Tungsten Contamination by Neutral Beam Shine-through in the JET ILW

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The JET ILW experiment will have W divertor and Be main chamber walls. However, the W coated neutral beam shine-through protection tiles are in the main chamber. Therefore, shine-through of the 120 kV injected neutral beams will cause some W sputtering, which can contaminate the JET plasma. EDGE2D based calculations are presented which indicate that 0.1 MW of W radiation might occur in the absence of impurity pinches.

The 16 JET NB sources can each produce 2.1 MW of deuterium NBI power. The fractional power of the JET neutral beams is 0.515, 0.382, and 0.103 for the full, ½, and 1/3 energy components. The total 120 kV power passing through the plasma and hitting the wall is up to 1.7 MW deceasing with plasma density. This calculation ignores charge exchange with Be which will further reduce the shine-through. Since the operation with the maximum beam voltage will cause the most shine-through and the most W sputtering, we perform these calculations at 125 kV, and do not further consider the 1/3 energy component.

The fraction of the total power which reaches the vessel wall opposite the injector deceases with plasma density [1]. Since each PINI follows a different path through the plasma, then each PINI will experience a different shine-through at any single plasma condition. For the plasma equilibrium considered in this calculation (78647) the values of the full energy shine-through as a function of plasma line average density are plotted in figure 1. Apparently, most of the shine-through power is caused by the two most normal PINIs which have the shortest paths though the plasma. For the plasma used in this calculation, the full energy power striking the vessel protection plates is about 1.7 MW and the half energy power is 0.5 MW.

The W sputtering caused by the energetic neutrals is described in [2]. The 120 kV and 60 kV neutral deuterium fluxes were used to infer the tungsten sputtering for the angle of incidence for each NBI source. The 1/3 energy component produced a comparatively negligible sputtering. These energies are so high that the sputtering yield is decreasing with increasing deuteron energy. The decrease occurs because much of the damage done by the

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*See the Appendix of F. Romanelli et al., Proceedings of the 23rd IAEA FEC 2010, Daejeon, Korea incident deuteron occurs so deep into the material that the W cannot escape back out of the surface.

The sputtering yield at normal incidence is about 0.4% at 120 kV and 0.7% at 60 kV. The angle between the normal to the W surfaces and the incident deuterons is 15 – 68^o and the sputtering yield is enhanced by the grazing incidence of the incident particles. Essentially, this acts to keep more of the damage to the material closer to the surface and allows more W to escape the surface. This effect was shown for 2 kV H in figure 125 of [3]. The W sputtering yield varies between 0.4 to 2.1 %. The sum for both beam lines, adding all PINIs and both the full and ½ energy components is plotted in figure 2. The total sputtering rate expected for the EDGE2D calculated case of 78647 is about 1.5 10^{18}.

The energy distribution of the sputtered W is the Thomson energy distribution with largest energy of 6 kV for the full energy and 3 kV for the half energy induced sputtering. These energies are larger than the typical energy used to model W penetration into the JET SOL, so EDGE2D calculations were performed varying the initial W energy. 6 keV W atoms fuel the core about 5 times more than low energy (<10 eV) tungsten atoms when injected at the NBI shine-through location. Greater neutral W penetration into the SOL, reduced the distance from W ionization to the separatrix and caused the higher fuelling efficiency. Integrating over the Thomson distribution, the physically sputtered W contaminates twice as effectively as lower energy W. Here the effect of the W energy on its penetration (figure 2) is approximated by assuming that the sputtering rate is increased by a factor–of-two (dashed line in figure 2). We do that since EDGE2D is not configured to calculate the screening from an energy distribution unless it were formed by sputtering from the SOL plasma.

The EDGE2D calculations tungsten injection at an injection rate of 2 10^{18} /sec from the inner mid-plane caused a core contamination of $n_W = 2\ 10^{15}\ /m^3$ with a W radiation of 0.14 MW from the pedestal region or 0.3 MW from the entire plasma if the radiation profile were flat (figure 3). If the tungsten were to experience a pinch effect or if the electron density were peaked, then higher W radiation would occur. These values seem small in terms of the global energy balance, since it represents only a few percent of the injected power. We conclude that W sputtering induced by NBI shine-through is unlikely to cause radiative collapse even with the largest shine-through (lowest density) so long as there is no W pinch.

One diagnostic possibility touse this main chamber source as a diagnostic tool would be to oscillate the NBI power in PINIs 3 and 4 at an appropriate frequency to increase the detection sensitivity by phase sensitive analysis of W spectroscopy or X-ray emission in the pedestal. An oscillation at that frequency would indicate the direct component of W released by shine-through sputtering and that phase lag would indicate the penetration time into the pedestal. Such measurement might help calibrate the total W concentrations (if the shine-through sputtering rate were considered well-known) and allow study of tungsten transport. In fact, AUG has already successfully implemented such a phase sensitive detection using ICRF power (1.3-3.3 MW) modulated at 10 Hz [4]. For AUG, the sputtered W is proportional to the applied ICRF power, so by modulating the RF power a modulated W source was applied to the large major radius edge of AUG. A phase lag (10-30 msec) and modulation amplitude

(1/2-3) were measured at r/a = 0.8 using the W quasi-continuum spectral features at 5 nm (ionization stages 28 to 35 or T_e = 1 keV implying r/a = 0.8) and 13-25 nm (ionization stages < 27).

JET [5] has previously tested its ability to measure in these quasi-continuum wavelengths using W impurity injection. The quasi-continuum spectral features were prominent although the spectrometer system has been modified since those experiments [5]. If phase sensitive detection can be employed at JET as was used on AUG, then tungsten diffusivity measurements can be made.

To support this idea, a sensitivity scan was undertaken with a series of EDGE2D/EIRENE calculations of both JET and AUG. For each machine, a 10^{19} background W injection and a 10^{18} 10Hz modulated source (at the inner mid-plane for JET, and at the outer mid-plane for AUG) was assumed. The tungsten diffusivity was scanned with different values used for each calculation. Three SOL values (0.5, 1, and 2 m^2/s), three barrier values (0.1, 0.25, and 0.5 m^2/s), as well as three pedestal values (0.5, 1, and 2 m^2/s) were used with the variations being applied to a base case of 0.5, 0.25, and 1 m^2/s for the SOL, ETB, and pedestal W diffusivities respectively. Thus a total of 18 EDGE2D cases were calculated in the sensitivity scan.

We found that the ETB transport coefficients made little difference to the W density determined at r/a = 0.8, as was separately found in the AUG sensitivity analysis [5]. The SOL diffusivity determined the amount of tungsten to reach the LCFS, and thus is a boundary condition for the core W density evolution. The SOL W diffusivity primarily determined the magnitude of the W density at r/a = 0.8 (figure 4). The pedestal W diffusivity primarily determined the phase lag, as might be expected since diffusion in the pedestal is the longest time scale. AUG differed from JET in that the magnitude of the signals was larger and the phase lag was smaller, as might be expected with both shorter SOL and pedestal widths.

Conclusions:

EDGE2D-EIRENE calculations have been presented which indicate that neutral beam shine-through onto tungsten protection tiles will cause a sputtered tungsten source in the JET main chamber vessel where the tungsten fuelling efficiency is higher. The magnitude of the sputtering will not cause significant tungsten radiation without a strong W transport pinch. Diagnostic use of this source is proposed in a manner similar to the modulated W sources (by ICRF) in AUG. The possibility looks promising, although the sensitivity of the JET W spectroscopic systems still needs further evaluation.

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References:

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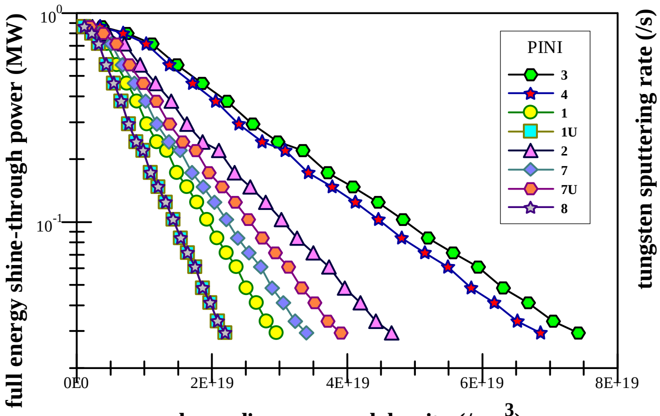

Figure 1. Shine-through power of the full energy component for each PINI as a function of the plasma line averaged density.

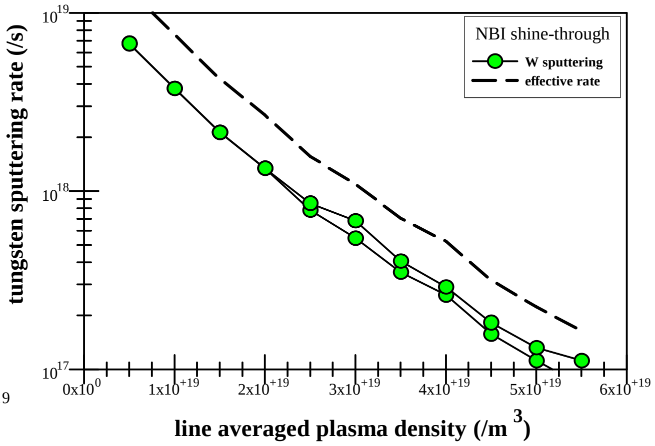

Figure 2. Total W sputtering rate from all PINIs plotted against the plasma density. The Thomson energy distribution yields an “effective” rate for core contamination

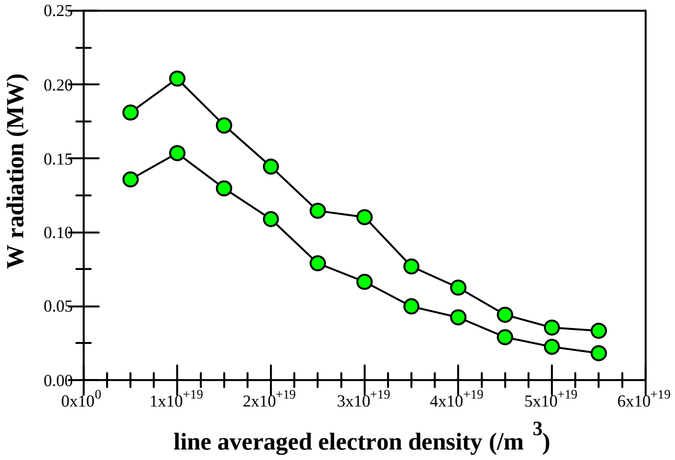

Figure 3. The predicted W pedestal (r/a>0.8) radiation as a function of plasma density. There are two lines which indicate the uncertainty in relating edge density (EDGE2D calculations) to core density (location of most of the W radiation).

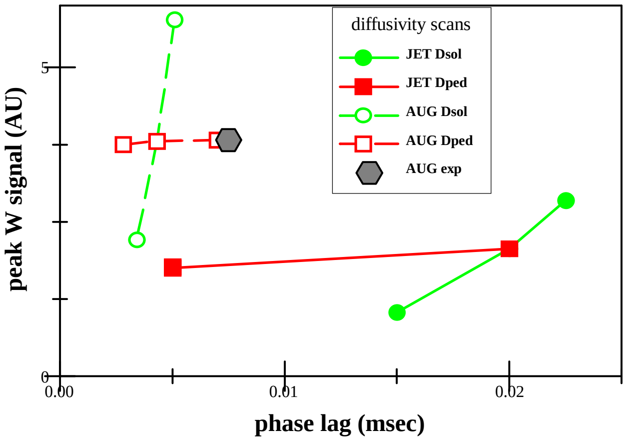

Figure 4. The magnitude of the EDGE2D calculated tungsten density (at r/a = 0.8) in response to an oscillating source. The AUG (hollow symbols and dashed lines) source was at the outer mid-plane (location of ICRF antenna). The JET (solid symbols and lines) source was at the inner mid-plane (location of W shine-through protection tiles. Each calculation had low/medium/high (0.5, 1, 2 m^2/s) values of SOL W diffusivity (green) and pedestal diffusivity (red). The AUG data is shown for illustration and is not a fit to the EDGE2D calculations.