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# High Power and Long Pulse ECRF System in JT-60U

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## Abstract

A 110 GHz 3 MW Electron Cyclotron Range of Frequency (ECRF) heating system in JT-60U is presented. A 1 MW ECRF line was constructed at March in 1999 and a construction of the other two ECRF lines of 2 MW will be started from spring in 2000. The system is featured by a 1 MW gyrotron per a line which is designed to be operated more than 5 second. The antenna with two mirrors is designed to steer the RF power injection position from plasma center to edge during a shot. The polarization is optimized by a pair of polarizers by real time control. Temperature rise of RF components after high power and several second operation was demonstrated. The effective control of narrow RF deposition and polarization was also demonstrated.

**Keywords:**
ECRF, gyrotron, ECCD, real time control, JT-60U

## 1. Introduction

On steady state operation of a tokamak fusion reactor, the non-inductive current drive and the control of MHD instability are required. Electron Cyclotron Current Drive (ECCD) is useful for non-inductive localized current drive, i.e., suitable for stabilizing the MHD instability. Two technical issues are very important for high power and long pulse operation of an ECRF system in a steady state tokamak: one is the heat load to several parts of the ECRF system, for example, windows for gyrotron and torus vacuum vessel. The transmission RF power density at the windows is about 350 MW/m$^2$ at 1 MW operation. The other is the control of ECCD position during a plasma shot. The injection of RF beam into an exact position of the magnetic island is necessary for the stabilization of tearing mode. The position of the magnetic island may shift due to the change in the plasma pressure for a long pulse operation of tokamak. Therefore, the narrow deposition (less than 10 % of minor radius) and the real time deposition control of the RF power is required. The 3 MW ECRF heating system is planned to be constructed in JT-60U to demonstrate the technical feasibility of the high power, long pulse and the improvement of plasma performance. In this paper, the design of the 110 GHz 3 MW ECRF system, which consists of three 1 MW gyrotrons and transmission lines, is presented. The operational result of the first 1 MW ECRF heating system which was constructed last March is also reported.

## 2. 3 MW ECRF Heating System

The main design parameters of the ECRF heating system are listed in Table I.

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Table 1: Main design parameters of ECRF system on JT-60U

| | |
|---|---|
| Frequency | 110 GHz |
| Power | 3 MW |
| Pulse duration | 5 sec. at first stage<br>10 sec. limited by the power supply system |
| Number of gyrotrons | 3 |
| Number of transmission lines | 3 |
| Length of transmission line | ~ 60 m |
| Transmission efficiency | 80 % |
| Injection mode | tangential O-mode injection from the low field side |

The overview of 3 MW ECRF heating system is shown in Fig. 1. The gyrotron and the transmission system that can withstand the high heat load in long pulse and high power operation were based on the developed technology during ITER EDA [1]. We also designed steerable mirror which can quickly control the RF injection angle during a plasma shot. The poloidal RF injection angle is controllable from plasma center to edge, besides the polarization of RF wave is optimized to excite pure O-mode.

### 2.1 Gyrotron and Transmission system

The development of the 1 MW gyrotron is a key component for the 3 MW ECRF heating system in JT-60U. The heat loads of collector, output window and cavity are one of the key issues on the development of the high power and long pulse gyrotron. However, this problem has been solved in recent progress. An energy recovery technique [2] has been developed to improve the gyrotron efficiency, which yields in the reduction of the heat load of the collector. The heat load of collector can be kept about 2.5 MW/m$^2$ at 1.1 MW operation. The higher oscillation mode $TE_{22,6}$ has been adopted so as to reduce the electric field at cavity wall, i.e., reduce the heat load of the cavity wall. To solve the thermal limit of the output window, we have developed a Chemical Vapor Deposition (CVD) diamond window for the gyrotron [3]. The CVD diamond is characterized by very low RF absorption (loss tangent ~$2 \times 10^{-5}$) and very high thermal conductivity (~ 1800 W/mK). A thermal analysis indicates that the temperature rise of the center of the diamond window was saturated less than 25 degree for 1 MW operation with the Gaussian beam output [4].

Since small sized corrugated waveguide ($\phi$31.75 mm) has been adopted, the RF transmission loss in the transmission line due to an abrupt tilts and a bend owing to mass of waveguide are small. The position of the main heat load of the transmission line are at the miter bends and the polarizers which have been designed for 1 MW, 10s operation by water cooling [5,6]. Thermocouples and acoustic sensors have been equipped to measure its temperature to estimate RF loss and to detect arcing in the transmission line. Each transmission line has the CVD diamond at the inlet of the JT-60U vacuum vessel to isolate the vacuum vessel from the transmission line. Each line has the pair of polalizer in order to make an optimum polarization. These lines are evacuated from both ends of the transmission line to prevent the arcing.

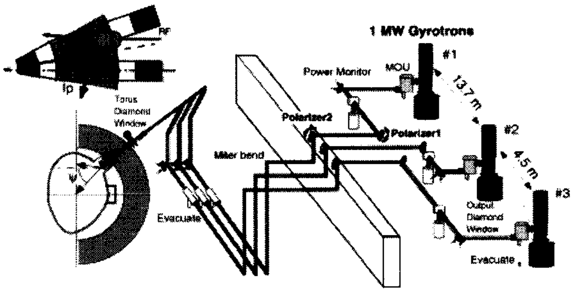

Fig. 1 Illustration of transmission lines and gyrotrons.

### 2.2 RF deposition control

The antenna system consists of a fixed focus mirror and a flat steerable mirror. The surface of the flat steerable mirror is made of the copper, while, the body is made of stainless steel to reduce the eddy current due to plasma disruption. The RF beam reflected by the focusing mirror is guided into the flat steerable mirror to control the beam angle in the poloidal direction. The beam angle at the toroidal direction is fixed at ~15 degrees to drive the plasma current effectively [7]. The flat steerable mirror is controlled by a servomotor through a camshaft with vacuum bellows. The simple structure of the mirror (without water cooling and fixed toroidal angle) has been adopted in order to actualize fast steering speed. It takes ~1.25 second for the RF wave ray to be scanned from the center to the edge. The designed e-folding radius of the RF power density being focused by the mirror is about 6 cm (~10 % of the minor radius). The measurement of the beam profile was carried out at low power. The obtained RF power profile is well fitted by Gaussian function. The e-folding radius of the RF power density was confirmed within 6.5 cm which is almost consisted with design value. In the

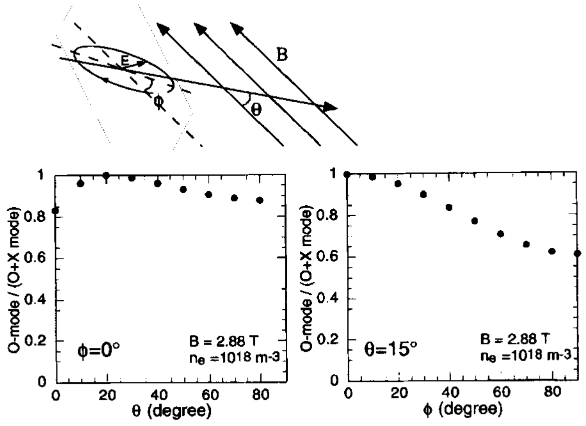

Fig. 2 Calculation of O-purity. The ratio of minor radius to major radius of the elliptical polarization is 0.45.

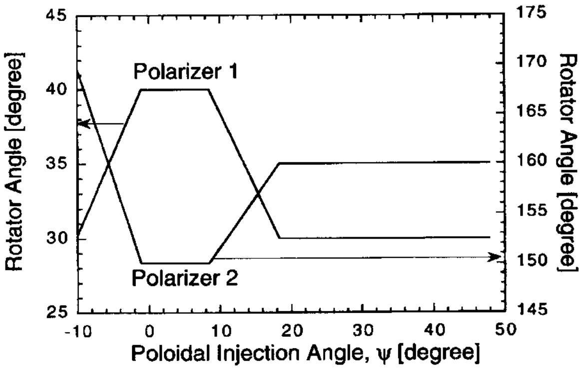

Fig. 3 Example of calculation result with the optimum polarizer rotator angles corresponding to the poloidal injection angle $\psi$. The angle $\psi$ of –10° is the edge injection and 50° is the center injection

calculation of ray-tracing and Fokker Plank code, the maximum power density in a magnetic surface is expected up to 2.6 MW/m$^3$, when the RF beam is set on the plasma center. The peak current density and the total driving current of 3.4 MA/m$^2$ and 160 kA are expected at the central density $n_{e0}$ = 2.4×10$^{19}$ m$^{-3}$ and electron temperature $T_{e0}$ = 6.5 keV.

Since the cutoff density for X-mode launched from the low magnetic field side is lower, the O-mode injection with high mode purity is necessary. The polarization for pure O-mode is the elliptical polarization, due to the oblique injection in the toroidal direction. The optimum polarization depends on the magnetic field strength, the plasma density and the angle between the RF ray and magnetic field line. There are two angles, the angle $\theta$ between the RF ray and the magnetic field line at the plasma edge and the angle $\phi$ between the major axis of ellipse and the magnetic field line. However, the dependence of the density and the magnetic field strength are very small. Therefore, we mainly considered $\theta$ and $\phi$ to optimize the mode purity.

Figure 2 shows the angle dependence of the O-mode purity for an elliptical polarization at the edge density of 10$^{18}$m$^{-3}$, the magnetic field strength of 2.88 T. The calculation does not include the refraction of the RF wave at the plasma edge, because the refraction index is almost one.

When the beam angle is changed in the poloidal direction, the optimum angles of $\theta$ and $\phi$ are also changed. Therefore, the adjustment of the polarizer is necessary. The polarizer has the structure that a sinusoidal grooved grating on a rotator stage is fabricated on a mirror of a miter bend [5]. The polarization changed by rotating the stage. Two gratings with different groove depths in successive miter bends are sufficient to generate a rather wide range of polarization. The typical calculations for the optimization of rotations of the polarizers corresponding to the poloidal injection angle $\psi$ are shown in Fig. 3. When the poloidal injection angle $\psi$ is changed from the plasma center ($\psi$ = 50°) to the plasma edge ($\psi$ = –10°), the rotations of the polalizers are required about 20 degree. The injection angle $\psi$ is defined as the angle from horizontal plane in the JT-60U vacuum vessel as shown in Fig. 1. Here, the density is 10$^{18}$ m$^{-3}$ and toroidal magnetic field is 2.9 T at plasma edge. The plasma current, the surface $q$, the elongation and the triangularity are 1.2 MA, 6.8, 1.32 and 0.31, respectively.

The injection angle and the polarizer rotator angle are preprogrammed in this system. The injection angle can be changed with keeping pure O-mode. In the future, the automatic optimization is planned by feedback in accordance with plasma parameters.

## 3. Result of 1 MW System Operation

One line of the 1 MW-ECRF system (one of the 3 MW system) [7] has been operated since March in 1999. The injection angle and the polarizer rotator angle were changed shot by shot in this operation.

The gyrotron successfully generated the output power up to 1 MW - 2 s [4] and 0.5 MW - 6 s after gyrotron conditioning of thirty days. Here, the pulse length was limited by the shortage of experimental shots. Temperature rise of the output window and the cavity were saturated around 25°C and 60°C at the

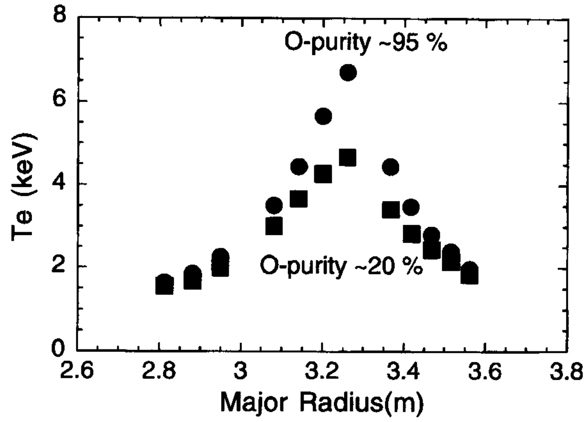

Fig. 4 Electron Temperature profile by RF injection with different polarization.

operation of 1 MW for 2 sec, respectively. These results are consistent with the design. The collector temperature was not saturated completely for 2 sec, because the thermal diffusion time of the collector was more than 5 sec. Indeed, the collector temperature rise was saturated at 0.5 MW for 6 sec. These results indicate that the heat load at the gyrotron is not a critical issue for a long pulse operation.

The transmission efficiency of 75 % was obtained using the calorimetric measurement at a dummy loads in the short pulse operation. It was approximately consistent with design value of 80 % [8]. The temperature rise of outside wall of miter bend in the transmission system was in the range of ~2–3°C at 1 MW for 1 sec without water cooling. It is the same order of the calculation result. The temperature increase in the antenna mirror was ~5°C due to the RF power dissipation and the radiation from the plasma. These results show the heat load of the transmission system and antenna is not crucial for several second long pulse, when the water cooling is applied.

In plasma experiment, the deposition width was studied by the power modulation technique. The RF power was modulated around 50 % at the frequency of 35 Hz and the RF deposition width was estimated less than ~15 cm by the constant phase delay [7]. Moreover, the effective plasma heating was observed with optimized polarization. The electron temperature profile is shown in Fig. 4 [8]. The closed circles and squares show the electron temperature profiles at the O-mode purity of 95 % and 20 % respectively. (the injection power of 0.75 MW for 300 ms at the plasma density of $9 \times 10^{18}$ $\mathrm{m}^{-3}$) The RF beam was set into the plasma center. Very high and peaked temperature rise ($\Delta Te$ ~ 4.4 keV) was obtained at high purity O-mode injection. The data indicate that the optimization of the polarization is required for long pulse operation, where the RF beam may be changed during a plasma shot.

## 4. Summary

In JT-60U, a 3 MW - 5 sec ECRF heating system is being constructed to study the application of EC heating and current drive. The real time control of injection point of RF beam is planned. The antenna with two mirrors is designed to steer the RF injection position from plasma center to edge during a shot. The polarization is optimized by a pair of polarizers by real time control.

A 1 MW-ECRF heating system has been operated since March in 1999. The 1 MW - 2 sec and 0.5 MW - 6 sec operations were achieved. The temperature rises of several parts on the gyrotron and the transmission system were small enough for a long pulse operation. Then, the injection power of 2.3 MW with the transmission efficiency of 75 % and more than 5 sec pulse length is expected in the 3 MW - ECRF heating system.

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