Initial Plasmas in the Electric Tokamak[1]

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Abstract. The UCLA Electric Tokamak (ET), a low field ITER sized device, has been operating with well equilibrated clean plasmas since January 2000. The operating scenario is still evolving as the magnetic configuration and the power supplies undergo refinements. The goal of equilibrating near unity beta plasmas will require 10 second long discharges at 3 kV temperatures in a toroidal field of 0.25 Tesla due to current shaping requirements. Short, 0.9 sec, discharges are now routinely obtained with kT_e, kT_i ~ 120 eV at a toroidal field of 0.1 Tesla. The discharges are feedback controlled in up/down position and in plasma current. Biased electrode driven H-modes have been obtained and compare well to the results obtained on CCT and to the "neoclassical bifurcation" theory. Very successful second harmonic ion heating has been demonstrated with an ICRF antenna outside of the vacuum system and 50% single pass absorption. These discharges also indicate that edge bifurcation can be achieved by RF alone due to fast ion losses. The remaining critical item needed for the exploration of unity beta plasma stability is the demonstration of RF current profile shaping near the Troyon limit. We expect that ion-ion hybrid mode conversion (high field side launch) will allow current drive at low beta. This can then be supplemented by high harmonic current drive at higher beta. Ultimately, near ignition conditions could be reached if magnetic omnigeneity (classical transport physics) were obtained at a toroidal field of 1 Tesla. The test of this concept is to be carried out at 0.25 Tesla in the coming year, if RF current profile shaping can be achieved and supplemented by bootstrap and diffusion driven current.

1. Introduction

Initial plasma discharges in the Electric Tokamak (R=5 m, a=1 m, b=1.5 m, B=0.1 T, I_p = 30 kA) have validated its "ohmic" design. $Z_{eff} < 1.1$, $\tau_E (0) < 150$ ms, $M_{oh} < 2$ and $V_{loop} \sim 0.75$ V have been achieved in ohmic discharges with boundary H-mode (M_{oh} is the Murakami density index.). The central electron temperature is nominally, $T_{eoh}(0) < 150$ V, and it is sufficiently high to allow for gas puffing in this very large tokamak with titanium coated walls. The transition to H-mode discharges is through bifurcation in poloidal rotation, achieving $V_{pol} < 50$ km/s in a 10 cm wide boundary layer using first a biased electrode and now ICRF-induced ion orbit loss. The characteristics of the H-mode have been confirmed by examining the electrode current-voltage characteristics, the poloidal rotation profile using correlation probes, and from reflectometry using Doppler shift of the fluctuation spectrum.

In the electric tokamak, thermal ion transport can be assumed classical when $E_r > \varepsilon v_{thi} B$ where v_{thi} is the ion thermal speed, $\varepsilon = r/R$, B is the total magnetic field and E_r is the radial electric field. This is achievable with subsonic poloidal flow but not with toroidal rotation or shear. The above condition on the radial electric field has been exceeded in the boundary layer during the H-mode in ET and correspondingly the particle confinement time is longer than the length of the H-mode itself, $\tau_p >> 100$ msec.

ET has been designed to explore the generation and maintenance of unity beta plasmas in tokamaks at high aspect ratio [1]. If high beta can be achieved, the mod-B surfaces will align with the magnetic surfaces (Omnigeneity [2]). Omnigenous magnetic condition can result in classical (not just neo-classical) confinement of electrons and ions. These conditions cannot be achieved in an H-mode via poloidal rotation, much less by using toroidal flow shear. We propose to achieve unity beta equilibrium using relatively inexpensive ICRF technology. Validation of the ICRF system, using low

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field side power insertion for heating and high field side current drive is under way at the second harmonic of hydrogen and at the ion-ion hybrid frequencies, respectively. Very encouraging results have been obtained so far with kT_{bulk} ~ 400 eV, kT_{tail} ~ 1 keV at the second harmonic of hydrogen, including ICRF driven poloidal/toroidal rotation via ion orbit loss.

2. Ohmic discharges and edge H-modes

Figure 1 shows a typical ohmic discharge, followed by an electrode-induced H-mode. The present ohmic system is limited to 2 V-s due to power supplies. ET will have a 20 V-s OH system in the near term. We are using partially completed magnetic coils to test RF and control systems while the tokamak construction is being completed.

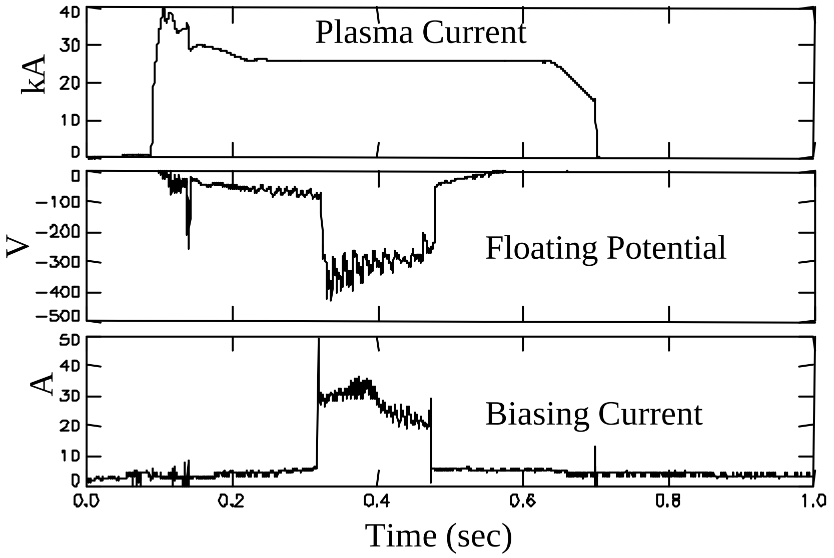

FIG. 1 Biased H-mode signatures in ET.

The titanium-coated stainless steel walls act as giant belt limiters and facilitate the production of clean and reproducible discharges with 30 kW of power input. Without titanium coating, ET does not break through the ionization barrier which requires 1 MW initial ohmic power input. Edge H-modes produced by a biased electrode similar to the ones observed in CCT [3] have been obtained in ET on “day one”. A bifurcation in the electrode current and in the poloidal rotation speed (in agreement with neoclassical bifurcation theory [4]) are seen. The plasma density increases during H-mode, indicating an improved particle confinement.

3. Analysis and validation

ET has been scaled and designed using our in house understanding of low field ohmic heated tokamaks, including the vitues of biased H-mode and that of Z_{eff} ~1 plasmas. For operating well below the Murakami density limit we used the loop voltage scaling, $V_{loop} = 0.75/a^{1/2}$ to predict the performance of ET. But after the fact, the 0.75 coefficient has been revised down to below 0.5. The other parameters used in the projections were based on standard tokamak science with no adjustable parameters but with the understanding that a density limit has no basis in the theory in lieu of a power balance. Nevertheless, it is prudent to use a Murakami/Greenwald type density prediction provided it not taken seriously. All of our projections have been made with M=0.5 although we have now obtained 5 times higher density than the original design assumed. This has resulted in achieving very efficient 2nd harmonic ICRF heating without the assistance of neutral beams. However, at such relatively high densities ET switches over from neo-Alcator type behavior to neoclassical ion limited transport. This observation is summarized in Figure 2, graphically.

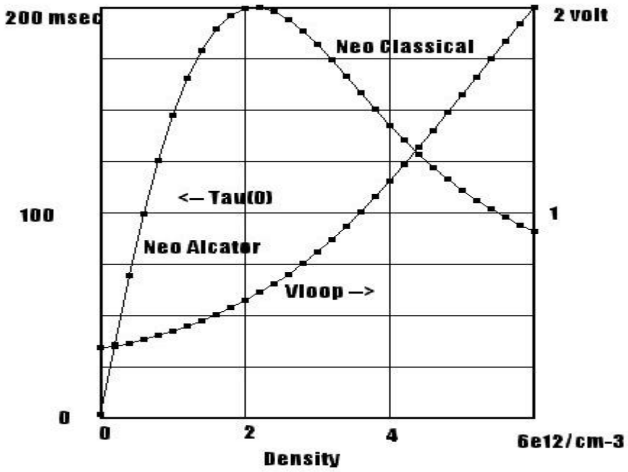

FIG. 2. Confinement summary of ET ohmic discharges. The key variable here is the density and the resulting loop voltage. The modified neoAlcator and the original neoclassical limits are combined.

For simplicity, only the central confinement is of interest here. The Murakami limit is 10^{18} m^{-3} on this plot. The electron temperature is Te = $480(B/V)^{2/3}$, where B is in Tesla and V is the loop voltage in volts. This is based on having a sawtooth limit for q(0) =1, which is easily achieved in most tokamaks, including ET. Due to its parameter range, ET also achieves thermalization between the ion and electron temperatures. We have checked the resulting peak ion temperature (100 –150 eV) using a fast neutral analyzer (CX). The ion temperature measured in this way agrees with the ohmic electron temperature.

In the modified neo-Alcator limit we assume: $V = 0.75/a^{1/2}$, Z=1, q(0) =1, $n(0) = 10^{20}$ MB/R, M = 0.5 (Murakami coefficient), R = 5 m, a = 1 m, B = 0.1 Tesla, $T(0) = 480(B/V)^{2/3}$ (from Spitzer), $T_i = T_e$, $j(0) = 2*B/\mu_0R$, all in MKS, and predict $\tau_E(0)$ as:

$$\tau_E(0) = 3n(0)eT(0)/j(0)E(0) = 80 \text{ msec}$$

In the neo-Alcator limit, we obtained for ET, V < 0.5 volt instead of V = 0.75 volt. As the density increases, the loop voltage also increases and no disruptions are seen. The density is however clamped by MHD oscillations if the boundary H-mode is not applied. In an H-mode, the net confinement depends on density as summarized in FIG. 1 above. The neoclassical regime cannot be entered without the boundary H-mode for reasons of incessant MHD oscillations. The H-mode also reduces the edge convection and magnetic flutter.

If we turn the above analysis into a scaling law, in the spirit of neo-Alcator scaling we get:

$$\tau_E(0) = (0.15\sim0.2)M_{oh}Ra^{5/6}B^{2/3} \text{ (MKS)}$$

Here the exponent of the minor radius, a, could in fact be unity. This scaling favors high Murakami number and large, high field devices. Nevertheless, such scaling should not be used for estimating the performance of ET type devices at high beta, where omnigeneity is expected to remove toroidal effects and possibly allow for classical confinement. The favorable confinement projections for ET indicate that the Troyon limit can be reached well below the anticipated 2 MW heating requirement.

4. Second harmonic heating results

We have made small signal loading resistance measurements at the second harmonic frequency (3.2 MHz) and at frequencies above and below the “range” of the second harmonic domain. The results are suggestive of good second harmonic absorption. ICRF wave absorption at the second harmonic and away from it has been evaluated from a slab model full-wave code. The analysis confirms the experimental finding that a 50% single pass power absorption is possible at the second harmonic proton resonance. High power (< 3x P_{OH}) ICRF has been applied to ET at 3.2 MHz where single pass absorption indicated that efficient ion heating may be achieved.

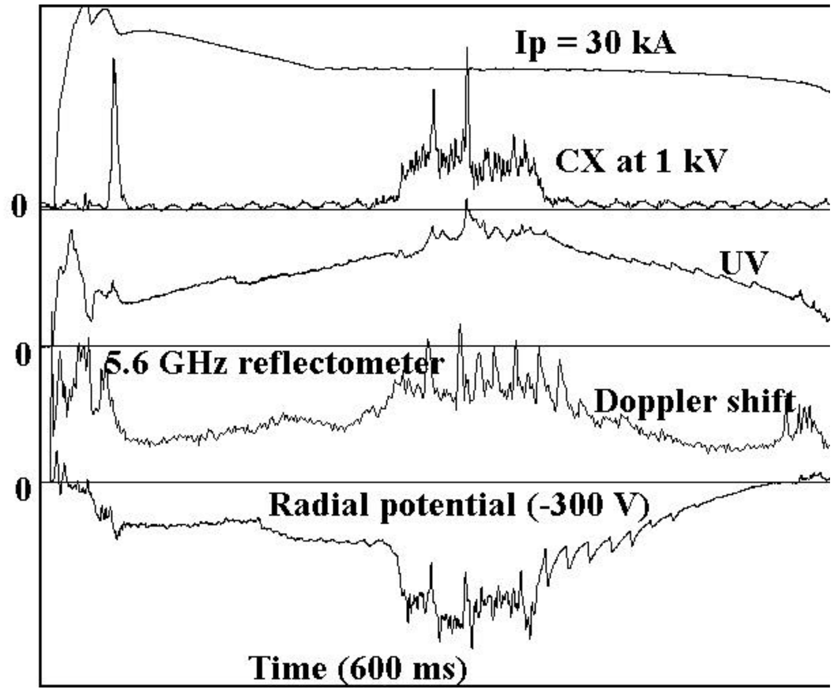

FIG. 3. Summary of heating and rotation signatures.

Figure 3 shows a typical set of time signals, validating that high quality ion heating is indeed possible. No significant impurity effects were found with even though there was no Faraday shield used on the dielectric window. The windows are about 2 meter tall and 0.8 meter wide. The ICRF antenna is placed outside the vacuum chamber. This provides us with excellent flexibility to optimize the ICRF components without venting ET. Figure 3 also shows that the radial floating potential (measured 12 cm into the plasma) becomes more negative during RF heating. A detailed investigation shows that this potential is due to fast ion orbit loss. Bifurcated poloidal rotation (measured by reflectometry as indicated in FIG. 3), has been achieved by supplemen-ting the ICRH driven ion orbit loss by an electrode-driven radial current of 10 A. Using data from bias-induced H-modes we have determined the plasma-wall contact impedance to be about 10 ohms. A potential change of 100 V therefore implies an ion loss current enhancement of 10 Amperes due to the ICRF heating.

Figure 4 shows the charge exchange data from the fast neutral particle analyzer. This data indicates the presence of fast ions and an increase of the plasma ion temperature to ~ 400 eV. From power

balance considerations, the observed ion heating is consistent with neoclassical ion transport. With more RF power we expect an increase in the negative radial potential.
If the potential can be controlled by varying the position of the resonant layer then it may be possible to move towards classical ion heat transport as $kT_i > 1$ keV. At this point current drive will be needed for MHD equilibration and stabilization of the plasma.

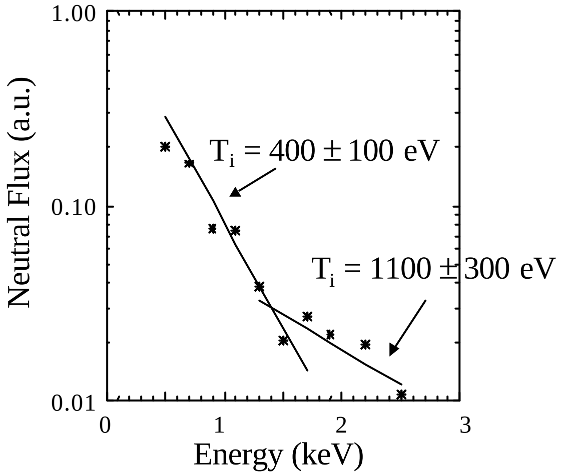

FIG. 4 Fast neutrals energy profile during second harmonic heating.

5. Future expectations

The remaining uncertainty for ET is the achievement of current drive. We have high field side access for this at 32 possible toroidal locations. MHD analysis shows that the toroidal current needs to be aligned with the gradient for stability. Bootstrap current can do this but we need to lead the current shift relative to the increase of the plasma beta. Diffusion-driven current [5], produced by the large outboard pressure gradient at high beta, is also expected to contribute. To accomplish this level of control ET has been designed for long pulses and elongated plasmas. The beta should be raised slowly so that the current profile can lead. This implies that heating rate needs to be controlled to not exceed 5% per confinement time. Similar to the advanced tokamak concept plasma shaping and control become the primary tasks. The initial experience with ET indicates that the large size and the built in flexibility are important advantages.

6. Conclusions

Clean and controlled ohmic target plasmas have been obtained in ET at low cost with high confinement. The ICRF heating needed as a tool to reach unity beta regime is performing better than expected, along with all other parameters of ET. It remains to be seen if unity beta, the primary objective of ET, can be achieved using ICRH heating and current drive. Plasma edge rotation, an omnigenous magnetic configuration, and current profile shaping are the critical elements needed for this exploration. We expect that the required current drive will soon be demonstrated. If the ET science program is successful at a toridal field of 0.1 - 0.25 Tesla than near ignition conditions could be produced at 1 Tesla at extremely low cost. It is our view that for convenient exploration of neutron based technologies, a device twice the size of ET with R=10 m, A~4 and B = 2 T would still be needed.

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