New Results in Development of MW Output Power Gyrotrons for Fusion Systems

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Introduction

The paper presents the latest achievements of the Russian gyrotron team in development of MW power gyrotrons for fusion installations. During two last years four new gyrotrons were designed and tested: a new version of 170 GHz gyrotron for ITER; multi-frequency (105-140 GHz) gyrotron for Asdex-Up, 84GHz gyrotron for LHD and 82.7 GHz gyrotron for SST-1. All these gyrotrons are equipped with diamond CVD windows and depressed collectors.

Table 1. Russian gyrotrons tested in 2002-2004 years

Frequency	Output power	Pulse duration	Note
140 GHz	0.7 MW	10 sec	Delivered to TEXTOR
170 GHz	0.5 MW 0.7 MW 0.9 MW	80 sec 40 sec 20 sec	ITER project
84 GHz	200 kW 500 kW	1000 sec 10 sec	Delivered to LHD
82.7 GHz	200 kW	1000 sec	For SST-1
105 – 140 GHz	1 MW	10 sec	Under tests

170 GHz gyrotron for ITER

The most efforts were spent for development of 1MW/170 GHz gyrotron for ITER.. The gyrotron operates at very high order mode $TE_{25.10}$ which allows efficient cooling of their cavity walls. The calculations show the possibility of 1 MW microwave generation in the cavity in CW regime. Potential depression at the collector provides power load on the collector surface essentially (up to two times) lower than without electron energy recovery. A quasi-optical mode transforms the operating mode into a paraxial wavebeam.

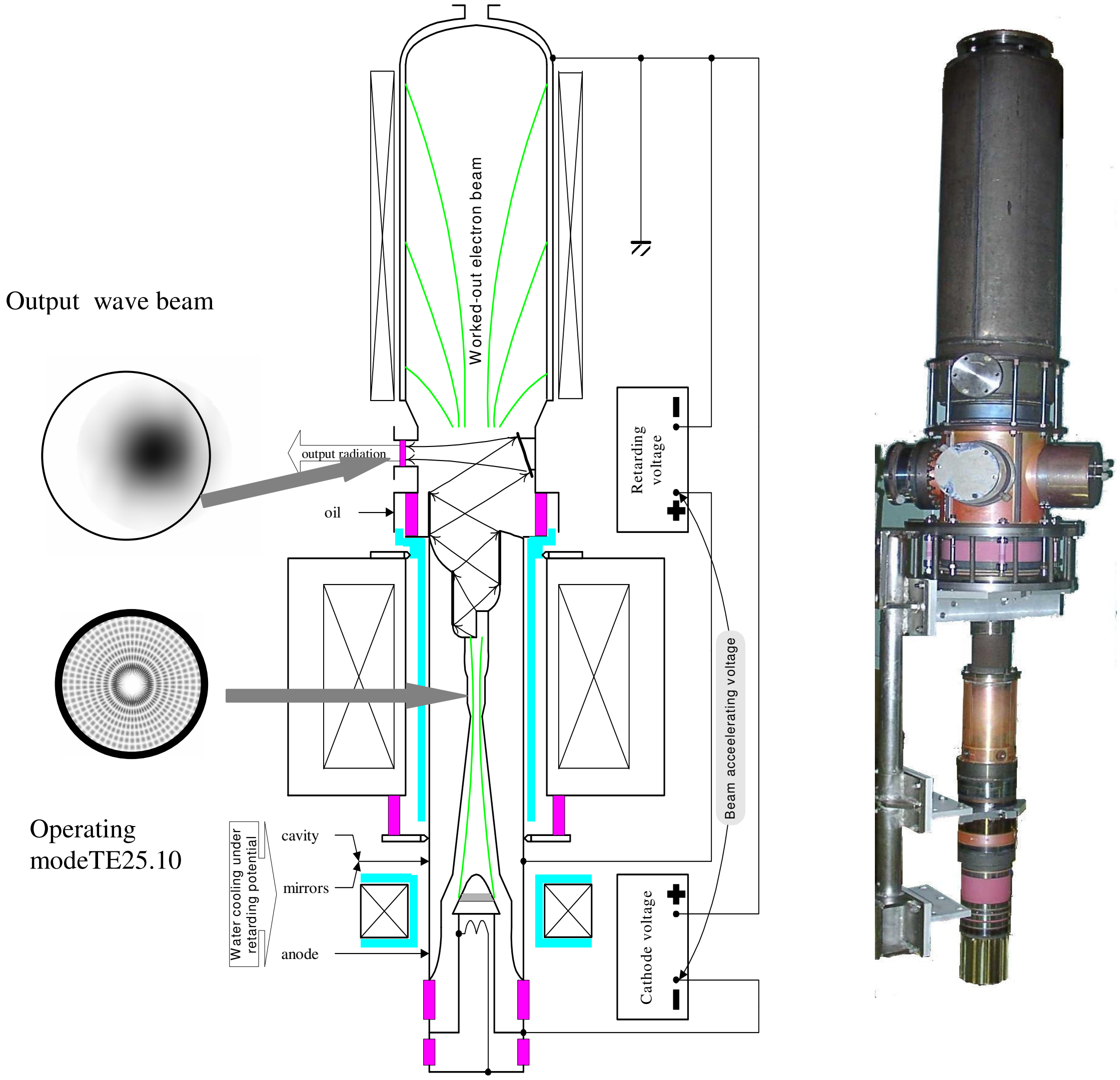


Fig.1. Scheme and photo of the Russian 170 GHz gyrotron for ITER.

The tests were performed at the specially prepared test stand in Kurchatov Institute.

The following gyrotron output parameters were demonstrated: in many pulses 0.9MW/20 sec; 0.7MW/40sec and 0.5MW/80 sec. Gyrotron behaviour in tests is illustrated by figs.2,3. Energy of output pulses was limited by capabilities of microwave load and some other auxiliaries. Nearest plans (2004 year) include the pulse extension up to 300 seconds.

Gaussian mode content of the output wave beams exceeds 96%. Due to diffraction losses some amount of radiation is lost in the gyrotron. This radiation is very dangerous because of possible overheating gyrotron body, and, especially, insulators in the electron guns and depress collectors. Additional (so called relief) ceramics window is applied in the gyrotron in order to diminish power of stray radiation in the tube. Breakdown of the losses is shown in the tTable 2.

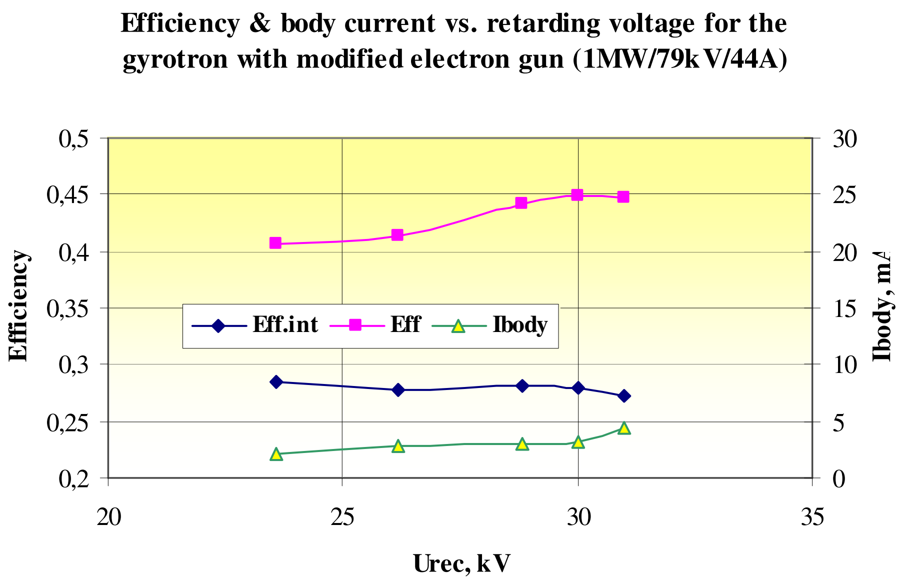


Fig.2. Main parameters of 170 GHz gyrotron operating in the regime with energy recovery of the electron beam. Small value of the current to the insulated body (>5 mA) shows proper operation of the gyrotron electron gun.

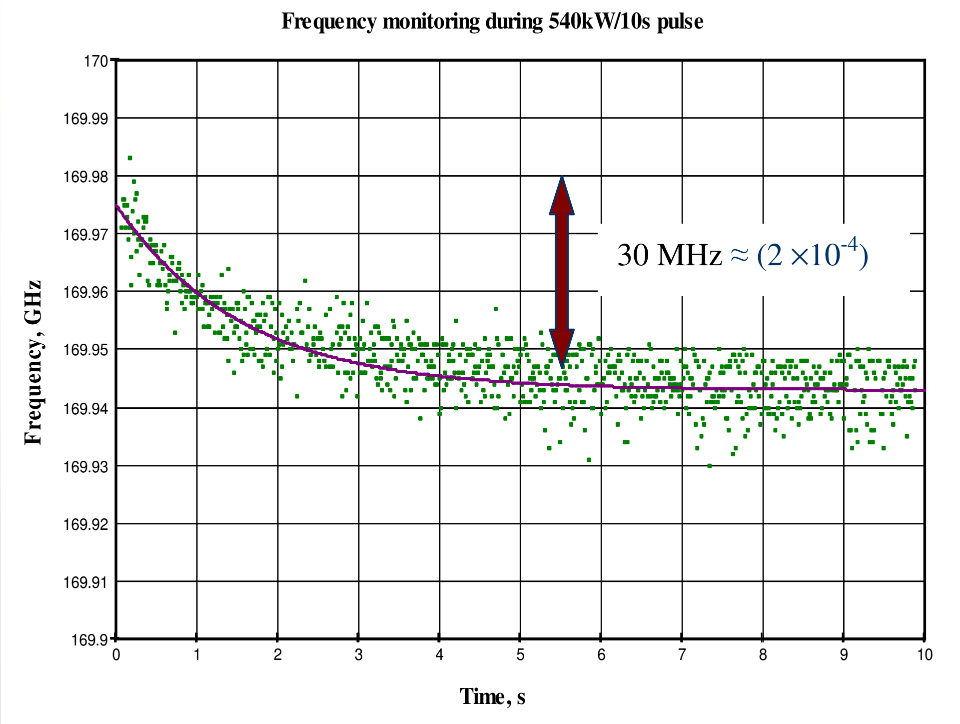


Fig.3. 170 GHz gyrotron. Drift of gyrotron frequency due to the thermal expansion of the cavity. Very small relative change of the frequency confirms a proper operation of cavity cooling system.

Table 2. Breakdown of the losses in the 170 GHz gyrotron.

Fractional power	*Value, kW/%*
Total power input	**2009/100**
Total generated power	**1015/50.5**
Gaussian beam power	**875/44.2 /(100)**
CVD diamond window dissipation	2/0.2
Cavity+mirrors dissipation	43/4
Total stray radiation	**95/11**
Absorbed in the MOU	50/6
Absorbed in the relief load/ window	41/4.6
Radiated through DC break	4/0.4
Collector power dissipation	**990/49.3**
Anode power dissipation	**4/0.2**

The total amount of stray radiation in 170 GHz gyrotron is rather high. In order to diminish the power of stray radiation a new high-efficiency quasi-optical mode converter (fig.4) was developed and tested in a short pulse version of the next 170 GHz gyrotron. 1.2 MW power was demonstrated in the gyrotron with efficiency 35% (without energy recovery). Measured power of stray radiation is below 2%. CW gyrotron of the new design is in fabrication now.

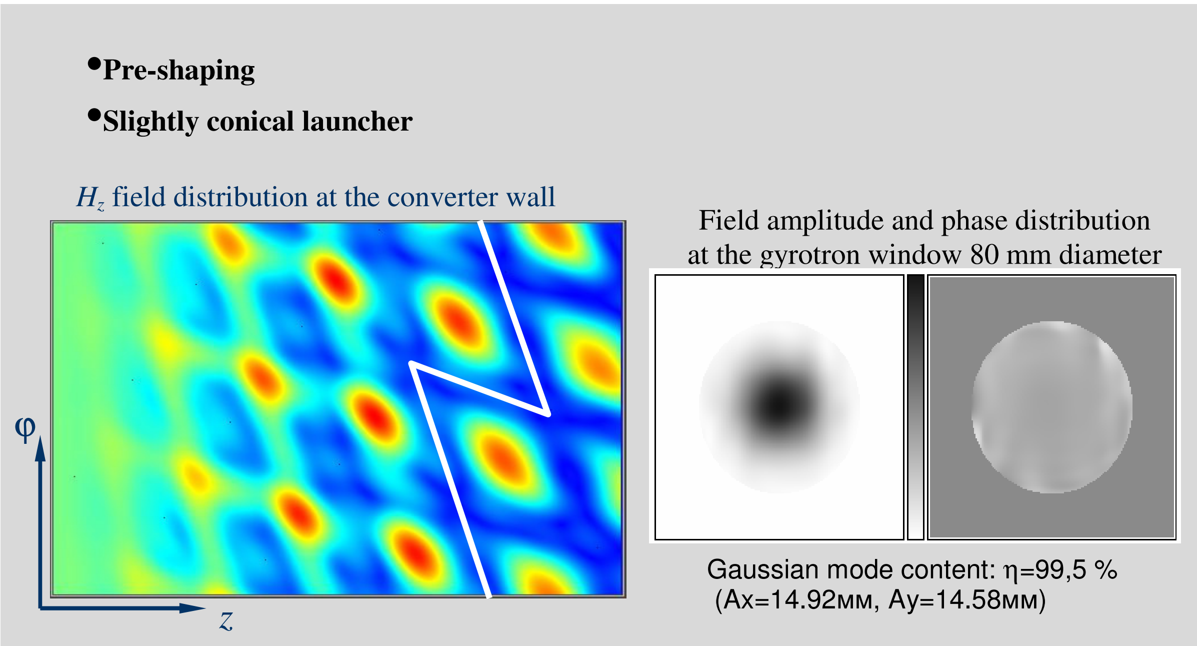


Fig.4. Design features of the new quasi-optical mode and parameters of the output wavebeam.

2.Multi-frequency gyrotron

The multi-frequency gyrotron was designed to operate at 5-7 frequencies in the range of 105-140 GHz with pulse duration of 10 seconds. Change of the main magnetic field gives a possibility to make a step frequency tuning with a typical step of 2-3 % depending on the gyrotron cavity size (fig.5). Development of such a tube includes the following tasks: design of an electron gun operating in wide range (30-40%) of magnetic fields; a proper choice of the set of operating modes with the same direction of rotation, design of a depressed collector capable to operate at various magnetic fields and a mode converter transforming all operating modes into Gaussian wavebeam, choice of a broad band or tunable window

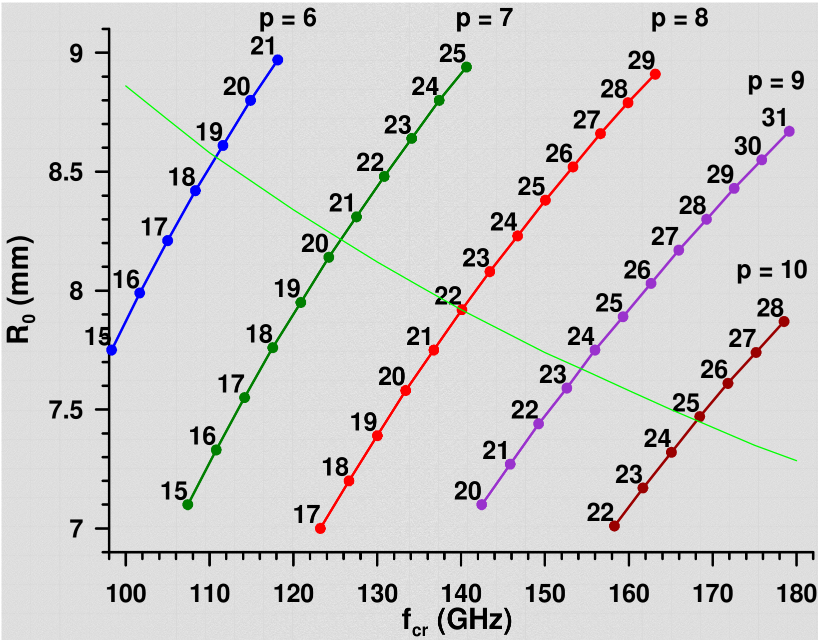


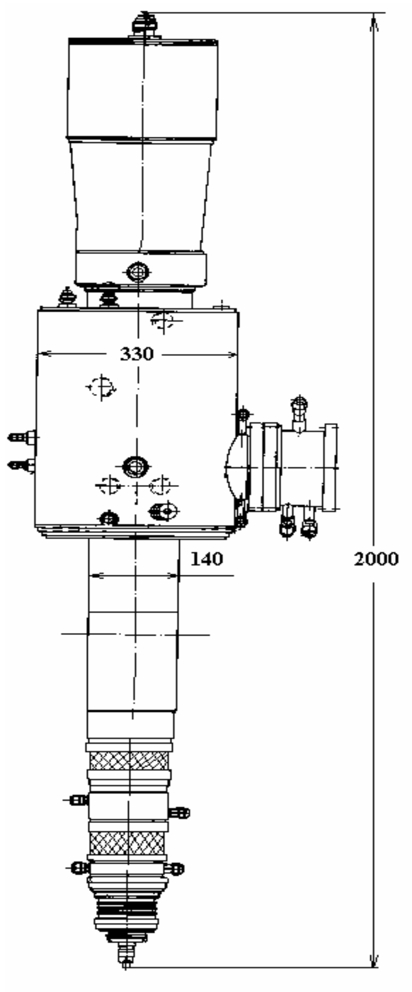
Fig.5. Modes of the same gyrotron cavity. The mode TE22.8 corresponds to 140 GHz frequency of the multi-frequency gyrtron.. Vertical axis show caustics of the modes. The curve dropped to the right indicates the optimal mode caustic for a diode-type electron gun.

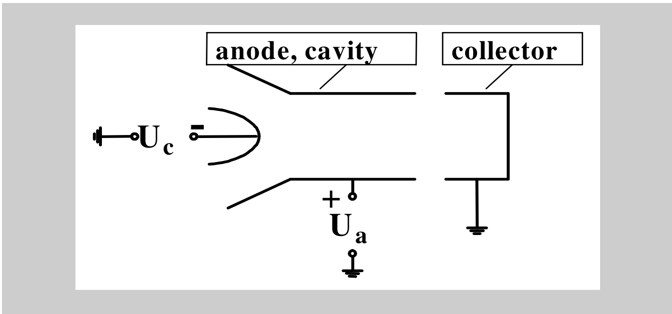
The multi-frequency gyrotron is based on a diode type of electron gun. This resulted in the change of optimal electron beam radius (approximately as $f^{1/3}$, f is frequency) and consequently in the necessity of an additional collector coil correcting position of the beam on the collector surface. The shapes for reflectors of the mode converter were found which provide a rather high (94-96%) Gaussian mode content in the output wave beams for all operating modes. Two window concepts were considered: Brewster window and two-discs adjustable window. Both concepts imply the use of CVD diamond discs with diameter of brazed cuffs of 88 mm. The Brewster window is very attractive because of very wide instant frequency band, however the converter design in this case is more complicated and it was decided that in initial tests the first frequency tunable gyrotrons would be equipped with the two-discs windows.

The prototypes of frequency tunable gyrotrons were tested recently. At this stage BN ceramics windows were used in the gyrotron constructions. High power (over 1 MW) and high efficiency (about 50%) at seven frequencies in microwave pulses about 100 microseconds. 0.5 seconds were demonstrated in the experiments. After this short pulse experiment an industrial tube was manufactured. The tube at the first stage of experiments is equipped with a single disc diamond window which has pass bands near 105GHz and 140 GHz. In the very first tests megawatt power level was demonstrated at three frequencies 105 GHz, 108GHz, 140 GHz.

3. New CW gyrotrons for fusion installation

Practically CW operation (up to 1000 sec) of gyrotrons at power of 200 kW was shown for two other tubes (84GHz and 82.7 GHz) delivered to plasma installations LHD and SST-1. Such an operation revealed specific gyrotron critical points of CW regime. This information is very important for development CW of megawatt power level. For the second case (82.7 GHz frequency) a complete set of components including gyrotron, magnet, matching optics, waveguides, bi-directional couplers, miter bends, polarizer, DC breaks, dummy load was tested and delivered to the customer.





Design features:

- Diode-type electron gun
- CPD lens located after the wavebeam launcher
- Operating mode TE12,5, wave beam outpu
- Water cooling of all mirrors, cases, screens and ion pump (12 cooling circuits)
- Oil cooling of the CPD insulator

Fig.6. Sizes, power supply scheme and design features of 200 kW/ CW gyrotrons.

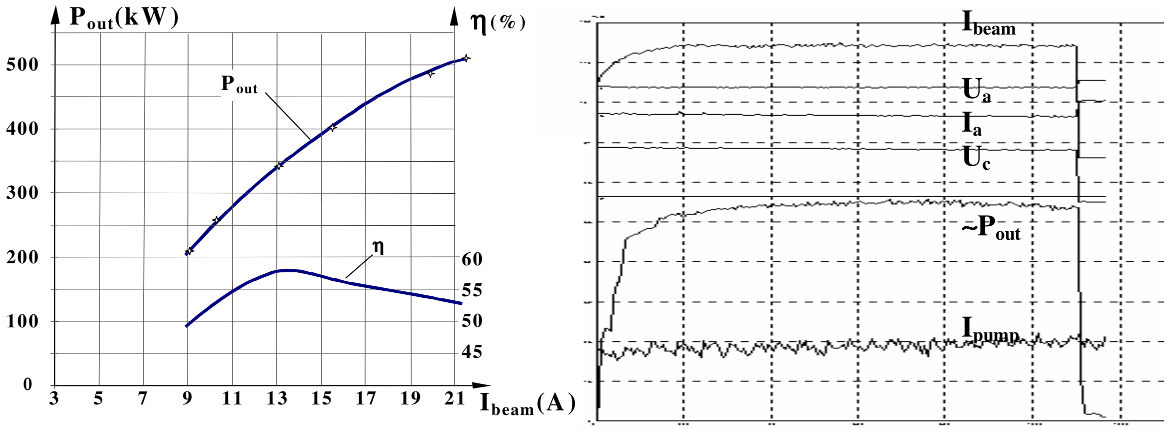
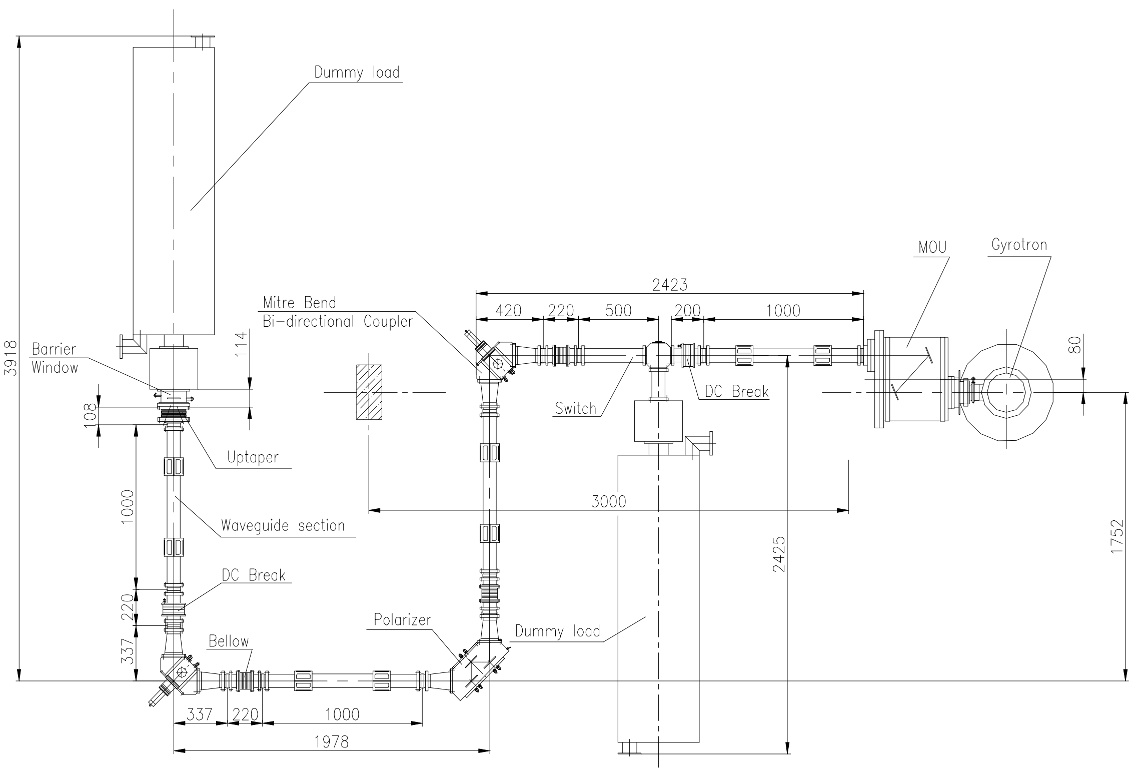


Fig.7. 84 GHz Gyrotron. Operating regimes: 200 kW in CW / 500 kW in 10 s regime. Accelerating voltage (Uc+Ua)=46 kV + 22 kV. Time traces correspond to 1000 second test.



(a)

(b)

Fig.8. Scheme (a) and photo (b) of the 82.7 GHz/200kW/1000 sec gyrotron system under test. Losses in the transmission system: matching optics 11 %, transmission line 4 %.

Summary

A gyrotron is capable to produce output power of megawatt level at different frequencies in the wide range of millimeter and centimeter waves: from 15 GHz to 200 GHz.

In the period of 2002-2004 years a number of unique gyrotrons for fusion systems were designed, manufactured and tested in Russia. Nearest development plans include parameters enhancement of the gyrotron for ITER: output power increase up to 1.2-1.5 MW and pulse extension up to 1000 seconds. There are also very strong collaborative (with European team) efforts to develop and apply in the experiment at ASDEX-Up a number of multi-frequency gyrotrons.