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COMPLETION OF MANUFACTURING AND TESTING OF 8 ITER GYROTRONS WITH ITS AUXILIARY SYSTEMS

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Abstract

After the last FEC conference in 2023, all 8 gyrotron conditioning and testing in National Institutes for Quantum Science and Technology (QST) is completed. Despite the identical design and manufacturing process, the output powers of each gyrotrons are not identical. The reason is not clear, but the optimized parameters are not identical for all gyrotrons, which causes the scattering of the gyrotron power of ±46kW and frequency of ±82MHz among 8 gyrotrons.

1. GYROTRON DEVELOPMENT FOR ITER

QST, cooperated with Canon Electron Tubes & Devices, has been developed gyrotron for ITER since 1991. The first breakthrough is the development of the Depressed collector gyrotron in 1994. The accelerated electron beam goes through the cavity which generates the rf with frequency of 170GHz, but the energy conversion ratio at cavity is around 30%. It is proved that the energy can be increased from 30% to more than 50% by applying a deaccelerated voltage to reduce the dissipated electron energy at collector [1]. The second breakthrough is applying the chemical vapor deposition diamond as an output window, which has high thermal conductivity and low loss tangent. The development of the diamond disk window is performed by cooperation between QST and FZK in Germany. The successfully developed window is mounted on QST gyrotron and tested in 1997 [2]. After these major breakthroughs, the gyrotron can be operated 1MW power with high electrical efficiency, but there is overheating problem inside the gyrotron by stray rf which prevents the long pulse operation. There are two breakthroughs to overcome this problem. One is the changing beam tunnel material from metal to ceramic to prevent the parasitic oscillation [3]. The other is the improvement of the mode convertor, which converts the cylindrical cavity mode to the Gaussian like beam for propagation inside the gyrotron. The loss of the mode convertor is decreased from 20% to 5% by applying the quasi-optical mode converter [4] instead of the Vlasov convertor. After these modifications, the gyrotron successfully operate 800s with 1MW output power and 55% electrical efficiency in 2007 [5]. It is also demonstrated 1 hour operation with 800kW power with higher electrical efficiency of 57%. After successful 1MW-800s operation, the cavity was damaged by an overheating with higher power generation at beginning of the pulse, when the beam current was larger than the target value. To avoid the damage on the cavity, the cavity radius is increased from 17.90 mm to 20.87 mm and the cavity mode is changed from $TE_{31,8}$ to $TE_{31,11}$ which decrease heat load from 2kW/cm^2 to 1.45kW/cm^2 with 1MW operation. However, the mode competition is increased by adopting the higher order mode, which prevents the hard-excitation operation. Hard-excitation operation is the high efficiency operation technique; it is realized by accessing the operation parameter space where the rf cannot be generated from the beginning of the pulse [5]. It is found that the large cavity gyrotron operation parameter space, especially for the hard-excitation region, is narrower than small cavity gyrotron because of the excitation of the counter rotating mode. To avoid the counter rotating mode, the beam radius at cavity is carefully adjusted and the time evolution of the applied voltage is optimized, as a result, the electrical efficiency reached ITER requirement of 50% with power of 1MW with large cavity gyrotron in 2015[6].

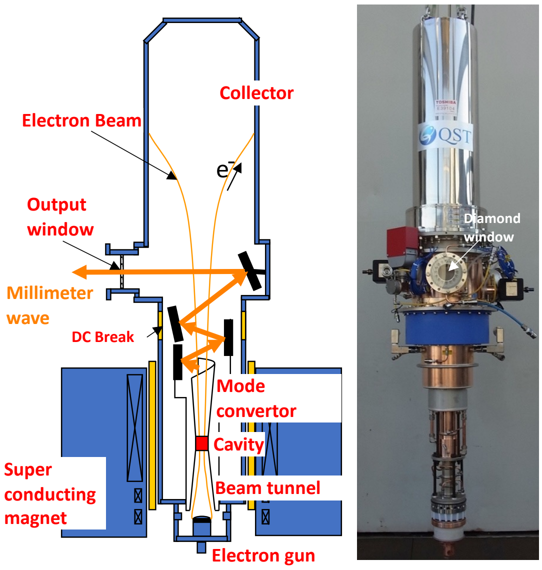

Fig. 1 Picture (right hand side) and Cross-section view (left hand side) of gyrotron

2. MULTI FREQUENCY GYROTRON DEVELOPMENT

When the cavity radius is increased during the ITER gyrotron development, there are several candidate modes which has similar beam radius at cavity with existing electron gun, such as $TE_{31,10}$, $TE_{31,11}$, $TE_{31,12}$, and so on. At the same time, there is request from ITER for 103GHz gyrotron for plasma start up. It makes the motivation to develop the multi frequency gyrotron in parallel to the ITER gyrotron. For the output window, the frequencies of the integral multiple of half wavelength of window thickness can be transparent. In our case, the window thickness is 1.853mm which allows to go thorough 236GHz, 203GHz, 170GHz, 137GHz and 104GHz rf. In addition, QST ITER gyrotron has a triode electron gun which enables to adjust the electric field around the gun for different magnetic fields strength for multiple frequency operation, which is necessary for high efficiency operation for each frequency. The remaining problem is the mode convertor. As shown in Fig. 2 and Table 1, the propagation angle θ inside the mode convertor depends on the mode numbers, which is calculated as follows.

$$\theta = \cos^{-1}\left(\frac{m}{\chi_{m,n}}\right)$$

Here, the $\chi_{m,n}$ is the nth root of mth-order derivative Bessel functions $j'_m(\chi_{m,n}) = 0$. The oscillation mode at cavity is decided by the cavity radius and frequency. If the cavity radius is selected for 170GHz with $TE_{31,11}$ the 137GHz oscillation mode is fixed as $TE_{25,9}$. Similar for the other candidate mode, by selecting the cavity radius for $TE_{31,10}$ and $TE_{31,12}$ for 170GHz, the 137GHz mode is fixed for $TE_{28,7}$ and $TE_{24,10}$, respectively. While the difference of angle θ between $TE_{31,10}$ and $TE_{28,7}$, and $TE_{31,12}$ and $TE_{24,10}$ is 6.5° and 1.1°, respectively, it is found that the difference angle θ for $TE_{31,11}$ and $TE_{25,9}$ is remarkably small which is 0.05° [7] as shown in Table 1. By selecting the $TE_{31,11}$ and $TE_{25,9}$, the mode convertor design is significantly improved compared to the other selection such as $TE_{31,8}$ and $TE_{27,6}$ as shown in Fig. 3. This finding makes it possible by selecting the oscillation mode $TE_{31,11}$ for the 170GHz ITER gyrotron, the gyrotron can radiate 170GHz and 137GHz naturally, even if the mode convertor is not optimized for the multiple frequencies. Moreover, the radiation angle for the other window transparent frequency, which is 104GHz and 203GHz 236GHz also has similar radiation angles. It was confirmed that the ITER gyrotron can generate 104GHz, 137GHz, 170GHz and 203GHz as reported in ref [8]. It is also reported in last FEC conference that the successful operation of 170GHz / 300sec / 46%, 137GHz / 300sec / 44% and 104GHz / 300sec / 41% by a gyrotron which mode convertor is optimized for these three frequencies [9].

TABLE 1. The list of difference θ (see Fig. 2) between the mode for 170GHz and 138GHz at certain radius of the cavity.

170GHz	138GHz	Δθ
$TE_{31,8}$	$TE_{27,6}$	4.2°
$TE_{31,10}$	$TE_{28,7}$	6.5°
$TE_{31,11}$	$TE_{25,9}$	0.05°
$TE_{31,12}$	$TE_{24,10}$	1.1°

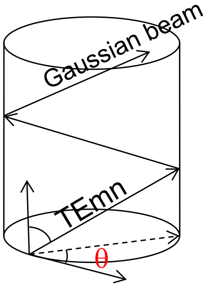

Fig. 2 Propagation angle of $TE_{m,n}$ mode inside the mode convertor

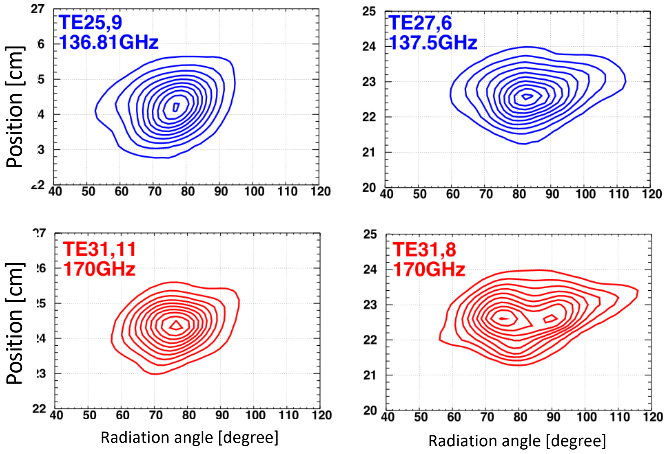

Fig. 3 Launcher optimization results for two multi frequency gyrotron case.

3. COMPARISON OF ALL 8 ITER GYROTRONS

Figure 4 shows all 8 gyrotron typical waveforms for 300sec shot. The averaged voltages, i.e., cathode, anode and body voltages are -44.4kV, -1.5kV and 31.7k, respectively. The differences of maximum and minimum voltages for cathode, anode and body are 4.4kV, 4.6kV and 5.9kV, respectively. The averaged beam current is 47.3A and the maximum and minimum beam current difference is 5.5A. As a result, the power of each gyrotron and frequency is scattered as shown in Fig. 5 and Fig. 6. These data are obtained from 20 times repetition of 300s shot. The data are averaged number for each gyrotron. Scattering of the power of all 8 gyrotrons is ±46kW and the frequency is scattered ±82MHz. Even if the identical design, the optimized parameters and resulting output power and frequency is scattered in these ranges. It is not critical, but this shows it still need to precisely adjust the parameter for each gyrotron by human operator. It should be taking care in near future for fusion devices which may need more than hundreds gyrotron.

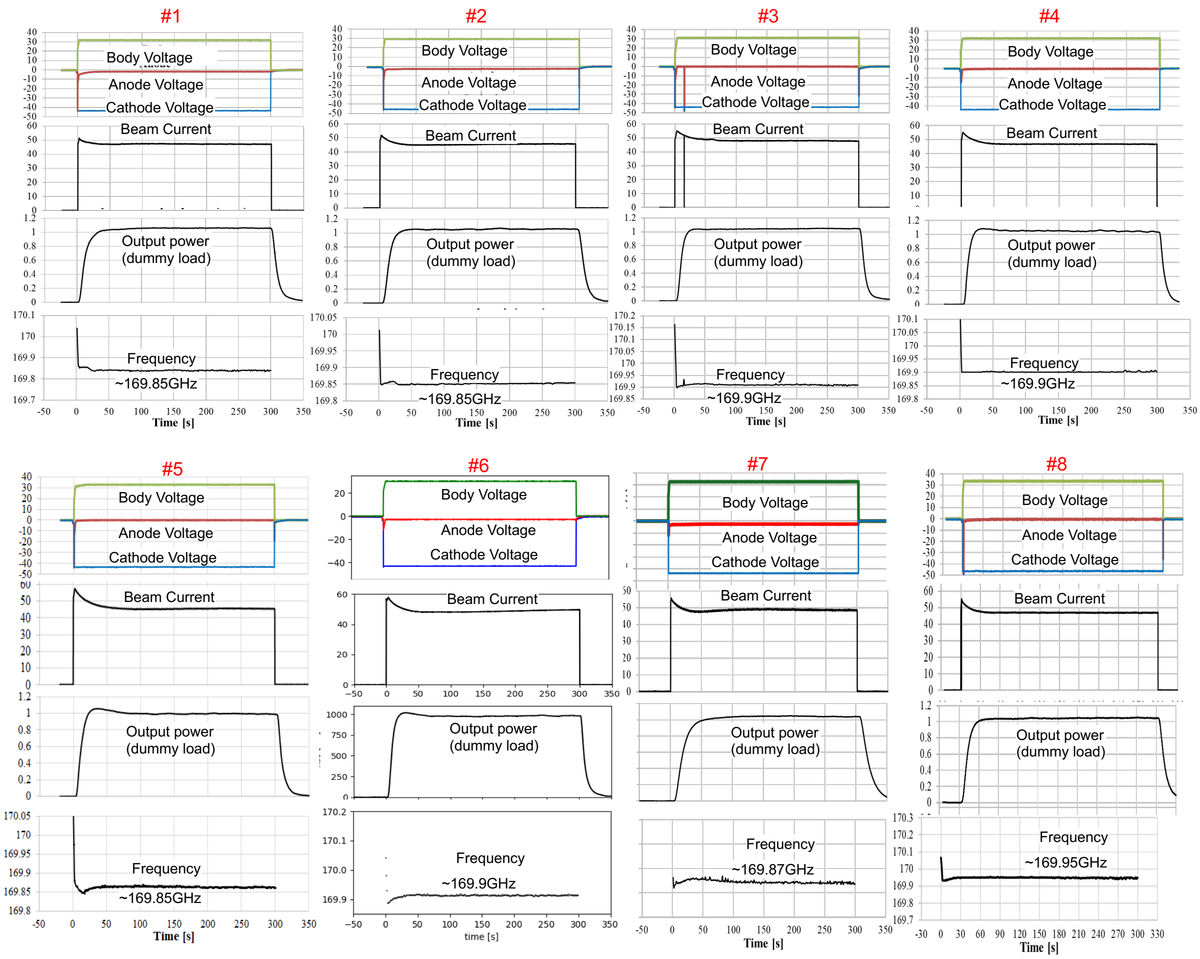

Fig. 4   All 8 gyrotron typical waveforms for 300sec operation

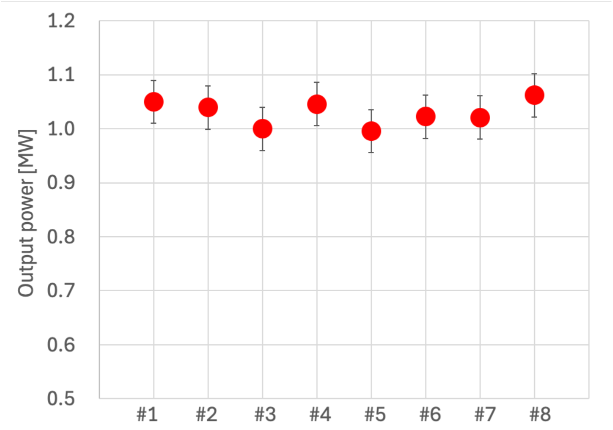

Fig. 5   All 8 gyrotron averaged power which is obtained by averaging 20 shots with 300 s pulse length.

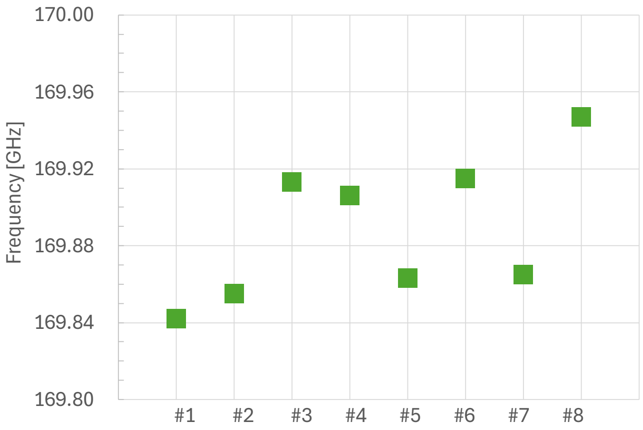

Fig. 6 All 8 gyrotron averaged frequency which is obtained by averaging 20 shots with 300 s pulse length.

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