Spherical Plasma Confinement by External Poloidal Field

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1. Introduction

Effective plasma confinement requires that the magnetic field lines of force do not escape from some volume and do not cross any solid element of a device and the magnetic field increases from the center toward the periphery. In the magnetic configuration, the charged particle losses along magnetic lines can be excluded and plasma instabilities are suppressed, so that the better plasma confinement is realized. Such magnetic configuration may be realized not only with ground-based electric current-carrying conductors and coils, but also with conductors (or currents) imbedded into the plasma volume. As early as the 1960s, Skornyakov has considered a magnetic configuration where closed magnetic surfaces form a spherical separatrix and an absolute minimum magnetic field is assured [1]. The systems of this magnetic configuration were also studied earlier by Lehnert and Yoshikawa, and their advantages were demonstrated [2]. The Tornado magnetic trap belongs to these systems [3]. The experiment with the Tornado trap have started from 1970s in Russia and modified tornado machines are manufactured in Russia (T-322R) and Japan (T-322J)[4]. In this report, we examined the T-322J Tornado trap and the effect of tornado plasma characteristics.

2. Apparatus and Experimental

Schematic view of T-322J Tornado trap is shown in Fig.1. The trap is made of two geometrically similar, concentric, spherical helices, of different radius, wound with a constant angular pitch and arranged in such a way that with the same radius drawn from the system's centre and the cubic spiral of the inner helix crosses that of the outer helix as well. Jumpers at the poles connect the helices. The opposite-directed currents I_{out} and I_{in}, flowing along the helices are related through $m_0 = I_{out} / I_{in}, = (R_{in} / R_{out})^{1/2}$, where R_{in} and R_{out} are the radii of the inner and outer helices, respectively. In this case the trap has a spherical separatrix of radius $R_s = (R_{in} R_{out})^{1/2}$. The separatrix separates the magnetic field into two regions. The field lines within the separatrix encircle the conductors of the inner helix and do not leave the R_s sphere, while those outside it enclose the outer-helix conductors and can go to infinity. The magnetic field lines in the tornado trap form a regular structure divided into a number of regions, each of them characterized by specific features, with field lines of one region never crossing over into another. The volume

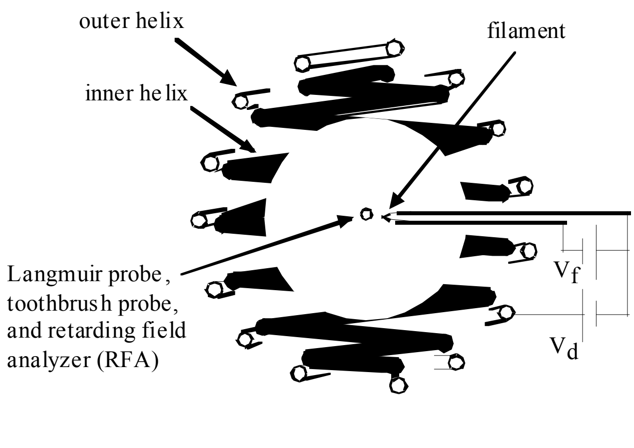

Fig. 1 Schematic view of the double spiral Tornado coil in T-322J.

inside the separatrix is used for plasma confinement. This volume includes a region surrounded by a magnetic barrier being formed by the poloidal field. The barrier is located near the spherical separatrix. The helices are placed in a vacuum chamber larger than the tornado coils. Two eight turn coil with stainless steal 18 mm tubes are winded with a spherically shape with a radius of R_{out}= 0.175 m for the outer helix and R_{in} = 0.149 m for the inner helix. Five turns of copper conductor with cross section of 8 mm^2 are placed inside the tube. Adjusting the combination of these five copper conductors can change the current ratio between the outer helix and the inner helix. The optimum ratio of the outer coil current to the inner one is m_0 = 0.92 and the magnetic field magnitude is maximum at the separatrix, denoted B_{max}, and at the center of the tornado coil the magnetic field magnitude is $B_{max}/4$. The radius R_s of the separatrix for optimal ratio is 161 mm or a diameter of 322 mm, which is derived from the name of the device.

Electrostatic probes were used for plasma diagnostic in the T-322J device. The plasma profile of the tornado plasma was observed with the electrostatic probe inserted inside the tornado coil. The toothbrush probe is a 5 channel double probe having a capability to measure the density n and the electron temperature T_e profile simultaneously [5]. The ion temperature T_i is measured with the retarding field analyzer (RFA) near the center.

Normally, plasma is generated within the tornado coil. In the T-322J the plasma generated by a DC discharge with the filament in the core region of tornado coil as shown in Fig. 1. The discharge voltage is applied between the filament and the helices of the tornado. The filament electrode is a treated-tungsten wire with the diameter of 0.1 mm. The filament voltage and current are 20 V and 1.2 A, respectively. The discharge voltage and current are about V_d= 100 V and I_d= 0.04 A, respectively. When the current ratio of the magnetic field differs from the optimum value, some kind of instability occurs and the formation of plasma is unstable. We successfully get stable plasma just at I_{out} / I_{in} = 0.92. The feeding gas is Argon or Helium. When the magnetic field is applied, where the time duration of the magnetic field is about 10 to 20 msec, the time behaviour of the ion saturation current at the various points are

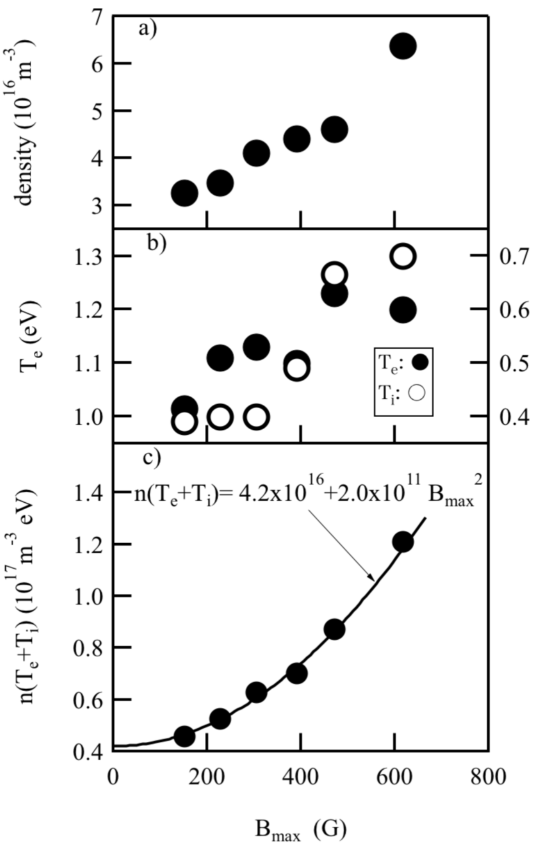

Fig. 2 Dependence of (a) the density, (b) electron temperature T_e and the ion temperatrue T_i, (c) plasma pressure $n(T_e+ T_i)$ on the magnetic field B_{max} for Ar plasma, where the gas pressure p_{gas} = 4.3 mTorr, the discharge voltage is 100 V and the discharge current is 0.04 A.

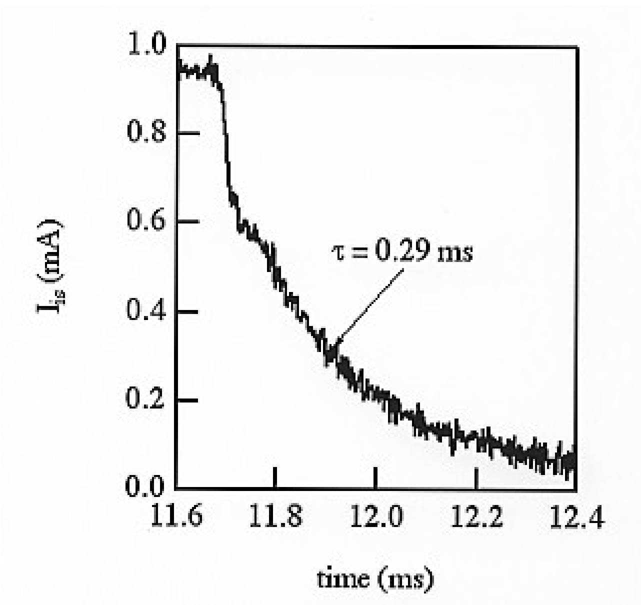

Fig. 3 Decay time of Ar plasma after the plasma discharge is cut off, where P_{in}= 4 W, P_{gas}= 4.5 mTorr and B_{max}= 533 G.

observed simultaneously. We found that the density is peaking in the center and becomes nearly zero at the radial point r = 9 cm. Figures 2 (a) and (b) shows the plasma density n and the temperatures T_e and T_i near the center against the magnetic field B_{max} for Ar plasma. The density n, the temperatures T_e and T_i increase with increase in B_{max}. It should be noted that the plasma pressure $n(T_e+T_i)$ increases with the scaling of $n(T_e+T_i) = 4.2\times10^{16} + 2.0\times10^{11}\ B_{max}^{\ 2}$ (m^{-3} eV) as shown in Fig. 2(c). The same experiment is performed with the He plasma. We expect the transport properties improved for plasma with light atomic number since the Larmor radius is smaller, however, the observed scaling for He plasma is $n(T_e+T_i) = 2.05\times10^{16} + 7.6\times10^{10}\ B_{max}^{\ 2}$ (m^{-3} eV). The decay time of the tornado plasma for Ar plasma, which may exhibit the energy confinement time, is shown in Fig. 3.

3. Discussion

The power balance of the plasma is

$$\frac{\partial}{\partial t}\int n(T_e + T_i)\,dV = P_{in} - P_{rad} - \frac{\int n(T_e + T_i)\,dV}{\tau_E}, \qquad (1)$$

where P_{in} is the input power, P_{rad} is the radiation loss, τ_E is the energy confinement time and the volume integral of eq. (1) is taken over the confinement region. We consider the stationary state ($\partial/\partial t = 0$), and P_{rad} (= $P_{brem} + P_{cy}$) = 0 for such a low temperature case as T-322J, where P_{brem} is the Bremsstrahlung radiation loss and P_{cy} is the synchrotron radiation loss. For simplicity, we think the integral in eq. (1) is given by $n(T_e+T_i)V$, where $V = 4\pi r^3/3$ and r = 9 cm. So, eq. (1) is given by $n(T_e+T_i) = 3P_{in}\tau_E/(4\pi r^3)$. If we assume the observed value is almost coincides with the classical diffusion, the energy confinement time τ_E is

$$\tau_E = \frac{r^2}{\chi_E} = \frac{r^2}{\rho_i^2 \nu_{ie}}, \qquad (2)$$

where ρ_i ($=1.02\times10^{-4}(1/Z)(AT_i)^{1/2}(1/B)$ m) is the ion Larmor radius, ν_{ei} ($=6.3\times10^9 Z(T_e)^{-3/2}(n/10^{20})$ sec^{-1}) is the ion-electron collision frequency, Z is electronic charge, A is the mass number, and T_i and T_e are in eV. In this scheme, the plasma pressure is scaled as, $n(T_e+T_i) \propto B^2$ from eqs. (1) and (2). In the T-322J plasma, this scaling is represented in Fig. 2 (c). For Argon plasma we get ρ_i = 8 .9x10^{-3} m and ν_{ei} = 2.72x10^6 sec^{-1} with Z = 1, A = 40, B = 0.06 T, T_i = 0.7 eV, T_e = 1.3 eV, n = 6.4x10^{16} m^{-3} and r = 0.09 m, then τ_E = 0.04 msec, which is 1/7 of the value given in Fig. 3.

In the torus configuration the symmetry is not good which may cause the bad field pattern to destroy the stability and it is clear that the micro instabilities to bring the anomalous transport cannot be eliminated completely. The tornado field can be considered as an Ioffe bar configuration is realized in three-dimensional space. The similar field to use the effectiveness of the barrier poloidal field is also realized in the Surmac plasma where it is shown that the transport nearly equals to the classical diffusion [7] although there exists still a bad magnetic field curvature due to the torus configuration. In the field reversal configuration (FRC), a relatively high beta plasma is obtained by using the poloidal magnetic field, however, this magnetic field formation is due to the electromagnetic induction to cause the unstable plasma such as the kilt instability and FRC plasma is not completely spherical since there exists a half opened magnetic field. The high beta plasma is also formed at the barrier dipole magnetic filed in the Jovian magnetosphere [8]. In order to avoid the unstable poloidal field formation in the FRC an active control of the field pattern is performed to suppress instabilities by using a quadrapole and a hexapole magnetic field [9]. This magnetic configuration is close near to that of the tornado coil if the more multipole coils are used.

One concern is the heat exposure of the inner tornado coil in the hot plasma. It indicates that the core plasma in the tornado configuration is far from the coil as seen in the DC discharge in T-322J and the heat damage to the tornado coil itself may be smaller than to the divertor plate in the tokamak case since the magnetic field lines would not collide directly to the material of the tornado coil. Similar configuration to the tornado plasma is proposed by using the intense laser beam at the superconducting metal chamber, where the inverse current at the inner helix of the tornado configuration is intended to be generated by the circular laser [10].

The dipole field for the fusion confinement scheme proposed by Hasegawa [11] is considered to be a special case of the tornado configuration, that is, this is the case that the inner and outer helices of the tornado configuration are in the only one turn. The terrestrial scale experiment of the high beta plasma using the dipole magnetic field is performed [12], however, the plasma boundary is not definite since the poloidal magnetic field lines stretch out infinity. The tornado plasma is defined poloidal magnetic field by using the inverse current flowing. The next step of our experiment is focused to the higher temperature experiment larger than this experiment. The magnetic field is more upgraded. The high density and hot tornado plasma experiment is concentrated for whether transport is still classical and plasma instabilities do not really appear. Especially the scaling of τ_E dependence on plasma density and temperature must be established. For the additional heating for the tornado plasma, the electron cyclotron heating (ECH) or the ion cyclotron heating (ICH) would be effective, because these resonance zones are spherically closed inside the tornado plasma.

4. Conclusions

Classical collisional plasma transport leads to a modest scale reactor with a reasonable magnetic field. The tornado plasma with a spherical separatrix, a minimum magnetic field and closed magnetic surfaces has a quasi-stable plasma and confinement governed by classical diffusion. It is confirmed for the low temperature tornado plasma the stored energy increases with increase of the square of the applied magnetic field strength to support the scaling of the classical diffusion. The tornado plasma may save the weak points of the unstable poloidal magnetic field formation in the tokamak and the FRC plasma as well as the anomalous transport in many machines.

Acknowledgements

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