RELATIVISTIC MAGNETRON OF 8 mm WAVEBAND

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The first experimental study of relativistic magnetron of 8 mm wavelength with diffraction microwave output has been produced. Data that compare experiment and simulation are considered.

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1. INTRODUCTION

To promote into the area of higher frequencies a design of relativistic magnetron (RM) should meet two inconsistent requirements. The first is concerned to reduction of interaction space of an electron cloud and electrodynamic structure (EDS) according to scaling, d_{CA} = $1/2(d_A\text{-}d_C)\sim\lambda$ [1]. The second is caused by type of emission which is explosive for relativistic high-current electron devices. Last requirement rigidly regulates the increase of d_{CA} till the size at which the electrode plasma expansion across the focusing magnetic field does not impact the dynamics of parameters of diode system and excitation conditions of EDS. For RM operating with the pulse width of up to several hundreds of nanoseconds d_{CA} should exceed 6…8 mm.

A diameter of the cathode also is the parameter corresponded to another pair of inconsistent conditions. It is known, that the condition of magnetron excitation (Buneman-Hartree) is defined by synchronism of drift movement of an electron cloud in crossed electric and magnetic fields, and slow electromagnetic wave of chosen oscillation mode: $v_{DR} = E_0/B_0 = v_{PH}$. Thus, lower accelerations can be realized only at smaller electric fields. However the electric field intensity in a coaxial system that is great enough in RM, increases quickly with reduction in the cathode diameter. To compensate the drift speed increase, it is possible to increase the magnetic field intensity (that is not always possible) or increase the cathode diameter that leads usually to $d_C \geq$ 1 cm.

Apparently, there are very rigid restrictions on reduction of dimensions of the cathode and EDS of RM which are the basic distinctive feature of these devices in comparison with their non-relativistic analogues. It is necessary to notice that for RM of a cm wave range these differences are not dramatic that allows to demonstrate the highest impulse power up to tens of gigawatt. Thus, typical RM with EDS cross-section of tens of square centimeters has small number of resonators (N = 6-8) that reduces the start currents and noises, and provides generation at one frequency.

A choice of excitation conditions and oscillation mode of EDS becomes a key problem at transition into mm wave lengths. Since the restrictions on the cathode and EDS dimensions remain the same as for RM of cm wavelength, a number of resonators $N \approx \pi d_A/\lambda$ can achieve of several tens. In this case, there is a danger for strong mode competition, absence of pure oscillation spectrum and stable generation. Apparently, during the years, the listed circumstances prevented creation and study of RM of mm wave length. The present work addresses to creation and, as authors are considered, to the first experimental study of such a device.

2. EXPERIMENTAL SETUP

Studied RM has rather traditional design except for a MW energy output (Fig.1).

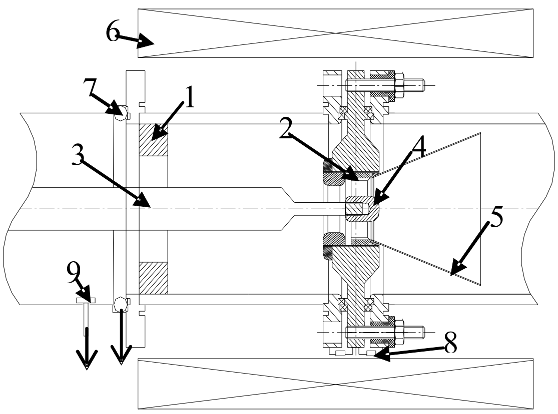

Fig.1. Schematics of 8 mm RM. 1. Return current collector. 2. Anode. 3. Cathode holder. 4. Cathode. 5. Output horn. 6. Solenoid. 7. Rogowski coil. 8. Shunts of anode and collector currents. 9. Capacitor divider

The slow-wave system of the magnetron is presented by 40 identical resonators of a slot type located on periphery of the ring anode (d_A=28 mm, L=12 mm). The cathode (d_C=12 mm) is a continuation of the cylindrical leg connected to the vacuum output of HV forming line. The cathode and anode of RM are located in the middle of a long cylindrical overdimensional waveguide (d=80 mm, L=600 mm). The focusing magnetic field induction is of 1…6 кG. To avoid breakdowns at the MW energy output a diffraction channel with the overdimensional waveguide and milar window at the end face of the waveguide is used. At the side of the output window the EDS is connected to the horn antenna, and at the opposite side the ring tuning plunge is adjusted.

The magnetron was powers by a negative voltage pulse U_0=160 kV, I=3.5…4 kA, t_P=40…45 ns (Fig.2) submitted to the cathode.

The goal of preliminary experimental study was investigation of operational regimes of RM and dependence of the 8 mm signal intensity on the focusing magnetic field variation, Fig.3.

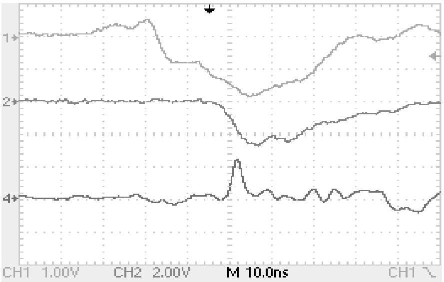

Fig.2. Plots of magnetron signals. 1. Diode net current. 2. Voltage. 4. 8 mm detector. 10 ns/div

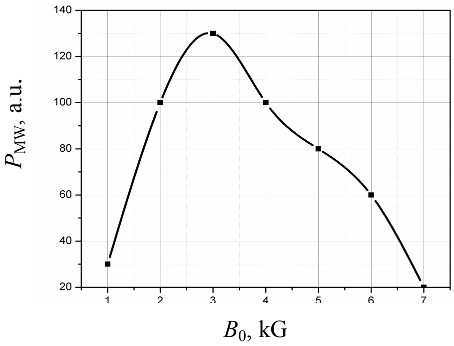

Fig.3. Dependence of intensity of 8 mm signal on focusing magnetic field inductance (U_0 = 160 kV)

Simultaneously, registration of microwave signal corresponded to cm wavelength was provided. Qualitative data corresponded to the wavelengths of 8 mm, 3 cm, and 10 cm were obtained with the help of crystal detectors. Quantitative characteristics of 8 mm signal were obtained with the help of 6D13D vacuum diode.

3. EXPERIMENTAL DATA ANALYSIS

The first tests of the magnetron had shown that MW generation conditions were not fulfilled during a whole current pulse (see Fig.2). It is possible to assume that this is caused by dense plasma formation around small-size resonators of the EDS structure that disrupted the generation process.

More detailed study of designed RM system (see Fig.1) that consists of the overdimensional waveguide and RM EDS gave evidences of the presence of two types of radiation related to the magnetron and cyclotron radiation mechanisms. Radiation of 8 mm waveband was registered only in the case of the presence of the resonator system. Removal of the RM EDS created conditions for realization only of the last mechanism.

4. RESULTS OF EXPERIMENT AND SIMULATION

To differentiate the radiation mechanisms the frequencies of the exited electromagnetic waves corresponded to H_{0N} modes were estimated only for the overdimensional coaxial waveguide. These data can be added by the results of 3D PIC simulation of the same system excited at the electron cyclotron frequency and its harmonics. These data show that in the area of operational B_0=2…3.5 kG excitation of the overdimensional coaxial waveguide realized due to the cyclotron mechanism is possible in the range $n w_{ce}$ = 6…13 GHz (Fig.4). This corresponds to the harmonic number $n \leq$ 2-3. It is interesting to note that MW radiation which could meet for higher n was not observed experimentally.

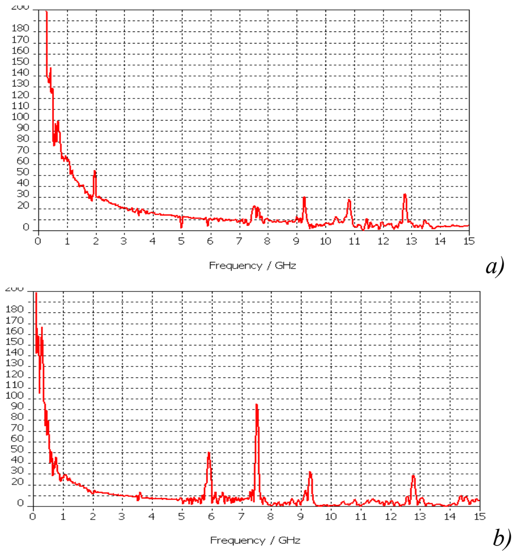

Fig.4. Frequency spectrums of E_r (a) and E_θ (b) components of H_{0N} modes excited in overdimensional coaxial waveguide, d=12 mm, D=80 mm by means of electron cyclotron oscillations. Results are produced with the use of 3D simulation model based on CST Particle Studio [2]

A question of the excited oscillation modes still remains without full enough experimental acknowledgement. Nevertheless, a range of the magnetic field values related to RM generation (see Fig.3) is in good correspondence with estimated operational parameters which meet for the conditions of excitation of $\pi/2$ oscillation mode at λ = 8.4 mm.

Preliminary answer can be obtained at simulation of electron trajectories and dynamics of electromagnetic fields in RM using 3D electromagnetic PIC code [2]. The particle trajectories for the case U_0 = 100 kV, B_0 =2…3.5 kG testify that the dense electron cloud takes part in drift movement near the slow-wave structure, and bidirectional axial electron flow creates intense losses of beam current. The electric field distribution of the slow wave traveling around the EDS testifies to formation of competing $\pi/2$ and $\pi/3$ modes that has not complete correspondence to chosen conditions of excitation of $\pi/2$ modes in the real system for U_0 = 160 kV and B_0 = 2…3.5 kG.

The electron beam current distribution in studied system plays important role in the magnetron operation. Measurements of currents were carried out by a number of probes, Fig.1. The net, anode and axial currents were registered, accordingly, by the Rogowski coil *7*, and shunts established on periphery of the anode and collector flanges *8*. Their values usually are of 3.5…4 kA, 50…100 A, and 600…1000 A, accordingly, that testifies of significant beam current losses before the anode block. Thus, one and the most significant loss channels is geared to an axial return beam current which is intercepted from one side by the return current collector *1*. The current losses of minor intensity (by a factor of

~4 obtained experimentally) correspond to an axial leakage of beam electrons as it is shown in Fig.5.

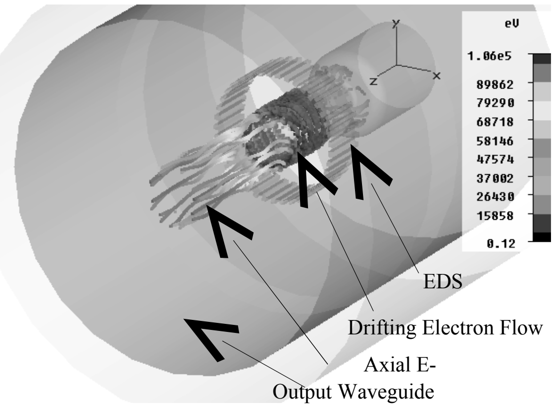

Fig.5. Electron trajectories in electrodynamic structure of RM and overdimensional output waveguide

Measurements of intensity of the output radiation in millimeter wave range was made with the help of horn reception system and calibrated vacuum detector established along an axis of the overdimensional waveguide at different distances from the waveguide window. Conditions of the detector calibration defined its tuning to the wavelength of 8.26 mm. Ignoring possible difference in the wavelengths of calibrating and radiating signals it is possible to count, that the impulse power of RM in preliminary experiments did not exceed P_{MW} = 48…52 kW.

The MW power efficiency of RM can be estimated as a relation between measured MW power P_{MW}, and beam impulse power obtained from experimental data of the anode current, $P_B = U_0 I_A$. For typical regimes I_A = 75 A, and P_B = 12 MW, that gives the MW power efficiency of RM of ~0.4%.

CONCLUSIONS

Preliminary study of first experimental variant of RM demonstrated MW emission in 8 mm wave range. Experimental data coincides with estimated ones for the focusing magnetic field and electron energies that correspond to the conditions of $\pi/2$ mode excitation at λ = 8.4 mm and also in part to the results of 3D simulation.

Measurement of the impulse power of MW emission at 8 mm wavelength gives the efficiency of RM on power of ~0.4%. Further investigations of RM will be focused on improving the radiation efficiency by means of eliminating the beam current losses in vacuum chamber.

REFERENCES

1. J. Benford, J. Swegle. *High-Power Microwaves.* Artech House Inc, Boston, London. 1992, Ch.5, 412p.
2. CST Particle Studio. *CST Studio Suite 2006.* Computer Simulation Technology, CST GmbH, Darmstadt, Germany.

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РЕЛЯТИВИСТСКИЙ МАГНЕТРОН 8 мм ДИАПАЗОНА

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Проведены первые экспериментальные исследования релятивистского 8 мм магнетрона с дифракционным выводом микроволнового сигнала. Приводится сравнение данных эксперимента и численной модели. Предварительные исследования РМ показали наличие генерации в диапазоне 8 мм. Экспериментальные данные совпадают с расчетными значениями для фокусирующего магнитного поля и энергии электронов, соответствующими условию возбуждения колебаний $\pi/2$-вида при длине волны 8.4 мм, а также с результатами численного 3D-моделирования. Измерение мощности 8 мм излучения позволило оценить КПД РМ около 0.4%.

РЕЛЯТИВІСТСЬКИЙ МАГНЕТРОН 8 мм ДІАПАЗОНУ

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Проведено перші експериментальні дослідження релятивістського 8 мм магнетрону з дифракційним виводом мікрохвильового сигналу. Запроваджено порівняння даних експерименту та чисельної моделі. Попередні дослідження РМ вказали існування генерації у діапазоні 8 мм. Експериментальні дані збігаються з розрахунковими значеннями для фокусуючого магнітного поля та енергії електронів, відповідно умовам збудження коливань $\pi/2$-виду при довжині хвилі 8,4 мм, а також з результатами чисельного моделювання. Змінення потужності 8 мм випромінювання дозволили зробити оцінку ККД РМ біля 0,4%.