

## Powerful terahertz gyrotrons based on pulsed magnets

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**Abstract:** The terahertz radiation has been demonstrated in pulse gyrotrons. Pulsed coils with field intensity up to  $50T$  have been developed and tested. After more than 3500 shorts no any variation at solenoid operation observed. The repetition rate one short per minute was limited by coil cooling. The output power  $5\text{ kW}$  at  $1\text{ THz}$  and  $0.5\text{ kW}$  at  $1.3\text{ THz}$  has been obtained with pulse duration 40 microseconds at the fundamental harmonic with  $30\text{ kV}/5\text{ A}$  electron beam. The design of a sub-THz sub-MW gyrotron has been presented.

**Keywords:** Terahertz, gyrotron, pulsed solenoid

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### 1. Introduction

Development of compact, simple and reliable sources of terahertz (THz) radiation is important for numerous applications, which include plasma diagnostics, electron-spin resonance spectroscopy, enhancement of NMR sensitivity using dynamic nuclear polarization, standoff detection and imaging of explosives and weapons, new medical technology, atmospheric monitoring, chemical technologies, communications and production of high-purity materials. Gyrotrons - vacuum devices based on interaction of electrons gyrating in external magnetic fields with fast waves are known as the most powerful sources of coherent electromagnetic radiation in the millimeter wavelength ranges (see, for example, reviews [1-3]). The general view of a gyrotron is shown in Fig.1. During several last years gyrotrons broke through  $1\text{ THz}$  mark [3-6].

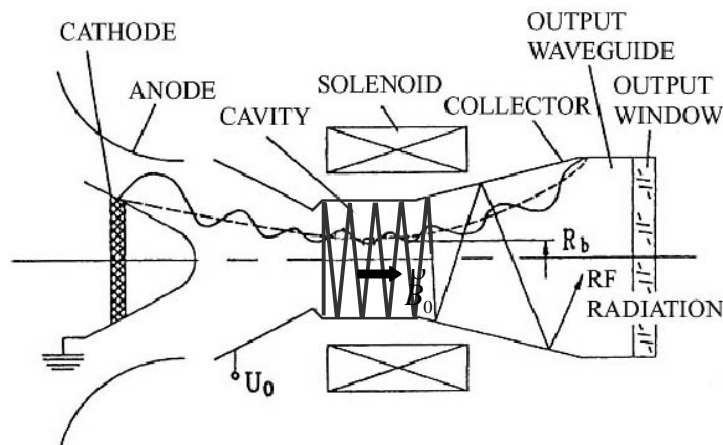


Fig. 1 Schematic view of a gyrotron

In comparison with Free Electron Lasers (FEL), gyrotrons can operate with electron beams having significantly lower energies of  $10\text{-}100\text{ keV}$ . Correspondingly, gyrotrons are much more compact than FELs and available for many laboratories. Gyrotrons can provide power much

higher power than solid-state sources. However, to provide cyclotron resonance between gyrating electrons and fast waves excited in smooth waveguides at THz frequencies near cutoff, high magnetic fields are necessary: in the range of  $40\text{ T}$  for the fundamental harmonic interaction. In principle, efficient operation can be obtained in gyrotrons not only at the fundamental cyclotron resonance, but also at high cyclotron harmonics. The latter regime is very attractive, because it requires a weaker operating magnetic field which is inversely proportional to the harmonic number. However, realization of high-harmonic short-wave gyrotrons at high harmonics, in its turn, runs into rather complicated problems of mode competition and ohmic losses, which take many efforts to overcome. High intensity magnetic fields can be realized with the use of pulsed non-destructible coils. Below we present results of the design, manufacturing and experimental test of pulsed magnetic field gyrotrons where coherent THz range radiation was produced.

## 2. Design and experimental tests of fundamental harmonic gyrotron

A compact (total length  $400\text{ mm}$ ), demountable THz gyrotron tube with a pulse magnet has been designed, constructed and tested. This work is based on the previous results obtained with gyrotrons using pulsed solenoids [7] and on the development of an improved pulsed solenoid, producing magnetic field up to  $50\text{ T}$ . Gyrotron photo and block diagram of the experimental facility is shown in Fig. 2 and Fig. 3, correspondently.

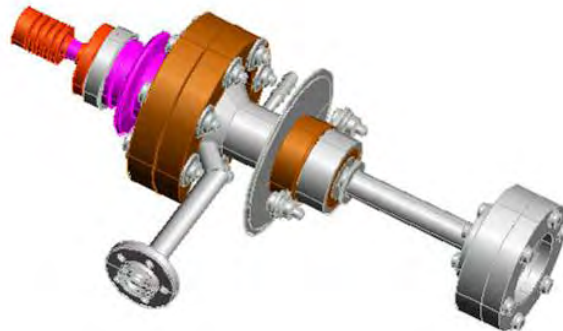


Fig. 2 Fundamental harmonic THz range demountable gyrotron with pulsed solenoid

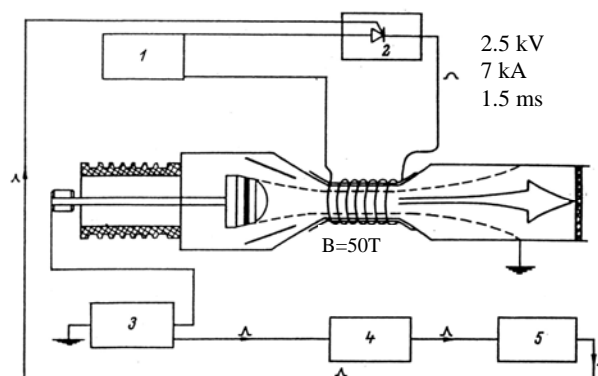


Fig. 3 Block diagram of experimental facility for pulsed magnetic gyrotron tests: 1- capacitor bank 2- thyristor switch, 3- high voltage power supply, 4- delay unit, 5- control unit

In the design of terahertz gyrotron a number of specific requirements for gyrotrons operating with pulsed magnetic fields were taken into account. First, to provide cyclotron resonance condition accurately enough, magnetic field should be reproducible from pulse to pulse and its value during the high voltage pulse should vary by less than 0.1%. Second, conductivity of a resonator wall should meet contradicting requirements: on the one hand, this conductivity should be rather poor to allow varying magnetic field to penetrate into the resonator; on the other hand its inner surface should have conductivity high enough to provide reasonably low level of ohmic losses. Then, as in conventional gyrotrons, magnetic field distribution on axis should be uniform in the interaction space. Finally, the tube and the solenoid should be robust enough to sufficient mechanical stresses caused by high pulsed magnetic fields.

To give an impression about some problems of pulsed magnetic field gyrotron design, we present the photo of gyrotron cavity after magnetic field impact. The copper cylindrical cavity with oversize diameter 22 mm and wall thickness from 3 mm in central part to 0.2 mm at the ends of the input and output tapers was tested at the field about 15 T. As shown in Fig.4, the strong deformation took place immediately after single short. The same profile stainless steel cavity was successfully tested. To reduce the ohmic losses electroplated coating of thin copper layer was proposed and realized on internal wall.

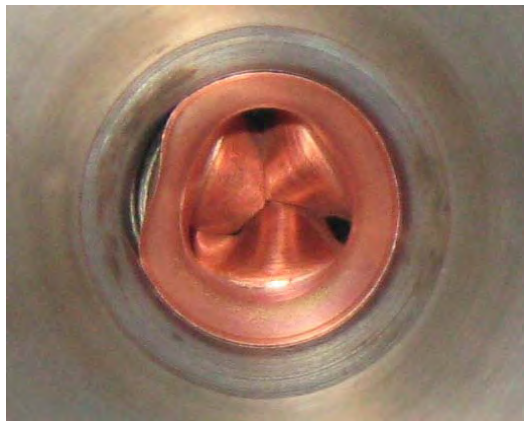
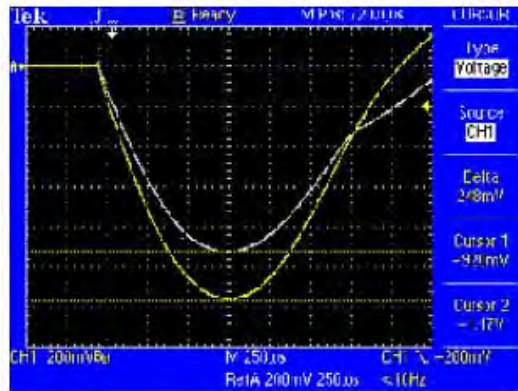


Fig. 4 The deformation of copper cavity walls due to pulse field effect

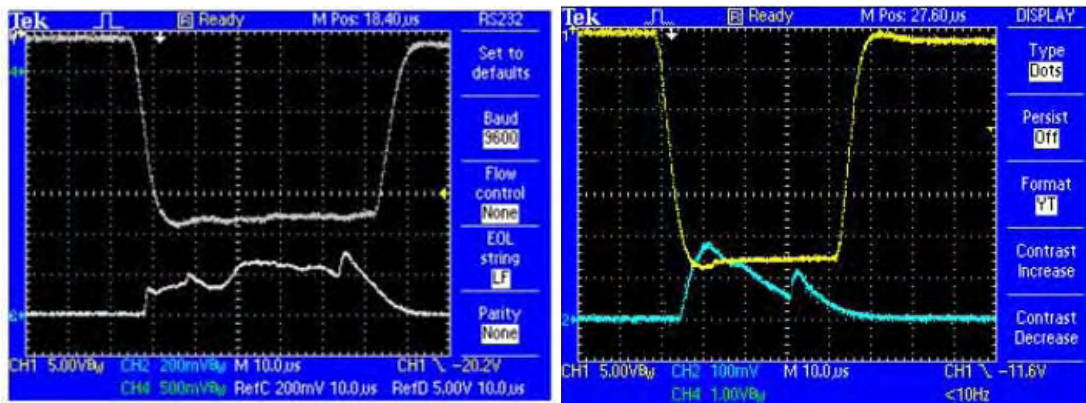
The solenoid [4] was made of a composite cable consisting of a 40%Nb-60%Ti alloy mechanically reinforced in an outer copper shell. For reducing ohmic heating and stabilizing the operation, the solenoid was cooled by liquid nitrogen, which reduces the resistance by a factor of 7 in comparison with the room temperature resistance. The cable was wired directly on a thin stainless steel gyrotron body. This allowed for significant reduction of the solenoid inner bore diameter (up to 6 mm) and the energy required for obtaining the necessary magnetic field. Magnetic field was produced in the course of discharge of a bank of capacitors. In comparison with [4] the number of capacitors was increased and as a result the maximum coil current in 1.5 ms pulses was 7 kA (capacitors voltage 2.5 kV, storage energy about 7.6 kJ). The pulse-to-pulse reproducibility of the magnetic field was within 0.05%. Due to limitations caused by cooling the pulsed solenoid, the repetition rate was limited by one shot in a minute for 40T magnetic field operation and one shot in a three minute for 50T field. After more than 3500 pulses with magnetic fields above 35T no signs of solenoid deterioration had been observed.

Gyrotron components included the conventional cylindrical cavity (3 mm diameter) and the

diode-type magnetron injection gun (accelerating voltage 20-25 kV, beam current up to 5 A, pulse duration 50 microseconds). The cavity was made of beryl bronze; its diffractive and ohmic Q were estimated as 2500 and 8200, respectively. The high-voltage pulse was synchronized with the peak of the pulsed magnetic field.



(a)



(b)

(c)

Fig. 5 Oscilloscope trace of solenoid current for 40T and 50T field (a), microwave power and high voltage for 1 THz (b) and 1.3 THz (c) operation regimes

Experimental results were obtained for high frequency operation at the fundamental cyclotron resonance. The microwave power was detected by a silicon point contact diode and by the dummy load, which has the sensitivity allowing for detecting the radiation energy in single shots at a 10 mJ level. To measure the THz frequency in single-shot operation regime the method based on mixing the gyrotron signal with the signal from a millimeter-wave frequency synthesizer has been used. To get the intermediate frequency (IF) in a relatively narrow frequency band of the IF amplifier (1 GHz) the frequency of the backward-wave oscillator (BWO) was swept during the microwave pulse several times. Then, by gradually narrowing the bandwidth of BWO frequency modulation it was possible to determine the radiation with the precision determined by the bandwidth of the IF amplifier. By varying the magnetic field, a number of various modes with frequencies close to 1 THz were excited in a step-tunable manner [3]. Two cavities with variable length of a straight section (3 mm and 2 mm) and series of cathodes differing by the quality of emission area was tested. The maximum output power was

measured at the frequency  $1.02\text{ THz}$ . The radiation power averaged over the pulse was  $5\text{ kW}$ . This power level for a  $27\text{ kV} / 3\text{ A}$  electron beam corresponds to  $6.1\%$  output efficiency. The highest generation frequency  $1.3\text{ THz}$  was observed at magnetic field about  $50\text{ T}$  with power averaged over the pulse about  $0.5\text{ kW}$ . Oscilloscope trace of solenoid current for  $1\text{ THz}$  and  $1.3\text{ THz}$  operation regime and corresponding detector signals are shown in Fig. 5.

### 3. Project of compact sub-THz sub-MW gyrotron

The third-harmonic axis-encircling electron beam gyrotron (Large Orbit Gyrotron [8]) with a  $250\text{ kV} / 4\text{ A} / 10$  microseconds electron beam has been realized at the Institute of Applied Physics RAS [9]. The power up to  $20\text{ kW}$  in single-mode regimes was obtained at the frequencies  $371$  and  $414\text{ GHz}$ . However, this power is not sufficient for number of promising applications, for example, for plasma experiments directed on production of localized discharge as pointer source of multicharged ions and X-ray radiation [10]. To increase output power the sub-MW level fundamental harmonic gyrotron with operating frequency about  $0.33\text{ GHz}$  was designed based improved solenoid with field intensity up to  $15\text{ T}$  and repetition frequency up to  $1\text{ Hz}$ . The solenoid consists of 10 sections with independent water cooling and for pulse duration about  $2.5\text{ ms}$  the repletion rate about  $1\text{ Hz}$  was obtained. The calculated gyrotron efficiency at fundamental harmonic for helical electron beam with voltage  $70\text{ kV}$ , current  $60\text{ A}$  and transverse energy  $0.6$  from total energy closed to  $0.25$ . The gyrotron (Fig. 6) is under experimental tests now.



Fig. 6 The general view of MW level gyrotron with operating frequency about  $0.3\text{ THz}$

#### 4. Conclusions

Despite the requirement of strong operating magnetic fields, the THz frequency has been achieved by the pulse gyrotrons operating at the fundamental harmonic. Today it is clear that relatively small-size tubes with a kilowatts level of output power at the frequencies of 0.3-1.5 THz will be available soon for many applications.

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