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Progress in the development of low-voltage gyrotron for integration with NMR spectrometer

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While high-power, high-voltage gyrotrons for plasma fusion are most important gyrodevices nowadays, compact and less expensive gyrotron tubes with low operating voltage [1–4] could be an attractive opportunity for spectroscopic applications. The project of the medium-power gyrotron which can be integrated with nuclear magnetic resonance (NMR) spectrometer in a single cryomagnet (Fig. 1) is under development in the Institute of Applied Physics [1, 5]. This compact and low-voltage gyrotron ("gyrotrino") is aimed at dynamic nuclear polarization (DNP) technique and should deliver the CW power about of 10 W at the frequency of 263 GHz. The integrated solution [2–3] could eliminate the need for an additional superconducting magnet, result in a shorter terahertz transmission line, and make DNP systems less expensive.

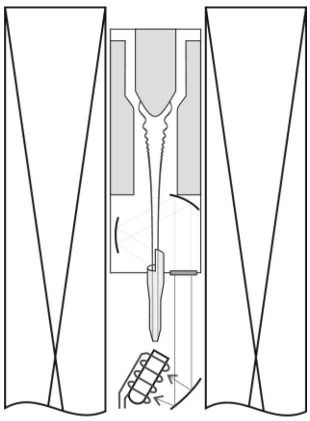

Fig. 1. Layout of the gyrotrino in NMR spectrometer magnet (not in scale)

The integration of the gyrotron with NMR-spectrometer in a single cryomagnet results in a number of specific features of such a THz oscillator, including electron-optical system, beam-wave interaction, and collector-end power output. The very low operating voltage of 1.5 kV results in very small anode-cathode distance in the electron gun and low electrical field at the emitter. To minimize velocity spread, electron gun is designed [6] to form a laminar electron beam, see Fig. 2. As a result, the transverse velocity spread in the electron beam is determined mainly by the initial velocity spread caused by thermal electron velocities and emitter surface roughness; for 5 μm roughness, the calculated spread is about of 30%. The lack of space in the NMR-spectrometer magnet necessitates placing the electron-beam collector in a region of homogeneous magnetic field [5]. Utilization of the electron beam with very high power density of 10 kW/cm^2 is possible due to very thin footprint of the electron beam on the inner collector wall; as it shown in Fig. 3, the heat spreads over all directions, i.e., in the angle range π, unlike the conventional gyrotron collectors, so heat flow density at the outer collector surface is less than 400 W/cm^2.

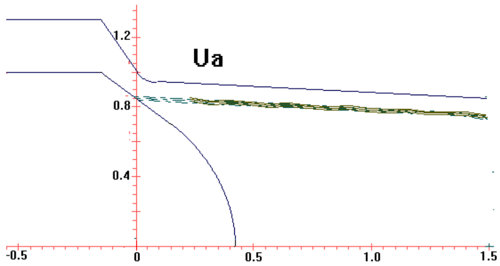

Fig. 2. Designed geometry of a magnetron-injection gun for the gyrotrino and simulated laminar electron beam trajectories in the emitter region. The dimensions are in cm

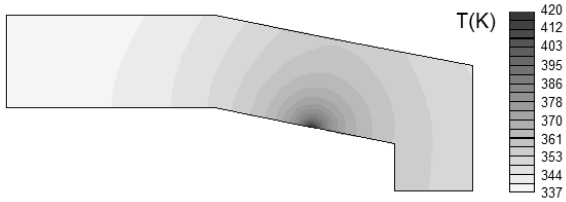

Fig. 3. Temperature distribution in the 2.4-mm-thin copper collector wall. The beam power is 270 W and the beam footprint width is 0.3 mm

The electron-wave interaction for integrated gyrotron configuration also demonstrates a number of specific features caused by lack of space and condition of matching the gyrotron and NMR frequencies. These factors results in very low gyrotron accelerating voltage and short cavity. An alternative way to provide frequency matching for integration of the gyrotron and the spectrometer is substantial modification of the cryomagnet instead of the gyrotron, namely, providing the two distinct uniform-field regions for the gyrotron cavity and for the NMR probe [7].

For gyrotron with low voltage and short cavity, the use of abrupt decrease in cavity diameter instead of smooth cathode narrowing can provide 20 % increase in gyrotron output power (Fig. 4). This result seems counterintuitive, since it is known that smooth cavity up-taper and down-taper typically increase the gyrotron efficiency. The reason for this result is the non-optimal operation regime caused by the limitation on the length for the designed tube. Abrupt termination of the electron-wave interaction cause a decrease in the gyrotron starting current and, therefore, shifts the operation point further from the self-excitation border. In principle, this effect can be used in more common THz gyrotron devices, although it is not so pronounced for long cavities. For 527 GHz second-harmonic gyrotron with operating voltage of 15 kV, simulations predict 5% of power increase due to use of abrupt cutoff narrowing.

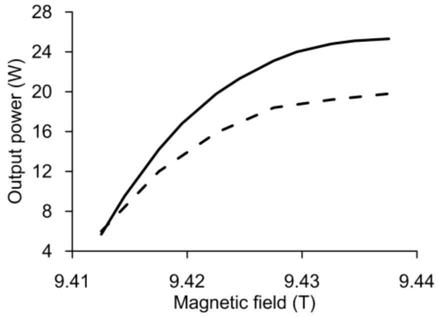

Fig. 4. The output power of 264 GHz low-voltage gyrotron with short cavity and operating mode $TE_{6,2}$ in cases of smooth (dashed line) and abrupt cathode narrowing (solid line). The voltage and current are 1.5 kV and 200 mA

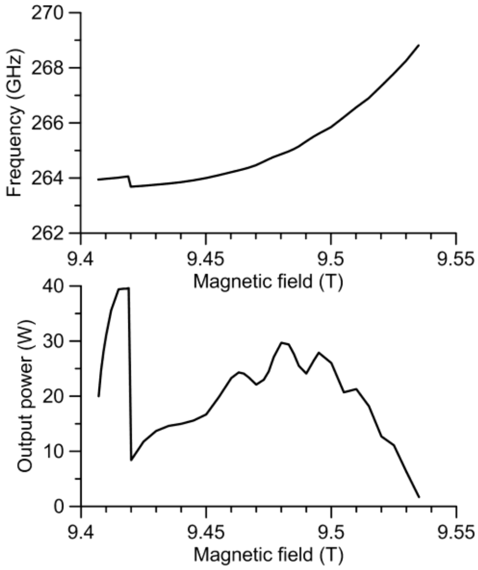

Fig. 5. Gyrotron power and frequency vs. the magnetic field for cavity length of 20 mm with cathode-end power output. The step at the left corresponds to electron synchronism with forward wave (traveling-wave tube regime)

One more surprising result is that the gyrotrino output power at the high axial modes can be significantly higher than at the fundamental mode [8]. This effect is most pronounced at traveling-wave tube regime, see Fig. 5; for a 2-kV gyrotron with beam current of 150 mA, the output power can be as high as 40 W at the second axial mode while only few watts at the fundamental axial mode. This effect can be used to provide smooth frequency tuning in spectroscopy-aimed gyrotrons. The collector-end power output is also favorable [9] for smooth frequency tuning. Simulations show that wider-than-percent FWHM frequency tuning can be achieved in 2-kV device with current of 150 mA.

The possibility of low-voltage gyrotron operation was verified in the demonstration experiment using the gyrotron tube designed for operation voltage of 15 kV. To obtain low-voltage electron beam with acceptable pitch-factor, we applied a higher voltage between cathode and first anode while decreasing the voltage between the cathode and the cavity. The gyrotron operation at the voltages down to 1.5 kV was demonstrated at the frequency of 250 GHz (the operating mode $TE_{5,2}$ at fundamental cyclotron resonance).

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