Progress of high power long pulse gyrotron development in JAEA

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Gyrotrons are a coherent high power mm wave source, which is a major power source of Electron Cyclotron Hating and Current Drive (EC H&CD) for magnetic confined plasmas. The gyrotrons of various frequencies, 28 GHz-170GHz, are under development at many institutes for EC H&CD application. In JAEA, a stable 1MW, quasi-CW operation was demonstrated with the oscillation mode of $TE_{31,8}$ in the open resonator [1]. Following this, several activities are underway, i.e., power increase of more than 1 MW, multi-frequency operation, and power modulation for MHD suppression. For power increase, the higher oscillation mode of $TE_{31,11}$ (170 GHz) is under study [2]. By raising the mode number, the resonator (cavity) radius a increases from 17.9 mm to 20.87 mm. Consequently, the maximum Ohmic-power loss density to the resonator wall decreases by the factor of ~1.4, which gives a margin at the ITER standard 1MW operation and a future power increase. Another major reason why the $TE_{31,11}$ is selected is that the $TE_{31,11}$ has sister modes suitable for the oscillation at 203 GHz, 137 GHz, 104 GHz, which are the transparent frequencies of the output window (diamond disk). In parallel, the fast frequency control is tried by changing the resonant magnetic field at the cavity. Here, an inner coil is installed inside the original super-conducting magnet (SCM) for the fast magnetic field control. As for the power modulation for MHD instability suppression, 1.1 MW, 5 kHz full power modulation was demonstrated by a full beam modulation method.

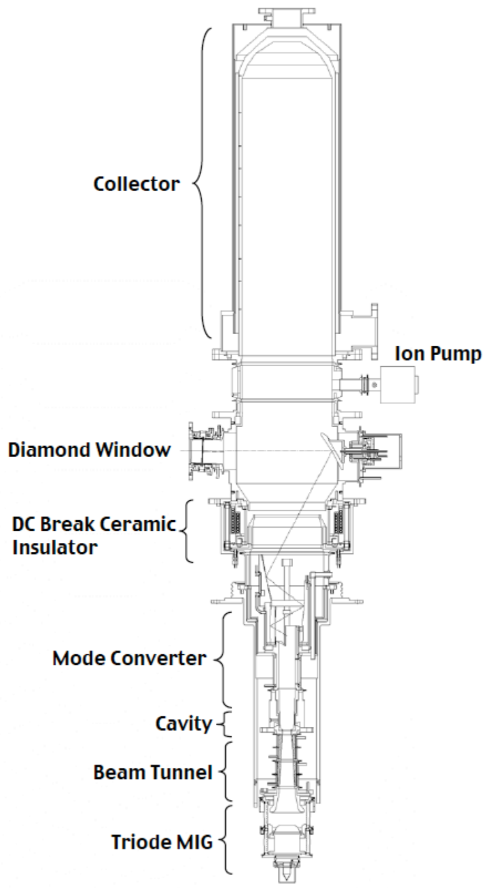


Fig.1 Cross sectional view of multi-frequency gyrotron.

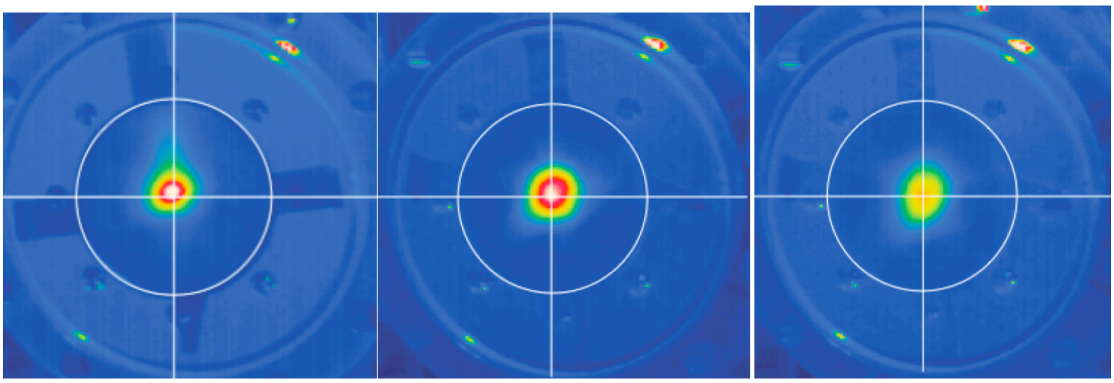
High power multi-frequency gyrotron

A cross sectional view of the multi-frequency gyrotron is shown in Fig.1, which is a same configuration with the $TE_{31,8}$ mode gyrotron [1]. The annular electron beam with a finite pitch factor (ratio between the perpendicular and axial electron velocity) is generated at the triode-electron gun (MIG) and injected into the cylindrical open cavity along the axial magnetic field where the beam-RF interaction occurs. Its unloaded Q-value is 1740 at 170 GHz. The oscillation mode, which has a specific frequency, is controlled by adjusting the

Mode: TE(m,n)	Oscillation frequency	θ_w(deg)	Transparent frequency	r_b(mm)	B_c(T)
(37,13)	203 GHz	65.3665	204 GHz	9.1	7.93
(31,11)	170 GHz	65.3492	170 GHz	9.14	6.64
(25,9)	137 GHz	65.3235	136 GHz	9.19	5.35
(19,7)	104 GHz	65.3003	102 GHz	9.25	4.06

Table 1 Operation modes for multi-frequency oscillation and these frequencies, azimuthal bounce angle θ_w, diamond transparent frequency at 1.853 mm and operation parameters r_b, B_c.

annular electron beam radius r_b and the magnetic field B_c. The oscillation mode is converted to the Gaussian beam by the built-in mode converter placed at the downstream of the cavity. The beam power is transmitted quasi-optically to the output window using the mirrors. The triode MIG has a great advantage that the r_b can be adjusted independently with other beam parameters. Consequently, the oscillation mode is selected arbitrary at the optimum condition. For multi-frequency operation, following two conditions should be satisfied. (1) Each oscillation mode should be converted to the Gaussian beam by the identical built-in mode converter and the beam power should be transmitted to the center of the window, (2) the frequency of the mm-wave beam should satisfy the transparent condition of the disk,



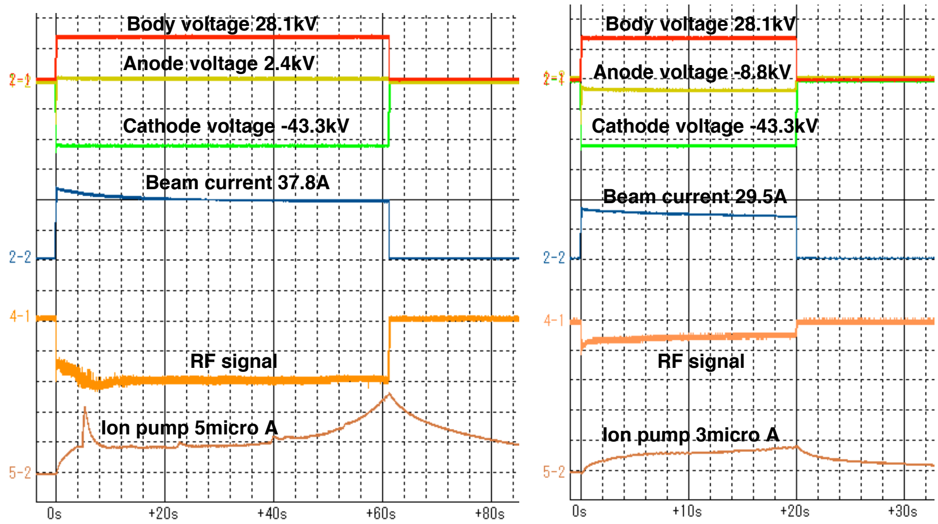
(a) 170GHz (b) 137GHz (c) 104GHz

Fig.2 Mm-wave power profiles measured at the output window

$f = nc/(2d\sqrt{\varepsilon})$. Here, n: integer, c: light speed, d: window thickness, ε: dielectric constant of the window material. To satisfy the condition (1), it is important to select the mode series that have similar bounce angles $\theta_w = cos^{-1}(m/\chi_{mn})$ in azimuthal direction. Here, χ_{mn} is an n-th root of $J'_m(x)=0$ except zero ($J_m(x)$: m-th Bessel function). (The axial bounce angle θ_B (=$\sin^{-1}(c\chi_{mn}/(2\pi fa))$) is automatically satisfied because all modes excited in the cavity have same θ_B.) For such modes, the mode converter works similarly and generates the Gaussian power profile. It is found that the mode series including $TE_{31,11}$ (170 GHz) satisfies these two conditions. In Table 1, the sister modes of $TE_{31,11}$, i.e., $TE_{37,13}$ (203 GHz), $TE_{25,9}$ (137 GHz), $TE_{19,7}$ (104 GHz), and those θ_w are shown. These frequencies locate near the transparent frequencies of the single disk diamond window of 1.853 mm in thickness. In addition, the optimum beam radius and typical resonant cavity field are shown to obtain the objective mode. Fig.2 shows the power profiles at the window measured by an infrared camera for 170 GHz, 137 GHz and 104 GHz operation. As designed, the clear power profiles are formed at the center of the window. The powers couple with the HE_{11} mode of the corrugated waveguide (63.5mm in diameter) using two mirrors in a matching optics unit (MOU). High mode contents of HE_{11} were obtained, i.e., 96 % for 170 GHz and 94 % for 137 GHz. In the high power experiment, the power of >1.3 MW was confirmed for both frequencies at the short pulse operation. Examples of time behavior of 170 GHz (760 kW) and 137 GHz (540 kW) operations are shown in Fig.3. The pulse extension is underway, and at present, 1.1 MW/5sec/45%, 900 kW/70s/45% are obtained at 170 GHz. The oscillation is stable at long pulse operation. On the other hand, the oscillation efficiency is still smaller than the record achieved in the $TE_{31,8}$ mode gyrotron experiment (>55 % at 1MW) [1]. The active parameter control will be conducted for efficiency increase. As shown in the Table.1, the higher frequencies, 203 GHz, is also available with this gyrotron if the higher magnetic field is applied to the resonator. Since the higher frequency gyrotron has a merit to increase the current drive efficiency, the next target will be the higher frequency at 1MW-CW for the DEMO reactor and advanced devices.

Frequency control

Fast control of the gyrotron frequency is possible by changing the B_c using the inner coil of the SCM and the beam voltage. As the inner coil is also super conducting, the CW operation is available. Preliminary experiment was conducted using the $TE_{31,8}$ gyrotron. Then the frequency is controlled between 170 GHz and 167 GHz. The oscillation mode is $TE_{31,8}$ and $TE_{30,8}$, respectively. The power and the efficiency without the depressed collector are 615 kW (32 %) and 538 kW (27 %), respectively. This gives a prospect for the power deposition



170GHz 137GHz

Fig.3 Typical time behavior of the multi-frequency gyrotron for 170GHz (left) and 137 GHz(right). Output powers are 760 kW and 540 kW for 170 GHz and 137 GHz, respectively.

control in the plasma without mirror at CW mode, which will be important for DEMO. Rough estimation indicates that 3 GHz corresponds to ~10 cm shift in the ITER class Tokamak.

Power modulation for the suppression of MHD instability

For the application to the MHD instability suppression, a power modulation experiment was performed using the 170 GHz gyrotron of $TE_{31,8}$ mode oscillation. The ITER requests 5 kHz power modulation. For this purpose, the full beam current modulation was adopted for the power modulation taking advantage of the triode type electron gun. As a result, 5 kHz power modulation between 1.16 MW-0 MW was achieved for 60 s, which satisfy the ITER requirement. The electrical efficiency at 1.16 MW was of 48%. The efficiency was relatively moderate level because the operation occurs in the so-called soft-excitation regions. And at the start-up phase of each pulse (~20 μs of anode voltage rising time), the parameter crosses the oscillation region of $TE_{30,8}$ mode (167 GHz). The excitation time period of unwanted $TE_{30,8}$ mode should be minimized. For further improvement, the anode and body power supply system using additional switches is under development to minimize the excitation of unwanted mode, to increase the efficiency and to increase the modulation frequency.

References

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