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OVERVIEW OF RECENT RESULTS FROM THE ADVANCED TOROIDAL FACILITY

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Fusion Energy Division

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Date Published: February 1990

Prepared for the
Office of Fusion Energy
Budget Activity No. AT 10

Prepared by
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PREFACE

This paper was prepared for presentation at the 1st International Toki Conference on Plasma Physics and Controlled Nuclear Fusion, held at Toki, Japan, December 4–7, 1989, and will be published in the proceedings.

ABSTRACT

An overview of recent experimental results from the Advanced Toroidal Facility (ATF) is presented. Beam-heated plasmas with $\bar{n}_e$ of 10^{20} m^{-3} and τ_E* of ≈20 ms have been achieved. Thermal collapse of the plasmas is mitigated by wall conditioning and particle fueling. Confinement time scales positively with density and magnetic field, offsetting deterioration with power. Results fit the Large Helical Device (LHD) scaling and the drift wave turbulence scaling. Bootstrap currents observed during electron cyclotron heating agree with neoclassical theory in magnitude and parameter dependences. Fast reciprocating Langmuir probe measurements show that edge fluctuations in ATF have many similarities to those in the Texas Experimental Tokamak (TEXT). The location of $\tilde{B}$ instabilities has shifted outward in radius, consistent with the broader pressure profiles.

1. INTRODUCTION

In the past year, significant progress has been made in extending the research capabilities of the Advanced Toroidal Facility (ATF).[1] After verification of the successful repair of the error field, the maximum magnetic field was increased from 0.95 T to 1.9 T, a power supply was added for the mid-vertical field (VF) coils, six getter sources and a second 53-GHz gyrotron were installed, and profile diagnostics were improved [two-dimensional Thomson scattering, scanning neutral particle analyzer, far-infrared (FIR) interferometer, etc.]. Recent experiments[2] have concentrated on (1) plasma performance improvement and confinement scaling, (2) bootstrap current, and (3) fluctuation studies.

2. IMPROVEMENT OF PLASMA PERFORMANCE AND CONFINEMENT SCALING

Recent improvements in plasma performance are the result of improved impurity and particle control. Previously, glow discharge cleaning with vacuum vessel baking (at 150°C) was used for wall conditioning. Although quasi-stationary discharges with electron cyclotron heating (ECH) lasting for up to 1 s were obtained at 0.95 T, discharges with neutral beam injection (NBI) suffered thermal collapse in spite of low impurity density and low radiative power fractions ($Z_{eff} \leq 2$ and $P_{rad}/P_{input} < 40\%$ until the time of the collapse).[3,4] The low radiation levels suggested that impurities might not be the sole culprit. The collapse has not been eliminated, but extensive gettering (≈60% wall coverage) and better gas programming have led to extended longevity (up to 0.27 s) for NBI discharges.

Figure 1 shows the time evolution of several plasma parameters for a typical recent discharge with NBI (H^0 into D^+, 1.4 MW total from co- and counter-injecting beams, 1.9 T, titanium gettering). "Reheating" occurs after cessation of the strong gas puff at the beginning of the beam pulse. At the peak of the soft X-ray signal, the line-average density $\bar{n}_e \approx 6.1 \times 10^{19}$ m^{-3}, the diamagnetically measured plasma stored energy $W_p = 19$ kJ, the global energy confinement time $\tau_E^* = W_p/P_{in} \approx 12$ ms, and the "apparent" ion temperature obtained from neutral particle analysis is 0.28 keV. Profile analysis based on Thomson scattering profiles taken at this time indicates that the "apparent" ion temperature is approximately consistent with neoclassical ion conductivity. The analysis yields a stored energy of 17 kJ (with a 5% contribution from the fast ion component), and a (thermal) gross energy confinement time, $(W_e + W_i)/(P_{be} + P_{bi}) = 12$ ms $\approx \tau_E^*$. The optimal gas puffing (a strong, short fueling which results

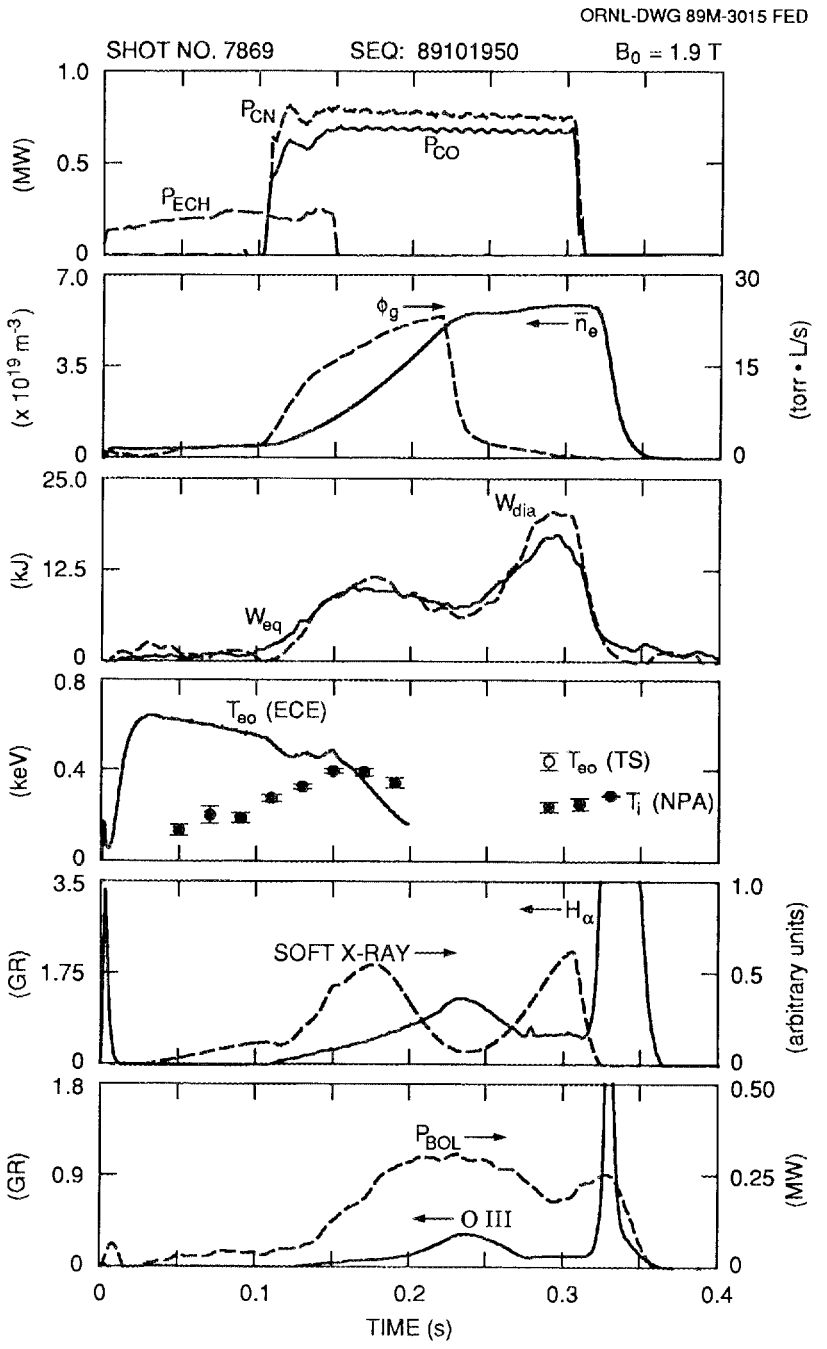

Fig. 1. Time evolution of a typical NBI discharge.

in reheating) is reminiscent of successful pellet injection and of the Improved Ohmic Confinement (IOC) mode in ASDEX.[5]

The maximum value obtained for W_p (27 kJ at $B_0 = 1.9$ T) is an increase by factor of 3.5 over the level achieved in 1988.[3] Global confinement times of 20 ms have been obtained with injected power > 1 MW; confinement times as high as those in the Impurity Study Experiment (ISX-B) even including the operations with impurity-enhanced confinement (the Z-mode).[6] The highest volume-average β ($\langle\beta\rangle = 0.84\%$ at $B_0 = 0.95$ T) was achieved with NBI and fueling with two 0.5-mm pellets at 1.0 km/s.

Higher densities are possible with NBI, and the positive density dependence offsets the degradation with power. Global confinement in ATF is consistent with the LHD scaling,[7]

$$\tau_E^{LHD} = 0.17 P^{-0.58} n^{0.69} B^{0.84} a^{2.0} R^{0.75}$$

(with τ_E in seconds, P in megawatts, n in particles $\times 10^{20}$ m^{-3}, B in tesla, and R and a in meters) as shown in Fig. 2. ATF (and other stellarator) data also fit well the drift wave turbulence (gyro-reduced Bohm) scaling,[8,9]

$$\tau_E^{dw} = (1 \times 10^{-9}) . P^{-0.6} n^{0.6} B^{0.8} a^{2.4} R^{0.6} \kappa A_i^{-0.2}$$

(in SI units) as shown in Fig. 3. This suggests that drift waves, in particular trapped-electron instabilities, may be important in stellarator (and tokamak) plasmas. ATF can make a significant contribution here because the fraction of confined trapped-particles and the magnetic shear can be externally controlled, thereby directly influencing the instabilities.

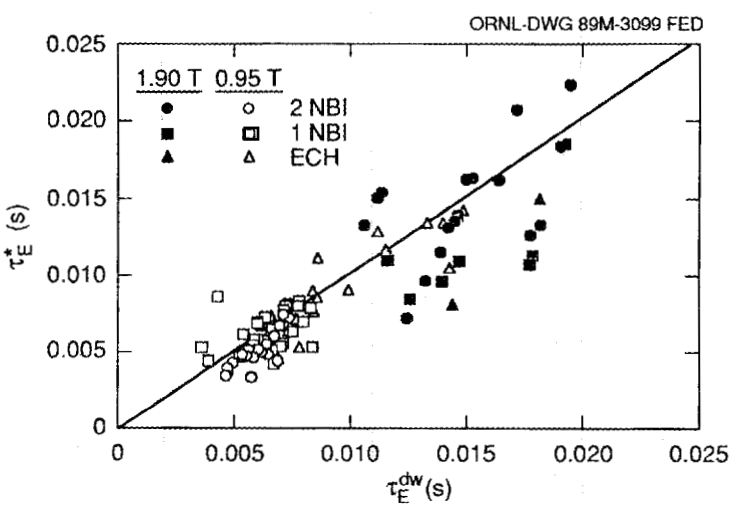

Fig. 2. Global energy confinement vs LHD scaling.

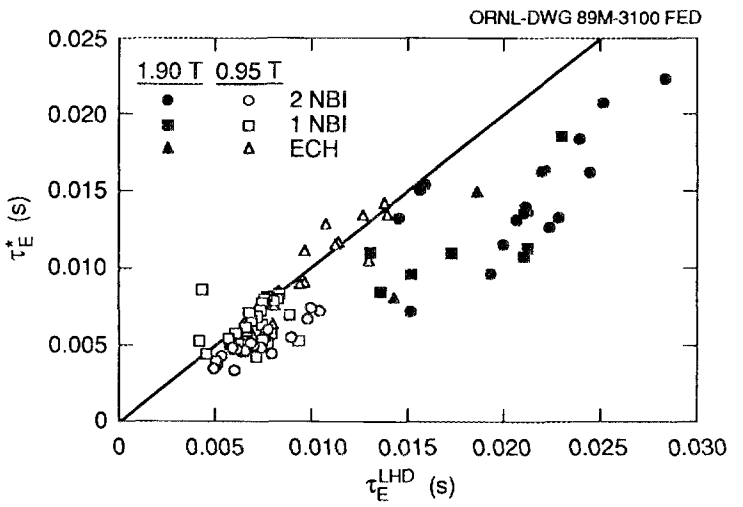

Fig. 3. Global energy confinement vs drift wave turbulence scaling.

3. BOOTSTRAP CURRENT

The present ATF experiment is aimed at verifying neoclassical theory on bootstrap current through direct measurements (in the absence of other current) and parametric scans (in particular, with magnetic configuration). Neoclassical theory[10] predicts that, in the low-collisionality limit, the bootstrap current is given by $j_b = -3(f_t/f_c)\, G_b\, B_0^{-1}\, \nabla p$, where G_b is a magnetic geometry factor that depends on the |B| spectrum on a flux surface and changes with the quadrupole (shaping) or dipole (vacuum axis) component of the vertical field.

The toroidal current observed during ECH in ATF is predominantly bootstrap current. There is negligible ohmic heating (OH) loop voltage ($\bar{V} \leq 0.003$ V). ECH current drive is negligible, because (1) the microwave power is launched perpendicular to the magnetic field, and (2) the observed current responds to reversal of the helical coil current and to changes in $\bar{n}_e$, in contradiction to the expectations for an ECH-driven current. More importantly, the following results confirm the parametric dependences on vertical field that are predicted by neoclassical theory.

Figure 4 shows the currents observed as a function of the mid-VF coil current ratio, the parameter that changes the quadrupole component of the vertical field. Also shown are the bootstrap currents calculated with neoclassical theory. The agreement is good in both magnitude and dependence on the quadrupole field. The bootstrap current decreases as the plasma is vertically elongated (as the coil current ratio increases). Figure 5 shows that the bootstrap current observed in the dipole field scan is also consistent with the theory. The

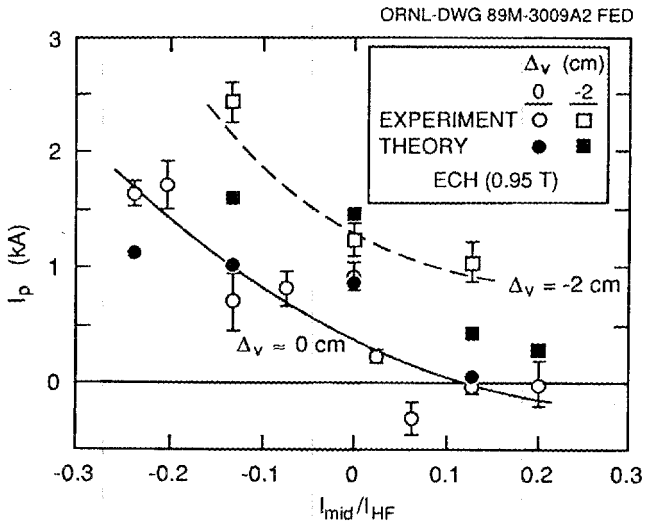

Fig. 4. Bootstrap current vs mid-VF current ratio in the quadrupole field scan: experiment and theory.

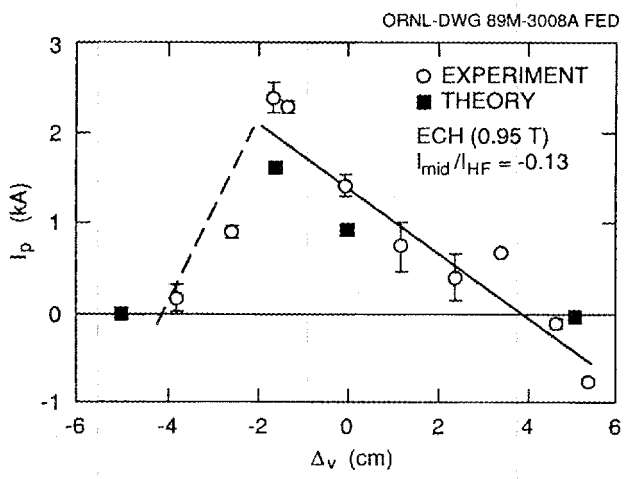

Fig. 5. Bootstrap current vs vacuum axis shift in the dipole field scan: experiment and theory.

current increases as the vacuum axis is shifted inward ($\Delta_v < 0$), until it eventually decreases owing to reduction of plasma pressure by confinement deterioration. We also observe that the current normalized to the stored energy (or total pressure) for operation at 1.9 T is lower by about a factor of 2 than that at 0.95 T, supporting the assertion that I_p is inversely proportional to B_0.

The results show that the neoclassical theory of the bootstrap current describes the current flow in ATF even in the presence of anomalies in particle and heat flows. In addition, the

results demonstrate the ability to reduce the toroidal current down to zero, as is desirable for stellarator operation. The directions of the vertical field components to minimize the current are the same as those needed for high-β plasmas (which optimize with outside shift and elongation).[1]

4. FLUCTUATION STUDIES

There are three general classifications of fluctuation studies in ATF: (1) plasma edge turbulence; (2) high-β stability; and (3) the low-collisionality regime. We have initial results in the first two areas, and are starting investigation of the third with the recent installation of a second gyrotron.

In the edge fluctuation studies we use a fast reciprocating Langmuir probe [like that used on the Texas Experimental Tokamak (TEXT) tokamak[12]] to measure density ($\tilde{n}$) and potential ($\tilde{\phi}$) fluctuations in the plasma edge ($0.95 < r/a < 1.13$) of ATF and then compare the results with those from TEXT. The general features of the fluctuations are the same on both devices. In particular, the data show a departure from the Boltzmann relationship; experimentally, $\langle e\tilde{\phi}/kT_e \rangle > \langle \tilde{n}/n \rangle$, as shown in Fig. 6(a). These features are generally consistent with a model of radiative thermal instability coupled with resistive instabilities.[13] The calculated fluctuation-induced particle flux [Fig. 6(b)] is comparable to the total particle flux estimated from H_α measurements, assuming that particle flux is constant on a magnetic flux surface.

In recent work, instabilities seen by magnetic fluctuation ($\tilde{B}$) probes have shifted outward in radius. We interpret this shift as a consequence of pressure profile broadening brought on by the field error repair and performance improvement. A clear change in the edge density fluctuation spectrum measured by the microwave reflectometry occurs during the "reheating" phase described in Sect. 2 and appears to have a $\langle\beta\rangle$ threshold. Part of its spectrum is then correlated with $\tilde{B}$.

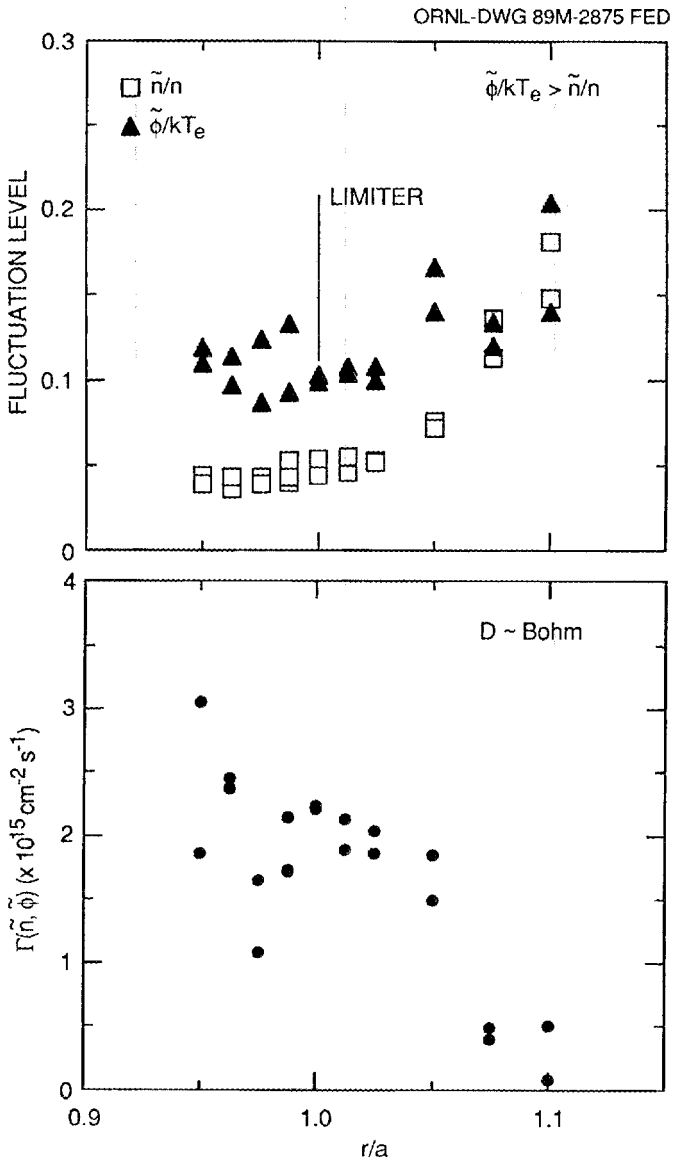

Fig. 6. Radial dependences of (a) edge density and potential fluctuations and (b) calculated induced particle flux.

ACKNOWLEDGMENTS

We acknowledge with appreciation the efforts of our technical support group (G. H. Henkel, L. A. Massengill, C. R. Schaich, T. F. Rayburn, W. L. Redmond, and J. L. Yarber), our engineering group (R. D. Benson, W. R. DeVan, W. A. Gabbard, J. W. Halliwell, R. L. Johnson, J. A. White, C. T. Wilson, and R. E. Wright), and our data handling group (C. A. Giles, D. C. Giles, D. E. Greenwood, D. L. Million, D. R. Overbey, T. C. Patrick, and K. G. Young). We are grateful for the encouragement and support of Drs. M. J. Saltmarsh and J. Sheffield.

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