SUNIST Microwave Power System*

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Abstract Experiments on the start-up and formation of spherical tokamak plasmas by electron cyclotron heating alone without ohmic heating and electrode discharge assisted electron cyclotron wave current start-up will be carried out on the SUNIST (Sino United Spherical Tokamak) device. The 2.45 GHz/100 kW/30 ms microwave power system and 1000 V/50 A power supply for electrode discharge are ready for experiments with non-inductive current drive.

Keywords: spherical tokamak, microwave, current drive

PACS: *52.55.Fa*

1 Introduction

Recent experiments [1,2] have verified the theoretical advantages of the spherical torus (ST) concept, such as good stability and confinement in high beta plasmas, introduced by Peng and Strickler [3]. A compact fusion reactor may be realized by ST. Experiments in the middle-size ST's such as NSTX and MAST are being performed eagerly and promising results have been obtained. In order to produce the ST configuration, however, a large plasma current comparable to the toroidal field coil current should be driven. There is a limited space around the center column for the center solenoid coils for ohmic heating (OH) to ensure the virtue of a low aspect ratio. Therefore, it is necessary to develop an effective current drive scenario to initiate, raise and sustain the plasma current by non-inductive methods.

One of the attractive candidates is the electron cyclotron wave (ECW) method since plasma initiation, current start-up, raising and sustainment can be realized simultaneously by injecting a microwave power from a launcher. When it is shown that the ECW method is effective to produce sufficiently a high plasma current and density, fusion ignition may be obtained by applying a neutral beam injection to this target plasma and the plasma current may be self-sustained by a pressure driven current. Thus the OH solenoid can be eliminated, which allows a simplified, compact steady state ST reactor with an advanced toroidal coil system of high temperature superconductor.

The scenario of the ECW current drive spherical tokamak formation is as follows: First, the breakdown and production of an initial plasma is easily obtained near the electron cyclotron resonance layer. Next, applying a weak vertical field superimposed to a toroidal field, the field lines connect the top and the bottom of the plasma and the toroidal current flows to shorten the charge separation caused by the gradual toroidal field drifts in the vertical direction. The suitable external field improves the particle confinement and the toroidal current increases further, resulting in the formation of closed flux surfaces. Once the closed flux surfaces are formed, particle confinement is further improved and the plasma electron density may easily exceeds the cutoff density. Then the injected microwaves are reflected back and do not penetrate into the core plasma. Fortunately, the linear theory predicts that the microwave mode effective conversion to electron Bernstein wave (EBW) occurs with the adequate choice of the injection angle and the polarization of injected microwaves at the upper hybrid resonance layer [4]. EBW propagates into the core plasma without density limit and heats electrons efficiently even in a low temperature plasma. The resultant high electron temperature by ECW and the upward shift of the refractive index parallel to the magnetic field lead to efficient ECW, and the large toroidal current will flow. ST plasma will be obtained by the microwave only.

One of the main objectives of the SUNIST machine is to demonstrate the start-up and formation of ST plasmas by ECW without OH power and to demonstrate the electrode discharge assisted ECW.

2 SUNIST device

The SUNIST is a university scale spherical tokamak with parameters listed in Table 1.

Fig. 1 shows the side view of SUNIST device. The vacuum chamber of SUNIST is a 0.5 m tall and 1.2 m diameter stainless steel cylinder capped on each end with an elliptical dome 6 mm in thickness. The central stack has a radius of 6.5 cm and a thickness of 1 mm. The electric parameters of coils are listed in Table 2 and it can serve the toroidal field current up to 240 kAT for 0.1 s and also the OH magnetic flux up to 0.03 V s for 10 ms.

* The project supported by National Natural Science Foundation of China (Nos. 10275041, 10375089)

Table 1. Main parameters of SUNIST

Item	Symbol	Unit	Value
Major radius	R	m	0.3
Minor radius	a	m	~ 0.23
Aspect ratio	A	R/a	~ 1.3
Elongation	κ		~ 1.6
Toroidal field at R_0	B_{T0}	T	~ 0.15
Plasma Current	I_P	kA	50
Central rod current	I_{rod}	kA	225
Flux swing	$\Delta\Phi$	Vs	0.06

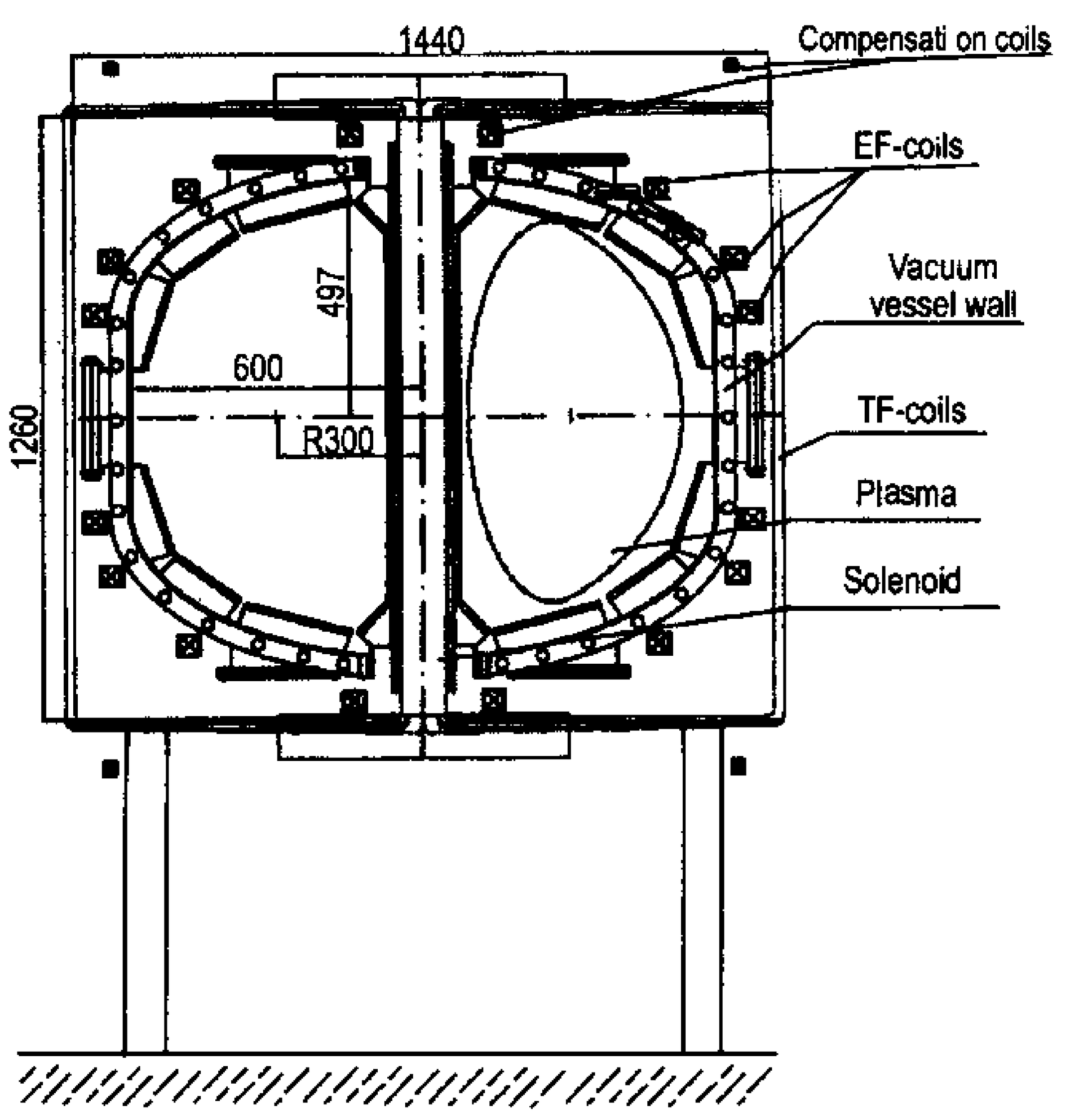

Fig.1 The SUNIST device

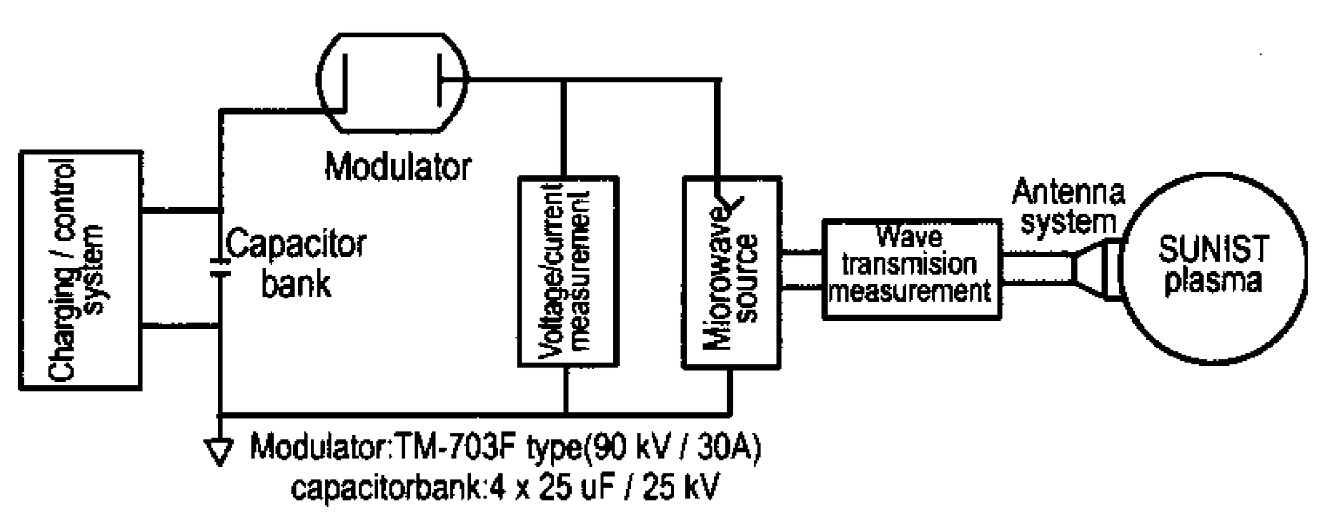

Fig.2 The arrangement of ECW on SUNIST

3 Microwave power system

The SUNIST microwave power system consists of a $-30\,\text{kV}/30\,\text{A}$ high voltage power supply, 2.45 GHz / 100 kW microwave source, a wave transmission system and a control / measurement system as shown in Fig. 2. The microwave pulse power from a magnetron (2.45 GHz / 100 kW / 30 ms) is injected to the toroidal field from the outboard side in circular TE10 with E vector parallel to the toroidal field (O-mode) as shown in Fig. 3. The fundamental frequency ($\omega = 1\,\Omega$), two-fold and three-fold frequency ($\omega = 2\,\Omega$ and $\omega = 3\,\Omega$) electron cyclotron (EC) resonance layers in SUNIST for different toroidal coil currents can be found in Fig. 4. SUNIST plasma is located in the range of 10 cm $\leq R \leq$ 50 cm and the fundamental EC resonance layer (B_T = 875 G) for 2.45 GHz microwave is generated at R = 33 cm as the toroidal coil current is 6 kA. When the toroidal field at the plasma center is in the range of 729 G $\leq B_0 \leq$ 1458 G, only the fundamental EC resonance layer is in the high field side or in the low field side. When B_0 is less then 729 G, many EC resonance layers are located in SUNIST. The -30 kV / 30 A / 10 ms negative high voltage power supply is composed of a capacitor bank and a modulator (type TM-703F), and it offers a negative high voltage pulse to the cathode of magnetron reliably and safely. Magnetron, filament power supply and magnet power supply is the main parts of the microwave power source. The output microwave power can be described as

$$P = \eta U I, \qquad (1)$$

where U is the negative voltage in the cathode of magnetron, I is the current pulse flowing at the anode of magnetron and η is the efficiency of generating microwave. Usually, η goes up gradually with the increasing of I which is not only related to U but also to the current I_F flowing in the filament of magnetron and the current I_M in the magnet for the magnetron. Therefore, the output microwave power is the function of U, I_M and I_F. Fig. 5 shows the output power results of microwave power using a water-load for absorbing microwave with I_M = 2.2 A and I_F = 0.36 A where I_F is the primary current of the filament transformer of magnetron. The maximum output microwave power is 94.7 kW and η is more than 60%. This microwave power system is a piece of powerful equipment for ECW experiments on SUNIST.

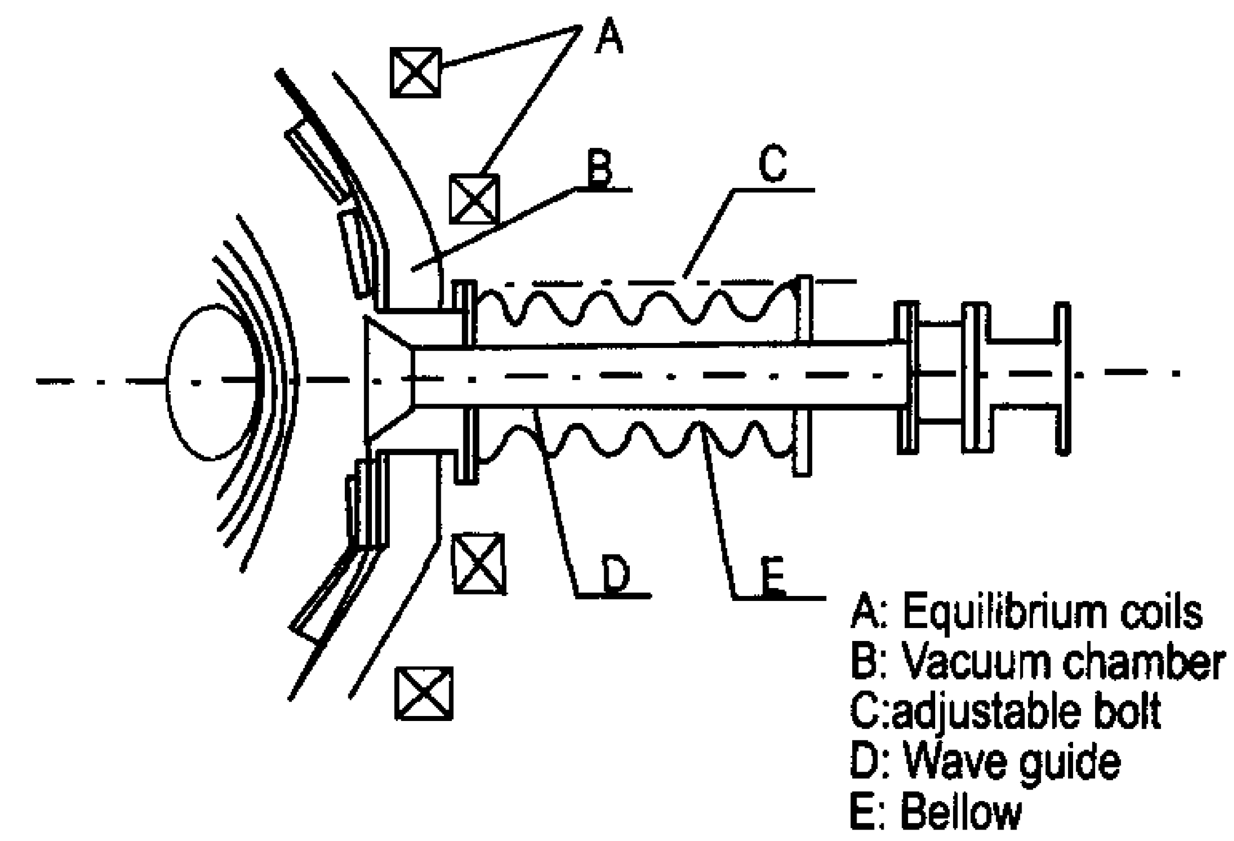

Fig.3 The 2.45GHz launcher

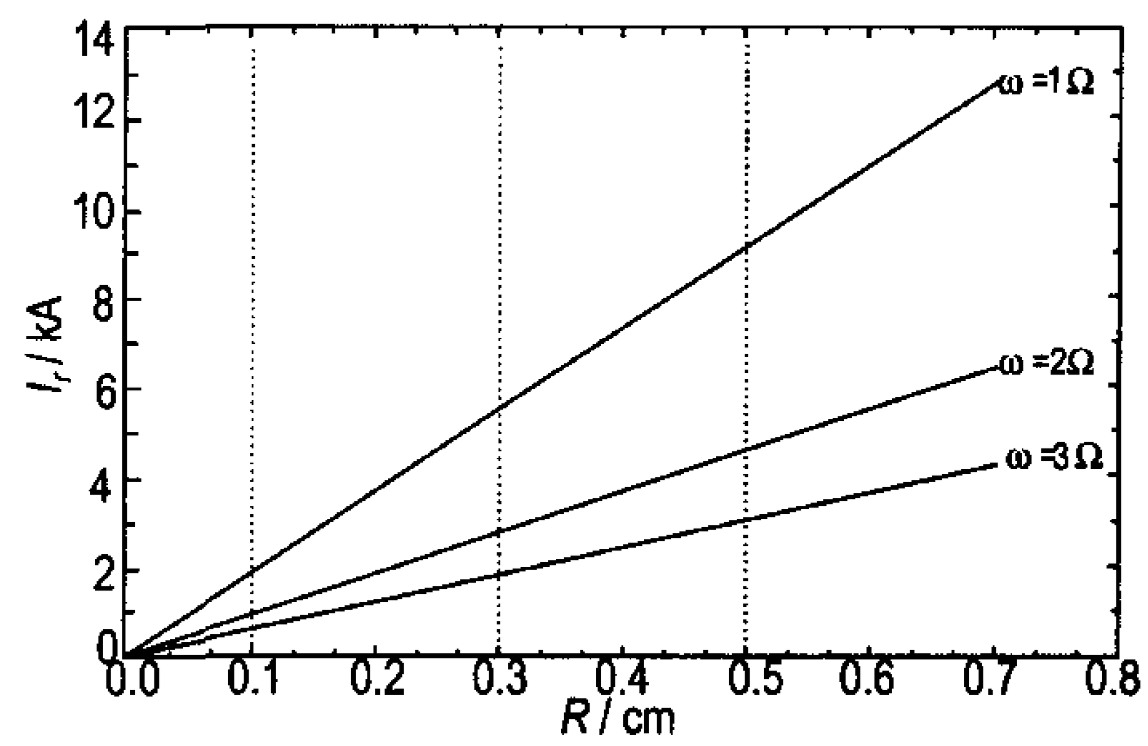

Fig.4 SUNIST electron cyclotron resonance layer

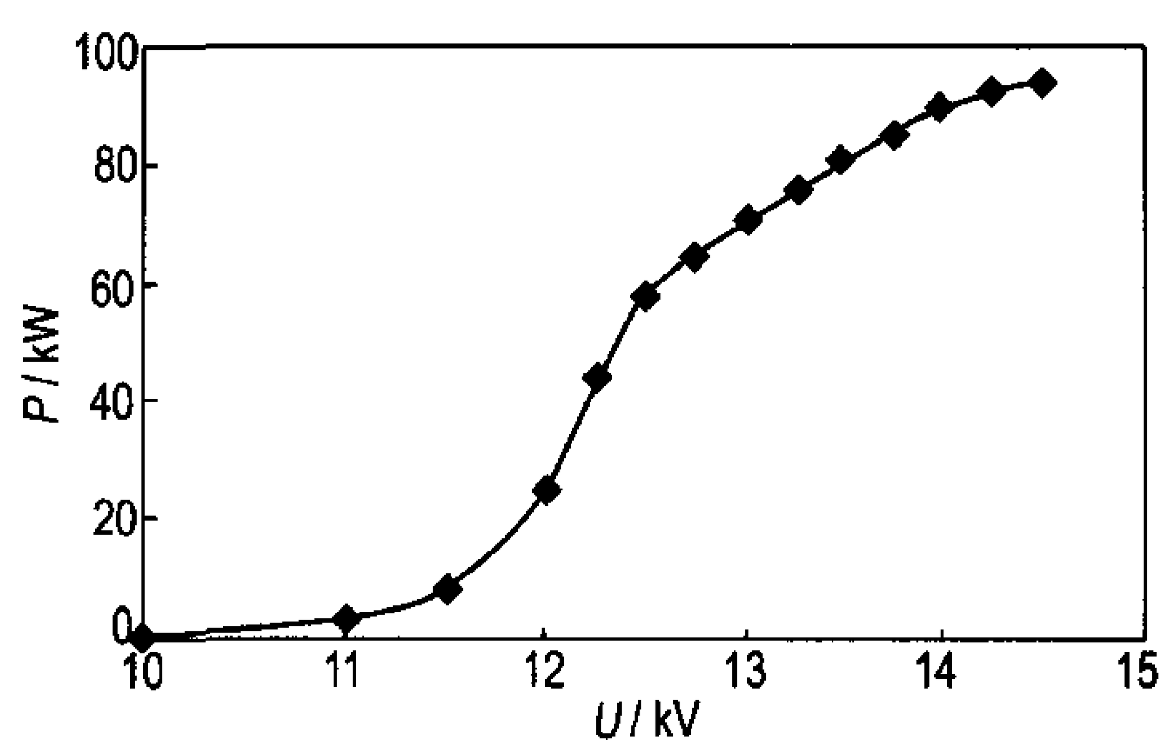

Fig.5 The relationship between U and P

4 Electrode discharge system

In order to increase the current drive efficiency in the

Table 2. Electric parameters of coils

Item	Unit	Toroidal coil	Ohmic coil	Equilibrium coil
Turns		24	236	26
Inductance	mH	0.45	0.53	0.69
Resistance	mΩ	6.43	23.3	13.9
Current	kA	10	13	1.5
Energy		1.28 F / 400V	13.3 mF / 5000V	1 mF / 2000V+ 476 mF / 200V

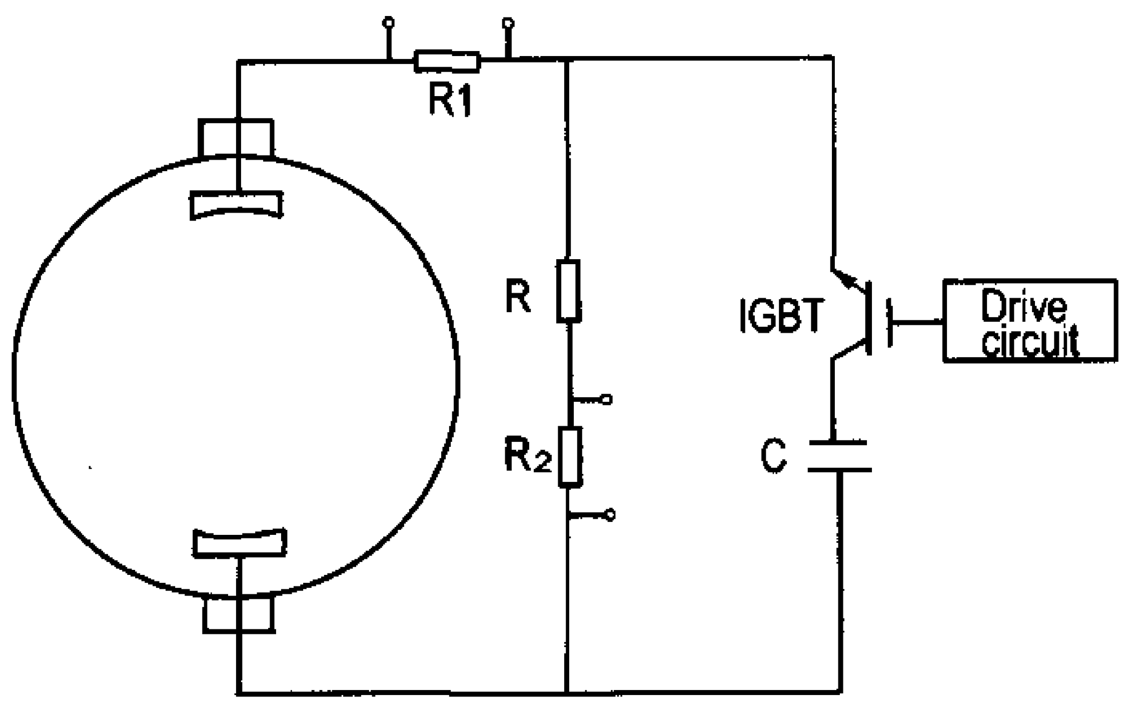

Fig.6 Discharge electrodes in a transverse cross-section of the vessel together with the power supply for the electrode discharge

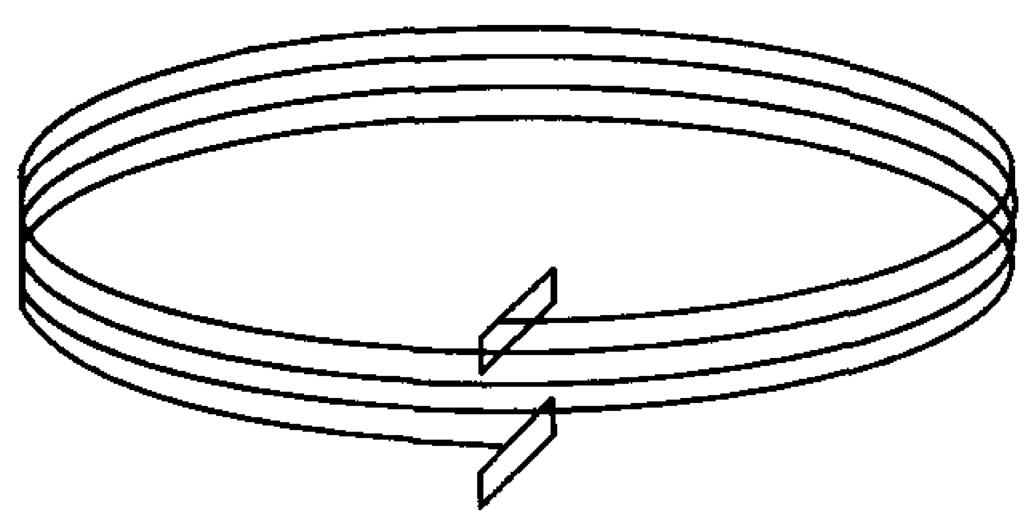

Fig.7 Magnetic field configuration and electron trajectories for electrode discharge assisted ECW

ECW scheme, a novel method has been experimentally demonstrated on the CT-6B tokamak [5]. As this method has it, a pair of electrodes is installed on the top and on the bottom of the vacuum vessel and a voltage is applied to these during ECW and a weak vertical field is also needed as shown in Fig. 6. Two resistors are connected in series and one in parallel in the discharge circuit for measurements of the discharge current and the electrode voltage, respectively. As the microwave beam is injected and a plasma is generated, a discharge between the two electrodes is triggered with the help of the Insulated Gate Bipolar Transistor (IGBT) and this produces toroidal current additional to the wave driven currents. The basic idea of the ECW scheme with an electrode discharge is shown in Fig. 7. If a DC discharge occurs between two electrodes, the electrons carrying the current will follow an oblique field composed of a strong toroidal field and a weak vertical field, and move around the torus many times until they arrive at the other electrode. In other words, the electron trajectories form helices, and then the discharge current between the electrodes is magnified in the toroidal direction. In order to estimate the design parameters of the electrode discharge power supply, we adopt the electron saturation current as the reference value. The electron saturation current at the electrode is [6]

$$I_{es} = 2.5 \times 10^{-14} \times \bar{n}_e \times S \times \sqrt{kT_e} \approx 50 \text{ A}, \quad (2)$$

where plasma density and temperature are assumed to

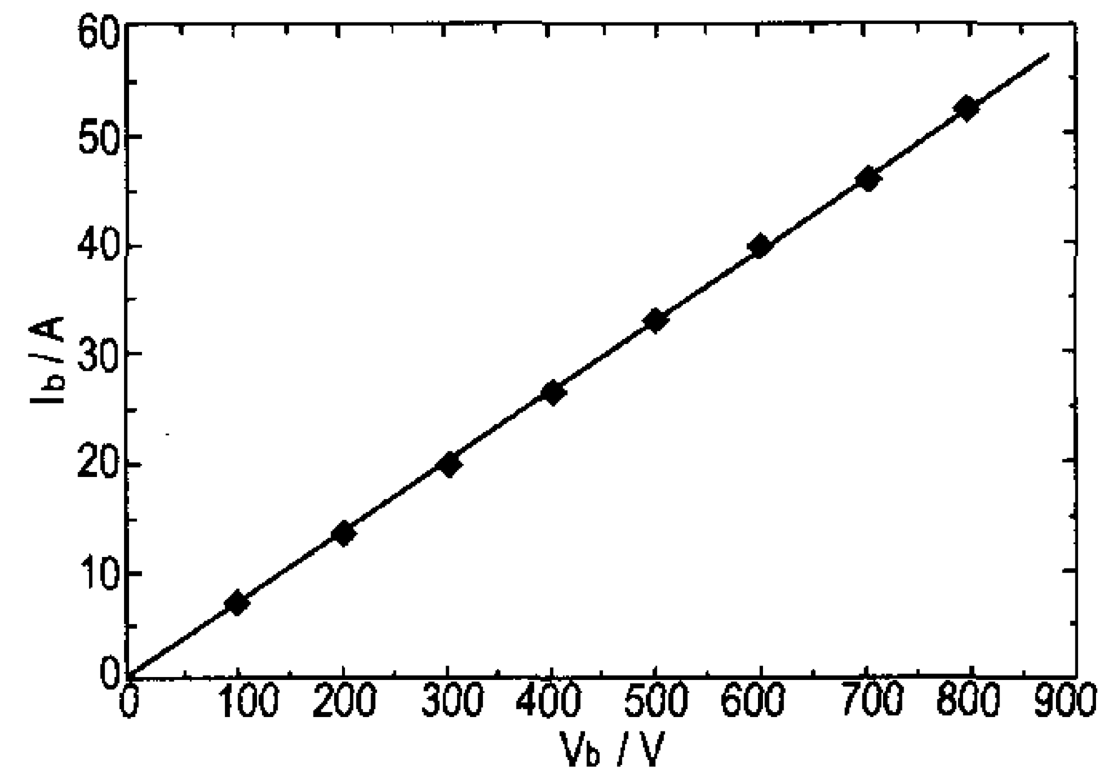

Fig.8 Current vs. voltage characteristic of electrode discharge power supply

be $\bar{n}_e \approx 3 \times 10^{11}/\text{cm}^3$, $T_e \approx 15$ eV, the total collecting surface area of the electrode $S = 1.75 \times 10^{-3}\,\text{m}^2$. Fig. 8 shows the electrode discharge power supply output characteristic in which a 16 Ω resistance is used instead of ECW plasma.

5 Conclusions

The 2.45 GHz / 100 kW / 30 ms microwave power system and 900 V / 50 A electrode discharge power supply are ready for demonstrating SUNIST ECW and also for electrode discharge assisted ECW experiments. A 1 kA / 5 ms ECW SUNIST plasma current is expected to be produced.

Acknowledgements

The authors wish to acknowledge technical assistance from Wang Mingwei, Zhang Jinsong and Zhou Jun of Southwestern Institute of Physics.

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(Manuscript received 3 September 2004)

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