Development of a High Power Gyrotron Prototype for GW-Class Microwave Beam Source Study

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***Abstract*—To realize the GW-class power source for *Microwave Rocket*, the cost reduction of gyrotrons is one of the solutions to lower the threshold to realize the beam station. In this study, a sub-MW-class gyrotron which adapted a smaller bore diameter of the superconducting magnet was designed and developed. The output power, pulse duration, and frequency are respectively 600 kW, 100 µs, and 94 GHz. The electron current is driven by a charged capacitor bank and in-house IGBT switches. The gyrotron tube was aligned with the superconducting magnet to achieve high electric efficiency.**

I. Introduction

Microwave Rocket is a space launch system propelled by a strong millimeter-wave beam and expected to realize low-cost space transportation. An analytical study [1] based on experimental results of *Microwave Rocket* [2] with high-power gyrotrons represented that GW-class beam power is required to launch a 100 kg-class payload into low earth orbit. The manufacturing cost of the beam station which generates GW-class beam power is expected to be 3350 M$ [1] so that the cost reduction of gyrotrons is necessary to lower the threshold to realize the beam station. The beam station consists of hundreds of gyrotron tubes, high voltage power systems, and infrastructural components such as superconducting magnets (SCM). A small bore diameter of SCM, for instance, contributes to a significant cost saving of the system due to the reduced amount of superconducting material. One of the obejectives of this gyrotron development is to demonstrate the employment of a superconducting magnet with a small bore diameter of 100 mm.

To realize a GW-class beam station, at least hundreds of kW output power per gyrotron is required to decrease the number of clustered gyrotrons and keep the land area of the beam base small. Accordingly, sub-MW is the target output power of our gyrotron. The sub-MW-class gyrotron is useful for *Microwave Rocket* research. In the thruster, intermittent millimeter-wave irradiation from the ground to a vehicle sustains a thrust generation cycle of air-breathing and blast-wave formation [3,4]. Millimeter-wave energy is converted into the blast wave energy via discharge-detonation supported by a high-power millimeter-wave beam, as presented in Figure 1 [5]. In the Millimeter-wave Supported Detonation (MSD), an ionization front propagates toward a beam source at a super-sonic speed with various self-organized structures in wavelength scales [6,7]. The complicated filamentary structure in Figure 1 is unique to millimeter-wave discharge, which was not observed in the discharge plasma using a CO_2 laser. Hence, the experimental investigation of the plasma is strongly demanded. For the observation of the microscopic plasma structure, the output power and pulse width are determined at 600 kW and 100 µs, respectively.

This paper describes the design and development of a 600 kW gyrotron prototype which employed a SCM whose bore diameter is 100 mm. The gyrotron allows us to invesitigate atmospheric millimeter-wave discharge plasma for elucidating the thrust generation mechanism of *Microwave Rocket*.

II. Gyrotron Design

A sub-MW-class gyrotron prototype that adapted 100 mm bore diameter of SCM (JMTD-8T100, JASTEC Co., Ltd.) was designed. Three ordinary coils (TMC-10-7620, Techno Electric Industry Co., Ltd.) were also installed around an electron gun to adjust the magnetic mirror ratio. $TE_{10,8}$ mode was selected for 94 GHz oscillation at a cavity and in-tube quasi-optical mode converter was designed to produce a Gaussian output beam. The molded RF beam is radiated through a single-disk alumina window to the outside of the gyrotron.

The gyrotron utilized a diode type electron gun (Canon Electron Tubes & Devices Co., Ltd.), which was immersed in an oil tank to avoid atmospheric discharge. The nominal electron beam voltage and current are respectively 65 kV and 25 A, which correspond to the power of 600 kW at an electric efficiency of 37 %. The output power is controllable by adjusting the magnetic flux of SCM or the electron beam

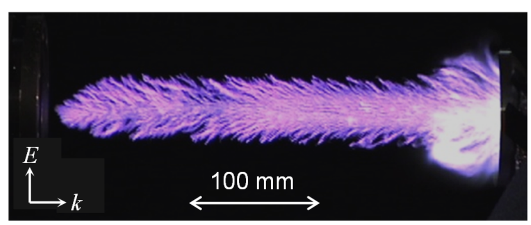

Fig. 1 A side view of atmospheric breakdown plasma. A 170 GHz millimeter-wave beam is incident from the left side. The output power and pulse duration are respectively 900 kW and 0.5 ms. [5]

Table 1. Design specification of the gyrotron prototype.

Frequency	94 GHz
Target power (Calc.)	600 kW
Pulse duration time	100 µs
Electrode	Diode
Oscillation mode at cavity	$TE_{10,8}$
Electron beam voltage	65 kV
Electron beam current	25 A
Electric efficiency (Calc.)	37 %
Condenser bank's capacitance	0.85 µF
RF window's diameter	60 mm

current. The degree of vacuum inside the gyrotron tube reached about 10^{-6} Pa by conducting the aging procedure of the electron gun.

The electron current is supplied from a condenser-bank. A power supply unit firstly charges the condenser-bank at low current and high voltage, and a high-voltage IGBT switches control the current of the main circuit. This method enabled the operation of the high-power gyrotron with an in-house power supply. However, the pulse width is limited by the capacitance of the condenser bank. The current capacitance of 0.85 μF is capable of oscillating a square wave of 100 μs pulse duration, which can be extended by adding condenser banks in the future.

The design specification of the gyrotron prototype is summarized in Table 1.

III. Gyrotron Tube Assembly and Test

All the gyrotron tube components, an electron gun, a cavity, a mode converter, an RF window, and a collector were assembled for high power tests, as shown in Figure 2.

The system of high voltage power supply was developed using a condenser bank (Toei Electric Co., Ltd.) and IGBT-based HV switches (SKM150GB17E4, Semikron). The withstand voltage and current of an IGBT switch are respectively 1700 V and 150 A so that 50 series of the elements can secure the withstand voltage of 85 kV. Furthermore, the voltage rise time can be less than 1 μs by synchronizing each IGBT switch. The initial test was carried out using a dummy load resistor instead of the gyrotron tube. The high voltage power supply system worked well, as presented in figure 3.

IV. Alignment of Gyrotron Tube with Magnetic Axis

Oscillation at high efficiency is expected by aligning the gyrotron tube with the magnetic axis, and centering the cavity' origin in the magnetic axis. Therefore, the tilt and the center of the magnetic axis was investigated beforehand with an accuracy of 0.1 mm by identifying the center of magnetic flux density B_z on the upper and lower surface of the SCM. It was found that the magnetic axis was tilted by about 0.045 degrees to the upper surface of SCM, and the magnetic center at the cavity's height was about 0.15 mm off the center of the bore.

For this gyrotron, it is possible to adjust the tilt and position of the gyrotron tube on the upper surface of SCM. Therefore, the gyrotron tube was installed into a 100 mm bore SCM with reference to the results of the magnetic field measurement. High power test results of the gyrotron will be presented at the conference.

Fig. 2. A photograph of a 100 mm bore diameter of SCM and assembled gyrotron tube.

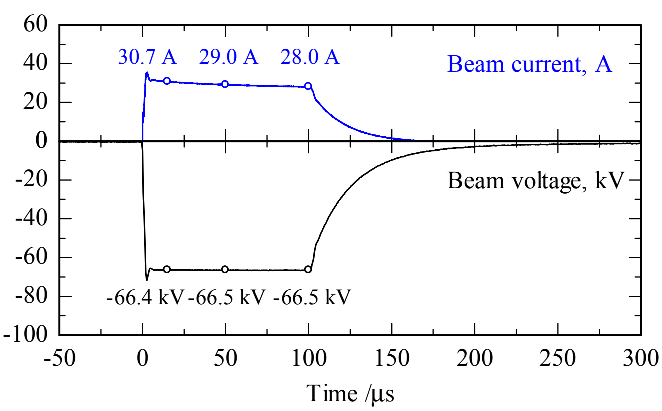

Fig. 3. Time history of beam voltage and beam current obtained from a high voltage applied test with a dummy load resistor.

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