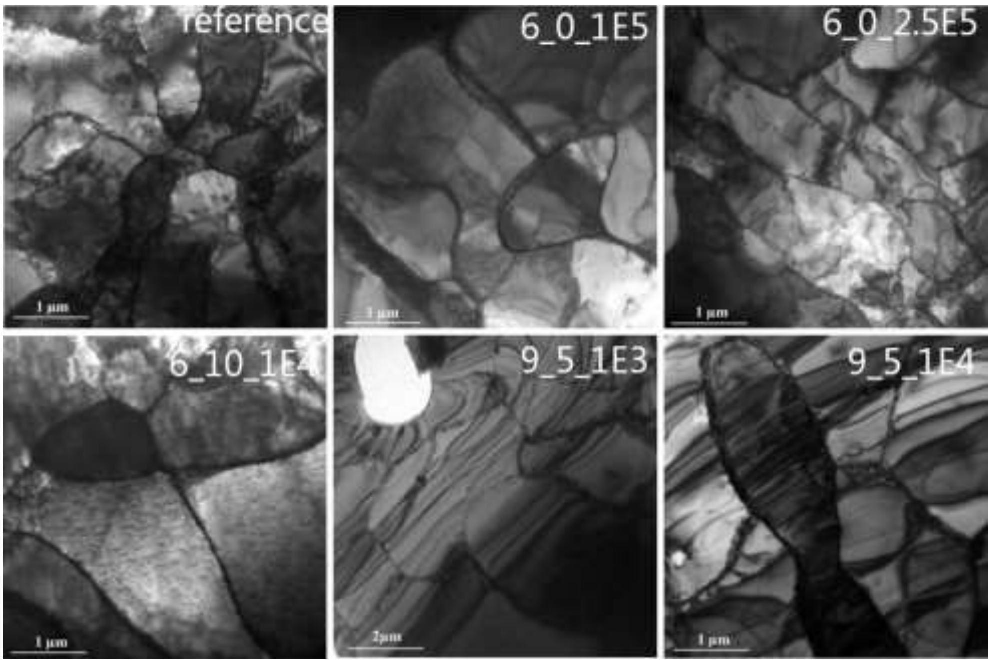


Figure 13: Low magnification TEM images revealing the grain boundary structure of the reference material and the samples after exposure.

The defect structure in the exposed part of the material, is very similar to the reference. As shown in Figure 13, the small-angle grain boundaries are still present. Differences in sub-grain structure, if any, are too small to be quantified. A higher amount of line dislocations, Figure 14, were found in the samples that showed the least cracking. It is, however, difficult to relate this effect to the electron exposure as only the final defect structure, and not the evolution, can be observed.

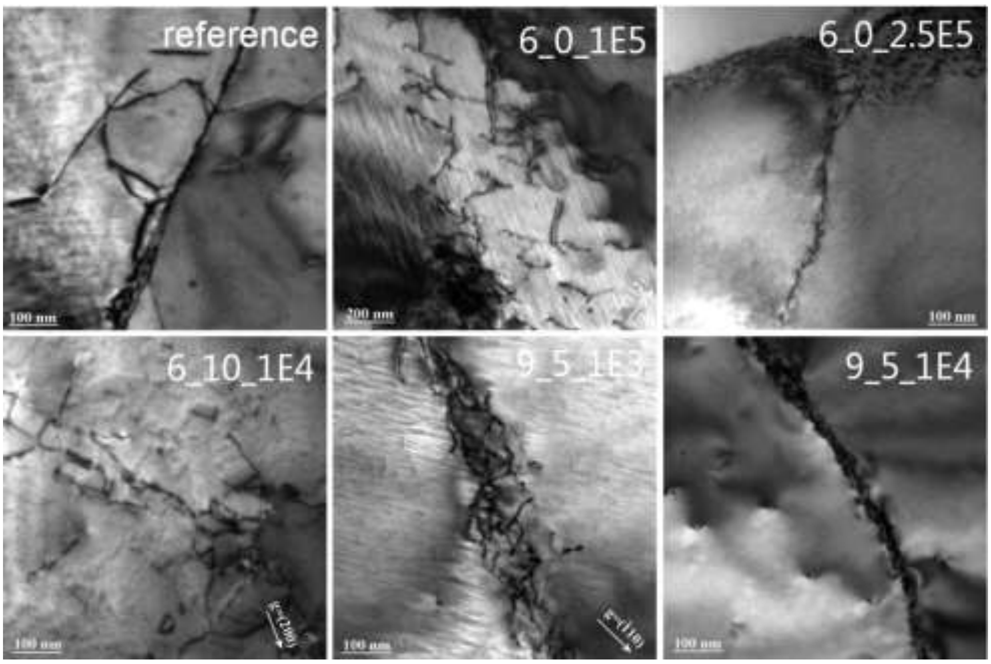


Figure 14: TEM images of the dislocation structure in the reference and exposed samples.

Contrary to a recrystallized material, the defect structure of the stress relieved double forged pure tungsten material in the sub-surface region, where the heat load is maximal, is not affected by the electron beam exposure under conditions that are relevant to simulate ELMs in ITER. Only the surface is affected showing roughening and micro-cracking. The main reason is that the as-produced microstructure contains already a high amount of small-angle tilt boundaries, which can accommodate for defects resulting from the heat load.

PARTNERS

- FZJ (Forschungszentrum Jülich), Germany
- TEC (Trilateral Euregio Cluster)

4.1.1.4 W surface morphology changes under D, He, D/He plasma exposures – Effect of nitrogen seeding on the surface morphology and on the deuterium retention of W (SCK•CEN WP nr 4.1.1)

EFDA Task nr:	*WP13-IPH-A01-P3*
Principal Investigator:	*I. Uytdenhouwen (iuytdenh@sckcen.be)*
Scientific Staff:	*Y. Zhang (Mcs thesis student UGent), W. Broeckx, H. Van Eyck, W. Van Renterghem*

OBJECTIVES

In order to reduce the severe heat loads on the diverter areas in ITER, it is foreseen to have detached and recombining plasma operations. In addition impurity seeding can be used in ionizing plasmas as a radiator to obtain cold and dense diverter plasmas. N_2 (nitrogen) gas has been proposed, apart from noble gases, due to comparable ionization characteristics of N and C.
The objective of this task is to understand the effect of nitrogen seeding on the surface morphology and D retention characteristics of a pure W grade. Several questions should be addressed:

- Is there a bonding or an interaction of the nitrogen with the W surface and how does it look like?
- Does the changes in the surface chemical composition have an effect on the total D retention and the trapping sites?
- Does a history of nitrogen implantation in W have an effect on the D retention?
- Is there an effect of the seeding ratio (percentage of N compared to D)?

The effect of exposure temperature on the retention in pure W under 100%D plasmas was investigated for low-flux exposures in VISIONI.

ACHIEVEMENTS

In total 11 samples were exposed to a variety of plasma compositions in VISIONI. A summary of the plasma compositions, obtained flux, fluence and specimen temperature during exposure can be found in Table 5.

spec#	exposure#	history	plasma		flux [m-2s-1]	fluence [m-2]	Tprobe [K]
0	58	-	none	reference	no plasma exposure		
1	66	-	1%N	mixture	3.40E+21	1.00E+25	626.9
2	64	-	5%N	mixture	2.90E+21	1.00E+25	578.5
3	63	-	1%N	mixture	2.00E+21	6.60E+24	525.9
4	62	-	100%D	reference	2.90E+21	1.00E+25	577.2
5	56	N implantation	100%D	history	2.90E+21	9.90E+24	634.8
6	65	nitride furnace	100%D	history	2.40E+21	9.90E+24	604.1
7	61	N implantation	100%D	history	2.40E+21	9.90E+24	649.6
8	57	-	100%D	reference	8.20E+20	2.90E+24	523
9	81	-	1%N	mixture	7.90E+20	2.80E+24	523.9
10	82	-	5%N	mixture	1.00E+21	3.60E+24	517.6
11	83	-	100%D	reference	9.00E+20	3.30E+24	509.5

Table 5: Summary table on pre-treatment of the samples, main plasma composition, flux, fluence and probe temperature.

Three different campaigns were proposed. The reference scan exposed the samples to pure deuterium plasmas with a variation in the sample temperature. The history campaign gave a pre-treatment to the samples by exposing them to a nitrogen plasma or a hot nitrogen gas in a furnace (600K). Finally the mixture campaign was performed to investigate the real effect of the added nitrogen concentration (1%N or 5%N) to the pure deuterium background plasma.

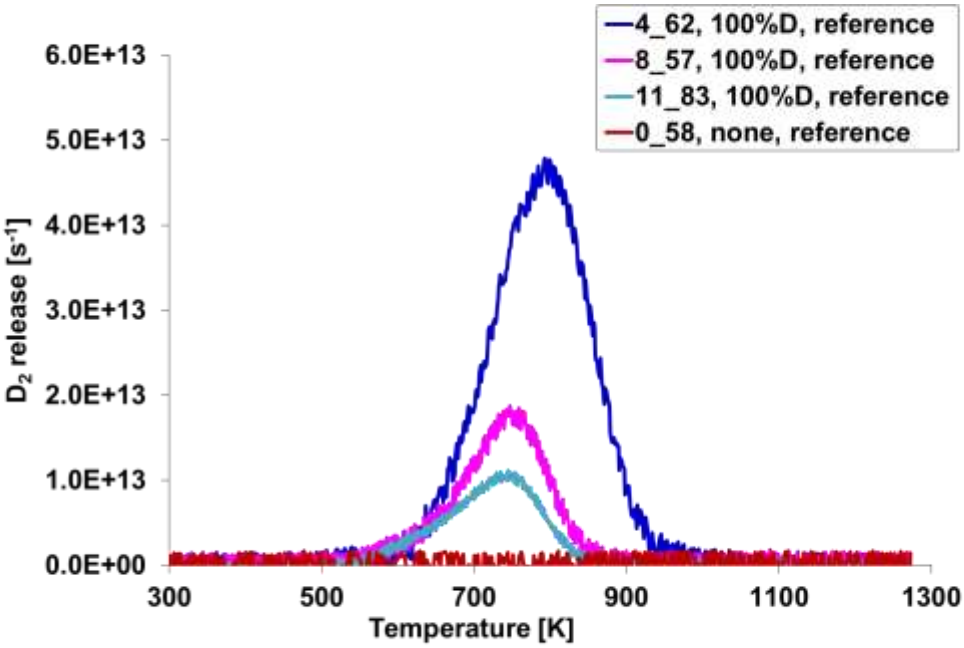


Figure 15: TDS D_2 release spectra of pure W samples after a 100%D plasma exposure.

Three reference samples (62, 57 and 83) were exposed to a pure 100%D plasma with varying specimen temperature (~580K, ~520K and ~510K). An increase in total retention was found for increasing surface temperature (see Figure 15). There is an obvious shift of the peak only when the exposure temperature was raised from 520K to 580K indicating that new traps were filled for the sample at the highest exposure temperature. Other mechanisms of trapping were also found for WTa samples (see report PhD thesis Y. Zayachuk) within this temperature ranges.

Within the history campaign, three samples (56, 61 and 65) were pre-treated by a nitrogen plasma (56, 61) or a hot nitrogen gas in a furnace at 600K (65). The two implanted nitrogen samples showed remarkably different D retention behaviour (see Figure 16a).

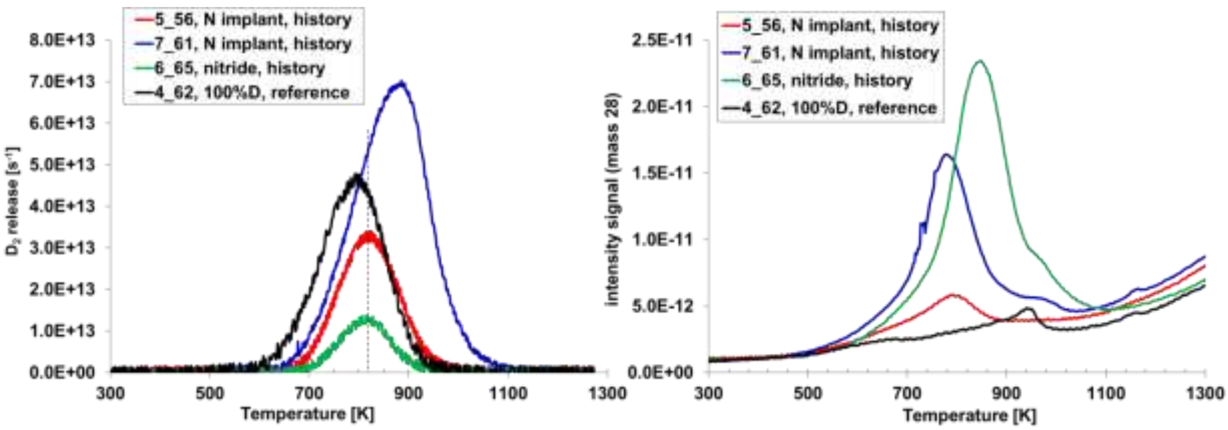


Figure 16: TDS spectra with D_2 release of the history samples and the intensity signal graph of mass 28 (N_2).

The first sample 56 was exposed to a nitrogen plasma and was then stored for some time in air. While the second sample 61 was exposed to the D plasma immediately after the N implantation. The sample with immediate consecutive plasma exposures had a large increase in total D retention and even a shift in the peak. More detailed analysis in future will show if this is due to a shift in the activation energy of the trap site or if a secondary trap site was formed. It could be expected that the N implantation creates additional trap sites. The total deuterium retention of the 56 sample is slightly lower than the pure reference sample without any pre- treatment (Figure 16a).

It can be concluded that the storage in air has removed a large part of the nitrogen inside the W sample before the D exposure. This is confirmed by the release of the nitrogen from the bulk of the sample which is significantly lower for the 56 case (Figure 16b). Surprisingly the nitride sample 65 had even lower total retention values while the bulk contained a rather large amount of nitrogen. All surfaces were investigated with XPS after D exposures and before. Even though samples 61 and 56 had higher nitrogen, no large N1s peak could be found for all three conditions (see Figure 17b). So the available nitrogen is mainly stored deep within the bulk.

However, still some tungsten nitride was formed containing between 2-4 atomic% of the surface composition. A detailed analysis by peak fitting is not justified due to the small signal-to-noise ratio. But the peak shapes clearly indicate that the N1s showed more than one peak. This can be caused by different tungsten nitride stoichiometry, or by nitrogen in different local atomic arrangements within the tungsten lattice. For all three conditions a peak around 397.6eV can be found which is typical for W nitrides. Specimen 65 and 61, who still had a large amount of nitrogen in the bulk, showed a peak around 400.15eV due to surface adsorbed N_2. This peak could not be found in the 56 sample with a very low nitrogen content.

However a shift to lower binding energies of 399.63eV was detected, which is often correlated to N atoms or molecules in the grain boundaries of WN_x. This means that the free adsorbed N_2 was removed from the surface and the bulk due to the time lag between implantation and D exposure.

The remaining Nitrogen was trapped at the grain boundaries, therefore blocking trap sites for the incoming deuterium atoms resulting in a reduced total D retention even compared to samples without any nitrogen pre-treatment. The additional decrease of retention for the 65 sample should be probably found in the fact that some annealing occurred during the nitrification treatment in the furnace and no additional defects were created due to implantation as was the case for the 61 sample. In addition the XPS W4f spectra showed some peak shifts for the 65 nitrided sample, indicating that the furnace treatment resulted in a different top surface compared to plasma implantations.

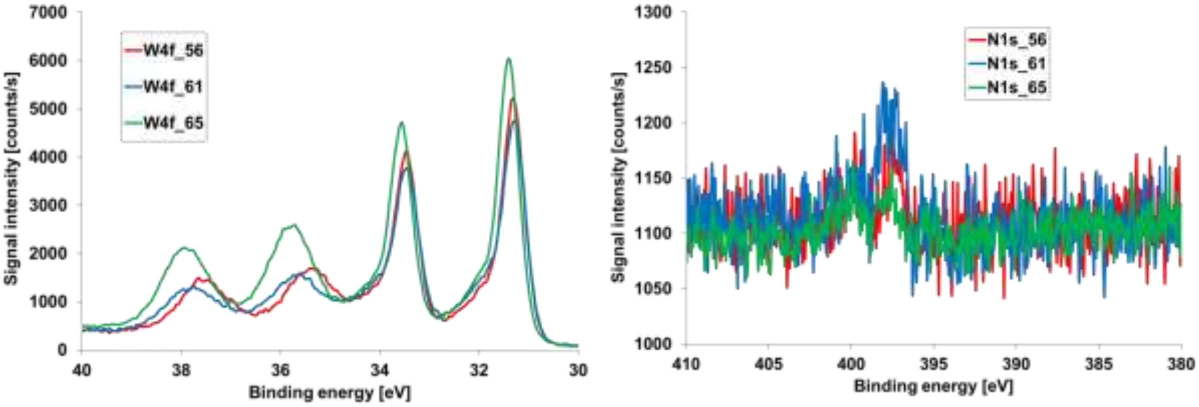


Figure 17: XPS spectra in the W4f and N1s BE region for the W history samples after N pre-treatment and D plasma exposure.

The last and final campaign investigated mixed plasma compositions where 1% (samples 63, 81 and 66) or 5% of nitrogen (samples 82 and 64) was added as a seeding gas to the D plasma.

There was a clear difference in the total retention values and spectra of the low temperature and high temperature exposures. A small increase in the total retention was found for the lowest exposure temperature with no distinction between the 1%N and 5%N seeding gas added (Figure 18a). For the high exposure temperature (Figure 18b), there seems to be no measureable effect on the D retention for the 1%N, while a huge increase was found for the 5%N seeding gas.

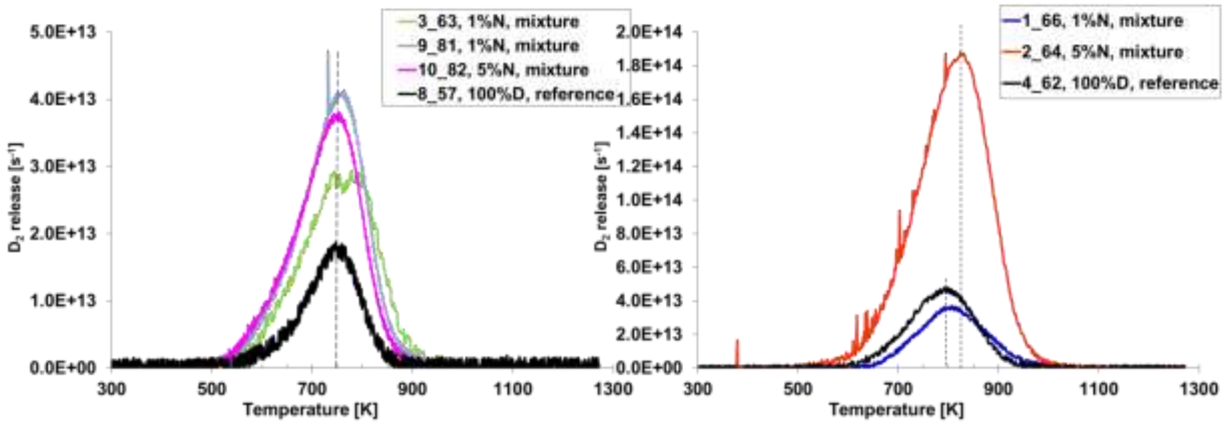


Figure 18: TDS spectra of D2 release from the mixed plasma samples for low temperature (left) and high temperature (right) exposures.

The nitrogen release from the bulk as measured by TDS was highest for the sample 66 and 64. The increase of the temperature from 520K (all low temperature cases) to 580K (sample 64) and even ~630K for the sample 66 had a huge effect on the nitrogen storage in the materials. Again a shift in the peak was found for samples exposed at temperatures at 580K or above as was already detected for the reference samples as well. XPS showed that all samples showed a double peak in the N1S spectra (Figure 19b) with one fixed peak at 397.7eV typical for W nitrides. Only sample 63 (low temperature) had a second peak at 399.8eV typical for N in W-O-N bonds while 66 (high temperature) did have a shift of the second peak to 400.08eV indicating that the nitrogen is as adsorbed N_2 on the surface.

This is in agreement with the fact that WN is not stable anymore above 600K probably explaining why the total D retention for the sample 66 is similar to the reference case with no nitrogen added. The XPS N1s also showed an increased contribution of nitrogen on the surface as compared to the implanted or nitrified surfaces in the previous campaign, especially for sample 63 and 64.

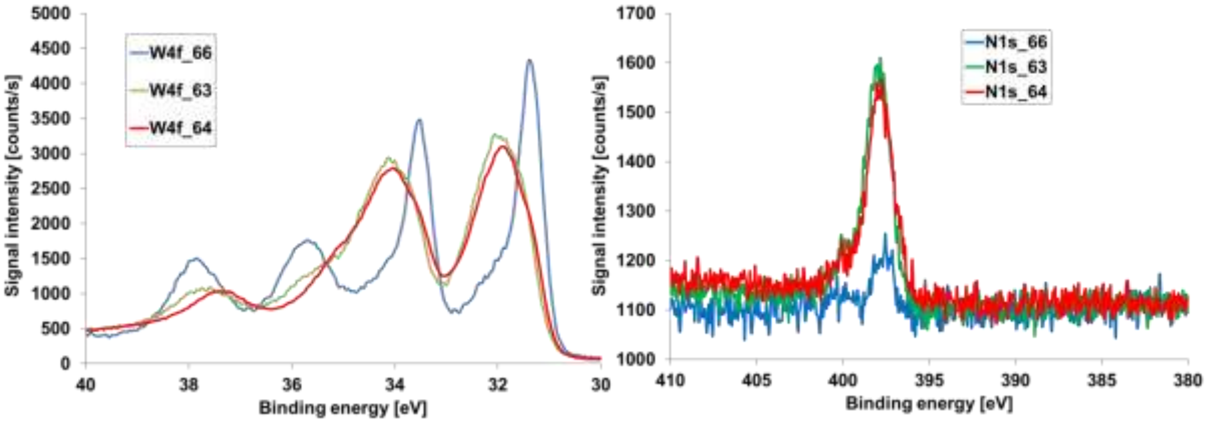


Figure 19: XPS spectra in the W4f and N1s BE region for the W mixed samples after exposure to D plasmas with 1%N (samples 66, 63) and 5%N (sample 64) seeding gas.

CONCLUSIONS

The plasmatron VISIONI showed to be a powerful and accurate plasma exposure device. In addition the combination of stored gas in the bulk by TDS and the surface state condition after plasma exposure as measured by XPS revealed useful information for the interpretation of the retention spectra. For increasing exposure temperature in this flux, fluence case, an increased D retention was found. An additional trap site was found for specimens exposed above 580K. N implantation only increases the total D retention in case that immediate and consecutive plasma exposures took place. For the mixed plasma exposures only a small increase in the D retention was found and no differences between 1%N or 5%N seeding gas could be detected. For higher temperatures, a clear increase in nitrogen uptake was found while for 5%N of seeding gas, this resulted in a tremendous increase in the total D retention. For very high temperatures above 600K where WN becomes unstable, the D retention values drop back towards the reference samples without N seeding gas.

PLANNED ACTIVITIES

A detailed peak analysis of all TDS and XPS spectra will be performed to indicate the true trapping sites and the effect of the surface state on the retention.

It should be verified if the nitrified sample showed a reduced deuterium retention due to the annealing or due to the nitride layer formed on top of the sample. A sample annealed under vacuum at 300°C for 1 hour should be exposed to a pure 100%D plasma and will be compared with a reference sample and the nitride sample.

PARTNERS

- FOM-DIFFER, the Netherlands
- TEC (Trilateral Euregio Cluster)
- UGent, Belgium

4.1.1.5 D fuel retention changes in W due to He – D fuel retention in W and W-Ta alloys (SCK•CEN WP nr 4.1.1)

EFDA Task nr:	*WP13-IPH-A03-P1-01 (PhD SCK•CEN-UGent)*
Principal Investigator:	*Y. Zayachuk (yzayachu@sckcen.be)*
Scientific Staff:	*Inge Uytdenhouwen (iuytdenh@sckcen.be)*

OBJECTIVES

Earlier studies showed significant differences in retention and plasma-induced material modification between W and W-Ta alloys. However, the investigated pure W and the W-Ta alloys differed not only in chemical composition, but also in grain size by more than an order of magnitude. This study was dedicated to the separation of the effects of compositions and microstructure. The effect of exposure temperature on retention in W and W-Ta was investigated as well.

ACHIEVEMENTS

A preliminary study of the deuterium retention as a function of grain size has been performed, see Figure 20. Two pure reference W grades were compared with a W-Ta alloy. One pure W had large grains and another had a similar grain size as compared to the W-Ta alloy. It was shown that the two investigated W grades and W-Ta, all feature different retention properties (total retention, shapes of TDS spectra and shapes of depth distributions as measured by NRA). This indicates that there exist separate effects of microstructure (grain size) and alloying (with or without Ta), with eventual retention being the result of an interplay of both.

On the other hand, divertor-relevant high-flux exposures at elevated temperatures (above 520 K) showed that W and W-Ta feature different temperature dependences. In pure W, the retention decreases over the temperature range 450 – 520 K. While in W-Ta it increases. In previous studies it was found that around the temperature of 450K, W-Ta has lower retention values than pure W. While at exposure temperatures above 520K, W-Ta features higher retention than W.

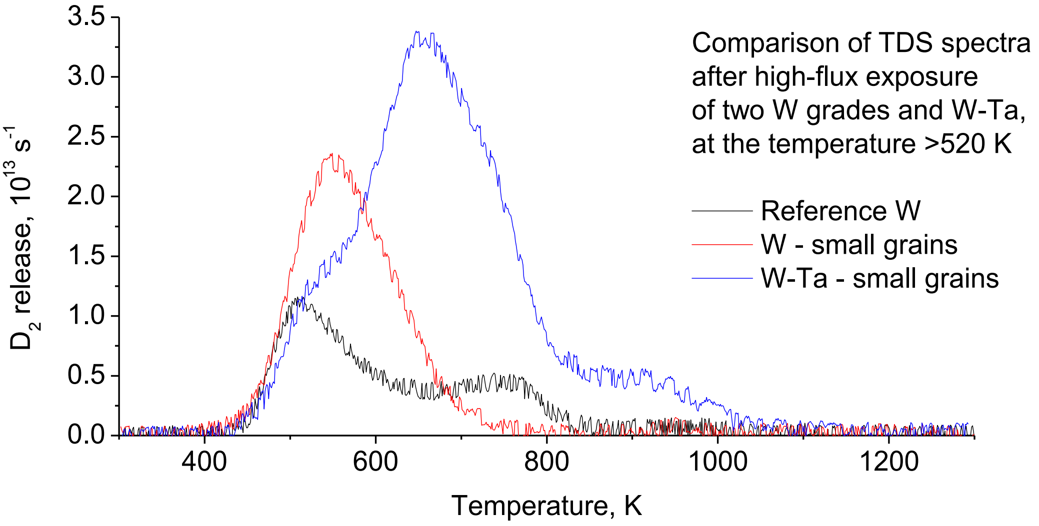


Figure 20: Results of a preliminary study of the deuterium retention as a function of grain size.

PARTNERS

- FOM DIFFER, the Netherlands
- TEC (Trilateral Euregio Cluster)
- Max Planck Institute for Plasma Physics, Germany
- UGent, Belgium

4.1.1.6 Effects of H & He on W surface morphology changes (SCK•CEN WP nr 4.1.1)

EFDA Task nr:	*WP13-IPH-A11-P1-01 and* WP13-IPH-A03-P1-01
Principal Investigator:	*I. Uytdenhouwen (iuytdenh@sckcen.be)*
Scientific Staff:	*W. Broeckx, W. Van Renterghem*

OBJECTIVES

The objective of these two tasks was to address the synergistic effects of plasma exposures in VISIONI to helium/deuterium plasmas. The first task is related to changes in the surface morphology with respect to blistering, nano-fuzz formations, …. The second task should answer how deuterium is trapped in tungsten if helium is already present and if it changes the deuterium retention and why? The combined results of the two tasks will give the possibility to answer if changes in surface morphology are related to differences in the retention and trapping sites.

ACHIEVEMENTS

Some initial pure Helium plasma exposures were done in order to determine the optimal experimental parameters. Within these tests the ion energy (80eV – 200eV) and ion flux were varied. The specimen surface morphology was characterised with scanning electron microscopy (SEM). A typical example is shown in Figure 21a for a reference polished sample and Figure 21b after a helium plasma exposure. Pitting was clearly visible on the surface and increases for higher ion energies. Based on these results, it was decided to expose the tungsten samples to He ions with an energy of 200 eV. The pure deuterium reference plasma as well as the mixed plasmas (He/D) will use similar parameters.

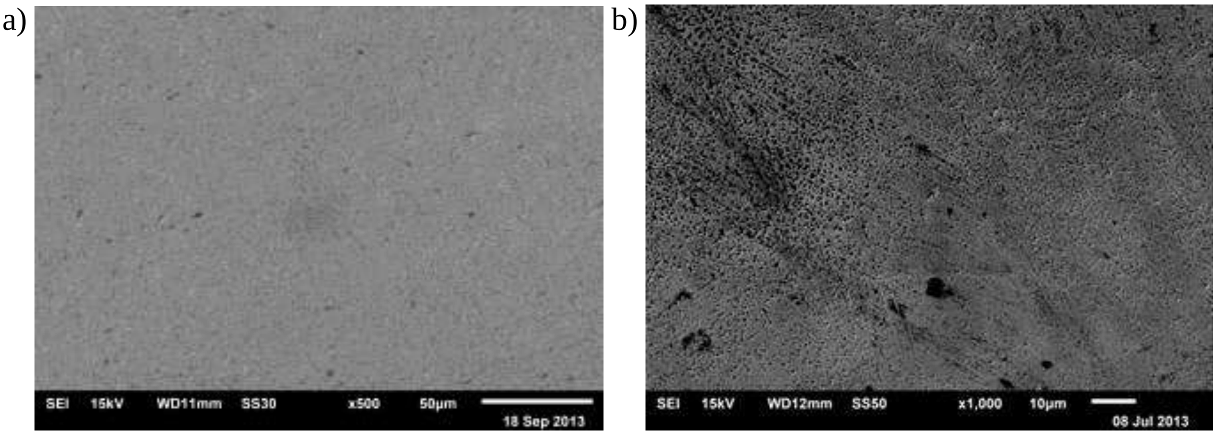


Figure 21: SEM images of the surface of a) a freshly polished sample and b) a tungsten sample after exposure to 200eV helium ions in VISIONI

The reference double forged pure tungsten samples have been polished and were annealed at 1000°C for 1 hour to remove induced defects created by the polishing. Initial surface conditions after annealing have been mapped for 5 different samples with SEM (see Figure 21a). Each sample was investigated at 9 fixed locations with 2 different magnifications (x500, x5000) After exposure, these positions will be compared with the initial surface conditions.

PLANNED ACTIVITIES

Sample #	1st plasma exposure	2nd plasma exposure
1	D (100%)	
2	He (100%)	
3	He (100%)	D (100%)
4	D (100%)	He (100%)
5	He/D (50%/50%)	

Table 6: Summary of the plasma exposure conditions in VISIONI.

In total 5 samples will be exposed in the plasma device VISONI. A summary of the planned exposure conditions is shown in Table 6. First two reference scenarios with a 100%D and a 100%He plasma will be performed. SEM analysis will show if there are blisters, nano-fuzz formations. The TDS analysis will give information on the trapping sites related to a certain plasma specie (D or He only). The following 2 samples will be sequentially exposed to Helium and Deuterium and vice versa. Possible induced damages created by Helium or D exposure could result in different trapping sites for the following D or He exposure. Differences with the 2 first reference scenarios will be addressed both with respect to the surface morphology and the retention spectra. Finally the last experiment will investigate the true synergistic effects when He and D species are simultaneous implanted. It was chosen to keep the total fluence (1.15×10^{24} n/m^2) the same for all samples for comparison reasons. The temperature will be fixed between 200°C and 250°C.

Afterwards sample surfaces will be characterised with SEM and compared to the surfaces of the samples before exposure. The questions related to He, H blistering, and nano-fuzz formations will be answered with respect to all the different conditions. Finally thermal desorption measurements will be performed at FOM (Netherlands) to determine the spectra and total He/D retention.

PARTNERS

- FOM-DIFFER, the Netherlands
- TEC (Trilateral Euregio Cluster)

4.1.1.7 Cu and Be joints irradiation (SCK•CEN WP nr 4.1.1)

EFDA Task nr:	*TW6-TVM-NAJT (from FP6)*
Principal Investigator:	*P. Jacquet* (pjacquea@sckcen.be)
Scientific Staff:	*J. Janssens, M. Lambrecht*

OBJECTIVES

In previous tasks like TW4-TVM-CUSSIR and TW4-TVM-CUSSPIT the strength of the joint between CuCrZr and SS was measured after irradiation at different temperatures. The conclusion was that the irradiation influences the joint strength, but it also affects the base material strength. The toughness of the joint between these joints decreases sharply with increasing temperatures and it is therefore necessary to know the joint strength variation with temperature. It is intended to repeat these tasks at an higher irradiation temperature, i.e. 300°C and different dpa. Since material samples will also be available containing joints between Be and CuCrZr, it is also proposed to include some of these joints in the irradiation and testing campaign.

The objectives are to engineer and build the experiment for irradiation in the BR2 reactor of SCK•CEN at Mol, and to execute the PIE tests on CuCrZr/SS, CuCrZr/Be joint specimens and base material.

These materials are candidate materials for the future fusion reactors (ITER and DEMO).

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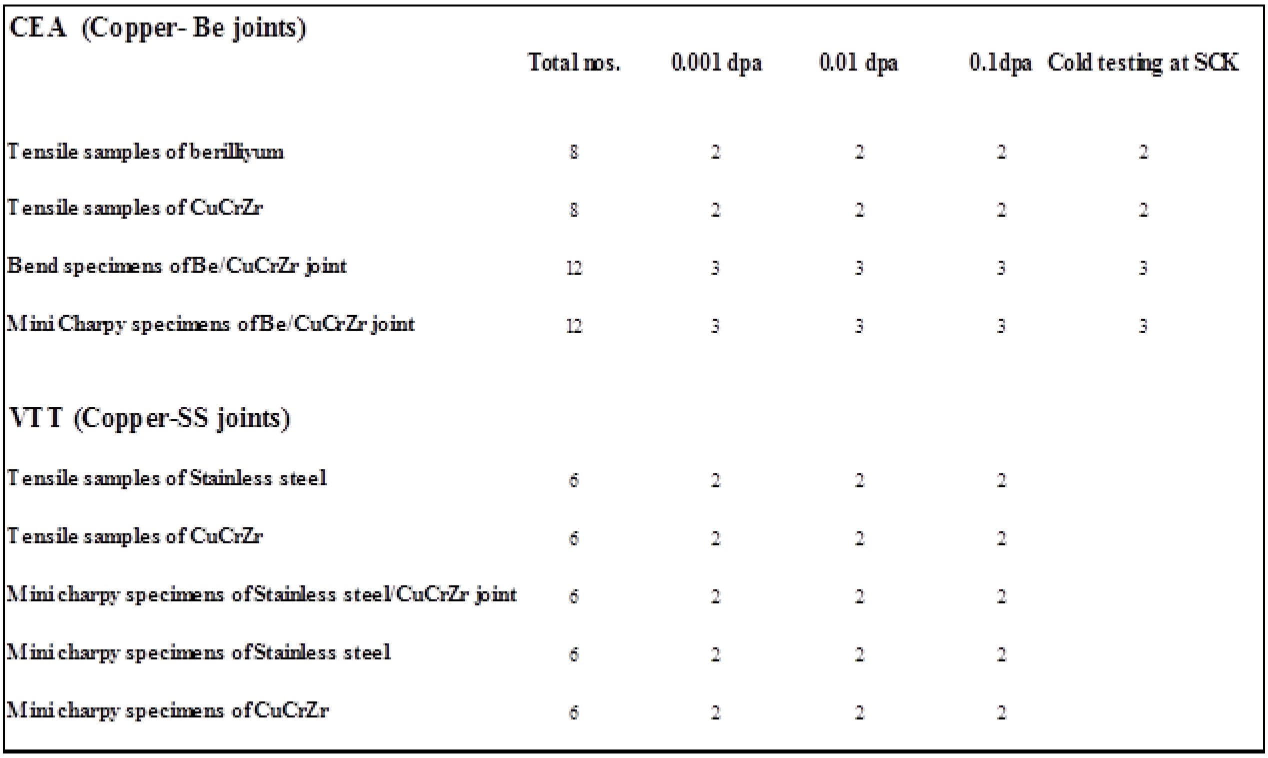
By the end of 2012, the original irradiation programme, as shown by the **test matrix** in Figure 22, could be finalized. The 0.01dpa irradiation was done during cycle 04/2012, and the samples of the next 0.1dpa irradiation were already loaded into the reactor also during cycle 04/2012. The remaining part of the 0.1dpa irradiation was accomplished during cycle 05/2012. Both irradiations went according schedule. The irradiation rig was moved to the hot cells to recuperate the samples, which were temporarily stored in the hot cell to cool down, before transporting to the material testing laboratories.



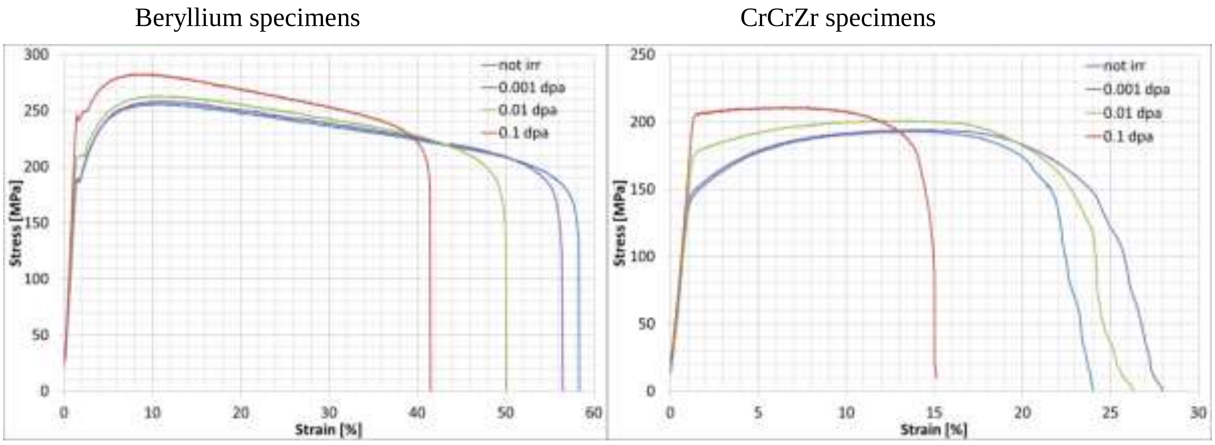
CEA (Copper- Be joints)	Total nos.	0.001 dpa	0.01 dpa	0.1dpa	Cold testing at SCK
Tensile samples of berilliyum	8	2	2	2	2
Tensile samples of CuCrZr	8	2	2	2	2
Bend specimens of Be/CuCrZr joint	12	3	3	3	3
Mini Charpy specimens of Be/CuCrZr joint	12	3	3	3	3
VTT (Copper-SS joints)					
Tensile samples of Stainless steel	6	2	2	2	
Tensile samples of CuCrZr	6	2	2	2	
Mini charpy specimens of Stainless steel/CuCrZr joint	6	2	2	2	
Mini charpy specimens of Stainless steel	6	2	2	2	
Mini charpy specimens of CuCrZr	6	2	2	2	

Figure 22: Test matrix.

The capability to test (active) beryllium has been rechecked before starting the post-irradiation examination. Afterwards, the work method was defined, including the dismantling of the samples, preparation of hot cell 14 for beryllium testing, dimensional control of the specimens, the post-irradiation testing, dimensional control after testing, photographing the fracture surface and cleaning of the hot cell.

During dismantling, four samples were found to be broken. These samples consisted of two Be/CuCrZr joins irradiated to 0.1 and 0.01 dpa, respectively. The reason of this failure is not known, but the examination showed a very low toughness of these joins after irradiation, especially when testing at room temperature.

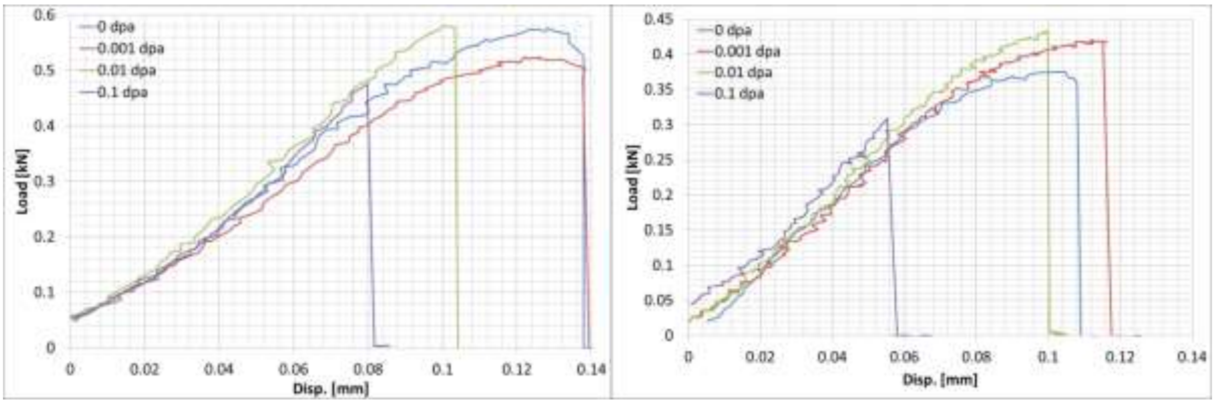
The post-irradiation examination was performed in September 2013. Preliminary results can be found in Figures 23 and 24. Full analyses of the results, summarized in a report, are ongoing.



Beryllium specimens

CrCrZr specimens

Figure 23: Results of tensile tests performed at 300 °C before and after irradiation at 300 °C.


Bend specimens

Charpy specimens

Figure 24: Results of four-point bending tests performed at 300 °C before and after irradiation.

PARTNERS

- VTT, Finland, is the supplier of the CuCrZr/Be samples.
- CEA, France, is the supplier of the CuCrZr/SS samples.

4.1.2 Technical improvements of the diagnostics in the plasma simulator VISIONI for migration studies (SCK•CEN WP nr 4.1.2)

EFDA Task nr:	*no EFDA task*
Principal Investigator:	*J. Schuurmans (jschuurm@sckcen.be)*
Scientific Staff:	*W. Broeckx, J. Schuurmans*

This activity us included in section 3.1.1 - Characterization of the plasma behaviour in VISIONI (SCK•CEN WP nr 3.4.1).

4.1.3 Assess high temperature and radiation effects on optics: study radiation effects on glasses and mirrors, with the capability of reflectivity measurements on in-reactor exposed mirrors (SCK•CEN WP nr 4.1.3)

EFDA Task nr:	*no EFDA task (REPER)*
Principal Investigator:	*A. Goussarov (agoussar@sckcen.be)*
Scientific Staff:	*A. Goussarov*

No effective work was carried out in 2013 on this task.
A proposal was submitted to JET-FT, but was finally not kept for this year.

4.1.4 Microbeam and SEM/EDX analysis of the co-deposition layers of JET divertor tiles (SCK•CEN WP nr 4.1.4)

EFDA Task nr:	*JW12-FT-3.74*
Principal Investigator:	*I. Uytdenhouwen (iuytdenh@sckcen.be)*
Scientific Staff:	*W. Van Renterghem (wvrenter@sckcen.be)*

OBJECTIVES

The objective is to improve the understanding of the deposition in the divertor in JET from the carbon wall, based on detailed comparison of the layer structure in different parts of the divertor and at surfaces exposed over different periods of operation. And relating these structures with the JET operations history and with specific diagnostics. The most basic issue is to clarify more precisely which features in the deposited layers are determined by the deposition sequence and which are due to migration within the layer after deposition. Then, the aim will be to establish the experimental correlations between layer structures and main plasma- and divertor conditions.

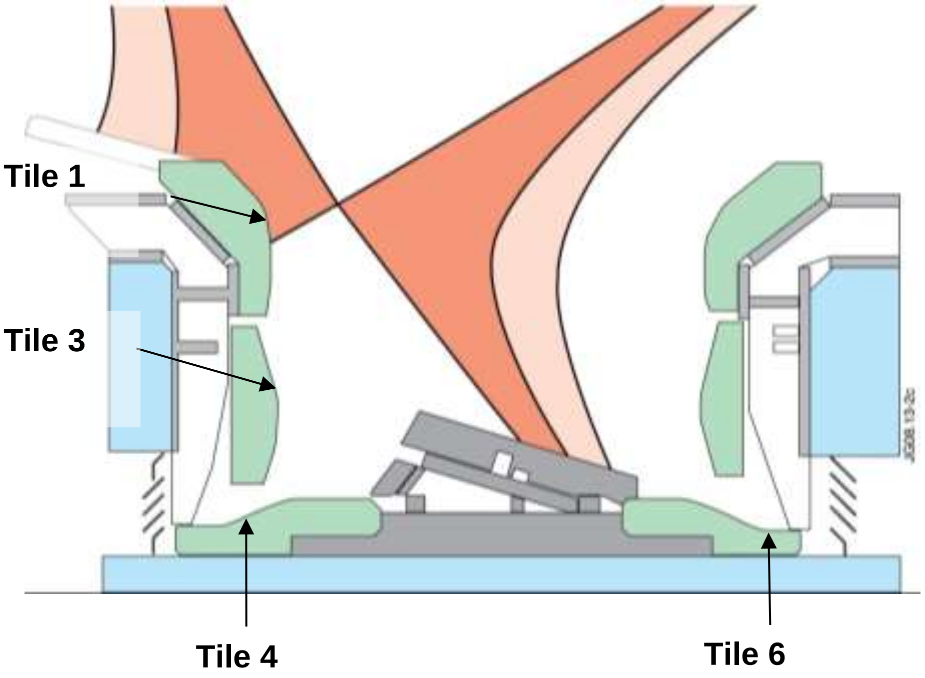


Figure 25: Cross section of HD divertor configuration from JET showing the relative location of the divertor tiles. (Note that whilst the design of the tiles shown in green have remained the same from 1998-2007, the grey tile at the bottom of the divertor tile has been altered.)

ACHIEVEMENTS

In total 21 samples, retrieved from tiles 1, 3, 4 and 6 of the JET divertor (see Figure 25) and exposed during different periods of operation, were sent to SCK•CEN for scanning electron microscopy (SEM) observations and energy dispersive X-ray spectroscopy (EDS) analyses. The same samples were analysed previously with optical microscopy (OM) and microbeam analysis. All samples were embedded in a resin for cross-section observations of the deposited layers. As an example, six selected SEM images of the deposited layers are given in Figure 26.

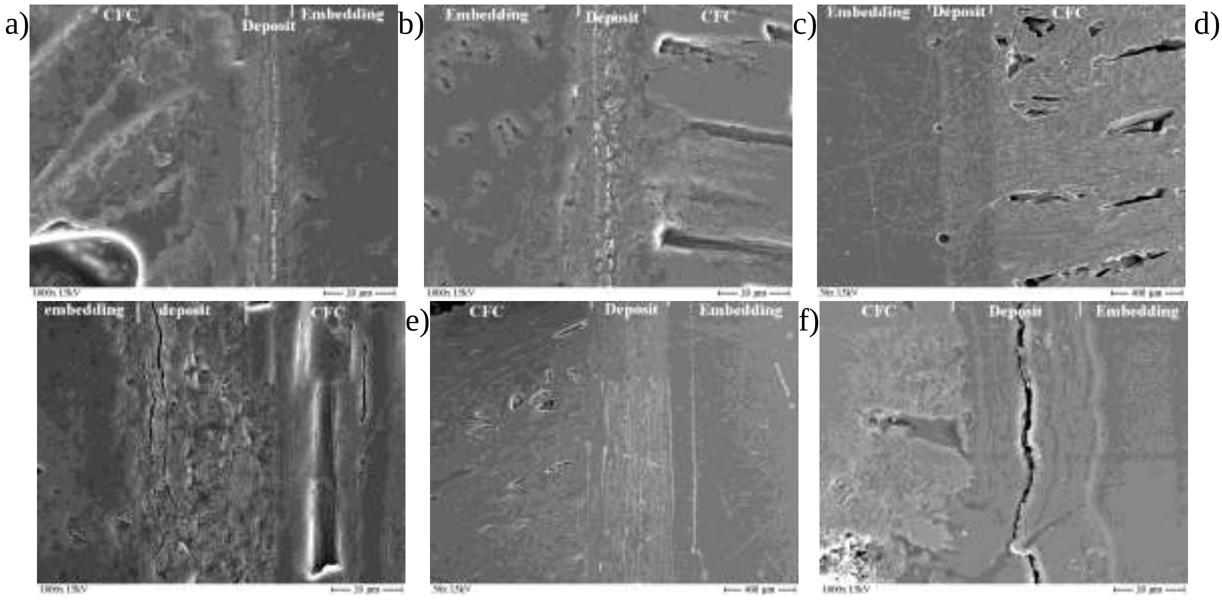


Figure 26: Typical SEM images of the deposit on samples a) 2IWG1A/8, b) 2IWG3A/8, c) 2BNG4C/10a, d) 2BNG4C/1, e) 2BNG6D/6a and f) 14BWG6B/9a.

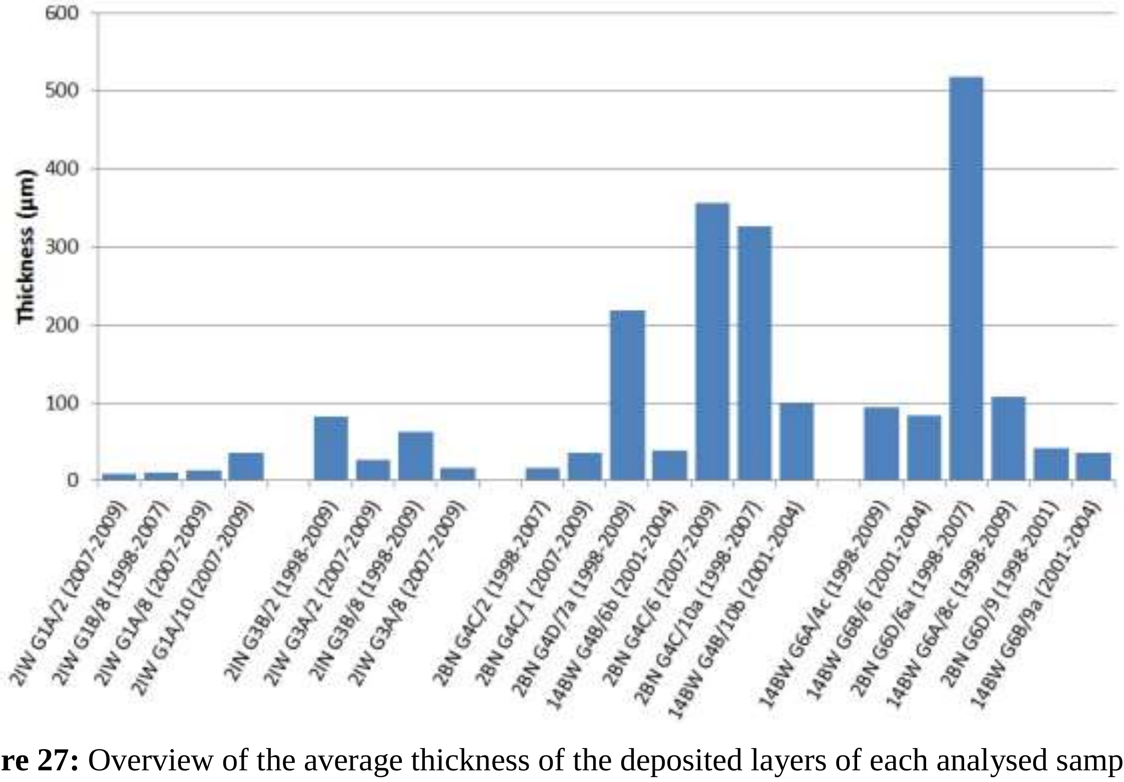


Figure 27: Overview of the average thickness of the deposited layers of each analysed sample.

The measured thickness of the deposited layer is in good agreement with the location in JET and the exposure period. In Figure 27, the average thicknesses measured on all samples are plotted.

Tile 1

The least amount of material is deposited on tile 1. This was expected since it is partly exposed to the plasma. The deposition will therefore be partly eroded. The thickness is of the order of 10 µm at core positions 2 and 8. Only sample 10, which is located in the apron of the divertor, the thickness of the deposit increases to 35 µm. The two samples on position 8, which were exposed in the periods of 1998-2007 and 2007-2009, have a comparable deposit thickness. Because of the shorter exposure time, it can be stated that the deposition rate was higher in the 2007-2009 campaign than before. On all samples of tile 1, Inconel fragments were found. It is deposited as micrometre size particles, but many particles were deposited forming an homogeneous single layer as if all of the Inconel particles were sprayed on the divertor tiles at one or a few distinct moments during exposure. When comparing the different exposure periods, it was found that the amount of deposited Inconel is much higher during the 2007-2009 exposure period than in the 1998-2007 period. Sample two, which is at the lower part of tile 1, seems to be more shielded against deposition of Inconel.

Tile 3

The deposit on the samples of tile 3 is thicker than on tile 1, but still below 100 µm. Samples were retrieved from the upper and lower part of the tile. The deposit thickness increases slightly on the lower part of the tile, but the differences are relatively small. Two samples were analysed from the same poloidal position, but with different exposure times. One sample was exposed from 1998-2009 and the other sample from 2007-2009. As expected the thickness increases with the longer exposure time, but contrary to tile 1 there is no indication of a significant increase of the deposition rate in the period of 2007-2009. There is a very good agreement between the grain structure and the Inconel deposits between the deposits on the samples exposed from 2007-2009 and the outer part of the deposits on the samples exposed from 1998-2009. This should be the case as both layers were deposited at the same time. Small particles of Inconel were deposited, but the amount is lower in general than on tile 1. Most of the Inconel was found near the outer part of the deposit in the samples exposed from 1998-2009. In the samples exposed from 2007-2009, the Inconel is deposited on a few layers, distributed homogeneously in the deposit. It indicates that a deposition of Inconel occurred on a few occasions during the 2007-2009 campaigns, while hardly any was deposited in the earlier periods.

Tile 4

The thickness of the deposit on tile 4 shows much more variation. The deposit is the thinnest on positions 1 and 2, near tile 5, regardless of the exposure period. Still, an increase of the deposition rate occurred in the period of 2007-2009. On the other hand, very thick deposits up to a few 100 µm were found on positions 6 and 7 and on position 10, in the shaded area. At these locations, the exposure period had a major impact on the thickness of the deposit. In the period of 2001-2004, when the MKII-SRP configuration of the divertor was installed, a significantly lower deposition rate was noted and the deposition thickness remained below 100 µm. Hardly any Inconel particles were deposited on tile 4.

Only in the two samples at position 6, a small number of isolated particles were found. In view of their locations, these particles might have been deposited on tile 3 and fallen on tile 4.

Tile 6

In the samples of tile 6, the deposition layer is the thickest at position 6. The sample that was exposed from 1998-2007 has a deposit of about 500 µm thick, which is 4 times the thickness of the deposits on positions 4 and 8 that were exposed even longer. The sample at position 6 that was only exposed from 2001-2004 has a much lower thickness. It suggests that the deposition rate during this period was lower. A similar conclusion can be made for samples on position 9. The deposit thickness is lower than at position 6 and the sample exposed from 2001-2004 has a slightly lower thickness that the sample exposed from 1998-2001. Traces of Inconel were found on 3 of the 6 samples only. In these samples, the Inconel was located on the outer part of the deposited layer.

PARTNERS

- EFDA-JET, Culham, UK
- TEKES, VTT, Finland
- VR, Sweden

4.1.5 SEM/EDX and micro-beam analysis of normal and cross-section samples of JET ITER-like Wall JET divertor tiles (SCK•CEN WP nr 4.1.4)

EFDA Task nr: *JW13-FT-3.81*

Principal Investigator: *I. Uytdenhouwen (iuytdenh@sckcen.be)*

Scientific Staff: *W. Van Renterghem (wvrenter@sckcen.be)*

OBJECTIVES

The main project objective is to characterize the divertor surfaces on a microscopic scale following the first period of operation with the ITER-like wall containing only tungsten in the divertor and beryllium at the first wall. A poloidal set of core samples and polished layer cross sections will be studied microscopically and with scanning electron microscopy (SEM) in combination with energy dispersive X-ray spectroscopy (EDS) by SCK•CEN and with micron ion beam analysis (µ-IBA) by VR. The elemental composition (at least Be, W, C, Ni) and the fuel content (D) will be determined and it will be investigated if Be-W mixed layers were formed during the plasma operations. The W coatings are sprayed on CFC substrates. Therefore the diffusion of the carbon inside the W coating layers and possible tungsten carbide formation should be addressed. The integrity of the W coating interlayer and possible WC formation will be investigated.

ACHIEVEMENTS

After the experimental campaign from 2010 to 2012, with the ITER like wall configuration, tiles 1, 3 and 4 (14IN G1C, 14IN G3B and 14BN G4D) were recovered from JET. At TEKES, series of 1 cm discs were cut from these tiles. Eleven of these discs were sent to SCK•CEN for SEM/EDS analysis.

The analysis is still ongoing but the first results indicated significant results between tiles 1, 3 and 4. Differences between different parts of the same tile seem to be more subtle.

Tile 1

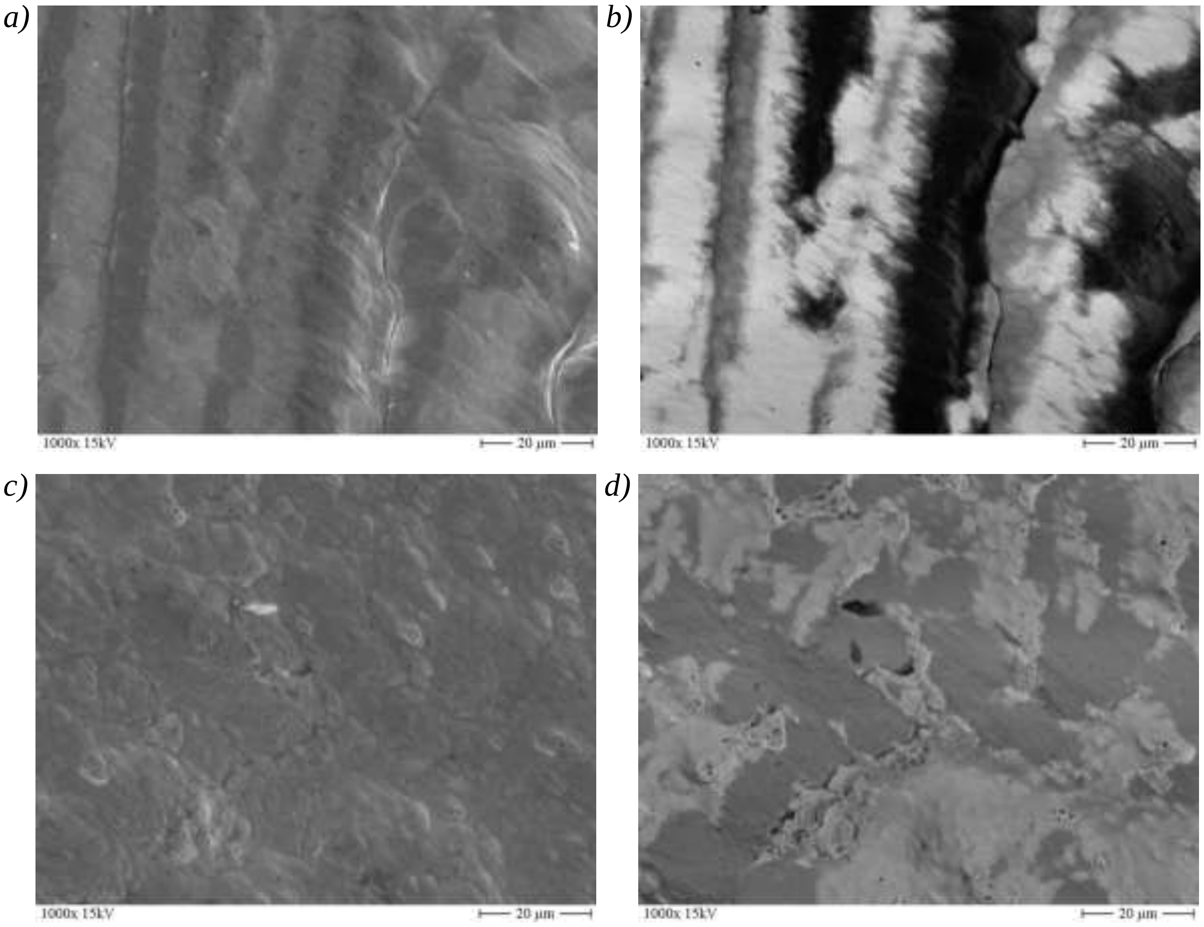
On tile 1 material is deposited on top of the coating as shown in Figure 28a and 28b. The backscattered electron (BSE) images indicate 3 different phases. EDS was used to determine the compositions, but the results are not unambiguous because it was not possible to detect Be. However, the results indicate that the brightest phase in Figure 28b is pure W, while the grey and black phases are a mixture of Be and W. The Be/W ratio cannot be determined, but in principle the Be content in the black phase must be higher.

Tile 3

The top layer of the coating on tile 3 was a Mo layer, but in the SEM/EDS analysis after exposure, shown in Figure 28c and 28d, tungsten was found at the surface. More W was deposited in the upper part of the tile compared to the lower part. The tungsten migrated from the eroded part of tile 1. Only plan-view samples were analysed and these samples did not contain indications of the deposition of Be on this tile.

Tile 4

On tile 4, shown in Figure 28e and 28f, it was verified that again material is deposited. Also here differences in intensity are related to difference in composition, but in EDS only W can be detected. Similar to tile 1, regions of lower intensity in the BSE image have a lower W content, which indicates that a mixed W/Be phase is formed.



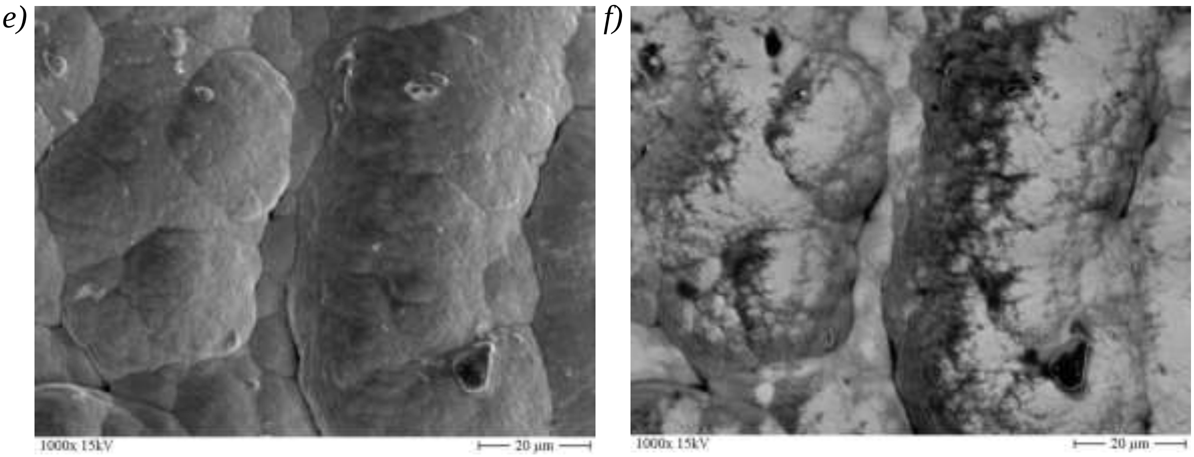


Figure 28: a,c,e) Secondary electron and b,d,f) backscattered electron images of the surface of tile 1 (a and b), tile 3 (c and d) and tile 4 (e and f).

PARTNERS

- JET-EFDA, UK
- TEKES, Finland
- VR, Sweden

4.2 Materials modelling

4.2.1 Radiation effect modelling and experimental validation – Kinetics: evolution of microstructure (SCK•CEN WP nr 4.2.1)

EFDA Task nr:	*WP13-MAT-01-IREMEV-02-01*
Principal Investigator:	*D. Terentyev (dterenty@sckcen.be)*
Scientific Staff:	*D. Terentyev*

OBJECTIVES, BACKGROUND AND PREVIOUS INVESTIGATIONS

He embrittlement is one of the key issues to be addressed in the development and characterization of structural materials for fusion applications [7]. It is long known that He affects the evolution of microstructure in metals (see e.g. [8; 9]) and steels (see e.g. [10; 11; 12; 13]), which is why it is of concern for the Fusion structural steels. One of the strongest effects of He upon irradiation at elevated temperature (i.e. 300°C and above) is the promotion of void swelling even in BCC Fe-Cr alloys which are superior with respect to swelling resistance [10; 14]. Another effect is the enhancement of dislocation loop formation and preferential growth of cavities on dislocations [12; 15].

The presence of He upon irradiation (both electron and neutron) essentially influences both evolution of vacancy- and self-interstitial atom (SIA) type defects. However, the full atomic-scale details about the He-defect interaction cannot be easily assessed by experimental techniques. The interpretation of the experimental observations therefore requires certain assumptions about thermal stability, mobility and mutual interaction of He-vacancy and He-SIA defects. The problem is especially emerging when it comes to the interaction of He with point defects and their small clusters, which on the one hand are not accessible to direct experimental observations, and on the other hand, have too large size to be considered by heavily demanding but rigorous *ab initio* calculations. Large scale atomistic calculations with interatomic potentials is an option, however, their reliability is essentially determined by the quality of interatomic potentials, which keep improving as more and more *ab initio data* appears (as will be discussed later). Let us therefore first overview the available *ab initio* data on fine-scale He-defect interaction.

The interaction of vacancies with interstitial He (occupying a tetrahedral position in bcc Fe) is relatively well studied by *ab initio* calculations. Different *ab initio* works [16; 17; 18] in general converge to the following results : (i) He is deeply trapped by a single vacancy with the binding energy Eb(He-V)=2.3 eV; (ii) there is an optimum He-to-vacancy ratio offering a maximum thermal stability of He_n-V_m clusters, which is n/m~1.3 corresponding to the dissociation energy of ~2.6 eV; (iii) He-V_2 cluster has a migration energy of ~1.1 eV, which is lower than its dissociation energy (1.45 eV) and therefore should be considered as a potentially mobile object at sufficiently high temperature (above ~450K). The interaction of SIA defects with interstitial He is much less clear. A limited number *ab intio* studies report that in BCC Fe, interstitial He exhibits weak attraction with a <110> split dumbbell depending on relative position, with maximum binding energy of 0.07 and 0.26 eV, respectively reported in [18] and [19]. The interaction of a substitutional He with an SIA results in the recombination-replacement reaction, releasing He to a tetrahedral interstitial position [19].

The interaction of He with SIA clusters, small dislocation loops and straight dislocation lines so far was performed only by the use interatomic potentials. The most intensively exploited set of potentials was Fe-Fe developed by Ackalnd et al.1997 [20], for Fe-He by Wilson & Johnson [21; 22; 23]. There is a number of essential drawbacks of this set of potentials with regard to the properties of point and extended lattice defects in BCC Fe [24] and He-defect interactions as follows from the comparison with the above mentioned *ab initio* data [18; 25]. These are listed below. (i) underestimated difference in the formation energy of a <110> split dumbbell and <111> crowdion; (ii) incorrect ground state for small self-interstitial clusters; (iii) three-fold degenerate structure of a $a_0/2$<111> screw dislocation; (iii) incorrect ground state (octahedral) for He; (iv) essentially overestimated He-vacancy binding energy; (v) essentially overestimated or wrongly predicted SIA-He interaction.

Even though the results obtained with that potential (especially for SIA-He interaction) should be taken with precaution, we provide a summary of the results since it was extensively used to study He-dislocation and He-SIA interaction. 1D migration of small <111> SIA clusters is not be affected by the substitution He (in concentration of 2500 appm) [18], implying that substitutional He atoms exhibit weak of negligible interaction with dislocation loops. The interaction of <111> SIA cluster (containing 11 SIAs) with a He_4-V_6 cluster results in the SIA-vacancy recombination and decoration of the reformed SIA cluster by He atoms. The decorated cluster was then seen to be immobile for the whole MD run (for 100 ps at 1000K), suggesting that interstitial He atoms are strongly bound to the core of dislocation loops. From static simulations [18], the binding energy between an interstitial He and 20 <111> SIA cluster is calculated to be 1.4 eV (and it goes up to 4.4 eV for four He atoms). The binding of 1.4 eV is consistent with the estimation of the interaction energy of He with a 1/2<111>{110} edge and ½<111> screw dislocations, being 2 eV and 1 eV, respectively [26; 27]. In addition, those works reported that interstitial He migrates along the dislocation line with the energy barrier of 0.4-0.5 eV (for both the screw and edge dislocations), which points at a possibility of He-dislocation and He-loop drag.

Recently, several new upgraded interatomic potentials for Fe-He have been proposed to account for different properties learned from *ab initio* calculations [25; 28; 29; 30; 31]. Further studies with the updated potentials, involving He_n-V_m clusters interacting with the edge dislocation, have shown that He-rich clusters are attracted in the tensile dislocation region, while vacancy-rich clusters are attracted to both dislocation sides [32]. Wang et al. [33] reported that stable He_3 cluster exhibits 1D migration in the core of the edge dislocation, at this, the cluster moves faster than in bulk. This result points at a possibility of the pipe diffusion not only on the straight dislocation but also on the dislocation loop.

From the experimental side, a number of fundamental studies in ultra pure Fe and Fe-Cr alloys has been recently established to reveal mechanisms through which He influences the evolution of microstructure [34; 35; 36]. The most recent and statistically significant experimental observations reported by Prokhodtseva et al.[34] undoubtfully show that mixed He-Fe ion beam impacts the evolution of dislocation loop population as compared to a mono Fe-ion beam. In particular, upon 500 keV Fe^+ and 10 keV He^+ irradiation at 300K, 99% of loops have Burges vector $a_0/2$<111>, while in a single Fe^+ beam 89% of loops are of a_0<100> type. The density of <100> loops was lower and size is larger than that of $a_0/2$<111> ones. The author's interpretation is that He suppresses the mobility of $a_0/2$<111> loops, which otherwise escape to free surface or mutually interact producing a_0<100> loops. Such reaction mechanism was already observed *in situ* in ulta pure Fe but upon 1 MeV e^- irradiation (i.e. no cascades are produced) at 140K [37]. The fact that He irradiation also leads to a higher density of the loops was also mentioned in that work but without any deep analysis of Burgers vector distribution.

Considering the above described strong effect of He, it is important to rationalize in which sequence He leads to the modification of the microstructural evolution, and which mechanisms may explain such a strong difference between the morphology of the loops formed in dual (He-Fe^+) and single (Fe^+) beams. Sufficient understanding of the atomic-level processes that govern the mobility and growth of loops and bubbles would allow to adopt the already existing modelling tools (see e.g. [38; 39]) to predict the microstructural evolution.

The purpose of this work is to provide details of the interaction of He and He-vacancy clusters with ½<111> and <100> dislocation loops, and quantify the mechanisms by which He may affect mobility of dislocation loops and their mutual interaction. To do that, we perform a set of atomistic calculations using molecular dynamics (MD) and molecular statics (MS) simulations to extract, mechanisms and corresponding activation energy, respectively. The simulations were carried out using two recent Fe-He potentials proposed by Juslin et al.[25] and Gao et al.[29].

ACHIEVEMENTS

Interaction of He with lattice defects at 0 Kelvin

First of all, we have applied the two potential to assess the interaction of interstitial He (He_T) with vacancies, 3D-migrating SIA clusters, 1D migrating <111> SIA clusters, straight dislocation lines and circular dislocation loops (with ***b***=<100> and ½<111>, which are known to present in Fe and high-C steels upon neutron irradiation [40; 41]).

Basic data on the formation and binding energies for different He-defect arrangements are presented in Tables 7 and 8. Both applied potentials predict a tetrahedral site to be the most favourable position for an interstitial He in agreement with DFT result [16]. As has been mentioned in the earlier studies [28; 29], the DFT calculations demonstrate some disagreement especially for the binding energy of two interstitial He in tetrahendaral sites (i.e. He_2 cluster).

The binding energy calculated by VASP (by Seletskaya et.al.[16]) is 0.02 eV whereas with the SIESTA (by Fu et.al. [17]) it is 0.43 eV. The presently used potentials predict the binding energy for the H_2 cluster to be inside these two bounds. The formation energy for the He-rich He-V clusters also follows well the trend obtained from the DFT calculations. The binding energy of He_T to the core of the ½<111> screw and ½<111>{110} edge dislocations obtained with the potentials and DFT calculations [42] (applying fixed boundary conditions around dislocation code) are compared in Table 7. The higher binding energy for the edge dislocation is correctly predicted by both potentials, and the absolute values for the screw dislocation are in good agreement with the DFT result. In the case of edge dislocation, the binding energies obtained with the potentials are underestimated by about a factor of two.

	E_O	**E_T**	**E_I(T-T 1nn)**	**E_I(T-T 2nn)**	**E_I(T-SD)**	**E_I(T-ED)**
Juslin potential	4.51	4.39	0.13	0.08	0.3	0.8
Gao potential	4.47	4.38	0.15	0.16	0.45	0.92
DFT	4.57a 4.60b	4.39a 4.37b	0.43a 0.02b		0.49c	1.66c

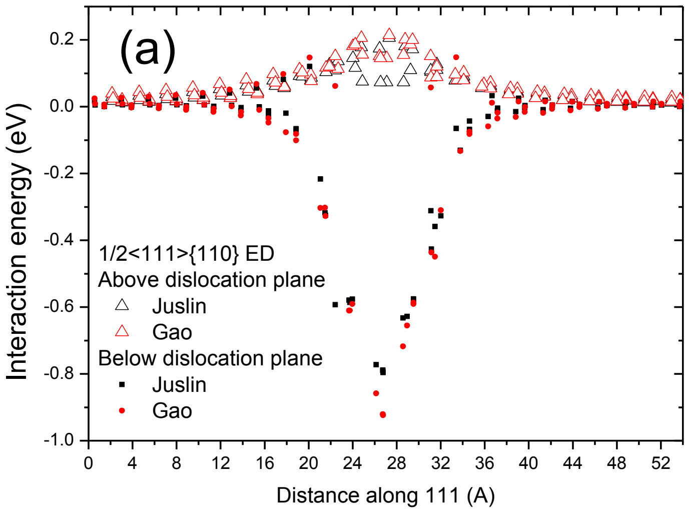
* edge dislocation with a {110} glide plane.

Table 7: $E_{T/O}$ formation energy in a tetrahedral/octahedral position, E_I(T-T Nnn) interaction energy between two He atoms placed in tetrahedral sites at Nth nearest neighbour distance, Eb(T-SD/ED) interaction energy between He atom placed in tetrahedral site and ½<111> screw/edge dislocation*. Vacancy formation energy = 1.72; SIA formation energy= 3.54 Cohesive energy =-4.013.

	E_{sub}	**He_2-V**	**He_3-V**	**He_T-He_T**	**He-V2**	**He-V3**	**He-V4**
Juslin potential	4.10	7.43	10.68	8.65	5.39	6.33	6.98
Gao potential	3.76	6.90	9.98	8.49	4.96	5.89	6.51
DFT	4.22a 4.08b	6.63b	9.94b	8.72	5.5	6.6	7.55

a: Fu [17], b: Seletskaya [16]; c: Zhao [42].

Table 8: Formation energy of He-vacancy clusters.



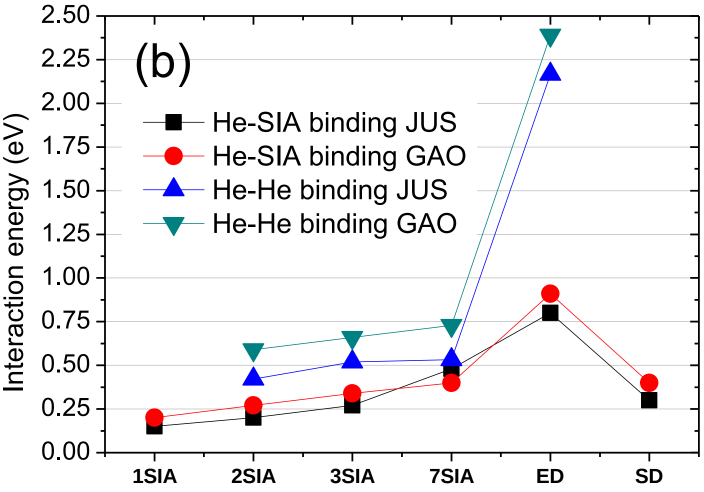


Figure 29: (a) Interaction energy of He_T with a ½<111>{110} edge dislocation as a function of the distance from its core; (b) Interaction energy of He_T and He_{T2} cluster with and SIA, 3D-migrating SIA clusters, 1D-migrating 7 SIA cluster and the core of ½<111>{110} edge and ½<111> screw dislocations.

A comparison of the interaction energy, obtained using the two potentials, for He_T with a ½<111>{110} edge dislocation and SIA complexes is presented in Figure 29 (a) and (b), respectively. It is clear that both potentials predict the same qualitative and very similar quantitative results. The interaction energy for HE_T with a core of the edge dislocation is about 0.9 eV, which is about twice smaller than the result obtained with the older Fe-He potential [26], discussed in the introduction. As concerns the interaction for SIA complexes, we see that a single He_T is weakly bound to di- and tri-SIA clusters. Given a very low migration energy of He_T (0.07 eV), one cannot expect any effect of He on the diffusion of 3D-migrating SIA defects at elevated temperature. The interaction with a small 1D-migrating SIA cluster (containing 7 SIAs) is stronger. Importantly, that adding a second He_T leads to an increase of the interaction energy by approximately a factor of two. Hence, multiple He clusters can reside on the 1D migrating SIA clusters and dislocations. It is therefore important to (i) to explore how 1D-migrating SIA clusters would interaction with multiple He-vacancy clusters, which are thermally stable at elevated temperature; and (ii) to investigate whether or not the dynamic drag of He clusters is possible or sufficiently high decoration of He at dislocation loop is enough to block its migration.

The interaction energy was computed using two potentials (from Juslin and Gao). The maximum binding energy for several He_N-V_M clusters interacting with 3D and 1D-migrating SIA clusters is summarized in Table 9. For the 3D migrating SIAs, the strongest interaction is found for the He_2V cluster and the binding energy goes up to 2 eV. For the 1D migrating SIA clusters, the binding energy increases with the size of SIA cluster, and also reaches about 2 eV for largest He-V cluster containing four He atoms and one vacancy. Overall, the results show that the binding of He-clusters to 1D migrating SIA clusters exceeds 1 eV, which implies that He atoms (clustered at the loop core) will stay attached to the SIA clusters for a long time at room temperature, but will exhibit extremely short life time at the elevated temperature (250-300°C).

3D-SIA Data for Juslin potential.

	He – tetra	**He2V**	**He3V**	**He4V**
I1	0.15	2.1	1.5	0.65
I2	0.20	1.75	0.8	0.8
I3	0.27	1.75	1.0	1.0

3D-SIA Data for Gao potential.

	He – tetra	**He2V**	**He3V**	**He4V**
I1	0.20	1.8	1.1	0.9
I2	0.27	1.4	0.6	0.9
I3	0.34	1.4	0.6	0.8

1D-SIA Data for Juslin potential.

	He – tetra	**He2V**	**He3V**	**He4V**
I7	0.48	1.25	1.0	1.5
I19	0.49	1.25	1.0	1.8
I37	0.5	1.25	1.25	1.8

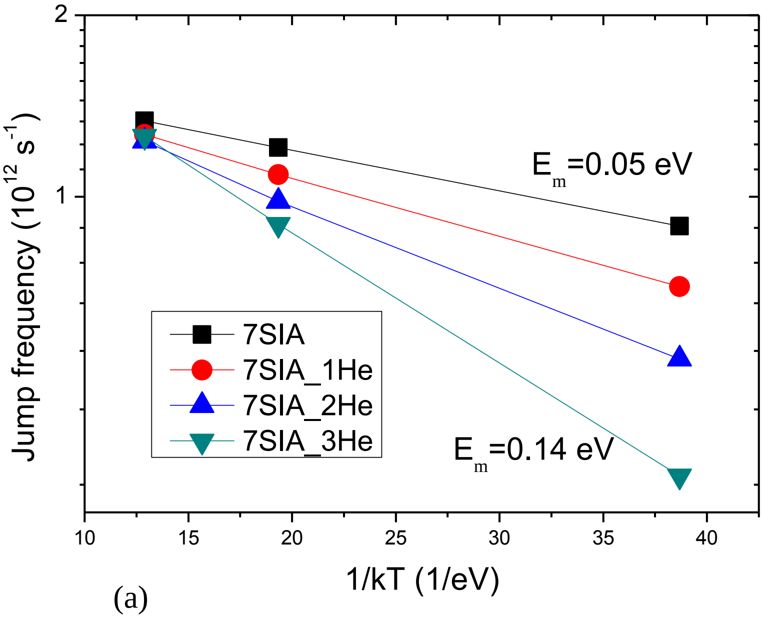
1D-SIA Data for Gao potential.

	He – tetra	**He2V**	**He3V**	**He4V**
I7	0.4	1.0	1.0	1.6
I19	0.42	0.75	1.0	1.75
I37	0.6	1.0	1.25	2.0

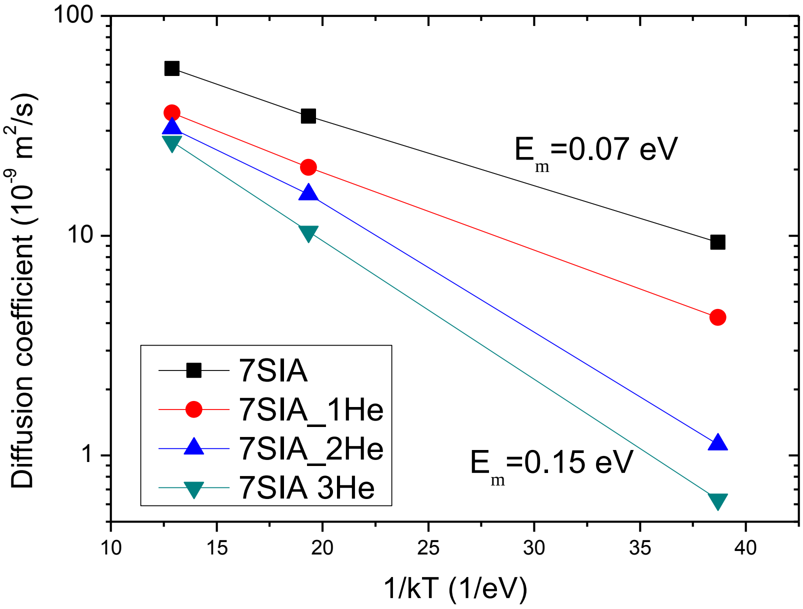
Table 9: Binding energy between He_NV_M and I_K complexes.

Drag of He by dislocation loops at finite temperature

The MD simulations to investigate the drag of HeT and small HeT clusters were performed for 7 SIA clusters in the temperature range 300-600K. It was found that He_T follows the cluster and perform the migration along the loop core as it migrates in a <111> direction. If several He_T atoms are added in the crystal, they quickly migrate to the loop and form compact cluster in the tensile region. The evaluation of the diffusion characteristics of SIA clusters containing different amount of He atoms is presented in Figure 30. It is found that decoration of loops by He atoms results in the increase of the activation energy for jump frequency from 0.05 to 0.14 eV for the cluster decorated by 3 He atoms. One can expect that the activation energy will increase further with adding other He atoms. The migration energy calculated from the Arrhenius slope of the diffusion coefficient also increases from 0.07 up to 0.15 eV. Note that 0.15 eV is very close to the migration energy of He_3 cluster in bulk, which suggests that the migration of I_7-He_N complex is mediated by the diffusion of He cluster.


Jump frequency (10^{12} s^{-1})
2
1
10
15
20
25
30
35
40
1/kT (1/eV)
E_m=0.05 eV
E_m=0.14 eV
7SIA
7SIA_1He
7SIA_2He
7SIA_3He

(a)


Diffusion coefficient (10^{-9} m^2/s)
100
10
1
10
15
20
25
30
35
40
1/kT (1/eV)
E_m=0.07 eV
E_m=0.15 eV
7SIA
7SIA_1He
7SIA_2He
7SIA 3He

(b)

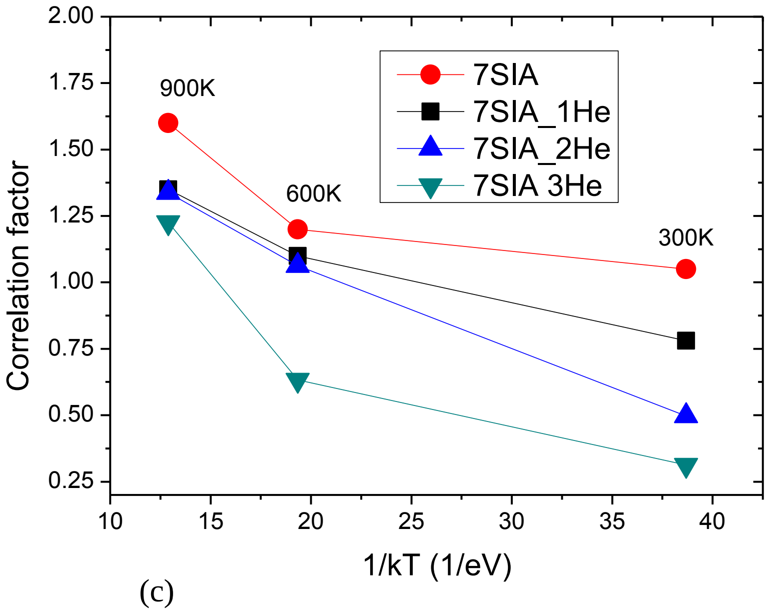


Figure 30: (a) Jump frequency, (b) diffusion coefficient and (c) correlation factor of 7 SIA cluster migrating freely and with one, two and three He_T attached.

SUMMARY AND FUTURE PERSPECTIVES

The results obtained so far show that complete immobilization of 1D-migrating SIA clusters by multiple He clusters (up to three He atoms) is not possible. He atoms decorate the tensile region of dislocation loop core and migrate along with the loop. The higher content of He in the loop the slower the loop diffusivity. Additional studies are necessary to complete characterization of the interaction of loops with He-vacancy clusters.

In a future work, we shall develop a full-time-scale microstructural model in collaboration with CIEMAT to predict the evolution of microstructure and He-accumulation under implantation conditions relevant to JANNUS (CEA, France) experimental setup. This activity will be embedded as a part of the proposal for Eurofusion consortium for 2014 and 2015-2018 work programme.

PARTNERS

- CEA, France (R. Pasianot and M.I. Pascuet)
- CIEMAT, Spain (C. Ortiz)
- PNNL, USA (F. Gao)

4.2.2 Radiation effect modelling and experimental validation: phase stability and bonding (SCK•CEN WP nr 4.2.2)

EFDA Task nr:	*WP13-MAT-IREMEV-01-01*
Principal Investigator:	*D. Terentyev (dterenty@sckcen.be)*
Scientific Staff:	*D. Terentyev and A. Bakaev*

The work performed under this task is included in 4.2.3 Radiation effect modelling and experimental validation: deformation and plasticity (SCK•CEN WP nr 4.2.3).

4.2.3 Radiation effect modelling and experimental validation: deformation and plasticity (SCK•CEN WP nr 4.2.3)

EFDA Task nr:	*WP11-MAT-REMEV-03-01 (& WP13-MAT-IREMEV-01-01)*
Principal Investigator:	*D. Terentyev (dterenty@sckcen.be)*
Scientific Staff:	*D. Terentyev and A. Bakaev*

OBJECTIVES AND BACKGROUND

Dislocation loops (DL) form in metals and metallic alloys after quenching from high temperature, upon plastic deformation and under irradiation by heavy particles [42]. The presence of DLs in crystalline materials leads to yield stress increase and reduction of work hardening up to its disappearance [43; 44]. In the case of Fusion structural steels, radiation-induced degradation limits their low temperature limit for the safe application and therefore loop-hardening needs to be assessed [44]. Iron (Fe) and its alloys are the basis for wide-spread structural steels, therefore extensive experimental effort has been put to investigate irradiation hardening in it by SCK•CEN researchers and others [45; 46; 47; 48; 49; 50].

The physical origin of hardening comes from the interaction of dislocations with lattice defects, impeding their movement. Two main mechanisms have been proposed to explain dislocation loop hardening: dispersed barrier hardening (DBH) model and loop decoration of dislocations. The DBH model accounts for obstacles that pin dislocations by intersecting their glide plane [51]. The decoration hardening is explained by the elastic interaction between dislocations and loops [52]. Since DLs, produced in Fe under neutron irradiation, are known to be small and highly mobile, the DBH model is usually applied to correlate the hardening and radiation-induced microstructure e.g. [53].

The loop – dislocation interaction has been extensively studied in Fe by molecular dynamics (MD) [54; 55; 56; 57; 58; 59; 60; 61]. Two principally different interaction mechanisms were revealed: (i) elastic drag, realizing for the loops whose Burgers vector (***b***) is contained in dislocation glide plane [61], and (ii) a direct dislocation reaction resulting in the formation of a junction, occurring for DLs with ***b*** inclined to the dislocation glide plane [56]. The former interaction does not offer any significant resistance as long as DL as easily glissile, which is the case of $a_0/2<111>$ loops in Fe [62]. Inclined DLs exhibit a dual behaviour: at low temperature loops are strong non-absorbable obstacles, while at high temperature their strength is reduced and loops are completely absorbed by dislocations [63]. The duality originates from the temperature dependent mobility of a junction segment (JS), formed as a result of dislocation – DL interaction (see Figure 6 in [55] and Figure 31 here), which depends on both temperature and applied stress. At high enough temperature, absorption mechanism realizes via thermally activated movement of the JS whose propagation across the loop surface reforms the pre-existing loop [56; 57; 64]. While at low temperature zip-unzip interaction takes place [56]. This behaviour is common for both $a_0<100>$ and $a_0/2<111>$ loops, which are present in Fe-based alloys depending on irradiation temperature [49; 50; 65].

The character of the impinging dislocation plays an important role in the absorption reaction. Loops reform as glissile superjogs on edge dislocations [57; 58], and accommodate as sessile helical turns on screw dislocations [59; 60]. Operation of the absorption mechanisms upon deformation is of crucial importance being related with the formation of 'clear channels' [50; 53] believed to be responsible for plastic instability and premature failure of irradiated materials [44].

Discrete dislocation dynamics (DD) simulations is the usual way to rationalize the interaction of dislocations with loops. However, its straightforward application to the problem is not obvious due to the specificity of dislocation loops formed upon neutron irradiation, namely: (i) DLs typically do not exceed ten nanometers in size [46; 50; 64]; (ii) DLs exhibit athermal one-dimensional glide, behaving as a set of independent crowdions rather than dislocation objects [67; 68]. The consideration of loops as objects made by a set of dislocation segments is complicated because it requires a high grid of discretization penalizing the evolution of the whole system. Recently, DD simulations were applied to study the interaction of dislocations with isolated loops [69] and an array of DLs [70]. The former work did not include the reaction of JS formation, which implies the reaction as occurs in MD could not be reproduced [69]. The latter work was applied to model deformation of 3D crystals containing different density of large hexagonal loops 25 nm in size. However, no benchmark of the applied parameterization proving the adequacy of the description of dislocation-loop interaction has been presented [70]. This step is, however, essential because allowed reaction pathways and junction mobility rules are fully responsible for DD outcome. In addition, the simulation method considered in [70] requires significant computational resources. Therefore, an accurate and computationally efficient method to include nanometric dislocation loops in DD simulations is desirable to model strengthening of neutron irradiated metals and alloys.

As a task for this year, we formulated a comprehensive and efficient method to model the thermally activated loop-dislocation interaction in DD. We analyze the MD-simulated interaction mechanisms and demonstrate that DLs can be implemented in DD method as stochastic finite-size and finite strength obstacles. The reaction pathway and unpinning stress are determined by the stress-dependent activation energy function, derived using MD results. The derivation is performed for a $a_0/2<111>\{110\}$ edge dislocation interacting with $a_0/2<111>$ loops, whose Burgers vector (***b***) is inclined to the dislocation glide plane. The derived law is implemented in 'microMegas' DD code [71] and applied to estimate the strengthening of neutron irradiated Fe to compare with available experiments [50].

ACHIEVEMENTS AND MAIN RESULTS

Consider the interaction between a mobile edge dislocation with $\vec{b}_D = a_0/2[111]$ gliding in the $(1\bar{1}0)$ plane and DL with $\vec{b}_L = a_0/2[\bar{1}1\bar{1}]$, which is inclined to the dislocation glide plane, as schematically presented in Figure 31. Several works dedicated to this type of interaction can be found [56; 57; 63]. The interaction begins with the formation of the JS. An upper loop segment and dislocation line react as $\vec{b}_L + \vec{b}_D = \vec{b}_{JS}$, so that $\vec{b}_{JS}$ = [010] in the considered example, as shown in Figure 31(a). The junction, whose $\vec{b}_{JS}$ is defined by atomic disregistery analysis [57], is sessile in the $(1\bar{1}0)$ plane so the dislocation arms bow out under the action of increasing stress and form a screw dipole.

The dipole arms perform cross-slip movement (see $F_{[1\text{-}10]}$ in Figure 31(b)) and push the JS to propagate along the $(\bar{1}01)$ dislocation loop habit plane. As a result, the loop is completely absorbed in mobile dislocation and forms a superjog on it, see Figure 31(c). The reaction pathway, unpinning stress and outcome are determined by the junction resistance.

To translate this interaction mechanism to DD formalism, loop is represented as a spherical obstacle with a diameter L_{JS}, which is crossed by the dislocation if a certain critical stress τ_C is applied. For a periodic row of obstacles, the highest value of τ_C would be determined by Orowan stress [72] corresponding here to the annihilation of the screw dipole behind the loop, as shown in Figure 31(d). This situation realizes if the JS remains immobile, i.e. applied resolved shear stress, RSS, applied to the dipole arms connected with the JS, is not high enough to active its glide. The activation of the JS glide and subsequent τ_C depend on loading conditions, i.e. temperature and strain rate, as MD loading histories shown in Figure 32 demonstrate [57; 64]. Thus, an RSS-dependent energy function $\Delta G(\tau_C)$ for the activation of the JS glide triggering the absorption reaction needs to be determined.

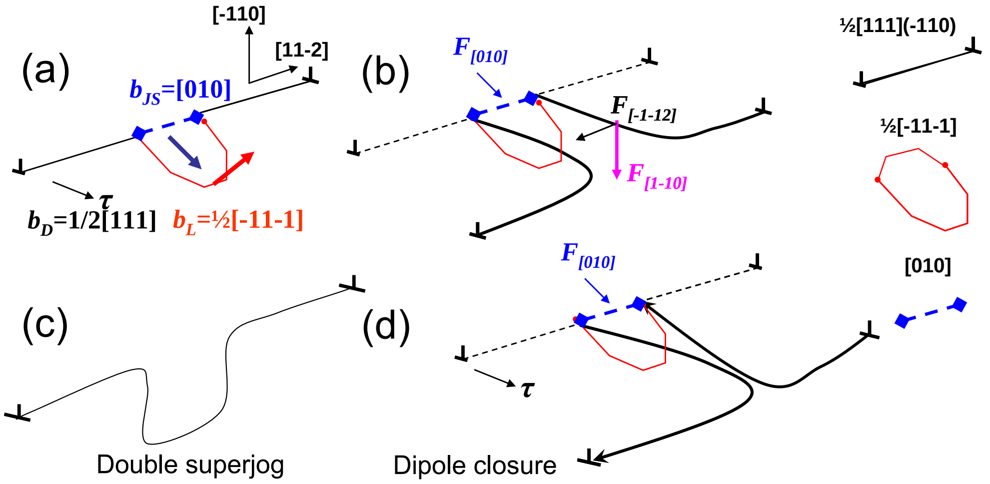


Figure 31: Interaction between $a_0/2[\bar{1}1\bar{1}]$ DL and $a_0/2[111](1\bar{1}0)$ edge dislocation. → τ denotes the direction of dislocation movement and orientation of the Burgers vector of dislocation. Red and blue arrows denote the orientation of DL and JS, respectively. Symbols *F* denote the direction of forces acting on JS and screw dipole segments.

To derive $\Delta G(\tau_C)$ function we apply a recently developed approach [73] based on the stochastic analysis of the loading history obtained from MD simulations. It was demonstrated that a thermally activated dislocation movement, simulated by MD, can be reduced to a Poisson's process, i.e. a stochastic process with an exponential distribution between two consecutive events, with an equivalent rate and activation stress enabling to compute the activation energy for a given loading history. Here, we apply the procedure from [73] to compute $\Delta G(\tau_C)$ for a_0<111> loops, using MD data obtained from the constant strain rate simulations, as was done for voids in [74]. The fundamentals of the approach are described in [73], while here we provide only its essence.

Consider the stress-strain curves shown in Figure 32(a) corresponding to the DL-dislocation interaction in the same geometry as shown in Figure 31(a). The MD results were obtained using the interatomic potential from [75]. The critical RSS for absorption, τ_C, decreases with temperature, indicating a thermally activated interaction nature. We shall use these data to compute ΔG as a function of effective stress, τ_{eff} , applied to the JS. τ_{eff} is applied via the screw arms (see Figure 31(b)) and is related to the RSS measured in MD simulations, τ_{MD}, as [74]:

$$\tau_{eff} = \left(1+\frac{L-D}{D}\right)\tau_{MD} - \frac{L-D}{D}\tau_f \tag{1}$$

Where τ_f is the friction threshold stress necessary to induce movement of the $a_0/2$ an($\bar{1}10$) edge dislocation before interacting with the loop. τ_f, typically not exceeding few MPa at finite temperature [76], is considered to be negligible. L and D is the loop spacing and loop size, respectively. Note that $D \approx L_{JS}$, the junction length.

By considering the activation of the JS glide as a Poisson's process, τ_C, ΔG, and τ_{eff} obey the following relationship [73]:

$$\Delta t \exp\left(-\frac{\Delta G(\tau_C)}{kT}\right) = \int_0^{\Delta t} \exp\left(-\frac{\Delta G(\tau_{eff})}{kT}\right) d\theta \tag{2}$$

Where Δt is the interaction time, i.e. a period from the moment when τ_{MD} exceeds τ_f up to the unpinning, as schematically shown in Figure 32(a). Following transformations described in [73], one deduces τ_C as:

$$\tau_C = \frac{kT}{V}\ln\left\langle \exp\left(\frac{V\cdot\tau_{eff}}{kT}\right)\right\rangle_{\Delta t} \tag{3}$$

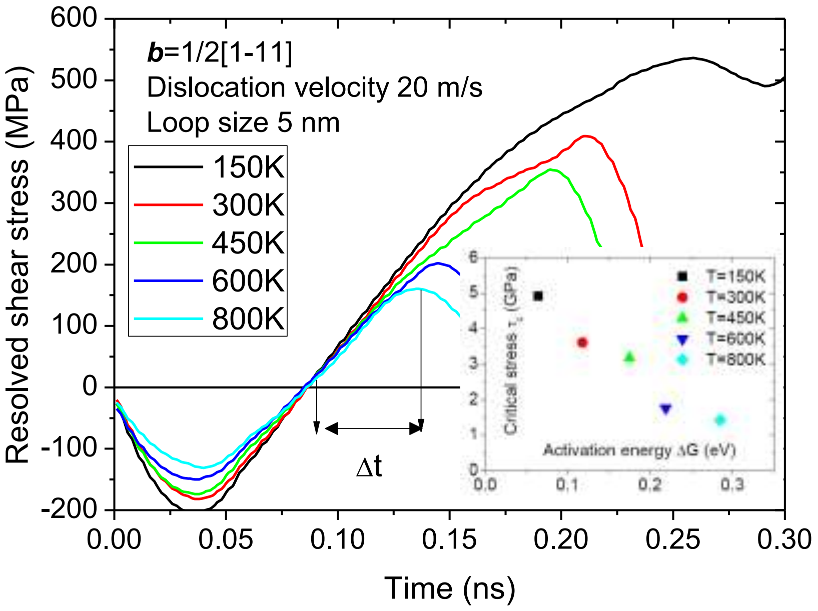
Here, V is the activation volume, which relates ΔG as $\Delta G = C - V\cdot\tau_{eff}$. Given the geometry of the JS, V can be taken as $L_{JS} \times b^2$. For a given loading history and τ_C, ΔG can be calculated on the basis of the survival time as $\Delta G = kT\ln(\Delta t\cdot v)$ [73].

The above consideration imply that: (i) the ambient MD temperature increases negligibly within Δt, and (ii) the attempt frequency, v, is known. The first condition is respected as the typical increase of temperature in such MD simulations is only few degrees [56; 57]. A rigorous calculation of v is delicate as it requires knowledge of obstacle shape, size, strength and vibration spectrum of material. However, v appears as pre-exponential factor, while variation of ΔG present in the exponent is large. A rough estimation is therefore enough, which is $v \approx v_D \times b/L_{JS}$, where v_D is the Debye frequency and $b = a_0$.

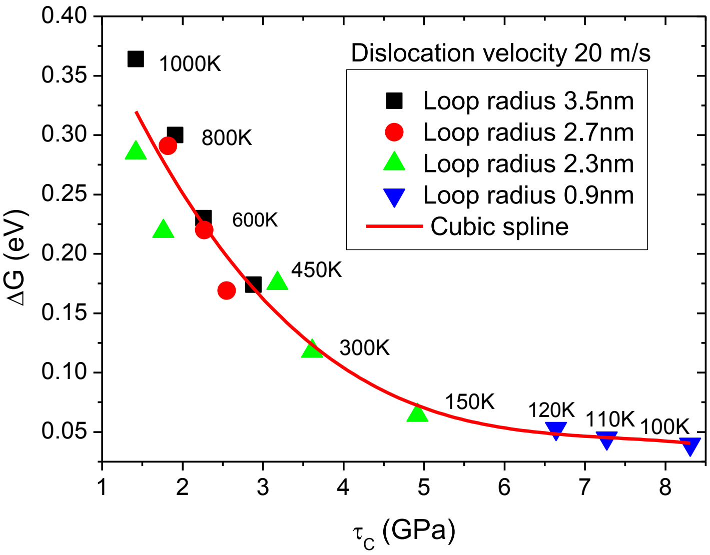
Inset of Figure 32(a) shows $\Delta G(\tau_C)$ calculated from the loading histories provided in the same Figure. The result obtained at each temperature is marked by its own colour and symbol. By applying the same procedure for other $a_0/2<111>$ loops with a size varied from 1.8 to 7 nm, we constructed ΔG points presented in Figure 32(b). $\Delta G = 0.55 - 0.2\ \tau_C + 0.025\ \tau_C^2 - 0.0012\ \tau_C^3$ function was then obtained by fitting a cubic spline to these points. The dimensionality of ΔG and τ_C is, respectively, eV and GPa.

The validation of the derived $\Delta G(\tau_C)$ law was realized by comparison of the resolved critical stress and dislocation curvature measured in MD and DD simulations. We employed the 'microMegas' DD code [77] operating with edge, screw and mixed segments for which the total force acting on each segment is computed and a mobility law is applied to update positions of segments in time. To model a glide of $a_0/2<111>$ dislocations in a {110} plane in bulk Fe, we applied the mobility laws established earlier [78]. The mobility of pinned segments was parameterized by the law obtained here. DLs were introduced as spheres, whose centre coincided with the dislocation glide plane. The resistance to dislocation motion inside the sphere was imposed by assigning the friction stress to be overcome [79]. The probability for the segment penetration within a time step, t_s, was defined as: $p = v \cdot t_s \exp\left(\frac{-\Delta G(\tau_{eff})}{kT}\right)$, where τ_{eff} is the stress exerted on the segment, i.e. effective stress, while v and ΔG are given above. The shear reaction in DD simulations is equivalent to the absorption in MD simulations.

Figure 33 presents the results of benchmark calculations where the interaction was modelled by DD and MD in the equivalent loading conditions. Each MD point is the average over five runs. Clearly, good agreement for the critical RSS computed from MD and predicted by DD is obtained in the whole temperature range. The shape of the dislocation line at the unpinning moment at 300 K identified in MD and DD simulations is shown in two inset Figures. The two dislocation configurations exhibit similar curvature, although the MD-obtained curvature is asymmetric. This originates from the anisotropy, naturally reproduced in atomistic simulations but not accounted for in DD. The relative ratio of the two areas swept by the dislocations in MD and DD is ~0.8 at 300K and getting closer to a unity at higher temperatures.



(a)



(b)

Figure 32: (a) Evolution of RSS corresponding to the interaction of $a_0/2<111>$ DLs with a ½<111>{110} edge dislocation modelled. Δt is the interaction time (see text) at 800 K. Inset Figure displays critical stress - activation energy dataset deduced from the τ-γ curves. (b) $\Delta G(\tau_C)$ function obtained from MD simulations.

Finally, we apply the DD model to assess strengthening of Fe neutron-irradiated at 70 °C up to 10^{-3} - 0.79 dpa [50]. The microstructure formed consisted of $a_0/2<111>$ dislocation loops and nanometric cavities [50]. The mean loop size increased from 1 to 4 nm, while the maximum loop size from 1 to 8 nm. The loop density increased from 10^{21} up to 6×10^{22} m^{-3} in this dose range.

Nano-cavities of sizes up to 0.5 nm with a density ranging from 10^{23}- 4.5×10^{24} m^{-3} were present as well, as detected by positron annihilation spectroscopy. At the highest dose, the cavities with sizes up to 1.5 nm and density of 5×10^{23} m^{-3} were seen by TEM. The initial dislocation density was 10^{12} m^{-2}. These microstructural data are used to evaluate the flow stress increase by DD simulations. The loop densities were reduced by a factor of two to account for the presence of DLs in glissile configurations, as discussed in introduction.

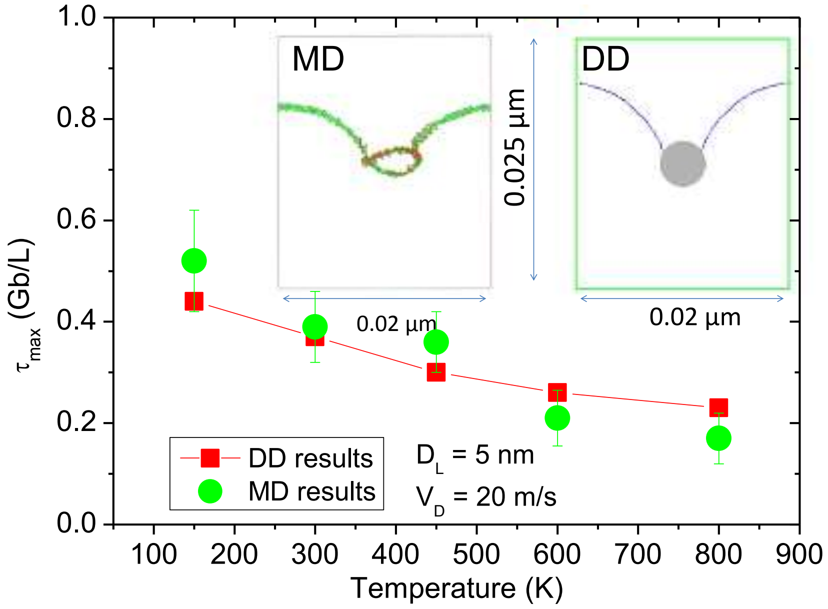


Figure 33: Critical RSS (expressed in reduced units) calculated by MD and DD simulations for the interaction with 5 nm loop as a function of temperature. The error bars for MD results are obtained over five runs for each temperature varying random seed to initialize temperature. Inset Figures show the shape of the dislocation line at the unpinning in MD and DD calculations at 300K.

The dimensions of DD sample are $5\times5\times0.2$ μm^3 with the glide plane perpendicular to z axis. A single $a_0/2<111>\{110\}$ edge dislocation line is introduced in the periodic simulation box, resulting in the dislocation density of 10^{12} m^{-2} as in experiment. 5 µm dislocation line length ensures a smooth evolution of stress-strain curve and accurate estimation of the flow stress. Periodic boundary conditions are applied in the three directions, leading to an infinite dislocation line. Constant strain rate load, resulting in the dislocation velocity of 1 m/s, is applied at 70°C. To distinguish the contribution to hardening from voids and dislocation loops we consider samples containing only voids, only loops and mixture of the defects. Voids are 3D randomly distributed and $\Delta G(\tau_C)$ function for the void strength, $\Delta G = 0.1922\times\tau_C^2 + 0.2297\times\tau_C + 0.0454$ for 2nm void, is taken from [74], also based on MD simulations. The loops are initially introduced randomly but then the loops located at a distance $\pm D_L$, the loop diameter, from the glide plane are positioned exactly on the glide plane. By doing that, we accounted for the limited loop glide near the approaching dislocation, which occurs in MD simulations [57]. To compare the DD resolved flow stress with the experimental data, we scaled the simulation results by a factor of 3, the Schmidt factor. Typical time required to consider one DD run on a single CPU is ~24h.

The calculated flow stress increase due to cavities, $a_0/2<111>$ dislocation loops and mixture of the defects is presented in Figure 34. The loops cause higher strengthening than voids for the whole dose range. The contribution from the voids becomes essential only at the highest considered dose, when cavities are already resolvable in TEM. The total strengthening of the mixture of the defects calculated at 10^{-3} and 0.01 dpa is comparable to the experimental values. Whereas, the $\Delta\sigma$ predicted at 0.79 dpa for the mixture of the defects exceeds the experimental result. However, we should keep in mind that (i) the formation of dislocation loop rafts causing spatial heterogeneity was reported at 0.79 dpa [50], which may reduce the actual contribution to hardening from loops; (ii) and the contribution from screw dislocations still needs to be assessed, which is possible using the method proposed here. At this point, we can mention that mobility of $a_0/2<111>$ screw dislocations at room temperature and above is comparable with that of edge dislocation, and the principal mechanism of DL absorption is also the same [60]. It is therefore reasonable to assume that the strength DL opposed to screw lines will be comparable with that for edge dislocations.

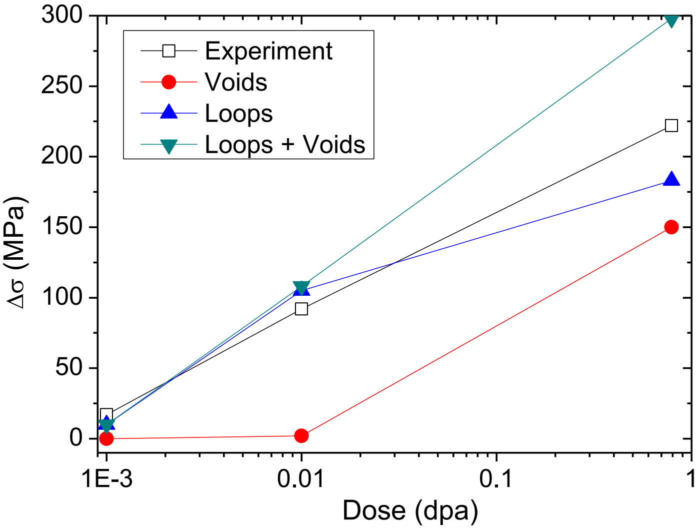


Figure 34: Strengthening computed from DD simulations and experimental data from [50].

To summarize, we have discussed a general mechanism of DL-dislocation interaction, studied earlier by MD, and proposed a simple and comprehensive way to transfer it to DD models. Analysis of MD data demonstrates that the reaction pathway, unpinning stress and the outcome product are determined by the resistance of the junction formed in the reaction. Dislocation – loop interaction can be translated into DD formalism, by representing loops as spherical obstacles, which can be swept by dislocations if the effective stress acting on junction segments exceeds a certain critical stress τ_C.

MD results show that junction glide is a thermally activated process, hence a stress-dependent activation energy determining the probability of the activation of the junction is required for its application in DD at finite temperature. $\Delta G(\tau_C)$ for $a_0/2<111>$ loop – dislocation interaction was determined using the stochastic analysis of loading histories from MD simulations and implemented in 'microMegas' DD code and benchmarked showing a good agreement in a wide temperature interval.

The DD model was used to evaluate the strengthening attributed to a microstructure consisting of dislocation loops and voids, as experimentally reported for neutron irradiated Fe [50]. A reasonable agreement between the predicted increase of the flow stress and experimental data is found for low doses, which induce homogenous distribution of dislocation loops. For the highest dose of 0.79 dpa, our model overestimates the hardening, probably due to the formation of rafts of loops, observed in the experiment. The contribution to hardening from voids becomes significant only when their size exceeds 1 nm.

We can conclude that consideration of small but resolvable and numerous dislocation loops as stochastic thermally activated short-range obstacles can be done in a simple, fast and reliable way. This methodology can be applied to other types of dislocation-like objects, e.g. <100> loops and stacking fault tetrahedral, as long as the interaction mechanism is determined by the properties of junctions. Hence, the proposed treatment opens a new possibility to evaluate strengthening and evolution of complex microstructure upon deformation of pre-irradiated materials.

PARTNERS

- FZD, Germany (F. Bergner)
- UPC, Spain (A. Serra, N. Annento and H. Khater)
- ORNL, USA (Yu.N. Osetsky)

4.2.4 Radiation effect modelling and experimental validation: material science, simulation of armour material (no SCK•CEN WP nr)

EFDA Task nr:	*WP13-MAT-IREMEV-04-01*
Principal Investigator:	*Giovanni Bonny (gbonny@sckcen.be)*
Scientific Staff:	*D. Terentyev and A. Bakaev*

OBJECTIVES AND BACKGROUND

Following the need to continue multi-scale modelling to simulate radiation damage in W and W-based alloys (e.g. W-Re appearing due to the transmutation or W-Ta being a potential candidate) we propose to study the stability and mobility of radiation defects (beyond the scale of ab initio calculations) in the presence He & H and its impact on mechanical properties. This study will primarily address the issue related to the well-known synergy of He and H with respect to the macroscopic changes such as, blistering, retention, swelling and accumulation of radiation damage, which all in synergy leads to the degradation of different material's properties.

To perform the latter study, the development of a ternary W-He-H potential is necessary. Currently, for tungsten more than 30 different interatomic potentials are available in the literature in the form of pair potentials [80, 81, 82, 83], central force many-body potentials [84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99] and its empirical modification [100], bond order potentials [101, 102, 103, 104], modified embedded atom method potentials [105, 106, 107] and fourth moment tight binding potentials [108, 87, 109]. Each potential comes with its own strong points and weaknesses. Since all results hinge on the quality of the interatomic potential it is important that its properties are well understood. Given the vast amount of available potentials, a review summarizing their basic properties is in place.

Here we focus on the central force many-body formalism, which is a good compromise between transferability/predictability and computational speed. The central force many-body framework was developed independently under the forms: 'embedded atom method' (EAM) [110], 'Finnis-Sinclair formalism' [84] and 'glue model' [111, 112]. We review the properties of 18 such potential for W found in the literature [84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99].

As basic properties we consider the lattice stabilities, elastic constants and point-defect properties which are benchmarked against experiments and density functional theory (DFT) calculations from literature and where appropriate extended by ourselves. In addition we also investigate more extended defects: free surfaces, grain boundaries, the ½<111> {110} and ½<111> {112} gamma surface cuts and ½<111> screw dislocation core. We also provide the Peierls stress for 1/2<111> edge and screw dislocation as well as the glide path of the latter. The potentials that show appropriate dislocation behaviour are also tested with respect to their interaction with dislocations loops.

ACHIEVEMENTS

The investigated potentials are summarized in Table 10. To simplify matters, we note that both AT and JW are modifications at short interaction range of FS, which only affect the interstitial formation energy. Henceforth, all conclusions for FS are also valid for AT and JW, unless explicitly stated otherwise. The potentials ZSG and ZKG are identical except for a small difference in cut-off. The latter, however, does not influence the results, thus henceforth only ZSG is discussed. Potential BND is the stiffened version of DND and does not change the equilibrium properties of the former discussed in this work. Therefore only DND is discussed in the following.

From all potentials, we also found that WB, GKL and ZSY to stabilize the fcc lattice more than the bcc one. Therefore, the latter potentials were not considered in the following.

FS	Finnis and Sinclair, 1984, Ref. [84].
AT	Ackland and Thetford, 1987, Ref. [85].
JO	Johnson and Oh, 1989, Ref. [86].
FOI	Foiles, 1993, Ref. [87].
WB	Wang and Boercker, 1995, Ref. [88].
ZWJ	Zhou et al., 2001, Ref. [89].
KLL	Kong et al., 2002, Ref. [90].
GKL	Gong et al., 2003, Ref. [91].
ZSG	Zhang et al., 2004, Ref. [92].
ZKG	Zhang et al., 2004, Ref. [93].
ZSY	Zhang et al., 2005, Ref. [94].
DLK	Dai et al., 2007, Ref. [95].
DND	Derlet et al., 2007, Ref. [96].
BND	Björkas et al., 2009, Ref. [97].
JW	Juslin and Wirth, 2013, Ref. [98].
MVG1	"EAM-2" of Marinica et al., 2013, Ref. [99].
MVG2	"EAM-3" of Marinica et al., 2013, Ref. [99].
MVG3	"EAM-4" of Marinica et al., 2013, Ref. [99].

Table 10: Nomenclature of the investigated central force many-body potentials.

In the following, we consider the lattice stabilities, elastic constants and point-defect properties which are benchmarked against experiments and density functional theory (DFT) calculations from literature and where appropriate extended by ourselves. In addition we also investigate more extended defects: free surfaces, the ½<111> {110} and ½<111> {112} gamma surface cuts and ½<111> screw dislocation core. We also provide the Peierls stress for 1/2<111> edge and screw dislocation as well as the glide path of the latter. The results for all considered potentials are summarized in Table 11.

The results of a potential are considered "consistent" (C) with experimental or DFT data when there is qualitative (correct order or smooth curve) and quantitative (within 10% of the given range) agreement; "inconsistent" (IC) when there is no qualitative agreement; "underestimated" (UE) when there is qualitative agreement and the target value is underestimated by more than 10%; and "overestimated" (OE) when there is qualitative agreement and the target value is overestimated by more than 10%. The present summary serves as basic for the discussion of all properties as the presentation of all data is outside the scope of this brief report.

Property	**FS**	**JO**	**FOI**	**ZWJ**	**KLL**	**ZSG**	**DLK**	**DND**	**MVG1**	**MVG2**	**MVG3**
Elastic Constants	C	C	C	C	IC	C	C	C	C	C	C
Ef(Vac)	C	C	C	C	C	C	C	C	C	C	C
Em(Vac)	UE	C	IC	C	C	IC	C	C	C	UE	C
Eb(Di-Vac)	IC	IC	IC	IC	IC	IC	IC	UE	UE	IC	UE
Ef(SIA)	UE*	IC	IC	IC	IC	IC	IC	C	C	C	C
Screw dislocation core	IC	IC	C	C	IC	C	C	IC	C	C	C
Screw dislocation glide	IC	IC	IC	IC	IC	IC	IC	IC	C	C	C
Free surface	UE	UE	UE	UE	UE	UE	UE	UE	UE	C	UE
Gamma surface cuts	UE	C	IC	C	C	IC	UE	IC	C	UE	C

IC – Inconsistent with experimental or DFT data.
C – Consistent with experimental or DFT data.
OE – Overestimation compared to experimental or DFT data.
UE – Underestimation compared to experimental or DFT data.
* For both AT and JW are consistent with the DFT data.

Table 11: Schematic summary of the performance of the potentials for different physical properties.

With respect to the elastic constants, all potentials were fitted to experimental data, in particular, FS, KLL, DND was fitted to [113], JO, FOI and ZSG to [114] and MVG1, MVG2 and MVG3 to [115]. We note, that for ZWJ and DLK no references regarding the target data are given. All potentials and DFT data, except for KLL, are in excellent or satisfactory (<10% deviation) with the experimental data. For KLL the deviations for C11 and C12 go as high as 70%. We also note that all DFT data is within 10% of the experimental data.

With respect to the formation energy of self-interstitial configurations, all DFT data suggests the <111> crowdion as most stable configurations. This trend is followed by FS, AT, DND, JW, MVG1, MVG2 and MVG3, while JO, FOI, ZWJ, ZSG and DLK predict the <110> dumbbell and KLL the <100> dumbbell as most stable self-interstitial configurations. We remark that only DND, JW, MVG1, MVG2 and MVG3 were explicitly fitted to interstitial configurations, namely, DND and JW to [121] and MVG1, MVG2 and MVG3 to [116].

All potentials were fitted to the experimental or DFT calculated vacancy formation energy. In particular, FS and KLL were fitted to [117], JO, FOI and ZSG to [118, 119, 120], DND to [121] and MVG1, MVG2 and MVG3 to [116]. All potentials and DFT data are in good agreement with experiments, i.e., within the experimental range of 3.15-4.1 eV.

The vacancy migration barrier was not explicitly fitted for any of the potentials. Nevertheless, all potentials and DFT data, except for FS, FOI, ZSG and MVG2, are within 10% of given experimental range (1.7-2.0 eV). Besides the absolute value, also the migration energy path followed by the vacancy is of importance. In Figure 36 we compare the vacancy migration energy path between DFT and the potentials. The DFT curve shows a plateau (or shallow minimum) around the saddle. This specific shape is reproduced by JO, ZWJ, KLL, DND, MGV1, MVG2 and MVG3. However, more important than this specific shape is the overall smoothness of the curve. We note that in addition to the latter, FS and DLK exhibit a smooth curve, while FOI and ZSG exhibit unphysical humps.

With respect to the binding energy for the divacancy, the combined field-ion microscopy and electrical resistometry experiments by Park et al. [122] predict a strongly bound (0.7 eV) 1nn di-vacancy complex as most stable di-vacancy configuration. While all DFT data indicates less binding or stronger repulsion for a 2nn di-vacancy compared to 1nn one, it is only the data by Derlet et al. [96] that provides significant binding (0.41 eV) at 1nn. All other data suggests insignificant binding or repulsion. The origin of the 2nn repulsion is explained in [99] in terms of the shape of the local density of states near the Fermi level. The latter is a purely quantum mechanical effect that is not expected to be reproducible by any of the central force many-body potentials. Indeed, none of the potential reproduces 2nn repulsion and they all underestimate the experimentally estimate binding energy. In fact, only DND, JW, MVG1 and MVG3 predict the 1nn di-vacancy to be significantly more stable than the 2nn one. All other potentials, except for FS, AT and DLK that provide similar binding at 1nn and 2nn distance, predict the 2nn di-vacancy as most stable configuration.

In Figure 35 we show the relative energy difference of the low index free surface orientations {110}, {100}, {111} and {112} calculated by both DFT and the potentials. Both presented DFT data sets give similar results, except for the (111) free surface that shows a discrepancy of about 400 mJ•m^{-2}. As shown in the figure, all potentials predict the {110} surface to be the most stable, consistent with DFT. With respect to the DFT trends, DND is the only potential that consistently with DFT predicts the {100} free surface with highest energy difference. In fact, the resulting curve from DND is in excellent agreement with the DFT data from [Vitos98]. All other potential predict the {111} free surface with highest energy difference. In Tab. T3 we added the absolute values for the {110} free surface as calculated by the potentials and DFT and as obtained from experiment. While the DFT calculated values lay within 10% of the experimental data range, for the potentials this is only true for MVG3. All other potentials underestimate the latter.

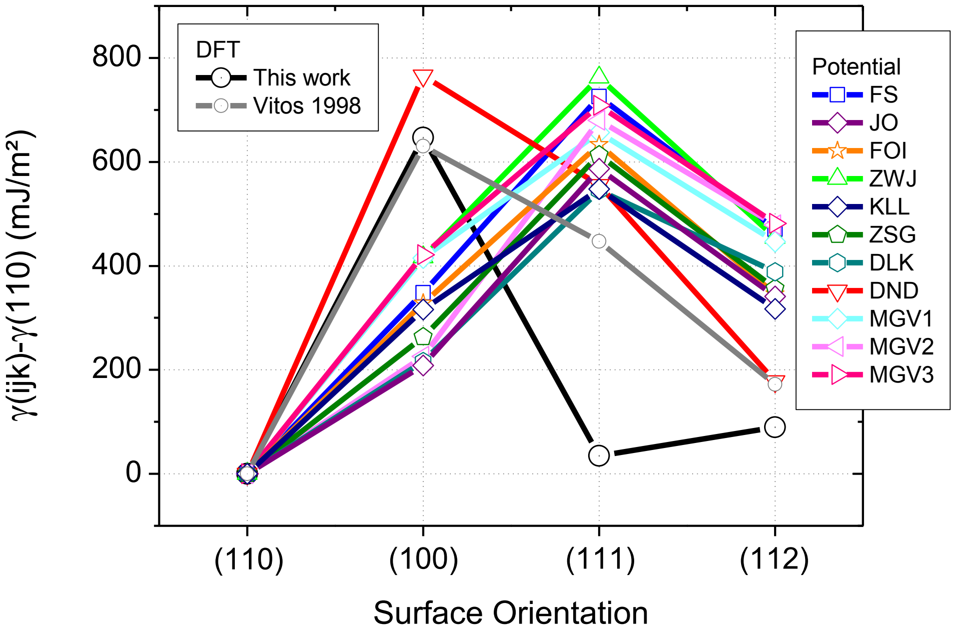


Figure 35: Free surface energy per unit area for various low index surface configurations.

In Figure 36 we show the ½ <111> {110} and ½ <111> {112} gamma surface cuts, respectively, calculated by both DFT and the potentials. The latter provides information with respect to the energy landscape for shear process of a perfect crystal in {110} and {112} atomic planes, and can be related to the dislocation core structure and Peierls stress [123, 124]. As shown in the figures, all DFT data predicts smooth behaviour with a single well defined maximum. For both gamma surface cuts, FOI, ZSG and DND exhibit unphysical humps, while all other curves are smooth. From the smooth curves, JO, KLL, ZWJ, MGV1 and MGV3 are within 10% of the DFT data for the ½ <111> {110} gamma surface cut, while the same is true for MGV1 and MGV3 for the ½ <111> {112} gamma surface cut.

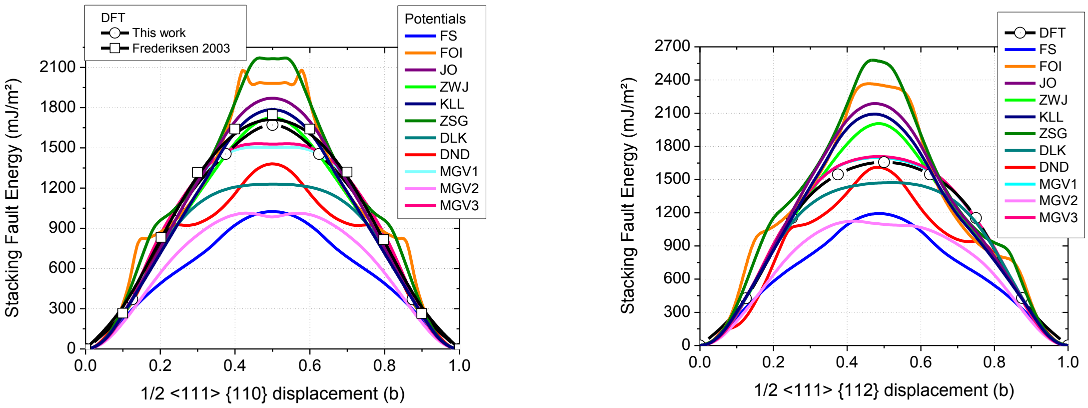


Figure 36: Comparison between DFT and the potentials of the ½ <111> {110} (left) and ½<111> {112} (right) gamma surface cuts.

For all bcc transition metals and W in particular, DFT predicts a compact isotropic core structure for a ½<111> screw dislocation. Consistent with the DFT result, the compact core is reproduced by ZSG, DLK, MVG (all), FOI and ZWJ. The three fold core structure is predicted by FS, JO, KLL and DND. Note that FOI and ZSG fail to reproduce (even qualitatively) the DFT-predicted gamma-lines and <111> row - barrier, but adequately describe the SD dislocation core structure. Hence, there is no direct correlation between the shape of the gamma-lines and screw dislocation core structure.

The mechanism of dislocation movement under <111> {110} shear load was also found to be essentially dependent on the applied potential. Overall, it is possible to separate three mechanisms frequently observed, namely: (i) glide of the compact core; (ii) split of the core into a planar structure and glide of the dissociated dislocation; (iii) transformation of the core into three fold degenerate one and emission of gliding 1/6<111> partial dislocation. We remind that according to DFT, the dislocation overcomes the Peierls barrier without changing its compact structure. Among the tested potentials, qualitatively, the movement mechanism was predicted correctly by ZWJ and MVG, but the expected {110} glide plane is reproduced only by MVG2 and MVG3 potentials. The latter two potentials predict the Peierls stress to be 0.98 and 4.43 GPa, which is in between the DFT value of 1.7 GP. The values of the Peierls stress for the SD obtained with other potentials are not discussed as the movement mechanism is inconsistent with DFT predictions.

In conclusion, the MVG potentials are substantially more consistent with experiment and DFT than all others and will be used as a base to develop the ternary W-H-He potential.

PARTNERS

- UGent, Belgium (G. Van Oost, D. Van Neck and V. Van Speybroeck)
- EdF, France (C. Domain)
- KTH, Sweden (P. Olsson)
- TUDelft, the Netherlands (P. Klaver)

4.2.5 Radiation effect modelling and experimental validation: experimental validation (no SCK•CEN WP nr)

EFDA Task nr:	*WP13-MAT-IREMEV-05-01*
Principal Investigator:	*Uytdenhouwen Inge (iuytdenh@sckcen.be)*
Scientific Staff:	*B. Minov, M. Konstantinovic, W. Broeckx*

OBJECTIVES

The objective of this project is to explore the effect of Helium and Hydrogen on Fe, Fe-Cr alloys, steels and refractory alloys with respect to the dislocation dynamics. Thermal desorption of helium from the Fe-Cr alloys and W from the experimental as well as from the modelling point of view will be studied. Finally, the exploration of the synergistic effects of He-H will be addressed.

Experimentally, the objective will be achieved using two techniques, Thermal desorption spectroscopy (TDS) and Internal friction (IF). Both techniques are sensitive to the motion of small interstitials and thus can provide essential information on their dynamics in the materials. In addition, the IF techniques provide unique information on dislocation interstitial interaction through dislocation-related relaxation processes.

ACHIEVEMENTS

The primary task was to investigate the possibility to identify the hydrogen peaks in IF spectra of Fe-Cr alloys and W. The preliminary IF measurements are performed on as-received and hydrogen implanted Fe-9%Cr alloy and pure W.

The Fe9Cr alloy is fabricated by furnace melting of industrial purity Fe and Cr in the form of plate. The plate was then annealed for 3 h at 1320 K in high vacuum for austenitization and stabilization, followed by air cooling down to room temperature. The tempering procedure was performed at 1000 K for 4 h, followed by air cooling. The production route of pure W (purity of 99.7 %) consisted of four steps (1) densification of cylindrical cold isostatically pressed powder compacts by vacuum sintering at 2000-2500 °C, (2) hot forging of the sintered cylinder in the radial direction, (3) Hot forging along the cylinder axis into a flat disc shaped geometry, (4) removal of residual stresses by a thermal treatment at 1000°C. The chemical compositions of these alloys are provided in Table 12.

C	N	O	Al	Si	P	S	Ti	V	Cr	Mn	Ni
0.02	0.015	0.07	0.007	0.09	0.01	0.001	0.003	0.002	8.4	0.03	0.07

Table 12(a): The chemical composition of Fe9Cr alloy (wt. %).

Ag	Pb	Co	Fe	Nb	Ta	Mo	O	Si	Al	Cr	K	Na
0.001	0.002	0.001	0.003	0.001	0.002	0.01	0.002	0.002	0.0015	0.002	0.001	0.001

Table 12(b): The chemical composition of W (wt. %).

Both materials were implanted with hydrogen in low energy temperature plasma. The Fe9Cr IF sample (with a typical size of 1.3 × 1.3 × 30 mm^3) was exposed from one side (1.3 × 30 mm^2) under the operating conditions of 230°C and 80 V, while the implantation of the H in W was performed on all sides at 600°C and 80 V.

Measurements of the IF coefficient, Q^{-1}, as a function of temperature were made in the temperature range from 100 K to 600 K in an inverted torsional pendulum, working at the frequency between 1.8 and 2.5 Hz [125]. The resonance frequency ω, and the internal friction coefficient, are determined by measuring the free decay signal. The measurements have been performed at a strain amplitude of about $\gamma_0 = 10^{-4}$ in a He atmosphere with a heating rate of about 1.5 K/min.

The IF spectra of W and Fe9Cr samples are shown in Figures 37 and 38.

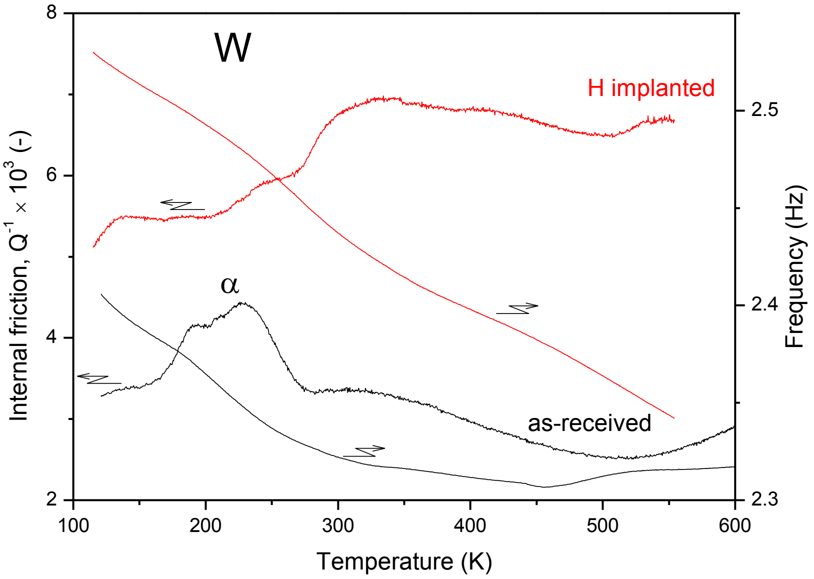


Figure 37: Internal friction spectra of as-received and H-implanted W samples.

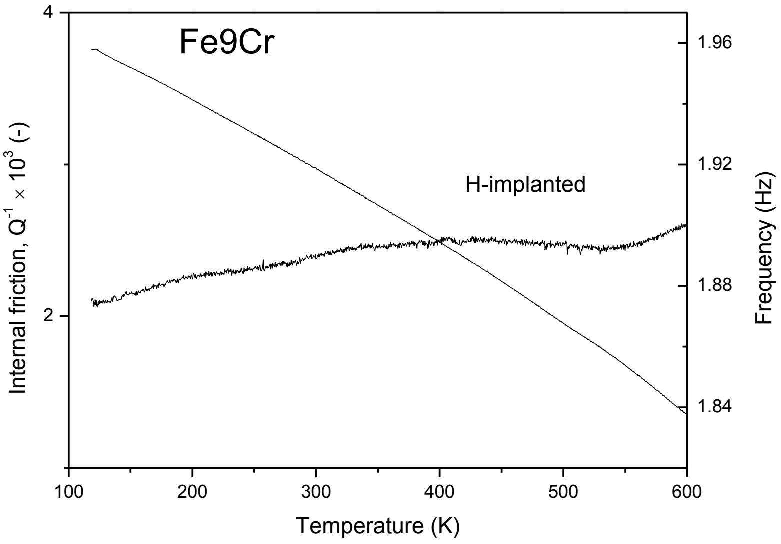


Figure 38: Internal friction spectra of H-implanted Fe9Cr samples.

The spectra of W samples indicate that exposure at 600°C causes the change in the relaxation behaviour of this material. The relaxation peak observed in the range between 180 and 270 K in the spectrum of the as-received sample, denoted as α-peak, represents thermal activation of edge dislocations. The presence of two local maxima in this range agrees well with the literature which suggests that this peak is composed of several constituent subpeaks [126]. After a high-temperature implantation, the peak(s) disappears as a consequence of edge-dislocation annealing. Sudden increase of the background of H-implanted spectra with regard to the as-received sample, in the range between 270 and 470 K, indicates the presence of several relaxation processes. One of them could be the relaxation process of hydrogen atoms in the vicinity of moving dislocations (so called Snoek-Köster(H)- peak) [127]. Nevertheless, these are just basic assumptions and in order to reveal it, additional measurements on samples implanted by different amount of H are planned.

On the other hand, the spectrum of Fe9Cr H-implanted sample does not show the trace of any relaxation process (no change in frequency), see Figure 38. The reason for such behaviour could be an insufficient exposure (the H was implanted only on one side of rectangular bar). Therefore, to investigate the impact of defects on the dislocation movement, the implantation of H in the sample should be significantly larger.

The plan for the future research is to continue the IF measurements on FeCr alloys (Fe2.5Cr, Fe5Cr, Fe9Cr and Fe12Cr) as well as on pure Fe and W. The focus will be given on investigation of the possibility to identify the hydrogen peaks in these materials from TDS in comparison with peaks obtained by IF.

PARTNERS

- TEC (Trilateral Euregio Cluster)
- FOM-DIFFER, the Netherlands

4.3 Techniques for waste recycling

4.3.1 Feasibility analysis of industrial recycling routes and back end of the fusion materials (SCK•CEN WP nr 4.6.1)

EFDA Task nr:	*no EFDA task*
Principal Investigator:	*F. Druyts (fdruyts@sckcen.be)*
Scientific Staff:	*P. Van Iseghem*

No activity was carried out during 2013 under this task by lack of resources.

5. Training and Career development

5.1 Collective training of young engineers and scientists

5.1.1 Training in project oriented quality assurance related to VISIONI (GOT4-PQM-NET) (SCK•CEN WP nr 5.1.1)

EFDA Task nr:	*GOT-PQM-NET*
Principal Investigator:	*W. Broeckx (wbroeckx@sckcen.be)*
Scientific Staff:	*I. Uytdenhouwen, V. Massaut*

OBJECTIVES

Design and commissioning of the secondary confinement for the tritium phase of the VISIONI plasmatron with ISO 9001 compliant document management system under Alexandria and a QMS for the setup and diagnostics. Including handling of the QA aspects of industrial partners supplying the components.

Education in the field of project and quality management with an emphasis on Fusion for Energy (F4E) and ITER International Organisation (ITER-IO) projects and contracts.

ACHIEVEMENTS

The current Tritium lab at SCK•CEN has a walk-in process cell which can be used to enclose the plasma chamber and diagnostics of the VISIONI setup (Figure 39), which have a limited tritium inventory. This allows easy accessibility to the setup in a well-ventilated environment. Routine operations should be conducted from outside the process cell and maintenance operations can be conducted from within the process cell with proper protections. The tritium storage and supply can be enclosed in a glove box with a dedicated air detritiation system which is activated during an experiment or in case of an incident. The detritiation system will oxidize tritium and capture it on molecular sieves. By using this confinement approach it is possible to expose materials to a tritiated plasma while maintaining good accessibility of the VISIONI setup. This proposal is submitted for poster presentation at the tritium 2013 conference and a paper is submitted for publication of the congress proceedings in Fusion Science and Technology

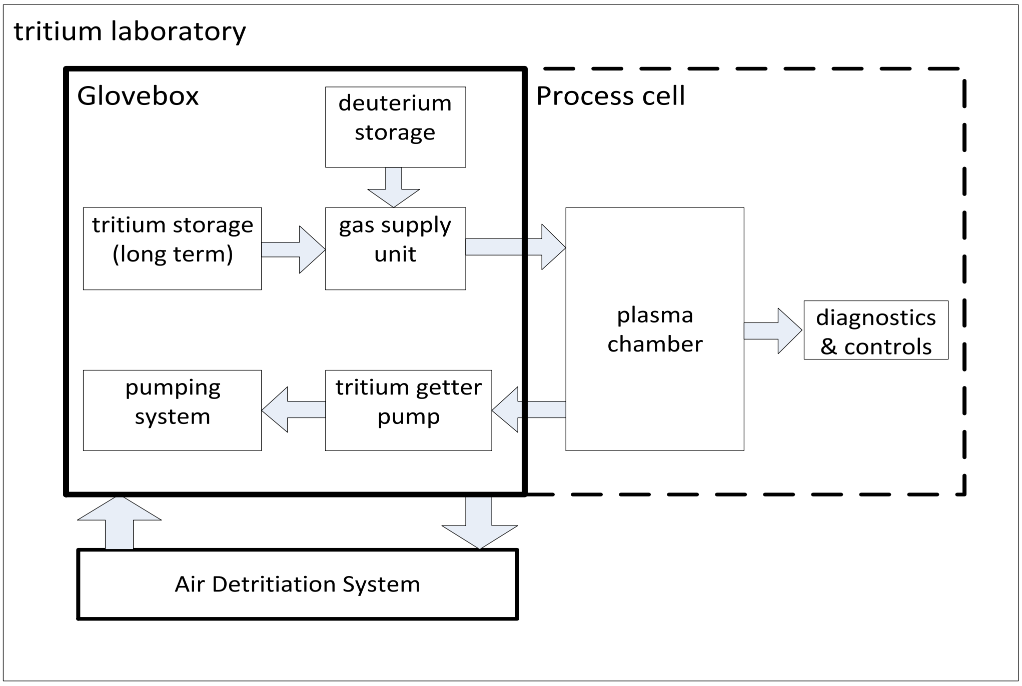


Figure 39: Secondary confinement proposal for VISIONI.

Related to the education in the field of project and quality management, the following Table 13 shows a list of attended trainings. Except from the Carolus Magnus Summer School all courses focused on document management and quality management. Document management is also an essential part in handling F4E and ITER related contracts.

Course Title / Topic / Goals	**Date / Duration (days)**	**Location**	**Training Organization**
ISO 9001: Introduction to ISO9001	2013-06-04 – 2013-06-11 (2 days)	Gent (Belgium)	Amelior
Carolus Magnus Summer School on Fusion Overview of fusion plasma and energy physics	2013-08-26 – 2013-09-06 (10 days)	Bad-Honeff (Germany)	TEC
KIT-1 Quality Management Systems for ITER-related Contracts	2013-06-25 – 2013-06-27 (3 days)	KIT (Germany)	KIT
KIT-2 Planning Tools and Documentation Management Systems in use for ITER-related Contracts	2013-10-15 – 2013-10-17 (3 days)	KIT (Germany)	KIT
Alexandria Introduction to the document management system at SCK•CEN	Workshop (0.25 days)	SCK•CEN	SCK•CEN
Bizagi process modelling Software tool to visualize process flows for the IMS at SCK•CEN	Workshop (0.25 days)	SCK•CEN	SCK•CEN

Table 13: Training overview.

PLANNED ACTIVITIES

Migration of the current VISIONI documentation into Alexandria, the new document management system at SCK•CEN.

Involvement in the F4E grant OFC-358 and/or F4E grant OFC-413.

PARTNERS

- KIT (Karlsruhe Institute of Technology), Germany
- CCFE (Culham Centre for Fusion Energy), UK
- CRPP (Centre de Recherches en Physique des Plasmas), Switzerland
- ENEA (Italian National Agency for New Technologies), Italy
- HAS (Hungarian Academy of Sciences), Hungary
- IST (Instituto Superior Técnico), Portugal

5.1.2 Training in fibre optics and magnetic sensor for tokamaks (GOT1-MAGNOR) - Goal Oriented Training on optical diagnostics and radiation resistance (SCK•CEN WP nr 5.1.2)

EFDA Task nr:	*GOT-MAGNOR*
Principal Investigator:	*A. Goussarov (agoussar@sckcen.be)*
Scientific Staff:	*M. Aerssens*

OBJECTIVES

This Goal Oriented Training MAGNOR (MAGNetic Optical diagnostics under Radiations) is a collaboration between SCK•CEN, CEA Cadarache, and FZJ Jülich. The training consists in following a program on the problematic of operation of magnetic diagnostics for future burning plasma experiments (BPX) and fusion power plants. Two types of constrains are taken in to account. Firstly, radiation load released by the burning plasma induces a series of short and long term spurious electrical effects (RIEMF, RIC, etc.), which require careful consideration in the choice and manufacturing of electrical cabling. Secondly, the steady-state operation by itself is not well suited for inductive (derivative) sensor technologies. Time integrators exist for medium term (1000 s), but such an approach remains still limited for true long term operation of BPX.

A major task in the training consists in the development of a new steady state sensor for plasma current and magnetic fields measurement in thermonuclear fusion reactor. These sensors present several important advantages vs. inductive sensors, such as steady-state current compliance, high frequency bandwidth, high linearity over a wide current range, radiation resistance and a low installation volume.

The GOT started on 1 May 2011 for a period of 3 years. This grant allows establishing a strong collaboration link with the IRFM department of the CEA Cadarache and Textor in FZJ.

ACHIEVEMENTS

Simulation of a fibre-optics current sensor for ITER

In this work, we quantified the error induced by the linear birefringence on the plasma current measurement by simulating different FOCS set-up. The results allowed to define the adequate optical fibre to be used and to stress out the importance of implementing a FOCS in a reflection scheme. We evaluated the performances of an optical fibre current sensor with respect to the ITER requirements. The ITER specifications are defined on one hand by the physical environment where the sensitive fibre will be placed (neutron radiation, temperature changes and vibrations) and on the other hand by the required accuracy of the plasma current measurement. The results presented in this report were obtained by modelling the FOCS system with the Jones formalism. We first compared the performances of spun fibres with standard fibres and we clearly demonstrated that the former is by far the best candidate for both the leading and sensing fibre sections. For example, a 28 m long spun fibre with a spin period of 1 m and with a local beat length of 30 m keeps the relative error on the plasma current below 4.10-4.

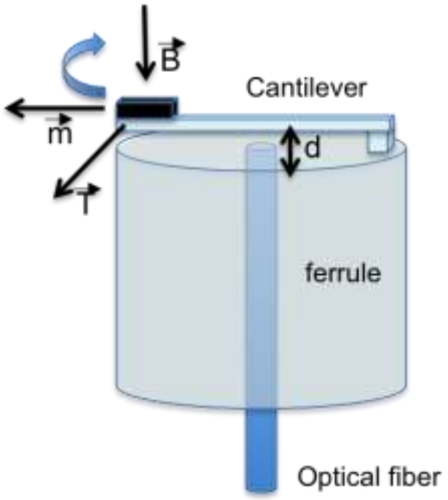
We also quantify the error induced by the temperature change of 10°C during ITER operation. The error is mainly due to the dependence of the Verdet constant with temperature. The variation on the Verdet constant is estimated to 0.08% and the maximum relative error is $1.2*10^{-3}$ which is still below the ITER specifications. The main source of disturbances is the vibrations transmitted by the vessel to the sensing fibre. In this context, the best set-up configuration is a reflection setup using a Faraday mirror at the end of the sensing fibre, which allows a partial compensation of disturbances induced by perturbations (especially when it is close to the Faraday mirror). We take the vibrations into account in the modelling of the vibrations. Some experimental investigations have been carried on at SCK•CEN. The data obtained from the experiments have been used to refine the simulation work. It has resulted that the corresponding perturbations are acceptable regarding the ITER requirement.

*F*errule-top optical fibre sensor for the measurement of magnetic field

We developed a magnetic field sensor based on a micro-machined cantilever (with a N45 Neodymium magnet fixed on the upper end) carved on top of a ferruled fiber by means of a cost-effective picosecond-laser ablation (Figure 40). The interferometry readout of the ferrule-top (FT) sensor is based on a 1544 nm laser diode and an infrared photo-detector (Figure 41). The FT calibration was obtained by moving the sensor along the principal axis of a stack of permanent toroidal magnets with a maximum magnetic field of 0.24T. The developed sensor has no hysteresis and presents a proportional relationship between the magnetic field and the interferometry cavity size (Figure 42 and Figure 43).

Some Perspectives:

- Bearing in mind that sensor calibration was performed based on a simulation of the magnetic field generated by the toroidal magnet; it would be interesting to measure with a gauss-meter the field actually generated.
- It would also be interesting to realize a measurement system with two wavelengths in order to remove the uncertainty related to the periodicity of the interferometer output.



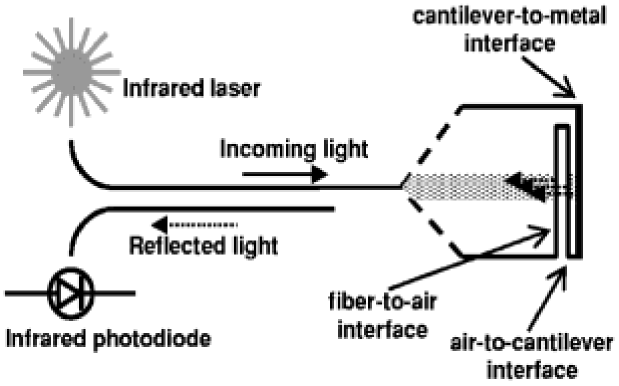


Figure 40: magnet with a magnetic moment **m** on top of a cantilever submitted to a magnetic field **B**. The magnet and the beam undergo a torque that changes the size of the cavity between the end of the optical fiber and the bottom of the cantilever.

Figure 41: Schematic view of the readout technique. The continuous arrow represents the input light. Dashed arrows represent the light reflected at the fiber-to-air, air-to-cantilever, and cantilever-to-metal interfaces.

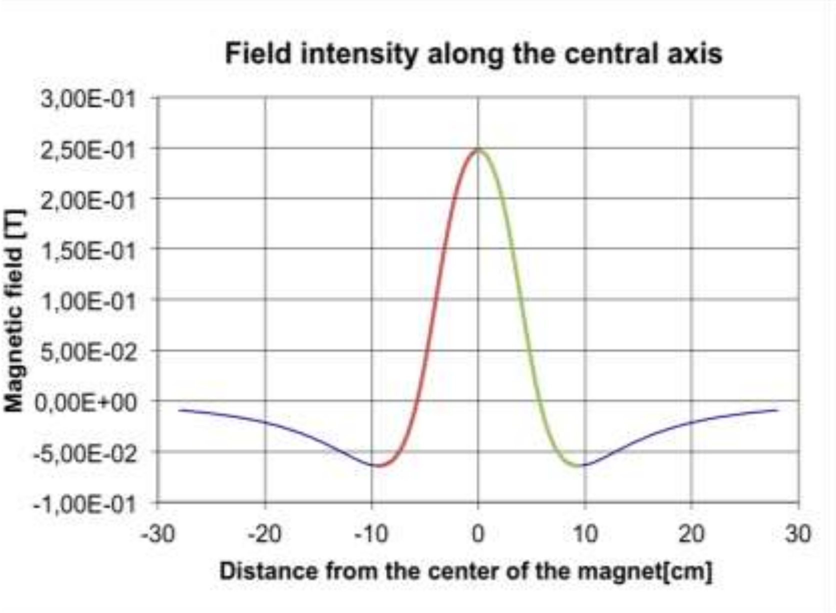


Figure 42: Magnetic field along the axis of a stack of permanent toroidal magnets.

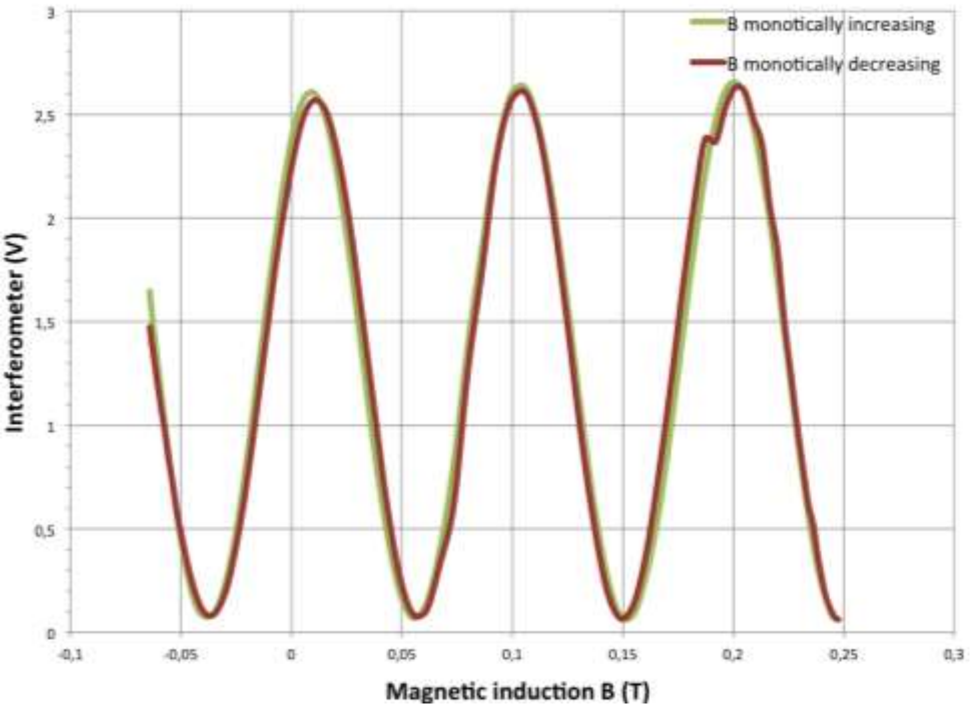


Figure 43: Evolution of the interferometer output for the monotonous increasing (red curve) and the monotonous decreasing (green curve) area of the magnetic field.

PARTNERS

- UMons, University of Mons, Belgium (Prof. P. Mégret and Prof. M. Wuilpart)
- VU University Amsterdam, the Netherlands, (Prof. D. Iannuzzi and Dr. G. Gruca, IDEAS)

5.1.3 Training in diagnostic for tokamak (GOT4-DIAG) (SCK•CEN WP nr 5.1.3)

EFDA Task nr:	*GOT4-DIAG*
Principal Investigator:	*W. Leysen (wleysen@sckcen.be)*
Scientific Staff:	*A. Goussarov*

OBJECTIVES

The construction of a new Tokamak-like ITER requires extensive knowledge and competences in different fields of engineering. The aim of the training is to reinforce the knowledge of the trainee thanks to his involvement in an engineering team constituted of experts in various domains. Specific courses will also be chosen in order to quickly become familiar with fusion physics and fusion technology. After a successful completion of the GOT-4-DIAG training programme, the trainee is expected to be in position to contribute independently and significantly to the European fusion research and engineering work in preparation of ITER and also of DEMO or other large future fusion devices.

In the frame of a structured training programme, early-stage engineers will be trained during 3 years. The programme will take place within a large collaborative group to provide the technical know-how and the skills which are necessary for the engineering of components for ITER and for the management of ITER relevant projects.

ACHIEVEMENTS

One student will attend the trainee programme at SCK•CEN from 11 November 2013 till 20 December 2013. The student will attend a course of the (BNEN) master programme in nuclear engineering: ‘Radiation protection and nuclear measurements’ from 2 until 20 December 2013. The student will also assist in conducting irradiation experiments: Irradiation of optical fibres in a gamma source; irradiation of a semiconductor neutron sensor in BR1 (graphite reactor) and possible observation of the dismantling of an experiment in BR2 (material test high flux reactor).

PARTNERS

- KIT, Germany (Coordinator GOT-4: Theo A. Scherer)
- CEA, France (Trainee: Frédéric Micolon)

5.1.4 Training in modelling and experimental validation (GOT-RIMES) (no SCK•CEN WP nr)

EFDA Task nr:	*GOT-RIMES*
Principal Investigator:	*B. Minov (bminov@sckcen.be)*
Scientific Staff:	*D. Terentyev (dterenty@sckcen.be)*

OBJECTIVES

The general objective of the Goal Oriented Training (GOT) programme - RIMES, falling under the topic of 'Materials Technology for In-Vessel components', is to contribute to education and training of specialists for development of in-vessel structural materials for DEMO and ITER. This objective will be achieved through hands-on training on activities ranging from modelling to experiments, aimed at the understanding of the interrelation between radiation induced micro-structure and hardening in high-Cr steels, with and without oxide dispersion strengthening (ODS) inclusions. More in detail, the hands-on training will concern:

1. Establishment of a high-performance numerical tool to describe accumulation of radiation damage defects at the nanoscale under high-temperature/high neutron flux irradiation conditions.
2. Matching the nanoscale tool with continuum plasticity models operating at the mesoscale level, to assess the contribution to hardening of a variety of nanostructural features produced under neutron irradiation.
3. Experimental characterization of the evolution of nanostructure and deformation mechanisms in irradiated high-Cr steels for the validation/calibration of the developed models.

This report contributes to the third task and describes combined experimental study of Fe-Cr model alloys using transmission electron-microscopy (TEM) and structural relaxation techniques, internal friction (IF) and magnetic after effect (MAE).

ACHIEVEMENTS

The primary task of this research line is to understand how the concentration of Cr affects the microstructure of the Fe-Cr-based alloys before and after neutron irradiation, as this would be the reference data to reconcile radiation-induced hardening. The following materials model alloys are studied: Fe - 2.5%Cr; - 5%Cr; - 9%Cr; and 12%Cr.

The alloys were fabricated by furnace melting of industrial purity Fe and Cr in the form of plates. The plates were then annealed for 3 h at 1320 K in high vacuum for austenitization and stabilization, followed by air cooling down to room temperature. The tempering procedure was performed at 1000 K for 4 h, followed by air cooling. The chemical compositions of these alloys are provided in Table 14.

Material	Composition in wt.%						
	C	N	O	Al	Si	P	S
Fe-2.5% Cr	0.01	0.012	0.04	0.003	0.02	0.01	0.002
Fe-5% Cr	0.02	0.013	0.07	0.003	0.04	0.01	0.006
Fe-9% Cr	0.02	0.015	0.07	0.007	0.09	0.01	0.001
Fe-12% Cr	0.03	0.024	0.03	0.003	0.11	0.05	0.006

Table 14(a): The chemical composition of the Fe-xCr alloys.

Material	Composition in wt.%				
	Ti	V	Cr	Mn	Ni
Fe-2.5% Cr	0.004	0.001	2.4	0.01	0.04
Fe-5% Cr	0.003	0.001	4.6	0.02	0.06
Fe-9% Cr	0.003	0.002	8.4	0.03	0.07
Fe-12% Cr	0.004	0.002	11.6	0.03	0.09

Table 14(b): The chemical composition of the Fe-xCr alloys (continued).

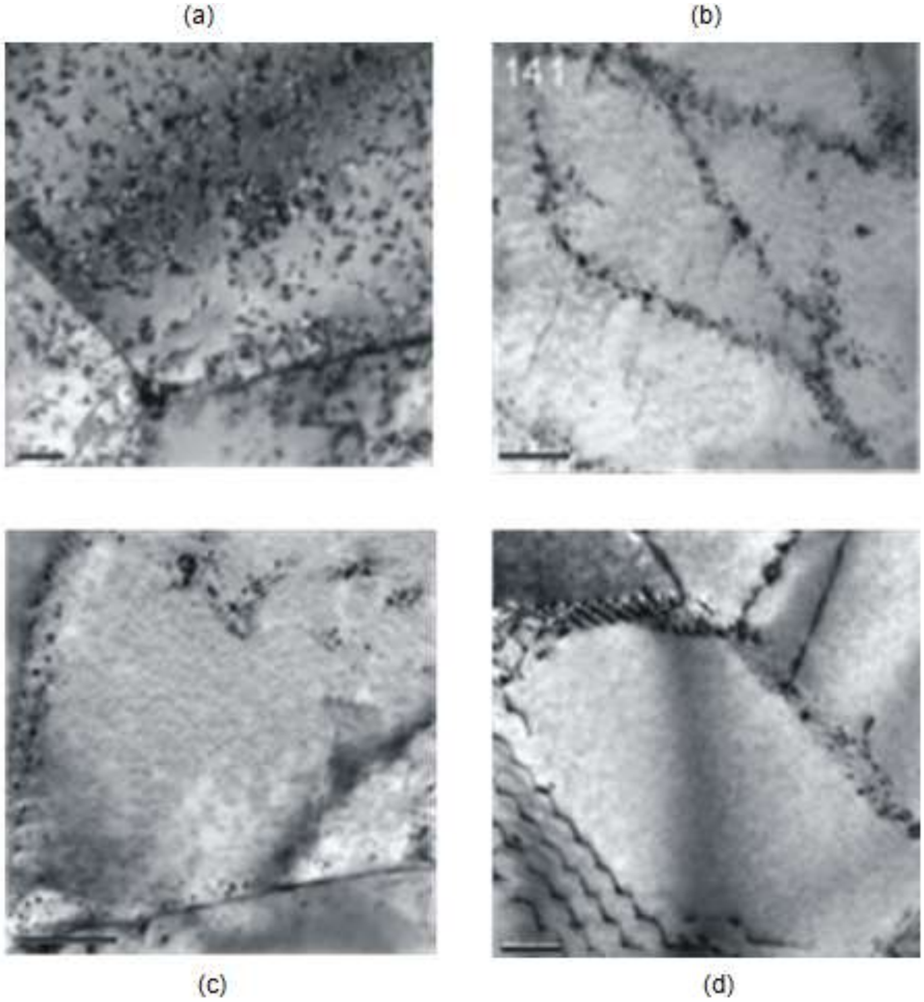


Figure 44: Transmission electron-microscope micrographs of (a) Fe2.5Cr, (b) Fe-5Cr, (c) Fe9Cr, and (d) Fe12Cr alloys neutron irradiated at 300°C up to 0.6 dpa [128].

Neutron irradiated alloys (up to 0.6 dpa in the Mire-Cr programme) were firstly examined at CIEMAT. The TEM micrographs of the alloys irradiated at 300°C are shown in Figure 44 [128]. The presence of dislocation loops (seen as black dots in Figure 44) produced by neutron irradiation is evident in all micrographs. However, it is clear that spatial distribution of the loops depends the alloy's Cr content. The homogeneous distribution all over the grain interior (and limited decoration of dislocations and grain boundaries) is observed only in the Fe-2.5Cr alloy, while in the alloys with higher Cr content majority of dislocation loops are mainly sited close to grain boundaries and dislocation arrays (which are low angle grain boundaries).

Such behaviour and discrepancy between 2.5Cr and the other alloys is interrelated with the spatial distribution of Carbon and its amount dissolved in the matrix, as revealed by in-depth analysis of the microstructure of the un-irradiated samples. We have concentrated on Carbon distribution, as a number of atomistic studies indicate that highly stable Carbon-vacancy complexes may act as strong traps for 1D migrating dislocation loops (directly produced in cascades upon neutron irradiation).

In this work, distribution of carbon atoms is studied by using the IF and MAE techniques. Both methods represent efficient tools to study dynamics of various types of interstitial impurities (e.g. carbon, nitrogen, hydrogen …) and dislocations by measuring Debye relaxation peaks on the basis of which one can determine the corresponding activation energy for defect migration.

Measurements of the IF coefficient as a function of temperature were made in the temperature range from 100 K to 620 K in an inverted torsional pendulum, working at the frequency of about 2 Hz. The resonance frequency ω, and the internal friction coefficient Q^{-1}, are determined by measuring the free decay signal. The measurements have been performed at a strain amplitude of about $\gamma_0 = 10^{-4}$ in a He atmosphere with a heating rate of about 1.5 K/min.

The MAE measurements are performed in the temperature range from 100 K to 520 K using an open magnetic circuit, working at 275 Hz and measuring the time dependence of the reciprocal value of the initial susceptibility χ, i.e. the initial reluctivity $r = 1/\chi$. The data acquisition of the different susceptibility isotherms started at 1 s (t_1) and ended at $t_2 = 180$ s. More details about both relaxation techniques can be found in [129].

In order to induce the migration of Carbon atoms located in the vicinity of grain boundaries it was necessary to induce a certain stress in the material prior the measurements. Therefore, the second set of IF and MAE samples are, in a consistent way, subjected to a torsional cyclic plastic deformation by an angle of π/2 over a length of 30 mm at room temperature. This corresponds to a local deformation of about 6% [130]. According to the previous investigations based on the tensile tests [131], this amount falls in the region of uniform deformation (work-hardening regime).

The IF and MAE spectra as a function of the temperature are measured in as-received and cold-worked conditions, and are shown in Figures 45 and 46.

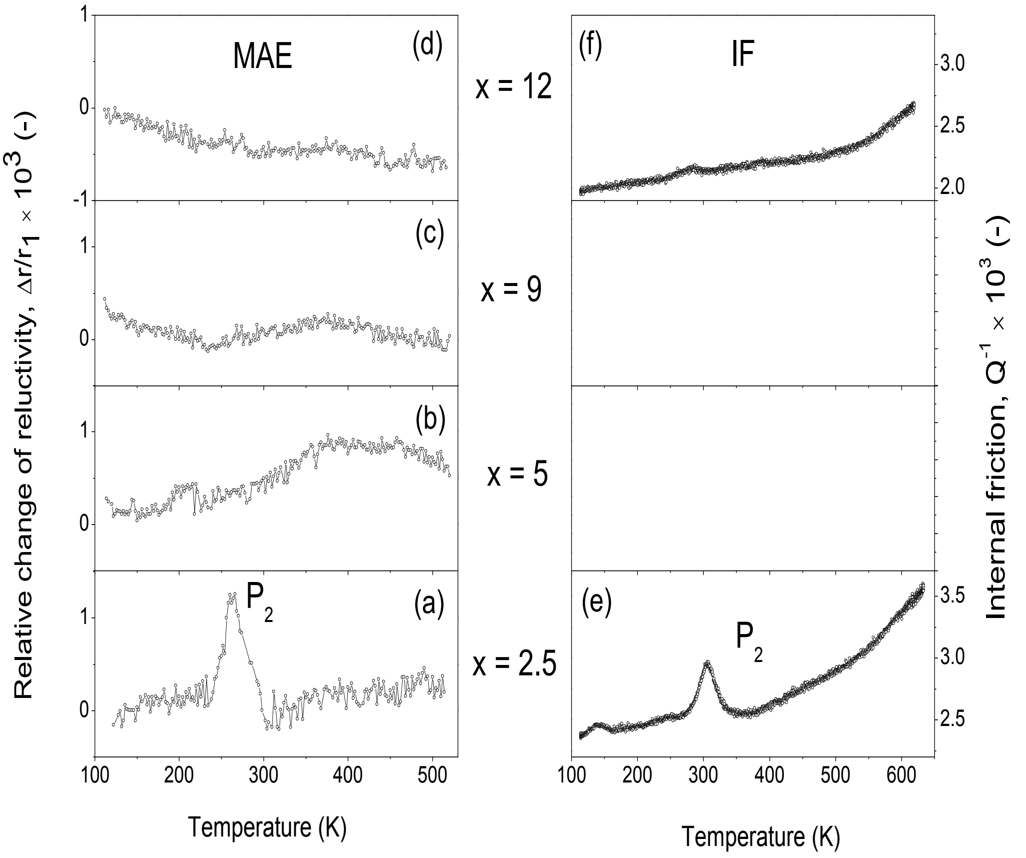


Figure 45: The temperature dependent magnetic after-effect (a - d) and internal friction (e, f) spectra of as-received Fe-x%Cr alloys, with x=2.5, 5, 9 and 12.

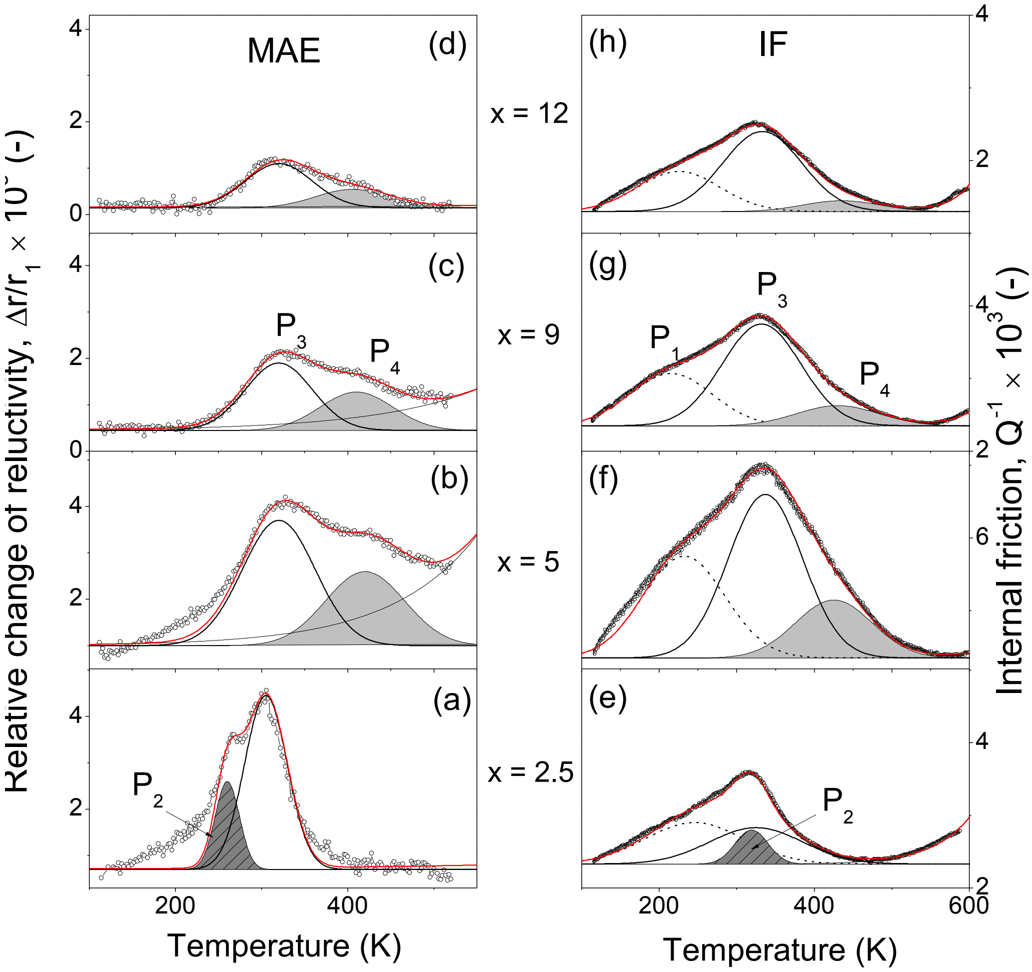


Figure 46: The temperature dependent magnetic after-effect and internal friction spectra of cold-worked Fe-x%Cr alloys, with x = 2.5, 5, 9, and 12.

One can immediately notice the difference between the spectra of Fe2.5Cr and other binary FeCr alloys. Namely, the IF and MAE spectra of the as-received Fe2.5Cr alloy exhibit the peak denoted as P_2 at 310 K (Figure 45e), and at 265 K (Figure 45a), respectively. Both peaks can be assigned to the onset of the migration of interstitial Carbon atoms dissolved in bcc Fe-Cr matrix, known in the literature as the Snoek carbon peak [132]. In Fe5Cr, Fe9Cr and Fe12Cr this relaxation process is not found, see Figure 45b-d, f.

The spectra of cold-worked samples are presented in Figure 46. In addition to the Snoek peak (P_2), additional broad structures are observed. On the basis of the overall shapes and peak parameters, the peak denoted as P_3 and centered at about 320 K in both IF and MAE spectra, is assigned to thermal activation of dislocation motion [133]. The peak P_1 observed only in the IF spectra at about 220 K represents single-kink relaxation process [134]. The relaxation process at about 420 K observed only in Fe5Cr, Fe9Cr and Fe12Cr alloys originates from stress-induced motion along the grain boundaries [135].

According to the literature, this peak is a fingerprint of the presence of martensite phase (i.e. BCT phase enriched with Carbon) since it corresponds to the carbon movement at the lath boundaries [135]. Clearly, the spectrum for Fe2.5Cr alloy does not exhibit peak P4 and therefore no martensite phase is expected to be present there.

On the basis of these results, we conclude that Carbon atoms are dissolved in BCC matrix in the Fe-2.5Cr, while they mainly present in martensite laths in the alloys with higher Cr content. This means that BCC Fe-Cr matrix of the high-Cr alloys is depleted with Carbon as compared to the 2.5Cr alloy.

Such discrepancy in the Carbon distribution could be the reason for different distribution of the dislocation loops observed in the Fe2.5Cr and high-Cr alloys. Presumably, the availability of Carbon atoms in the matrix leads to the formation of immobile and thermally stable Carbon-vacancy clusters, which efficiently trap 1D migrating dislocation loops and therefore prevents their escape from the grain interior to the dislocations and grain boundary interfaces. On the contrary, in the Fe5Cr, Fe9Cr and Fe12Cr alloys the dislocation loop migration is not sufficiently suppressed by the alloying Cr atoms and they are found to decorate dislocations and grain boundary interfaces.

PARTNERS

- KIT, Germany (P. Vladimirov)
- CIEMAT, Spain (C.J. Ortiz, M. Hernandez-Mayoral)

5.2 Summer course

5.2.1 Carolus Magnus Summer Course on Fusion Physics and Technology (organized by TEC) (SCK•CEN WP nrs 5.1.4 and 5.3.1)

EFDA Task nr:	*no EFDA task*
Principal Investigator:	*V. Massaut (vmassaut@sckcen.be)*
Scientific Staff:	*I. Uytdenhouwen*

OBJECTIVES

The Carolus Magnus Summer School (CMSS, http://www.carolusmagnus.net/) is organized every two years by the Trilateral Euregio Cluster (TEC, agreement between the fusion laboratories of three neighbouring countries: FOM/DIFFER in the Netherland, FZJ in Germany, ERM/KMS and SCK•CEN in Belgium). The courses are organized each time by rotation in one of the three countries. This year (2013), the CMSS was held in the Physikzentrum, Bad Honnef, Germany.

ACHIEVEMENTS

The SCK•CEN participates in the organization of the school (partial participation to the organizing committee) as well as giving one lecture entitled “The nuclear aspects of a fusion power plant: new constraints and challenges”. The CMSS took place from 26 August until 6 September 2013.

PARTNERS

- TEC (Trilateral Euregio Cluster)

6. Other activities in magnetic confinement fusion

6.1 Public information (SCK•CEN WP nr 6.1)

Responsible person: *V. Massaut (vmassaut@sckcen.be)*

OBJECTIVES

This activity is a continuous one, allowing to inform the public on the development in fusion energy. The topic is also part of the general missions of the SCK•CEN. The main objectives are indeed to let understand to the general public and policy makers the importance of developing alternative energy routes and how fusion can be one of the new energy sources in the future. It is also important to show where are the difficulties and the challenges to bring this energy source to a mature state.

ACHIEVEMENTS

The SCK•CEN participated in various conference and seminar for the large public, concerning the fusion developments. After the Fusion Expo set up in Liège in September-October 2012 in parallel to the SOFT-2012 conference, this year there were several smaller conferences for the SEII (European Society for Engineers and Industrialists), the group of engineers Post-ACEC, etc.

The SCK•CEN gives also yearly scientific seminars on fusion technological challenges to the University of Ghent (UGent), to the Catholic University of Louvain (UCL), and from this year on, it will also give such a seminar to the engineering students of the University of Mons (UMons). It participates to the Antwerp Fusion Show organized by the Flemish regional government for informing last year secondary school students on the challenges and interest of developing fusion energy for the future.

Finally, for the SOFT-2012 conference, remains the follow up of the publication of the proceedings of the conference (through the Elsevier Fusion Engineering and Design editor) a last activity closing the conference.

PARTNERS

- UGent, University of Ghent, Belgium
- UCL, Catholic University of Louvain-la-Neuve, Belgium
- UMons, University of Mons, Belgium
- TEC (Trilateral Euregio Cluster)

6.2 Technology transfer (participation in ITERBelgium) (SCK•CEN WP nr 6.2)

Responsible person: *V. Massaut (vmassaut@sckcen.be)*

OBJECTIVES

This activity is a continuous one, intended to involve the industry in the developments of fusion energy. Therefore the Belgian federal government set up a platform, called ITERBelgium based on a cell mainly coordinated by the Agoria Federation of industries. The SCK•CEN participates in these activities as supplier of knowledge and R&D centre. Moreover there is an incentive to imply or collaborate with industry on various aspects of fusion developments.

ACHIEVEMENTS

Few activities were carried out in 2013 with ITERBelgium, but SCK•CEN and Agoria are keeping to survey the market and inform the concerned industrial partner when an opportunity appears for an industrial involvement in fusion development. The SCK•CEN also participated to Agoria Corporate events, where the industry meets policy makers and research centres.

We also try to involve industrial partners (through their R&D departments) in some of the fusion R&D or early developments.

Moreover, through F4E contracts and calls, the SCK•CEN is now collaborating with international industrial partners (from UK and Germany) on several proposals and works for F4E and ITER.

PARTNERS

- Agoria Federation, Brussels, Belgium
- Oxford Technology Limited OTL, Oxford, UK
- TÜV-Rheinland Industrie Service GmbH, Germany
- OCAS, Ghent, Belgium

6.3 Socio-Economic research

6.3.1 Analysis of views from informed civil society on fusion energy research & development policy (SCK•CEN WP nr 6.4.1)

EFDA Task nr:	*WP13-SER-ACIF-T02*
Principal Investigator:	*G. Meskens (gmeskens@sckcen.be)*
Scientific Staff:	*G. Meskens*

OBJECTIVES

The study aims to assess views from informed civil society on fusion energy research & development policy in general and on the way it is currently undertaken under the European Fusion Development Agreement.

ACHIEVEMENTS

The period from May 2013 to September 2013 included was devoted to literature study. The interviews with selected experts will be organised in the period from October to December 2013. That period will also be used to write the report.

6.3.2 The EFDA-SERF Modelling Assessment Workshop 2012 (SCK•CEN WP nr 6.4.1)

EFDA Task nr:	*WP12-SER-ACIF-2*
Principal Investigator:	*G. Meskens (gmeskens@sckcen.be)*
Scientific Staff:	*G. Meskens*

OBJECTIVES

The project concerned the preparation and organisation of a one-day workshop that took place on the 19th of September 2012 at the headquarters of the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) in Rome. The meeting was held with a selected group of invited experts and focused on the use of long-term energy scenarios in energy research and policy, and in particular on the role the EFDA-TIMES modelling tool can play in this context. The meeting, the preparatory work and the synthesis of the discussions were the topic of the 2nd phase of the ISAF research project. This second phase continued on research done under WP11-SER-ACIF-2 (Integrated Sustainability Assessment of Fusion as an energy option of the future) in 2011.

ACHIEVEMENTS

The period from October 2012 to April 2013 included was devoted to:

- Analysing the transcripts of the workshop discussions;
- Writing the synthesis report;
- The review of the synthesis report by the workshop participants;
- The finalisation of the synthesis report.

In September 2013, the results were presented during the EFDA-SERF satellite meeting held in conjunction with the ISFNT conference in Barcelona.

PARTNERS

- Max-Planck-Institut fuer Plasmaphysik, Germany
- Research Studio iSPACE, Austria
- ENEA (Italian National agency for new technologies, Energy and sustainable economic development), Italy

7. Fusion developments outside the Contract of Association

Responsible person: *V. Massaut (vmassaut@sckcen.be)*

INTRODUCTION

Several other activities are going on in parallel to the works done under the contract of Association. These activities concern mostly the Broader Approach agreement between the EU and Japan, and the contracts and actions done in the framework of F4E and ITER. One should also add the support from the Belgian Government for the development of prototypes for ITER, but this concerns mostly the development of the FOCS sensor already described earlier.

THE BROADER APPROACH AGREEMENT

The Broader Approach for fusion (BA) is an agreement signed between the European Union and Japan, in the frame of the decision of ITER implementation in Europe. It comprises mostly three main programme lines:

- the IFMIF/EVEDA (International Fusion Material Irradiation Facility / Engineering Validation and Engineering Design Activities) project;
- the JT60 Super Advanced project (Japan Tokamak);
- the IFERC (International Fusion Experimental Research Centre) project;

Within Europe, the participation to the activities of the BA is based on voluntary contribution from several Members States, among which Belgium that declared officially its will to participate in 2007 and confirmed its contribution in June 2009.

Moreover, the Belgian Government, like all the other Member States, designated one of its institution, the SCK•CEN, as "designated institution" (so-called VC-DI, Voluntary Contribution Designated Institution) to coordinate the works of the Belgian contribution.

The Belgian contribution to the Broader Approach is divided into the different projects of the programme itself. Belgium is participating in the three main projects of the Broader Approach, as follows:

- IFMIF/EVEDA: Belgium is contributing to the Test Facility, to the Accelerator Facility and to the Target Facility:
  - Test facility: irradiation in fission reactor (of the High Flux Test Module); conceptual design of the Low Flux Test Module; design of the Start-up Monitoring Module (STUMM), participation in the development of micro fission chambers.
  - Accelerator facility: procurement of the Radio Frequency final power amplifiers for the accelerator of the EVEDA facility (to be located in Rokkasho, Japan).
  - Target facility: participation to the assessment of the liquid Lithium free flow modelling, using various computational tools.

    - In 2010, F4E and the services from the European Commission asked Belgium if it was possible to change the foreseen participation (of Tractebel Engineering) in DEMO design by an active participation in the Engineering design of IFMIF. This was accepted.
- JT-60 SA: Belgium is contributing to the cold test of the Toroidal Field coils, by supplying the cryostat and attached accessories for carrying out these tests.
- IFERC/DEMO: Belgium will contribute to the DEMO R&D project in the field of materials testing and small samples testing technology (SSTT).

Various institutions and companies were designated to carry out the different activities in the Royal Decrees defining the Belgian contribution and its funding and funding principles. Ion Beam Applications (IBA) will deliver the RF final power amplifiers for the IFMIF/EVEDA accelerator. The Université Libre de Bruxelles (ULB) will carry out the modelling of the free surface Lithium flow constituting the target of the IFMIF facility. Apart from the management and coordination of the whole Belgian contribution, the SCK•CEN is also contributing directly by executing all the foreseen activities for the IFMIF/EVEDA test facility mentioned above as well as the contribution to DEMO R&D by the evaluation of the use of small samples (from IFMIF) to qualify materials to be used in large commercial power plants. The delivery of the cryostat for the cold tests facility of the toroidal field coils of JT-60 SA is carried out by les Ateliers de la Meuse (ALM), in collaboration with the company AMOS. Tractebel Engineering, part of the GDF Suez group, will deliver an important contribution to the engineering design of IFMIF.

The main achievements obtained during the year 2013 within the Broader Approach Belgian contribution are the following:

- final delivery of the main parts of the huge cryostat and auxiliary systems for the cold test of the Toroïdal Field Coils of the JT-60 SA Tokamak at CEA-Saclay, France;
- prototype tests of the IFMIF/EVEDA accelerator RF power amplifier, and start of the pre-serie production of 2 more power amplifiers;
- end of the preparation of the irradiation device for the HFTM modules of IFMIF (part of the validation activities); this activity was delayed due to the problems encountered at KIT for the NaK filling and closing of the modules to be irradiated;
- calculation of the Lithium free surface flow modelling for the IFMIF/EVEDA target and for the actual IFMIF target by ULB;
- the continuation of the cold testing of the various materials, and analysis of results, the modelling of the samples for the IFERC/DEMO R&D project on small specimen testing (the irradiation of specimen, foreseen in the project, is delayed due to the delay mentioned above);
- the completion of the second and last phase of the engineering design activities of the IFMIF plant (4 tasks), by Tractebel Engineering.

The complete report of the Broader Approach Begian Contribution, with reference SCK•CEN-ER-259 from May 2014, is issued seperately.

The SCK•CEN also executes the complete coordination of these activities and insures that the Belgian contribution is delivered as foreseen.

WORKS FOR F4E AND ITER

Several contracts (Grants, procurements, subcontracts) are running with F4E and some other are in preparation.

The main topic in 2013 is the awarding of the Framework Contract for irradiation of diagnostics components under gamma and neutrons (OFC-358) to the SCK•CEN led consortium, after almost one year of discussions and negotiations. The first effective work orders for this contract are expected in 2014.

The SCK•CEN has also submitted in 2013 a proposal, with several European partners, for the OFC-413 call for framework contract on irradiation of TBM and ITER materials.

Several other projects are currently on-going:

- GRT-157 on pick up coils, as subcontractor to the CEA;
- GRT-294 for the front end engineering of the FOCS sensor for ITER;
- GRT-291 on the irradiation of Cu and Be joints, in collaboration with European partners;
- OMF-272, on the radiation hardening of remote handling systems, as subcontractor of OTL, UK.

PARTNERS

- Agoria Federation, Brussels, Belgian proposal for OTL (Oxford Technology Limited), Oxford, UK
- TÜV-Rheinland, Germany
- KfKI, Budapest, Hungary
- CEA, Saclay and Cadarache, France
- KIT, Karlsruhe, Germany

III. List of publications for the period 2007 - 2013

A. The year 2007

Journal Papers

I. Uytdenhouwen, M. Decréton, T.Hirai, J. Linke, G. Pintsuk and G. Van Oost, "Influence of recrystallisation on thermal shock resistance of various tungsten grades", Journal of Nuclear Materials, vol. 363-365, pp. 1099-1103, 2007.

W. Van Rentergham, A. Al Mazouzi, S. Van den Berghe, "Defect structure of irradiated PH13-8Mo steel", Journal of Nuclear Materials, vol. 360, No. 2, pp. 128-135.

M. Scibetta, A. Pellettieri, L. Sannen, "Experimental determination of creep properties of beryllium irradiated to relevant fusion power reactor doses", Journal of Nuclear Materials, vol. 367-370, pp. 1063-1068, 2007.

I. Uytdenhouwen, M. Decréton, T.Hirai, J. Linke, G. Pintsuk and G. Van Oost, "Influence of recrystallisation on thermal shock resistance of various tungsten grades", Journal of Nuclear Materials, vol. 363-365, pp. 1099-1103, 2007.

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E. Lucon, A. Leenaers and W. Vandermeulen, "Post-irradiation mechanical behaviour of three Eurofer joints", SCK•CEN Report BLG-1029, August 2006, submitted for publication in Fusion Engineering and Design.

R.W. Bosch, S. Van Dyck, A. Al Mazouzi, D. Sapundjiev, "Investigation of the susceptibility of Eurofer97 in lead-lithium to liquid metal embrittlement", SOFT Symposium, Warsaw, 11-15 September 2006, published in Fusion Engineering and Design, vol. 82, pp. 2615–2620, 2007.

M. Matijasevic, E. Lucon, A. Almazouzi, "Behaviour of ferritic martensitic steels after irradiation at 200 and 300°C", accepted for publication in Journal of Nuclear Materials, 2007.

M. Matijasevic, A. Almazouzi, "Effect of Cr on the mechanical properties and icrostructure of Fe-Cr model alloys after n-irradiation", accepted for publication in Journal of Nuclear Materials, 2007.

D. Terentyev and L. Malerba, "Interaction of <100> and ½ <111> dislocation loops with oint defects in ferritic alloys", to be published in Journal of Nuclear Materials, 2007.

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