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# Development of high-efficient gyrotron based complex for industrial applications

M.D. Proyavin[1], M.Yu. Glyavin[1] and V.N. Manuilov[1,2]

[1]Institute of Applied Physics of Russian academy of Sciences, Nizhny Novgorod, Russia, mdchase@yandex.ru
[2]Lobachevsky State University, Nizhny Novgorod, Russia

## Introduction

CW gyrotrons with operating frequencies from 24 to 28 GHz and an output power of several tens of kilowatts are being considered as the next stage in development of well-known technological complexes [1, 2] for the sintering of composite materials, growing CVD diamonds and other advanced technologies. In this regard, the total efficiency of microwave system plays a key role for real industrial employment. The report examines the possibility of reducing power consumption of magnet by the installation of ferromagnetic screens surrounding the main solenoid [3]. The project of 25 kW / CW / 28 GHz gyrotron based system is presented.

## Development of the magnetic system

To reduce the power of the main coil it was surrounded by the system of disk screens and inner and outer cylindrical screens (fig. 1 a). As a result, after optimization of the screens shape, it was possible to decrease the value of power consumption of the magnetic system in more than 2–2.5 times (see also fig. 1 b).

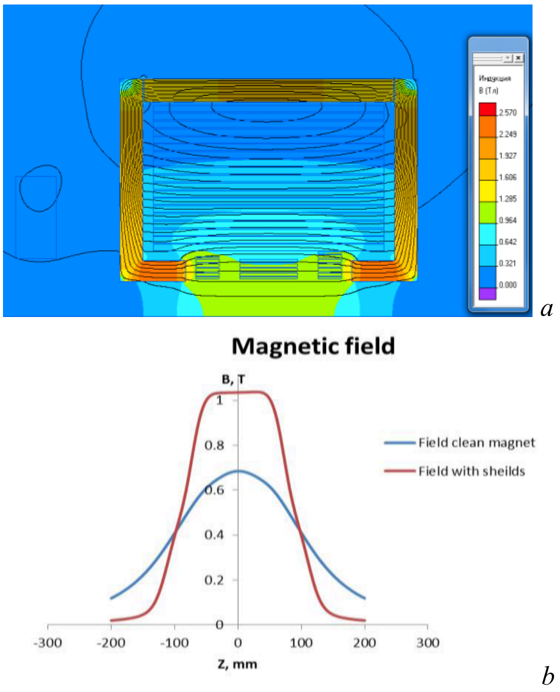

**Fig. 1.** The scheme of magnetic system with shielded solenoid (a). Magnetic field lines are shown. The axial magnetic field distributions (b) for the cases without (lower curve) and with installed ferromagnetic screens (upper curve) are shown

Small correcting coils placed inside main coil volume allowed to adjust the magnetic field distribution Bz(z) in such a manner as to provide its inhomogeneity less than 1% and reach the operating magnetic field 1.03 T in the cavity.

At the same time ferromagnetic screens substantially increases the inhomogeneity of the magnetic field outside the screens, where the initial formation of the helical electron beam (HEB) takes place. So the coefficient of non-adiabaticity $\varepsilon = h/L_B$ (here $h$ is the step of electron trajectory, $L_B$ is the scale of the magnetic field) exceeds 2 in the formation region (fig. 2). This makes it difficult to use well developed and reliable magnetron-injection gun (MIG) to form HEB with good enough parameters. To smooth the magnetic field distribution the additional cathode coils was installed to the left from the screen region (see fig. 1a). It allowed to form adiabatic distribution of the magnetic field with $\varepsilon < 1$ (fig. 2) and to employ adiabatic electron optical system (MIG) to minimize effects of misalignment, variation of technical parameters, etc.

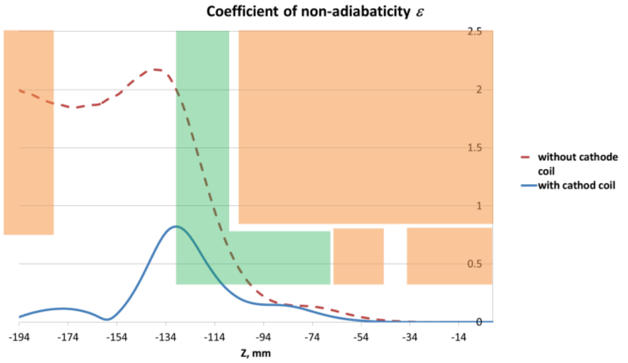

**Fig. 2.** The dependence of the coefficient of non-adiabaticity ε on the longitudinal coordinate in the optimized magnetic system. $Z = 0$ corresponds to the cavity center

## Electron-optical system

Initial form and position of MIG was found on the basis of adiabatic theory of MIGs [4]. Accelerating voltage was chosen 23 kV, maximum operating current 2.4 A, cathode radius 19 mm. To diminish the influence of the space charge forces on the beam quality the angle of emitter cone with respect to the axis was chosen 30 degrees to form laminar beam. Further optimization of the electrodes shape (fig. 3) has shown that HEB parameters (see fig. 4) are acceptable for high efficient (about 50%) microwave generation.

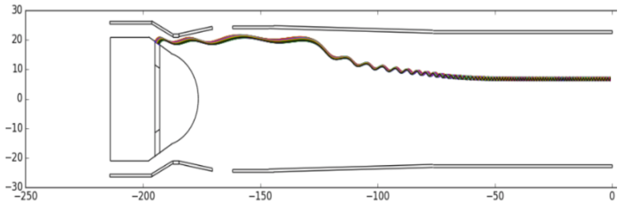

**Fig. 3.** Optimized geometry of MIG and corresponding electron trajectories

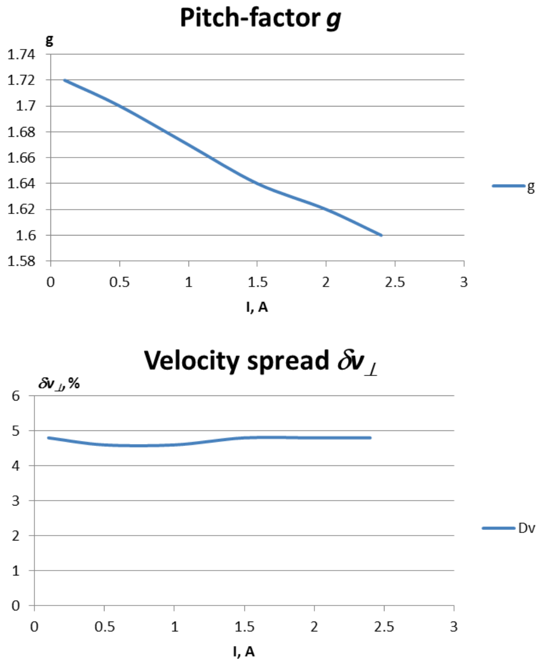

**Fig. 4.** Dependence of the pitch-factor g and velocity spread on the operating current in the optimized version of MIG

### Choice of the operating mode and cavity design

The analysis of the mode spectrum as well as the comparison of value of the coupling factors for some candidates to the operating mode with moderate azimuthal and radial indexes (modes $TE_{02}$, $TE_{22}$, $TE_{03}$ $TE_{13}$ and $TE_{13}$ were considered) and the neighboring competing modes has shown that the most suitable is $TE_{13}$ one. Further preliminary optimization of the output efficiency η of the gyrotron within the model of fixed RF field distribution [6] with taking into account the ohmic losses has shown the possibility to overcome the value η = 50%. Final optimization was performed on the basis of more complete model [7], which takes into account the influence of the own beam space charge on the interaction process (see fig. 5). According to the results of numerical simulation the total gyrotron efficiency is 51%, output power 25 kW.

During the optimization the restrictions on the power consumption of the main coil and its length also were considered.

### Conclusion

Technological gyrotrons with hot magnets surrounding by ferromagnetic screens allow to increase the operating value of the magnetic field in 1.5–2 times approximately and thus to use the generation on the first cyclotron harmonic in the frequency range 24–28 GHz with power level some tens kW and at the same time to keep the existing and well mastered coil cooling system. This opens up new opportunities in mastering novel promising technologies based on powerful CW radiation sources.

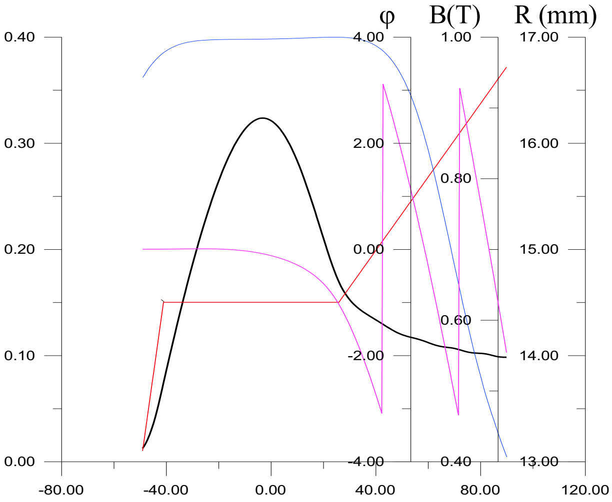

**Fig. 5.** Distribution of the RF field (black), the cavity profile (red) and the axial magnetic field distribution (blue) along the cavity region

### Acknowledgements

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### References

1. *V.A. Flyagin, A.N.Kuftin, V.K.Lygin, O.V.Malygin, B.V.Raisky, Gh.Tsimring, V.E.Zapevalov.* CW technological gyrotrons in the range 15-50 GHz // 4th Russian-German meeting on ECRH and Gyrotrons, N.Novgotrod, Russia, May 11-17, 1992
2. *Yu. Bykov, A. Eremeev, M. Glyavin, V. Kholoptsev, A. Luchinin, I. Plotnikov, G. Denisov, A. Bogdashev, G. Kalynova, V. Semenov, and N. Zharova.* 24-84 GHz Gyrotron Systems for Technological Microwave Applications // IEEE Transactions on Plasma Science, vol.32, no.1, 2004, pp.67-72
3. *A.N. Kuftin, S.P. Belov.* Magnetic shielded electron optical system of a gyrotron in space charge limited current regime // Applied Physics, 2000, №3, c.76-81.
4. *A.L. Gol'denberg and M.I. Petelin.* The Formation of Helical Electron Beams in an Adiabatic Gun // Radiophys. Quantum Electron., 16(1), 106-111 (1973)
5. *P.V. Krivosheev, V.K. Lygin, V.N. Manuilov, and Sh.E. Tsimring*. Numerical Simulation Models of Focusing Systems of Intense Gyrotron Helical Electron Beams // Int. J. IR MM Waves, 22(8), 1119-1146 (2001)
6. *G.S. Nusinovich.* Introduction to the physics of gyrotrons. Baltimore; London: The Johns Hopkins University Press, 2004, 352 p.
7. *N.S. Ginzburg, G.S. Nusinovich, N.A. Zavolsky.* Theory of non-stationary processes in gyrotrons with low Q resonators // Int. J. Electronics. 1986. Vol. 61, № 6. P. 881.