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PARTICLE REFLECTION AND TFTR NEUTRAL BEAM DIAGNOSTICS

BY

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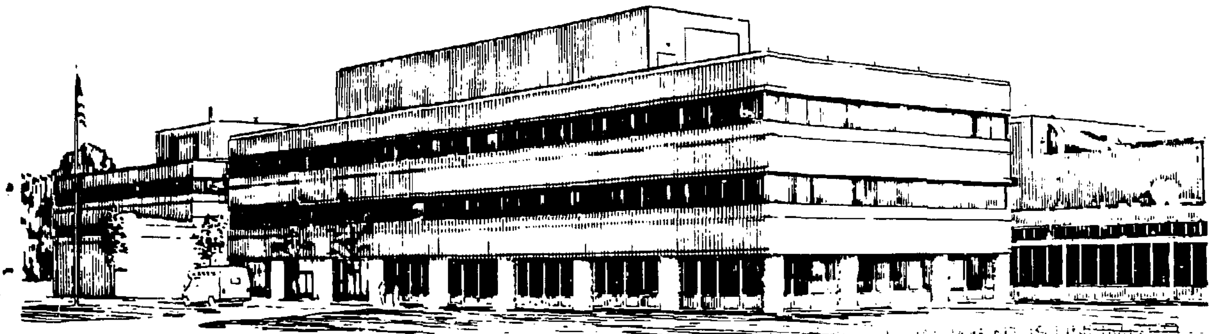

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Particle Reflection and TFTR Neutral Beam Diagnostics

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Determination of two critical neutral beam parameters, power and divergence, are affected by the reflection of a fraction of the incident energy from the surface of the measuring calorimeter. On the TFTR Neutral Beam Test Stand, greater than 30% of the incident power directed at the target chamber calorimeter was unaccounted for. Most of this loss is believed due to reflection from the surface of the flat calorimeter, which was struck at a near grazing incidence (12°). Beamline calorimeters, of a 'V'-shape design, while retaining the beam power, also suffer from reflection effects. Reflection, in this latter case, artificially peaks the power toward the apex of the 'V', complicating the fitting technique, and increasing the power density on axis by 10 to 20%; an effect of import to future beamline designers. Agreement is found between measured and expected divergence values, even with 24% of the incident energy reflected.

I. INTRODUCTION

Over the years, many diagnostics have been devised to quantify neutral beam operation. Chief among these are the measurement of power[1-3] and divergence.[4] Power is an especially important parameter for the Tokamak Fusion Test Reactor (TFTR) since its stated goal is to achieve Q = 1 (Q ≡ fusion power/plasma heating power). Estimates of the injected neutral beam power into TFTR are based upon the power delivered to the beamline calorimeters. From an operational point of view, it is also important to account for where all the power in the beamline is deposited, since, at full power, up to 8.4 MW of power is extracted from TFTR ion sources. The loss of a small fraction of such power has been known to damage beamline components.[5]

Likewise, beam divergence is an important parameter, it being a measure of the angular dispersion of the beam. One of its uses is to quantify whether the ion sources are being operated optimally. Perveance ($I/V^{3/2}$) is varied in a search to find the minimum divergence, a process referred to as tuning. When used in this manner, divergence is a relative parameter. The absolute value of the divergence is equally important, since it is used to estimate the beam's geometrical transport through the beamline.

Since the accelerator structure of the TFTR ion source consists of slots, two divergence parameters exist, one parallel to the slots and one perpendicular. The divergence perpendicular to the slots, $\theta_{\perp}$, is the divergence of most interest during a tune, since it is a function of the plasma meniscus location, and, hence, the perveance. $\theta_{\parallel}$, the divergence parallel to the slots, is primarily a function of the temperature of the plasma ions.

Power distributions "more highly peaked in the center than a bi-Gaussian function"[6] and "unexpectedly high power densities"[7] have been observed at the

Lawrence Berkeley Laboratory on the Neutral Beam System Test Facility and the Neutral Beam Engineering Test Facility, respectively. Particle reflection off 'V'-shaped calorimeters probably contributed to both of these anomalies.

In the design of the beamlines for the major tokamaks, TFTR[8], JET[9], JT-60[10], and DIII-D[11], major beam absorbing components are generally tilted at shallow angles relative to the incident beam to reduce the surface power density. Unfortunately, this creates the possibility of error, due to particle reflection, in the measurement of both power and divergence.

II. EXPERIMENTAL APPARATUS

The data to be discussed were all obtained during operation of the Neutral Beam Test Stand (NBTS), of which figure 1 is a schematic plan view. The purpose of the NBTS was to qualify all components of the neutral beam injectors for use on TFTR and to quantify the loss of power in the duct between the beamline and the tokamak. It was composed of a neutral beam injector, identical to those in use in the tokamak test cell, connected to a target chamber, simulating the tokamak target location.

Evident in figure 1 are three 0.75" thick, 'V'-shaped, water-cooled copper calorimeters within the beamline, one for each ion source. Incident neutral beams approximately bisect the 12° included angle of the calorimeters, striking the surface at an angle of ~6°. This near-grazing angle of incidence reduces the power density by a factor of ten relative to normal incidence. A vital component of the NBTS, not present in the heating configuration on TFTR, was a calorimeter installed in the target chamber. It was a water-cooled, flat one-inch-thick copper plate which the beam impacted at an angle of 12°. In principle, the difference in power between the beamline calorimeter and this calorimeter is a measure the power lost in traversing the calorimeter exit scraper and drift duct .

Waterflow calorimetry was used to measure the power deposited on the calorimeters and other beamline components. A description of this system has been given elsewhere.[3]

Each beamline calorimeter is instrumented with 60 thermocouples in a 10 x 6 array (ten tall and three wide on each half of the 'V'). The target chamber calorimeter had 120 thermocouples in an array ten tall by twelve wide. In both cases, a least squares fitting algorithm[4] was used to determine the beam divergence from the thermocouple temperature rise data. The model in the algorithm assumes that each point on the ion source emits particles in a gaussian angular distribution. A further assumption is that the emitters are uniformly spread over the area of the ion source and equally weighted. The power density at any point downstream is the convolution of the gaussians and the emitter weighting function. For uniform extraction, the result is a set of error functions.[12] By fitting the calorimeter's thermal profiles to this model, the 1/e half-width of the emitting angular gaussian distribution can be determined.

III. RESULTS

A sequence of shots, with pulse lengths ranging from 0.5 s to 2 s, were taken onto the target chamber calorimeter and then repeated onto the beamline calorimeter.[3] In all cases, the deflection magnet was energized, the ion source extraction voltage was 105 kV and the extracted current was in the range 53±1 A. Results of this experiment are presented in table 1. Given are the energy delivered to the target chamber and beamline calorimeters as a fraction of the energy extracted from the ion source (IVΔt), for pulse lengths of 0.5, 1, 1.5, and 2

s. The ratio of the energy delivered to the target chamber calorimeter to that delivered to the beamline calorimeter is 64%, implying that 35% of the power available at the beamline calorimeter was not delivered to the target chamber calorimeter!

Table 2 shows $\theta_{\parallel}$ and $\theta_{\perp}$ for the same cases as in table 1. Differences in $\theta_{\perp}$, for the same calorimeter, are due to variations in perveance caused by the ±1 A deviation in the extracted current. In cases where the perveance was the same for the shots on the two calorimeters (i.e., at 1.5 s and at 2 s), $\theta_{\perp}$ was the same. Surprisingly, there is no difference in $\theta_{\parallel}$ between the two calorimeters. Reflection would be expected to peak the power density toward the apex of the beamline calorimeter while having little or no effect on the thermal profile for the flat target chamber calorimeter. It is noted, however, that χ^2 is larger for the beamline calorimeter than for the target chamber calorimeter.

IV. DISCUSSION

Reflection of incident neutral atoms off the copper calorimeters have been modelled using the TRIM code.[13] For the case of neutral particles from 105 kV ion source operation incident on the target chamber calorimeter, the model predicts an energy reflection coefficient of 15%.[3, 14] This value is believed to be too small. Losses in the duct connecting the beamline to the target chamber were insignificant as measured with thermocouples. A reflected loss of ~25% with negligible loss in the duct is consistent with observation.

TRIM was also used to model the reflection of particles incident upon the 'V'-shaped beamline calorimeter.[14] In this case the energy reflection coefficient was 24%. While this value may be too small, as deduced above, it will be used to illustrate the effect of peaking the distribution toward the apex of the calorimeter and the resultant effect on the divergence calculation.

Figure 2 shows the angular distribution of the reflected particles as computed by TRIM. This distribution is seen to be sharply forward peaked about the spectral reflection angle. In the model below, it will be approximated by an exponential.

The incident linear neutral beam power distribution downstream of the ion source is:

$$P(x,z) = \frac{P_0}{4\,x_0}\left[\operatorname{erf}\left(\frac{x + x_0}{z\,x'_0}\right) - \operatorname{erf}\left(\frac{x - x_0}{z\,x'_0}\right)\right] \qquad 1)$$

where P_0 is the incident power, x_0 is the half-dimension of the ion source, x'_0 is the 1/e divergence of the beam, z is the distance from the ion source to the target point, and x is the orthogonal distance from the beam axis to the target point.[12]

The reflected distribution, the convolution of equation 1 with the exponential fit to figure 2, is given in figure 3, for $z = 575$ cm, $x_0 = 6$ cm, $x'_0 = \tan(0.35°)$, and P_0 being arbitrary. Shown as solid circles is the incident distribution, given by equation 1, while open circles are the reflected distribution. In either case, the result is the creation of a distribution more highly peaked than the error function model. A peaking factor of ~25% is noted, a value approximately equal to the energy reflection coefficient.

When divergence is computed from the thermal profile on the calorimeter, the error function model of equation 1 is used. The best fit to the reflected power distribution in figure 3, using equation 1, is given in figure 4. Open circles are the distribution being fit and the solid circles are the results of the fit. The algorithm has difficulty with the peakedness of the distribution, as is evident, but arrives at a divergence of 0.34°, a value within 5% of that assumed at the ion source for computing the incident distribution.

By constraining the fitting algorithm to equation 1, correct divergences are computed (assuming that the incident distribution is actually of the form of equation 1). The price willingly paid for this is a larger χ^2, which results because of the peakedness of the distribution relative to the model.

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TABLE 1. Energy delivered to the beamline and target chamber calorimeters as a fraction of the energy extracted from the ion source for pulse lengths varying from 0.5 s to 2 s.

pulse length	target chamber calorimeter	beamline calorimeter
0.5 s	24.8%	40.1%
1.0 s	27.0%	40.9%
1.5 s	25.5%	40.1%
2.0 s	26.7%	41.0%

TABLE 2. Beam divergences on the beamline and target chamber calorimeters under the conditions of Table 1.

pulse length	target chamber calorimeter			beamline calorimeter		
	$\theta_\perp$	$\theta_{\parallel}$	χ^2	$\theta_\perp$	$\theta_{\parallel}$	χ^2
0.5 s	1.42°	0.32°	3.7	1.35°	0.33°	6.7
1.0 s	1.13°	0.32°	4.3	1.24°	0.34°	4.8
1.5 s	1.29°	0.32°	4.4	1.33°	0.35°	5.9
2.0 s	1.38°	0.32°	3.9	1.36°	0.35°	4.7

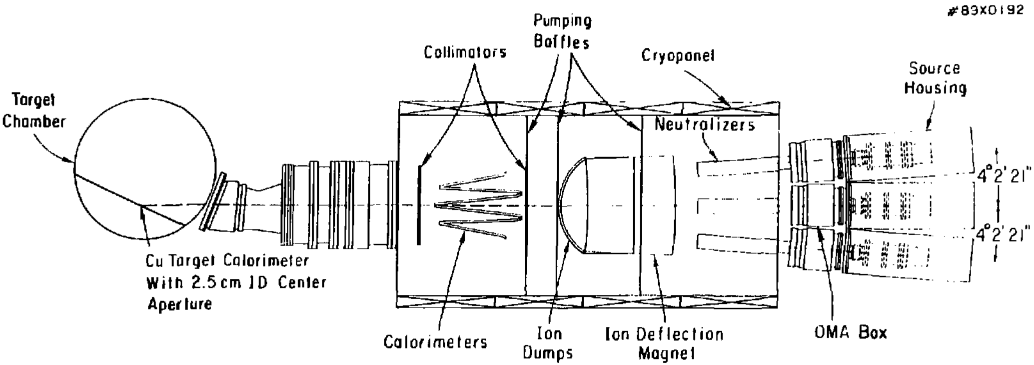
FIGURE CAPTIONS

Figure 1. Schematic plan view of the Neutral Beam Test Stand.

Figure 2. Angular distribution of reflected energy for a beam incident on a copper plate at 84° from the normal.

Figure 3. Incident neutral beam power distribution, in the horizontal direction, on the beamline calorimeter for a beam divergence of 0.35°; solid circles. Resultant distribution after reflection of 24% of the incident energy is convolved with the incident distribution; open circles.

Figure 4. Resultant distribution (open circles) from figure 3, and the best fit (solid circles).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4°2'21"
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Cu Target Calorimeter With 2.5cm ID Center Aperture
Calorimeters
Ion Dumps
Ion Deflection Magnet
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Fig. 1

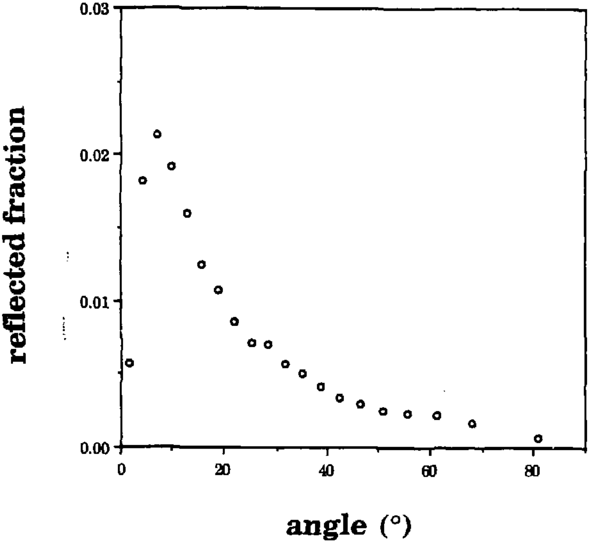

Fig. 2

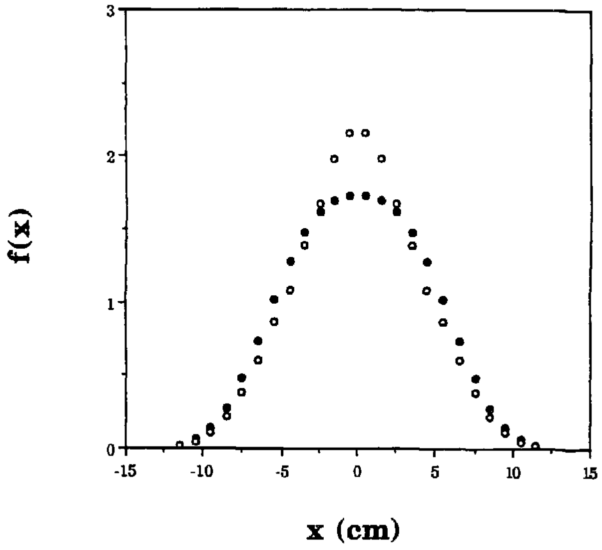

Fig. 3

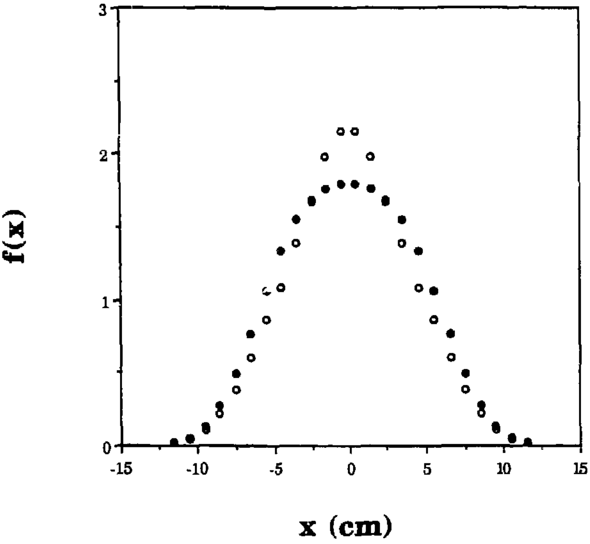

Fig. 4

EXTERNAL DISTRIBUTION IN ADDITION TO UC-420

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