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Highly Elongated Low Aspect Ratio Tokamak Produced by Negative-Biased Theta-Pinch

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1. Introduction

An extremely highly elongated (κ=10) low aspect ratio tokamak has been produced by a negative-biased theta-pinch device, with a center conductor rod, which is named NUCTE-ST [(1)]. To improve plasma parameters, this device is modified. By this modification, the maximum current of the center conductor rod (I_{tfc}) increases to about 55kA and the main magnetic field strength is extended to about 4.5kG. As a result, the plasma temperature reaches to 55eV by the stronger magnetic compression at a formation phase. Some parameters of the plasma, such as a minor radius a, a major radius R_0, an aspect ratio A, an electron density n_e, a life time of a configuration τ, a plasma current I_p and an edge safe factor q(a) are 3-5.5cm, 4-6.5cm, 1.2-1.3, 2-4x10^{21}m^{-3}, 40-120µs, 170-340kA and 30-60, respectively.

An numerical solution of the Grad-Shafranov equation of a low aspect ratio tokamak with a high elongation is obtained, and the solution is compared with experimental results. The safety factor is estimated from the solution.

2.Modification of the device and optimization of the time sequence of the discharge

In the previous device, the maximum I_{tfc} was limited to 30kA because the center conductor rod was made of a composite rod of a stainless steel (ϕ 20) and an aluminum (ϕ 11), and not able to bear the electromagnetic force produced by the current itself. The new rod is made of the all-aluminum rod (ϕ 20) and its weight is lightened and equipped the ability to flow the current up to 55kA and the decay time is prolonged to 270µs. The modified NUCTE-ST is shown in Fig.1. By the increase of I_{tfc}, the strength of the toroidal field makes the plasma keep away from the center conductor rod at a formation phase. So that the maximum main magnetic field increases to 4.5kG, which is produced by a current in the theta pinch coil. The increase of the current of I_{tfc} is also effective in suppressing the vertical displacement. In addition, two

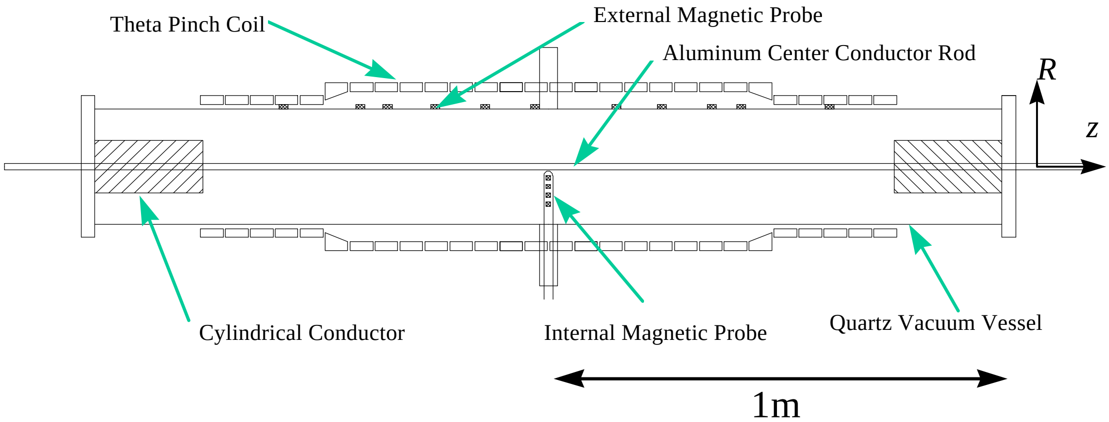

Fig. 1 Experimental device NUCTE-ST

cylindrical conductors are prepared at the both ends of inside of the vacuum vessel to control the vertical displacement.

The energy of a ringing magnetic field for a pre-ionization is increased from 3.5 to 5.9kJ to make and maintain a sufficiently ionized and a high temperature plasma. The pre-ionization plasma is formed at 35μs before the main magnetic field is driven. The initial bias field is risen from about -600 to -800G to increase a poloidal flux at an equilibrium phase. The toroidal field starts after the pre-ionization plasma formed and attains a maximum strength when the main field is applied. The working gas is deuterium and is filled statically in the discharge tube with 10mTorr filling pressure.

3.Experimental result

We present the experimental results of two typical plasmas. The both plasmas are produced under the condition of the maximum current of I_{tfc}=55kA. The plasma of Type(a) has the main magnetic field strength of 1.6kG. In Type(b), a stronger main magnetic field of 3.2kG is applied.

The shape of the poloidal cross-section of the tokamaks are shown in Fig.2. The open circles are the outer board separatrix radius estimated by the poloidal diamagnetism and the closed lines indicate the fitting curve estimated from the following equations.[2]

$$R(\theta) = R_0 + a\cos(\theta + \sin^{-1}\delta\sin\theta)$$
$$z(\theta) = Z_0 + \kappa a\sin(\theta + \zeta\sin 2\theta) \qquad (1)$$

Here, Z_0, δ and ζ are a deviation along *z*-direction, a triangularity and a squareness, respectively. The shape of Type(a) is plump. The outer board separatrix radius (= $a + R_0$) is about 11cm, and this is close to the vacuum vessel inner radius (=12.5cm). On the other hand, Type(b) plasma is compressed by a stronger magnetic field, and becomes a tight shape. The plasma length (=κ*a*) is the same as Type(a). Since the shape of both ends have some errors of a measurement, there are less reliability in this region. The shape parameters of above plasmas are listed in Table1.

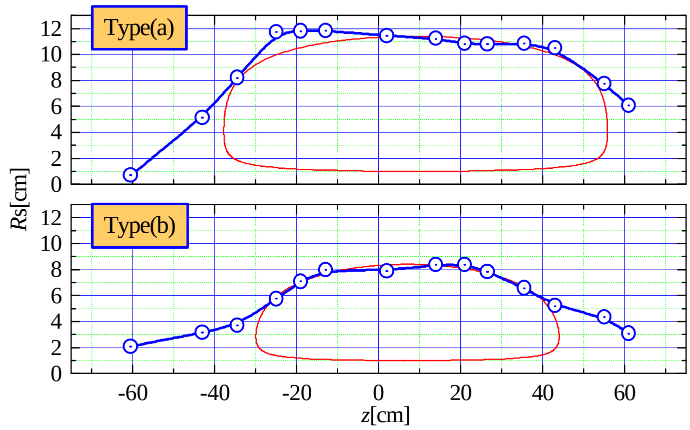

Fig. 2 Shape of poloidal cross-section

The plasma pressure profiles estimated from the internal magnetic field profile and the assumption of the pressure balance are shown in Fig.3. Note that these are not the same shots of the Fig.2 because the internal magnetic probe is inserted and the main magnetic field is slightly changed. The main magnetic fields of Type(a) and Type(b) are 1.2 and 3.3kG, respectively.

Table 1 Shape parameters

	Type(a)	Type(b)
Major Radius[cm] R_0	6.2	4.7
Minor Radius[cm] *a*	5.2	3.7
Elongation κ	9	10
Triangularity δ	0.4	0.5
Squareness ζ	0.3	0.2

The external magnetic pressure of Type(b) is about 8 times stronger than that of Type(a). Therefore the maximum pressure of Type(b) at the null point is about 8 times higher than that of Type(a). The averaged electron densities of Type(a) and (b) are $2.4\mathrm{x}10^{21}$ and $3\mathrm{x}10^{21}\mathrm{m}^{-3}$, respetively. The plasma temperature of Type(a) 10eV and Type(b) 55eV are estimated from the pressure and the electron density. From the observation of the internal magnetic field, the time evolution of the null point is obtained(Fig.4). In Type(a), the position of the null point does not move during its lifetime, whose position is about 7cm. On the other hand, in Type(b), it moves to the inner region near the end of its lifetime.

The above results suggest two possibilities, that the plasma is able to be heated by the magnetic compression at a formation phase and the shape of the poloidal cross-section is able to be controlled, keeping the high elongation.

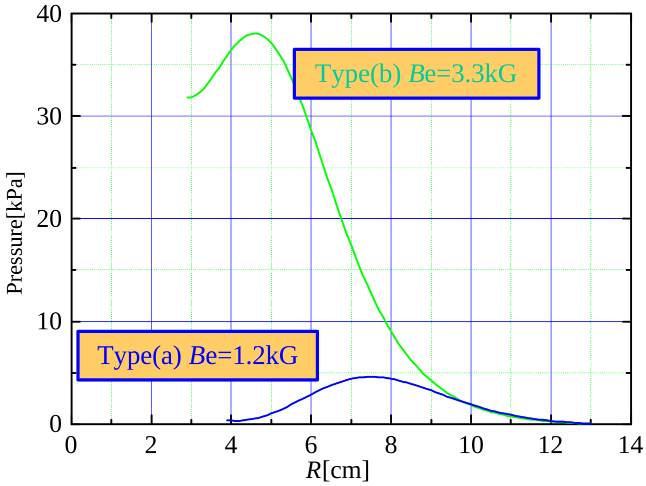

Fig. 3 Pressure profile obtained from internal magnetic field profile

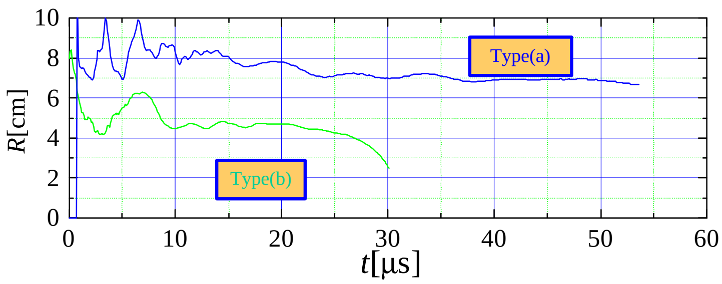

Fig. 4 Time evolution of the null point

4.Numerical solution of the Grad-Shafranov equation for a highly elongated low aspect ratio tokamak.

The following two-dimensional Grad Shafranov equation,

$$R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial \Psi}{\partial R}\right)+\frac{\partial^2 \Psi}{\partial Z^2}=-\mu_0 R^2\frac{dp(\Psi)}{d\Psi}-F\frac{dF(\Psi)}{d\Psi} \quad (2)$$

has been solved. Here, Ψ, $p(\Psi)$ and $F(\Psi)$ are a flux function, a pressure function and a net poloidal current function, respectively. The boundary condition on the theta-pinch coil wall of a center region ($0<z<50$cm) is $\psi=1$, and a mirror region ($50<z<75$cm) is 1.5 corresponded to the

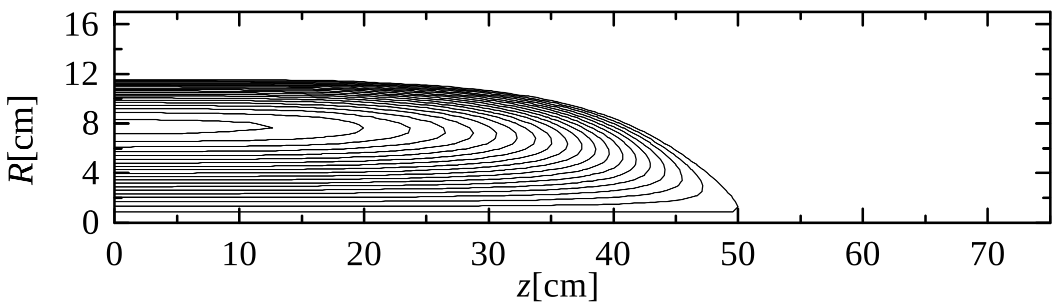

Fig. 5 Contour of flux function of highly elongated low aspect ratio tokamak

mirror ratio R_M=1.5. The $p(\Psi)$ and $F(\Psi)$ of the Type(a) plasma is adopted as the boundary condition of the calculation. The contour of the flux function is shown in Fig.5. The contour is similar to a field-reversed configuration (FRC) plasma. The outer board separatrix shape is similar to that of the experimental one (See Fig.2(a)). At the center region, the flux surface in the outer board region is flat. The end of the plasma reaches to near the mirror region(z=50cm). This is the characteristic of this highly elongated low aspect ratio tokamak. In the conventional ST plasma, there are not the flat surface at the outer board region.

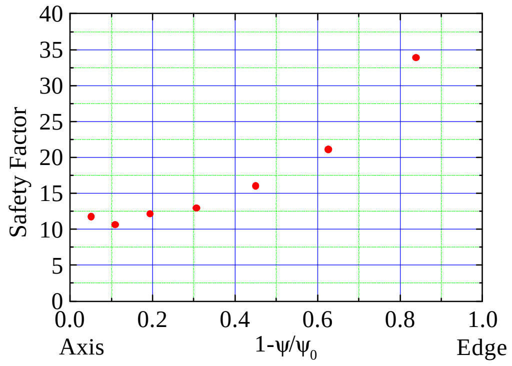

Fig. 6 Safety factor profile estimated from the numerical solution

The safety factor profile is shown in Fig.6. Its value of highly elongated plasma(κ=9) is large compared with the conventional ST plasmas(κ=2). The q-value gradually increases with the normalized flux. The magnetic shear ($dq/d\Psi$) is positive over the whole region of the inside of the plasma. It is evaluated that the center q value ($q(0)$) at the magnetic null point is about 10 and the edge one ($q(90)$) at 90% of the normalized flux is more than 35.

5. Summary

To improve the plasma parameters of a highly elongated low aspect ratio tokamak, the negative biased theta pinch device NUCTE-ST is modified. The low aspect ratio tokamak with the plasma temperature of 55eV, the electron density of $3\times10^{21}m^{-3}$ and the elongation of 10 is produced. The experimental result suggests two possibilities by the magnetic compression at a formation phase, (1) the plasma heating, (2) the plasma shape control keeping the high elongation. Grad-Shafranov equation is numerically solved. The solution is similar to that of FRC plasma and has a flat surface in the outboard region. The estimated safety factor of $q(0)$ and $q(90)$ are about 10 and more than 35 respectively. These value are larger than the conventional ST plasma.

References

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