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* Lawrence Livermore National Laboratory, USA.
† Kurchatov Institute for Atomic Energy, USSR.

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John Lohr, R.W. Harvey, R.A. James,† T.C. Luce, C.C. Petty
General Atomics, P.O. Box 85608, San Diego, California 92186-9784
V.V. Alikaev, A.A. Bagdasarov, A.A. Borshchegovsky, Yu.V. Esipchuk,
Yu.A. Gorelov, A.B. Pimenov, K.A. Razumova, I.N. Roi, V.M. Trukhin,
N.L. Vasin
Kurchatov Institute for Atomic Energy, Moscow, USSR

ABSTRACT

The combination of electron cyclotron current drive and the bootstrap effect has produced completely non-inductively driven current of 75 kA for up to 200 msec in the T–10 tokamak. At higher values of plasma current $I_p \sim 175$ kA, $I_p \geq 60$ kA was maintained by ECCD. These experiments have been modeled with the coupled ray training and transport codes TORAY and ONETWO. Within the uncertainties in the experimental data, the calculations show that the sum of bootstrap and ECCD substantially exceeded the net programmed plasma current.

EXPERIMENT

Up to eleven gyrotrons were operated during these experiments. Nine gyrotrons at 81.3 GHz were arranged in three groups consisting of 4, 3 and 2 tubes respectively separated by 90° toroidally. These tubes injected into the torus at an angle of 21° to the radial at the injection point from the low field side in the ordinary mode for ECCD. The gyrotron groups were operated serially, therefore absorbed power of approximately 0.75 MW for periods of up to 0.5 sec was achieved. When these groups were superimposed, power in excess of 1.0 MW was absorbed, although this was for shorter durations up to 0.25 sec. The remaining two tubes were at 75 GHz and injected approximately 0.65 MW. These two tubes injected radially and were used for heating only. The two resonances are 12 cm apart in T-10.

A wide range of parameters was explored during these experiments. I_p = 75–175 kA; $\bar{n}_e = 0.5 - 1.6 \times 10^{19}/m^3$. Ohmic electron temperatures were $T_e(0) \sim 1.5$ keV and this increased to $T_e(0) \sim 7$ keV during ECH. The primary uncertainty in the analysis came from determination of Z_{eff}, which increased from ~2 to ≥5 during the ECH pulses. A B_T scan showed largest ECCD for 2.78 T and generally this was the value used. For this field, the absorption at 81.3 GHz coincides with the peak value of T_e.

ANALYSIS

Although the data were distributed throughout the parameter space described above, two regimes were of particular interest. This report will focus on them:

Low current regime $I_p = 75$ kA $T_e(0) \sim 5$ keV $\bar{n}_e \sim 1.0 \times 10^{19}/m^3$.
High current regime $I_p = 175$ kA $T_e(0) \sim 7$ keV $\bar{n}_e \sim 1.1 \times 10^{19}/m^3$.

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† Lawrence Livermore National Laboratory, Livermore, California 94550

The parallel current density is given by

$$j_{\parallel} \sim j_{\Omega} + j_{\rm boot} \pm j_{\rm ECCD} \quad . \tag{1}$$

The neoclassical bootstrap contribution is parameterized as

$$j_{\rm boot} \sim -\frac{\epsilon^{1/2} nT}{B_\theta} \left(C_1 \frac{1}{n}\frac{dn}{dr} + C_2 \frac{1}{T_e}\frac{dT_e}{dr} - C_3 \frac{1}{T_e}\frac{dT_i}{dr} \right) \quad , \tag{2}$$

Where j_Ω is the ohmic current and $j_{\rm ECCD}$ is the ECCD current, either in the same or the opposite direction to the ohmic. The bootstrap current is the same direction as the ohmic current for all but the most pathological profiles, and is enhanced by large temperatures and densities and their gradients and by low ohmic current operation. The quantities C_n are constants or slowly varying functions of temperature and density.

The analysis was performed by the coupled codes TORAY, which performed ray tracing and power deposition calculations and ONETWO, which evolved the kinetic profiles self-consistently. The density profile was not evolved and the energy confinement was forced to follow a $P^{-1/2}$ parameterization. The fundamental transport model was approximately Alcator scaling, however the calculated electron temperature during ECH was matched to the experimental value by adjusting the constant coefficient of χ_e. The effective χ_e thus obtained was about 75% of the Alcator value.

LOW CURRENT REGIME

In the low current regime the entire plasma current was maintained non-inductively by a combination of ECCD and bootstrap. From Eq. (2) it is seen that the lower plasma current operation is expected to enhance the bootstrap current fraction and this is borne out by the simulation.

The calculation for this situation is summarized in Fig. 1. At 100 msec, 650 kW of heating power was applied, followed 100 msec later by 750 kW of ECCD in the co-direction. Even during the period of heating only, the bootstrap current was nearly equal to 75 kA and the ohmic current decreased to a few kA. With the additional ECCD power, which drove ~25 kA, the bootstrap current increased to $I_{\rm boot} > 100$ kA and to maintain the programmed value, the ohmic current reversed direction and approximately − 60 kA was driven.

The experimental loop voltage traces and $T_e(r)$ profile are seen in Fig. 1 to be well represented by these calculations. In the experiment a reverse ECCD case was run and this had approximately zero $V_{\rm loop}$. The corresponding calculation showed zero central current density which, in the absence of an MHD fluctuation model, was unphysical. As expected from the driving terms for the bootstrap current, both $j(r)$ and $q(r)$ have off-axis peaks.

HIGH CURRENT REGIME

The TORAY/ONETWO simulation for the high current regime indicates that an ECCD current of 70 kA was maintained while the bootstrap current was ~60 kA. Heating power was 640 kW and current drive power was 1.46 MW. In order to maintain the programmed total current of 175 kA, an ohmic current, of ~40 kA was required during ECCD. These results are summarized in Fig. 2 in which the experimental and calculated surface loop voltage traces for ECCD parallel to the ohmic current are shown. The experimental loop voltage is coupled to the vertical field, therefore no significance should be attached to the time lag in the V_{loop} decrease following the initiation of ECH. Although $T_e(0)$ is reproduced by the calculation, the experimental profile is more peaked than the calculation. This discrepancy is attributed to uncertainties in the experimental measurements and the choice of the transport model. A Z_{eff} value of 5.5 with flat radial profile was used and this gave good agreement with the experimental loop voltage difference for the co- and counter-ECCD cases while simultaneously reproducing $T_e(0)$.

CONCLUSION

Complete non-inductive current drive from ECCD and the bootstrap effect has been observed on T-10. Electron cyclotron current drive in excess of 60 kA has also been achieved. The experiment has been modeled by TORAY/ONETWO the calculations support this conclusion by indicating a sum of bootstrap and ECCD well in excess of the plasma current.

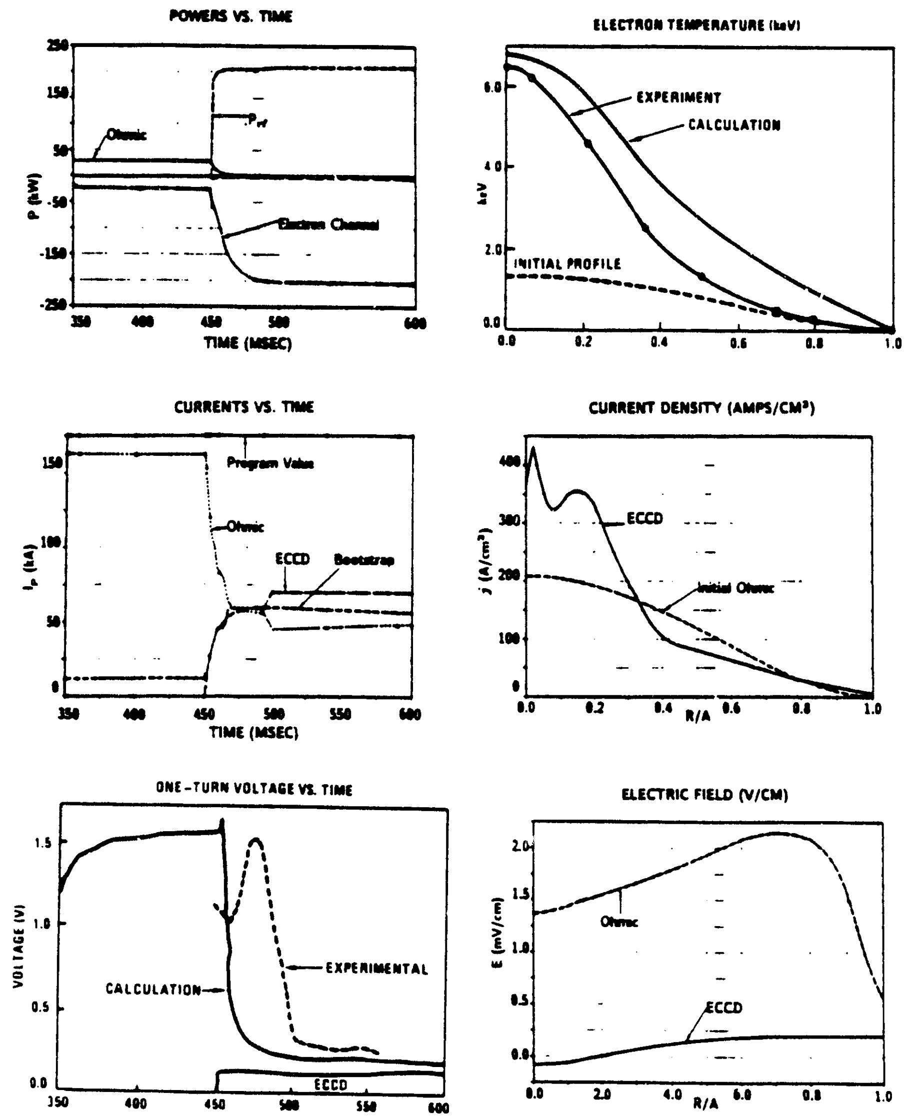

Fig. 1. Summary plots for the high density regime in which the bootstrap and ECCD are approximately equal. The calculated loop voltage approximately equals the experimental value at long times. The residual inductive current is approximately 40 kA.

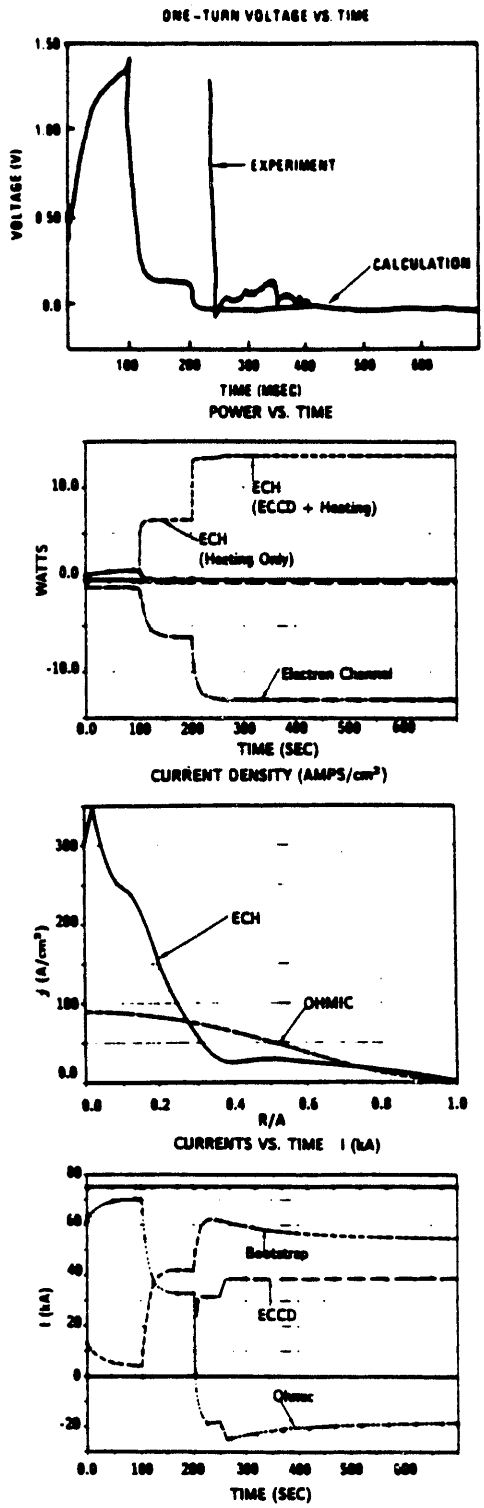

Fig. 2. Summary plots for the low density regime in which bootstrap plus ECCD account for the entire current. In order to maintain the program value, the inductive current reverses direction and the loop voltage is slightly negative.

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