*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-4.171 (2006)*

Be light emission and transport in PISCES-B modelled by the ERO code

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Introduction. The investigation of beryllium (Be) as a plasma-facing material, which is chosen for the ITER main wall alongside with tungsten (W) and carbon (C) in the divertor, and of the mixing of all thee species is important for predictive modelling of target lifetime and tritium retention in ITER. Dedicated Be experiments were carried out in the PISCES-B divertor plasma simulator. This device can produce ITER-relevant plasma conditions and is equipped with an extensive set of diagnostics. The safety enclosure allows experiments with toxic Be. A number of effects were observed at PISCES [1]: enhanced re-erosion of Be at elevated surface temperatures, carbide formation and mitigation of chemical erosion of carbon even at Be plasma concentrations well below 1%. To model these effects it is important to understand the transport of Be in the device. The aim of this work is to model the transport and light emission of Be and to benchmark the modelling by experimentally observed spectroscopy patterns using the ERO code.

The 3D Monte-Carlo code ERO [2] can model plasma-surface interaction (PSI) processes, the build-up of surface layers (including time evolution), the transport of plasma impurities and their light emission. In the frame of this work a version of the ERO code containing the PISCES geometry, plasma parameters and physical effects discussed below was developed. Recently a coupling between ERO and TRIDYN [3] codes was provided. The latter one allows to follow depth resolved concentration profiles of elements in the surface.

PISCES-B is a linear plasma simulator. The cylindrical plasma chamber has a radius of 7.6cm whereas the plasma covers only a radius of about 2–3cm. An exchangeable circular target is located at the end of the plasma column. The deuterium plasma can be seeded with a pre-set amount of Be. A narrow beam of neutral thermal Be evaporated from an oven penetrates perpendicularly into the plasma at an axial distance of 15cm from the target. In the experiments discussed below the ‘standard’ PISCES plasma conditions were used: $T_e \sim 7$ eV, $n_e \sim 2*10^{12}cm^{-3}$ at the centre of the plasma column, T_{target}~450°C, T_{oven}~1300°C (it determines the puffing rate). The observed light intensity profiles of neutral Be (BeI at 457nm) and ionized Be^+ (BeII at 467nm) along the plasma column can be used to characterise the transport of Be.

New atomic data. To improve the modelling of spectroscopic observations the ERO database was updated with ADAS [4] reaction rates for light emission and ionization. These are effective values, representing many processes, taking into account the dependence on plasma density and temperature. The new data (rates shown in fig.1) for neutral Be are quite different from those used in ERO before, which were obtained with the Lotz formula. For Be^+ the difference is minimal. In future it will be possible to introduce an essential part of the collisional-radiative model into ERO by means of a small number of specially constructed 'effective' metastable states. Using this way it is possible to avoid a dramatic increase of data amount and computational time.

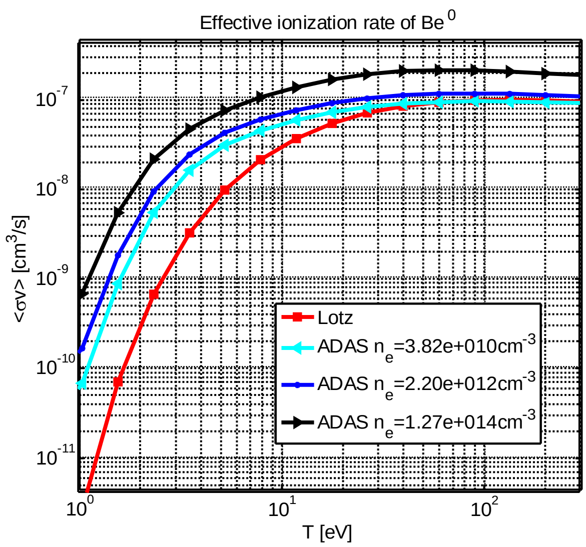

Fig.1. Old (Lotz) and new (ADAS) effective ionization rates for neutral Be used by ERO.

Be seeding experiments. These experiments are carried out in such a way that the Be concentration in the plasma solely results from the Be oven without any influence of target. The observed two dimensional distribution of the BeI emission reveals an asymmetry in radial direction such that the maximum of light emission occurs off-axis shifted to the direction of the oven. This means that a considerable part of Be is ionized before it reaches the opposite wall. Fig.2 shows the observed profile of BeI emission in axial direction. It is seen that a relatively broad profile evolves. The exact angle distribution (and amount) of seeded Be penetrating into the plasma is unknown, however it should be not very broad due to the collimation in a tube-like oven. None of the reasonable angle distributions we have tried can provide such a broadening. If the collisions with neutrals are considered ERO modelling shows that the influence of angle distribution of the incoming Be is not very important: cosine or uniform distribution with or without truncation at angles 12^O-45^O give results which differ from each other only by 5 - 10%. Therefore, in the following we always assume cosine distribution. Fig.2 shows the simulated BeI profile in axial direction without including collisions of Be atoms with neutral D_2 (blue curve). As can be seen compared to the measured profile (red curve) the simulated one is much more peaked at the location of the Be oven. We, thus, follow that the broadening of the BeI emission in axial direction takes place mostly due to collisions with neutral D_2 (this deuterium density is much larger than the one of D^+ even inside the plasma column). For collisions with neutrals the following model is applied; we use randomization to decide whether a tracked Be particle has experienced a collision and if so, than it changes its direction randomly (isotropic distribution). The effect of including neutral collisions on the simulated BeI profile is shown in fig.2 (green curve). Although it is significantly broader than without neutral collisions it is still more peaked than the observed

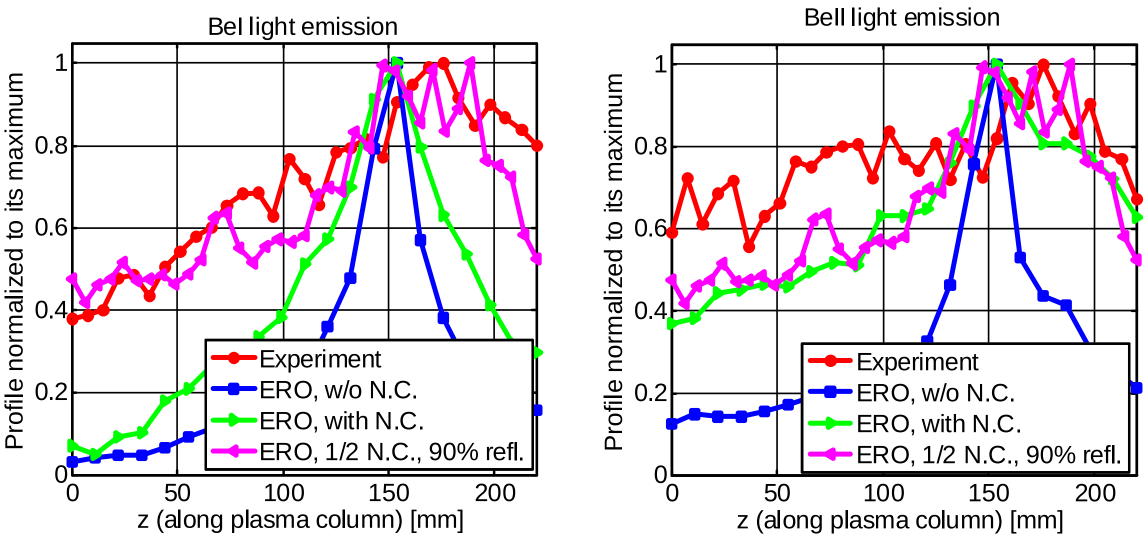

Fig. 2. Axial profiles of BeI (left) and BeII (right) emission resulting from Be seeding into the plasma. The experimental profiles are compared with ERO simulations where a cosine angle distribution for the seeded Be is assumed. Simulated profiles are shown without and with collisions between Be and neutral D_2 (N.C.). Furthermore the magenta profiles also include Be atoms reflected from the walls.

profile. In addition to neutral collisions also the reflection from the walls can lead to a profile broadening. For reflection, we suppose that if a particle reaches the wall it is re-emitted with a cosine distribution directed to the PISCES central axis with a given probability. The best agreement between observed and modelled axial BeI profile was achieved including neutral collisions in the modelling applying half of the measured neutrals density and 90% reflection from the wall (magenta curve in fig.2).

The ionised Be moves along the magnetic field lines towards the target. Its broadening is defined by the flow velocity and by the place where ionization of neutral Be took place. Fig.2 (right) shows the observed BeII profile together with the simulated profiles applying the same parameter variations discussed before. Here it is even more obvious that collisions between neutral Be and D_2 are essential to reproduce the observed BeII emission.

Be target experiments. These experiments are carried out with a Be target and applying an additional negative biasing. This leads to an increase of the impinging energy of plasma ions and, thus, an increase of the sputtering yields. Here we concentrate on the modelling of the axial BeI intensity profiles along the plasma column (fig.3). Application of different biasing leads to minor changes in the plasma conditions, which has been taken into account in the ERO modelling. ERO modelling shows that ionization affects the profiles (up to 30%), however, the penetration depth is mostly determined by a loss of Be to the wall. Collisions with neutrals or reflection from the wall can take place but the most part (>60%) of Be we see comes directly from the target.

The modelled absolute values are in fair agreement with the experimental ones (fig. 3). The sputtering yields used in ERO were calculated using the TRIDYN code [3]. They depend on the impinging energy of the ions determined by the sheath potential influenced by biasing and electron temperature. The Maxwellian distribution of ion velocities also leads to an increase of the yield. The different erosion yields by atomic and molecular ions (D^+, D_2^+, D_3^+) are taken into account: we suppose that D_2^+, D_3^+ dissociate during collisions at the surface resulting in 2 respectively 3 D^+ with 1/2 and 1/3 of the impinging energy.

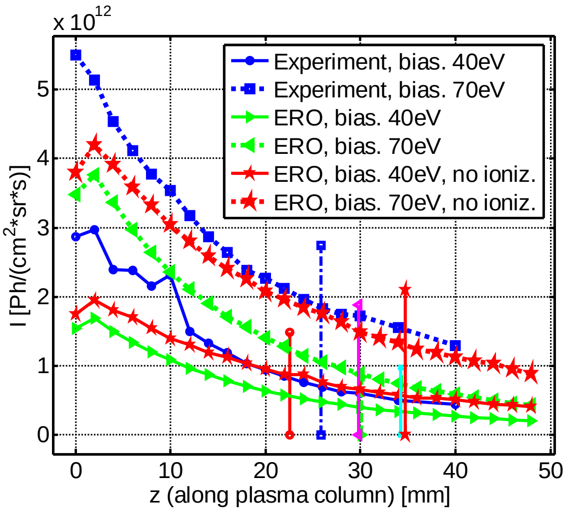

Fig.3. *Be target experiment – absolute BeI axial intensity profiles. Comparison of observed and calculated data. The green curves are calculated without ionization to demonstrate its effect.*

Summary. A version of ERO for PISCES has been developed, which contains an according plasma configuration, Be oven and target. A number of physical effects have been introduced and proved by comparison with experimental results to be necessary to model the transport of Be in PISCES. Especially collisions of beryllium atoms with neutrals, erosion by molecular ions and reflection from the wall have to be taken into account. State-of-the-art data for erosion (TRIDYN), spectroscopy and ionization (ADAS) have been implemented.

Next step of this work is to apply the PISCES version of ERO to model ITER-relevant effects such as chemical erosion mitigation by Be seeding and carbide formation.

[1] M J Baldwin and R P Doerner "A time resolved study of the mitigation of graphite chemical erosion in deuterium plasmas containing beryllium", submitted to Nucl.Fusion

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[3] Version 'SDtrimSP'; W.Eckstein "Computer Simulation of Ion-Solid Interaction", "Springer Series in Materials Science", 10, Springer, 1991, Berlin

[4] H P Summers "JET Joint Undertaking Report", JET-IR(94), 1994; ADAS User Manual; webpage http://adas.phys.strath.ac.uk/