Magnetron Injection Gun for a Multi-Frequency Gyrotron

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Abstract— **A triode electron gun was developed to realize step-frequency tunability in a sub-THz gyrotron. Helical electron beams are formed with high-laminarity such that the velocity spreads are maintained at low levels in a wide operation range. The stable oscillations were experimentally confirmed at expected frequencies from 162 to 265 GHz with powers of the order of 1 kW.**

I. INTRODUCTION AND BACKGROUND

A step-frequency tunable gyrotron, which is operated at fundamental harmonic frequencies from 161.9 to 265.0 GHz, has been developed in FIR-UF [1, 2]. Its objective is enabling use of a gyrotron for alternate or more general needs in this frequency range. The frequency is primarily changed with the magnetic field in a cavity, in which different TE modes are excited in association with the electron cyclotron frequencies. A 10 T superconducting magnet which has a room temperature bore diameter of 100 mm is used. The tube is equipped with an internal mode convertor consisting of a helically-cut Vlasov launcher to output all modes as Gaussian beams.

The critical issues are selecting suitable modes, adjusting the transmittance of an output window and formation of high quality electron beams. The cavity has a radius of 5.50 mm and a length of 15.0 mm. The selected oscillation modes are listed in Table 1. The frequencies were calculated using the cold-cavity model. As their radiation angles θ are nearly equal, generated waves at all frequencies can be transmitted to the vacuum window as Gaussian like beams with a single mode convertor [2]. The vacuum window is made of a c-cut single crystal sapphire-disk, and the thickness is determined to minimize the reflection rate at 265.0 GHz. The transmittance for the other modes is improved with another sapphire-disk placed outside and parallel to the vacuum window. The optimum spatial-distances between two disks for maximum transmittance depend on each frequency.

Mode ($TE_{m,n}$)	F [GHz]	B_C [T]	$\theta = \cos^{-1}(m/\chi'_{m,n})$ [deg.]	R_B [mm]	B_C / B_K
$TE_{10,6}$	265.0	9.71	70.9	1.93	42.0
$TE_{9,6}$	253.6	9.29	72.1	1.81	47.7
$TE_{8,6}$	242.1	8.86	73.3	1.69	54.7
$TE_{7,6}$	230.4	8.44	74.7	1.55	65.0
$TE_{9,5}$	224.7	8.23	69.7	2.05	37.2
$TE_{8,5}$	213.4	7.82	71.0	1.91	42.8
$TE_{7,5}$	202.0	7.39	72.5	1.77	49.9
$TE_{6,5}$	190.5	6.97	74.1	1.61	60.3
$TE_{7,4}$	173.2	6.35	69.5	2.07	36.5
$TE_{6,4}$	161.9	5.94	71.2	1.89	43.7

Table 1. Oscillation frequency, magnetic field strength, transverse radiation angle, electron beam radius, and magnetic compression ratio for each cavity mode. The term $\chi'_{m,n}$ represents the n-th root of derivative of the m-th order Bessel function, $J'_m(z)$.

II. ELECTRON GUN DESIGN

The magnetron injection gun (MIG) is triode-type which is appropriate for modulation of the beam trajectories. In order to selectively couple to the desired cavity modes, electron beams should have different injection-radii with different cyclotron frequencies while maintaining a high velocity pitch factor, α and small velocity spreads, $\Delta\alpha$. The design of electrodes is a quite complicated task owing to significant changes in electron trajectories and magnetic compressions which increase inhomogeneity in the space-charge distribution.

To reduce the space-charge effect, we paid considerable attention to making the space-charge distribution as uniform as possible; i.e., producing laminar electron flow [3, 4]. The electron trajectories were numerically simulated with a calculation code, EGUN. The optimized configuration of electrodes, the corresponding electrostatic potential distribution and representative electron beam trajectories are shown in Fig. 1. The cathode voltage and beam current were set as $V_K = -20$ kV and $I_B = 0.5$ A, respectively.

Since electrons on different trajectories are emitted from different axial points on the cathode, they have different gyration phases in a beam cross-section perpendicular to the magnetic field line. In Fig. 1, the points having a certain gyration phase are represented with circles, and connected by

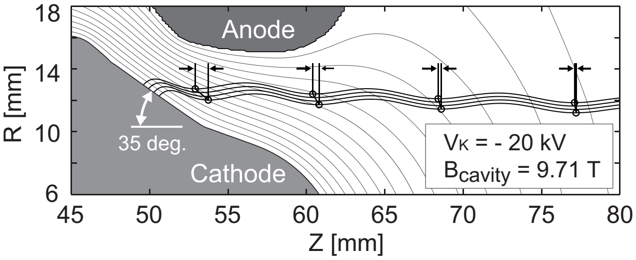

Fig. 1. Distribution of electrostatic potential and the beam trajectories calculated with EGUN for the $TE_{10,6}$ mode operation.

line segments between innermost and outermost trajectories for each period of gyration. In ideal laminar flow, these line segments are parallel to the beam cross-sections. As shown in Fig. 1, the line segment gradually leans on the beam cross-section during several periods of gyro-motion, whereas it is almost parallel to the cathode immediately after the emission. On this occasion, the electrons on outer guiding-center radii are accelerated by steep potential slopes, while inner electrons are accelerated by gentle potential slopes [4]. In the well-laminated beam, the axial pitch of each gyration is modified such that all electrons in the subsequent beam cross-sections have almost the same gyration phase. This improvement of the laminarity is possible with a properly arranged potential profile between the cathode and anode.

As the result, very small $\Delta\alpha_{\text{cavity}}$ less than 6% in a wide α_{cavity} range from 0.9 to 1.5 was predicted for every mode in EGUN simulations (Fig. 2).

III. EXPERIMENTAL RESULTS

The gyrotron (named; FU CW GV), equipped with the above designed MIG, showed stable oscillations at expected frequencies for all of the designed modes (Fig. 3). The frequencies were confirmed with a heterodyne receiver system. No influences of mode competitions and instabilities in the electron beams have been observed. A double-disk window system was arranged to maximize the transmittance for different frequencies. The measured power variations for the electron beam properties were in good agreements with the calculated ones. With -20 kV, 0.5 A electron beams, the calorimetrically measured powers have attained kilo-Watt levels.

The power can be modified by the voltage between the anode and cathode, V_{KA} with respect to α in the cavity (Fig. 4). While α increased up to approximately 1.5, the power also increased. If the value of α exceeds the optimum, there is saturation and substantial deterioration in the power owing to the over-interaction. In this case, also, the observed characteristics coincide very well with the calculated characteristics.

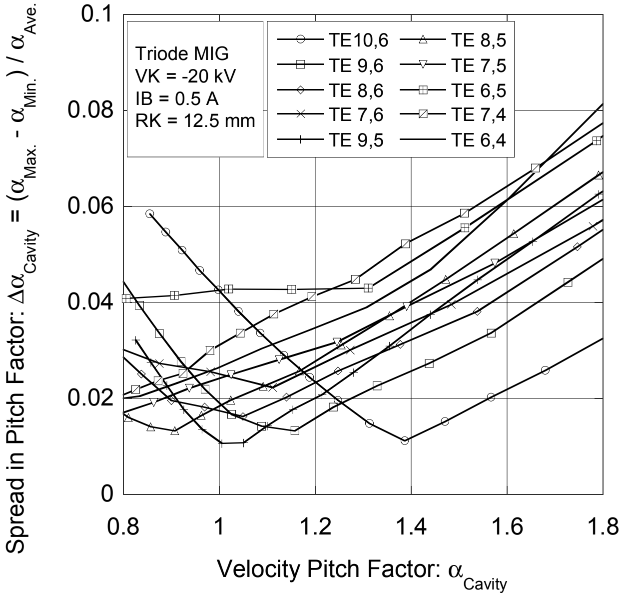

Fig. 2. Electron beam properties in the cavity calculated with EGUN.

The results show that the MIG provides the expected beam properties in a wide range of α.

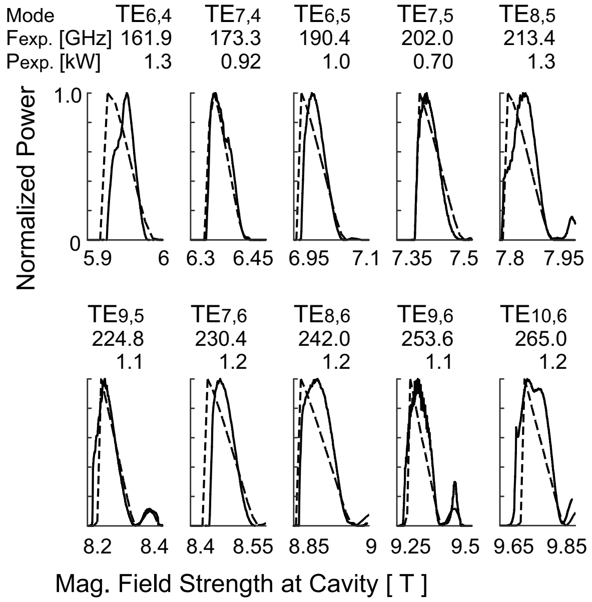

Fig. 3. Calculated (dash) and observed (solid curve) power dependence of cavity magnetic field.

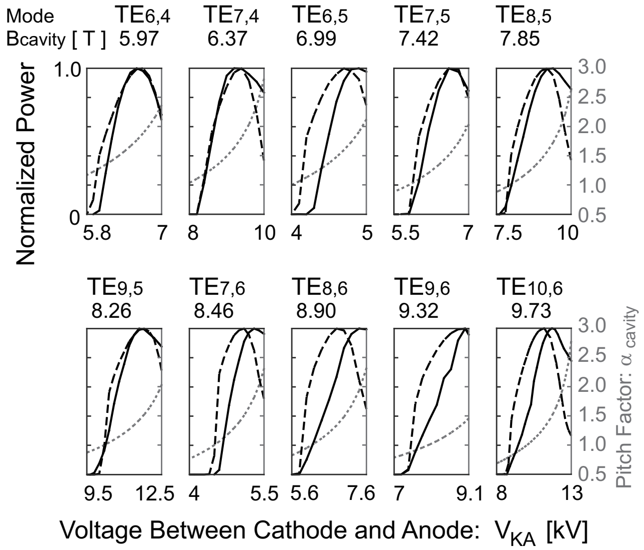

Fig. 4. Dependences of power (long-dash: calculated, solid curve: observed) and calculated velocity pitch-factor (short-dash) on the voltage between anode and cathode.

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