Paper

Spontaneous Formation of Spherical Tokamak by ECH on LATE

Hitoshi Tanaka* Non-member
Yuichiro Abe* Non-member
Kazunori Hayashi* Non-member
Jun Yamada* Non-member
Taisuke Matsumoto* Non-member
Tomokazu Yoshinaga* Non-member
Masaki Uchida* Non-member
Soichiro Yamaguchi** Non-member
Takashi Maekawa* Member
Sunao Maebara*** Non-member
Tsuyoshi Imai**** Member

Spontaneous formation of spherical tokamak is observed during a microwave discharge at the electron cyclotron resonance (ECR) under a steady vertical magnetic field. In the course of slow plasma current increase, a fast rise of current (usually within several ms) occurs and the magnetic field topology changes drastically from open field type to closed one. After this current jump, a steady plasma current is maintained. The plasma current in the steady stage is proportional to the strength of the vertical field which balances the outward hoop force of the plasma current and maintains the MHD equilibrium. When a 5 GHz, 130 kW, 60 ms microwave power is injected at 85 G vertical field, plasma current of 6.8 kA is obtained.

Keywords: spherical tokamak, spontaneous formation, electron cyclotron heating

1. Introduction

It is a crucial issue for realizing the compact reactor based on spherical tokamak concept (1) to remove the center solenoid and to start-up the plasma current without Ohmic heating (2). It has been demonstrated that a spherical tokamak can be formed by injecting a microwave power at the electron cyclotron (EC) range of frequency under an applied vertical magnetic field B_V without Ohmic heating (3) (4). In these experiments, 2.45 GHz microwave is used and injected power level is $P_{inj} \leq 30$ kW. Firstly, a plasma current I_p and an initial closed flux surface is spontaneously produced under a weak B_V with low P_{inj} (5), and then, I_p is ramped up in the time scale of a second with slow ramp-up of B_V and P_{inj}.

In addition to the 2.45 GHz ECH system, a new 5 GHz ECH system has been installed with collaboration with JAERI ECH group. The available power is $\lesssim 200$ kW. This paper reports the spontaneous formation of spherical tokamak under a steady vertical field at higher injected power and higher toroidal field.

The formation of closed flux surface by ECH under a steady vertical field was carried out in CDX-U and DIII-D at a large decay index of B_V (6) (7) and the plasma current was attributed to the several types of pressure driven currents. The distinct character described in this paper is the appearance of a sharp current jump, where plasma current increases rapidly in the time scale of a few milliseconds, even at a low decay index of $n \simeq 0.1$.

2. Experimental Setup

Experiments are carried out in the LATE device (8) (9). The vacuum vessel is a stainless steel cylinder with the inner diameter of 100 cm and the height of 100 cm. The outer diameter of the center post is 11.4 cm and there is no center solenoids. The toroidal coils in the center post consist of 60 Cu pipes cooled by water. The power supply can flow regulated pulse currents I_T up to 180 kAT for 0.1 s. The vertical field B_V is generated by 3 sets of coils, which currents can be controlled independently by 3 regulated power supplies. Then, the decay index of B_V can be changed by setting the different ratio of each coil current. In these experiments, each coil current is kept constant during a discharge.

Figure 1 shows the schematic view of the 5 GHz ECH system. The TE_{10} mode from a klystron (max. 200 kW,

---

* Graduate School of Energy Science, Kyoto University
Kitashirakawa, Oiwake-cho, Sakyo-ku, Kyoto 606–8502
** Graduate School of Science, Kyoto University
Kitashirakawa, Oiwake-cho, Sakyo-ku, Kyoto 606–8502
*** Japan Atomic Energy Research
801-1, Mukouyama, Naka, Ibaragi 311–0193
**** Plasma Research Center, University of Tsukuba
1-1-1, Tennoudai, Tsukuba 305–8577

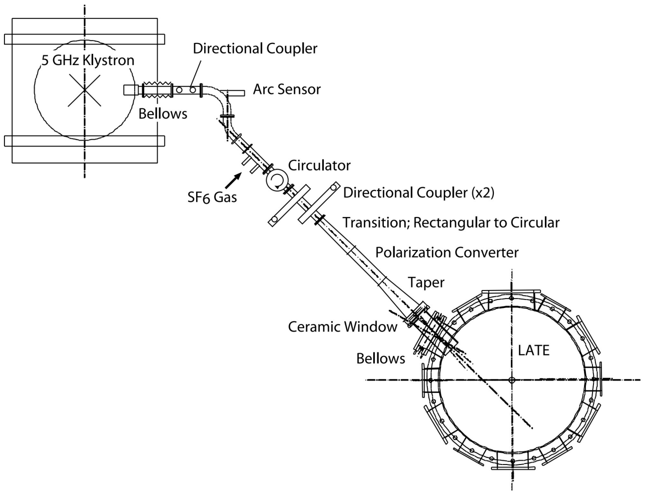


Fig. 1. 5 GHz ECH system

0.1 s) is converted to circular TE_{11} mode, then to the left-handed-circularly-polarized one. The left-handed-circularly-polarized wave is launched from the low field side of the torus on the midplane, with an angle of 15 degree from the perpendicular direction to the toroidal field, in order to excite electron Bernstein mode by O-X-B scheme (10).

For magnetic measurement, 13 flux loop signals are used. Five of them are wound in the center post and others are wound around the vacuum vessel. The line-integrated electron density is measured by two 70 mm microwave interferometers. One chord is a vertical path at $R = 27$ cm, the other one is a oblique path between the top and bottom ports at different toroidal angle and passes through $R = 17$ cm on the midplane. There is a fast CCD camera viewing from the radial port and the visible light images of almost whole the plasma are obtained at every 4 ms. Four soft X-ray cameras, each of which is composed of a pin hole type slit and a 20 ch detector array, are equipped in one toroidal section and provide the time evolution of emission profile. An NaI scintillator is set to view the plasma to observe hard X-ray emission.

3. Experimental Result

The experiments were carried out at the toroidal coil current of $I_T = 90$ kAT. The position of the fundamental electron cyclotron resonance (ECR) layer is $R = 10.1$ cm and the higher harmonics up to 4th are located in the vacuum vessel.

Figure 2 shows the time evolution of the discharge with 5 GHz, 130 kW, 60 ms microwave power and the steady vertical field of 85 G at the major radius of $R = 27.4$ cm. Initially, hydrogen gas is introduced into the vacuum vessel through the piezo valve at a low pressure value of about 4.5×10^{-3} Pa. There is no additional gas puffing during the discharge. When the microwave power is injected, break down occurs at the fundamental ECR and a weak toroidal plasma current starts to flow. The visible image of the plasma is a vertical cylindrical sheet around and near the center post, which corresponds to the fundamental ECR layer. When the plasma current gradually increases up to about 2 kA, it suddenly rises up to 4 kA in ~ 1.5 ms (the first current jump), stays at nearly the same value for ~ 2 ms, and again rises up to 7.4 kA (the second current jump). Then it decreases gradually to 5 kA but increase again to 6.8 kA (the third current jump). After the first current jump, the poloidal flux within the center post on the midplane, Φ_{C0}, changes its sign, i. e., reverses its direction, and the visible plasma images show that the plasma spreads within the vacuum vessel and becomes spherical torus. These facts support the formation of closed flux surfaces. After these events, the plasma current is kept steadily till the end of the microwave pulse. The line-integrated electron density along the oblique inner chord is 3×10^{13} cm^{-2}. Because the path length is less than 100 cm, the electron density should exceed the cutoff density.

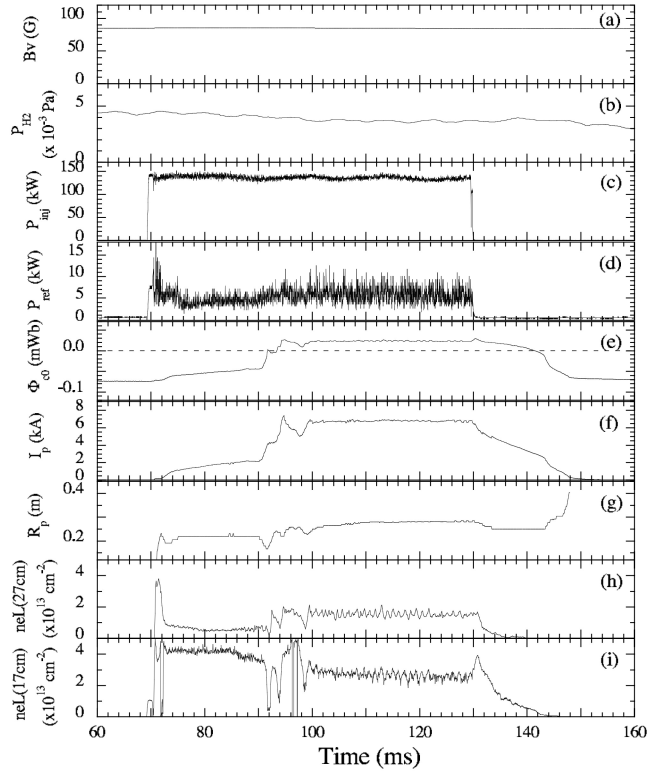


Fig. 2. Waveform of a discharge with 5 GHz microwave (130 kW, 60 ms): (a) Applied vertical field at $R = 27.4$ cm, (b) neutral gas pressure, (c) injected microwave power, (d) reflected microwave power, (e) poloidal flux within the center post on the midplane, (f) plasma current, (g) radial position of plasma current center, (h) line-integrated electron density along the vertical chord at $R = 27$ cm, (i) line-integrated electron density along the oblique chord; The chord passes through $R = 17$ cm on the midplane

In Fig. 3, the value of the plasma current at the final steady stage is plotted against the strength of the applied vertical field B_V for various microwave power. The plasma current is proportional to B_V and the coefficient is nearly the same as that in the slow formation case (4). The plasma current may be limited by the MHD equilibrium condition that the outward hoop force of the plasma current is balanced by the inward $\mathbf{J} \times \mathbf{B}$ force produced by the vertical field.

When $B_V = 40\,\mathrm{G}$, $P_{inj} \geq 50\,\mathrm{kW}$ is necessary for occurrence of the current jump, while $P_{inj} \geq 100\,\mathrm{kW}$ is necessary when $B_V = 80\,\mathrm{G}$. The minimum microwave power for the spontaneous formation of closed flux surfaces is nearly proportional to the applied vertical field strength.

To investigate the plasma current distribution from the magnetic measurement, we adopt a model expressing the current flowing both in the open field region and within the closed flux surface. In this model, the plasma current flows in the area composed of 4 one-quarter-ellipses ($i = 1, 2, 3, 4$) centered at $(R, z) = (R_c, z_c)$ with parabolic profiles

$$J_i(R, z) = J_0 \left(1 - \left(\frac{R - R_c}{a_i} \right)^2 - \left(\frac{z - z_c}{b_i} \right)^2 \right),$$

where R is the major radial coordinate, z is the vertical coordinate, J_0 is the value of the maximum current density, a_i, b_i are axis lengths of the ith one-quarter-ellipse. Unknown parameters are determined by least-squares-error fitting method with measured poloidal flux values.

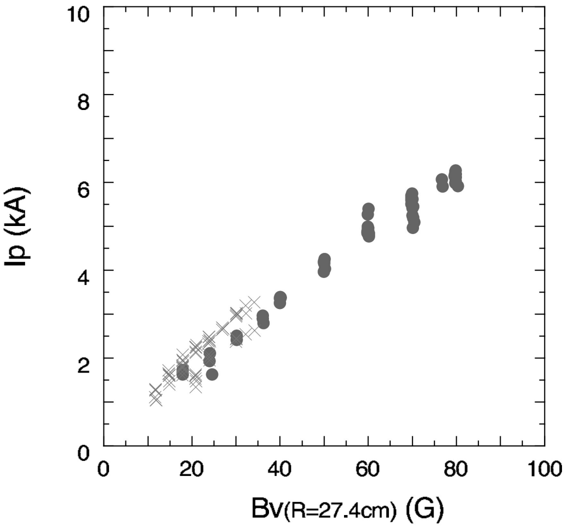


Fig. 3. Maximum I_p after current jump increases with B_V; Closed circles denote the data with 5 GHz microwave and crosses denote the data with 2.45 GHz microwave

Time evolutions of the poloidal flux contours and the current distributions are shown in Fig. 4. The current profile just before the current jump ($t = 89.5\,\mathrm{ms}$) is elongated vertically near the second harmonic ECR layer ($R = 20.2\,\mathrm{cm}$). The poloidal flux contours are vertical lines and the field line is a helix. This is the open field configuration. Comparing with the vacuum case, the plasma current flowing in the open field region changes the field in the distributed area significantly, bends the field lines and enhances the local magnetic mirror. After the first current jump ($t = 91.7\,\mathrm{ms}$), the current profile expands to the high field side and a small closed flux surface attached to the center post appears. And after the second current jump ($t = 94.7\,\mathrm{ms}$), the current profile as well as the closed flux surface expands to the low field side. At the final steady stage ($t = 122.5\,\mathrm{ms}$), the current distribution is detached from the surface of the center post and a broad current profile expanded to the outboard vessel wall is formed. The poloidal flux contours show the closed flux surfaces and the field line is just a spherical tokamak type as shown in the cubicle at upper-right in Fig. 4. It is remarkable that the open field configuration before the microwave injection changes spontaneously into a closed field configuration by ECH only. The plus marks in Fig. 4 denotes the

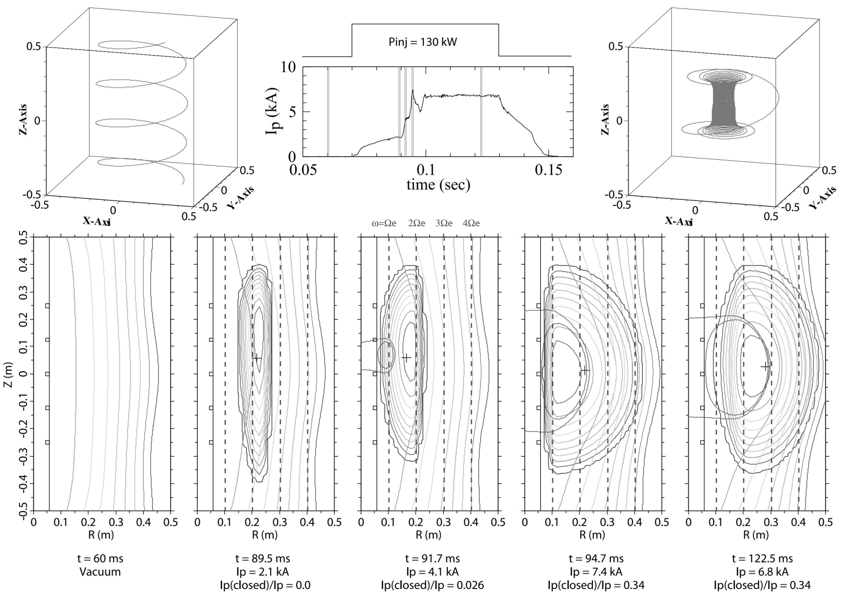


Fig. 4. Time evolution of the poloidal flux surfaces and the current distributions for the same discharge in Fig. 2; The fraction of toroidal current flowing in the closed flux surfaces is described by Ip(closed)/Ip. In the cubicles at upper-left and upper-right are shown the field lines before microwave injection and at the final steady stage of discharge, respectively

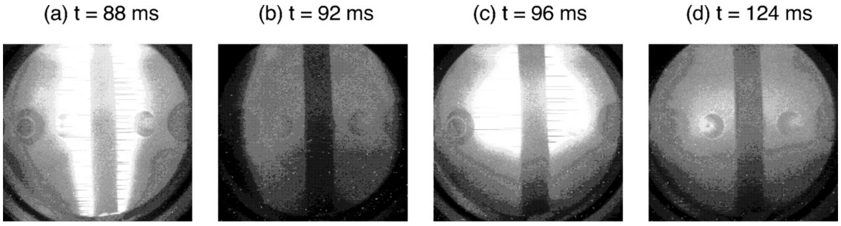


Fig. 5. Visible light images for the same discharge in Figs. 2 and 4 taken at each indicated time; Exposure time is 0.5 ms

location of the current center in the approximation of the single current loop for the dipole moment of the current distribution. Its location in the final steady stage is between the second and the third harmonics of ECR layer.

Figure 5 shows the visible light images taken by a fast CCD camera. Before the current jump (Fig. 5 (a)), the bright area looks like a slightly embowed vertical sheet along the open magnetic field configuration. Although the images are taken at every 4 ms and do not catch sight of the variation during the current jump at the right timing, Figs.5 (b) and (c) show that the change of shape occurs during the current jump. After the current jump (Fig. 5 (d)), the bright area become a circle, indicating the closed flux surfaces. These time variation supports the result of the model calculation of current distribution in Fig. 4.

4. Discussion and Summary

Above current distribution is not a unique solution. But the visible light images and soft X-ray emission profile support the result qualitatively. Then we can speculate about the mechanism of spontaneous formation.

Before starting the process of current jump, some amount of plasma current should be made flowing in the open field region. Mechanisms of driving such currents are discussed by Forest et al. (6) (7) and it is attributed to the several types of pressure driven currents. Such current may enhance the local magnetic mirror as shown in Fig. 4 and the number of trapped electrons will increase. Perpendicular heating by ECH can assist trapping effectively and the plasma pressure will increase farther, resulting in the increase of pressure-driven current.

Can such pressure-driven current flow plasma currents sufficient to cancel out the vertical field and to close the flux surfaces? The pressure-driven current is inversely proportional to the strength of the applied vertical field. On the other hand, the plasma current whose poloidal field can cancel out the vertical field is proportional to the vertical field. Then, one might suppose that the necessary microwave power increases proportionally to the vertical field strength squared if the confinement time is the same and the plasma pressure is proportional to the microwave power. But as mentioned before in Fig. 3, the minimum microwave power for the current jump is almost linearly proportional to the vertical field. This fact suggests that other current drive mechanisms may be working. For example, a current can be carried by electrons whose toroidal drift is canceled out by the vertical component of the parallel velocity (11).

Anyway, small closed flux surfaces appear if the enough current are driven. Then the auto-selected current could flow because of the different direction of shift of drift surfaces of passing electrons in the closed flux surfaces. The shift of the drift surface of electrons carrying counter-current is inward and they may hit the inner wall (center post), while that of electrons carrying co-current is outward and may not be disturbed to go round the torus. Such positive feedback mechanism increases plasma current till the initial closed flux surface is formed and balanced by the MHD equilibrium condition.

Of course, contribution of bootstrap current and/or EC driven current should be considered. Role of electrostatic potential caused by the fast loss of electrons to the wall may become important. Moreover, high energy electrons produced by strong ECH might play an important role. We observe a strong hard X-ray emission when B_V and P_{inj} are strong. For passing electrons whose energy are in the range of tens of keV, the drift surface is order of several cm and the current carried by such high energy electrons can flow in the open field area in the low field side of the closed flux surface. Further experiments should be carried out.

In summary, by injecting a microwave power near the electron cyclotron resonance under a steady vertical field at low gas pressure, plasma current suddenly increases in the course of slow current rise. By this process, initial closed flux surfaces are spontaneously formed and the magnetic field topology changes drastically from open field type to closed one.

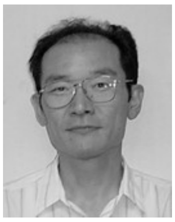
The steady value of plasma current after the formation of the closed flux surfaces is proportional to the vertical field strength so as to maintain the MHD equilibrium. By increasing both vertical field strength and injected microwave power, more plasma current can be generated. So far, plasma current up to 6.8 kA is obtained when 5 GHz, 130 kW microwave power is injected at $B_V = 85\,\mathrm{G}$.

By the magnetic measurement and model calculation of current distribution, we consider about the mechanism of spontaneous formation of the closed flux surface.

(Manuscript received Jan. 25, 2005,
revised March 30, 2005)

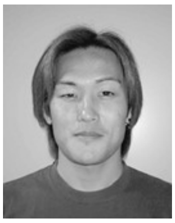
References

(1) Y-K. M. Peng and D. J. Strickler: *Nucl. Fusion*, Vol.26, p.769 (1986)
(2) S. Nishio: Proc. 19th IAEA Fusion Energy Conf, IAEA-CN-94/FT/P1-21, Lyon, France (2002)
(3) M. Uchida, K. Higaki, T.Yoshinaga, et al.: *J. Plasma Fusion Res.*, Vol.80, No.2, p.83 (2004)
(4) M. Uchida, T. Yoshinaga, J. Yamada, Y. Abe, K. Hayashi, S. Yamaguchi, H. Tanaka, and T. Maekawa: STW2004, Kyoto, Japan, 2004 (This Workshop).
(5) T. Yoshinaga, M. Uchida, H. Tanaka, and T. Maekawa: The 2nd International Symposium on Sustainable Energy System, Kyoto, Japan, 2004, SF-20 (2004)
(6) C. B. Forest, Y. S. Hwang, M. Ono, and D. S. Darrow: *Phys. Rev. Lett.*, Vol.68, p.3559 (1992)
(7) C. B. Forest, Y. S. Hwang, M. Ono, et al.: *Phys. Plasmas*, Vol.1, p.1568 (1994)
(8) H. Tanaka, K. Higaki, T. Yoshinaga, H. Igami, M. Uchida, and T. Maekawa: Proc. 29th EPS Conf. on Plasma Phys. and Contr. Fusion, P-5.050, Montreux, Switzerland (2002)
(9) M. Uchida, K. Higaki, T. Yoshinaga, H. Igami, H. Tanaka, and T. Maekawa: *J. Plasma Fusion Res. SERIES*, Vol.5, p.283 (2002)
(10) H. Igami, M. Uchida, H. Tanaka, and T. Maekawa: Plasma *Phys. Control. Fusion*, Vol.46, p.261 (2004)
(11) T. Shimozuma, J. Takahashi, H. Tanaka, T. Maekawa, Y. Terumichi, S. Tanaka, and M. Okamoto: *J. Phys. Soc. Jpn.*, Vol.54, p.1360 (1985)



Hitoshi Tanaka (Non-member) was born in Japan. He received a Ph. D. degree in physics from Kyoto University in 1990, is presently an associate professor at Kyoto University. He has worked on ECH of toroidal plasmas.

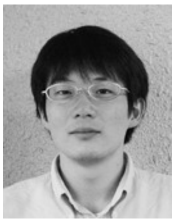
Yuichiro Abe (Non-member) was born in Japan. He received a Master degree in energy science from Kyoto University in 2005. Now he works at Kobe Steel, Ltd. His main interests are electrical & control system in energy plant.



Kazunori Hayashi (Non-member) was born in Japan. He received a Master degree in energy science from Kyoto University in 2005, and is presently an engineer at Nippon Sheet Glass Co., Ltd.

Jun Yamada (Non-member) was born in Japan. He received a Bachelor degree in physics from Kyoto University in 2004, is presently a graduate student at Graduate School of Energy Science, Kyoto University. He has worked on soft X-ray computer tomography of spherical tokamak.

Taisuke Matsumoto (Non-member) was born in Japan. He recieved a Bachelor degree in chemical engineering from Kyoto University in 2004, and is presently a graduate student at Graduate School of Energy Science, Kyoto University. He has worked on ECH of toroidal plasmas.



Tomokazu Yoshinaga (Non-member) was born in Japan. He received a Master degree in energy science from Kyoto University in 2002, and is presently a graduate student at Graduate School of Energy Science, Kyoto University. He works on ECH start-up of ST plasmas.

Masaki Uchida (Non-member) was born in Japan. He recieved a Master degree in energy science from Kyoto University in 1999, and is presently a research associate at Kyoto University. He works on ECH of ST plasmas.

Soichiro Yamaguchi (Non-member) was born in Japan. He received a Ph. D. degree in physics from Kyoto University in 2005, is presently a COE researcher at National Institute of Fusion Science. He has worked on the MHD instability of toroidal plasmas.

Takashi Maekawa (Member) was born in Japan. He received a Ph. D. degree in physics from Kyoto University in 1978, and is presently a professor at Kyoto University. He works mainly on radio frequency heating current drive in tokamaks.

Sunao Maebara (Non-member) was born in Japan. He received a Ph. D. degree in energy science from Kyoto University in 2000, is presently a senior scientist at Japan Atomic Energy Research Institute. He has worked on developments of LHCD system for fusion research.

Tsuyoshi Imai (Member) was born in Japan. He has worked on physics and technology of plasma heating in the GAMMA 10 tandem mirror and other magnetic confinement devices. He received a Ph. D. degree from Osaka University in 1992, is presently a professor at University of Tsukuba.