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High-current THz-band gyrotrons based on axial-slit cavities

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Abstract. We propose a variant of a slotted cavity for high-current gyrotrons based on the coupling of modes with proportional azimuthal indexes and close eigenvalues. A finite-element method simulation is presented, which confirm its high selectivity. 3D PIC simulations of a high-current relativistic gyrotron in the 0.3 THz and 0.5 THz bands with an output power of about 70–80 MW are performed.
Keywords: gyrotron, terahertz radiation, mode selection in cavities.

1. Introduction

At present, the prospects of generation high-power terahertz-band radiation are under intense investigation. For instance, in [1], a 330 GHz surface-wave oscillator was studied with output power exceeding 40 MW fed by an electron beam with an energy of 380 keV and a current of 2.2 кA. In [2], prospects for realization of 2 THz planar free electron lasers with a multi-MW power were discussed. Currently, gyrotrons are known to be the highest-power CW radiation sources in THz band, as they feature high mode selectivity allowing for use the highly oversized electrodynamical systems [3]. Gyrotrons fed by high-current relativistic beams can potentially be used as sources of high-power THz radiation. However, the selective excitation of the operating oscillation can constitute a significant problem in this case. Here we propose a new type of high-selectivity resonators for high-current gyrotrons based on the coupling of modes with proportional azimuthal indexes and close eigenvalues.

2. Electrodynamic properties of an axial-slit cavity

First, we consider the mode selection principle in the proposed cavity. Assume that in a circular cross-section waveguide, two modes at a single frequency are excited simultaneously, possessing m and $2m$ variations along the azimuthal coordinate, with equal field amplitudes at the waveguide wall. The combined field of these modes would have m variations with double amplitude and m variations with half the amplitude of each mode. If one makes m azimuthal gaps in the waveguide wall, such a mode combination would be advantageous with respect to the other modes in terms of diffraction loss value.

Consider the mechanism of excitation of such a cavity. An azimuthally-periodical system of axial slits allows for azimuthal selection of a TE mode structure with several minima along the azimuthal coordinate. Such a standing wave might emerge due to selective coupling of the two rotating TE modes characterized by close eigenvalues, i.e. roots of the corresponding Bessel function derivative at the perturbed side wall of the cavity. On the azimuthally periodic surface, the effective magnetic current associated with the cavity eigenmode possessing an azimuthal index of m_1, has a harmonic synchronous to the cavity eigenmode possessing an azimuthal index of m_2 under condition $m_2 - m_1 = qm$, where q is integer and m is the number of slits.

Selective coupling of TE modes with azimuthal indices of m and $2m$ is provided by a structure with m slits. Assume that an electron beam with a spicifically chosen radius of R_{beam} excites $TE_{2m,n}$ mode with a certain direction of azimuthal rotation. This mode excites co-rotating $TE_{m,q}$ due to coupling on the first harmonic of the corrygation. Counter-rotating $TE_{2m,n}$ and $TE_{m,q}$ modes due to coupling on the third harmonic of corrugation. This results in excitation of the combination of two coupled TE modes with m and $2m$ indexes and close eigenvalues.

Among the spatially extended TE modes with *m* and 2*m*, the following combinations can be distinguished which satisfy the condition of Bessel derivative root proximity in the best way: $TE_{6,4}$ and $TE_{12,2}$; $TE_{8,7}$ and $TE_{16,4}$; $TE_{11,9}$ and $TE_{22,5}$, etc.

Simulations of the axial-slit cavity were conducted using the CST Microwave Studio software. Taking into account that the gyrotron operates at a frequency close to the operating mode cutoff, for a first approximation one might take the axial wavenumber to be zero. This allows the dimensionality of the problem to be reduced and simulate the interaction in 2D cross-section. Since CST Microwave Studio is a 3D code, this simplification is equivalent to simulating a thin layer along the cavity axis with ideal magnetic surface boundary conditions. In the transverse directions, at some distance from the metallic walls of the slitted waveguide, the open boundary conditions were used, which allow the radiation coming out of the cavity through the slits to leave the simulated area.

Time solver was used in order to find the operating mode of the cavity and its quality factor. The field inside the cavity is excited by a small-length dipole thread with a finite-duration current; its frequency band includes the assumed eigenfrequency of the operating mode. After the excitation, the field decays freely inside the cavity. At first, low-*Q* modes die out and their relative share in the total field rapidly decreases. Since the operating mode is the highest-*Q* mode, its decay is the slowest. At some instant, the field inside the cavity can be considered the operating mode field decaying exponentially. In log scale, the energy decay plot is a straight line; its inclination characterizes the *Q*-factor of the eigenmode.

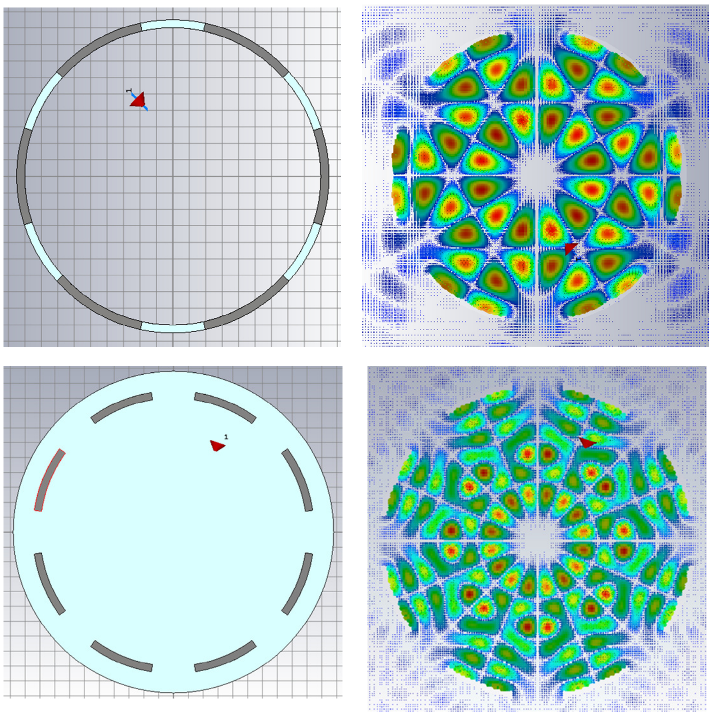

Fig.1. Cross section of cavities (left column) and transverse structure of the axial component of the microwave magnetic field in the case of "supermode" excitation (right column).

We have studied cavities with six and eight slits (Fig.1), calculated for $TE_{6,4}$+$TE_{-6,4}$+$TE_{12,2}$+$TE_{-12,2}$ and $TE_{8,7}$+$TE_{-8,7}$+$TE_{16,4}$+$TE_{-16,4}$ mode combination. Simulations confirms the existence of the "supermode" with a a *Q*-factor much more than those of the neighboring oscillations. Fig.1 demonstrates the transverse structure of the obtained "supermodes". It can be clearly seen that in the internal area (close to the system axis), the field distribution has six and eight variations along the azimuthal coordinate while in the outer area (close to the cavity wall), it has twelve and sixteen variations. The *Q*-factor was about 2400 and 6800 for a six and eight slits cavities, correspondingly.

3. 3-D PIC Simulation of a High-Current Gyrotron

Numerical simulation of the possibility of excitation of the slitted cavity by a helical electron beam was undertaken using the particle-in-cell method within the 3D PIC solver in the KARAT software [4]. We consider the possibility of obtaining single-frequency oscillation in THz band. For 0.3 THz waveband, a cavity based on $TE_{6,4}$ and $TE_{12,2}$ mode combination would have a radius of 3 mm, which is acceptable in terms of manufacturing such a cavity. The magnetic field strength should be about 180 kOe. For 0.5 THz waveband, a cavity based on $TE_{8,7}$ and $TE_{16,4}$ mode combination would have the same radius. The magnetic field strength should be about 300 kOe. Currently, the technologies of obtaining such a fields in pulsed regimes are well elaborated [5].

In simulations, a helical electron beam with an energy of 500 keV, current of 2 kA, pitch of 1.0, injection radius of 2.2 mm and initial transverse velocity spread of about 40% excited a cavities with six and eight axial slots (Fig.2). Cavity wall conductivity was taken equal to the copper conductivity. A helical beam with a required radius can be obtained using an electron optics system with a kicker providing electrons transverse velocity in the area of relatively low magnetic field [6]. Similarly to conventional magnetron injector guns, in such a system a section of rising magnetic field can be introduced where the beam radius would decrease proportionally to the square root of the guiding magnetic field strength.

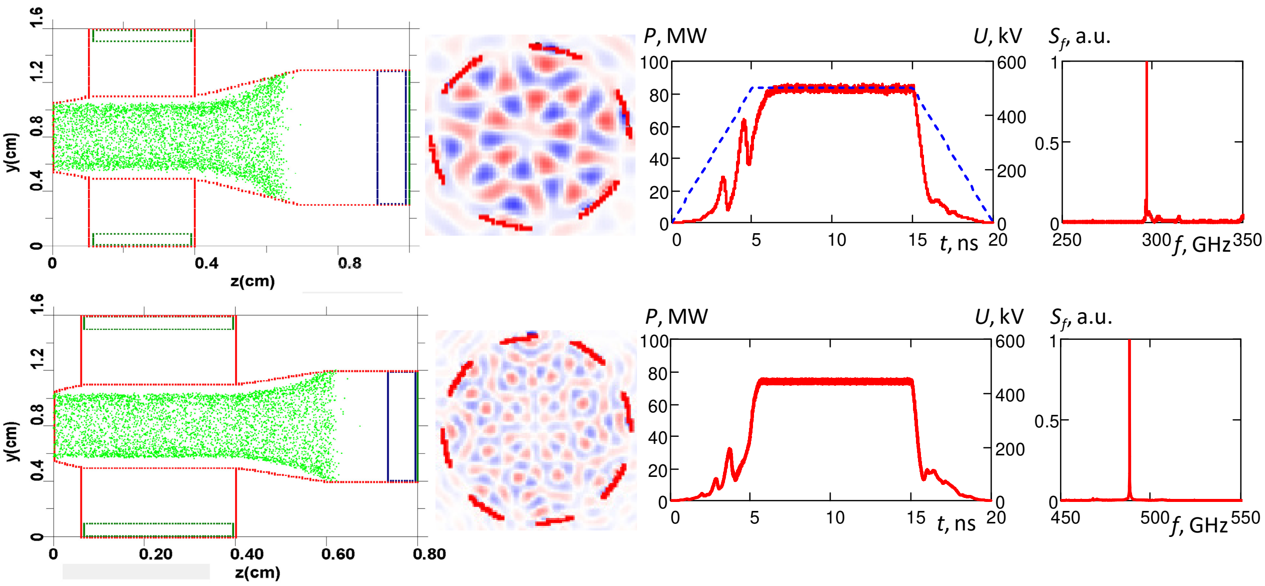

Fig.2. Axial cross-sections of the interaction space in PIC simulations, spatial structure of the axial component of magnetic field, accelerating voltage pulse (dashed) and output power (solid line) and corresponding output signal spectrum. Top row – 0.3 THz gyrotron at combination of $TE_{6,4}$+$TE_{12,2}$ modes, bottom row – 0.5 THz gyrotron at combination of $TE_{8,7}$+$TE_{16,4}$ modes.

The current pulse had a form of trapeze with forward and backward front duration of 5 ns and a plateau of 10 ns. After the end of interaction, electrons are deposited at the wall of the electrodynamics system by means of decreasing magnetic field region. In order to simulate the radiation condition, an absorbing layer with variable conductivity is placed at the collector side of the interaction space; reflection coefficient of this layer is less than 1% of power in the incident wave. Similar layer was placed outside the cavity to absorb the radiation outcoming through the slots.

In the simulation, it was shown that in a gyrotron with a slotted resonator there is a wide zone in the magnetic field in which the "supermode" is excited, formed by the modes of a circular waveguide with multiple azimuthal indices. The maximum output power in this case can reach 70–80 MW.

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5. References

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