EPJ Web of Conferences **149**, 04036 (2017) DOI: 10.1051/epjconf/201714904036
10th International Workshop 2017 "Strong Microwaves and Terahertz Waves: Sources and Applications"

Development of field emitter non-adiabatic electron optic system for the spectroscopic 263 GHz/CW gyrotron

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Introduction

At present, gyrotrons occupy the leading position among high-power microwave radiation sources in the millimeter and submillimeter wavelength ranges. One of the most promising new applications of gyrotrons is the increase of the sensitivity of the spectrometry based on the nuclear magnetic resonance (NMR) and dynamic nuclear polarization (DNP). In such case the power level about some tens watt in the frequency range 200–400 GHz is needed. In spite of successful experiments [1] with first 263 GHz / CW gyrotron, where the output power reached even 1 kW, the traditional scheme of the gyrotron with adiabatic magnetron-injection gun for mentioned above application has some disadvantages. The most important are small sizes of high temperature thermionic cathodes (it causes high sensitivity to thermal deformations), big influence of emitter roughness (lead to big velocity spread) and longtime of the switch on process. To avoid the mentioned above problems it is interesting to examine the quite new scheme of the helical electron beam formation system, based on two principles – to use non-adiabatic electric and magnetic fields [2] and besides, field emitter [3] instead of hot cathode. First approach allows eliminate the influence of the cathode roughness, because the rectilinear electron beam is formed initially; second - to make the device inertia-free and not sensitive to the cathode temperature.

In what follows the feasibility of the described above approach is examined on the example of a gyrotron with an operating frequency of 263 GHz, an accelerating voltage of 15 kV, and an output power about ten watts, which is sufficient for spectroscopy applications.

Gyrotron

To check the feasibility of the described above idea, it was decided to try it using the already existing gyrotron for spectroscopy [8] (f = 263 GHz, power up to 1 kW), with only the beam generation system replaced and the other components (resonator, radiation-to-wave beam converter, collector, and magnetic system) left unchanged. Such an approach reduces the cost of first experiments and checking the principle itself of using field emission in gyrotrons. Owing to this, the main gyrotron parameters, were chosen as in the classical gyrotron implemented before [8].

Field emitter

The field emitter based on the multi-pin silicon structures (fig.1) on a flat substrate was chosen as the source of electrons because the technology of its manufacturing is fairly simple and well mastered [4]. Silicon pins have, as a rule, a low conductivity, but it can be increased using a thin (about 10-20 nm) layer of molybdenum. Fullerene or metallofullerene protective coatings deposited on the molybdenum metallization are effective against the destructive effect of ion bombardment. Estimations show that corresponding cathode can provide currents of up to 40 mA for the emission area S=0.2-0.3 cm^2. Average current densities over the emitter surface reach j~0.15-0.2 A/cm^2. To obtain the required values of the field emission current, approximately N~10^4 pins on the emitting cathode surface must be placed, while the electric field on the emitter surface should exceed 5-5.5 kV/mm. The estimates based on the Fowler-Nordheim formula show that even a field difference by 2-3% changes the emission current density by about 30% and, therefore, makes the space charge field non-uniform in the formation region and consequently may adversely affect the quality of the helical electron beam.

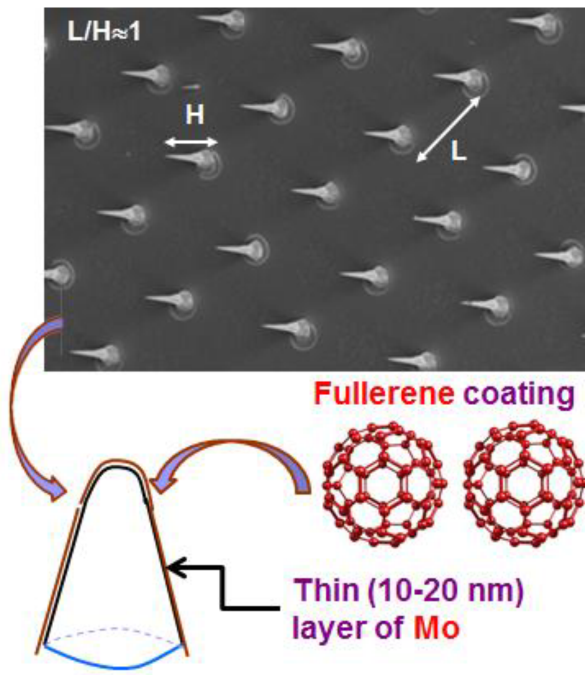

Fig. 1. Typical multi-pin cathode structure. Pin height H = 30 μm. The distance between the pins L = 30 μm. Pin tip diameter D = 36 nm. The scheme of the each pin coating is shown

Electron beam formation system design

The above requirements to the structure and characteristics of the emission surface are fairly rigid and were taken into account in the gyrotron electron optic system (EOS) development.

With the existing technology for manufacturing of multi-pin emitters, which we are going to use in a diagnostic gyrotron, it is nearly impossible to create conic emitters typical of the gyrotrons. However, the multi-pin emitting system in the form of a ring can be mounted on a flat end of a cylindrical cathode. With this cathode configuration, it is virtually excluded to use the well-developed adiabatic magnetron-injection guns (MIGs) [5] for the formation of a helical electron beam (HEB), Therefore, for the HEB formation in a gyrotron with field emitter, it was decided to use a non-adiabatic EOS, the scheme of construction of which is given in detail in [6]. Such an EOS permits one to use butt-end cathodes for the HEB formation. Here, primary gyration energy of the beam is provided by injection of the initially formed rectilinear electron flow obliquely to the magnetic field. The further increase in the oscillatory energy of the particles to the required level is reached by adiabatic compression of the beam in a gradually increasing magnetic field. Note that the scattering field of the main solenoid (fig. 2) has very small angles of inclination of the magnetic field line to the axis, i.e., the field lines are almost parallel to the normal to the cathode, and therefore a pair of counter-running cathode coils located symmetrically with respect to the emitter should be installed before the beam injection obliquely to the magnetic field to ensure the required angle of inclination of the magnetic field to the axis with minimum energy consumption.

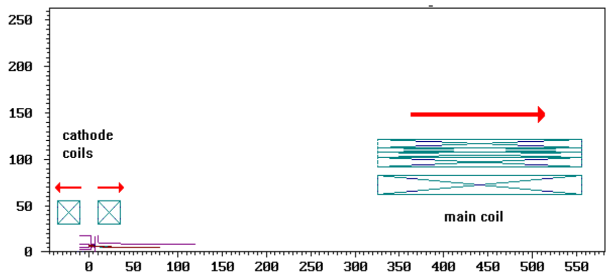

Fig. 2. General view of the system. Arrows show the coil polarities. Left: auxiliary coils at the cathode. Right: the main solenoid. All sizes are given in mm

With the existing technology, it is difficult to manufacture multi-pin ring field emitters with an average radius R greater than 10 mm. On the other hand, the minimal cathode radius is also limited since it is needed to provide the operating beam current about 40–50 mA. Summing up, it can be inferred that the average radius of a ring emitter should satisfy the inequality $4 < R$ [mm] < 10. Therefore during the numerical simulation, the values of R were enumerated with 2-mm step in the mentioned interval.

Numerical optimization of the location, shape, and currents of the counterrunning cathode coils, and the shape of the electrodes was performed using two-dimensional code EPOS [7]. Simulation shows that for optimized version of the electron gun R = 7 mm. In the range of currents 0–50 mA the pitch-factor and velocity spread remains close to 1.2 and 30% respectively that is quite admissible to achieve a typical efficiency of a few percent for such gyrotrons.

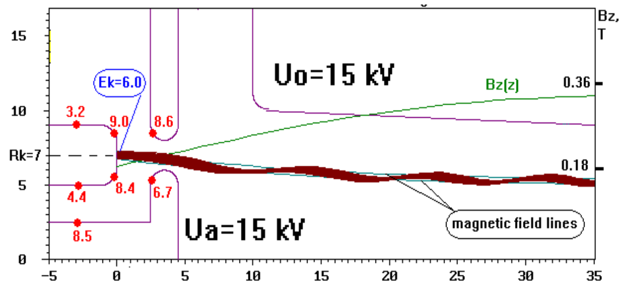

Fig. 3. Scheme of the primary formation of the beam in a non-adiabatic EOS. Distributions of the axial magnetic field B(z) (right axis, data are in T) is presented. Dots and corresponding numbers show the electric field value (kV/mm) at the most critical points. Electric field Ek at the emitter center is also specified. All dimensions are in mm

Conclusion

The concept of an electron-optical system of a sub-terahertz gyrotron with field emitter is described. It is shown that the non-adiabatic scheme of the beam formation with a flat ring multi-pin emitter makes it possible to form the HEB with quality acceptable for operation of modern gyrotrons intended for spectroscopy and diagnostics of various media.

Acknowledgements

The work was supported by the Russian Science Foundation, project No. 16-12-10010.

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