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CHARACTERISTICS OF RADIATED POWER
FOR VARIOUS TFTR REGIMES

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By

C.E. Bush, J. Schivell, D.H. McNeill, S.S. Medley, H.W. Handel
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ABSTRACT

Power loss studies were carried out to determine the impurity radiation and energy transport characteristics of various TFTR operation and confinement regimes including L-Mode, detached plasma, co-only neutral beam injection (energetic ion regime), and the enhanced confinement ("supershot") regime. Combined bolometric, spectroscopic, and infrared photometry measurements provide a picture of impurity behavior and power accounting in TFTR. The purpose of this paper is to make a survey of the various regimes with the aim of determining the radiated power signatures of each.

NUMBER

INTRODUCTION

The role of plasma-wall interactions in obtaining various confinement and operating regimes in TFTR has been considered recently from two different perspectives. The first is concerned with the evolution and behavior of impurities¹ resulting from these interactions, and the second with the role of recycling of neutral gas from the walls and the methods of wall conditioning² used to control this recycling. In fact, a variety of operating and confinement regimes are possible in TFTR due to the availability of two limiter configurations which involve different plasma-wall interaction scenarios, the use of graphite as a limiter/wall material, and the availability of up to 20 MW of neutral beam injection power. In addition, flexibility in partitioning the beam power between co- and counter-injection and in injection angle also helps to expand the operational/confinement space. There are two different graphite limiter configurations: a toroidally continuous inner bumper and a toroidally localized movable outer limiter. Both ohmic and neutral beam injection (NBI) heated plasmas may be run on either limiter, and in the case of detached plasmas,³ without limiter or wall contact. Also, different confinement regimes are obtained depending on whether or not the limiters are pre-conditioned using high power helium and deuterium ohmic discharges.

Power loss studies were carried out to determine the impurity radiation and energy transport characteristics of four types of discharges: outer and inner limiter L-Mode, detached plasma, energetic ion,⁴ and enhanced confinement⁵ regimes. The last two are mostly run on the inner limiter. Each of these regimes will be discussed briefly in this paper. Combined bolometric, spectroscopic, and infrared photometry measurements provide a picture of impurity behavior and power accountability in TFTR. Impurity radiation and energy efflux, in general, are monitored by a system of bolometers, which includes two 19-channel arrays that provide horizontal and vertical fan views of the plasma cross section, uncollimated bolometer power monitors at six toroidal locations (including the movable limiter sector), and a pair of tangentially viewing bolometers used to estimate power lost through charge exchange (cx) of fast ions. The uncollimated bolometers measure the toroidal distribution of the combined loss from radiation, P_{rad} , and thermal cx, P_{thcx} . The collimated arrays measure the radial distribution of the volume emissivity $Q_{rad+thcx}$. The degree of symmetry of in/out and up/down chord-intensity profiles provides additional information about the plasma-limiter interaction. Work reported here is basically a survey to

determine the radiated power signatures for several regimes.

OUTER LIMITER OPERATION: POWER ACCOUNTABILITY

A detailed accounting of input power for OH and NBI heating has been done for plasmas run on the outer limiter. The outer limiter is narrow toroidally and is subjected to high heat loading. This results in surface temperatures high enough to be measured accurately using an infrared camera from which the contribution to the power balance due to heat flow to the limiter can be determined. The results of the power balance for outer limiter operation are plotted in Fig. 1. The P_{rad} term (which includes P_{thcx}) is measured bolometrically while P_{lim} is determined from infrared camera measurements. The error bars reflect primarily the uncertainty introduced into the calculation of P_{lim} from the infrared camera data due to the accuracy of the derived energy scrape-off length, $\lambda = 1.5 \pm 0.3$ cm, and the modeling limitations of the thermal analysis code. Data are shown for ohmic, L-Mode NBI, and energetic-ion regime plasmas. Also included are discharges in which neon was added to obtain 100% radiative loss during NBI while the infrared camera measurements confirmed that P_{lim} was negligible. For most discharges in Fig. 1, the radiated power was < 50% of the input power, with the contribution from the main plasma often in the range of 25-35%. With the toroidal array of six uncollimated bolometers, the toroidal distribution⁶ of radiated power was found to be significantly peaked at the limiter sector during NBI with outer limiter operation. Thus, a multiplicative toroidal asymmetry correction factor of 1.15 is included where applicable in the plot points of Fig. 1. These data show that good power accountability has been obtained in TFTR over a wide range of plasma operating conditions.

DETACHED PLASMAS

In the detached plasma regime the plasma is decoupled from the walls and limiters.³ The radiated power and $T_e(r)$ and $n_e(r)$ values become small over distances of up to 15 cm or more inside the limiter radius. Since the plasma is decoupled from material surfaces, power can only be lost through radiation (and cx neutrals). Almost 100% of the radiated power is from a relatively thin layer (< 20 cm thick) at the boundary of a plasma whose minor radius is ≈ 65 cm. Thus, these plasmas can be used to validate the accuracy of the bolometric diagnostics. Another bolometric signature of the detached plasma is the very steep rise in Q_{rad} at the discharge edge.

The rise in radiated power after beam turn-on can be delayed significantly when beam power deposition is mainly within the detached plasma core. This delay can be comparable to the energy confinement time. This might be expected since energy deposited in the core of a detached plasma must be transported to the edge plasma in order to be lost as radiation.

INNER LIMITER OPERATION

The best enhanced confinement plasmas or "supershots" have been obtained with $I_p \approx 0.9$ MA and balanced beam injection at power > 9 MW into a low density target plasma. At $I_p \approx 0.9$ MA, deuterium target plasmas with a very low density of $\bar{n}_e \approx 0.6 \times 10^{13} \text{ cm}^{-3}$ can be obtained after the inner bumper limiter has been conditioned using low density, 1.4 MA ohmic helium discharges.² The radiated power fraction versus total input power, $P_{\text{tot}} = P_b + P_{\text{OH}}$, for a 0.9 MA balanced injection power scan on a conditioned inner bumper limiter is plotted in Fig. 2a. For comparison, Fig. 2b shows similar plots for two 1.4 MA L-Mode power scans, one with low target density of $\bar{n}_e \approx 1.1 \times 10^{13} \text{ cm}^{-3}$ and the other with high target density of $\bar{n}_e \approx 2.2 \times 10^{13} \text{ cm}^{-3}$. The radiated fraction for the high target density L-Mode plasma is not only lower than for the low density target plasma, but decreases somewhat faster at lower powers (2 to 5 MW). In Fig. 2a, the discharges with $P_{\text{tot}} > 9$ MW exhibited enhanced confinement. For the low target density L-Mode case, the rate of decrease in the radiated fraction with increasing P_{tot} was similar to the low target density balanced injection scan (Fig. 2a).

Figure 3 shows P_{rad} and the neutron source strength (neutrons/sec produced in the plasma), S , during the beam injection for a supershot and a co-NBI discharge, both with $I_p \approx 0.9$ MA and $P_b \approx 12$ MW. The maximum values of P_{rad} for the two plasmas are nearly the same while those of S differ by a factor of 3. Note, however, that the initial rate of rise of P_{rad} in Fig. 3a for the co-NBI discharge is significantly faster than for the supershot. Figure 4a shows a plot of the rise time for P_{rad} (τ_{rise} is the time required for P_{rad} to reach 63.2% of its final value) as a function of the NBI balance parameter, $\text{Bal} = (P_b^{\text{Co}} - P_b^{\text{Ctr}})/(P_b^{\text{Co}} + P_b^{\text{Ctr}})$. Figure 4b shows the fusion power gain⁷ Q_{DD} (D-D fusion power/input power) for the same plasmas. Here the balance of beam injection ranges from all counter-injection ($\text{Bal} = -1$) to all co-injection ($\text{Bal} = 1$). Plasmas near the peak in Q_{DD} have better confinement parameters⁵ (τ_E , S , β_p). A comparison of Figs. 4a and 4b suggests that better confinement is

obtained for plasmas in which P_{rad} rises more slowly. This in turn may also indicate that a larger initial radiated power at early times of the beam pulse (Fig. 3a) is a factor leading to the absence of enhanced confinement in unidirectional beam-heated discharges. Observed line intensity data combined with MIST code⁸ impurity modeling indicate that the impurity behavior in the two cases of Fig. 3 is somewhat different. (See Table I.) The pre-beam plasma has very low density and the carbon concentration of 14% is responsible for $\approx 80\%$ of the Z_{eff} of 6.6. By the end of the beam pulse, $\bar{n}_e$ is significantly higher due to beam fueling and Z_{eff} is reduced to 3.4 in the balanced-NBI and 4.2 in the co-NBI cases. (In the earliest TFTR supershots of summer 1986, Z_{eff} was somewhat lower at 2.5-3.5.) The deuterium concentration is lower in the co-only plasma. The concentration of metals (Ni, Fe, Cr) is approximately four times higher in the supershot than in the co-only shot; however, the contribution of these metals to Z_{eff} and the total radiated power is small.

Further impurity radiation and power balance comparisons between the co-only plasmas and supershots are complicated by two characteristics of inner limiter operation. First, the inner limiter surface is large and results in surface temperatures which are too low for use in determining P_{lim} by IR thermography. Second, plasma interaction with the inner limiter leads to a highly radiating layer of plasma on the inner edge of the minor cross section. This layer causes a large in-out asymmetry in the chord-integrated vertical array bolometer data⁹ for ohmic and NBI heating. This can also be seen in the visible wavelength region with the optical system of the Thomson scattering system (TVTS). A 3-D plot of the chord-integrated bolometer data from the vertical array for the co-NBI case of Fig. 3 is given in Fig. 5, and the effect of the inner limiter layer is clearly evident. The outer half of this distribution is, therefore, more representative of the impurity radiation profile for the main confined plasma. Figures 6a and 6b are Abel inversions of the outer half of the profile data at four beam power levels for discharges from the balanced injection power scan of Fig. 2a and from a co-only power scan, respectively. The peaks of the volume emissivity profiles are shifted to larger minor radii as P_b is increased in each case. At the highest powers ($P_b \approx 13$ MW) the shift is significantly larger for balanced NBI heating (Fig. 6a). This enhanced shift is a characteristic signature of a supershot as seen by the bolometers and correlates with the outward Shafranov shift of $n_e(r)$ and $T_e(r)$ in this type of discharge.⁵

In conclusion we have illustrated the response of the bolometer system to

various TFTR plasma regimes. Some features of the radiated power and emissivity profiles are unique to certain regimes and therefore can serve as signatures. A more complete analysis of these signatures and their relation to the plasma confinement is underway and will be reported elsewhere.

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TABLE I

SHOT :	OHMIC	SUPER	CO-ONLY
P_{beam}	0 MW	11.6 MW	13.1 MW
$\bar{n}_e$	$0.62 \times 10^{13} \text{ cm}^{-3}$	$2.4 \times 10^{13} \text{ cm}^{-3}$	$2.0 \times 10^{13} \text{ cm}^{-3}$
Z_{eff}	6.6	3.4	4.2
$\bar{n}_D / \bar{n}_e$	0.10	0.55	0.38
$\bar{n}_C / \bar{n}_e$	0.140	0.065	0.095
$\bar{n}_O / \bar{n}_e$	0.0055	0.0070	0.0060
$\bar{n}_{\text{Cr}} / \bar{n}_e$	0.00053	0.00046	0.00018
$\bar{n}_{\text{Fe}} / \bar{n}_e$	0.00065	0.00067	0.00015
$\bar{n}_{\text{Ni}} / \bar{n}_e$	0.00062	0.00069	0.00011

Table I Impurity fraction measured by SPRED¹⁰ and analyzed by the the MIST code for the conditioned pre-injection phase of a supershot, the end of the neutral beam pulse of a supershot, and the end of the neutral beam pulse of a co-injection shot.

FIGURE CAPTIONS

- Fig. 1 Power accountability for a variety of OH and NBI-heated TFTR inner limiter discharges.
- Fig. 2 Fraction of power radiated as a function of input power for (a) a 0.9 MA balanced neutral beam power scan and (b) for two 1.4 MA L-Mode beam power scans, one with a low density and the other, a higher density.
- Fig. 3 Radiated power P_{rad} (a) and neutron source strength S (b) for two NBI-heated inner limiter plasmas, a co-injection only plasma, and an enhanced confinement plasma or "supershot." $P_b \approx 12$ MW for both plasmas.
- Fig. 4 (a) The rise time of P_{rad} and (b) the fusion power gain Q_{DD} as functions of the co/counter balance parameter.
- Fig. 5 Time history of the chord-integrated vertical bolometer array data for a 12 MW co-NBI heated plasma on the inner bumper limiter.
- Fig. 6 Volume emissivity profiles from Abel inversion of the outer half of the vertical array data for (a) the balanced NBI power scan of Fig. 2a and (b) for a co-injection power scan. $I_p \approx 0.9$ MA for both cases.

Fig. 1

87X1149

Fig. 2

#87X0345

Fig. 3

87X0831

Fig. 4

Fig. 5

87X1150

Fig. 6

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