

Design of one-octave bandwidth gyro-BWO with zigzag quasi-optical transmission line

S.V. Samsonov^{}, G.G. Denisov, A.A. Bogdashov, I.G. Gachev, M.V. Kamenskiy, K.A. Leshcheva*

Institute of Applied Physics RAS, Nizhniy Novgorod, Russia

^{}samsonov@ipfran.ru*

Abstract. Design of a proof-of-principle experiment on a broadband frequency-tunable gyrotron backward-wave oscillator (gyro-BWO) is discussed. The gyro-BWO under consideration is using a recently proposed interaction circuit in the form of quasi-optical transmission line where the mirrors direct a Gaussian wave beam along a zigzag-like path with vertical and inclined segments periodically spaced along longitudinal z -axis. A static B -field and translational electron velocity are directed along z -axis, so that the electron beam periodically intersects with the wave beam. The resonant cyclotron beam-wave interaction occurs at the regions of perpendicular beam-wave intersections resulting in low sensitivity to the particle velocity spread similar to a gyrotron. The 3D PIC simulations show prospects of this “zigzag” gyro-BWO in realization of frequency tunable oscillators capable of high power and unique (octave frequency band) tuning in the short-millimeter wavelength range. In the paper, a general layout and results of computer modeling of major experimental components (interaction circuit, electron gun, output microwave system etc.) are discussed for a CW device using a cryomagnet with the B -field of 4–8 T. According to CST simulations, the designed gyro-BWO ensures output of nearly Gaussian wave beam of kilowatt power level at any predefined frequency within 107–215 GHz range.

Keywords: gyrotron backward-wave oscillator (gyro-BWO), high-power millimeter waves, magnetic frequency tuning, octave-bandwidth millimeter-wave source.

1. Introduction

A gyrotron backward-wave oscillator (gyro-BWO) is a type of cyclotron resonance maser (CRM), which differs from a gyrotron (the most developed version of CRM) by the potential for a much wider-band smooth oscillation frequency tuning (see e.g. [1, 2]). In conventional gyro-BWOs using a section of a smooth waveguide, the frequency tuning is, as a rule, piecewise with strong variations in the power and spatial structure of the output radiation [3].

In [4] we proposed a concept of a CRM, based on the use of an open quasi-optical (QO) mirror transmission line as a microwave circuit, in which a Gaussian wave beam is directed by mirrors along a zigzag trajectory, so that its periodic intersections with the electron beam occur at right angles (Fig.1).

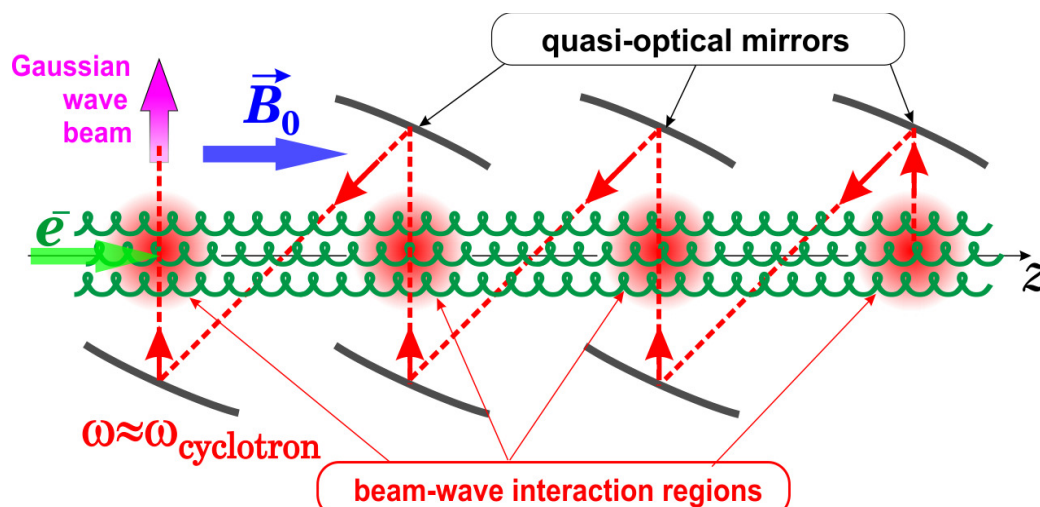


Fig.1. General scheme of a gyro-BWO with zigzag QO transmission line.

3D Particle-In-Cell (PIC) simulations show that such a configuration is prospective for implementation of relatively high-power short-millimeter-wave amplifiers and oscillators with extremely wide frequency tunability. In particular, in [4] it was simulated that a gyro-BWO of this type comprising of only two periods (4 mirrors) when powered by a 22 kV and 4 A electron beam with a pitch-factor of 1.6–1.7 and large velocity spread could generate a nearly Gaussian output beam with a power of 1–2.5 kW and piecewise frequency tuning from 120 to 320 GHz by varying the external B-field in the range of 4.5–11.6 T. It was also shown that the use of B -field hysteresis in CW operation could enable nearly continuous tuning avoiding the frequency gaps.

Taking into account available experimental facilities (first of all, a superconducting magnet and high-voltage DC power supplies) we have designed a feasible device which is going to be manufactured and used for the first proof-of-principle experiments.

2. Experiment design

The experiment is designed assuming an available 25 kV, 2.4 A DC power supply and a cryomagnet with maximum B -field of 8 T, uniform part length of about 40 mm and the warm-bore diameter of 140 mm (Fig.2).

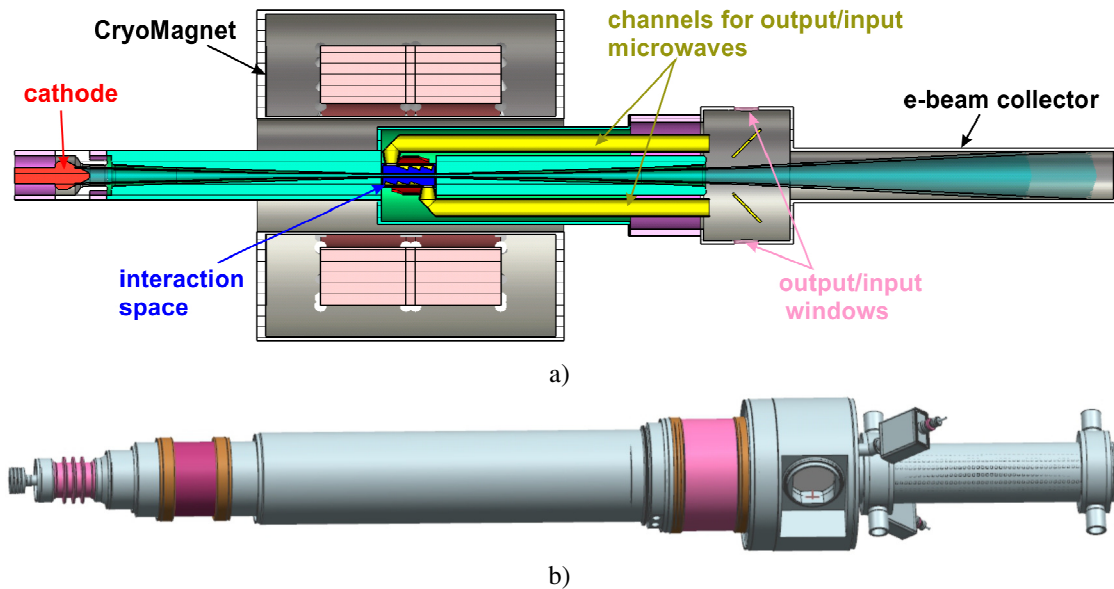


Fig.2. Schematic layout of experimental gyro-BWO (a) and 3D visualization of the designed tube (b).

2.1. Interaction circuit

The designed circuit comprises of 6 round-surface confocal mirrors of 15 mm in diameter, with the distances between their centers of 15 mm and 19 mm in Z- and Y- directions respectively (Fig.3, Fig.4).

The output port of 14 mm in diameter is situated opposite the up-stream mirror. In CST simulations, a tubular electron beam with radius of 2 mm, width of 0.5 mm, pitch-factor of 1.6 and perpendicular velocity spread of 7% (rms) excites the microwaves, about 50% of which are exited the circuit in the form of nearly Gaussian wave beam (Fig.3b). The rest of the microwave power is dissipated in the absorbing material which surrounds the circuit. As the simulations have shown, to ensure stable operation of the device at the desirable mode, the absorbing material should have conductivity of less than 10^{-4} S/m which corresponds to the single-reflection power loss of about 8% at frequency of 150 GHz. A composite material with very high thermal conductivity satisfying the mentioned above RF absorbing properties was investigated recently and is considered to be used

to shell the interaction circuit. It was also found in the CST simulations that the use of tilted walls made of stainless steel with some corrugations can also ensure the entire frequency sweep without parasitic oscillations.

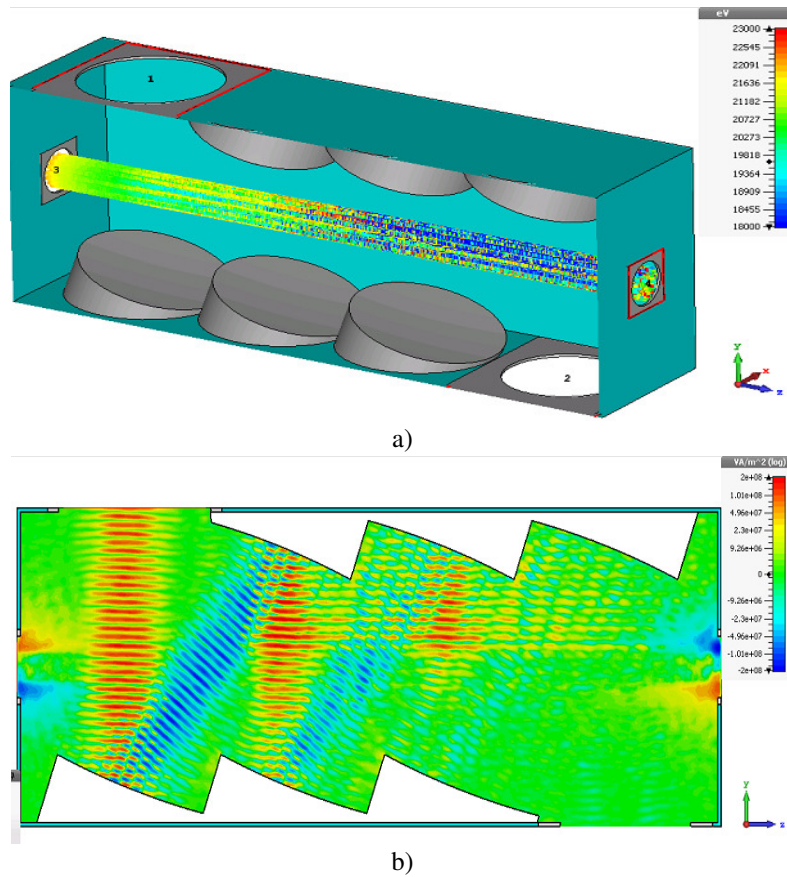


Fig.3. CST model of the gyro-BWO (a) and simulated 2D distribution of Pointing vector for steady-state oscillations at B -field of 8 T (frequency 215 GHz): an instant snapshot of the y -component (b).

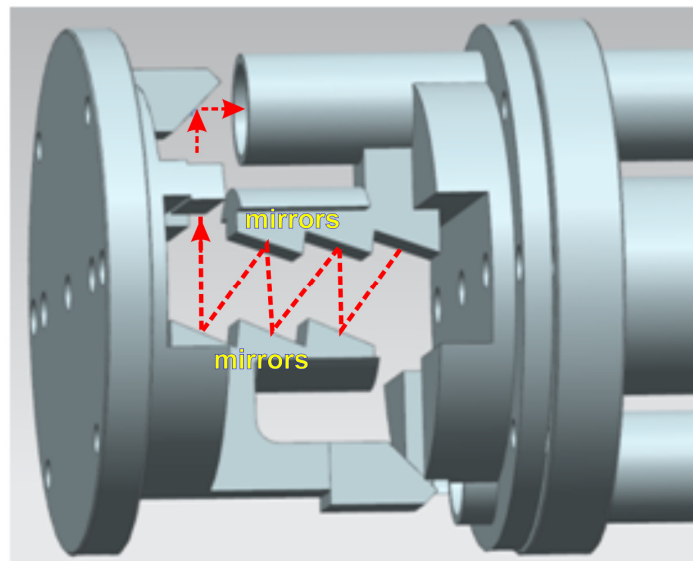


Fig.4. 3D visualization of the designed part of the interaction circuit (dashed red lines show the generated wave beam path).

The final tuning characteristic of the designed gyro-BWO was simulated with CST Particle Studio PIC Solver when the static B -field was swept in time with sufficiently slow rate modeling a practical situation when a device is operating in CW mode. Similar to results of [4, 5] it was found that periodical zeros in the output power and the jumps in the smooth frequency tuning can be avoided using the hysteresis with respect to positive or negative B -sweep (Fig.5).

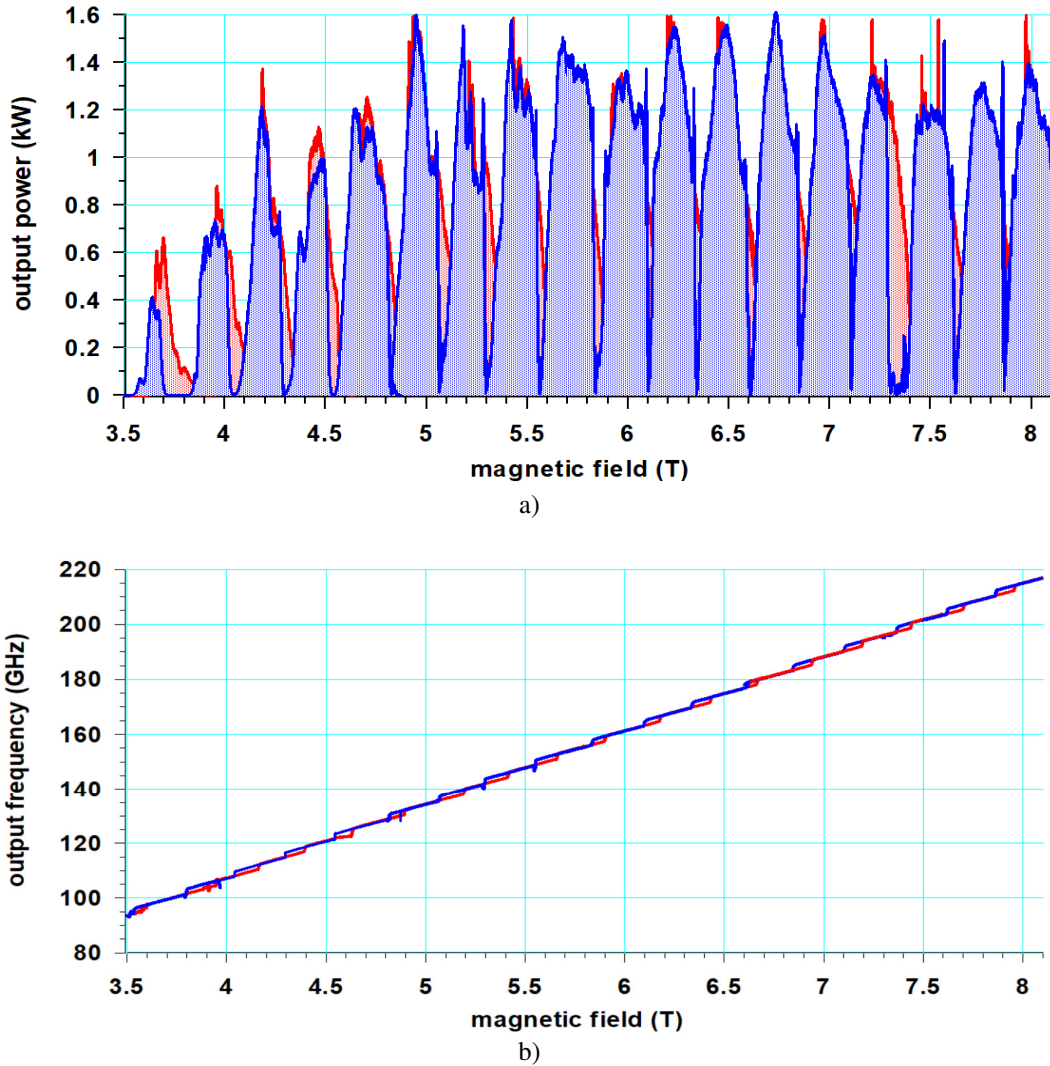


Fig.5. Simulated frequency tuning for beam energy of 22 keV and beam current of 2.3 A (blue and red colors correspond to B -field swept down and up, respectively).

2.2. Magnetic field correction

The B -field generated by an existing magnet has the homogeneous part in the center with the length of 37 mm at the level of 99%. The CST simulations showed that this length would be too short for stable operation of the gyro-BWO at the beam current below 2.5 A. Therefore an additional cylinder made of carbon steel was designed (Fig.6) which due to the magnetic screening should correct the B -field inside the interaction circuit. As the simulations showed the length of the homogeneous 99% part of the field distribution can be increased up to 50–68 mm depending on the absolute value of the field induction (Fig.6). Recent test of the cryo-magnet at 4 T with the manufactured iron insert resulted in good agreement between the measurements and design.

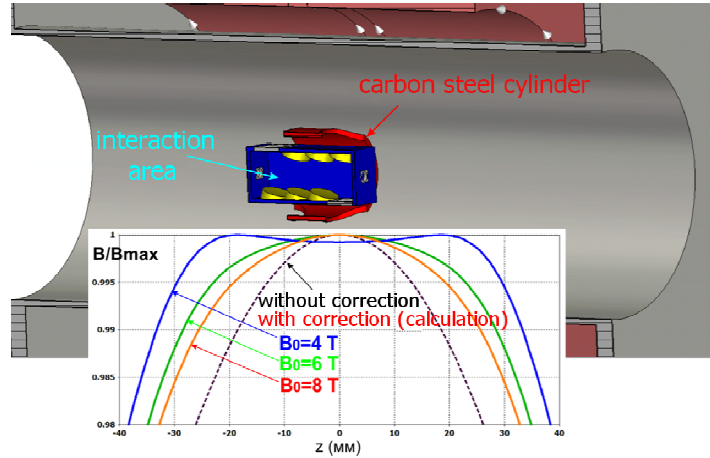


Fig.6. Gyro-BWO interaction circuit surrounded by an iron insert inside the cryo-magnet: the graph shows simulated distribution of the B -field for the operating space.

2.3. Microwave transport system

Since the transverse dimensions of the circuit are small (± 15 mm in Y -direction) with respect to the magnet inner radius (70 mm), the output microwave radiation is designed to be transported by a circular oversized corrugated waveguide supporting HE_{11} mode going down-stream parallel to the e-beam channel and having a barrier window of Brewster type at its end outside the magnet (Fig.2, 4, 7). The second similar channel (lower in Fig.2a) will be used to control that the major power is outputting through the main channel (upper one in Fig.2a) in the gyro-BWO mode. It can be also used to test a gyro-TWT mode of operation when the system is zero-drive stable and the seed signal is inputted through the main channel while the amplified signal will be outputted through the second channel.

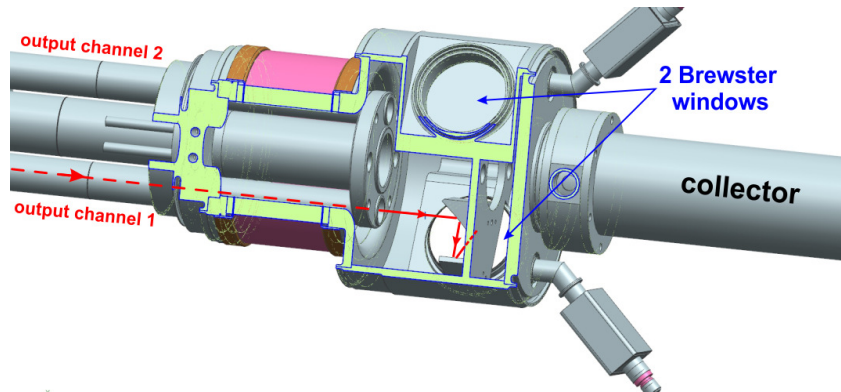


Fig.7. Layout of the designed gyro-BWO microwave transport system.

Both channels will be supplied by the matching mirrors and the wave beams will be directed under the Brewster angle with respect to the BN output windows to ensure the maximum bandwidth of low reflection (Fig.7).

2.4. Electron gun

The electron gun of magnetron-injection type is designed to generate the required e-beam for a very large range of the B -field (4–8 T) using a triode configuration (Fig.8). It is assumed that the first anode voltage (U_{an_1}) will be adjusted according to the B -field magnitude.

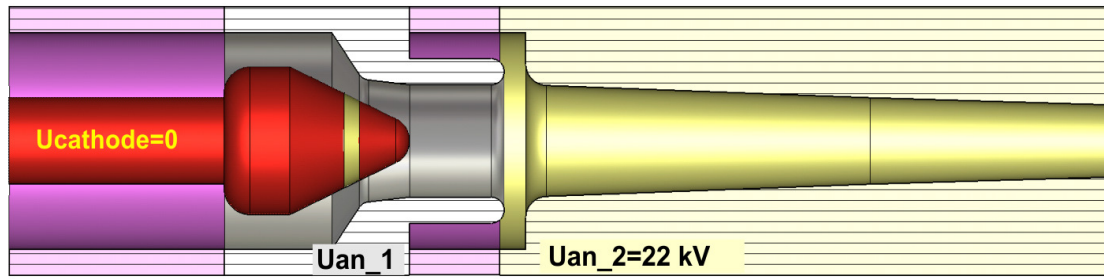


Fig. 8. CST model of the electron gun (the emitting ring at the cathode shown by light yellow).

According to 2D and 3D simulations, in almost the entire required range of magnetic fields, by adjusting the value of U_{an_1} from 12 to 22 kV, it is possible to achieve the operating value of the electron pitch factor in the range $g = 1.5\text{--}1.7$. In this case, the root-mean-square value of the transverse velocity spread does not exceed 4% at a magnetic field value above 5 T [6].

As the CST modeling have also shown, the minimum electron energy after the interaction is about 17 keV, which means that the implementation of a single-stage depressed collector (SSDC) can be very effective in this case, namely, it can raise the overall efficiency from 2–3% to 9–13% and reduce the collector load from 50.6 to 11.5 kW. The use of an SSDC is also considered for the planned experiment.

3. Conclusion

A novel variety of the cyclotron resonance maser using a QO zigzag-like mirror transmission line has been validated by 3D PIC CST simulations. A proof-of-principle experiment is under preparation. One octave tuning band at kilowatt power level is expected.

This type of gyro-BWO seems also feasible to be adopted for a 20-T 50 mm “warm” bore cryomagnet (commercially available) and capable for generation of 100-s Watts at the most demanded DNP-NMR frequencies (263, 395 and 527 GHz) with a single device instead of several single-frequency gyrotrons.

Acknowledgement

This work was supported by the Russian Science Foundation under Grant 21-19-00443.

4. References

- [1] Thumm M., *J. Infr., Millim., THz Waves*, **41**(1), 1, 2020; doi: 10.1007/s10762-019-00631-y
- [2] Nusinovich G.S., *Introduction to the Physics of Gyrotrons*. (Baltimore: Johns Hopkins Univ. Press, 2004).
- [3] Tsai C.-H., et al., *IEEE Trans. Electron Devices*, **68**(1), 324, 2021; doi: 10.1109/TED.2020.3036323
- [4] Samsonov S.V., Denisov G.G., Bogdashov A.A., Gachev I.G., *IEEE Trans. Electron Devices*, **68**(11), 5846, 2021; doi: 10.1109/ted.2021.3114141
- [5] Samsonov S.V., Denisov G.G., Bogdashov A.A., Gachev I.G., *2021 Photonics & Electromagnetics Research Symposium (PIERS)*, 2790, 2021; doi: 10.1109/PIERS53385.2021.9695051.
- [6] Gachev I.G., Kamenetskiy M.V., Lestcheva K.A., Samsonov S.V., *XI Vserossiyskaya nauchno-tehnicheskaya konferentsiya «Elektronika i microelektronika SVCH»*, St. Peterburg, Russia, 2022. [in Russian].