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# Comparison of Calculated Neutral Beam Shine Through with Measured Shine-Through in DIII-D\*

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**Abstract** — A comparison of the calculated shine through of neutral particle beams in the DIII-D plasma to measured values inferred from the target temperature rise is reported. This provides an opportunity to verify the shine through calculations and makes them more reliable in those cases where the shine through can not be measured. The DIII-D centerpost neutral beam target tiles are safe-guarded against excessive beam shine-through by pyrometry and thermocouple (TC) arrays on the tiles. Shine-through beam power is calculated from the measured temperature changes reported by the target tile TC array. These measurements are performed at the beginning of each operational year at DIII-D. Theoretically, the beam energy deposited into the plasma can be expressed as a function of the change in beam density:  $E_{b \rightarrow p} = \epsilon \left[ \int (dt) * \int (dV) * \int (-ds N_b(s)) \right]$ . The expression for beam density propagating in a plasma is:  $dN_b(s)/ds = -N_b(s)n(s)\sigma$ . Where  $N_b(s)$  is the beam particle density,  $n(s)$  is the plasma density,  $\sigma$  is the interaction cross section, and  $\epsilon$  is the energy per beam particle. The beam energy deposited onto the centerpost (shine-through) is then of the general form:  $E_{cp} = \epsilon \left[ \int (dt) * \int (dV N_b(a)) \right]$ ,

where;

$$N_b(a) = A \left[ N_b(0) e^{-(na\sigma)\gamma} + C \right]. \quad (1)$$

Given that  $a$ , is the plasma diameter,  $(na)$  is the line density.  $N_b(0)$  is the initial beam density, where  $A$ ,  $C$  and  $g$  are system dependent constants. The line density and uncollided beam density are measured quantities. Values of  $\sigma$  are available in the general literature. Neutral beam energy deposition in plasma (of known density) is inferred by comparing the results of a series of shine-through measurements for the 1997 campaign at DIII-D to the expected shine-through given by theory.

## INTRODUCTION

The fraction of beam energy deposited on the centerpost of a tokamak varies with the plasma density, and is indicative of the beam energy deposited in the plasma. Intuitively, one would expect a dense plasma would attenuate a beam of neutral particles more than a less dense plasma. Looking at the general expression for beam density at the

centerpost, and writing  $L$  and  $L'$  for differing plasma line densities; We have:  $N_b(a)|_L = A [N_b(0)e^{-(L\sigma)\gamma} + C]$  and  $N_b(a)|_{L'} = A [N_b(0)e^{-(L'\sigma)\gamma} + C]$ . The shine-through power is just:  $N_b(a)|_L/N_b(0) = A [N_b(0)e^{-(na\sigma)\gamma} + C]/N_b(0)$ , and  $N_b(a)|_{L'}/N_b(0) = A [N_b(0)e^{-(L'\sigma)\gamma} + C]/N_b(0)$ . The ratio of beam particles reaching the centerpost or the shine-through power as a function of plasma line density alone is:

$$N_b(a)|_L/N_b(a)|_{L'} = e^{-(L' - L)\sigma\gamma}, \quad (2)$$

given that  $C \ll N_b(0)$ . If the beam and target tile conditions are held constant, the logarithm of (2) should be linear with respect to changes in plasma line density:

$$\text{Ln}[N_b(a)|_L/N_b(a)|_{L'}] = (L - L')(\sigma\gamma) \quad (3)$$

The system and transport dependent term  $(\sigma\gamma)$  is then indicative of the density dependence of beam energy deposition in a plasma, for the given system constraints.

The neutral beam shine-through power was experimentally quantified by measuring the temperature rise on a set of well characterized centerpost graphite target tiles embedded with thermocouples, and illuminated by the beam [1]. The measured temperature rise in these tiles were correlated to input beam power by the relationship:  $K_s = Pd \times t/\Delta T$  [1] The data presented here were measured during DIII-D shots 84384 to 84399.

The calculated values for shine-through power were generated by the ONETWO plasma transport modeling code [2]. The beam plasma interaction module of the ONETWO code encapsulates the methodology of the FREYA [3], and NFREYA [4] models. In these models the energy deposition by the beam is expressed as:  $Q_{b,e} = \sum_c f_{b,e,c} Q_{b,c}$  for electrons, and  $\sum_i Q_{b,i} = \sum_c \sum_i f_{b,i,c} Q_{b,c}$  for the ions. The shine-through power in this case is the difference between the specified input beam power and the calculated beam power lost to the plasma.

Utilizing the logarithmic relationship derived for the density dependent shine-through power ratio (3), a comparison was made of the experimental results and the calculated results. Plotting out this linear functions for the

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measured and calculated shine-through, the system and transport dependent term ( $\sigma\gamma$ ) are compared. The experimental error in the shine-through power measurements is quantified as  $\pm 5\%$ . The acceptance range for the calculated results is  $\pm 7\%$ .

### MEASURED AND CALCULATED SHINE-THROUGH POWER RESULTS

DIII-D shots 84384 to 84399 had values of  $B_T \sim 1.8$  T,  $T_e \sim 4$  keV and  $T_i \sim 2.5$  keV. The measured shine-through power as a function of line density is given in Fig. 1. The shine-through power for each line density normalized to the shine-through power of the lowest line density, is given in Fig. 2. Fig. 3 is a plot of (3) obtained for the measured shine-through power values.

Using values of  $B_T = 1.8$  T,  $T_e \sim 4$  keV and  $T_i \sim 2.5$  keV, and the range of plasma line densities, a series of ONETWO calculations for beam power deposition were performed to simulate DIII-D shots 84384 to 84399. The calculated shine-through power as a function of line density is given in Fig. 4. The shine-through power for each line density normalized to the shine-through power of the lowest line density, is given in Fig. 5. Fig. 6 is a plot of (3) obtained for the calculated shine-through values.

A plotted comparison of (3) obtained for the measured values, and the calculated values is presented in Fig. 7.

### CONCLUSIONS

The calculated beam shine-through power is in reasonable agreement with the measured values. The calculations used the average  $T_e$  and  $T_i$ , and assumed a static plasma density profile. The variations in local plasma density and

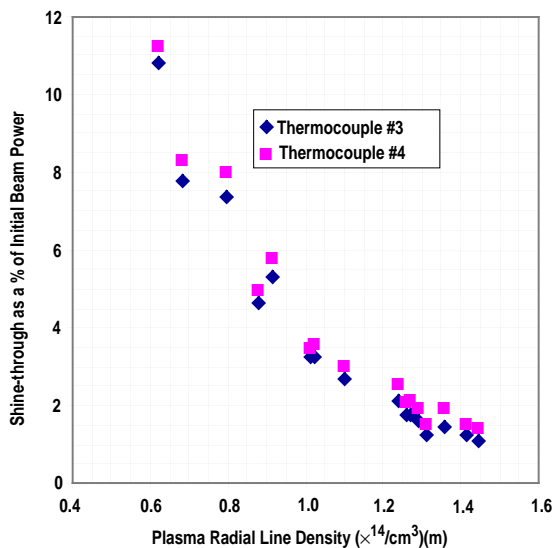


Fig. 1. Beam shine-through power as a function of line density.

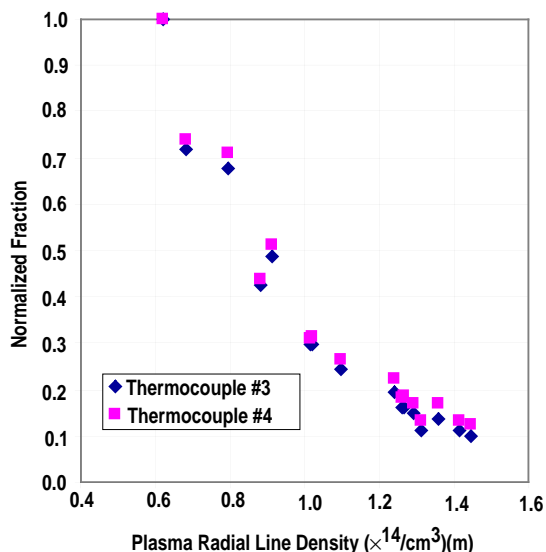


Fig. 2. Normalized shine-through power.

temperature would be sufficient to account for the divergence in the calculated and measured values. The shine-through power fraction is predictable for a given plasma shape, temperature, and plasma confinement parameters via (3). Once the system and transport term is derived, the shine-through power for a range of plasma line densities can be extrapolated.

The beam energy deposited in the plasma is just the difference between the input power and the shine-through power. Hence, the beam power deposition in a given plasma shape and confinement parameters, can be extrapolated once a few values for shine-through power are either measured or calculated for those conditions.

This may expedite future calculations for beam power deposition.

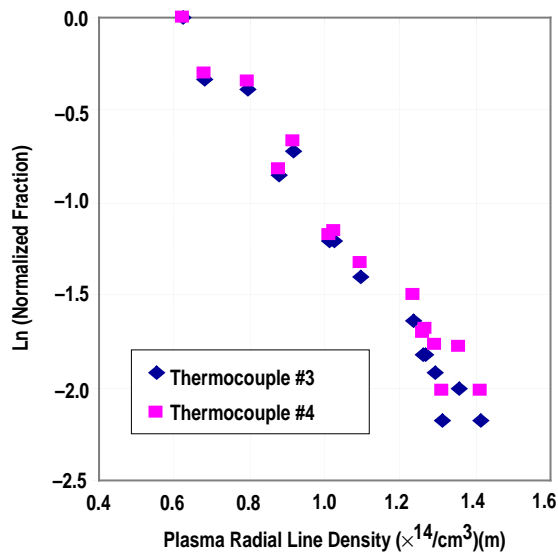


Fig. 3. Natural log of the normalized shine-through power fraction.

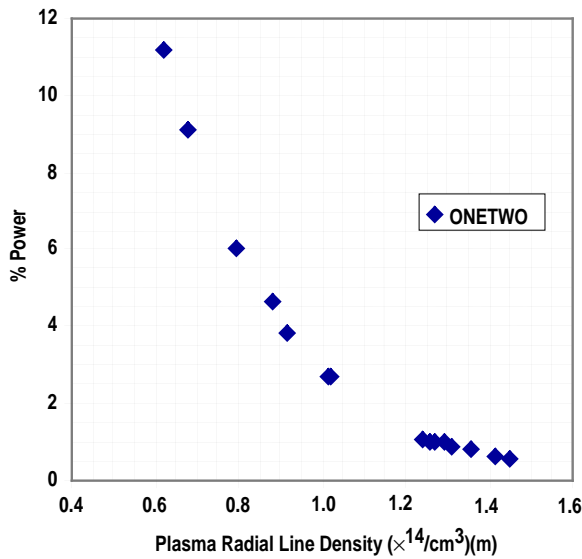


Fig. 4. The calculated shine-through power as a function of line density.

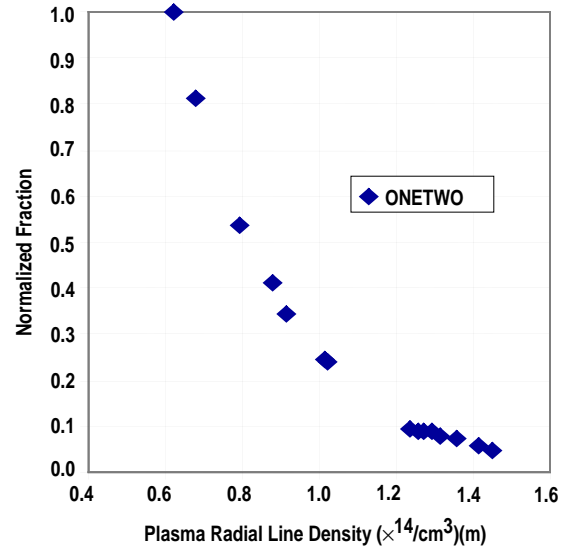


Fig. 5. Normalized shine-through power as a function of line density.

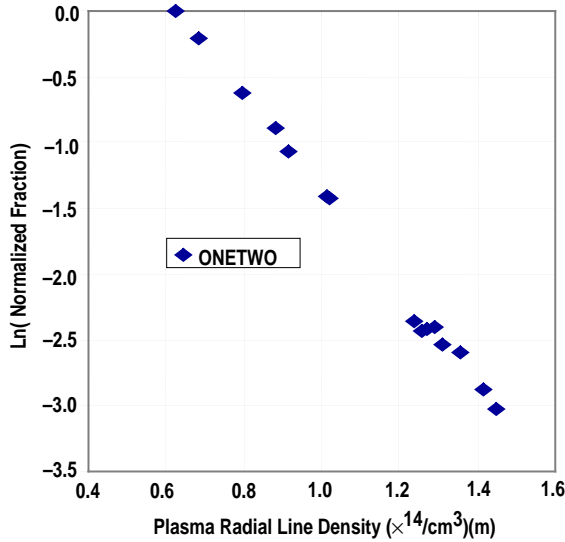


Fig. 6. Natural log of the normalized shine-through power fraction.

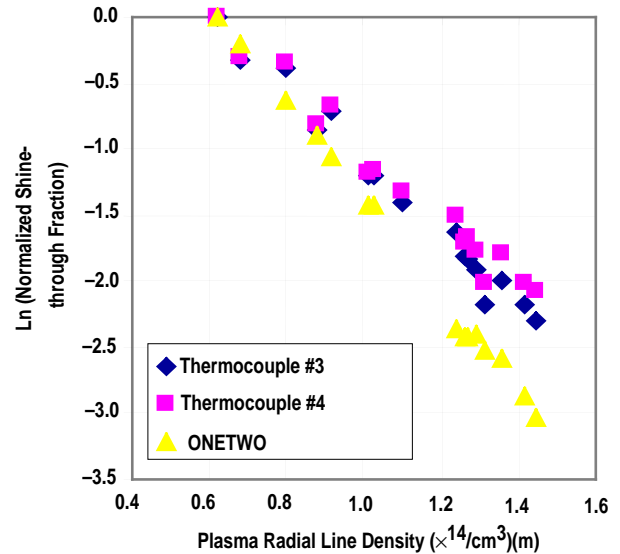


Fig. 7. Comparison between calculated and measured shine-through power fractions as a function of plasma line density.

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