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Data Needs for Erosion and Tritium Retention in Beryllium Surfaces

Summary Report of the Consultants' Meeting

IAEA Headquarters, Vienna, Austria

30–31 May 2011

Prepared by

B.J. Braams
International Atomic Energy Agency, Vienna, Austria

July 2011

IAEA Nuclear Data Section, Vienna International Centre, A-1400 Vienna, Austria

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Abstract

A Consultants' Meeting was held at IAEA Headquarters 30-31 May 2011 with the aim to provide advice about the scope and aims of a planned IAEA coordinated research project on erosion and tritium retention in beryllium plasma-facing materials and about other activities of the A+M Data Unit in the area of plasma interaction with beryllium surfaces. The present report contains the proceedings, recommendations and conclusions of that Consultants' Meeting.

July 2011

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1. Introduction

The presently favoured plasma-facing materials for nuclear operation in ITER are beryllium and tungsten: beryllium for most of the vacuum vessel and tungsten for the regions of highest heat load. (In the pre-nuclear phase of ITER carbon tiles will also be used.) Because of its toxicity beryllium has generally been avoided in fusion research to-date, but in ITER and in a reactor the radioactive environment anyway demands remote handling and the toxicity is not a particular concern. A new "ITER-Like" Be-W vacuum vessel wall has been installed on the Joint European Torus (JET) experiment, which is also equipped for tritium operation and remote handling, and plasma experiments on that machine are to start again in August 2011. Beryllium has in its favour good heat conductivity, strong gettering capability, high tolerance as a plasma impurity and low nuclear activation. On the other hand, erosion and tritium retention are issues of concern. Therefore there is very active interest at present in properties of beryllium as a wall material in the fusion environment. The central issues are erosion under regular heat and particle loads from the plasma, melting and ablation under extreme (pulsed) loads, tritium retention, and ways to extract trapped tritium. It must be taken into account that the material and surface properties are highly variable as a result of interaction with impurities (primarily C, N, O and W), implantation of H and He, redeposition of eroded Be and resolidification of melt layers.

The IAEA Atomic and Molecular Data Unit aims to provide internationally recommended databases for atomic, molecular and plasma-material interaction processes relevant to fusion energy. In order to encourage new research the unit manages at any time several IAEA Coordinated Research Projects (CRPs). Following advice from the Atomic and Molecular Data Subcommittee of the International Fusion Research Council (IFRC) the unit intends that the next CRP will be concerned with erosion and tritium retention in beryllium plasma-facing materials. The processes of interest include physical and chemical sputtering by H, He and Be, which release beryllium impurities into the plasma, trapping and reflection of hydrogen (H, D, T) on beryllium surfaces in the plasma environment, melting and ablation of beryllium under sudden localized high heat load (including radiation processes and self-shielding by the ablating layer), and the transport of hydrogen in beryllium and means to extract trapped tritium. A preliminary proposal for such a CRP was accepted by the Committee on Coordinated Research Activities (CCRA) for inclusion in the 2012-2013 Programme and Budget.

A Consultants' Meeting was held at IAEA Headquarters 30-31 May 2011 on the topic of erosion and tritium retention in beryllium plasma-facing materials. The aim of the meeting was to provide advice about the scope and aims of the planned CRP and about other activities of the A+M Data Unit in the area of plasma-material interaction with beryllium. The proceedings, recommendations and conclusions of that Consultants' Meeting are provided here.

2. Presentations and Discussion

R. A. Forrest: Welcome and introductions

The meeting was opened by Dr R. A. Forrest, Head of the Nuclear Data Section. Dr Forrest welcomed the participants to Vienna and the IAEA, noted the importance of beryllium in the international fusion programme and stressed the interest of the Atomic and Molecular Data Unit to support database developments on plasma-material interaction with beryllium through the organization of a coordinated research project.

Following the welcome participants briefly introduced themselves. Dr Sebastijan Brezinsek, from the Institute for Plasma Physics at the Forschungszentrum Juelich, Germany, is deputy leader of task force

E2 at EFDA/JET that is responsible for plasma-wall interaction studies. Dr Russ Doerner of the University of California at San Diego is head of the plasma-material interaction research program in the PISCES Laboratory at UCSD and of the UCSD co-center of the Plasma-Surface Interaction Science Center, a collaborative effort with the University of Tennessee and MIT. Dr Wolfgang Jacob of the Max-Planck Institute for Plasma Physics in Garching, Germany, is head of the group there on plasma-material interaction in laboratory experiments. Dr Daiji Kato of the National Institute for Fusion Science in Toki-City, Japan, is with the group on Atomic and Molecular Processes in the Fusion Systems Research Division where he carries out theoretical studies of atomic and molecular processes in plasmas and plasma-wall interaction. Dr Hyun-Kyung Chung is atomic physicist in the Atomic and Molecular Data Unit; before joining the IAEA she worked at Lawrence Livermore National Laboratory in the area of non-local thermodynamic equilibrium (NLTE) kinetic modelling. Dr Bas Braams is head of the A+M Data Unit; he came to the IAEA from the Chemistry Department at Emory University and has worked in molecular modelling and boundary plasma modelling.

B. J. Braams: Coordinated research projects and meetings of the A+M Data Unit

Introduction

The Atomic and Molecular Data Unit [1] is part of the Nuclear Data Section (12 professional staff) [2], which in turn belongs to the Division of Physical and Chemical Sciences [3] in the Department of Nuclear Applications. The unit is concerned with data that are of interest for fusion energy research, but the work has evolved beyond strictly atomic and molecular data so that at present about half of the unit's effort concerns plasma-material interaction data. The other fusion-related work in the Nuclear Data Section is the development of the Fusion Evaluated Nuclear Data Library (FENDL), which provides nuclear cross-section data relevant to fusion materials science. Within the Division there is also fusion work in the Physics Section, which has an extensive programme of fusion-related meetings including the biennial IAEA Fusion Energy Conference.

Coordinated research projects

The IAEA Coordinated Research Project (CRP) [4] is the main mechanism by which the A+M Data Unit (and the Nuclear Data Section) encourages new research. A CRP of the A+M Data Unit has focussed aims in data generation, compilation and evaluation for specific types of A+M or PMI processes relevant to fusion. The number of participants varies from 8 to 15 and the project normally lasts 4-5 years during which time 3 research coordination meetings are held. The IAEA pays the cost of attendance at these meetings, but does not provide direct research support. Therefore the participants must be active in the field of the CRP independent of the project. Outputs of a CRP include meeting reports, journal articles by participants, a final report in the IAEA Atomic and Plasma Material Interaction Data (greenbook) series, and data in the ALADDIN database and in the new knowledge base. Details of active and recent CRPs are in a section of the Unit's web pages [5].

Two recent CRPs are concerned with plasma-material interaction:

Data for Surface Composition Dynamics Relevant to Erosion Processes (2007-2011). The objectives of this CRP are to improve understanding of erosion and redeposition processes and of transport of eroded material, find new methods to control erosion and collect and generate data relevant to erosion dynamics in fusion reactors. The investigated materials are mainly the ones foreseen for ITER: carbon, beryllium and tungsten.

Characterization of Size, Composition and Origins of Dust in Fusion Devices (2008-2012). This CRP is concerned with methods to determine the size, composition and origin of dust in tokamaks, understand dust transport, improve dust estimates, understand tritium retention in dust and investigate dust removal techniques. The focus is on carbon and tungsten. After the 2nd research coordination meeting there are plans for a real dust database relying on automated analysis of tens of thousands of individual dust images.

Three other ongoing CRPs are concerned with atomic and molecular data: *Light Element Atom, Molecule and Radical Behaviour in the Divertor and Edge Plasma Regions* (2009-2013), *Spectroscopic and Collisional Data for Tungsten from 1 eV to 20 keV* (2010-2014) and *Atomic and Molecular Data for State-Resolved Modelling of Hydrogen and Helium and Their Isotopes in Fusion Plasma* (2011-2015).

Other meetings

The A+M Data Unit is involved in about 7-10 meetings per year [6], most of them small ones (5-15 partipants) held at IAEA headquarters. These meetings include the research coordination meetings of our active CRPs. On the regular schedule there is in the even years a meeting of our advisory committee, the Atomic and Molecular Data Subcommittee of the International Fusion Research Council (IFRC) and in the odd years a meeting of the International Data Centres Network. In recent years we have also coordinated an International Code Centres Network meeting biennially, and about twice per year we have organized a small meeting to advance the development of an XML Schema for Atoms, Molecules and Solids (XSAMS). Consultants' Meetings such as the present one are organized as the need arises. Occasionally the Unit cooperates in the organization of a larger meeting. In 2010 we cooperated in the organization of the ITER-IAEA Technical Meeting on ITER Technology and Materials (the Physics Section had the main role in that meeting) and in 2011 we cooperate in the 7th Code Comparison Workshop on Non-LTE Kinetics.

Proposed CRP on beryllium surfaces

The Unit receives programmatic advice from the atomic and molecular data subcommittee of the International Fusion Research Council (IFRC). At their meeting in April 2010 this subcommittee considered CRPs to initiate in the 2012-2013 budget cycle and they gave highest priority to a project on erosion and tritium retention in beryllium plasma-facing materials; as the next CRP after that they advised one on plasma interaction with irradiated tungsten and tungsten alloys in fusion devices. At their meeting in August 2010 the Committee on Coordinated Research Activities (CCRA) agreed to include these two CRPs in the (preliminary) 2012-2013 Programme and Budget. It is intended to submit the detailed proposal for the scope and objectives of the beryllium CRP to CCRA in August 2011. If the CRP is approved at that meeting then proposals from potential participating institutes could be reviewed at the next CCRA meeting in October, with December as a backup for some later proposals. The CRP could then have its first research coordination meeting in Q1 2012 and further meetings in Q3-Q4 2013 and Q1-Q2 2015 and the final report and database enhancements finished in early 2016.

The primary aim of this Consultants' Meeting is to gather advice about the detailed scope and aims of the planned CRP, which will have as its broad aim to enhance the knowledge base on fundamental plasma-wall interaction processes involving beryllium. Items of interest include sputtering, erosion, redeposition, hydrogen retention, transport of H in beryllium, ways to remove trapped tritium, and melting and ablation under high heat loads. We think that erosion and tritium retention are probably the key topics, and we wonder how much attention should be given in this CRP to the melting and ablation. We like to have advice about the balance between theory and experiment within the CRP, and suggestions for participating institutes with an indication of their expertise.

In addition to advice about the planned CRP we look for advice more broadly about activities of the A+M Data Unit in the area of plasma-material interaction. Are there areas in PMI where we may contribute by organizing a smaller single meeting, rather than use the heavy CRP mechanism? Perhaps even in relation to a CRP on beryllium surfaces there are some topics that are better addressed in a separate incidental meeting.

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S. Brezinsek: Beryllium - (experimental) preparation for the JET ITER-Like Wall

Introduction

Dr S. Brezinsek described the activities of the JET EFDA (European Fusion Development Association) Task Force E2 and the EFDA Task Force on Plasma-Wall Interaction. These EFDA activities are focussed on the ITER material mix of beryllium, carbon and tungsten.

The main experiment for beryllium and the focus of this presentation is the JET ITER-Like Wall. At the outset the other EFDA activities related to beryllium were briefly noted. There is a structured collaboration with PISCES-B that supports roughly one EFDA guest researcher at UCSD at any time. Forchungszentrum Juelich is preparing the JULE-PSI plasma generator that is expected to handle tritium and beryllium in 2014 or 2015. The JUDITH electron beam facility at FZJ is used for Be PFCs power load tests. IPP Garching has both diagnostic and modelling work (Be mixed layer analysis, MD, WALLDYN) as is reviewed here by W. Jacob. Modelling at FZJ is centered around the ERO code and is concerned with Be erosion, migration and spectroscopy. Several institutes carry out post-mortem analysis of JET tiles: Euratom-VR in Sweden, TEKES in Finland, CCFE in the UK, FZJ and IPP in Germany and CEK-MOL in Belgium. Molecular dynamics modelling of beryllium targets and mixed systems is done at TEKES, IPP, FZJ and several universities. MEdC in Bucharest fabricated the JET Be tiles and is a source of Be reference materials (e.g., surface layers) for studies elsewhere.

The ITER-like Wall in JET

The JET ITER-Like Wall (ILW) mimics the ITER wall in its nuclear phase, after the removal of carbon. The main wall is made of beryllium tiles and tungsten is used in the divertor. JET is the first experiment where this combination is used. The anticipated advantages of the carbon-free environment are reduced material migration to remote areas, reduced tritium retention and loss of carbon as the main radiator. The ILW experiments seek to address all issues related to use of beryllium in ITER: plasma scenarios, Be erosion and redeposition, Be migration, formation of Be-W mixed surfaces, re-erosion of mixed layers, W erosion and prompt redeposition, formation of Be:D layers and the associated (D,T) retention, Be spectroscopy, etc.. In addition there are issues having to do with high transient heat loads: melting and ablation, melt layer motion, and formation of metallic dust. Together with the introduction of the ILW the neutral beam injection system is upgraded from 20 MW to 34 MW peak and from 10 s to 20 s maximum duration. The operational space is changed and there will be need for better plasma control and for heat load mitigation schemes.

Installation of the ILW involved a two-year shut-down and was done almost entirely by remote handling. The installation was completed in May 2011 and experiments are scheduled to start again in August or September. The main wall is now made of 5384 Be tiles (∼2 tons Be, ∼1 m^3) and in the divertor area there are 1288 W-coated CFC tiles and 9216 W-lamellas (∼2 tons W, ∼0.1 m^3). All plasma-facing components are only inertially cooled.

The first task upon resumption of the experimental campaign will be to demonstrate operational scenarios that are compatible with the new wall. The magnetic shape must be optimized and controlled to prevent physical sputtering of tungsten and limit the erosion of beryllium, and the plasma density must be controlled to prevent beam shine-through. ELM flushing may be needed to reduce the W impurity concentration. Impurity-seeding scenarios are likely to be required at high input power to achieve semi-detached divertor operation. The candidate seeded species are N_2, Ar and Ne.

Operational limits and diagnostics

On the solid Be limiters the surface temperature must be limited to <900 C and the impact energy to 22 $MJ/m^2s^{1/2}$. On the W-coated CFC tiles the surface temperature limit is 1200 C (to prevent carbidisation) and the ELM pulsed heat load limit is ∼5 $MJ/m^2s^{1/2}$. For the W stacks the temperature limit varies from 1200 C to 2200 C and the pulsed heat load limit is (20-35) $MJ/m^2s^{1/2}$.

Diagnostics for edge plasma and PMI are designed to measure the following.

1. Source distribution at the wall and the divertor: erosion fluxes of Be, W and BeD, recycling flux of D and D_2, impurity fluxes of C, N, O, Ar, He, Ne etc;
2. Total radiation in the divertor by bolometric reconstruction;
3. Impurity concentrations from the wall to the core;
4. Plasma parameters and ion fluxes in the divertor and main chamber;
5. Heat and power loads to the divertor and the main chamber: peak values and profile information;
6. Net erosion and deposition and migration paths: net erosion rates of coatings, net deposition rates in remote areas, layer location and composition, comparison of gross and net erosion, fuel retention.

The edge spectroscopy systems measure neutrals and low ionisation stages in order to provide the impurity source distribution and the recycling flux. These systems include the KS8 main chamber impurity monitor and the KL11 divertor endoscope.

Deposition monitors and marker tiles give information about net erosion and deposition. Quartz micro-balances (QMB) provide shot resolved data on net deposition or erosion rates in remote areas; in combination with spectroscopy this provides information about material migration. Rotating collector probes can be sampled daily to measure deposition in remote areas. Sticking monitors are integrated over a campaign to provide sticking probabilities and layer composition. Marker tiles and mirror casettes are also integrated over a campaign to measure erosion rates, deposition rates and layer composition. Be marker tiles use a Ni interface layer. In the divertor the W coating techniques provide a natural Mo marker. Fuel retention can only be measured conclusively in post mortem analysis (after a campaign) by determining the net transport to the inner divertor leg.

2011-2012 work programme and questions related to the Be first wall

The work programme for Aug 2011 - Jun 2012 is devoted to the two areas of scenario development and plasma-surface interaction studies. A key objective for the PSI studies is to quantify Be erosion and determine the mechanisms. Net and gross absolute yields are required. The role of BeD is unclear; in the previous experiments on JET it was only observed after strong Be evaporation and the Be tiles of the ILW may behave differently. Formation of mixed layers of BeW, BeC and BeN and their influence on the erosion rates will be studied. Differences between original tile erosion and re-erosion of deposited material are of interest, also in connection with formation of Be dust.

Spectroscopy is used to determine the flux of Be and BeD into the plasma, and an effort will be made to correlate photon emission rates to actual tile erosion rates; the relation between photon emission rate and Be influx is not very precisely known. Modelling needs to include destruction processes of BeD and perhaps formation processes.

Beryllium redeposition will be studied in connection with hydrogen retention; the H retention may vary with surface composition and needs to be investigated in Be/C, Be/N and Be/W mixtures.

In all these studies one is dealing with a multidimensional parameter space as erosion and retention properties depend on plasma conditions (flux, fluence, energy, projectile mix) and on surface conditions (temperature, composition, morphology). Dedicated data are needed to interpret experimental results and to provide input for predictive modelling for ITER.

Beryllium data needs for ERO

This part of the presentation is based on a talk by D. Borodin at the PFMC-13 conference in Rosenheim, 09-13 May 2011, with contributions from A. Kirschner and C. Björkas.

ERO is a three-dimensional Monte Carlo impurity transport code. It relies on specification of a background plasma and combines calculation of impurity transport in plasma (ionization, dissociation, friction, thermal force, Lorentz force and cross-field diffusion) with calculation of plasma-surface interaction (physical sputtering and reflection, chemical erosion, re-erosion and re-deposition). ERO has been applied for beryllium modelling for the ITER divertor and the scrape-off layer. A benchmark study was done for PISCES-B and studies for the JET ILW are planned. Data for beryllium used in ERO are:

1. Sputtering yields, including angular part. These data are obtained from Eckstein (2007) based on calculations using SDTrimSP and homogeneous mixing model (HMM) molecular dynamics. There are many uncertainties still and it is difficult to interpret the experimental data.

2. Be chemical erosion and associated molecular processes: release of BeH from the surface, dissociation, charge exchange and spectroscopy of BeH in plasma. Data for release of BeH from the surface are recently available; molecular data are assembled with help from R. Janev.

3. Be atomic data: ionization, spectroscopy. These data come from ADAS.

4. Data for Be/C/W mixed layers, including formation of carbides and alloys and the influence on sputtering and retention. There are many experiments and some modelling, including the ERO studies for PISCES-B. However, the data set for mixed materials is very incomplete.

The uncertainty in the data is illustrated by various calculated and measured sputtering yields for Be by D^+. Even for normal incidence the calculated yields vary by a factor of 3 and the experimental yields even more. For self-sputtering one has only the calculated yields.

ERO was applied for a benchmarking study based on data from PISCES-B. The primary aim was to reduce the uncertainty in sputtering yields from Be/C mixed layers. The ERO calculation was calibrated against spectroscopic measurements, target weight loss and deposition on a witness plate [1].

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D. Kato: Data on sputtering and hydrogen retention of Be and Be alloys

Dr D. Kato of the Fusion Systems Research Division in the National Institute for Fusion Studies (NIFS) in Toki-City, Japan, described the sputtering yield database at NIFS and gave an overview of research on sputtering and hydrogen retention with special attention to work in Japanese institutes.

The NIFS Database SPUTY and research on sputtering of Be

The online numerical database of sputtering yields SPUTY (http://dbshino.nifs.ac.jp) is provided at NIFS. The database contains experimental and Monte Carlo (MC) simulation data on sputtering yield for mono-atomic targets by normal incidence ions (H, D, T, Be, O, Ne, Ar, Kr, Xe). Experimental data of light element projectiles have large scatter, which is attributed to surface oxidation conditions [1]. Yamamura and Tawara [2] reported compilation of the experimental data, comparison with MC simulation by means of the ACAT code [3], and empirical fitting formula for normal incidence. MC calculation data by Eckstein with the TRIM.SP code [4] are available at the NIFS web site [5]. The data include sputtering yields for several incident angles and for compound targets, e.g. BeO.

Material mixing effects are significant in cases that the incident particle makes a stable compound with target Be. Wu et al. [6] reported that the weight loss of Be target by O ion can be explained consistently by assuming surface oxidation forming BeO. The erosion yield was significantly reduced relative to that for a pure Be target. Erosion of Be first-wall in ITER would be affected by co-deposition of C and W. Korshunov et al. reported measurements of weight loss by Be ion impact on Be-C and Be-W co-deposited targets [7]. The co-deposited layers also contained O impurities. The Be-C mixed layer was eroded more effectively than pure Be target, while the erosion yield of the Be-W mixed layer was almost the same as that of self-sputtering of the pure Be target. These results may be affected by surface composition of the target. Eckstein [8] predicted fluence dependence of erosion yields of Be targets by W ions. Sielanko et al. [9] conducted SIMS measurement of partial sputtering yield of Cs ions from Be targets. Roth et al. [1] examined target temperature dependence of Be erosion by D and Be ions. Enhancement of sputtering yield due to radiation induced sublimation was observed at high temperatures (>700 C) for ion flux of $6 \times 10^{19}/(m^2 s)$. In plasma-wall interactions, besides plasma ions, impurities (e.g. C, O, metals, coolant inert gas) would affect sputtering properties. Hirooka [10] reported that a small content of C impurity in D plasmas made significant reduction of erosion yields of Be targets; the effect has been called ‘carbon poisoning’.

Sputtering data researches of Be materials have been conducted intensively focusing on the ITER application. Thus, many data are found in literatures and databases. Nevertheless, the following data are still not clear, and further investigations are encouraged; 1) low energy (<10 eV) data; 2) energy and angular distribution of sputtered particles; 3) identification of sputtered species: atoms, molecules, clusters; 4) ro-vibrational states of molecules and electronically excited states.

Recently, Ohya [11] examined sputtering of amorphous C:H layers by H ions at low energies (1-100 eV) by means of molecular dynamics simulation. In this simulation, Be co-deposition layer was also examined, and erosion mitigation due to Be-C and Be-H compound formation in the mixed layers was found. This result is consistent with experimental observation at PISCES-B [12].

Hydrogen isotope retention in beryllium

Anderl et al. [13] reviewed hydrogen retention properties of Be with a view to the ITER first-wall application. Database development has been undertaken at NIFS [14]. Yoshida et al. [15] reported thermal desorption spectra of Be specimens bombarded by 8 keV D_2^+ ions. Haasz et al. [16] reported similar measurements for lower ion energies up to a fluence of ~10^{24} D/m^2. Two groups of hydrogen release stages were observed in both measurements: at 500-700 K and at 700-900 K. The hydrogen desorption peak at 500-600 K was attributed to amorphous hydride formation by Wilson [17], whereas it was attributed to radiation induced damage defects by Haasz [16]. First-principles (density functional theory) studies on structures of the amorphous beryllium hydride and hydrogen-vacancy interactions were reported by Allouche et al. [18].

Beryllium metal has some disadvantages for high temperature (600-900 C) DEMO reactor application as neutron multiplier: low melting temperature and high chemical reactivity at high temperatures. Be alloys such as $Be_{12}Ti$, $Be_{12}V$, and $Be_{12}Mo$ are candidates as advanced neutron multiplier materials, because the $Be_{12}X$ structure gives good oxidation resistance and high Be content for the neutron multiplier, and Ti, V, and Mo have low activation and high melting temperatures. Kuwamura et al. [19] reported hydrogen release measurements in $Be_{12}Ti$ pebbles fabricated by means of an arc melting process. Measured hydrogen retention in the pebbles was smaller than that in Be. Thermal desorption spectra showed that the bulk of retained hydrogen in the pebbles was released at 373 K. The trapping sites were attributed to small vacancy clusters and impurities. Neutron irradiation ($4x10^{24}$ n/m^2, >1 MeV, 500 C) on the $Be_{12}Ti$ specimens has been performed at the Japan Materials Testing Reactor (JMTR) [19]. Tritium inventory in n-irradiated $Be_{12}Ti$ was smaller than that in n-irradiated Be.

Hydrogen retention data in Be alloys will be measured intensively for advanced blanket materials development that is being promoted in ITER-BA. Neutron irradiation effects (knock-on defects and helium transmutation) are key issues in future studies. Simulation studies on radiation induced microstructure development and hydrogen trapping are encouraged.

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R. Doerner: Research activities and data needs for plasma-material interaction with beryllium surfaces

The presentation reported ongoing research at the PISCES Program at UC San Diego, USA. PISCES-B is one of the few experimental plasma-material interaction research facilities in the world that is licensed for handling beryllium. The device is a reflex arc steady-state plasma source capable of achieving ITER-relevant particle fluxes and energies. The entire device is contained within an isolated safety enclosure to prevent the release of Be dust. In addition to the plasma capabilities the PISCES-B device is unique in that it contains an in-situ surface analysis station that allows interrogation of a plasma-exposed surface before exposure to atmosphere. A beryllium oven incorporated in the device allows the introduction of a controlled amount of Be impurity ions to an incident plasma. The experiments simulate Be erosion from the ITER wall and subsequent scrape-off layer transport and interaction with W baffles or C dump plates. Behavior of codeposited materials is investigated using witness plates.

The biggest uncertainty with relation to estimation of the first-wall lifetime for ITER has to do with the wide range of sputtering yields found in the literature. Sputtering yields measured on the PISCES-B device consistently fall in the low end of this range, being a factor of 5-10 below the yield from a binary collision model of sputtering. Two issues have been identified leading to a reduction in the measured yield. The first is the evolution of a fine hair-like or cone-like surface morphology. This morphology change can account for no more than a factor of two reduction in the measured yield. In addition, molecular dynamics calculations have revealed a reduction in sputtering yield of factors of 3-4 due to the inclusion of 50% D in a Be surface. Although it remains to be seen if this effect is involved in the PISCES results the calculations provide an interesting issue that should be investigated further.

Measurements of erosion by heavy ion bombardment are much more in agreement with TRIM calculations than those of erosion by D. The reasons for this behavior are not well understood; however, taking the case of Ar projectiles, the Be surface remains smooth after sputtering, the Ar implantation depth is less than for D and the reflection coefficient for Ar is lower than that for D or He.

Spectroscopic measurements of sputtered BeD and sputtered Be show a similar e-folding distance, which indicates that the BeD is physically sputtered rather than being chemically desorbed.

Measurements were made during Be impurity seeding of D and He plasmas, while measuring the gross and net erosion rates from the plasma exposed target. It was observed that the net erosion from a target did not change until a level of impurity influx to the target exceeded the sputtered flux measured without impurity seeding by almost an order of magnitude. The implication of this result is that either the sticking coefficient of Be on a plasma exposed surface is much lower than predicted by TRIM, or the re-erosion rate of the deposited Be is much larger than Be from the original surface. Modeling of both W and C deposition patterns in confinement machines has only been able to reproduce experimental results by assuming a similar effect. The experimental measurements in PISCES-B are the first indication that Be may also exhibit the same sort of material migration behavior.

Coupled to the issue of lifetime due to erosion is that of tritium accumulation. Retention in plasma exposed surfaces is observed to saturate at rather low levels (~$10^{21}/m^2$), but retention in codeposits will not saturate and will directly scale with the amount of material being eroded. Measurements of release of D from be codeposits during long term baking, lasting up to 24 hours, has shown a slow release of D throughout the bake. Although this release will help with detritiation of the ITER vessel, there is still a finite amount of D remaining in the codeposits that cannot be accessed during the bake. This remaining quantity will slowly ratchet up the in-vessel quantity following repeated baking cycles.

PISCES-B experiments for mixed materials Be-C, Be-W and Be-N were summarized. Chemical erosion (formation of CD) is mitigated by Be impurity due to formation of a Be_2C surface layer. Other impurities might erode this layer, but the mitigation of chemical erosion is unaffected by 10% Ar impurity in the incident plasma. When a W surface is exposed to Be-containing plasma a Be_2W surface may be formed when deposition exceeds erosion. This layer does not prevent the release of D implanted in the W. Sputter yields in nitrogen-seeded plasma (forming Be-N surface) are generally lower than for unseeded plasma.

Finally unresolved issues for PMI with Be surfaces are summarized. The physical and chemical sputter yields and reflection coefficients for plasma-exposed surfaces are poorly understood; what is the role of plasma atoms in the surface? We are far away from being able to predict evolution of surface morphology including effect of impurities, plasma fluence, surface temperature, and generation of dust. Hydrogen release during thermal excursions, and more generally the dependence of H release on heating rate, is not well known. The basic data for sputtering, penetration and retention for mixed materials are not well known, and in the experiment especially hydrogen retention and release from thick BeO surfaces is an important unkown.

W. Jacob: H isotope retention in Be and Be mixed materials

Introduction

ITER is expected to produce ∼500 MW of fusion power (∼400 MW in neutrons and ∼100 MW in alpha particle heating) and to take in ∼50 MW auxiliary heating. The alpha particle and auxiliary heating power will be deposited on the main wall and divertor, divided approximately evenly between the two. Thus we obtain an estimated power of 75 MW on the main chamber wall, which has an area of 700 m^2, and about 75 MW on the divertor strike plate. Power load on the main wall will not be uniform in space and, because of ELMs and other transient events not in time either. Accordingly the beryllium main wall of ITER must be able to withstand steady power loads of up to 1 MW/m^2 locally, and higher power in pulses. In the vicinity of the strike point in the divertor the steady power load can be up to 10 MW/m^2. To handle the power load requires development of plasma scenarios that provide (relatively homogeneous) radiative cooling and of appropriate plasma-facing materials.

Relevant plasma-surface interaction (PSI) and plasma-material interaction (PMI) topics include erosion rates (hence lifetime of components and influx of impurities), transport of eroded material through the plasma, redeposition of eroded material, tritium inventory in walls, in particular in redeposited layers, handling of power fluxes on plasma-facing components, and neutron damage and activation of materials. Physical sputtering yield and harmfulness of elements in the plasma are main selection criteria for first wall material, and in this respect beryllium and tungsten are at opposite ends of the spectrum. Beryllium erodes much more readily than tungsten, but in the plasma an impurity fraction of several percent in Be is tolerable whereas the tungsten impurity fraction is limited to $\sim 1\times10^{-5}$.

PSI/PMI processes of interest are physical sputtering, chemical erosion, radiation enhanced sublimation, photon-induced desorption, evaporation and sublimation, brittle destruction, melting and splashing, arcing, and neutron-induced damage. Physical sputtering is rather well understood for the case of beam-target interaction, and there is good agreement between experiment and molecular dynamics modelling for Be and W targets over a wide range of energy. For carbon targets it is clear that at low energy chemical sputtering becomes dominant. Other processes than beam-target interaction are much more complicated to describe.

Scientific programme at IPP

The work in the plasma-wall interaction group at IPP Garching covers 4 main topics: surface processes, tritium inventory, migration in fusion devices, and materials and components. The experimental facilities in the PWI group include the tandem accelerator and the GLADIS high heat flux test facility. The group cooperates with fusion programmes such as Asdex Upgrade at Garching and also JET, Tore Supra, Wendelstein-7X and ITER.

Surface processes

The key issue is the formation of mixed materials such as the Be-W-O system. X-ray photoelectron spectroscopy (XPS) is used to investigate formation of surface alloys and mixed phases; some of these experiments are carried out in collaboration with the Berlin Electron Syncrotron (BESSY). In XPS the signal is obtained as a function of photon energy and one obtains chemical information from peak position, compositional information from the intensity and depth information from variation of photon energy.

An ongoing thesis project by M. Köppen is focussed on beryllium and its alloys. The study looks at chemical phases that form in the surface, reaction temperatures, the role of diffusion and the interaction of the different phases with the boundary plasma.

H retention and release in pure Be

Prior work at IPP focussed on the Be-W system and pure Be. PhD thesis work by M. Reinelt [1] studied H retention in Be single crystals. The experiments involve temperature programmed desorption and the thermal desorption spectra (TDS) were simulated using the Tritium Migration Analysis Program (TMAP). In a recent PhD project [2] M. Oberkofler studied H retention in polycrystalline Be, also measuring the TDS and using TMAP for the simulations. The implantation was studied as a function of fluence while varying the impact energy. In these studies one recognizes the effect of D_2 bubbles in super-saturated regions and also that of material defects (vacancies) created by the implantation cascades.

H retention and release from mixed materials

For ITER the interest is in Be-W-C systems. There are some thermodynamically stable phases, notably Be_2C and $Be_{12}W$, but mainly one works with mixed material film deposits with arbitrary composition. The deposits are produced by MEdC in Bucharest, Romania (C. Lungu et al.) and characterization is done at IPP using ion beam analysis and X-ray photoelectron spectroscopy (XPS).

H implantation is done in the form of D_3^+ at 600 eV (200 eV/D) and the Thermal Effusion Spectroscopy Setup (TESS) is used to measure the release.

At IPP thermal desorption spectra (TDS) of D have been measured for pure Be, Be compounds $Be_{12}W$ and Be_2C, Be-W mixed deposited layers (W concentrations of ~10 % and ~60 %) and Be-C mixed deposited layers (C concentrations of ~8 % and ~50 %).

Deuterium retention and release behaviour of Be-containing materials were investigated for the ITER wall (240 C, 513 K) and divertor (350 C, 623 K) baking temperatures. In pure Be loaded with D at T < 340 K, D is predominantly released around 420-470 K within a relatively sharp desorption peak. Operation at elevated temperatures reduces the retained D amount, but the remaining D is less efficiently out-gassed at 623 K. Admixture of W or C changes the D release behaviour resulting in less efficient D removal by baking. Especially the presence of C in Be shifts the D release to higher temperatures.

Missing information: Release at increased holding times (so far maximum 20 min.) and release from thick films (so far only implanted films).

New experiments: Investigation of redeposited films produced in PISCES and magnetron sputtered Be/D films (D/Be ratios up to 0.3) with thickness up to 1 μm (Invited talk T. Schwarz-Selinger, PFMC-13); influence of longer holding times at ITER temperatures (planned for 2011).

Further activities and experimental possibilities at IPP

Some further activities related to beryllium are only briefly indicated.

- Investigation of surface processes in ternary system Be-W-O and in Be-N;
- Modeling of Be release using TMAP and new code developments;
- Collaboration with A. Allouche, DFT calculations of e.g. Be migration energies;
- D retention in mixed materials (increased holding times);
- Thick film model systems (collaboration with MEdC Bucharest);
- MD simulations (W-Be-H potential, first tests performed);
- Global impurity transport modeling (Schmid/Reinelt) – needs better input data.

The experimental possibilities for work with beryllium at IPP are on the whole limited to analysis of sample materials. There are no plasma experiments at IPP that involve beryllium.

A new glove box system (not yet commissioned) at the tandem accelerator will allow handling of JET ILW samples. Ion beam analysis (IBA) can be done for stoichiometry.

ARTOSS [3] is a dedicated surface science experiment that is used to study hydrogen inventory in multi-component surface layers on materials. Surfaces can be cleaned and prepared in situ. Photoelectron spectroscopies analyse the chemical state of elements within the surface layers. For ion beam analysis, low-energy (up to 5 keV) as well as high-energy ions (3 MV tandem accelerator) are available. ARTOSS has been used for beryllium studies in the past.

A high current source is available for sputtering and implantation studies.

The TESS temperature-programmed desorption (TPD) experiment can be used to examine Be-containing samples, but within severe limitations.

Needed data (personal view)

Sputtering yields are critical and there are large uncertainties that are attributed to surface chemistry (e.g., formation of BeO), surface condition and fluence. The most important projectiles are H, D, T, He, Ne, Ar and N, and the target surface includes mixed materials BeC, BeO, BeW and material impregnated with H. Sputtering yields are needed as a function of impact energy and angle, surface temperature, and also in some way flux and fluence. Projectile enrichment (retention) in the near surface layer may lead to reduction of sputter yields (e.g., for N on W) or to increase of sputter yields through chemical sputtering (e.g., for H on C).

Better data and understanding are needed on the difference in sputtering and erosion between exposure to plasma and exposure to ion beams. In the case of exposure to plasma there are many more species; e.g. H^+, H_2^+, H_3^+ and H^0 in the case of H_2 plasma, with a ratio $[H^0]/[H^+]\simeq100$ for laboratory plasma. Also impurity sputtering may play a role in laboratory plasma experiments. In ion beam experiments one measures erosion directly, but in the actual high flux plasma environment redeposition is important.

Better data are needed on the structure and the erosion properties of redeposited layers. They need to be characterized with respect to microstructure porosity, impurities, surface structure and morphology. Ion-beam analysis (IBA) is used for stoichiometry. X-ray photoelectron spectroscopy helps to identify the chemical state, crystalline phase or alloy structure. In all cases one expects to have mixed materials; they must be characterized and properties such as sputtering yield and sticking fraction must be determined as a function of the material structure.

References

[1] Reinelt et al., New Journal of Physics 11 (2009)
[2] Oberkofler et al., Nucl. Instrum. Methods 267 (4) (2009)
[3] Ch Linsmeier, P Goldstrass and K U Klages, Phys. Scr. T94 (2001) 28

H.-K. Chung: Plasma-material interaction data at IAEA

Dr H.-K. Chung described the organization of the web pages, databases and publications of the A+M Data Unit, especially recent work towards the development of a Wiki style Knowledge Base. All databases and publications are reachable from the Unit web home page [1].

Databases

The principal numerical database maintained by the Unit is ALADDIN [2]. It is divided into two sections: the original database for atomic and molecular processes and the more recent database for plasma-surface interaction processes. Data in ALADDIN are mostly obtained from Coordinated Research Projects of the Unit or from consultancies or from follow-up to such work. They are recommended data at the time of inclusion into ALADDIN; however, the database is not comprehensive. In many cases, especially for data obtained from a CRP, the published reference is an issue of Atomic and Plasma-Material Interaction Data for Fusion (APID).

Several other data sets that do not fit well into the ALADDIN framework are available directly through the Unit homepage. This includes data by U. Fantz and D. Wünderlich for radiative processes of (H,D,T) molecules and detailed atomic structure data obtained using the Los Alamos atomic physics codes for argon, chlorine and silicon.

The bibliographical database AMBDAS [3] is maintained by the Unit, based entirely on compilations done at National Institute of Standards and Technology (NIST) for spectroscopic data and at Oak Ridge National Laboratory (ORNL) for collision data. AMBDAS can be queried by process class and reactants and it returns citations to relevant literature. Whenever possible the result contains a link to a web version of the published article via its digital object identifier (doi).

The Unit provides access to external numerical databases through a common query interface via the GENIE search engine [4]. GENIE has one branch for spectroscopy and structure and another branch for electron-impact collision processes. Heavy particle collisions and surface processes are not covered by GENIE at this time.

Knowledge Base

Starting in 2010 the A+M Unit is developing a Wiki-style Knowledge Base for atomic, molecular and plasma-material interaction [5]. At the present stage the wiki draws heavily upon the meeting reports and APID volumes produced in the course of our CRPs. The wiki is addressed to scientists, both atomic and molecular physicists and plasma physicists, seeking to bring together producers and consumers of atomic, molecular and plasma-material interaction data. The content is open to the world for reading and open to editors that have been given a password for editing; however, to-date almost all the editing has been done in the Unit.

To conclude the presentation the APID series [6] was discussed. Several volumes were singled out that exemplify the data that may be produced by a focussed CRP: Vols. 7A and 7B are concerned with physical and chemical sputtering of Be, C and W targets and Vol. 8 is concerned with cross sections for hydrogenic atomic and molecular processes.

References

[1] http://www-amdis.iaea.org/
[2] http://www-amdis.iaea.org/ALADDIN/
[3] http://www-amdis.iaea.org/AMBDAS/
[4] http://www-amdis.iaea.org/GENIE/
[5] http://www-amdis.iaea.org/w/
[6] http://www-amdis.iaea.org/publications/APID/

3. Data Needs for Beryllium Plasma-Material Interactions

During the second day of the meeting the data needs for PMI on beryllium were reviewed, it was discussed what should be the focus of a CRP on beryllium and lists were made of which groups or institutes may contribute to such a CRP.

Throughout the discussions it was emphasized that mixed materials need to be considered, most importantly beryllium saturated with (H,D,T), BeC, BeO, BeW and higher complexes. The chemical structure of the surface greatly influences sputtering and hydrogen retention properties. Even if one believes that BeO will not be present in ITER, it is present in the laboratory experiments and it must be considered in order to make sense of measurements.

The most relevant projectiles are (H,D,T) and He as the main plasma constituents (note the intended non-nuclear experimental phase of ITER in which H and He will be the only filling gas), and Be, C, N, O, Ne and Ar as likely impurities. Be, C and O are ubiquitous impurities and N, Ne and Ar may be deliberately introduced for edge temperature control.

Measurements of sputtering and erosion show large scatter in ion beam data, and the explanation is probably the presence of BeO. Ion beam erosion yields at high temperature, where bulk beryllium atoms can diffuse through the BeO layer to the sample surface, are reasonably well understood. However, there are large uncertainties again at the high fluence found in plasma exposure facilities where any BeO surface layers are quickly eroded. Chemical erosion leading to BeH or possibly BeH_2 is poorly diagnosed because of lack of photoemission coefficients. One needs to know these emission properties as a function of surface conditions.

Redeposition and sticking fractions are poorly known under plasma conditions. A Be beam in vacuum sticks very well to a Be surface at low energy, but Be seems to attach much less readily under plasma exposure. Note the Be seeding experiments in PISCES-B. Redeposition changes the surface morphology and the erosion properties of redeposited layers are not well known; this is also important for the formation of dust.

Hydrogen retention in bulk Be is reasonably well characterized experimentally, but there are many open questions concerning atomistic modelling of diffusion of trapped hydrogen. Trapping and diffusion in co-deposited layers is not well explored or understood and is important for tritium retention in dust. Also there are many open questions experimentally and theoretically about hydrogen trapping and transport in mixed materials containing beryllium.

Baking is the basic way to remove trapped tritium. For a given material the removal efficiency depends on the surface temperature and that effect is studied experimentally, but a complete characterization of release rates as a function of material composition is not available from either experiment or modelling.

Melt layer, vapour shielding and ablation issues are important, but somewhat separate from the main interest of the CRP. These phenomena are studied on the plasma gun experiment QSPA-Be at the Bochvar Institute, by electron beam heat deposition experiments at Jülich, and in modelling at the Karlsruhe Institute of Technology. QSPA-Be poses big challenges for modelling because of issues such as vapour shielding; their experiments will be interesting for the CRP.

Spectroscopy is one of the most important tools to measure erosion, but the interpretation of spectroscopic measurements is difficult. This issue, too, is somewhat separate from the main interest of the CRP and the spectroscopic properties of BeH and BeH_2 belong rather to the CRP on light elements in plasma. The formation of BeH (BeD, BeT) on the surface is the key unknown. It would be good to see clean beam-target experiments to study formation of BeH, but such experiments seem not to be available. Instead we have the plasma experiments, foremost PISCES and (soon) JET.

4. Summary and Conclusion

Coordinated Research Project

A CRP on plasma-material interaction with beryllium is very timely in view of the start of operation with the ITER-Like Wall on JET and the preparations for operation of ITER. The consultants strongly endorsed the plan to initiate such a CRP as the first priority for a new CRP of the A+M Data Unit. The working title "Data for erosion and tritium retention in beryllium plasma-facing materials" is suitable.

In the presentations and discussions it was emphasized many times that it is essential to include mixed materials, especially Be-(H,D,T), Be-C, Be-O, Be-W and higher compounds, in the scope of the CRP, as the surface composition and chemistry greatly influences the sputtering, penetration and retention properties. Also it is appropriate to include within the scope of the CRP the principal plasma impurities as projectiles. The most important projectiles are then H, D, T, He, Be, C, N, O, Ne and Ar. On the other hand the meeting recommended that melting and ablation should not be emphasized in the CRP; they are important processes, but their study does not offer much synergy with the study of erosion and tritium retention. It was agreed (taken for granted) that materials issues such as neutron damage, fabrication and structural materials do not belong in this CRP, and likewise the behavior of sputtered or reflected material in the plasma is outside the scope of the CRP.

Due to severe safety concerns there is a limited set of institutes world-wide that carry out relevant experiments on plasma-material interaction with beryllium, but there is no such restriction for modelling work. In Annex 3 is found a list of groups and institutes that could contribute experimental or theoretical work to the CRP. The list is not intended to be exhaustive.

Additional Recommendations

The measurement of erosion under plasma exposure is important, especially spectroscopic measurements, and it was discussed what role this topic might have within the CRP. In the end the consultants advised the A+M Data Unit to organize a focussed meeting separate from the CRP on spectroscopic issues for erosion measurements of beryllium. The meeting would bring together researchers in plasma-material interaction, spectroscopy and the appropriate modelling. It is recommended to focus on Be, Be^+, BeH and perhaps BeH_2 in divertor plasma, and leave out the hydrocarbons. Look for participants from fusion experiments, but also (if possible) clean beam-target sputtering experiments. Initial contacts: S. Brezinsek, M. Stamp, R. Doerner, U. Fantz, D. Borodin, contacts at QSPA-Be, and participants in the Light Elements CRP.

It is understood that atomic and molecular processes in plasma of Be, BeH and BeH_2 are a subject of the existing CRP on Light Elements (2009-2013); therefore a strong coupling between the CRP on beryllium surfaces and the one on light elements should be ensured.

IAEA Consultants' Meeting on Data Needs for Erosion and Tritium Retention in Beryllium Surfaces

30–31 May 2011, IAEA Headquarters, Vienna, Austria

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Appendix 2

IAEA Consultants' Meeting on Data Needs for Erosion and Tritium Retention in Beryllium Surfaces

30–31 May 2011, IAEA Headquarters, Vienna, Austria

Agenda

Monday, 30 May **Meeting Room: A05-41**

09:30 – 09:40 R.A. Forrest: Welcome

Session I

09:40 – 10:20 B.J. Braams: Introduction; CRPs and Meetings of the A+M Data Unit

10:20 – 11:00 S. Brezinsek: Research activities and data needs for plasma-material interaction with beryllium surfaces

11:00 – 11:20 *Coffee*

11:20 – 12:00 D. Kato: Data on sputtering and hydrogen retention of Be and Be alloy

12:00 – 12:30 H.-K. Chung: PMI data at IAEA

12:20 – 14:00 *Lunch*

Session II

14:00 – 14:40 R. Doerner: Research activities and data needs for plasma-material interaction with beryllium surfaces

14:40 – 15:20 W. Jacob: Research activities and data needs for plasma-material interaction with beryllium surfaces

15:20 – 15:40 *Coffee*

15:40 – 17:20 Discussion: objectives for a CRP on PMI with beryllium surfaces

19:30 – *Dinner*

Monday, 31 May **Meeting Room: A05-41**

09:00 – 12:30 Round table; coffee as needed

12:30 – 14:00 *Lunch*

14:00 – 16:00 Writing the meeting report

16:00 – *Close of meeting*

IAEA Consultants' Meeting on Data Needs for Erosion and Tritium Retention in Beryllium Surfaces

30–31 May 2011, IAEA Headquarters, Vienna, Austria

Potential Participating Institutes

Institute, contact person or persons, brief indication of work. More institutes are named here than can participate in the CRP and there may well be participants that are not in this list.

IPP Garching: W. Jacob, Ch. Linsmeier, U. von Toussaint. Analysis of beryllium tiles after plasma exposure or beam impurity implantation. Plasma and PMI modelling.

IPP Juelich: A. Kreter, A. Huber, D. Borodin, C. Björkas. Analysis of beryllium tiles, in particular with use of Laser-Induced Breakdown Spectroscopy (LIBS). ERO impurity transport code development and application to PMI on beryllium. Development of interaction potentials for molecular dynamics.

JET/EFDA: S. Brezinsek, G. Matthews (experiments), P. Coad, J. Likonen (post mortem). JET will provide a wealth of information on plasma interaction with beryllium in circumstances closest to those in ITER.

PISCES-B: R. Doerner. The linear plasma device PISCES-B will continue to provide experimental data on plasma-material interaction with beryllium and beryllium compounds.

Bochvar Institute: I. B. Kupriyanov. The home of the new QSPA-Be plasma gun, derived from QSPA at Kharkov, but equipped to use beryllium targets. The plasma gun experiments provide short pulse intense heat and particle loads such as are relevant for study of ELM interaction with plasma walls.

MEdC Euratom, Romania: C. P. Lungu. The National Institute for Lasers, Plasma and Radiation Physics, MEdC, can prepare well-defined beryllium films and mixed beryllium deposition layers using vacuum arc technology.

MOL, Belgium: I. Uytdenhouwen. The Nuclear Research Centre at Mol is preparing a plasma device to work with tritium and beryllium.

University of Helsinki: K. Nordlund. Molecular dynamics simulations of PMI on beryllium and mixed materials; development of MD potentials.

University of Tokushima: K. Ohya. EDDY code, including simulations involving beryllium walls.

Doshisha University: T. Kenmotsu. Sputtering and reflection calculations, integrated MC.

Tokyo University: S. Tanaka, T. Oda. Evaluation of potentials for H in metals

Purdue University: J. Brooks, A. Hassanein. Molecular dynamics modelling of PMI; simulations of melting and ablation.

INEL: M. Shimada. TMAP code project; hydrogen in materials.

Université de Provence: A. Allouche. DFT calculations of materials, study of H in Be.

Technische Universität Wien: F. Aumayr; DFT calculations of materials.

Karlsruhe Institute of Technology: B. Bazylev. Melting, vapour shielding.
IMP Lanzhou: Home of the EAST tokamak. Contacts are Guangnan Luo at EAST and Yongtao Zhao at the highly charged ion and plasma physics group.

Josef Stefan Institute, Slovenia: V. Nemanic; hydrogen permeation in Be.
Other: Post-mortem analysis of JET tiles is carried out at Tekes in Finland (J. Likonen), VR in Sweden (M. Rubel), IPP Garching (M. Mayer), FZ Juelich (B. Unterberg) and IST Portugal (I. Nunes).

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