LOW FREQUENCY GYROTRONS FOR FUSION

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For some experimental plasma set-ups powerful RF sources with frequency from 5 GHz up to 30 GHz are requested. Gyrotrons as such sources are considered. The report presents the results of the low frequency powerful gyrotrons development in Russia. Several design versions of 5 GHz, 17.5 GHz and 28 GHz gyrotrons with output power 0.5-1 MW, its specific property details, special technical problems and test set-up are discussed. Test results for 5GHz/0.5 MW and 28GHz/0.5MW gyrotrons are presented.

Introduction

Megawatt power level long pulse and CW gyrotrons were developed mainly in millimeter wavelength range and used for ECR plasma heating experiments [1, 2]. Recently the interest for long pulse gyrotrons with the same power level but relatively low operating frequency begins to grow also because for some experimental plasma set-ups powerful RF sources with frequency from 5 GHz up to 30 GHz are requested. Up to now main application of low frequency gyrotrons (short centimeter wavelength range) was the advanced technology [3]. Required output power for such technological gyrotrons up to now is 1-10 kW only. But at present in particular for the program of EBWH of plasma in spherical tokamaks [4] 1 MW/5 sec gyrotrons at frequency range 15 ÷ 30 GHz are needed.

Such low frequency (LF) gyrotrons have some specific property details and special technical problems. Let’s trace main differences of high frequency (HF) or mm wavelength and cm (LF) powerful long pulse or CW gyrotrons which are given below.

For LF gyrotrons the problem of the mode competition is not so acute and significant as fore HF tubes because it is enough to use relatively low order operating modes to ensure the permissible thermal loads even at high output power level at CW regime. Simple estimations show that operation on the $TE_{m,p}$ modes corresponding to relative diameter of the cavity $D_c/\lambda \sim 4$ (λ is the wavelength) is enough to provide acceptable level of heat load density at the cavity wall.

On the contrary the choice of the most suitable way for effective conversion of operating mode to the liner polarized Gaussian beam (as usually needed for application) or other acceptable wave structure is more difficult problem for LF gyrotrons design. Relatively small (at the wavelength scale) aperture of quasi-optical (QO) mode converter elements is the cause of high diffractive loses. The converter dimension enlargement leads to abnormal escalating of gyrotron volume. That is the reason why at the cm wavelength region (especial at it's long-wave part) the best possible gyrotron mode converter have to be quite different on the conventional one at the mm wave-region.

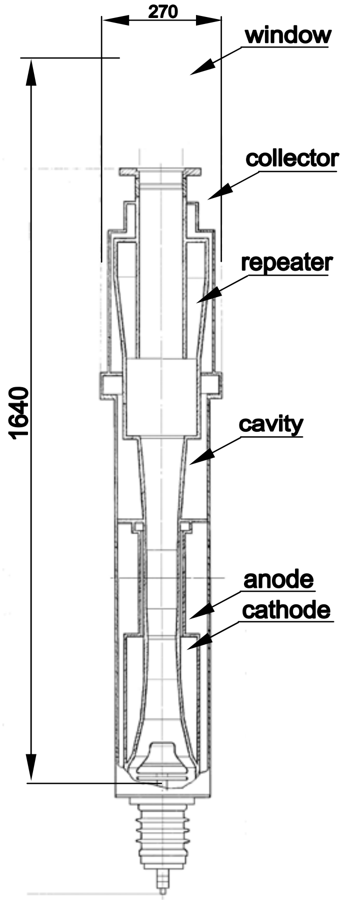
The problem of formation of high-power helical electron beam (HEB) with small transversal velocity spread and worked-out beam landing at the collector with acceptable heat load density are different at LF and HF regions as well. The initial velocity spread of emitted electrons is main cause of transverse velocity spread of HEB at the HF gyrotrons, but at the LF gyrotrons nonadiabatic effects at electron gun region play dominated role. At the mm-wavelength range (reached) to increase the electron beam landing surface at the collector is relatively uncomplicated by static or dynamic additional magnetic fields (formed by special collector coils) to spread or move electron beam at the collector. The situation at the cm-wavelength range is more complicated due to nonadiabatic movement of electrons in relatively weak magnetic fields. So, to predict reliably the longitudinal distribution of heat loading at the collector is not so easy. A full trajectory analysis at any concrete case is needed.

The solution of the output window problem for LF gyrotrons is not so problematical due to large enough operating wavelength. Even simple single-disk BN output window may be relatively broadband with small total loses of output power.

Industrial low-frequency gyrotrons

At the end of 80th the program of low-hybrid wave plasma heating on T-10 tokamak was under consideration and powerful RF source at frequency about 5GHz was requested. Accordingly to this program 0.5 MW / 5 GHz long pulse gyrotron was elaborated and manufactured in 1990 by "Salut" company (now GYCOM Ltd.). As this gyrotron data's have never published let us dwell on it. The general view and its main design parameters are shown on fig.1. The operation mode the $TE_{0,1}$ was selected to reduce the magnetic field volume. From other hand the $TE_{0,1}$ is the most suitable fore using of axial-symmetric mode converter usually named by "repeater". The repeater was carried out as the shielding slot of a regular waveguide. The conical collector was interfaced to the cylindrical screen of the repeater, and the electron beam was directed to the collector through a ring gap between the screen and an output waveguide. As the result we have no mode type changing but the RF and electron beams separation was provided on minimized length. Due to this reason the length of gyrotron tube was shorten about two times compare to gyrotron with traditional mirror QO converter. Calculated efficiency of "repeater" is more then 99%.

Electron beam with average radius in the cavity $R_B = 25.6$ mm and pitch-factor $g = 1.3$ formed by diode-type magnetron injection gun with cathode emitter radius equal to 45mm. Emitter current density was about 2 A/cm^2. The gun operated at weakly sub-critical regime (magnetic field at the cathode is about 0.06T). HEB with regular crossing trajectories forms by this gun. The special configuration of electrodes was found to compensate the resonance mechanism of increasing velocity spread due to space charge.



Operating mode	TE$_{0,1}$
Frequency	5 GHz
Electron beam voltage	70 kV
Beam current	25 A
Pulse duration	1 s
Efficiency	30 %
Output power	0.5 MW

Fig. 1. Design and main parameters of 5 GHz gyrotron.

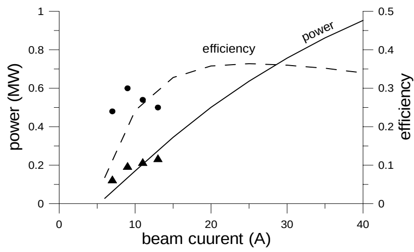
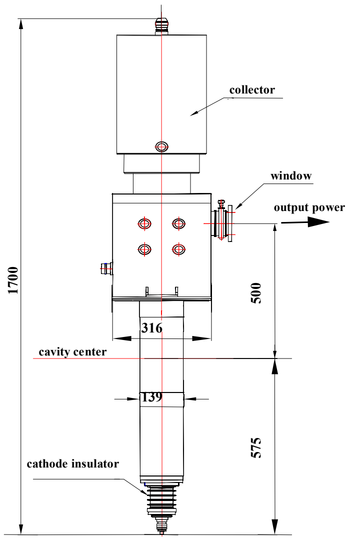


Fig. 2

Calculated dependences of output power and efficiency from electron beam current are shown on Fig. 2. Experimental dates marked by triangular sign on this plot too. Unfortunately the gyrotron testing was not completed. Experiments were stopped because of the tokamak low-hybrid wave plasma hiting program was canceled. One can see the tests were finished at half rate of design beam current.

Next industrial powerful low-frequency gyrotron was built in 1993 [5]. Its general view and main parameters are on Fig. 3. The three mirror QO built-in mode converter which transforms the $TE_{4,2}$ to the Gaussian beam was used in this gyrotron. The conversion efficiency was near 90%.



Operating mode	**$TE_{4,2}$**
Frequency	**28 GHz**
Beam voltage	**70 kV**
Beam current	**20 A**
Pulse duration	**0.1 s**
Efficiency	**36 %**
Output power	**0.5 MW**

Fig. 3. General view and main parameters of 28GHz gyrotron.

The diode-type electron gun design parameters were: cathode emitter radius 21.5 mm, beam radius in the cavity 7 mm, emitter current density 2.5 A/cm^2, pitch-factor 1.3, transverse velocity spread 5% (it was calculated by EPOS code minimum at operating beam current 20 A due to gun's electrodes optimization).

The result of the 28 GHz tube tests is presented on fig.4.

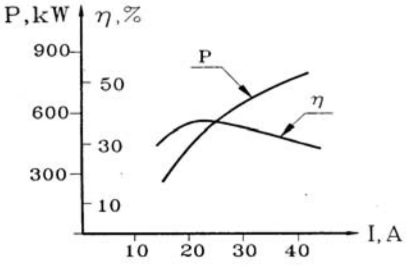


Fig. 4. Tests result fore 28 GHz tube.

New low-frequency gyrotron projects

Now the development of super-powerful long pulse gyrotrons operating in 15 ÷ 30 GHz frequency range is in progress. Two projects of 1MW/5sec gyrotrons operating at frequency 17.5 GHz and 28 GHz are presented below. The unified cryomagnet system is under development fore these projects.

Three modes the $TE_{5,2}$, the $TE_{4,2}$ and the $TE_{1,3}$ were under consideration for 17.5 GHz/1MW/5sec as design modes. Finally the $TE_{1,3}$ mode was choused as an operating mode due to several reasons.

First one is that the QO converter visor fore this the $TE_{1,3}$ mode is two times shorter. On other hand for the next QO converter improvement it was proposed to stop this mode by weak-elliptical taper after the cavity to provide a standing the $TE_{1,3}$ mode in the visor and so to minimize RF field at it's edges. As a result of this solution less diffraction losses will be achieved.

The electron gun for this gyrotron with an average radius of cathode emitter 35 mm and optimized electrodes geometry can produce helical electron beam with voltage U_0=100 kV, current I=40 A, average radius beam in the cavity R_0 = 11 mm, pitch-factor g= 1.3 and transversal velocity spread $\delta v_\perp \approx 20\%$ (EPOS-V code).

Next problem, which has to be solved according to this project, was the collector problem. Magnetic field at collector region is formed not by cryomagnet only but by additional collector coil also. Calqulations show that collector heating load may be quite inhomogeneous while the magnetic field distribution along collector is uniform enough. The reason is the small magnetic field at the collector region and therefore electron trajectory cyclotron period becomes comparable with the collector length.

To make the heating load distribution more homogeneous it was suggested to use one more additional coil system to disturb magnetic field fore additional electrons trajectories mixing before the collector. Optimized version of such collector magnetic system, electrons trajectories and heat load density distribution along the cylindrical collector with 150 mm radius are shown on fig. 5 and fig. 6. Peak load density is quite acceptable for this case.

Calculated output parameters for the 17.5 GHz/1MW/5s tube are given on fig. 7.

For the 1 MW/28 GHz / 5 sec gyrotron project the $TE_{6,2}$ operating mode was chosen because this mode is most suitable fore optimized improved mode converter [6] to have the least diffraction losses inside the tube. Optimized geometry of the electron gun forming 100kV/40A HEB with average radius in the cavity R_0 = 10.9 mm, g = 1.3 and $\delta v_\perp \approx 20$ % (EPOS-V code) was designed. Average radius of emitter is equal to 38.5 mm. Calculating output power and efficiency are shown on fig. 8. The collector problem at this frequency is not so hard due to stronger magnetic field and dynamic electrons beam sweeping can be used.

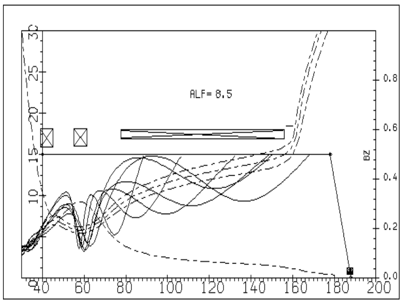


Fig. 5

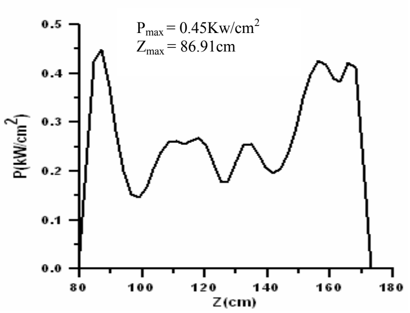


Fig. 6

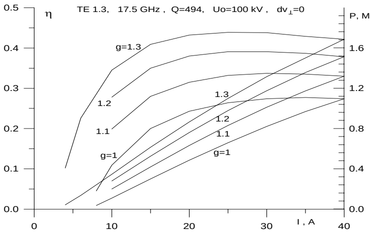


Fig. 7

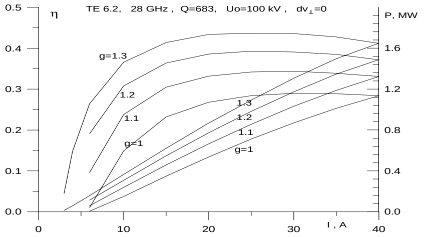


Fig. 8

Conclusion

Low frequency powerful gyrotrons development in Russia is presented. The 0.5MW/0.1s is shown at operating frequencies. Several design versions of 5GHz, 17.5GHz and 28GHz girotrons with output power 0.5-1 MW and its specific property details are presented. Main and special technical problems of low-frequency gyrotron and test set-up are are outlined and discussed. The long pulse and CW versions of low-frequency gyrotron are under construction now.

References

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