

Prospective THz Gyrotrons for High-Field Magneto-Resonance Spectroscopy

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Abstract

A high-harmonic Large Orbit Gyrotron and a low-voltage gyrotrino placed inside a spectrometer cryomagnet enable greatly simplify terahertz systems for magneto-resonance spectrometers. Large Orbit Gyrotrons provide a powerful third-harmonic generation at frequencies of 1 THz and 0.394 THz in pulsed and CW regimes, respectively, at significantly lower magnetic fields than conventional gyrotrons. According to simulations the gyrotrino with the voltage of 1.5 kV and frequency of 0.264 THz can generate a power of tens of watts; a possibility to operate at such a low voltage is demonstrated in the existing gyrotron with three-electrode magnetron-injection gun.

Introduction

THz medium power gyrotrons are in high demand for high-field DNP-NMR spectroscopy. However, only few installations are now equipped with such fairly expensive generators. Large Orbit Gyrotrons (LOGs) and gyrotrinos may make this method accessible for many laboratories due to the considerable simplification of the gyrotron magnetic system.

Conventional gyrotrons commonly operate at the fundamental or second cyclotron harmonics. The latter allows using simpler cryomagnets with a half-value of the magnetic field. A greater effect can be achieved in LOGs, capable of selective operation even at the third and fourth harmonics due to applying an axis-encircling electron beam [1-5], in contrast to a hollow poly-axis beam in a conventional gyrotron.

Another option is integration of a compact gyrotrino in single cryomagnet with an NMR spectrometer [6, 7]. This is based on the proximity of the electron cyclotron frequency and the frequency of the paramagnetic resonance in a sample. The integration eliminates the need for an additional cryomagnet and a long THz transmission line with high losses. An exact frequency matching can be achieved at a very low gyrotron voltage, namely 1-2 kV [6], or at special profiling the cryomagnet field [7].

High-Harmonic Large Orbit Gyrotrons

In a LOG cavity (Fig. 1), an axis-encircling electron beam can excite only co-rotating modes with azimuthal indices equal to the number of the resonant cyclotron harmonic [1-5]. This strong selection rule prevents the excitation of most of parasitic modes and makes it possible to operate at higher harmonics.

At the Institute of Applied Physics, LOGs, are being studied in parallel with conventional gyrotrons, for more than 20 years to obtain higher frequencies at lower magnetic fields. First experiments were carried out at high-current electron accelerators with moderately relativistic electron energy of (250 – 400) keV. These LOGs selectively generated high output powers at harmonics $s=2-5$ and frequencies from 20 GHz up to 0.4 THz [5]. At relativistic energy, electron-wave coupling at high harmonics can be stronger than at the fundamental resonance, but a problem of neighboring harmonics discrimination is fairly complex. In addition, use of relativistic energy decreases the cyclotron electron frequency and reduces the frequency gain.

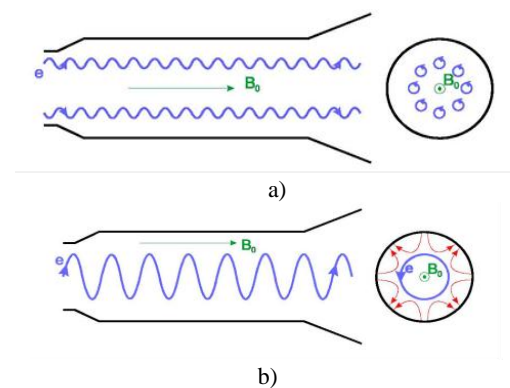


Fig. 1. Electron beams in conventional gyrotron (a) and high-harmonic Large Orbit Gyrotron (b)

The further progress in development of LOGs was associated with reducing the operation voltage that enables replacing the accelerators by simpler high-voltage modulators, as well as with increasing the radiation frequencies. In the 80-kV LOG (Fig. 2a) [4], a stable single-mode second- and third-harmonic generation with a power of 0.3–1.8 kW was obtained in 10- μ s pulses at four frequencies in the range of 0.55–1.00 THz at magnetic fields 10.5–13.6 T. A relatively low efficiency of this generator $\sim 1\%$ was caused by great Ohmic losses in a long gyrotron cavity at THz frequencies. This LOG was used for scientific applications and for testing novel versions of THz cavities [5] aimed to enhance efficiency by decreasing Ohmic losses, as well as to make possible the fourth-harmonic operation.

An important step in LOG progress is a development of a 30 kV/0.7 A gyrotron [5] with a 5 T cryomagnet designed for a CW operation (Fig. 2b). In this oscillator, an electron beam with a large pitch-factor of 1.5 is formed in a cusp gun and then the transverse electron velocity increases in an increasing

magnetic field. The main scope of this setup is operation at the second, third and fourth harmonics at the

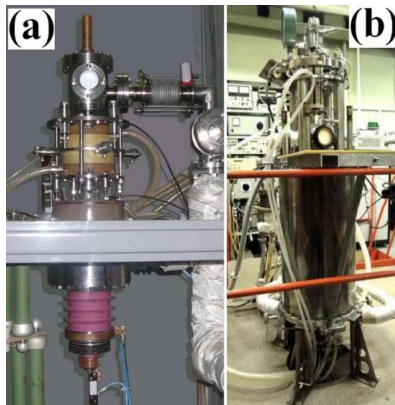


Fig. 2. LOGs with parameters 1 THz/80 kV (a) and 0.394 THz /30 kV (b).

typical DNP frequencies of 0.26 THz, 0.39 THz, and 0.52 THz with the power level of hundreds of watts.

In a good accordance with simulations, experimental zones of excitation of the second-harmonic $TE_{2,5}$ and third-harmonic $TE_{3,7}$ modes are well separated by magnetic field. Generation with parameters 800 W/ 0.267 THz and 300 W/ 0.394 THz is obtained at the fields $B=5.02$ T and $B=4.93$ T, respectively. Competition of these two modes is observed at intermediate magnetic fields. An increase in operating magnetic field up to 6.3 T and in the electron voltage up to 45 kV should allow achieving frequencies up to 0.65 THz at the fourth cyclotron harmonic [5].

Gyrotrino

Integration of a THz generator and an NMR spectrometer in single cryomagnet requires the exact matching of the DNP and gyrotron frequencies. Because of relativistic dependence of the cyclotron frequency on electron energy this is possible at an extremely low voltage of 1-2 kV only [6]. The very possibility of operating at a such low voltage was verified in an existing CW gyrotron [8]. A three-electrode magnetron injection gun of the gyrotron was initially designed for a higher voltage; to obtain an acceptable electron pitch factor for the low voltage, a high positive potential was applied to a modulating anode while keeping a negative cathode potential in order to increase the transverse particle velocity in the emitter region and decrease the longitudinal velocity in a region between the anode and the cavity. As a result, a stable generation with the frequency of 0.25 THz was observed at whole range of electron energies in the gyrotron cavity from 15 keV down to 1.5 keV.

According to simulations [10], a gyrotrino with an operating $TE_{6,2}$ mode, a voltage of 1.5-1.8 kV, a current of 200 mA, a pitch factor of 1.2 and a small cavity length can provide a power up to 15 W at the frequency of 0.264 THz with a required magnetic field about of 9.42 T (Fig. 3b). Since the gyrotron cavity is very close to the sample, a short transmission line is needed, that reduces the radiation losses and decreases

a required THz power. A magnetic field disturbance induced by the low-voltage electron beam at the sam-

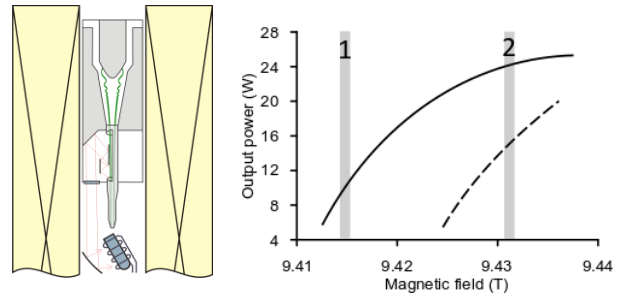


Fig. 3. a) Gyrotrino in cryomagnet of NMR spectrometer; b) calculated power vs. magnetic field for 1.5 kV / 200 mA (solid line) and 2 kV / 150 mA (dotted). Lines 1 and 2 show two regimes of gyrotron-DNP frequency matching.

ple is about of 10^{-8} and can be neglected. To save a limited space in the uniform magnetic field region, the radiation output from the gyrotron cavity can be directed toward the electron gun (Fig. 3a). Due to lack of space, the electron beam is to be collected in a cavity cut-off narrowing in a strong field [10].

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