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Development of a large orbit gyrotron with a permanent magnet system

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Abstract

In this paper we present some results of a computer-aided design (CAD) of a new high harmonic gyrotron with an axis encircling electron beam and a magnetic circuit based on a permanent magnet. It belongs to a class of gyro-devices known as large orbit gyrotron (LOG). The electron beam is formed by a novel diode electron gun with a gradual reversal of the magnetic field. The numerical experiments for optimization of the electron-optical performance of the system were carried out using the GUN-MIG/CUSP software package developed at the FIR Center. The CAD of the permanent magnet was performed by the ELF-MAGIC code. The cavity was optimized for excitation of the TE_{41} mode at the fourth harmonic of the cyclotron frequency. The target parameters of the gyrotron are: frequency of generated microwave radiation about 104 GHz, output power near one kilowatt and efficiency of several percent.

1. Introduction

Powerful sources of high frequency microwave radiation are in demand for great and continuously expanding number of applications in the basic research and technology. In many respects the gyrotrons are superior to other devices due to their capability to generate microwave radiation at unprecedented power levels in the millimeter and submillimeter wavelength region of the electromagnetic spectrum. As these sources operate near the cyclotron frequency, $\omega \approx \Omega_c$ ($\Omega_c = \eta B$, η being the electron charge to mass ratio, and B - magnetic field) or its harmonics $\omega \approx s\Omega_c$ there are two principal possibilities for further advancement towards shorter wavelengths. The first one is to use stronger magnetic fields. Nowadays, the superconducting cryomagnets are able to produce homogeneous static magnetic fields up to 10-15 T, which provides radiation of millimeter and submillimeter waves from strongly oversized interaction space in the resonant cavity. The operation and maintenance of such sources is both laborious and expensive. Due to their substantial dimensions and weight similar tubes are not suitable for a number of applications, which require compact portable devices. The second possible way, which offers possibility to reduce significantly the necessary magnetic field, is to use interaction at high cyclotron harmonics. Unfortunately, the high harmonic operation is much less effective compared with fundamental operation. Moreover, the high harmonic operation is prone to mode selection problems as a result of mode competition. These specific problems of the harmonic operation practically limit the maximum possible harmonic number to values of $s < 4$.

A relatively new and less studied scheme of interaction, known as a large orbit gyrotron (LOG) [1-4] allows to overcome the above mentioned problems. While in the conventional ("small orbit") gyrotron the annular electron beam consists of beamlets that have tightly wound off-axis helices with small Larmor radius, in the LOG the beam is composed of axis-encircling orbits with Larmor radius comparable to the cavity radius. An inherent feature of this device is its high-harmonic operation due to the fact that an axis encircling beam couples effectively only with co-rotating modes having azimuthal indices equal to the resonant harmonic number [2,4]. This leads to greater mode selectivity. The mode competition can be reduced further using cavities with magnetron-like azimuthal structure [1,3]. As the harmonic numbers for such scheme of operation can be significantly greater compared with traditional gyrotrons, the required magnetic field for gyro-devices with axis-encircling beams is greatly reduced and can be produced by a permanent magnet, thereby eliminating the need for cryogenic superconducting magnet. Important advantage of the gyro-devices with permanent magnets is that their weight and sizes are considerably reduced. Additionally, such portable devices are more economical and simple in operation.

Although this class of devices promises an advantageous alternative its potential is far from being realized completely mainly due to problems with the beam quality. While the MIGs have reached a high level of perfection and effective performance, the electron guns generating axis-encircling beams still pose serious electron-optical problems that need thorough consideration in order to improve beam quality and realize the potential of gyro-devices with axis-encircling beams (such as LOG, cusptrons [3] and peniotrons).

The main design goals of our project are development of a compact, portable high harmonic gyrotron with a novel electron optical system and a permanent magnet. The first stage of the design was a feasibility study. During this stage different operating modes and beam dependent parameters were considered in order to identify the possible operating conditions and to specify the requirements to the entire system taking into account the limitations which stem from the available power supply and attainable magnetic fields. It was found that operating modes of the class TE_{m1} are the most appropriate candidates for the following ranges of parameters: beam currents 1.0-2.0 A, accelerating voltages 35-40 kV and maximum magnetic field near 1 T. Both the conceptual and the electron-optical designs of the prospective device were performed by numerical simulation of the electron beam formation and its interaction with the high frequency electromagnetic field. After a great deal of iterations on which the configuration of the electron-optical system, magnetic circuit and electrodynamical systems were varied the device was optimized for operation on TE_{41} mode at fourth harmonic of the cyclotron frequency.

2. Outline of the physical models and software

One of the most critical issues for the efficient operation of a LOG is the formation of high-quality axis-encircling electron beam with both small ripple and small velocity spread. In order to be able to analyze different electron-optical designs of various electron guns generating such beams, we have modified our software package GUN-MIG [5]. The new version of the code, named GUN-MIG/CUSP [6] is a problem oriented trajectory analysis tool that traces the electron trajectories in combined static axisymmetric electric and magnetic fields and calculates beam parameters and electron-optical characteristics of the electron gun. Both, magnetron injection guns and guns with field reversal (or cusp guns) can be simulated by this code. The software package is based on a self-consistent physical model, which comprises relativistic equation of motion, Poisson's equation and relations governing extraction of beam current from different cathode regions (virtual planar diodes with thermionic emitters) [6].

The boundary value problem and the dynamics of the electrons in the beam are treated in a cylindrical coordinate system. Therefore the code is applicable to axially symmetric electron-optical systems. The boundary contour can be arbitrary. It is represented by segments such as straight lines and arcs of circles. A square-shaped grid and a five-point discretization formula are used for the solution of the Poisson's equation by the finite difference method (FDM) with successive over-relaxation (SOR) on a sequence of three grids with increasing finesse (i.e. decreasing step). The potentials and fields are interpolated using 4 by 4 mesh point stencil for Lagrange interpolation.

The axial magnetic field is input as a set of polynomial expansion coefficients or directly as an array produced by a separate program for magnet design. In our numerical experiments we used a field profile in the permanent magnet system designed using the ELF-MAGIC code. The off-axis components of the magnetic field are computed from the paraxial series expansion.

The electrons of the beam contribute to the electric field through their space charge. A finite number of electron trajectories, each associated with a definite current density are traced through the system integrating their equations of motion by the fourth-order Runge-Kutta method. The space-charge distribution is computed using a

combination of the particle-in-cell (PIC) method with the area-weighted algorithm (AWA) for allocation of the charges to the mesh. The cells are defined by the same mesh, which is used for the solution of the boundary-value problem. For each time step inside a given cell, the charge is deposited to the four adjacent vortices of the cell (mesh nodes) according to the AWA. Allocating the charge and summing up the contribution of all rays the charge density in each node is obtained.

The region near the emitter is divided into a number of small virtual diodes in which the current is governed by potential distribution and initial velocities of the thermoelectrons. It is also assumed that in each virtual diode the Langmuir's theory holds and the technique implemented in GUN-EBT software package is applied for computation of the extracted currents [7].

GUN-MIG/CUSP is written in FORTRAN-77. It consists of a set of computational modules and postprocessor program intended for systematization and visualization of the results of numerical experiments. Information is presented in the form of plots and tables on seven screens altogether and is stored in files with generic names which reflect the type of data they contain and the variant of the analyzed system. In such a way, by running the code with different initial parameters and conditions a database containing well-structured results from various simulations is being created.

For CAD of the permanent magnet circuit the ELF-MAGIC code was used [8]. It is based on a new computational technique called Integral Element Method (IEM). In fact, the IEM is a hybrid of the following methods: (i) the method of moments; (ii) surface charge method; (iii) the method of surface currents and (iv) the network method. Using them complementarily a number of advantageous features are realized making ELF-MAGIC a powerful tool for 3D simulations of magnetic phenomena. In contrast to other conventional methods (such as the Finite Element Method), the IEM does not need space meshes and boundary conditions.

In our simulations, the starting currents for different modes are calculated from the balance equation for the power of RF losses in the resonant cavity and the microwave power radiated by the electron beam assuming Gaussian longitudinal profile of the field distribution [9].

More detailed analysis of the possibility for stable single-mode operation at high cyclotron harmonics is performed by numerical stimulation of the non-stationary processes responsible for mode excitation. For this purpose we use the well-known multimode self-consistent system of shortened equations, which consists of the equations of motion and equations describing modes excitation [10,11].

3. Results of numerical experiments

3.1 Results of the simulation of the electron-optical system

Efficient operation of the gyro-devices depends critically on the quality of the beam. Therefore, although the electron gun represents only a small fraction of the device, its performance is of paramount importance for the overall efficiency of the entire system. Basic requirements, which must be satisfied by the design of the gun, are: (i) Formation of high quality beam with small velocity spread and beam ripple, which can be transported without losses to the resonant cavity. (ii) Electron beam in the cavity must be thin enough and have appropriate radius that ensures effective interaction with

the desired mode. (iii) Tunability of the velocity ratio by controlling the accelerating voltage. (iv) Simple electrode configuration, which is not very sensitive to the fabrication tolerances and allows for easy adjustment. Specifically, the gun design is subject to the following requirements: (i) Beam current $I_b = 1.0 - 1.5$ A (cathode loading < 8 A/cm²). (ii) Beam voltage $U_a \leq 40$ kV. (iii) Beam ripple < 15 %. (iv) Maximum operating magnetic field near 1.0 T. (v) Velocity ratio $\alpha = 1.5-2.2$. (vi). Perpendicular velocity spread < 2.5 %.

To achieve these demands, the electron gun should be carefully designed. The choice of the configuration of the gun and magnetic field distribution is as a rule a compromise between many contradicting requirements. The advantage of simulations is enormous as it allows exploring a very large number of possible design solutions, looking for the optimal one. In search of a superior variant a lot of simulations have been carried out.

Generally speaking, there are two possible arrangements for the gun and the cusp. In the first one the gun is immersed in a constant upstream magnetic field and electrons are accelerated in the cathode-anode gap before following into the cusp region. In the second, the emitter is located in the transition region near to the field reversal and electrons acquire rotational energy during their acceleration. One possible way for reduction of the beam ripple in the guns of the first type is to make the transition width of the cusp as narrow as possible and magnetic field distribution symmetrical in respect to the field reversal point. This however is very difficult to realize in practice. In the guns of the second type, different approach for generation of rotating hollow beam with little ripple can be used. In such systems the beam passes through a field reversal while it is still converging. By properly choosing the axial location of the transitional region, the convergence of the beam cancels the normal shift in the guiding center experienced when passing through field reversal. A distinguishing feature of such systems, which makes the design of the magnetic circuit easier, is the use of a gradual field reversal instead of abrupt one as in the traditional cusp guns. We selected this arrangement for our gun.

The shapes and locations of the electrodes were adjusted until a beam with desired parameters have been achieved. The final geometry of the electrodes that satisfies design requirements is shown in Fig.1 together with the axial magnetic field distribution and electron trajectories. It can be seen in Fig. 1 that electron trajectories pass far from the surface of the anode hole. In such a way the risk to have problems with beam interception is greatly reduced. The configuration of the gun is very simple as the electrode shapes are comprised solely of line and arc segments. The emitter surface consists of an annular ring of 0.40 mm width and 9.0 mm average radius. At a cathode loading of 5 A/cm² (which is well within the capabilities of the dispenser barium aluminate cathodes) it gives beam current 1.13 A. As the cathode operates in a temperature limited mode the beam current can be increased proportionally by increasing the loading through augmenting the temperature of the emitter.

Fig. 1 Configuration of the gun, profile of the axial magnetic field produced by the permanent magnet and electron trajectories of the beam (accelerating voltage 36.0 kV; beam current 1.13 A at cathode loading 5.0 A/cm²)

Distinguishing feature of the gun is that it uses a gradual (instead of abrupt) reversal of the magnetic field to form an axis-encircling electron beam. The required magnetic field is produced by a permanent magnetic system, designed using the ELF/MAGIC code [8]. The first guesses concerning the field profile were obtained as a result of simulations in which the field reversal region was approximated by hyperbolic tangent. The final optimal field distribution was found after numerous trials with different profiles of the axial magnetic field. Due to the fact that the magnetic field does not change so rapidly (as in the usual narrow cusps) the off-axis components can be calculated with sufficient accuracy from the paraxial expansion. This was corroborated in a number of tests comparing the results of calculation with those produced by ELF-MAGIC code. The distribution of the magnetic field generated by the permanent magnet (PM) is shown in Fig.2. It is produced by a magnetic circuit having both axially and radially magnetized segments. For fine tuning of the magnetic field profile several adjusting bolts in the PM are used together with additional coils at the cavity region. The most critical region is the field reversal region situated in the accelerating gap of the gun. Both, the position of the filed reversal point and the configuration of the profile at the adjacent sides influence heavily the ripple of the beam. The next region with rapidly increasing field is responsible for the increase of the proportion between the transverse and axial energy of the electrons. On this region they must attain the final required velocity ratio. Severe problem on this region could be reflection of the electrons due to mirroring effect. Next follows the flat-top region which must coincide with the interaction region in the resonant cavity. One of the most challenging problem in the magnet design is to ensure constant (uniform) field distribution over a long enough area.

Fig.2 On-axis magnetic field profile produced by the permanent magnet circuit

Finally, there is a region of decreasing magnetic field where an “unwinding” of the electron trajectories began before they enter the collector walls. One must account for the interplay between different regions in order to find appropriate magnetic field profile, which is necessary to form high-quality beam with desired configuration

The positions at which the electrons start from the emitter influences their final velocity components and pitch factor (velocity ratio). It should be noted that it is easy to find (for a given electrode configuration and magnetic field profile) a point on the cathode for which electron trajectories starting there have small ripple. Unfortunately, drifting away from this optimal position electron trajectories starting from regions with greater or smaller radial coordinate have progressively increasing beam ripple. The emitting area was reduced to minimize the spatial separation of the various electron trajectories and in such a way to reduce both velocity spread and beam ripple.

Another key advantage of the selected configurations of the system is the possibility to adjust the velocity ratio by controlling the accelerating voltage without appreciable changes of the beam quality (Fig.3). Simulations were performed for a range of accelerating voltages from 30 to 40 kV. As can be seen, the velocity ratio changes from 2.4 to 1.3, while the average ripple varies from 8.4 to 12.4 %. The corresponding variations of the spread of the axial velocities are shown in Fig. 4.

Presented results of computer simulations predict a satisfying electron-optical performance of the designed electron gun. It is expected that the gun will generate axis-encircling beams with small ripple, low velocity spread and appropriate beam parameters (current, velocity ratio, radius in the cavity) suitable for the gyrotron under development.

Fig.3 Average beam ripple and velocity ratio vs. accelerating voltage

Fig.4 Axial velocity spread vs. accelerating voltage

3.2 Results of simulation of the resonant cavity

As initial data for simulation of the resonant cavity we used beam parameters obtained from the trajectory analysis of the gun. In order to identify the possible candidate for excitation by beams of low voltage (< 40 kV) and low currents (< 2 A) different modes were considered. It follows from the calculations that the best separation of the resonant magnetic field can be realised for $TE_{m,1}$ modes. The starting currents for several $TE_{m,1}$ modes versus magnetic field are presented in Fig. 5. It can be seen that the increase of the harmonic number has two distinct consequences. First, it leads to higher minimum starting currents and, second, for higher harmonics the resonant lines in Fig.5 become narrower. It is obvious that for the given beam parameters and maximum value of the magnetic field the highest

mode that can be excited is TE_{41} at $s = 4$. Therefore, this mode was selected as operating one in the prospective LOG under consideration.

Fig.5 Starting currents versus magnetic field for $TE_{m,1}$ modes
($U=31$ kV, $\alpha=2.0$, $L=50$ mm, $R_c=2.39$ mm, $R_b=0.54$ mm)

Fig.6 Minimum starting currents for excitation of $TE_{4,1}$ mode versus accelerating voltage

The strong dependence of the minimum starting currents for excitation of TE_{41} mode on the accelerating beam voltage (at fixed velocity ratio) and on the velocity ratio (at fixed beam voltage) are shown in Fig. 6 and Fig. 7 respectively. Taking into account the imposed limitations on the beam energy, from these plots it follows that electron beams with higher pitch factor are required in order to keep the starting currents below the beam currents provided by the gun.

Fig.7 Minimum starting currents for TE_{41} mode versus pitch-factor
($U=31$ kV, $L=50$ mm, $R_c=2.39$ mm, $R_b=0.54$ mm)

Another parameter, which strongly influences the starting current, is the length of the resonant cavity (Fig. 8). From one hand, in order to reduce the starting current the length of the interaction area must be increased. From other hand, as can be seen in Fig. 8, this results in a significant increase of the fraction of ohmic losses in the total losses. Thus the choice of the cavity length is always a compromise between several contradictory requirements. It should be noticed that the longitudinal extent of the resonator is limited also by the fact that it is difficult to maintain the synchronism condition between the beam and RF field on long distances. Additionally, there are technological problems to produce permanent magnet with long uniform region (top-flat region) as well as to manufacture long cavities of small radius. Taking into account all these considerations the length of the cavity was chosen to be 50 mm.

Fig.8 Minimum starting current and ohmic losses for TE_{41} mode versus cavity length

Fig.9 Minimum starting current and optimal magnetic field vs. acc. voltage

The dependence of the starting current on the accelerating voltage for the chosen dimensions of the cavity is shown in Fig. 9. The values of the velocity ratio

corresponding to different voltages are those obtained from the simulation of the gun. This plot illustrates the increase of the starting current with increasing the beam voltage due to the decrease of the velocity ratio. A sufficient excess of the beam current over the starting current can be obtained for accelerating voltages in the range 30-35 kV at nominal cathode loading.

Another important observation concerns the optimum value of the magnetic field in the resonator. It is clear that alongside with the permanent magnet which produces the nominal required value of the magnetic field additional coils for adjustment and fine tuning of the magnetic field in the resonator are required.

Results from computer simulation of the mode excitation using the self-consistent physical model are presented in Fig. 10 and Fig.11. In Fig. 10 the time evolution of the output power is shown. Although the neighbouring modes were taken into account, the results of numerical experiments indicate that they are not excited and a single mode operation takes place. The energy spectrum of the spent electron beam with initial transverse velocity spread of 1.0 % is shown in Fig. 11. Here W is the energy of electrons after interaction, W_0 is the initial energy, dN is the number of particles with energy W and N_0 is the total number of particles. It can be seen that most of the electrons have given part of their energy to the field but the total efficiency is low (about 2.2 %) due to the considerable high ohmic losses and small excess of the operating current over the threshold starting current.

Fig.10 Time evolution of the output power

Fig.11 Energy spectrum of the electron beam after interaction

4. Conclusion

Computer aided design of a novel high harmonic large orbit gyrotron with axis-encircling electron beam and a permanent magnetic system has been performed at the Research Center for Development of Far-Infrared Region in the Fukui University. The presented results indicate the feasibility of a weakly relativistic LOG with output power near 1.0 kW and frequency of the generated radiation 104 GHz. The main advantages of

such prospective device would be the absence of cryogenic system, small weight and dimensions, simple and compact power supply. In combination, the predicted output power and frequency of the radiation makes this gyrotron suitable for different applications in the basic research and technology. Additionally, it is hoped that such device will be an excellent tool for accumulating knowledge and experience needed for development of more efficient gyro-devices with more powerful axis-encircling beams.

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