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Estimates of RF-Induced Erosion at Antenna-Connected Beryllium Plasma-Facing Components in JET

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***See the Appendix of F. Romanelli et al., Proc. of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

***Abstract**. RF-enhanced surface erosion of beryllium (Be) plasma-facing components is explored, for the first time, using the ERO code. The code is applied to measured, RF-enhanced edge Be line emission at JET Be limiters, in the presence of high-power, ion cyclotron-resonance heating (ICRH). In this first modelling study, the effect of the RF on the localized interaction region is simulated by adding a constant potential to the local sheath, in an attempt to match measured increases in local Be I and Be II emission of factors of 2-3. It was found that such increases are readily simulated with added potentials in the range of 100-200 V, which is compatible with expected values for potentials arising from rectification of sheath voltage oscillations from ICRH antennas in the scrape-off layer (SOL) plasma. Absolute erosion values are estimated within the uncertainties in the local plasma conditions, as well as the present limitations of the ERO simulation.*

1. Introduction

ITER, the international, next step magnetic fusion energy facility, is designed to operate with all beryllium (Be) wall, and an all tungsten (W) divertor. Furthermore, ITER's auxiliary heating systems will include high power, ion cyclotron resonance heating (ICRH) antennas. It has been long known that rectification of near-antenna, radio-frequency (RF) sheath voltage oscillations could induce plasma biasing to large DC potential, V_{DC}, and enhanced plasma-wall interactions (PWI) at near and/or distant plasma facing components. This effect has been associated with magnetic connections between high near-antenna electric fields and the affected plasma-facing components (PFCs). With the implementation of an ITER-like wall

(ILW), the presence in JET of toroidally-spaced, high-power, ICRH antennas, each bracketed by protective, outboard, poloidal limiters, now with all Be surfaces for both antennas and limiters, provides a unique opportunity to study such interactions on Be surfaces and evaluate potential erosion of beryllium plasma facing components in the presence of such RF-PWI. With ITER plasma pulses designed to be in the range of 400 – 3000 s, even small erosion rates could have a significant impact, and the effect would need to be considered in the plasma pulse design. Measured Be impurity concentrations on JET plasmas were significantly larger in presence of ICRH power [**Jacquet'14**]. Although Be itself had a minor impact on the overall plasma radiation, this light impurity could enhance the effective sputtering yield on pure W or W-coated surfaces, resulting in increased W contamination and consequent reduction in fusion plasma performance.

A first opportunity to study this effect appeared in the first JET-ILW experimental campaign of 2011-2012, in which ICRH-heated, L-mode JET pulses, combining sequential toggling of the antennas with q_{95} (edge safety factor) sweeping, were used to localize RF-enhanced Be I and Be II spectral line emission at an outboard poloidal limiter neighbouring one of the antennas [**Klepper'13**]. This first study highlighted that increases of edge Be line emission by factors of 2-3 depending on coupling scheme for the antennas, correlated much better with magnetic connection to a specific region of a distant antenna, rather than with the ON/OFF status of the nearest antenna (Fig. 1).

Fig. 1. Be I 457.3nm ($1s^2 2s2p\ ^1P^o$ - $1s^2 2s2d\ ^1D$) integrated chordal brightness (top graph) for JET Pulse Number (JPN) 81172 from 3 sightlines: Antenna side of limiter ("D14", blue), periscope side of outboard limiter ("D12", green) and sightline away from antenna and limiter ("background", purple); while scanning q_{95} (also shown on top graph) and sequentially toggling antennas, as shown on bottom graph with Ant-D in green, Ant-C in red and Antennas A&B (operated as one) in blue. Small Ohmic-only gaps were also included in each cycle. This pulse was repeated (JPN 81173) with the spectrometer set for Be II 467.3nm ($1s^2 3d\ ^2D$ - $1s^2 4f\ ^2F°$), and a similar response was obtained to the antenna toggling and q-edge sweep.

More specifically, the intensity at the spectroscopically accessible region, near the outboard mid-plane level of the poloidal limiter, exhibited the highest increase when q_{95} allowed connection of the observation region to the upper corners of the antenna at the next toroidal sector of JET (and when that specific antenna was ON). These results were presented in [**Klepper'13**] and related to a number of past ICRH antenna modelling studies that predicted higher near-fields at antenna corner regions. Since that time, the JET "type A2" antennas [**Kaye'94**] have been specifically modelled with the Topica code [**Milanesio'09**] and the outcome also points at such near-field localization (Fig. 2).

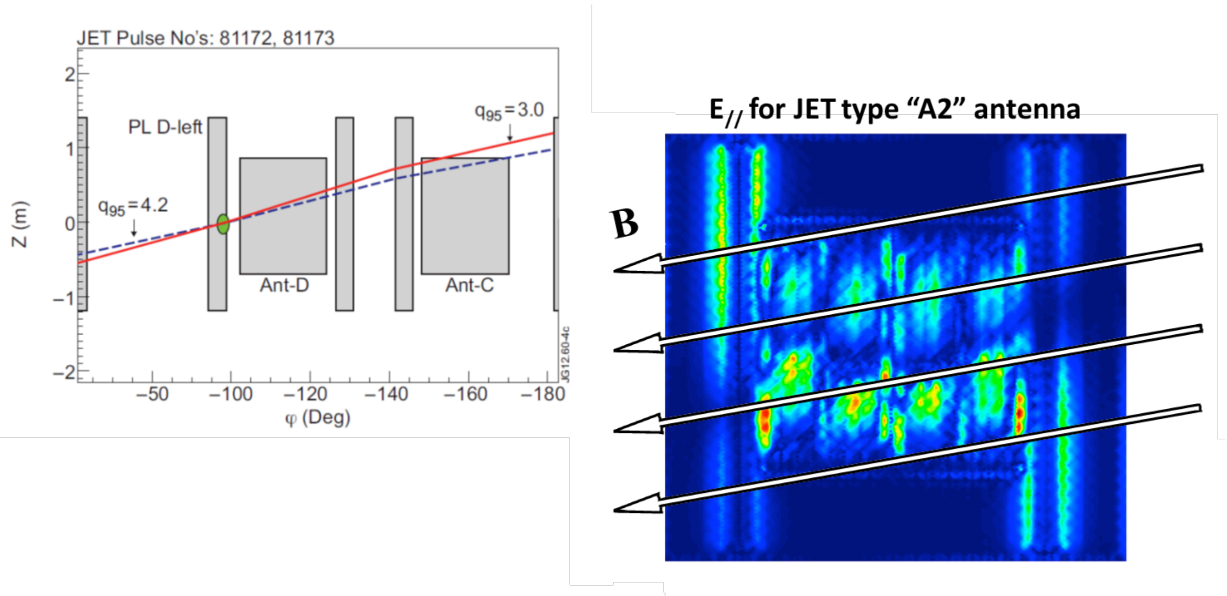

Fig. 2. Highlighting the key result from [**Klepper'13**], the image on the left hand side shows how the magnetic connections map the observed region of the limiter (green spot) and the upper corner region of Antenna "C", which is not the case for the mapping to Antenna "D". This is consistent with more recent antenna modelling using the Topica code, now applied specifically for the JET Type "A2" antennas (right-side images). The high $E_{//}$ at the upper corner is associated with the observed, enhanced RF-PWI effects at PFCs connected to this region by magnetic field lines. (Color scale for the $E_{//}$ images is ~0.05 – 0.50 kV/m).

In addition to antenna modelling, substantial progress has also occurred in the development of beryllium-specific, local erosion and re-deposition modelling. In fact, the 3D Monte-Carlo local impurity transport and plasma-surface interaction code ERO [**Kirschner NF2000**] has now been optimized for studying early JET-ILW limiter discharges and has already been successfully used in a comprehensive study of Be sputtering processes (including physical and chemical-assisted physical sputtering) for limiter plasmas riding on the high field-side (inboard) poloidal guard limiters [**Brezinsek'14**].

In the present paper, this first spectroscopic study of RF-enhanced Be sources is revisited, with the main goal of obtaining estimates of the impact of these RF-PWI on sputtering and net erosion of the affected limiter regions in diverted plasmas. The version developed for the present work is based on that used for ITER blanket modules simulations [**Borodin'11**] and later refined and applied to modelling JET ILW inner wall guard limiter [**Borodin'14**]. In the present study, ERO is re-deployed with the detailed geometry of a JET outboard limiter. In a first approximation, the effect of RF-PWI on sputtering is represented by applying and varying an additional surface negative biasing, which affects the incident ion energies and resulting sputtering yields. The aim is to determine if the observed variations in line emission of about factor of 3 (Fig. 1) can be reproduced by introducing a ~ 100 – 200 V bias, similar to the rectified RF sheath potentials determined in previous measurements in tokamak antenna PFCs (see e.g. [**Colas'07**], [**Bobkov'10**], [**Wukitch'07**]). As will be seen, ERO simulations show that the influence of added potential is mainly on the amount of sputtered Be whereas the local Be transport is localized near the surface and thus less affected. However, the distribution of the 3D plasma parameters, shadowing and other geometrical effects can have a significant impact on the distribution and also the intensity of Be light emission.

Since the plasma parameters are not directly measured in this interaction region, they are simulated, for the divertor scrape-off layer, by EDGE2D-EIRENE [**Groth'13**] and extrapolated towards the surface and mapped in 3D. The outer gap, i.e. the distance from the outer separatrix to the limiter tangency point was about 6 cm for the analysed pulses.

The paper is organized as follows. In Section 2, the experimental setup up and key results of the original study on RF-specific Be sources are briefly recalled. In Section 3, the background plasma characterization, and its extrapolation to the region of interest and to ERO code grid (out into the SOL) are described. In Section 4, initial ERO modelling results are presented for the range of potentials anticipated through RF sheath rectification. In Section 5, the results are discussed with emphasis on matching of the model to the experimental data. Shortcomings from both the modelling and experimental side are also discussed, as well as plans for improvements in both areas for the upcoming 2015 - 2016 JET campaign.

2. **Experimental Setup**

A detailed description of the experimental setup is provided in [**Klepper'13**]. The key measured quantities were spectrally and temporally resolved, edge Be line emission intensities, accessible via a tangential periscope, located in JET octant 1, and multi-chord spectrometer normally used for charge exchange spectroscopy (CXRS) in the plasma core. A fan of sightlines emanates from this periscope, mainly designed to intercept JET's octant 8 neutral beam at a number of radial locations and approximately on the mid-plane [**Giroud'08**]. For this antenna-specific study, two sightlines from this core CXRS system provided measurements in the neighbourhood of one of the four *type-A2* antennas, referred to as Antenna "D", and located between JET octants 6 and 7 and one of its protective, poloidal limiters, located in octant 7. These are the sightlines labelled D12 and D14 in [**Giroud'08**] and other CXRS documentation. Spatial calibration, via backlight of the optical part, showed that these sightlines terminate, respectively, one on the nearest side of Antenna "D" left-side protective limiter and the other, past the far end of this limiter on the nearest of the four Faraday screen's comprising the plasma facing surface of Antenna "D". Note that in [**Klepper'13**] these were labelled as sightlines 2 and 1, respectively. In the present paper, they will be referred to by the published names of sightlines, i.e. "D12" and "D14". A particular benefit of the use of CXRS sightlines is that they are absolute intensity calibrated. This makes it now possible to relate, in the present study, the measured brightnesses to simulated brightnesses from the erosion model.

3. Background Plasma and its Extrapolation to the PFCs of Interest.

The antenna toggling studies were performed in L-mode plasmas. This offers the advantage of quiescent scrape-off layer (SOL) plasma conditions, in which small changes on PFCs and the SOL resulting from changes in the antenna power and/or configuration, can be resolved. Since the original experiment, extensive characterisation of the SOL profiles for similar discharge conditions has been obtained. The characteristic plasma parameters (n_e, T_e) at the SOL, used by ERO as boundary conditions, were obtained from the 2D multi-fluid edge code EDGE2D [**Simonini'94**] coupled to the neutral Monte Carlo code EIRENE [**Reiter'92, Wiesen'06**]. Emphasis is given to a low-triangularity configuration with strike points at the horizontal divertor target plates, which has the most extensive experimental database to validate the simulations.

Key to this approach was the use of EDGE2D-EIRENE modelling to get a link between plasma conditions at the divertor plate and those upstream at the separatrix, greatly benefiting from significantly improved profile data in the low-field-side (LFS) pedestal and SOL regions from high-resolution Thomson scattering, a Li beam-emission spectroscopy system, and a reciprocating Langmuir probe (references to these diagnostic systems are also provided in [**Groth'13**]).

In the EDGE2D-EIRENE calculations, a diffusive radial transport model was used, with radially varying heat and particle diffusion coefficients adjusted to match the experimentally measured upstream profiles of n_e, T_e and T_i. The conditions for the total power crossing the grid core boundary were derived from the power balance in the core. In doing so, the upstream T_e profiles were matched for all upstream densities. In the simulations the electron density at the outer midplane separatrix ($n_{e,sep,omp}$) was varied to obtain sheath-limited, high-recycling and detached divertor solutions. In these studies, sheath-limited ($n_{e,sep,omp} = 0.8x10^{19}$ m^{-3}) and high-recycling ($n_{e,sep,omp} = 1.2x10^{19}$ m^{-3}) conditions were chosen. A detailed description of EDGE2D-EIRENE set-up (density and power scan, collisions, re-erosion and re-deposition, molecular species or fuelling rates, omission of drifts) can be found in [**Groth'13**].

Specifically, in preparation for ERO code input, the transformation of EDGE2D-EIRENE plasma parameters into the Cartesian grid used by ERO (Fig. 3) is done using bilinear interpolation within each EDGE2D-EIRENE grid cell (Fig. 4). In addition, the interpolated values are constrained between the minimum and maximum of cell corner values. In regions of low grid resolution the method can produce irregularities, which can be avoided by splitting the grid cells into smaller cells and a carrying out a first linear interpolation to specify values for the added nodes. Extension of the data into the far-SOL is done by adding new rings to the grid and extrapolating the plasma parameters exponentially outside the original grid before applying the bilinear method, as earlier applied in [**Airila'14**]. For example, for the far-SOL T_e values in the "HR" approximation, for the pulses modelled with ERO for this paper, the exponential decay approximation was used with a ~3cm e-folding length (assuming same trend as in the plasma modelled SOL region). With approximately 40 eV at the separatrix, T_e goes down to about 5 eV at the limiter tangency point. A constant value extrapolation (from the last point given from the background plasma simulation) would give a value of ~11 eV at the limiter for the same conditions. It is noted that the ERO simulations' volume includes a certain range, marked on Fig. 4, around the sightlines ending up close to the midplane.

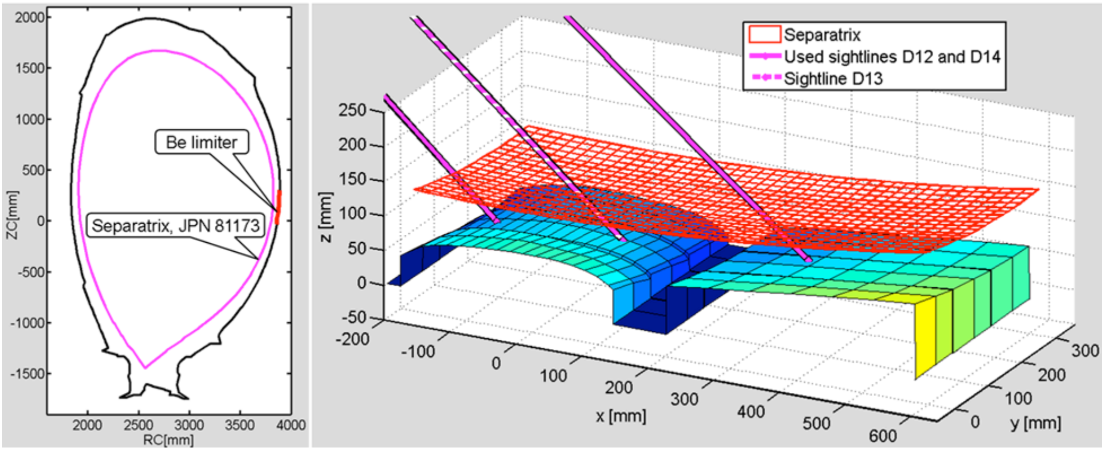

Fig.3. The ICRH antenna and near-by solid Be limiter geometry (right side) and a cross section of the JET tokamak, showing the poloidal position of the limiter included into the simulation box (left). The diagnostic observation chords ending on both limiter and antenna surfaces are shown. The ERO system of coordinates is used on the right part, where z corresponds to RC in the left figure.

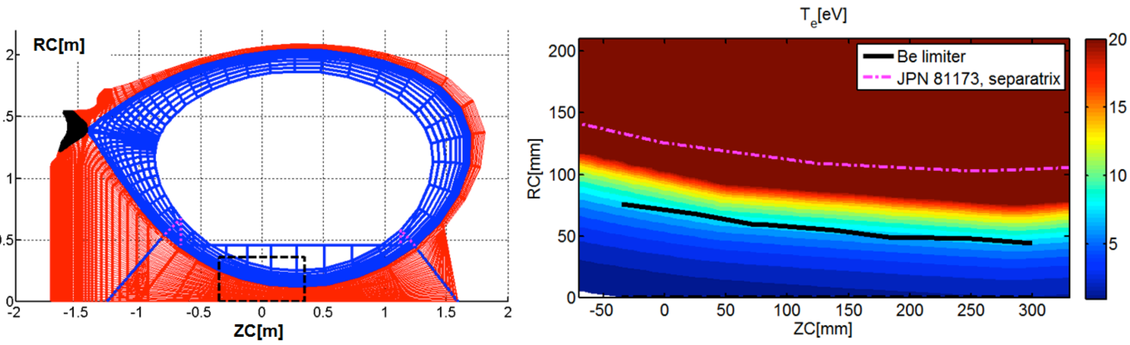

Fig. 4. The extrapolation of the plasma parameters towards the limiter and the antenna surface (left). The extrapolated T_e is depicted as an example (right). The dashed line shows the poloidal cross-section of the separatrix; the solid line is that of the limiter.

The drop of the plasma parameters in SOL is known to depend strongly on the local connection length (CL) [**Ding'15**]. Therefore, the respective patterns along the surface were introduced into ERO (Fig. 5). The CLs were simulated by PFCFlux [**Firdaouss'13**], averaging each surface cell. PFCFlux includes the detailed JET ILW geometry and uses the exact EFIT B-field for the respective JET pulses 81172/81173 and measured time window. As a first approximation, one can neglect the plasma density and flux for all locations, where the connection length is much smaller than in the peak zone on the antenna side of the limiter ridge (right hand-side, in Fig. 5). In our present simulations, any area with a connection length below 25 m (nearly all the left-hand side of the limiter and the whole ICRH antenna – see Fig. 5) were considered to be in a plasma shadow experiencing no erosion. Though the connection lengths on the most part of the left side of the limiter are 3 times smaller than in the strongly plasma-wetted area at the ridge and to the right from it, it is far from being fully shadowed. Still, the plasma density and thus flux will be considerably reduced. Obviously some erosion takes place where, which can be accounted by considering various zones of connection lengths similar to [**Ding'15**]. However, the crude assumption considered in the present first modelling attempt is better than total neglecting of the shadowing effects.

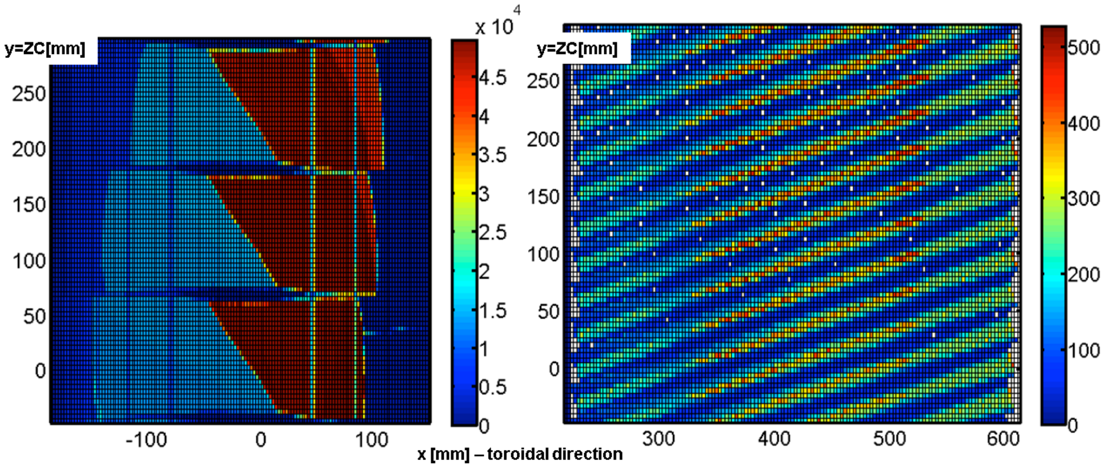

Fig. 5. 2D maps of the connection lengths [mm] simulated by the PFCFlux code [**Firdaouss'13**] across the limiter (left) and antenna (right) surfaces.

4. Erosion model and simulation of the measured local Be light emission

At each surface point ERO uses the plasma background as an input (local n_e, T_e) and simulates the D flux, which depends on the B-field inclination with respect to the surface. The surface sheath potential determines the impact energy of plasma ions. The resulting physical sputtering is calculated as in [**Borodin'14**] but assuming normal incidence, as a first estimate in the present qualitative study.

The trajectories of the eroded Be particles in the plasma and the resulting light emission are simulated by the ERO code (Fig. 6). ERO also integrates in 3D the light emitted by the tracked species in the sightlines. As shown in Fig 6, the Be I emission is localized around the plasma-wetted area on the right side of the limiter. Only a small fraction of this emission is coming into the D12 and D14 sightlines as most Be is ionized on the way. Unfortunately the D13 sightline, also illustrated in Fig. 6, was unavailable.

In contrast, the ionized Be is effectively pulled along the magnetic field lines. Therefore, current ERO simulations are expected to reproduce the majority of Be II light observed in the sightlines. The modelled light intensities are, indeed, in the same order of magnitude than the experimental ones (Fig.1 and 7c).

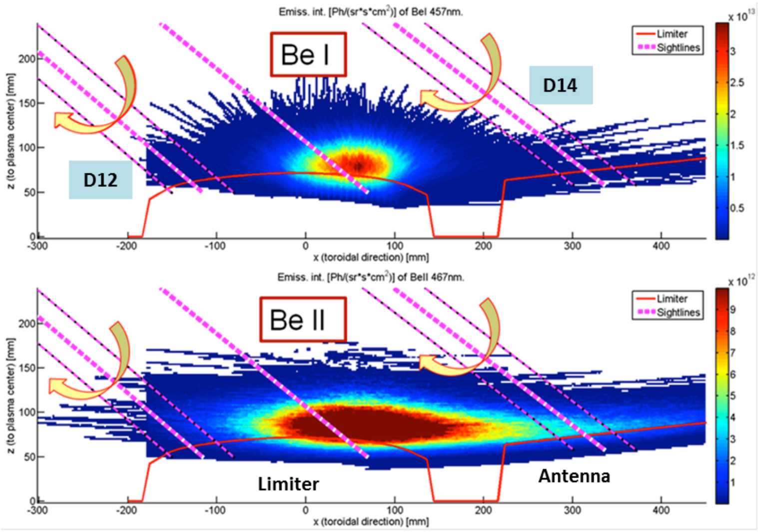

Fig. 6. . The light emitted by the eroded neutral and later on ionized Be. ERO simulations. The sightlines 'D12', 'D13', 'D14' are depicted (counting from left to right). D12 and D14 are integrated in 3D to produce a synthetic sightline emission for the direct comparison with the experiment. (D13 was unavailable for this measurement, but shown with single, dashed line, as it would be of great interest for future measurements).

The main aim, however, was to qualitatively evaluate if the observed light variations at the sightlines could be reproduced through surface biasing. The result of this added DC sheath potential (representing RF-sheath effects) on the integrated line intensity along sightlines D12, D14, is shown in Fig. 7. As seen in Fig. 7a, the biasing representation is appropriate: average erosion in the plasma-wetted area clearly grows between zero and 150-200V biasing. The effect is larger for the high recycling ('HR') plasma parametrization given by EDGE2D-EIRENE simulations, than for the low recycling ('LR') case. The simulated Be I and Be II emission levels show the same dependence on these assumptions used in the extrapolation of the background plasma (Fig. 7b, c). Having the plasma light simulation results at these two extremes ('LR' and 'HR') of the background plasma simulation, provides essentially a measure of the uncertaintly in the derived surface erosion values, in this situation where the plasma parameters cannot be measured locally.

Related to this, it is noted that D_α-filtered camera images of other antenna-limiter interaction regions during the same pulses showed some increase in recycling at the interaction region (i.e., when these limiter regions would magnetically connected with a corner region of an active ICRH antenna, in the process of antenna toggling and q_{95} sweeping). Although these measurements were not quantitative and not for the same region as the Be line spectroscopy, they nevertheless indicate that the RF-induced interaction may be impacting the local plasma parameters. To take such effect into account would require coupling the ERO simulation to the background plasma simulation, which is not presently the case.

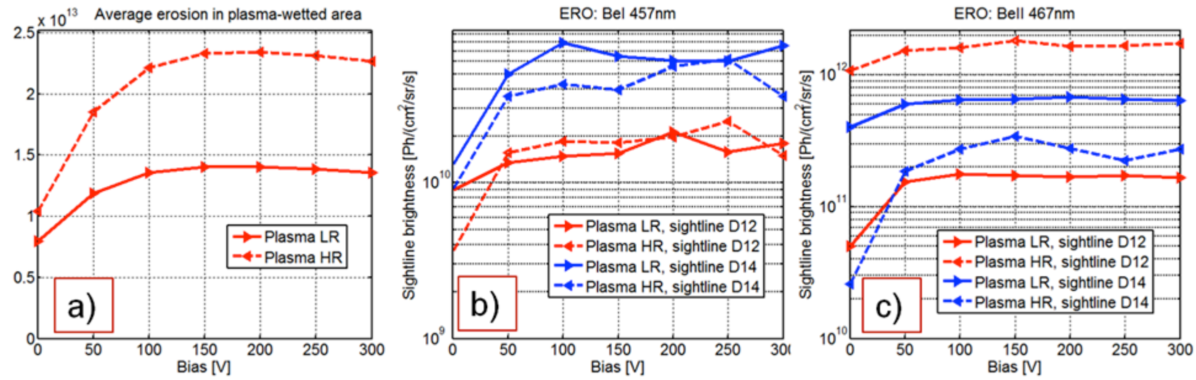

Fig. 7. Integrated results for the 2 series of the ERO simulations for low (LR) and high (HR) recycling plasma conditions. In a) the average erosion along the plasma-wetted area of the limiter is depicted for a varying biasing. In b) and c) the synthetic brightness from ERO is given for 2 sightlines used in the experiment.

Two things are noteworthy in the present ERO simulation results of Fig. 7: (1) Erosion increases by factors between 2 and 3 are reproduced for added potentials in the range of 100 – 200 eV, which is consistent with antenna-code predicted values, as well as experimental findings on AUG, Tore Supra and Alcator C-Mod, and; (2) The effect saturates as a result of the saturation of Be sputter yields (see e.g. Fig 2 in [**Borodin'13**]). The curves in Fig.7a more-or-less follow the trends for normal incidence sputtering yields. Also, note that the enhancement factor with the added RF effect, as determined from the experimental data (Fig. 1) depends on what is used as reference. If the Ant-C plateau is referenced to the Ant-D plateau, then a factor of ~2 is derived, while a factor of ~3 is obtained if compared with the OH (all antennas off). If the Ant-A&B plateau is used as the reference, then intermediate values are obtained.

5. Conclusions, discussion and future work

In this work, a first simulation of the enhanced edge Be line emission at a region of an outboard limiter of JET, magnetically connected to a high RF $E_{//}$ region of an ICRH antenna, has been carried out. The ERO modelling outcome matched not only the level of light emission, but also the relative change for values of rectified sheath potentials anticipated at the connected limiter, based on ICRH antenna simulations. ERO provides a synthetic diagnostic for the spectral line intensities integrated along the CXRS viewing chords. The simulated line intensity is of the same order of the magnitude as measured for Be II, however the model assumptions need to be refined to get a quantitative match (e.g. distributions of the energies and angles of the particles on impact should be included, also the charge exchange flux to shadowed areas, as well as chemical assisted physical sputtering of Be [**Brezinsek'14**]).

The relatively stronger emission found on the antenna side of the limiter is also consistent with experimental data (i.e. in comparing absolute brightness levels for sightline D14 versus those of sightline D12 in Fig. 1). The effect is explained by shadowing (differences in connection lengths) given in Fig. 5.

Based on the satisfactory outcome of the modelling, the effect of a Be PFC being magnetically connected to a high-power ICRH antenna can now be quantitatively estimated. According to the present calculations, the erosion would range between 0.15 – 0.25 nm/s, with the range given by the two recycling regime limits used in the modelling and extrapolation of the boundary plasma profiles. Thus, under the same operational scenario and for an ITER-like 400 s long pulse, an erosion of 60 – 100 nm/pulse would be expected.

New ICRH antenna technologies, in parallel with a continued antenna sheath modelling effort, are expected to reduce this risk by lowering the level of maximum sheath potentials “launched” beyond the antenna region along magnetic field flux tubes. In fact, one of such technologies, the ITER-like Antenna (ILA) [**Durodié’12**] has been re-commissioned in JET and is expected to operate in the upcoming 2015-2016 campaign. Past studies have shown reduced core Ni impurity concentration with ILA versus type-A2 antenna [**Czarnecka‘12**]. The development of the combination of experimental and modeling tools exhibited in the present paper should permit, in the next campaign, to extend the comparison to impurity sources and localized erosion. In this upcoming campaign, an effort should also be made to use the additional sightline D13, include BeD band to characterize molecular effects and refine the modelling, similar to the approach used in the study of limiter plasmas in [**Brezinkek’14**]. Plans are already under way to make use of filtered cameras with more toroidal coverage to better characterize the spatial distribution of the light emission.

Refinements in the simulation should also improve the simulation of the Be I emission of the existing measurements and sightlines. As the fraction of the Be I light from the main erosion source is quite small, the otherwise minor erosion contributions: 1) local erosion in the shadowed zones and 2) the part induced by the CX flux, cannot be neglected. Thus, to reproduce the experimental Be I light the modelling should be considerably refined.

As final note, longer term future work should also aim to progress beyond the simple RF-sheath model that was used in the present ERO modelling. In particular, it is noted that more advance models of long range RF-sheath interactions are now immerging [**Jacquot’14**] and these are able to also explain the situation seen in the right-side schematic of Fig. 2, in which the RF-sheath interaction occurs in spite of the fact that the connection between the high near-field region of the antenna and the “affected” region of the observed limiter is intercepted by two other poloidal limiters. Continuing development of such models is clearly synergistic with the development of improved experimental approaches in the RF-induced plasma-wall interactions in geometries relevant to next generation fusion energy devices.

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References

[**Klepper’13**] C.C. Klepper et al., J. Nucl. Mater. 438 (2013) S594–S598

[Kirschner NF2000] A. Kirschner et al., Nucl. Fus. 40 (5) (2000) 989

[Brezinsek’14] S. Brezinsek et al., Nucl. Fusion 54 (2014) 103001 (http://dx.doi.org/10.1088/0029-5515/54/10/103001)

[**Borodin’11**] D. Borodin et al., Phys. Scr. T145 (2011) 014008

[**Borodin’14**] D. Borodin et al., Phys. Scr. T159 (2014) 014057

[**Colas'07**] L. Colas, J.P. Gunn, I. Nanobashvili, V. Petržílka, M. Goniche, A. Ekedahl, S. Heuraux, E. Joffrin, F. Saint-Laurent, C. Balorin, C. Lowry, V. Basiuk, J. Nucl. Mater., 363–365 (2007) 555-559

[**Bobkov'10**] Nucl. Fusion 50 035004 (2010); http://iopscience.iop.org/0029-5515/50/3/035004

[**Wukitch'07**] Wukitch S et al 2007 J. Nucl. Mater. 363–365 491–7

[**Kaye'94**] A. Kaye, T. Brown, V. Bhatnagar, P. Crawley, et al., Fus. Engin. Design 24, 1 (1994)

[**Milanesio'09**] D. Milanesio, O. Meneghini, V. Lancellotti, R. Maggiora, and G. Vecchi,

Nucl. Fusion 49, 115019 (2009).

[**Groth'13**] M. Groth et al., Nucl. Fusion 53 (2013) 093016 ; M. Groth et al., J. Nucl. Mater. 438 (2013) S175–S179

[**Jacquet'14**] Physics of Plasmas (1994-present) 21, 061510 (2014); doi: 10.1063/1.4884354

[**Giroud'08**] Review of Scientific Instruments 79, 10F525 (2008); doi: 10.1063/1.2974806

[**Simonini'94**] Simonini R. et al 1994 Contrib. Plasma Phys. 34 368

[**Reiter'92**] D. Reiter et al., J. Nucl. Mater. 196–198 (1992) 80

[**Wiesen'06**] S. Wiesen, JET ITC-Report (2006) www.eirene.de/e2deirreport 30jun06.pdf

[**Eckstein'07**] W.Eckstein (2007) Topics Appl. Phys., 110, pp. 33-187; doi:10.1007/978-3-540-44502-9-3

[**Firdaouss'13**] M. Firdaouss et al./Journal of Nuclear Materials 438 (2013) S536–S539

[**Airila'14**] In press as: M.I. Airila et al., J. Nucl. Mater. (2014) http://www.sciencedirect.com/science/article/pii/S002231151400600X

[**Ding'15**] R. Ding et al., Nucl. Fusion 55 023013 (2015) doi:10.1088/0029-5515/55/2/023013

[**Borodin'13**] D. Borodin et al., J. Nucl. Mater. 438 (2013) S267–S271

[**Durodié'12**] F. Durodié, at al."Physics and engineering results obtained with the ion cyclotron range of frequencies ITER-like antenna on JET", Plasma Phys. Control. Fusion 54 (2012) 074012

[**Czarnecka**'12] A. Czarnecka, at al "Impurity production by the ICRF antennas in JET" Plasma Phys. Control. Fusion 54 (2012) 074013

[**Jacquot'14**] Jonathan Jacquot et al., Phys. Plasmas 21 (2014) 061509