

LOW ASPECT RATIO TOKAMAK PRODUCED BY NEGATIVE-BIASED THETA-PINCH

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Abstract

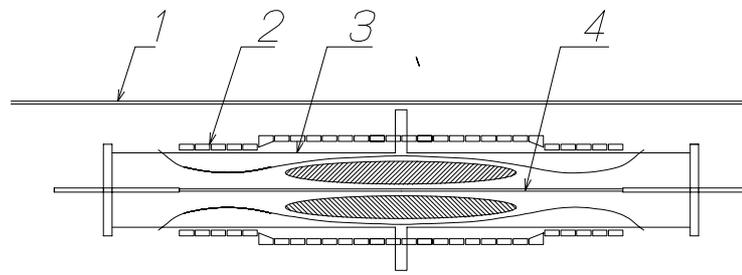
A spherical tokamak which has a highly elongated cross-section $\kappa \sim 10$ and a low aspect ratio $A=1.1$ is produced by a negative biased theta-pinch. The safety factor at the plasma edge is $q_{\text{edge}} \sim 30$ which is estimated from an internal magnetic field measurement at $I_{\text{tfc}}/I_{\text{p}} = 19.5\text{kA}/280\text{kA} \sim 0.07$. The overall behaviors of the plasma are investigated from many points of view.

1. Introduction

A combination of a low aspect ratio and high shaping of the plasma cross-section is important to achieve a high β value of a spherical tokamak (ST) [1]. On the START experiment, a high value $\beta_{\text{T}} \geq 30\%$, where $\beta_{\text{T}} = 2\mu_0 \langle p \rangle / B_0^2$ ($\langle p \rangle$ and B_0 are the volume averaged plasma pressure and the vacuum toroidal field at the geometric center of the plasma, respectively), has been recently achieved [2]. The plasma has an aspect ratio $A \sim 1.3-1.5$, a vertical elongation $\kappa \sim 1.7-1.9$ and a triangularity $\delta \sim 0.5$.

It is known that a field-reversed configuration (FRC) possesses intrinsically the high β value ($\geq 90\%$) since it has no toroidal field. And it has normally high elongation of the plasma cross-section $\kappa \geq 5$ [3]. These features of the FRC are available to study a ST with a highly elongated cross-section if the toroidal field can be added during the FRC formation.

Then, a conducting rod is installed into a vacuum vessel along the central axis of theta-pinch-coil to produce a toroidal



1. Return cable 2. Theta-pinch coil
3. Quartz tube 4. Central conducting rod

Fig. 1. Cross section of the NUCTE-ST device

field as a similar modification to the Heidelberg Spheromak experiment [4]. The schematic of the NUCTE-ST device is shown in Fig. 1. The rod is wrapped by a thin electrical isolation tape and covered by a quartz tube with 0.5cm radius to avoid the contact of the plasma with the tape. The toroidal field in the plasma can be controlled by the current flow I_{tfc} in the rod.

The poloidal field and the vertical field are produced by a combination of a slowly varying bias current and a fast rising current in the theta-pinch-coil. The coil consists of a confinement region with 100cm length and 17cm radius, and end regions with 25cm each length and 14cm radius. The fast rising magnetic field produced by the current heats the plasma through the radial and the axial compression at the formation phase of a ST. The I_{tfc} is applied at $20\mu\text{s}$ before the start of the fast rising current. The e -folding times of the poloidal field and the toroidal field are 0.08ms and 0.1ms, respectively. The vacuum vessel consists of a quartz tube with 200cm length and 12cm inner radius.

2. Experimental results

Figure 2 shows the I_{tfc} dependence of the configuration lifetime. The ordinate r_s of (a) means an outboard radial position of the separatrix. It is calculated from a vertical field on the quartz tube [5]. In case of $I_{\text{tfc}}=10\text{kA}$, the r_s drops to zero within 0.06ms. On the other hand, the r_s retained for 0.1ms is achieved in $I_{\text{tfc}}=30\text{kA}$. The average electron density near the horizontal plane is presented in Fig. 2-(b). In case of $I_{\text{tfc}}=30\text{kA}$, the density is almost constant ($n_e \approx 3 \times 10^{21} \text{m}^{-3}$) during the discharge. In other cases, the electron density increases gradually with time and terminates the discharge.

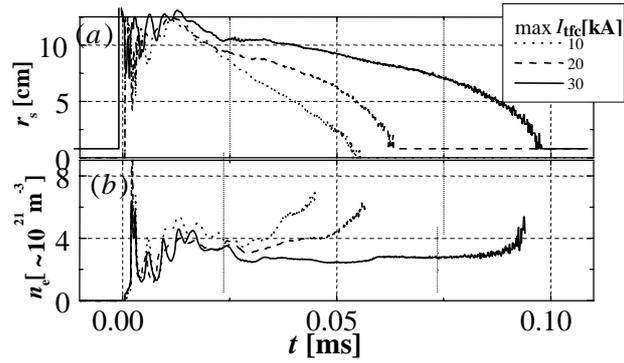


Fig. 2. Time evolution of (a) r_s and (b) averaged electron density

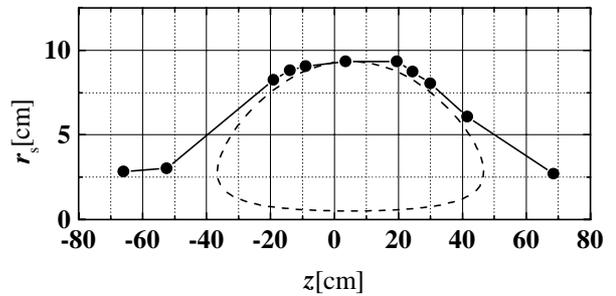


Fig. 3. Outboard edge of the separatrix and model shape

The separatrix edge profile is also obtained from the vertical fields which are detected by

a magnetic probe array on the tube. The closed circles in Fig. 3 are experimental data and the dashed line is a separatrix shape which is calculated from fitting the parametric expression [6].

$$\begin{aligned} R &= R_0 + a \cos(\theta + \delta \sin \theta) \\ z &= z_0 + \kappa a \sin \theta \end{aligned} \quad (1)$$

where θ is the azimuthal angle from the major radius, and R_0 , a , δ , κ , and z_0 are the major radius, minor radius, triangularity, elongation, and vertical displacement, respectively. The dashed line is used $R_0=4.9\text{cm}$, $a=4.4\text{cm}$, $\delta=0.5$, $\kappa=10$, and $z_0=5\text{cm}$.

Internal magnetic field profiles are presented in Fig. 4. The dotted line means the vacuum toroidal field. In the outboard region ($R \approx 9\text{cm}$), the poloidal field is larger than the toroidal field ($|B_p| > |B_t|$), but both magnetic fields are comparable ($|B_p| \sim |B_t|$) at the inner region ($R \approx 2\text{cm}$). The poloidal field is reversed at $R_{\text{axis}} \sim 4.5\text{cm}$ where the toroidal field is 1.7 times the vacuum field B_{t0} . This field increase can be explained from a paramagnetic current flow which is one of the characteristics of a spherical tokamak. The edge safety factor is estimated from the rectangular model [7] as $q_{\text{edge}} \sim 30$.

Figure 5 shows the toroidal current density estimated from Fig. 4. The plasma current I_p is about 280kA. Then the ratio I_{tfc} to I_p is less than 0.07.

The plasma pressure is calculated by using the equation of radial pressure balance at the horizontal plane

$$p(R) = \frac{1}{2\mu_0} (B_e^2(R_t) - B_i^2(R)) - \frac{1}{\mu_0} \int_{R_t}^R \frac{B_\theta^2(R)}{R} dR \quad (2)$$

where $B_e^2(R_t) = B_z^2(R_t) + B_\theta^2(R_t)$,

$$B_i^2(R) = B_z^2(R) + B_\theta^2(R),$$

and R_t is the quartz tube radius. The pressure profile (Fig. 6) has a peak at near R_{axis} and the pressure gradient is steep in the inner region $R=3\text{-}5\text{cm}$, but gentle in the outer region $R > 6\text{cm}$. The values β_T and β_p are 2.1 and 0.4, respectively, where $\beta_p = 2\mu_0 \langle p \rangle / B_p^2(R_t)$. The total temperature ($T_t = T_i + T_e$)

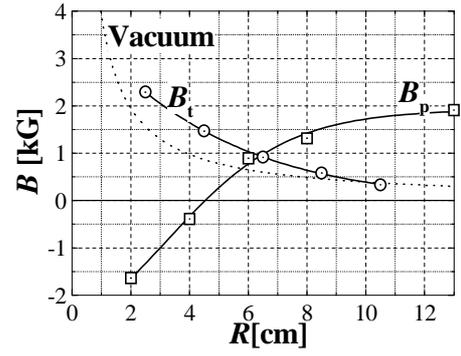


Fig. 4. Internal magnetic field and toroidal vacuum field

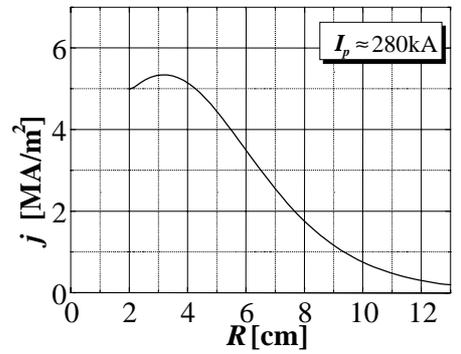


Fig. 5. Current density distribution

estimated from the average pressure and electron density is $\sim 14\text{eV}$.

3. Summary

A spherical tokamak is produced and confined in a theta-pinch-coil with a conducting rod. Typical shaping parameters of the plasma are $R=4.9\text{cm}$, $a=4.4\text{cm}$, $\kappa=10$ and $\delta=0.5$. The poloidal field strengths are $B_{p1}=1.6\text{kG}$ at the inner edge of the separatrix and $B_{p2}=1.6\text{kG}$ at the outer edge. The toroidal field is $B_t=1.5\text{kG}$ at the magnetic axis, the value of which is about 1.7 times the vacuum strength. The MHD instabilities with high growth rate such as a shift, a tilt [7] a kink and a ballooning mode [8] are not observed. The present plasma terminates the discharge with the decay of the external circuit.

The plasma parameters will be improved by a low fill pressure operation and an increase of the condenser bank in the near future.

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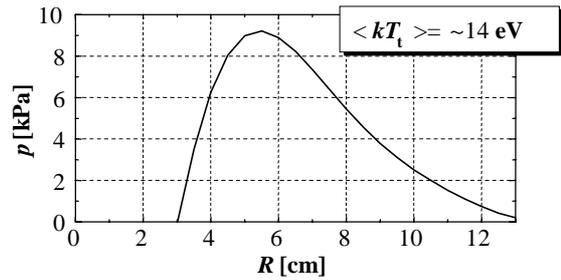


Fig. 6. Plasma pressure profile