Initial Results from the TST-2 Spherical Tokamak

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Abstract. A new spherical tokamak TST-2 was constructed at the University of Tokyo and started operation in September 1999. Reliable plasma initiation is achieved with typically 1 kW of ECH power at 2.45 GHz. Plasma currents of up to 90 kA and toroidal fields of up to 0.2 T have been achieved during the initial experimental campaign. The ion temperature is typically 100 eV. Internal reconnection events (IREs) are often observed. The internal magnetic field measured at r/a = 2/3 indicated growth of fluctuations up to the 4^{th} harmonic, suggesting the existence of modes with several different mode numbers. In the presence of a toroidal field and a vertically oriented mirror field, noninductively driven currents of order 1 kA were observed with 1 kW of ECH power. The driven current increased with decreasing filling pressure, down to 3×10^{-6} torr. A study of high harmonic fast wave (HHFW) excitation and propagation has begun. Initial results indicate highly efficient wave launching.

1. Introduction

TST-2 is a new spherical tokamak (ST) constructed at the University of Tokyo as an upgrade of TST-M [1]. Typical design parameters are: R ≤ 0.36 m, a ≤ 0.23 m, A ≥ 1.6, $\kappa \le 1.8$, $B_T \le 0.4$ T, $I_p \le 0.2$ MA, and discharge duration $\tau \le 50$ ms. Figure 1 shows a comparison of TST-2 and TST-M. The design of TST-2 is described in some detail in Ref. [2]. The most significant improvement of TST-2 over TST-M was on the OH volt-second capability, from 25 mVs to 130 mVs for single swing operation. This improvement has enabled plasma operations at higher plasma currents and longer durations. Presently, the power supply capability is being upgraded to take advantage of the improved OH solenoid capability. A conservative estimate of the stored energy based on the ITER98IPB(y,1) scaling [3] with $H_H = 0.5$ (*i.e.*, half of the H-mode scaling), assuming a loop voltage of 2 V, indicates that $\beta_T \le 10\%$ and $T_{e0} \le 300$ eV can be achieved by Ohmic heating alone.

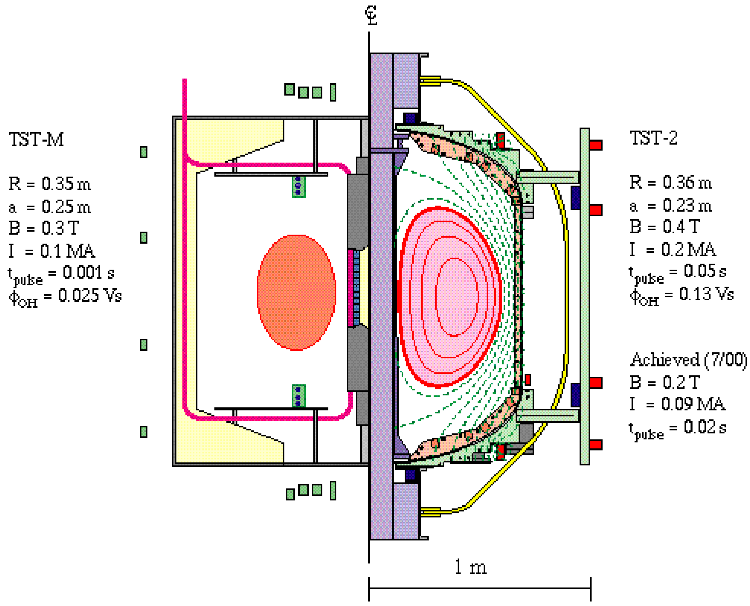

Fig. 1 Comparison of TST-M and TST-2.

2. Inductively Driven Plasmas

The first TST-2 plasma was obtained in September 1999. During the initial phase of the experiment, emphasis was placed on improving plasma initiation and plasma current ramp-up. Reliable plasma initiation is achieved with typically 1 kW of ECH power at 2.45 GHz. The fundamental ECH resonance layer is located inside the vacuum vessel near the outer wall. Inductively driven plasma currents of up to 90 kA were obtained (Fig. 2) at a toroidal field of 0.15 T, with typical discharge durations of approximately 10 ms. Longer pulse lengths of up to 20 ms were obtained at slightly lower currents (70 kA). Since these results were obtained with less than 40 mVs, operation at the 200 kA level should be achievable with the full volt-second capability. The ion temperature measured by Doppler broadening of the OV line (278.1 nm) in a plasma with 70 kA plasma current is approximately 100 eV. While there is no direct measurement of the electron temperature at present, it is also estimated to be of the order of 100 eV from the resistivity and from the time evolution of impurity line emission from different ionization states (Fig. 3).

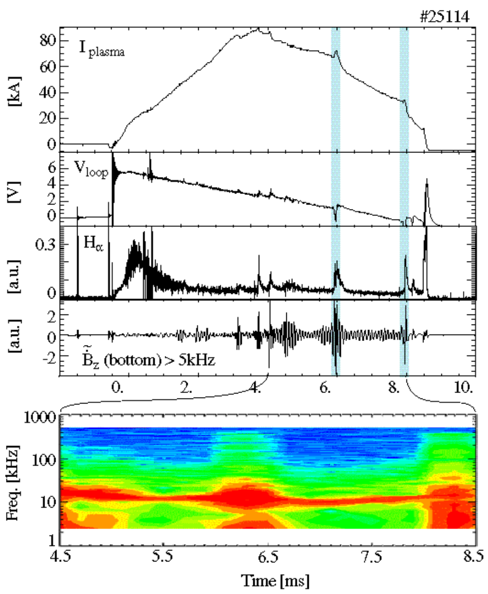

Fig. 2. A typical TST-2 discharge. IREs are observed during the current decay phase (at 6.4 and 8.4 ms).

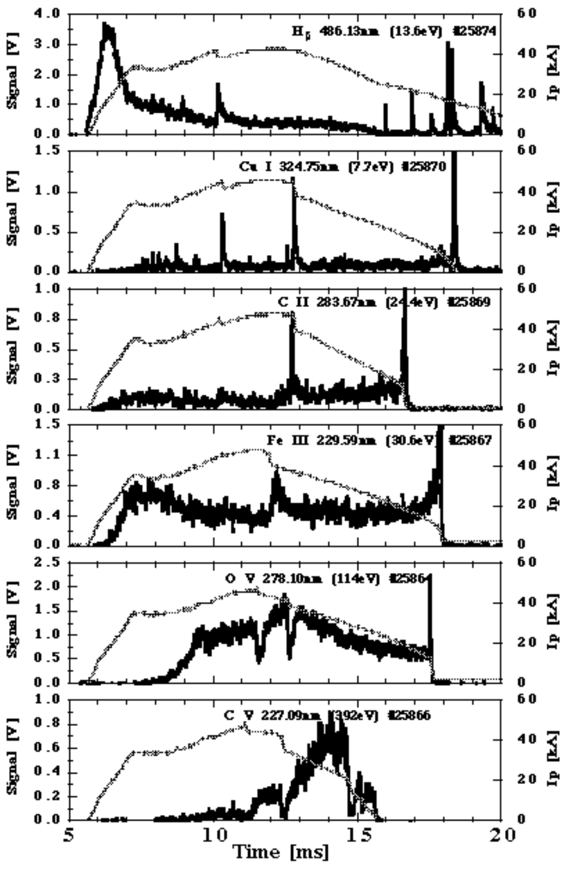

Fig. 3. Time evolution of impurity lines.

3. Internal Reconnection Events

MHD phenomena peculiar to the ST called internal reconnection events (IREs) [4] are often observed, particularly during the current decay phase. As shown in Fig. 2, positive spikes on the plasma current and negative spikes on the loop voltage are observed, suggesting a flattening of the current density profile. The line-average density decreases and the H_α emission increases abruptly during an IRE, indicating a significant particle loss. In some cases, substantial density drops of as much as 40% have been observed. Time evolutions of different impurity lines, obtained for similar discharges, are displayed in Fig. 3. The intensities of impurity line emission from states with higher ionization potentials such as C V (392 eV) decrease by larger factors during an IRE, suggesting that there is also a significant loss of electron thermal energy. On the other hand, a large increase of Cu I line emission is observed indicating influx of copper, which is the plating material of the high-harmonic fast wave (HHFW) antenna located on the outboard side of the torus.

Coherent magnetic fluctuations in the frequency range of 10–20 kHz are observed on the magnetic probe signal (measured in the shadow of the limiter) and on the line-average density, prior to and during an IRE. The toroidal mode number, measured by magnetic probes located near the midplane outside the vacuum vessel, was predominantly n = 1. The amplitude of this mode grows rapidly just before an IRE. Magnetic probes inserted inside the plasma at r/a ≅ 2/3 show generation of harmonics up to the 4^{th} harmonic [5], suggesting the existence of multiple modes. This result is consistent with the result of a 3-D numerical simulation of an IRE [6], which indicates the growth of modes with different toroidal mode numbers.

4. Noninductively Driven Currents

Elimination of the OH solenoid from the center of the device is a crucial step for the ST to be considered a candidate for a fusion reactor. Therefore, development of noninductive means of plasma startup is very important. In TST-2, plasma currents of up to 1.2 kA were generated by initiating and heating the plasma using 1 kW of ECH power, with negligibly small loop voltage (less than 0.1 V). Such currents were observed on CDX-U [7] and were identified as pressure-driven currents. The generated current increased with decreasing filling pressure down to the optimum value of 3×10^{-6} torr as shown in Fig. 4. Below this pressure no current was observed, and at 1×10^{-4} torr the observed current was 0.1 kA, an order of magnitude smaller than that at the optimum filling pressure. This is an indication that low collisionality is important for efficient current drive.

A magnetic mirror configuration in the vertical direction (such as that shown in Fig. 5) is required for efficient current generation. No observable current is detected when the poloidal field is purely vertical. The generated current increases when the location of the fundamental EC resonance layer approaches the inboard limiter (located at R = 0.127 m). However, no current is observed when the resonance layer is located too close to the inboard limiter (less than R ≅ 0.2 m, but the exact value depends on the operating condition). These observations suggest that the formation of vertically mirror-trapped orbits is important. Toroidal precession of these trapped electrons is believed to be important for initiation of the toroidal current [7]. An array of magnetic probes distributed along the center column indicated that the direction of the vertical magnetic field was reversed around the midplane (-0.4 m $\leq z \leq 0.3$ m). This is an indication that a closed magnetic surface has formed by generation of a toroidal current.

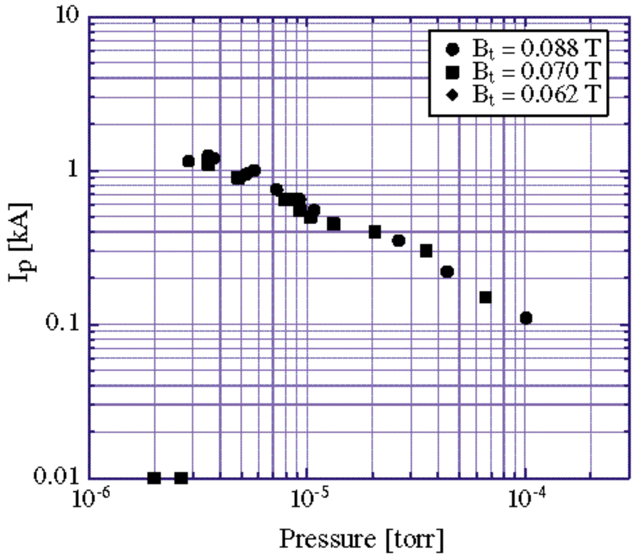

Fig. 4. Driven current as a function of filling pressure.

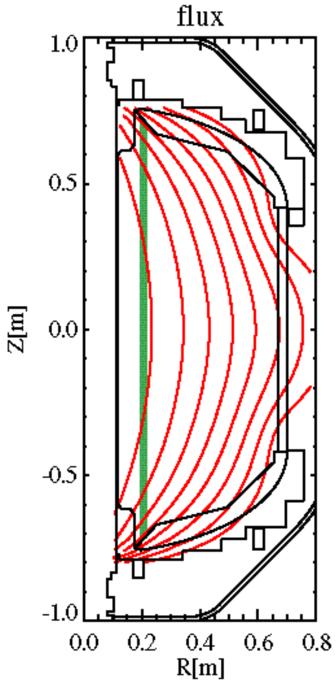

Fig. 5. Flux contour and the location of the ECH resonance layer at current maximum.

5. High Harmonic Fast Wave

Because STs can confine high pressure plasmas at low magnetic fields, ST plasmas can have much larger dielectric constants (~ $\omega_{pe}^2/\omega_{ce}^2$) than conventional tokamak plasmas. The high-harmonic fast wave (HHFW) is considered to be a promising wave for heating and current drive in such high-dielectric plasmas, because it has good accessibility to the core of a high density plasma, and it can be absorbed effectively by electrons. Important issues are absorption of the HHFW by ions and mode conversion of the HHFW to the IBW at high harmonics of the ion cyclotron frequency. On TST-2, radiofrequency (RF) wave physics experiments, concentrating on detailed studies of wave excitation, propagation, and absorption, have begun. A low-power (1 kW level) HHFW in the frequency range 20–30 MHz is launched from a 6-element combline antenna. RF power is applied only to the first element (current strap). RF currents in the other 5 elements are induced sequentially through mutual inductance between neighboring elements [8]. This antenna behaves as a bandpass filter with the passband in the frequency range 22–28 MHz. The phase shift between neighboring antenna elements can be selected in the range 0 to π by choosing an appropriate frequency within this passband. The net antenna input power (incident minus reflected) and the antenna current in the first current strap are shown for a typical TST-2 discharge in Fig. 6. As the plasma current increases and the plasma grows to its full size, the loading resistance increases as expected. Wave launching was found to be highly efficient. Almost all of the incident power was radiated from the first current strap. This result indicates that a two-strap antenna driven out of phase (“dipole antenna”) would work well for heating. However, in order to take advantage of the combline antenna for current drive, efforts to reduce the loading resistance would be necessary.

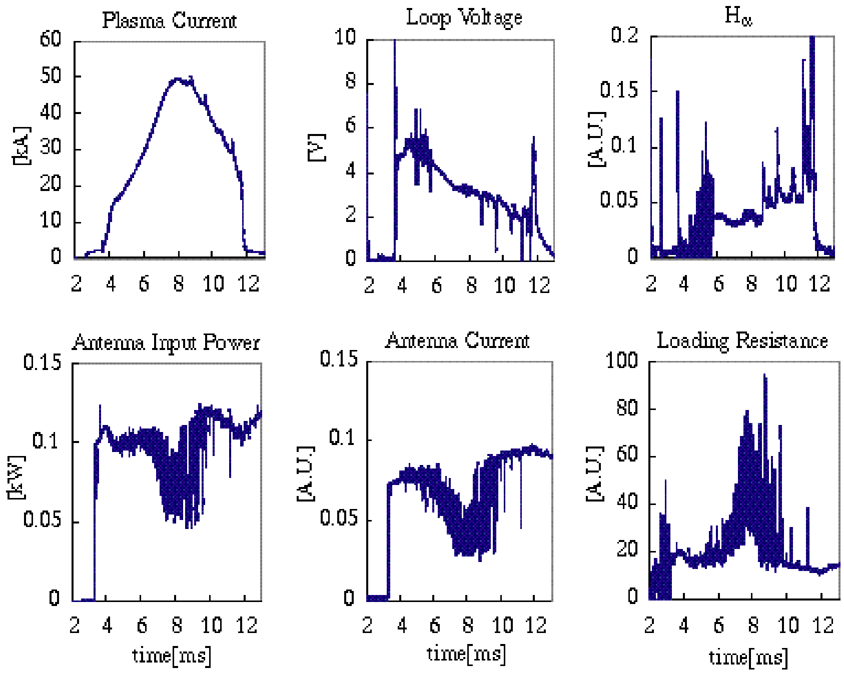

Fig. 6. I_p, V_{loop}, H_α, HHFW input power, antenna current, and loading resistance. The RF power is on for the entire discharge duration.

Acknowledgment

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