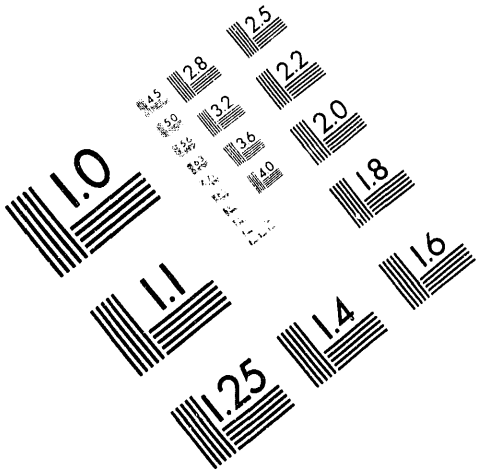

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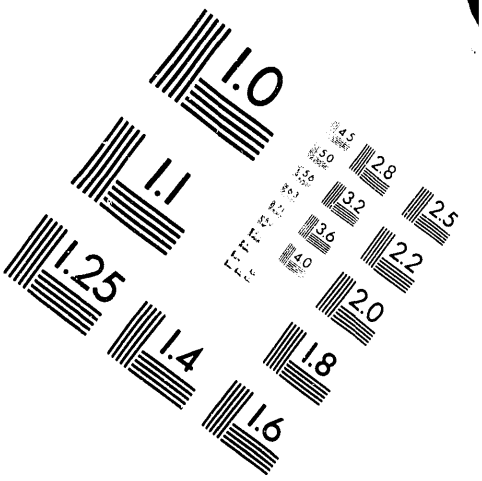

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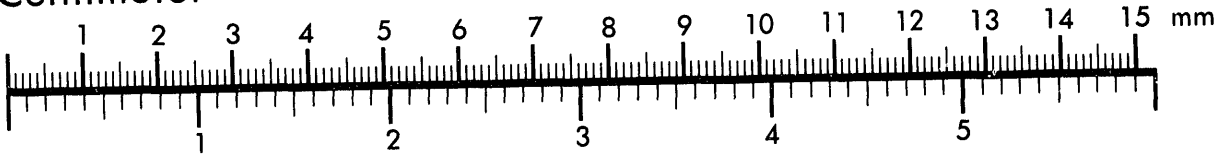

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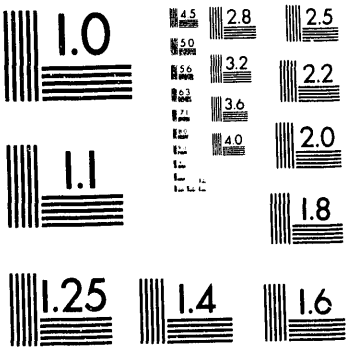

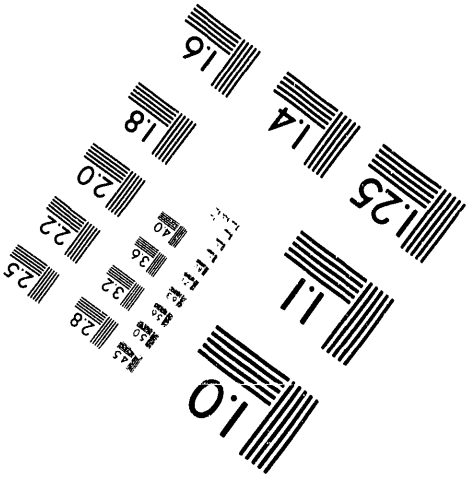

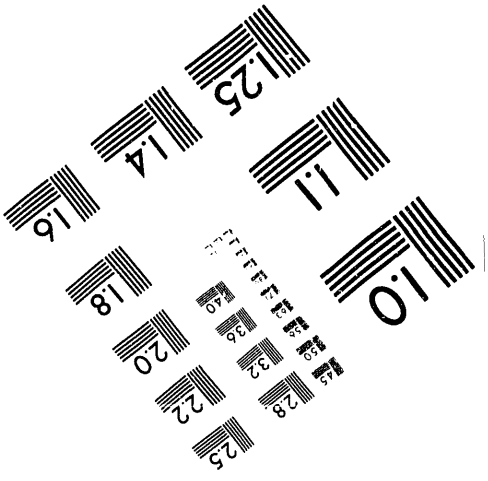

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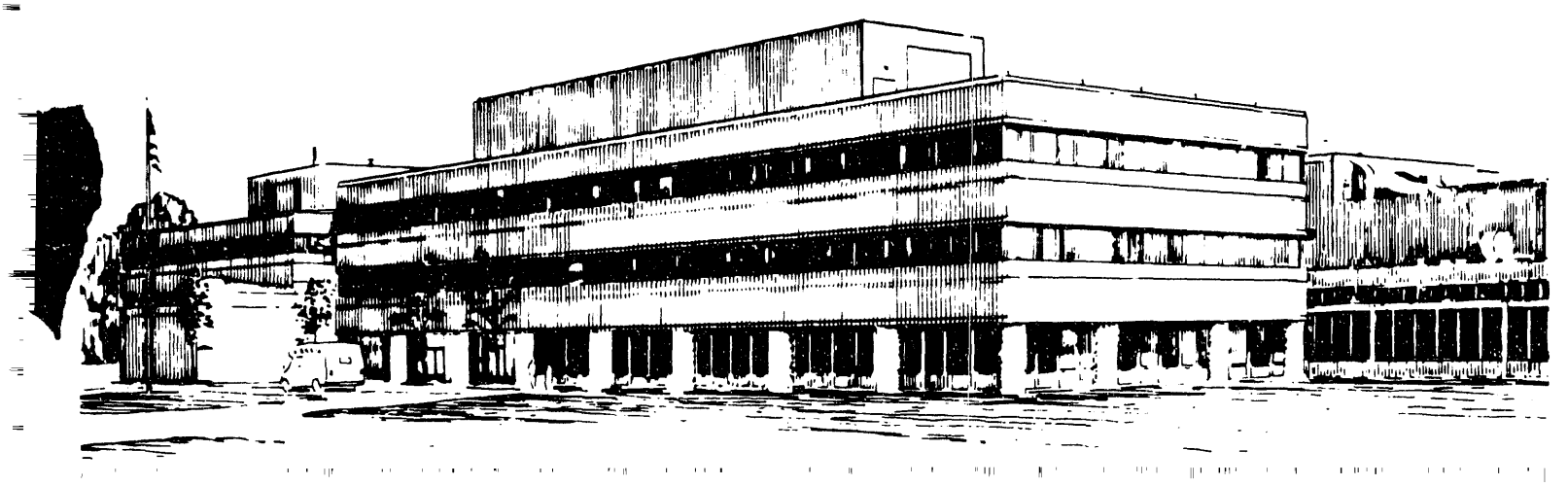
FAST WAVE DIRECT ELECTRON HEATING IN TFTR

BY

M. MURAKAMI, E.F. JAEGER, F.G. RIMINI, ET AL.

MAY, 1993

PPPL PRINCETON PLASMA PHYSICS LABORATORY



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FAST WAVE DIRECT ELECTRON HEATING IN TFTR

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ABSTRACT

Direct electron heating experiments were carried out in two regimes: $B_T = 4.6$ T with D^+ supershots; and $B_T = 2.3$ T with ^3He majority. The electron power deposition profiles measured with modulation of RF power are found to be strongly peaked in the core with the total volume-integrated power of up to 80% of the modulated power. The magnitude and profile shape agree well with those predicted by a full-wave code.

INTRODUCTION

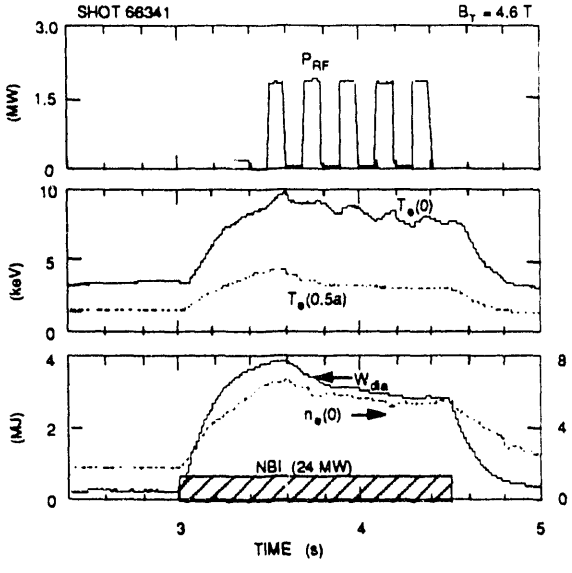

Fig. 1 Time evolution of modulated RF power and plasma parameters in the high field regime ($B_T = 4.6$ T with D^+ supershot)

Direct electron heating with fast waves is a prerequisite to a viable current drive scenario for future steady-state tokamaks; it is also an attractive alternative to the normal ion resonance method, since it does not require the addition of non-reactive ion species and avoids the complication of minority ion tails in studying the effects of alphas. Since the direct electron heating is relatively weak, it is essential to minimize competing ion damping. Direct electron heating experi-ments in TFTR have been carried out in two regimes: high field (B_T = 4.6 T) and low field (2.3 T). The results obtained are similar to those of earlier work.[1-3] Modulation of the RF power facilitated measurements of heating power deposition profiles. The centrally peaked electron power deposition represents a large perturbation in electron transport in NBI-heated plasmas even with modest RF power.

EXPERIMENTS IN THE HIGH FIELD REGIME

The high field experiments ($B_T = 4.6$ T at $R_0 = 2.62$ m) were conducted in the ^3He minority regime but with no ^3He present. The only ion resonance is the deuterium fundamental resonance on the high field side. Figure 1 shows the RF power waveform and time evolution of several plasma parameters. Strong D^0 NBI of 24 MW into a low

edge recycling D^+ plasma creates a supershot[4] target plasma with high central electron temperature $T_e(0) = 8$ keV and high central density $n_e(0) = 7 \times 10^{19}$ m^{-3}, which are necessary for reasonable single-pass absorption. The 47-MHz RF power was ≈100% modulated ($\Delta P_{FW} = 1.65$ MW) with a 5-Hz square wave. Modulation of $T_e(0)$ in response to the RF modulation demonstrates efficient direct electron heating. However, as is usual in supershots with NBI alone, the supershot performance later degrades, owing either to MHD instability or to limiter recycling. The electron temperature profile was measured by a 20-channel ECE grating polychrometor with 0.2-ms time resolution, and the electron density was derived from Abel-inversion of 10-channel FIR interferometer signals with 1-ms time resolution.

HEATING POWER PROFILES

The electron heating is analyzed by two methods. First, the step in the power per unit volume absorbed by electrons is inferred from the change in T_e slope through $\Delta q_e = (3/2)n_e\Delta(\partial T_e/\partial t)$ at the time when the RF power is turned on or off, provided the heat transport remains constant during the RF power transition and there is no discontinuity in electron density. The typical period to determine the slope is 10 to 15 ms before and after the RF transition. A second method involves a Fourier transform of T_e data whose fundamental frequency (ω_m) component can be related to the square wave amplitude of the power deposition through $\tilde{q}_e = (2/\pi)\omega_m(3/2)n_e\tilde{T}_e$ when the modulation is fast enough ($\omega_m\tau_E \approx 5$)

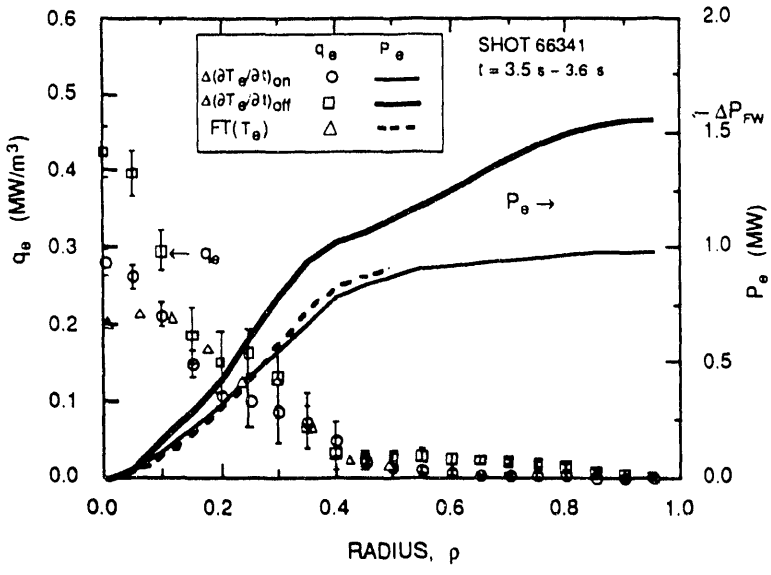

Fig. 2 Electron power deposition profiles (power density and volume-integrated power) measured for the first RF pulse shown in Fig. 1. Circles represent the power density to electrons inferred from $\Delta(\partial Te/\partial t)$ at the turn-on of the first pulse, squares represent the corresponding analysis at the turn-off, and triangles represent the results of the Fourier analysis.

Figure 2 shows the power deposition profiles measured for the first RF pulse (3.5 to 3.6 s). The electron absorbed power profiles derived from $\Delta(\partial T_e/\partial t)$ analysis are strongly peaked in the core, but become small at the outer half of the plasma radius. The total volume-integrated electron absorbed power $P_e(a)$ reaches 80(±15)% of ΔP_{FW}. The Fourier transform method also gives similar results, although it could only be used to determine core deposition owing to low signal at outer radii. Since the single-pass absorption is less than 10% under the present experimental conditions, these results indicate that multiple-pass absorption is taking place.

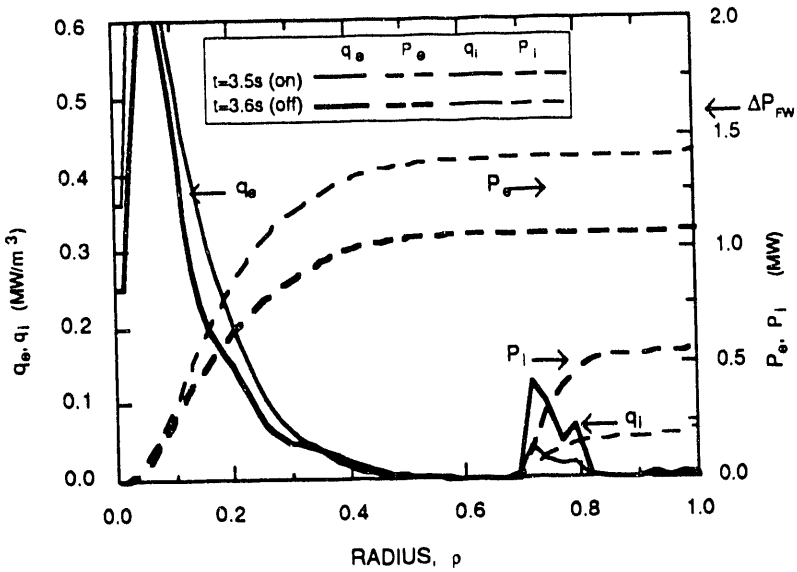

Fig. 3 Electron and ion power deposition profiles (power density and volume-integrated power) predicted by PICES full-wave code for the experimental conditic.. at the turn-on and turn-off of the first RF pulse shown in Fig. 1.

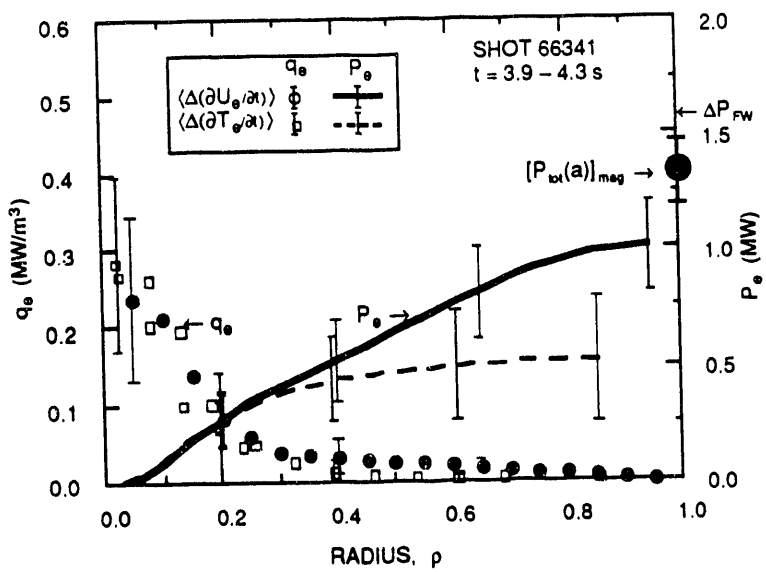

Fig. 4 Electron power deposition profiles (power density and volume-integrated power) measured for the last three RF pulses (t = 3.9 – 4.3 s) shown in Fig. Dots represent averaged values of the change of the time-derivatives of the electron storted energy at the RF power transitions, and squres represent corresponding values for the time-derivative of the electron temperature alone. The total absorbed power magnetically measured is shown by the large dot.

The measured power deposition profiles are consistent with those predicted by a 3-D, full-wave code, PICES (Poloidal Ion Cyclotron Expansion Solution) with multiple (100) modes.[5] The predicted power deposition profiles (Fig. 3) based on the experimental profiles show the centrally peaked $q_e(r)$ with integrated power of 75(±10)% of the input power. The fundamental deuterium ion resonance at the normalized radius $\rho \approx 3/4$ is predicted to absorb 20(±10)% of the input power, as shown in Fig. 3. The calculations of the electron and ion power absorption are subject to uncertainties due to eigenmode structure and shear Alfvén resonance near the edge, both of which are sensitive to details of the profiles assumed.[6]

The evolution of plasma conditions in the discharge influences the electron heating. Supershot performance degradation (not unique to discharges with RF) starts soon (≈30 ms) after the first RF pulse ends. The central electron temperature starts decreasing. The peaked density profile, characteristic of supershots, becomes broad, reducing the central density. Density modulation synchronized with RF power modulation begins shortly after the degradation starts and is probably caused by

limiter recycling. The electron density modulation (only present in the latter part of the discharge) must be taken into account in the power deposition analysis.

Figure 4 shows the electron power density calculated from the change in the slope of the electron stored energy density ($\Delta(\partial U_e/\partial t)$) based on the output of the time-dependent profile analysis code TRANSP (with 5-ms time resolution). Comparing this with the power deposition profile solely based on $\Delta(\partial T_e/\partial t)$, we observe that the density modulation has little effect on the profiles within $\rho = 0.3$, but has substantial effects on the volume-integrated power at outer radii. The total electron absorbed power $P_e(a)$ is 60(±10)%, of which about 30% is the density-related loss at outer radii. The total (electron and ion) power deposited in the plasma can be calculated from the modulated components of the plasma stored energy measured from the diamagnetism and equilibrium position. The modulated components of both magnetic signals (using "boxcar" averaging to remove slow evolution of the plasma energies) have the same peak-to-peak amplitudes. This is consistent with the absence of the velocity space anisotropy without minority ions. These measurements show that the total absorbed power $P_{tot}(a)$ is 80(±10)% of the input power. The difference (≈20%) between this value and the total electron absorbed power could be attributed to the power absorbed by D^+ ions in the fundamental resonance, although time resolution and statistics in the ion temperature measurements are insufficient to detect the modulation in the presence of large heat input from NBI.

EXPERIMENTS IN THE LOW FIELD REGIME

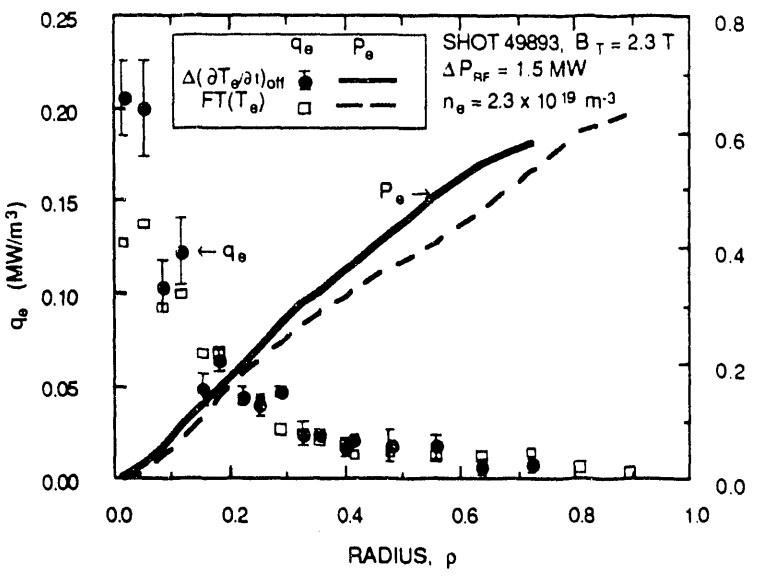

Fig. 5 Electron power deposition profiles (power density and volume-integrated power) measured in the low field experiment (B_T = 2.3 T with ^{3}He majority ions).

Low field experiments were conducted at B_T = 2.3 T with ^{3}He as the majority ion ion. The competing ion resonances include the fundamental H resonance at the high field edge, the second harmonic ^{3}He resonance at the center, and the third harmonic D resonance toward the low field side. Direct electron heating is clearly seen in the modulation of central electron temperature in response to the modulated RF power (100% modulation of 1.5 MW RF power with a 4 Hz square wave) The ion temperature measurements showed that the second harmonic ^{3}He is weak.[7] Figure 5 shows results of the electron heating power deposition analyses for one of the cases. The measured volume-integrated power absorbed by the electrons is 30 to 50% of the modulated power.

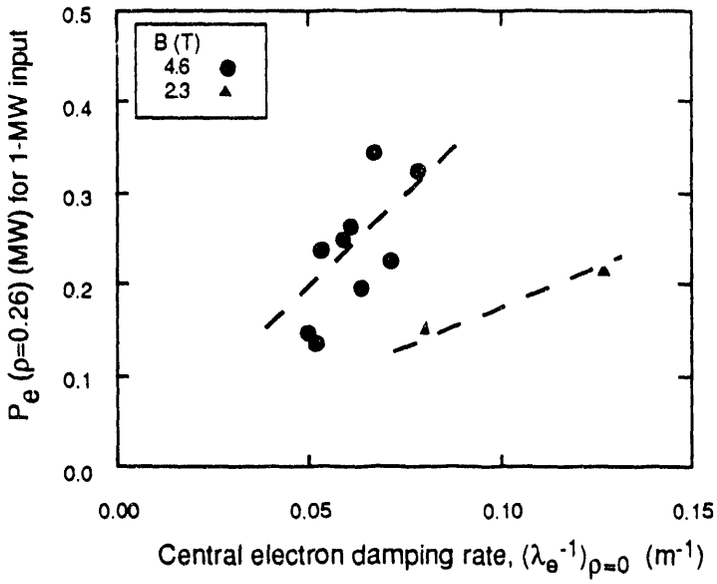

Fig. 6 Volume-integrated power absorbed by electrons in the core ($\rho < 1/4$) normalized to input power versus single-pass electron damping rates calculated at the center.

DISCUSSION

Direct electron heating has been observed in the low and high field regimes in TFTR. Although the competing ion resonances in these regimes are rather different, the observed electron power deposition profiles are similar, and are strongly centrally peaked. In both regimes the power deposition in the core (within $\rho = 1/4$) increases with increasing central electron pressure (product of $n_e(0)$ and $T_e(0)$). Although the magnetic field dependence is not certain, the core power depositions at two different fields are roughly proportional to corresponding electron damping rates calculated at the center, as shown in Fig. 6. In the high field regime, as much as 90% of the RF power can be damped directly on the electrons. The measured deposition profiles agree well with those predicted by the PICES code. Comparative experiments showed that the overall heating efficiency with direct electron heating is similar to that with either NBI alone or ^{3}He minority heating[8] with the same power input. The direct electron heating offers an attractive alternative in DT experiments on TFTR for studying the effects of alpha particles without the complication of minority ion tails. In addition, modulation of strongly centrally peaked power to the electron channel is a profitable way to study electron transport in beam-heated TFTR plasmas.

ACKNOWLEDGMENTS

We wish to acknowledge contributions of many members of the TFTR Group, and useful discussions with Drs. K. McGuire, C. C. Petty, R. I. Pinsker, and S. Scott. The research was sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC02-76-CHO-3073.

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