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Scaling 2XIIB Impurity Radiation to BPNS

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1. Introduction

We compute the oxygen impurity radiation to be expected from the BPNS, Beam-Plasma Neutron Source,¹ and find that it should account for only 2% of the neutral-beam injected power. The source of the oxygen is assumed to be the neutral beams, which include about 0.1% oxygen impurity in 2-5 s long pulse deuterium or hydrogen beams.²

We compare these predictions with measurements of $\sim 10 \text{ W/cm}^3$ oxygen radiation from 2XIIB,³ operating in the range of $T_e = 40\text{-}120 \text{ eV}$. Oxygen was found to be injected by the neutral beams and was the principal impurity in 2XIIB. Somewhat surprisingly, the predicted radiated power density increases only a factor of 2 in the BPNS, reaching 15 W/cm^3 , despite the density increasing by 1-2 orders of magnitude. This prediction of relatively low radiated power in the BPNS is a result of primarily two effects:

(1) The ratio of the ionization rate to the charge-exchange recombination rate increases nearly proportionally as the plasma density since the beam currents are similar. This results in the BPNS being dominated by O^{+6} with some O^{+7} which radiate two orders of magnitude less power⁴ than the O^{+4} and O^{+5} that dominated 2XIIB.⁵

(2) The fraction of oxygen in the beams decreases from 2% in the 2XIIB 10 ms duration beams³ to 0.4%⁶ or 1-2%⁷ in 0.5 s beams to 0.1-0.2% (which is near the OMA, Optical Multichannel Analyzer, diagnostic noise level) in 2-5 s long-pulse beams,² and presumably to even lower levels in steady-state beams.

The BPNS¹ is a relatively low cost, plasma-based, 14 MeV D-T neutron source for accelerated end-of-life testing of fusion reactor materials, Fig. 1. An intense flux (up to $5 \times 10^{18} \text{ n/m}^2\cdot\text{s}$

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corresponding to 10 MW/m²) of 14-MeV neutrons is produced in a fully-ionized high-density tritium target ($n_e = 3 \times 10^{21} \text{ m}^{-3}$) by injecting a current of 120 keV⁸ to 150-keV¹ deuterium atoms. The BPNS provides an 8-liter sample volume in which the 14.1 MeV neutron flux exceeds 2 MW/m², which is adequate for tests of welds and reactor submodules,^{9,10} in addition to the basic materials tests for which the BPNS was optimized.

As with other beam-target neutron sources,¹¹ the heat deposited by the beam must be removed. The tritium plasma target and the energetic D⁺ density produced by D⁰ injection are confined in a column of diameter $\leq 0.16 \text{ m}$ by a linear magnet set, which provides magnetic fields up to 12 T. Energy deposited by transverse injection of neutral beams at the midpoint of the column is removed by thermal conduction along the plasma column to the end regions. Longitudinal plasma pressure in the column is balanced by neutral gas pressure in the end tanks. The target plasma temperature is about 200 eV at the beam-injection position and falls to 5 eV or less in the end region. Ions reach the walls with energies below the sputtering threshold, and the wall temperature is maintained below 740 K by conventional cooling technology.

Although preliminary materials development is proceeding using fission neutron and low-level D-T neutron sources, final selection of materials, acquisition of engineering data, and qualification of fusion reactor materials require life tests in a facility that provides the appropriate D-T neutron spectrum.^{9,10,12,13,14} A plasma-based D-T fusion source would minimize questions of extrapolation, of displacement damage, energy of primary-knock-on atoms and the transmutation rates, because of differences in the neutron energy spectrum.¹³ The development of low activation materials,¹⁴ places stringent requirements on the absence of neutrons with energies exceeding 14.1 MeV.¹² A steady-state neutron source avoids questions of rate-dependent phenomena that arise with low-duty-cycle pulsed sources.¹³ Although the actual reactor environment can be realized only in a specific reactor, a fusion-based neutron source can give valuable design information on synergistic effects in this complex environment.

2. Impurity Radiation Rates

Our procedure in this report is to calculate the impurity radiation for 2XIIB³ using Ref. 4, show that the result is close to that measured by Drake, then calculate the ionization states and expected radiated power for the BPNS from Ref. 4.

The ionization states in 2XIIB were set by competition between electron impact ionization and charge-exchange recombination on the neutral beams. The time scales for these are given in Table 1, which is adapted from Ref. 5. From comparing these time scales, it is apparent that O V and O VI should have been the dominant ionization states of oxygen in 2XIIB, as they were observed to be.

Table 1. Impurity time scales in 2XIIB

Ionization state	O III	O IV	O V	O VI	O VII
$\tau_{\text{ionize}}(\mu\text{s})$	2.4	6.4	22	77	3.3×10^5
$\tau_{\text{cx}}(\mu\text{s})$	910	33	40	50	63

To estimate the radiation, we use an effective electron temperature that would produce the observed ionization states of 2XIIB without charge-exchange recombination. Fig. 2, from Hulse, et al.,¹⁵ plots the average charge state $\langle Z \rangle$ VS T_e for various ratios of neutral to electron density. Using the $n_n/n_e = 0$ line, 2XIIB data with O V dominating would correspond to $T_e = 20\text{-}25$ eV. In Fig. 3, from Jensen, et al.,⁴ we see that 20 eV corresponds to the peak radiation power of 0.8×10^{-25} W-cm³. The neutral density in 2XIIB corresponds to $n_n/n_e = 10^{-3}$ which is beyond the range computed by Hulse, et al. in Fig. 2.

Table 2 lists the electron impact ionization rates from Lotz,¹⁶ and the charge exchange recombination times obtained for 150 keV deuterium atoms incident on multiply charged oxygen, with the cross-sections from Meyer, et al.¹⁷ Parameters for the BPNS are taken from Ref. 1 and are compared with those of 2XIIB in Table 3. For $\tau_{\text{cx}} = 1/(n_D^0 \sigma_{\text{cx}} v_D^0)$, n_D^0 is reduced in the BPNS mainly by the increase in the deuterium beam velocity, v_D^0 . The charge exchange cross section for 150 keV deuterium atoms on multiply-

charged oxygen are approximately a factor of 5 smaller than with the 18 keV deuterium beams of 2XIIB.^{17,18} From comparing the bottom 2 rows of Table 2, we conclude that oxygen will ionize to at least O VII in the BPNS. The neutral density in the beam injected cell corresponds to $n_n/n_e=10^{-5}$ in Fig. 2, which is consistent with this conclusion.

Table 2. Impurity time scales in BPNS

Ionization state	O IV	O V	O VI	O VII	O VIII
Ionization potential	77	114	138	739	871
$\langle\sigma v\rangle$ 200 eV e^- impact	5.1×10^{-9}	1.8×10^{-9}	5.91×10^{-10}	3.15×10^{-12}	6.0×10^{-13}
$\tau_{\text{ionize}}(\mu\text{s})$	0.061	0.17	0.53	99	520
$\tau_{\text{CX}}(\mu\text{s})$	500	300	200	140	80

Table 3. Parameters of 2XIIB and BPNS

Parameter	Symbol	2XIIB ⁵	BPNS ¹
Density	$n_e \text{ (m}^{-3}\text{)}$	5×10^{19}	3.2×10^{21}
Electron Temp.	$T_e \text{ (eV)}$	100	200
Deuterium ion density	$n_D^+ \text{ (m}^{-3}\text{)}$	4.3×10^{19}	8×10^{20}
Deuterium ion average energy	$E_i \text{ (keV)}$	12	50
Oxygen ion density	$n_O \text{ (m}^{-3}\text{)}$	1.5×10^{18}	
Oxygen charge state	$\langle Z \rangle_O$	4.5	6
Magnetic Field	$B \text{ (Tesla)}$	0.5	4
Neutral beam energy	$E_D^0 \text{ (keV)}$	18	150
Neutral beam current	$I_D^0 \text{ (A)}$	500	400
Beam density averaged over plasma	$n_D^0 \text{ (m}^{-3}\text{)}$	4×10^{16}	1.3×10^{16}
Hot plasma full length	$l_h \text{ (m)}$	0.35	0.3
Plasma radius	$r_p \text{ (m)}$	0.07	0.08

We now need to estimate the impurity density to be able to obtain the impurity radiation. The impurity density will scale with the neutral beam impurity fraction and the impurity confinement relative to the energetic deuterium confinement. Drake measured about 2% oxygen impurity fraction in the 2XIIB 0.01 s neutral beams and determined that this was the primary source of the 3% oxygen impurity level in 2XIIB.³ TFTR 2 s neutral beams contain 0.1–0.2% of oxygen, near the noise level of the OMA diagnostic.² (This is determined from the low energy component of H or D resulting from the dissociation of accelerated water. Other impurities, that are not accompanied by hydrogen that radiates at the H_α line, are not measured.) The oxygen impurity fraction is decreased by a factor of 10–20 in going from 0.01 s to 2 s duration beams. We will use the 0.1% value, which should be conservative for steady-state beams.

Energetic impurity confinement, like deuteron confinement, is limited by electron drag. Energetic ions are magnetically trapped until they drag down to the ambipolar potential hole in energy space, then they are expelled out the ends.

$$\tau = \frac{\tau_D}{2} \ln \left(\frac{E_{D^0}}{Z\phi_p(R-1)} \right)$$

where the drag time scales as

$$\tau_D \propto \frac{AT_e^{1.5}}{Z^2 n_e \ln \Lambda}$$

Comparing the confinement times for O⁺⁶ and deuterium, only the A, Z and E_{O⁺⁶} = (16/18)E_D factors vary. In 2XIIB with Z=4, the drag time for O⁺⁴ is 1/2 that for a deuteron. The ratio of the confinement time of O⁺⁴ to a deuteron is then about 0.3. In the BPNS with Z=6, the ratio of the drag times decreases to 0.22, and the ratio of the confinement times ranges between 0.12 and 0.18 depending on the plasma potential. A plasma potential drop of 5T_e between the hot plasma and the mirror results in O⁺⁶ confinement 0.12 of that for a deuteron; whereas a near zero potential drop of 0.01T_e gives a confinement ratio of 0.18. We will use the value 0.18 as more appropriate to the BPNS which has a dense warm plasma to reduce potential differences along the plasma column. We then conclude that the higher charge state in the BPNS will reduce the impurity confinement relative to deuteron confinement by a factor of about 2.6 relative to 2XIIB. We will ignore this factor, and use unity to be conservative.

We now estimate the impurity radiation power density from 2XIIB (to compare with Drake's measurements) and from the BPNS. Fig. 3 (Fig. 1 from Jensen, et al. Ref. 4) shows the radiated power vs T_e. The 2XIIB parameters are listed in Table 3 (Data from Table 6 of Ref. 5).

$$\frac{P_{Rad}}{Vol} \left(\frac{Watts}{cm^3} \right) = \frac{n_i}{n_e} \cdot (n_e)^2 \cdot \frac{P}{n_e n_i} \quad (1)$$

For 3% oxygen plasma density, as found by Drake³, we have P/V = (0.03)(5 x 10¹³)²(10²⁵) = 7.5 W/cm³ which agrees with his result.

We now estimate the impurity radiation power density from the BPNS from Fig. 3. The effective temperature will be near the 100 eV level, if O⁺⁶ dominates due to charge-exchange recombination (See n_{ri}/n_e=10⁻⁵ in Fig. 2), and the 200 eV level which should apply in the plasma column where charge-exchange recombination will be

negligible (See $n_n/n_e=0$ in Fig. 2). To be conservative, we take the peak at 200 eV of about $1.5 \times 10^{-27} \text{ W-cm}^3$, recognizing that the real value could be a factor of 4 lower in the beam-injected cell. Then we have $P = (0.001)(3.2 \times 10^{15})^2(1.5 \times 10^{-27}) = 15 \text{ W/cm}^3$.

The radiated power from the 6 liter hot plasma volume is then in the range of 9 to 92 kW. The higher value ignores the factors of 2.6 and 4 that should lower the oxygen density and radiation. Samples at a 10 cm radius will have a radiative power loading of 50 to 500 kW/m², which is quite tolerable. The plasma column will also radiate at a comparable level (Here, since charge-exchange recombination will be negligible outside of the hot plasma, the 200 eV values from Fig. 3, as used above, should be appropriate.). The column volume will be equal to the 6 liter volume of the hot plasma, times the ratio of the lengths (10 m/0.3 m) divided by the mirror ratio of 3, yielding 67 liters. The total radiated power will then be 1.1 MW or 2% of the incident 60 MW power. If the oxygen impurity constitutes less than 0.1% of the neutral beam current as is likely, then the radiated powers given above will scale downwards proportionally.

This calculation neglects the power radiated at the ends of the column, where the volume increases rapidly and the temperature decreases towards zero. A high radiated power here is a desirable effect that helps to spread the heat load more evenly over the end cell and has little effect on the electron power balance (which is limited by Spitzer thermal conduction along the long column).

As an aside, it is interesting to compute the number of monolayers of water removed from the ion-source walls to produce the observed impurity fractions. 2XIIB sources extracted up to 80A for 0.01 s with 2% oxygen. With an ion source wall area of about 1600 cm², this corresponds to 0.1-0.2 monolayers of water. TFTR sources extract 50 A for 2 s with 0.1-0.2% oxygen, and an ion source wall area of 6800 cm², corresponding to 0.2-0.4 monolayers of water. The similarity in these numbers may tell us something about source conditioning requirements, or may be pure coincidence. In any case, a steady-state source should remove adsorbed gas layers from the walls rather quickly; within minutes to hours, the impurity content of the beams should be $\ll 0.1\%$.

Acknowledgments

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Fig. 1. Schematic of beam-plasma neutron source. The central section of the vacuum chamber and the neutron shielding of superconducting magnets are not shown.

Fig. 2 Oxygen neutral beam modified 'coronal' equilibria. Hydrogen neutrals at 20 keV amu⁻¹ are considered, using the OSCT cross sections. The curves are parameterised by the neutral fraction n_n/n_e . Shown are (a) the average charge state $\langle Z \rangle$, and (b) the overall radiation rate coefficient $P/n_e n_Z$, both as functions of the electron temperature.

Fig. 3 Total radiated power as a function of electron temperature for oxygen.

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