Overview and Initial Results of the ETE Spherical Tokamak

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Abstract. The ETE spherical tokamak is a small size aspect-ratio machine with major and minor radius of 30 cm and 20 cm, respectively. The vessel was made of Inconel 625 and provides good access for plasma diagnostics through 58 Conflat ports. The first plasma was obtained at the end of 2000 and presently plasma currents of about 45 kA lasting for about 4 ms with electron temperature up to 160 eV and densities of 2.2×10^{19} m^{-3} are routinely obtained. Achievement of the designed parameters for the first phase of operation is expected by the end of this year, with plasma current up to 200 kA lasting for about 15 ms. This paper describes some details of the ETE project, construction and mainly the first results and analysis of basic parameters.

1. Introduction: ETE tokamak

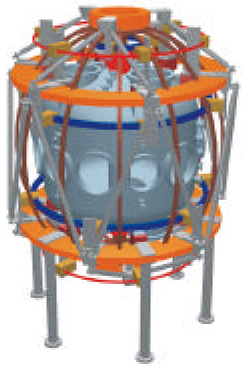
The ETE spherical tokamak (Experimento Tokamak Esférico) became operational at the end of 2000 and the main objectives of the project are plasma edge investigation, plasma heating by Alfvén waves and development of diagnostics [1]. Figure 1 presents a 3-D view of the ETE and the main parameters.

The vacuum vessel was manufactured with Inconel 625, a relatively high resistivity nickel alloy. The toroidal geometry of the vessel is formed by an external tube (diameter of 1.2 m, length of 0.6 m and thickness of 6.35 mm) connected to an internal tube (diameter of 0.18 m, length of 1.2 m and thickness of 1 mm) by two torispherical heads of thickness of 6.35 mm. A total of 58 Conflat ports (12xCF14", 4xCF250 and 42xCF40) provide good access for plasma diagnostics. The vacuum system comprises a turbo drag (1500 l/s) and an oil-free diaphragm (4 m^3/h) pumps. A base pressure of 8×10^{-8} Torr is achieved by conditioning the vessel with baking temperature up to 110 ^{o}C.

The D-shaped toroidal field coils ($I_{max} = 100$ kA) were manufactured from copper and comprise 12 turns in series that are connected by stray field compensation rings at the bottom and at the top. The solenoid ($I_{max} = 20$ kA) comprises 2 layers of 130 turns each connected in series with three pairs of compensation coils. The equilibrium field coils comprise a pair of 16 turns (4x4) each ($I_{max} = 6$ kA). The maximum currents are limited by stress and heating in the coils.

The power supplies of ETE are based on capacitor banks. Their energy is being continuously increased by adding more capacitor modules as well as by rising the voltage rating to its maximum to reach the first operational stage, as depicted in figure 1.

The control system of the machine is based on CAMAC technology that is being developed in C language [2]. An optical link provides an isolation of 2 kV (15 kV in the near future) between the control computer and the CAMAC modules. A galvanic isolation between the CAMAC and the hazardous environments is achieved by optical and pneumatic systems. Presently the data acquisition is based on CAMAC modules and digital oscilloscopes that, in a near future, will be replaced by VME bus standard. Figure 2 presents schematically the configuration of the control and the acquisition system with the safety barrier.



	Initial Phase	Extended Phase
Major radius R_O	0.3 m	0.3 m
Aspect ratio A	1.5	1.5
Elongation k	1.6 – 1.8	1.6 – 1.8
Triangularity d	0.3	0.3
Toroidal induction B_O	0.4 T	0.8 T
Plasma current I_p	200 kA	400 kA
Pulse duration t	15 ms	50 ms

Figure 1: 3-D view of the ETE tokamak and the main parameters for the initial and extended operational phases.

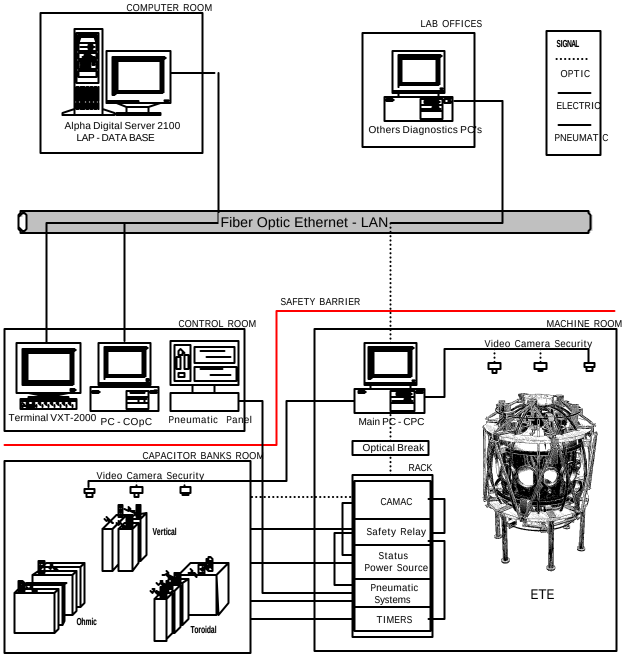


Figure 2: A schematic view of the ETE control and acquisition system showing the safety barrier.

2. ETE Diagnostics

For this initial phase of operation a set of basic electromagnetic diagnostics is installed, comprising: three Rogowski coils to measure the toroidal, equilibrium and ohmic currents; two Rogowski coils, one inside the vessel to measure the plasma current and one outside the vessel to measure the induced current in the vessel; twelve loop voltage coils in different positions (one placed inside the vessel); four fixed B_z/B_r magnetic pick up coils for MHD and magnetic field measurements protected by the graphite limiter; two movable magnetic pick up coils (B_z, B_r and B_T) and one movable electrostatic probe, both at the mid-plane. There are also a H-alpha detector with interference filter ($\Delta\lambda = 13.52$ nm); one visible light spectrometer (12 Å/mm) for impurity emission detection; one fast CCD camera with speed up to 500 FPS and frame velocity up to 1/10,000 and one hard x-ray detector. For electron temperature and density measurements an one-channel Thomson scattering system with a 10 J ruby laser and collecting lenses capable of scanning 22 different plasma positions at the mid-plane is installed [3,4]. Figure 3 shows a schematic view of the Thomson scattering setup. A 10 keV Fast Neutral Lithium Beam probe (FNLB) with glassy β-eucryptite source (up to 1 mA/cm^2) is under development in the laboratory for edge plasma measurements as shown schematically in figure 4 [5]. The FNLB consists of an ion gun (with the ion source and 3 electrostatic lenses), a sodium based neutralization chamber, a flight line with differential pumping and a detection system.

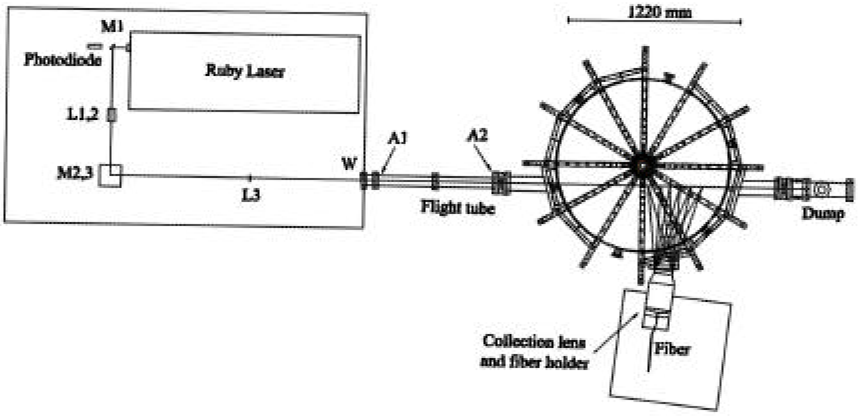


Figure 3: Top view of the ETE Thomson scattering system. M1,2,3 are mirrors; L1,2 are beam expander lenses; W is the beam injection window and A1,2 are apertures.

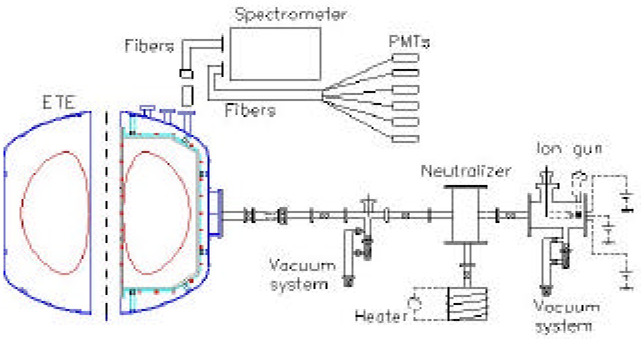


Figure 4: Schematic view of the FNLB setup for edge plasma measurements.

3. Results

Figure 5 shows some electromagnetic and optical signals obtained during a typical hydrogen discharge of 40 kA lasting for 4 ms. As the vessel presents no break in the toroidal direction, it can be observed a relatively high current induced in the vessel (peak of about 55 kA at the breakdown phase). Radial displacement of the plasma column (B_z coil placed at the inward side) as well as H-alpha and CIII emission can also be seen in this figure. A picture of the D-shaped plasma can be seen in figure 6, which was taken after 3.2 ms from the beginning of the discharge with the CCD camera set at a frame velocity of 1/10,000. Figure 7 shows temperature and density profiles obtained from Thomson scattering. The temperature varies from nearly 20 eV for t = 2.5 ms to a peak of 160 eV for t = 3.5 ms and the density reaches values up to 2.2×10^{19} m^{-3}. It can also be verified that the plasma column shifts towards the central tube of the vacuum vessel in agreement with the B_z measurements. This shift is due to the inward force caused by the unbalanced vertical field, which for the present coil configuration of ETE, is necessary to compensate the stray fields, generated by the induced current in the vacuum vessel during the gas breakdown.

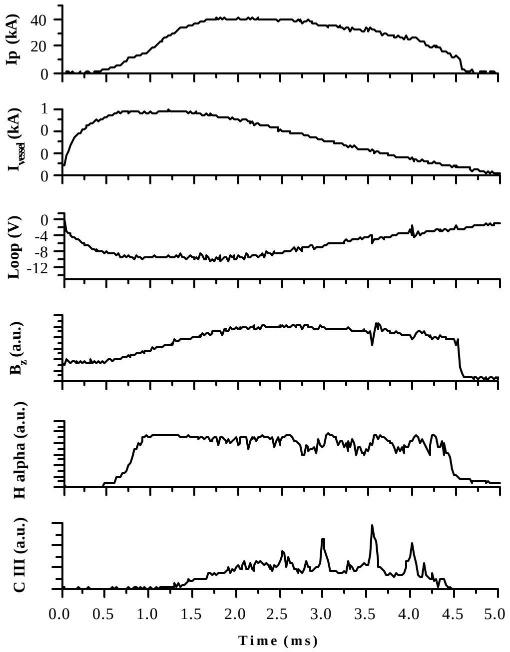


Figure 6: ETE plasma picture from CCD at 3.2 ms. The central column of the vessel is the dark bar at the left and the D-shaped plasma is close to it.

Figure 5: Electromagnetic and optical signals from ETE discharge: plasma current (I_p), induced vessel current (I_{vessel}), loop voltage (Loop), vertical magnetic field (B_z), H-alpha emission (H alpha) and carbon three emission (CIII).

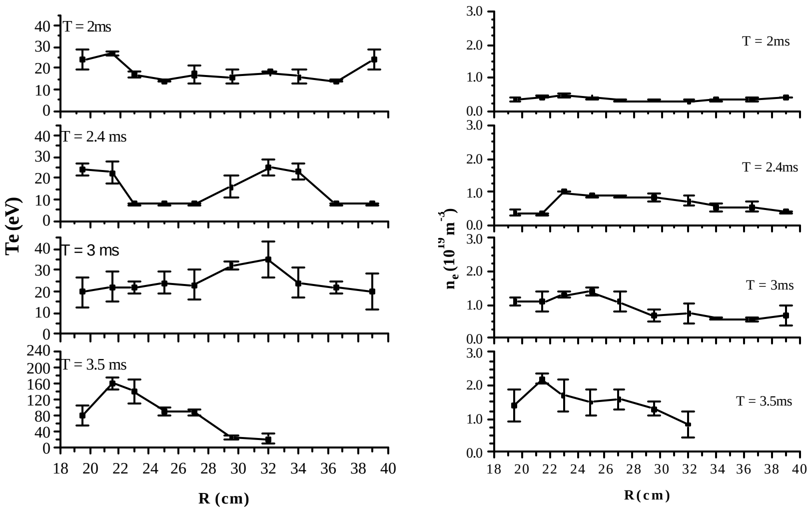


Figure 7: Temperature and density profiles obtained from Thomson scattering for different times during the ETE discharge.

Concerning the development of the FNLB probe, figure 8 shows the beam profile for two different ion gun geometries of the FNLB, measured at the neutralizer region (before neutralization). The square-dots profile was obtained after optimization of the ion gun geometry using the KARAT code. The measured average currents of the optimized beam was 350 µA against 200 µA for the previous geometry, represented by the circle-dots profile. The voltage values used in the electrostatic lenses are also showed in the figure.

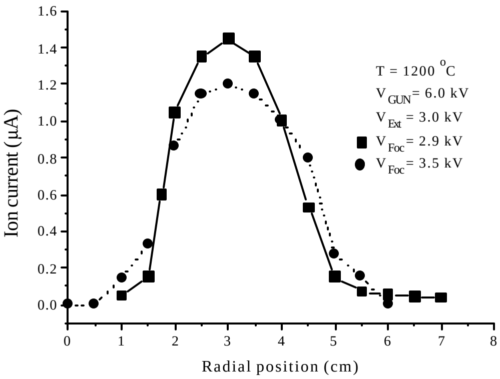


Figure 8: Radial beam profiles of the FNLB at the neutralizer for two different geometry of the ion gun. The temperature of the ion source was 1200°C and the best voltage values for each configuration are shown (V_{Gun} – acceleration, V_{Ext} – extraction, V_{Foc} – collimation).

4. Summary

The ETE spherical tokamak started operation at the end of 2000 with a plasma current of 10 kA (1.5 ms). After vacuum vessel conditioning and improvements on the magnetic coils configuration, plasma currents up to 45 kA (4.5 ms) are routinely achieved. During this period of operation, a set of basic diagnostic was installed as well as a ruby laser Thomson scattering system for temperature and density measurements. For edge plasma investigation a FNLB probe is under development.

The first results show a plasma temperature of 160 eV with densities of 2.2×10^{19} m^{-3} after the plasma compression. Because of the unbalanced vertical field, which is necessary to compensate the stray fields produced by the induced vessel current, the plasma column is shifted from the predicted position (R = 30cm) towards the central vessel column around $R \cong 21$ cm.

Presently, the main efforts are concentrated on the achievement of the first stage parameters of operation by improving the vacuum vessel conditioning, increasing the energy of the capacitor banks and compensating the stray fields. Other diagnostics are being planned as CO_2 interferometer, soft x-ray array and pick-up coils for magnetic reconstruction.

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5. References

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