Present Status of Operation of the ETE Spherical Tokamak

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Abstract. The ETE is a spherical tokamak with aspect ratio A = 1.5 (major radius of 0.3m and minor radius of 0.2m) under development at LAP/INPE. The ETE incorporates some innovative features that resulted in a compact and light weighted device with good plasma accessibility. Since the first plasma obtained at the very end of 2000 (Ip = 12kA, duration of 2ms, B_o = 0.1T), the machine is operational and improvements are being done in order to achieve the planned final parameter values for the first phase of operation (Ip = 220kA, duration 15ms, B_o = 0.4T), which are limited by the available capacitors. The efforts are being focused on incrementing the energy of the capacitor banks, lessening the stray magnetic fields in the plasma region, conditioning the vacuum vessel wall, implementing diagnostics and optimizing the discharge parameters. Presently, plasma currents in the range of 40-60kA (duration of 6-12 ms) are routinely obtained. Electron temperatures up to 160eV and plasma densities up to $3.0x10^{19}m^{-3}$ are being reached.

1. Introduction

The name spherical tokamak or Spherical Torus, ST, has been applied to tokamaks with aspect ratio A = R/a (ratio of the major to minor radii of the toroidal plasma column) close to the unit, typically A < 1.5. Several important theoretical advantages of this concept with significance for a future fusion reactor were firstly pointed out by Peng and Strickler in 1986 [1]. The spherical torus concept shows various favourable features that could improve the plasma confinement, basically producing a relatively high plasma pressure in a low magnetic field. The spherical torus concept can open an alternative route toward a more compact and less expensive fusion reactor [2,3].

Many of the predicted properties for a spherical tokamak were experimentally confirmed during the 90's in START (Small Tight Aspect Ratio Tokamak) (UK), the first spherical tokamak to produce high temperature plasmas [4], as well as in other smaller devices (e.g. CDX-U, HIT, TST, Medusa, Rotamak-ST). Immoderately high β (ratio of plasma pressure to the magnetic pressure) was achieved (up to 40%), high densities (Greenwald number G ~ 1.5) and practically no major disruptions are few examples of encouraging results obtained in START. These promising results have stimulated several laboratories worldwide to develop new ST devices, including Pegasus (USA), Globus-M (Russian Federation), ETE (Brazil), TS-4 (Japan), SUNIST (China). A second generation of spherical tokamaks with plasma current in the Mega-Amp range and strong auxiliary heating schemes are now operational: MAST (UK) [5] and NSTX (USA) [6].

The following sections of this paper show the present status of operation of the ETE spherical tokamak. More specifically, section two presents a brief description of the machine pointing out the relevant features, section three describes the main diagnostics already implemented, section four shows few results concerning the gas breakdown and plasma formation, section five presents results of the vacuum wall conditioning, section 6 shows preliminary measurements of the electron temperature and plasma density, and finally section 7 presents the conclusions and few remarks concerning the next steps.

2. Machine characteristics

The ETE (Experimento Tokamak Esférico) under development at the Associated Plasma Laboratory of the National Space Research Institute in Brazil, is a small-to-medium size spherical tokamak planned to study the basic physics of low aspect ratio geometry plasmas with emphasis on the plasma edge as well as on plasma wall interaction. Development of new diagnostics and training in tokamak operation are also important objectives of ETE.

A comprehensive description of ETE tokamak is presented elsewhere [7]. ETE was designed to operate with a plasma current up to 440kA (pulse duration of about 20ms) with a maximum toroidal magnetic field of 0.8T at the plasma axis. These ultimate parameters are limited by mechanical stresses in the demountable joints of the TF coils and by stresses and heating in the ohmic solenoid (~ 0.25Wb). The major and minor radii of the plasma column are 0.30m and 0.20m, respectively, while the elongation is 1.6. The ohmic discharge is entirely based on capacitor banks with no feedback control for the equilibrium magnetic field. Figure 1 shows a cross-section of the device where the relative position and dimension of the main components can be seen (e.g. vacuum vessel, poloidal coils, toroidal coils, support structure).

In the design of ETE a minimum set of coils was adopted for the poloidal and toroidal fields. Stray magnetic fields were minimized and good plasma accessibility was preserved. All coils are manufactured with standard pure cooper and are water cooled. The toroidal field system comprises 12 D-shaped single coils connected in series by two feed rings that compensate the stray magnetic field. The internal legs form a rigid rod, where the solenoid is wound, while the external ones are free to expand in the poloidal plane. The 12 coils produce a magnetic field ripple less than 0.3% at the plasma edge.

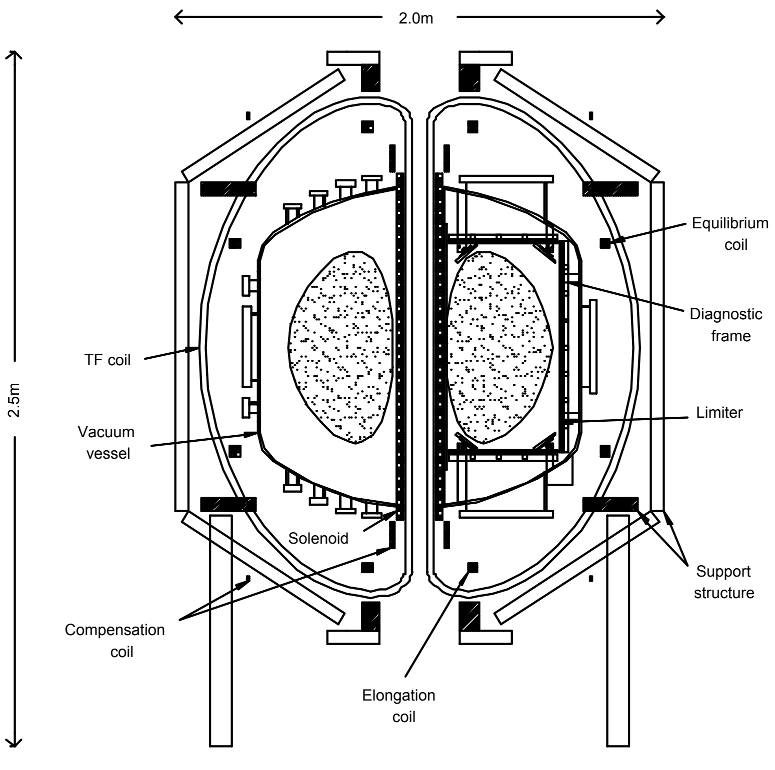

Figure 1. Cross-section of the ETE tokamak, showing the relative position of the coils, vacuum vessel, limiter and support structure.

The poloidal field system consists of: (1) the plasma magnetizing coils; (2) the equilibrium field coils and (3) the elongation coils. The magnetizing system is formed by the ohmic heating solenoid (two layers with 130 turns each) in series with two pairs of compensation coils. Presently, the elongation coils are also connected in series with the magnetizing coils. Some of the coils (equilibrium, elongation and one pair of compensation) allow small vertical adjustments.

The vacuum vessel of ETE is manufactured from Inconel 625 alloy, a relatively high resistivity material, in order to reduce eddy current effects in the continuous vessel. The inner cylinder of the vessel is 1mm thick and incorporates two stiff bellows at both ends where the tube is welded with the torispherical heads. Good access to the plasma is assured by 58 standard Conflat flanges. The vessel volume of about 1000 ℓ is pumped down to a base pressure of less than 1.3×10^{-5}Pa (1.0×10^{-7}Torr) by a turbo drag pump of 1500ℓ/s, backed by a $4m^3/h$ diaphragm pump.

3. Diagnostics

An initial set of electromagnetic diagnostics is installed, comprising: a Rogowski coil placed inside the vacuum vessel to measure the plasma current; a second Rogowski coil placed outside the vacuum vessel to measure the toroidal induced eddy current; twelve total flux coils distributed around the vessel (one is placed inside the vessel); four fixed magnetic pickup coils (B_z, B_r) placed inside the vessel and protected by the graphite limiters for magnetic field measurements; one movable (r-direction) magnetic pickup coil (B_z, B_r) coupled with a single Langmuir probe at the mid-plane, and a movable (r and θ directions) magnetic pickup coil for MHD oscillations and magnetic field measurements.

Concerning visible radiation ETE has already installed: a spectrometer (12Å/mm) for impurity emission detection; a photodiode with interference filter ($\Delta\lambda = 13.52$ nm) for H_α detection, and one fast CCD camera with speed up to 500FPS and frame velocity up to 1/10,000.

The electron temperature and plasma density is being measured by a Thomson scattering system consisting of a 10J (34ns) Q-switched ruby laser ($\lambda = 6943$Å), a 5-channel interference filter polychromator with avalanche photodiode detectors, and collecting lenses with f/6.3 capable of scanning 22 different plasma positions at the mid-plane covering approximately 51cm along the laser path [8]. Presently, only one polychromator is available allowing measurement of one plasma position per shot. In order to increase the number of measured points in one single shot, a low cost multiplexed time-delay technique using several optical monofibers with monotonically increased lengths are being tested. It is estimated a maximum of 10 monofibers (10 plasma positions) given reasonable signal to noise ratio with the available polycromator. Presently, 4 fibers with diameter of 0.8mm and length increasing steps of 14 m are installed [9].

A fast neutral lithium beam is being developed for plasma density measurements at the plasma edge. The beam is operated with an energy of 15keV ($1mA/cm^2$) with a neutralization efficiency of about 80%. The lithium ion source is a vitreous β-eucryptite compound heated to temperatures up to 1100°C. Three electrostatic cylindrical lenses accelerate the beam while deflection plates perform small adjustments in the beam trajectory. Neutralization of the ion beam is based on pulsed vapor sodium. Presently, just one point of plasma can be measured in one shot [10].

4. Plasma formation

Eddy currents in the vacuum vessel of ETE play an important role during the gas breakdown as well as in subsequent phases, since they produce stray magnetic fields in the plasma region and consume part of the ohmic heating energy. Figure 2 shows the time evolution of the currents in the three coil systems produced by the present configuration of the capacitor banks. It can be observed in figure 2-d the relatively high induced eddy current produced by the ohmic heating and equilibrium circuits. Fine compensation for the stray magnetic fields to help the gas breakdown is accomplished by proper tuning the time delay trigger between the ohmic heating and equilibrium circuits. It is worthwhile to emphasize that there is no feedback control for the equilibrium field. Figure 3 shows the characteristic breakdown curve obtained with and without pre-ionization. Since first plasma, clear progress has being obtained upgrading and improving the operation conditions, as can be seen in figure 4. In figure 5 the plasma cross section can be observed as measured by the fast CCD camera.

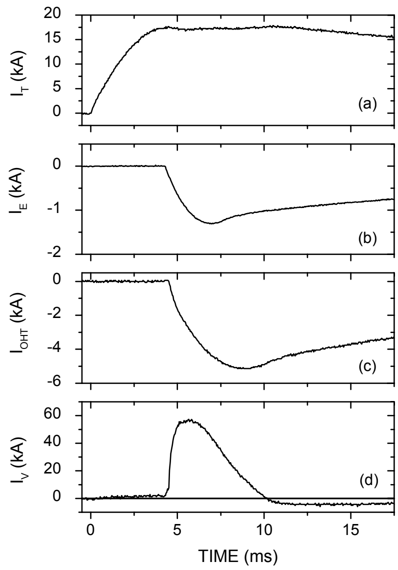

Fig. 2 Coil currents: (a) toroidal, (b) equilibrium, (c) ohmic heating, and (d) induced eddy current in the vacuum vessel.

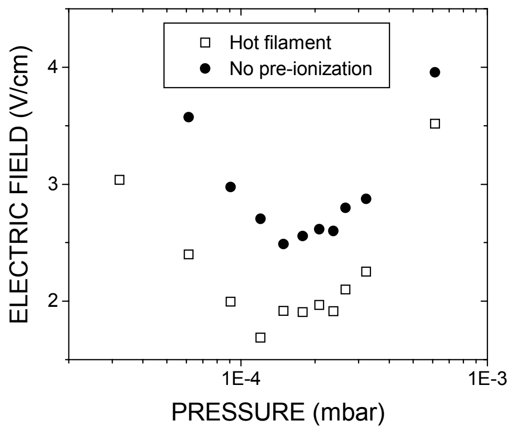

Fig.3.Breakdown curves obtained with and without hot filament pre-ionization for present configuration of the poloidal fields.

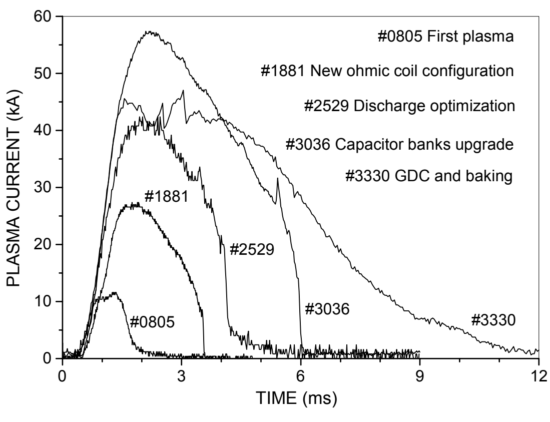

Fig. 4 Plasma current evolution since the first plasma

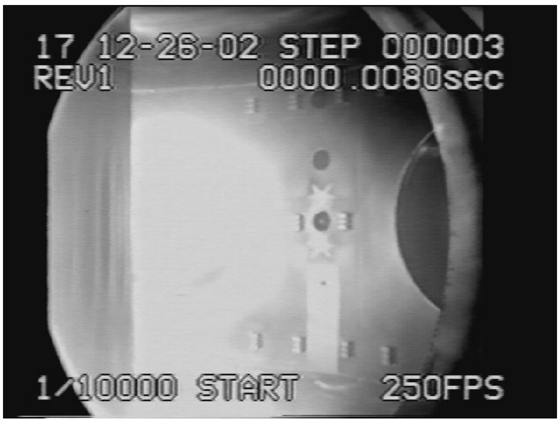

Fig 5. Cross section view of the plasma obtained with a fast CCD camera

5. Vacuum conditioning

The vacuum quality is a fundamental requirement for obtaining good tokamak plasmas. To achieve such needs two systems are implemented in the ETE tokamak: a vessel wall baking (VWB), and a glow discharge cleaning (GDC). The vessel is heated by several hot tapes fixed over the vessel surface which is thermally insulated by fiberglass blankets. The current in the tapes are controlled by an electronic circuit which maintains the desired temperature. The vessel can withstand a temperature as high as 200^{o}C. Presently, the vessel is baked to a safe steady state temperature of about 100^{o}C.

The GDC is based on a direct current discharge between one water cooled anode (40cm^2) and the vacuum vessel. An adjustable power supply of 1.2kV/20A having a ballast resistor breaks the gas insulation and maintains the discharge. Normal operation parameters are current of 0.5A, voltage of 500V and helium gas at pressure of about 3x10^{-4}Torr. During GDC the turbo pump is baked by a rotary vane pump of 30m^3/h. A residual gas analyzer is used to measure the gas composition after GDC/VWB.

Figures 5 and 6 show examples of plasmas obtained before and after a typical baking/cleaning campaign (few hours), respectively. It can be observed a decreasing of the H_α emission and a corresponding increasing of the pulse duration after GDC/VWB. Evidence of runway discharge (hard x-ray in the CIII detector) is observed for low pressure discharge after GDC/VWB, where plasma current exists although the loop voltage is zero. The loop voltages as shown in figures 5 and 6 are measured outside the vacuum vessel between the solenoid and the inner tube at the z = 0.

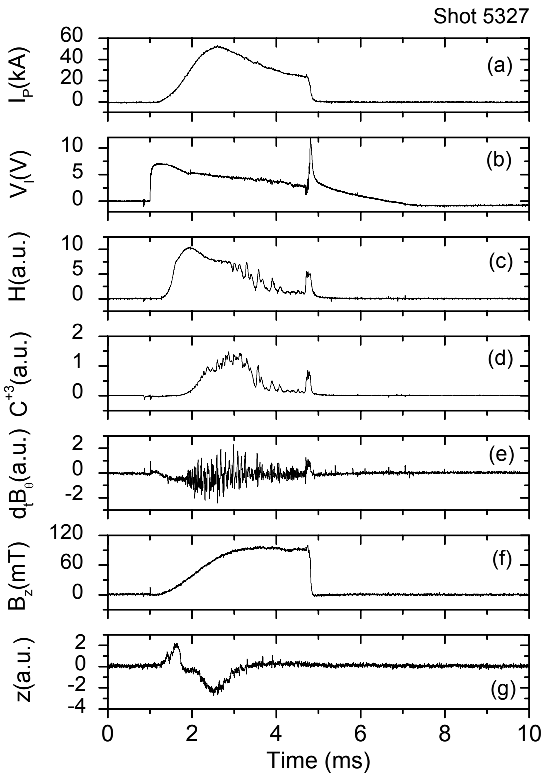

Figure 5. Typical discharge before GDC/VWB, (a) plasma current, (b) loop voltage, (c) H_α, (d) CIII, (e) dB_θ/dt, (f) B_z at z = 0, (g) vertical displacement.

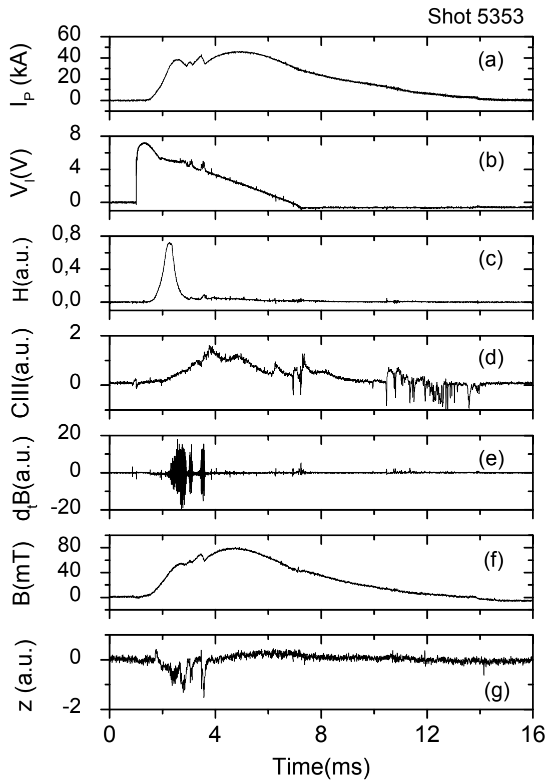

Figure 6: Typical discharge after GDC/VWB (a) plasma current, (b) loop voltage, (c) H_α, (d) CIII, (e) dB_θ/dt, (f) B_z at z = 0, (g) vertical displacement.

6. Electron temperature and plasma density

Figure 7 presents preliminary measurements of the radial profile of the plasma density and electron temperature obtained with the one-channel Thomson scattering using the shot by shot technique. The values are the average obtained from three shots at the same conditions (estimated error is about 7%). The density reached about 3.0×10^{19} m^{-3} while the temperature attained up to 160eV. Figure 8 shows the radial profile (4-points) of the electron temperature obtained with the one-polycromator multiplexed Thomson scattering system.

After extensive commissioning work the fast lithium beam was tested to measure the electron density at the plasma edge. Figure 9 shows the plasma density measured by the Thomson scattering (open squares), lithium beam (solid diamond) and Langmuir probe (solid circles). It can be observed a good agreement between the three diagnostics.

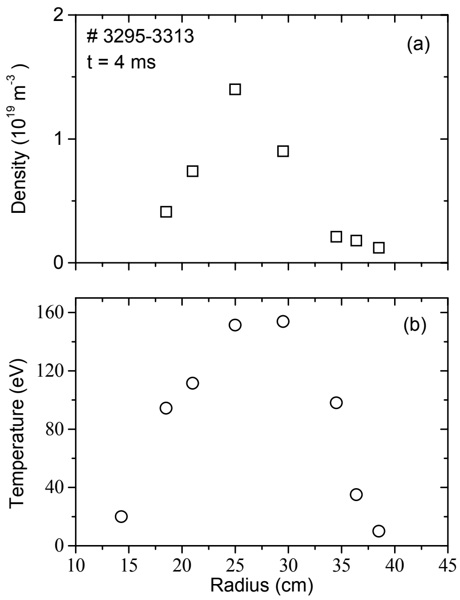

Fig. 7 One-channel TS measurements: (a) plasma density and (b) electron temperature profiles for discharges of type #3036 (fig. 4).

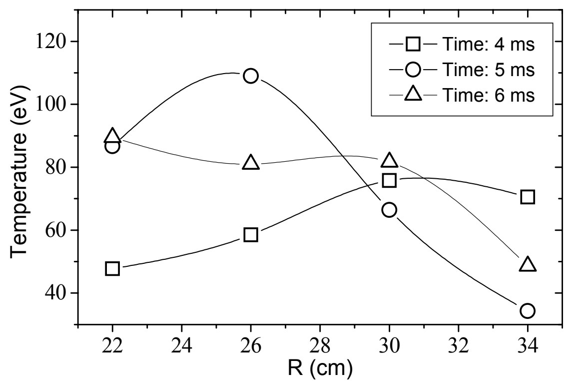

Fig. 8. Four-channel multiplexed TS measurement of the electron temperature obtained in one shot. The three curves where obtained in three different shots.

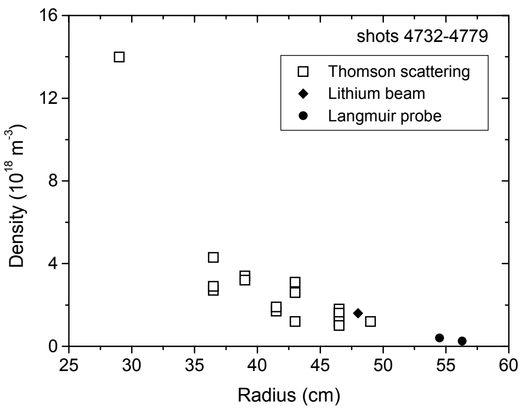

Fig. 9. Radial profile of n_e measured with: Thomson scattering; fast neutral beam and Langmuir probe.

7. Final remarks

Presently, only about ¼ of the total energy required for the first phase of operation (I_p ~ 220kA) is installed. Capacitors and power supplies are already available and need to be assembled. The voltage rating of the ohmic heating capacitor bank can also be increased in 75%. The installed diagnostics are running properly. Nevertheless, several others must be designed and installed (e.g. soft x-ray arrays, complete set of electromagnetic pickup coils, interferometer, hard x-ray detector). The laboratory is working in an improved conception of monotron valve of about 6.7GHz and 30kW of out put power for pre-ionization purposes. The available data acquisition system based on CAMAC standard is quite poor. A new data acquisition system based on VME standard is under way.

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