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Be Migration Studies at JET and their Interpretation by an Integrated Model for Plasma Impurity Transport and Wall Composition Dynamics

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ABSTRACT.

The migration of beryllium was studied in JET firstly to provide insight into the underlying transport processes and secondly to establish a reference for comparison to the upcoming bulk Be wall experiments (ILW). The JET wall was prepared in a state far from equilibrium by means of Be evaporation followed by a series of identical plasma discharges in which the relaxation of the wall composition towards the steady state situation was studied by measurement of wall erosion sources using visual range spectroscopy. The Be erosion flux at the midplane main chamber wall initially increased by a factor of up to 20 whereas the corresponding C flux decreased initially only by 50% with respect to the value before Be evaporation. From this observation one can infer that even extended Be evaporation does not lead to a uniform and closed Be layer on top of the carbon wall elements. The subsequent erosion of the Be layer, uncovering of substrate C and mixing with redeposited C occurs on a timescale of 120s in experiments where standard limiter phase start-up scenarios were used. After this time the Be flux in the limiter phase has already decreased to about a factor 5 above the reference value, whereas the C erosion flux has increased moderately to about 60% of the reference value. The corresponding decay of the Be flux in L-mode plasmas with early X-point formation and correspondingly short limiter phase is slower with a characteristic time constant of 400s.

To quantitatively interpret the spectroscopic data, which represent only material gross erosion rates and their change over time due to the evolution of respective material fractions at the wall surface, a new integrated model has been developed, which allows describing the evolution of plasma exposed wall surfaces by impurity transport processes in fusion devices with different first wall materials. The experimentally observed time scale of the Be source evolution can be well reproduced by the model. Parameter studies reveal that the timescale is closely linked to the fraction of local redeposition vs. long range migration of eroded material. The simulations show also that computational grids for transport modelling, which do not extend flush to the first wall, will introduce significant errors in the predicted migration pattern.

1. INTRODUCTION

The main objective of the ITER-like Wall (ILW) project at JET is the investigation of plasma performance and plasma wall interactions for the first wall material configuration, which will be used during the DT phase in ITER, i.e. beryllium main-chamber wall tiles and limiters and a full tungsten divertor. In such a multi-material environment, erosion and deposition processes lead to the formation of material layers which usually have very different properties with respect to hydrogen retention and physical properties (e.g. melting). In particular, it can be expected that co-deposited layers consisting of fuel species and Be and W are formed. Both the rate at which such layers are formed and their spatial distribution depend critically on both the local plasma parameters and on local and global impurity transport processes: The local plasma parameters thereby define the rate at which deposits or bulk material are (re-) eroded, and the local screening and global impurity transport

define the incident fluxes of impurities at a given location as a consequence of the corresponding redistribution of eroded material.

In previous studies at JET campaign integrated Be and C sources at the main chamber wall were compared to post campaign measurements of the amount of redeposited Be and C at retrieved divertor tiles [1]. It turned out that the amount of deposition in the inner divertor approximately matched the integrated wall source from which it was inferred that eroded wall materials are generally and predominantly deposited in the inner divertor [2]. This can be explained as a consequence of erosion dominating at main chamber wall and outer divertor strike point area and migration of eroded material to the inner divertor following the experimentally observed plasma boundary flow pattern from the low-field side to the highfield side of the boundary plasma [3]. A further factor in this migration pattern is the low reerosion of deposited material in the inner divertor, which is generally characterised by comparatively low plasma temperatures.

To improve the understanding of the underlying impurity transport processes, the migration of beryllium eroded from the main chamber wall was studied in recent JET experimental campaigns for individual well characterised discharge scenarios [4]. The experiments also served to establish a set of benchmarking data for comparison to the upcoming ILW experiments with bulk Be wall. In contrast to the ILW, the JET wall tiles were as yet made of carbon fibre composite (CFC). However, the main wall can be transiently covered by a thin Be layer by means of 4 evaporator systems, which are normally used for wall conditioning. For the Be migration experiments the evaporators were operated at elevated temperature and over extended time periods to maximise Be coverage. In subsequent series of identical discharges the time evolution of the transient Be sources was studied by spectroscopy of visible range impurity line emission.

To interpret the spectroscopic data, which represent only the material gross erosion rates and their change over time due to the evolution of respective material fractions at the wall surface, a new integrated simulation code package has been used, which allows to describe the evolution of plasma exposed wall surfaces by impurity transport processes via plasma in fusion devices with different first wall materials [5]. The experimental results at the same time provided the opportunity to benchmark the predictive capabilities of the code package.

2. EXPERIMENTS

2.1. DIAGNOSTIC SETUP

The migration studies require as primary diagnostics systems to quantify on the one hand the impurity erosion flux both at main chamber wall and in the divertor and on the other hand systems to quantify the resulting impurity concentration in the plasma. Complimentary diagnostics include deposition monitors and extended diagnostics of plasma boundary parameters for transport modelling.

Local Be and C sources were measured spectroscopically in the visible spectral range. The evolution of BeII (528nm) , CII (658nm) and D α line intensities from discharge to discharge allows to derive estimates for the relative change of beryllium and carbon surface concentration

and erosion flux respectively. Figure 1a shows a subset of the available lines of sight of the JET KS3A spectrometer viewing at the inner (I) and outer (O) divertor and horizontally at the mid-plane main chamber wall (H). In one experiment viewing chord H at the plasma mid-plane was additionally coupled to a high resolution overview spectrometer in cross-dispersion arrangement [6] for separate determination of inboard and outboard wall sources by Zeeman analysis [7]. Charge eXchange spectrometry [8] (CX) was used to monitor the evolution of the carbon and beryllium plasma concentration. Furthermore, the material deposition rates at several remote locations in the divertor (Figure 1b) were detected by Quartz MicroBalances (QMB) [9]. One QMB installed close to the outer divertor baffle with direct line of sight to the adjacent evaporator head (QMB6 in Figure 1b) was used to record the amount of Be deposition during the evaporation procedure.

For the plasma background modelling required for impurity transport simulations, electron temperature and ion flux at the inner and outer divertor plate were measured by Langmuir probe arrays. Radial profiles of mid-plane electron density and temperature were obtained from standard Li-beam and ECE diagnostics and complimented by high resolution Thomson scattering data.

2.2. DISCHARGE SCENARIOS

For the migration studies the JET wall was prepared in a state far from steady state equilibrium by means of Be evaporation. To achieve suitable Be coverage, standard operating procedures of the evaporator system were extended to insertion of all four available Be evaporator heads $\approx 0.3\text{m}$ below the outer midplane of the JET main chamber (Figure 1b) and operating them for a duration of up to 8 hours with maximum heating power at temperatures between 920°C and 960°C in vacuum. By integration of the local Be deposition rate, monitored by the QMB6 quartz microbalance, the final thickness of the Be layers at this location was estimated to 12nm . Combining this local value with recorded Be evaporator temperatures and literature values of Be vapour pressure, the total amount of evaporated Be was estimated to $\approx 2\text{g}$.

Right after the Be evaporation procedure a series of subsequent identical plasma discharges was carried out to follow the relaxation of the wall composition towards the steady state situation. This was done on the one hand by spectroscopic measurement of both Be and C wall sources and of Be and C plasma concentration and on the other hand by measurement of material deposition rates by QMBs installed in the divertor. The steady state wall conditions with respect to impurity sources, material deposition and residual gas composition were documented by a reference discharge with identical configuration at the end of the session preceding the Be evaporation procedure. Four such experiments were performed in both L-mode and H-mode discharges and at different plasma geometries, varying particularly the plasma-wall clearance and heating power.

The first L-mode experiment consisted of 15 L-mode discharges ($P_{\text{aux}}=1.5\text{MW}$) in a low triangularity configuration ($\delta=0.2$) with both strike points located symmetrically at the horizontal target plates to optimise the position of the divertor impurity sources with respect to the available spectroscopic viewing chords and QMB diagnostics. The main plasma geometry was tailored to

provide comparatively high wall clearance of 12cm at the plasma mid plane. To avoid excessive local erosion in the main chamber during start-up and ramp-down phases, the discharge schedule was programmed to ensure minimised plasmalimiter interaction by early X-point formation already in the ramp-up phase. It should be noted that in this first experiment Be evaporation was accidentally performed at standard operating parameters (3 heads at 850°C, 1 head at 700°C for 2 hours). Therefore the amount of evaporated Be was only 0.2g in this case. In a second L-mode experiment consisting of 13 L-mode discharges with the same heating power and similar plasma geometry the inner and outer mid-plane wall clearance was reduced to 7cm. A further experiment with similar geometry than the latter was carried out with H-mode plasma discharges at a heating power of ($P_{aux}=15\text{MW}$). The final experiment was performed again with H-mode discharges in the standard reference configuration for the ILW campaign [10].

2.2. EXPERIMENTAL RESULTS

As expected the Be erosion flux at the main chamber wall is strongly increased by a factor of 10 over the reference value right after the Be evaporation procedures whereas the corresponding C erosion flux decreases initially only by $\approx 50\%$ with respect to the reference value. This local measurement is confirmed by the similar evolution of the carbon plasma concentration measured by charge exchange spectroscopy [4]. From these observations one can already infer that even extended Be evaporation does not lead to a uniform and closed Be layer on top of the carbon wall and limiter tiles. In the first experiment with only about 10% Be evaporated compared to the subsequent experiments, the flux increased still by a factor of 7, which indicates that surface coverage was only about 30% reduced compared to the experiments with maximum Be evaporation. In the outer divertor the post-evaporation Be flux in the L-mode experiments increased by even higher factors of up to 20 over pre-evaporation reference level. In the H-mode experiment the increase was, however, less pronounced by ≈ 6 times over the reference value. It should be noted that the surfaces viewed by the spectrometer in the outer divertor are shadowed from direct line of sight to the adjacent evaporator head. Be deposition could only occur from toroidally further away evaporator heads. This already indicates that the observed increase of the Be erosion flux might be due to reerosion of Be eroded at the main chamber and transported to the outer target plate.

The subsequent erosion of the Be layer in the main chamber, uncovering of substrate carbon and mixing with redeposited C occurs on a characteristic timescale of $\approx 400\text{s}$. The relevance of establishing X-point operation already early in the current ramp-up phase with correspondingly reduced limiter phase is revealed by the last H-mode experiment in which standard limiter phase start-up scenario was used. The corresponding time scale was significantly shorter ($\approx 120\text{s}$). After this time the Be flux in the limiter phase had already decreased to about a factor 5 above the reference value, whereas the C erosion flux still had increased only moderately to about 60% of the reference value [10]. This confirms that limiter operation leads to a significantly higher Be erosion rate.

In contrast to the time evolution of both main chamber and outer divertor Be sources, which

follow a common pattern in all experiments so far, the situation at the inner divertor is fundamentally different for L-mode and H-mode experiments respectively: whereas in the Hmode experiment one finds a similar behaviour as in the outer divertor, in the L-mode experiments the Be erosion flux is initially only slightly higher by a factor ≈ 3 over the reference level with a much less pronounced decrease on the time scale of the main chamber and outer divertor evolution. This can be understood by the prevalently deposition dominated conditions in the inner divertor with a correspondingly constant fraction of embedded Be, which is not expected to change significantly by the transient change of the Be/C ratio in the incoming flux. QMB data from the inner divertor position (Figure 3) in the first L-mode experiment show indeed only a slight decrease of hydrocarbon remote deposition in the first three discharges after Be evaporation. In the H-mode case, however, the power flux to the inner divertor is sufficient to quickly erode deposited Be-rich layers reflected by the decrease of the Be erosion flux.

3. MODELLING

To interpret the spectroscopic data, which represent only the material gross erosion rates and their change over time due to the evolution of respective material fractions at the wall surface, a new integrated model has been developed, which allows to describe the evolution of plasma exposed wall surfaces by impurity transport processes via plasma [1] in fusion devices with different first wall materials. The implementation of the model consists of three coupled codes:

- Transport and re-deposition of eroded wall material is modelled by the 2D code DIVIMP, which simulates impurity transport projected into the poloidal plane assuming toroidal symmetry.
- Impurity erosion flux for given projectile flux from the plasma is modelled by TRIM.
- The evolution of wall surfaces is modelled by a new code [11] based on ERODEPDIF [5], which simulates the evolution of material surface composition along a poloidal wall contour on a set of discretized wall elements.

The coupling of the codes is realised on the assumption that the time scale of impurity transport processes is negligible against the time scale of wall composition dynamics. Therefore, the spatially dependent re-distribution of erosion sources can be described within the frame of the model by a so called re-deposition matrix, which is only calculated once by DIVIMP for a given scenario and given material species for the discretized wall contour. To provide a more accurate description of material redistribution along the main chamber wall, the re-deposition matrix was calculated using computational grids in DIVIMP, which were extended from standard grids as used in SOLPS and tailored to match the wall contour and fill out the entire volume defined by the first wall. The assumption of toroidal symmetry in the simulations implies that both the 3D structure of the first wall and toroidal asymmetries of Be evaporation are necessarily neglected.

The code describing the wall composition dynamics including chemical phase formations was benchmarked by comparison to laboratory experiments with X-Ray photoelectron spectroscopy (XPS) analysis of the chemical structure in mixed material phases. The relevant chemical phases

that were observed in the XPS measurements are well reproduced by the code in the ITER relevant surface temperature range [11]. The sputtering model used in the code was validated by TRIDYN simulations. The complete code package was then used to model the measured time evolution of the beryllium and carbon wall sources for the first Lmode experiment. The local distribution of initial Be coverage of the vessel wall was computed assuming a toroidally symmetric Be evaporation source at the exposure position of the Be evaporators [11]. With Be sublimation rates according to the measured evaporator temperatures the local Be deposition at the QMB position was well reproduced. First simulations using computational grids with both standard topology and grids extended and tailored to be in contact with most of the JET first wall showed significant differences of Be redeposition patterns depending on grid vessel coverage [11]. This shows that previously neglected parallel transport processes in the gaps between wall and standard grids must be taken into account for modelling of impurity migration. The experimentally observed time scale of the Be source evolution could also be reproduced well by the model. A parameter scan with varying $\square B$ impurity diffusion coefficient showed a strong correlation with the wall evolution time scale. This also demonstrates the significance of the closely linked local redeposition fraction versus global migration. The model initially failed, however, to correctly describe the behaviour at the outer divertor where in the simulation the initial Be erosion flux decreased to a level far below the experimentally observed value [11]. In the first simulations, the bulk substrate in the model was assumed to consist of pure carbon. Taking into account the long history of JET operation with ongoing Be evaporations, one would expect, however, that the wall tiles meanwhile contain a constant fraction of embedded Be to depths, which in the context of the simulation are counted as bulk material. To test this hypothesis, the Be fraction in the bulk material was varied as free parameter in the wall evolution code. Figure 4 shows the resulting simulated time evolution of the Be sources for the first L-mode experiment at the same locations as in Figure 2. By assuming a 5% fraction of Be in the carbon bulk material, both time scale and magnitude of the Be source flux can be matched to the experimental data. The remaining factor 2 discrepancy in the inner divertor could be either due to the more complicated structure of re-deposited layers there or due to a too high divertor temperature in the model. The question remains if the code will be able to describe both Lmode experiments with varying plasma-wall gap using the same base assumptions. Respective studies are under way.

CONCLUSIONS

Discharge resolved Be migration experiments provide a useful tool to improve the understanding of wall material erosion, transport and re-deposition processes in fusion devices. For their quantitative interpretation, a newly developed simulation code package has been used, which computes the corresponding evolution of plasma exposed wall surfaces for wall configurations consisting of different first wall materials. The underlying model integrates parameterised impurity redistribution probabilities pre-computed in Monte-Carlo DIVIMP simulations with a simplified plasma-wall

interaction model to a time dependent self-consistent global model of wall composition dynamics. Apart from sputtering by fuel ions it includes self-sputtering and sputtering by all other included impurity species and can be extended by additional flux contributions such as chemical phase formations or sublimation. The computational cost of this approach is sufficiently low to employ the code on a global machine scale in contrast to other code packages, which attempt to describe local wall evolution directly by binary collision codes coupled to impurity plasma transport codes. First benchmarks of the predictive capabilities of the integrated code package with the JET migration experiments successfully demonstrated the validity of the used modelling approach. Comparing the decay time of a depleting Be impurity source of the experiment and simulation reveals that the long range wall material migration processes are strongly coupled to local redeposition, which itself is influenced by local cross field diffusion. This also implies that for material migration modelling computational grids must be extended over their present topological limitations to cover the entire plasma cross-section up to the plasma facing wall.

After careful benchmarking and validation of the new code using the previous and future dedicated JET migration experiments, the code will provide an essential tool both for quantitative interpretation of present experimental results and for improving the quality of predictions of wall material migration for ITER and other planned fusion experiments.

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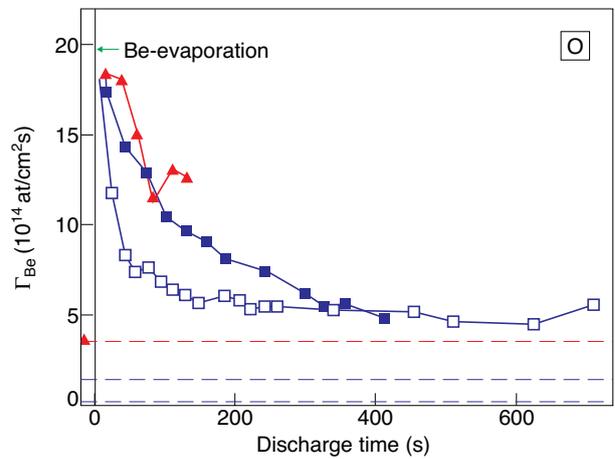
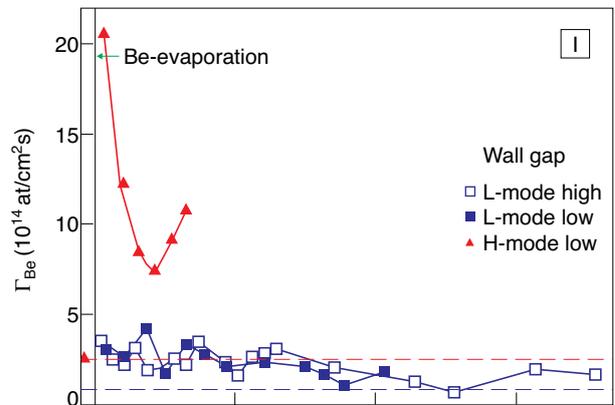
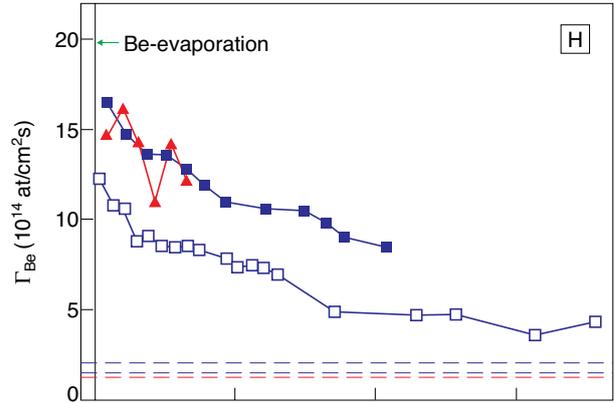
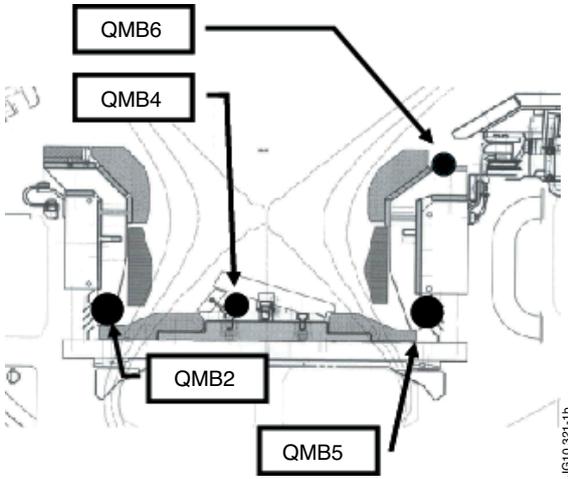
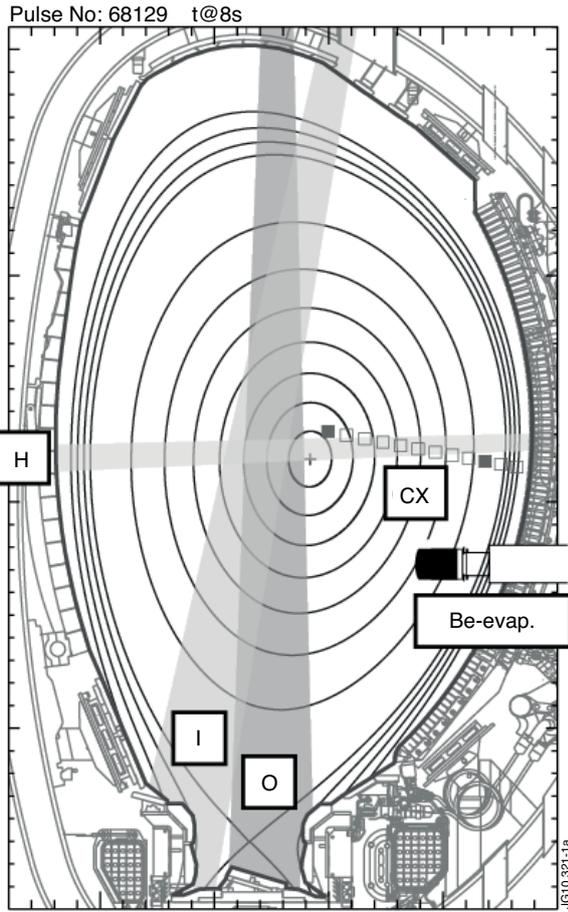


Figure 1a): Poloidal cross-section of JET with observation positions of visible range spectrometers at main chamber wall (H) and inner (I) and outer (O) divertor target plates. Also shown is the radial array of charge exchange observation points given by the intersection of respective neutral beam injector and viewing chords. 1b): Poloidal cross-section of the JET divertor with locations of installed quartz micro-balances.

Figure 2: Time evolution of beryllium erosion sources derived from BeII line emission for main chamber wall near vessel mid-plane (H), inner horizontal divertor plate (I) and outer horizontal divertor plate (O).

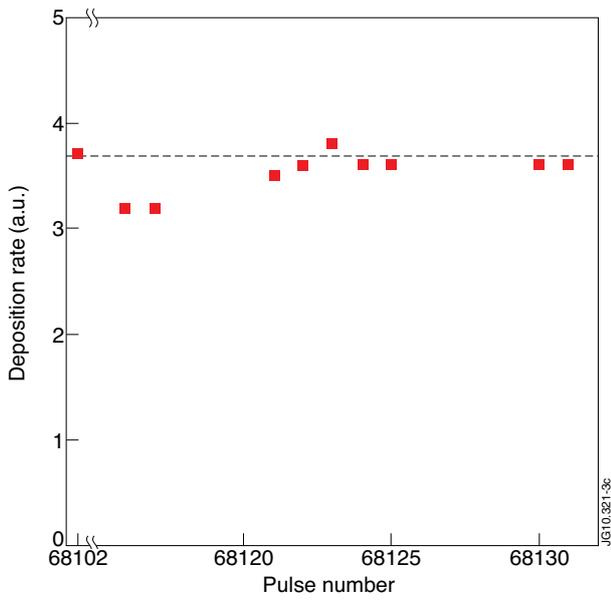


Figure 3: Evolution of deposition rate measured by quartz microbalance QMB2 at the inner divertor louver for the discharges in the first L-mode experiment with large wall clearance.

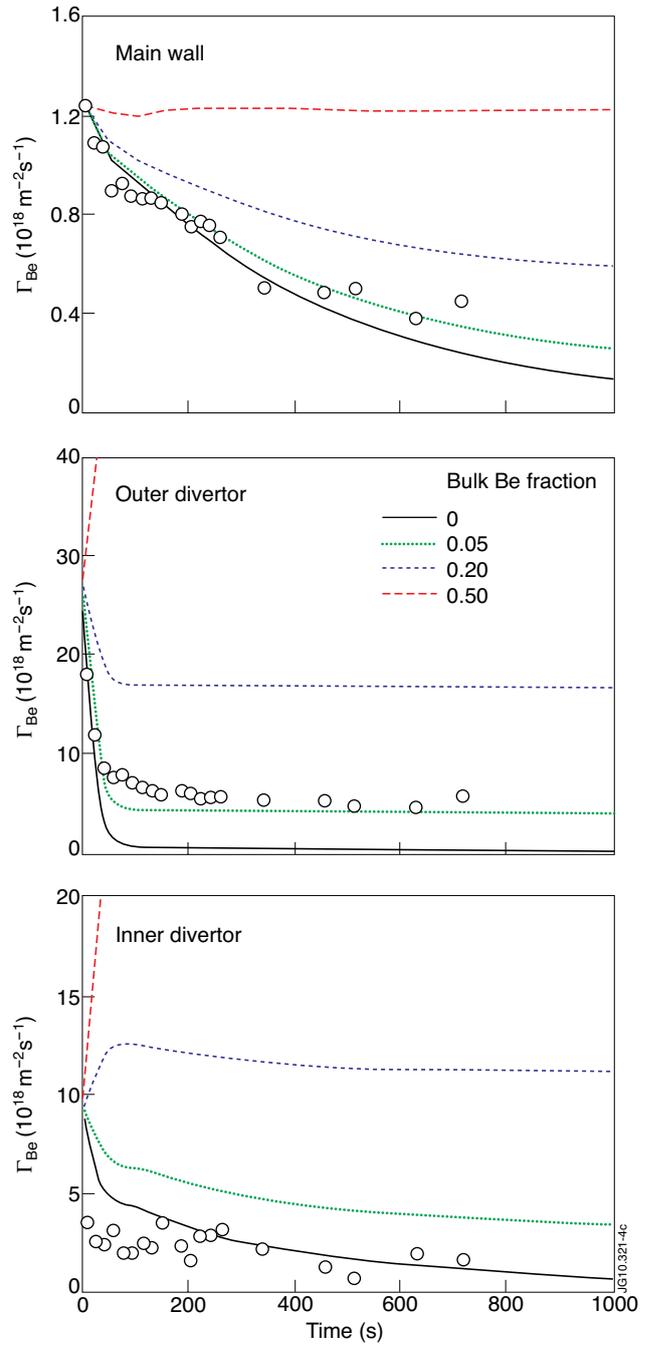


Figure 4: Computed time evolution of beryllium erosion sources for main chamber wall near vessel mid-plane, inner horizontal divertor plate and outer horizontal divertor plate. The circles denote the experimental Be erosion flux of the first L-mode experiment in the high wall clearance configuration.