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# Status of Collaborative Gyrotron developments in University of Tsukuba
# 筑波大学における共同研究用ジャイロトロン開発の現状


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In University of Tsukuba, development of Mega-Watt Gyrotrons of wide frequency range from 14 GHz to 300 GHz is performed as collaborative ECH study with several research organizations. For the first step of the collaborative research with Kyushu University, the Tsukuba 28 GHz gyrotron was adapted to QUEST ECH system and the good plasma heating and current drive effects were demonstrated. In the next step, the design studies of a 28 GHz 2 MW (0.4 MW CW) and 35 GHz 1 MW dual-frequency gyrotron for QUEST, NSTX-U, Heliotron J and GAMMA 10/PDX and a 14 GHz 1 MW gyrotron for QUEST and GAMMA 10/PDX are progressing. Moreover, 300 GHz gyrotron development has also started in collaboration with JAEA.


## 1. Introoduction

Development of Mega-Watt Gyrotrons is performed for some plasma experimental devices with cooperative research in University of Tsukuba.

Three 77 GHz and two 154 GHz gyrotrons have been developed for ECRH system of LHD under the joint program with NIFS. Typical achieved parameters of 77 GHz gyrotrons are 1.87 MW 0.1 s, 0.98 MW 10 s, 0.22 MW 75 min. and so on. In the 154 GHz gyrotrons, the maximum output power of 1.15 MW was obtained with the pulse width 1.2 s. Total injection power of 4.6 MW to LHD plasma has been achieved. The central electron temperature of 20 keV was obtained. The plasma stored energy of 530 kJ has been achieved [1-3].

A 28 GHz 1 MW 1 s gyrotron with $TE_{8,3}$ cavity has been developed to upgrade the ECH systems of GAMMA 10/PDX. After modification of the magnetron injection gun (MIG) to improve the oscillation efficiency in high current regions, the maximum power of 1.25 MW and the stable operation of 0.6 MW 2 s was obtained[4].

For the first step of collaborative research with Kyushu University, the Tsukuba 28 GHz 1 MW gyrotron was adapted to QUEST ECH system and the plasma heating effect was demonstrated. The gyrotron operation parameters in the first QUEST plasma experiment were 300 kW 1 sec., 270 kW 1.7 sec. and so on. In 2013 QUEST plasma experiment, successful results were obtained that the over dense plasma more than $1\times10^{18}$ $m^{-3}$ which is higher than cut-off density of 8.2 GHz was produced and EC-driven plasma current of 66 kA was non-inductively attained with the 28 GHz injection[5].

## 2. Development of Dual-frequency (28 GHz / 35 GHz) Gyrotorn

A 28 GHz 1.5-2 MW with pulse width of several seconds gyrotron is required for ECH systems of GAMMA 10/PDX and NSTX-U, and a 28 GHz CW gyrotron is required for QUEST. So, development of new 28 GHz gyrotron has started. A set of design parameters of new 28 GHz 2 MW gyrotron is shown in Table1. The MIG has same structure with 28 GHz 1 MW gyrotron. The target operation parameters are 2 MW 3 sec. and 0.4 MW CW. The 28 GHz cavity oscillation mode of $TE_{8,5}$ has been selected because the oscillation of 35 GHz $TE_{10,6}$ and the conversion from the wave guide mode RF to Gaussian beam are possible in the same 28 GH cavity resonator and the same 28 GHz mode convertor, respectively. Here, the reason to try the dual-frequency oscillation of 28 and 35 GHz is that a collaborative research with Heliotron J of Kyoto University is considered. Calculated beam current dependences of cavity oscillation powers with pitch factor α are shown in Fig.2. The oscillation power of 2 MW is expected with $V_k$ = 80 kV, $I_k$ = 70 A, and α = 1.0. Same calculation results are also obtained at 35 GHz oscillation as shown in Fig.3. Good performance results of a built-in quasi-optical mode converter were obtained. The transmission efficiency by inner mirror system of 98 % was obtained. The designs of mode converter and inner mirror system are modifying now for the purpose of obtaining the higher efficiency. The design studies of the assemble structure of each component will be completed until end of 2014. On the other hand, major components production has already started.

TABLE1. Dual-Frequency Gyrotron Design parameters

| 28 GHz 35 GHz Dual-frequency Gyrotron for GAMMA 10/PDX, QUEST, NSTX-U, Heliotron J | | | |
|---|---|---|---|
| Frequency | 28GHz | | 34.79 GHz |
| Output Power | 2 MW | 0.4 MW | 1 MW |
| Pulse Width | 3 s | CW | 3 s |
| Output Efficiency | 50% (with CPD) | | |
| Beam Voltage | 80 kV | 70 kV | 80 kV |
| Beam Current | 70 A | 20 A | 40 A |
| MIG | triode | | |
| Cavity mode | $TE_{8,5}$ | | $TE_{10,6}$ |
| Output mode | Gaussian like | | |
| Sappier Double Disk Output Window | | | |
| Depressed Collector with Sweeping coils | | | |

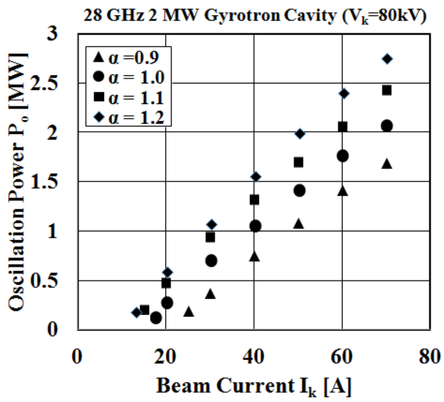


Fig.2 Calculated beam current dependences of 28GHz $TE_{8,5}$ mode oscillation powers .

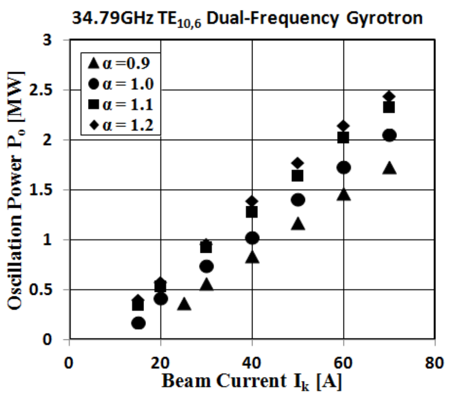


Fig.3 Calculated beam current dependences of 34.8 GHz $TE_{10,6}$ mode oscillation powers.

## 3. Design Study of 14 GHz Gyrotorn

The design study of 14 GHz 1 MW gyrotron is also in progress for GAMMA 10/PDX and QUEST. By considering the design result of cavity, MIG and electron beam trajectory, the cavity oscillation mode has decided in $TE_{4,2}$. The oscillation power of 1 MW is expected with $V_k$ = 75 kV, $I_k$ = 50 A, and α = 1.0 by cavity simulation cord. A cathode diameter is φ75 mm that is smaller than 28 GHz gyrotron.

## 4. First Test Results of 300 GHz Gyrotron

Moreover, based on a collaborative research with JAEA, the first experimental test of 300 GHz gyrotron has been carried out at Tsukuba gyrotron test stand. The JAEA 300 GHz gyrotron is conventional type gyrotron without a build-in mode converter. The burn pattern of output RF at the output window is shown in Fig.4. The smallest radius with strongest burn pattern agreed with the radius of first peak of $TE_{32,18}$ mode which is the designed cavity oscillation mode. The output power of over 500 kW was achieved with pulse width of 2 ms.

Fig.4 Burn pattern of 300 GHz Gyrotron Output Power.

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## References

[1] T. Kariya, et al., J. Infrared Millim. Waves 32 (2011) 295-310.
[2] R. Minami, et al., Nucl. Fusion 53 063003 (2013).
[3] H. Takahashi, et al., Phys. Plasmas 21, 061506 (2014)
[4] T. Kariya, et al., Plasma Fusion Res. 8, 1205107 (2013)
[5] H. Idei, et al., in Proceedings of the 25th IAEA Fusion Energy Conf., (2014).