PHOTOINJECTOR ACCELERATING SYSTEM FOR SUB-MM HIGH-POWER PULSE SOURCE

T.V. Bondarenko, S.M. Polozov
National Research Nuclear University MEPhI, Moscow, Russia
E-mail: smpolozov@mephi.ru

Generation of high-intensity sub-mm electromagnetic radiation can be performed by means of the scheme that implies generation of radiation by short monochromatic bunch of electrons which is traveling through dielectric or corrugated capillary. Short bunch of electrons can be obtained by using of a photoinjector. R&D of accelerating systems of S-band photoinjector and analysis of electron bunch dynamics in this system are declared. The aim of the work is to find optimal model providing large value of efficiency and magnitude of accelerating field with low RF power. Different structure's types are considered to achieve this aim, such as 1.6 cell disk-loaded waveguide (DLW) and 3 cells and 2 half-cells of DLW. Structure based on 7 cells and 2 half-cells of DLW and travelling wave resonator (TWR) based system are analyzed to consider the possibility of increasing the electrical strength of the system and decreasing of requirements to RF power source. Results of electrodynamics characteristics analysis of accelerating structures resonant models and structures with power ports are presented. Electron bunch dynamics study results are also discussed.

PACS: 29.27.-A, 29.27.Bd

1. INTRODUCTION

The gamma, electron or neutron facilities are used for introscopy at present including cargo introscopy. They are conventionally based on an electrostatic electron or ion gun or accelerator. But such facility has one great disadvantage because all of them are the radiation sources and can to activate the cargo. New generation of introscopy facilities with low activation are under design at present. The using of THz region radiation is one of possible methods. The design of THz (or sub-mm) radiation source is one of possible needs of photo guns. One of such facility based on Cherenkov or Smith-Parcell radiation given by short electron bunch with MeV energy and special decelerating system was discussed in [1]. The radiation in ps and sub-ps bands can be generated using this scheme. The electron bunch must also have ps duration and 100…200 μm transverse sizes. This condition follows as small width of irradiating capillary channel in which electromagnetic radiation is induced.

Accelerating systems that are used in photo injectors are conventionally based on disk-loaded waveguide (DLW). Most widely used normal conducting photo guns are based on 1.6 cells DLW and operate on standing wave mode. Electrodynamics characteristics comparison of 1.6 cell structure and traveling wave structures will done to investigate the possibility of developing more effective structures. Such structures must to have high rate of beam exit power in respect to low RF power and low possibility of electrical breakdown. Beam dynamics in all modeled systems with beam parameters corresponding to photoelectron beam emitted from cathode in typical photoinjector has also been investigated.

2. 1.6 CELLS ACCELERATING STRUCTURE

1.6 cells accelerating structure was computed for 2856 MHz MW source operating frequency which is standard for S-band. The general view of the accelerating system with MW power port is represented in Fig.1. Structure period was chosen according to the equation

$$l = \frac{\beta_p \cdot \lambda \cdot \theta}{2 \cdot \pi}. \tag{1}$$

Here λ – generator's wavelength, β_p – wave's phase relative velocity, θ – operating mode of the structure.

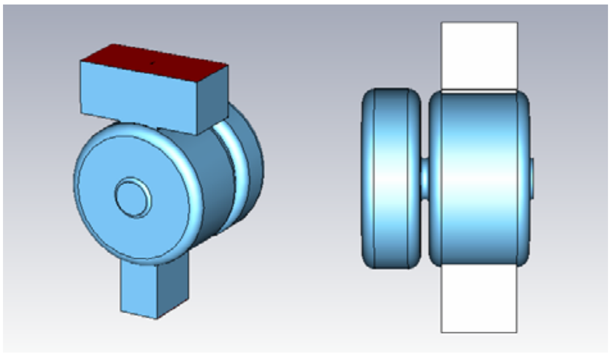

Fig.1. General view of 1.6 cell accelerating system

The photocathode will be arranged in 0.6 cell's sidewall, therefore accelerating field on the sidewall's surface must as high as possible. That is the reason of making half-cells length equal to $0.6 \cdot l$. Zero and π modes are excited in this structure, mode with $\mu = \pi$ phase shift per cell is the operating mode. The structure is characterized by the positive normal dispersion. The recess of the half diaphragm width was made in the sidewall of full cell in order to calculate the model correctly. The resonant frequency of the structure was tuned to the desired value by means of cell radius variation. Iris profile was made with rounding to eliminate the possibility of breakdown. This was done to reduce the electric field in the window's aperture because of high-rate accelerating fields in 1.6 cells accelerating structure that can lead to electrical breakdown. The ratio of iris window to the wavelength was set to 0.1. This value is a trade-off between the wish to get maximum amplitude of accelerating field and except probable beam loses on the iris. The structure performance was also increased by rounding of shells edges. The rounding radius value was chosen to provide the highest possible shunt impedance and Q-factor. Dependences of shunt impedance and Q-factor of 1.6 cell structure are shown in Figs.2 and 3 respectively.

The structures power input was realized analogous to BNL Gun I photoinjector [2]. I.e. standard S-band waveguide with 72×34 mm cross-section was attached to the full cell through the coupling diaphragm. The output of high order modes is connected symmetrically to the RF power input for better coupling and also to reduce the electromagnetic field asymmetries. Output of high order modes is designed in form of evanescent waveguide [3]. Output of high order modes cross-section matches sizes of coupling diaphragm. Full cell with RF port and output of high order modes waves forms the wave converter. The minimal value of power reflectivity factor from structure back to the supplying waveguide is the criterion of the wave converter's tuning.

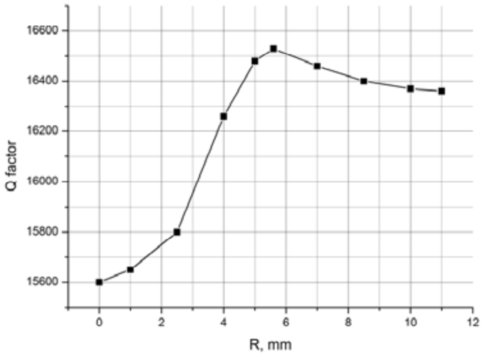

Fig.2. Dependence of Q factor versus shells blending radius

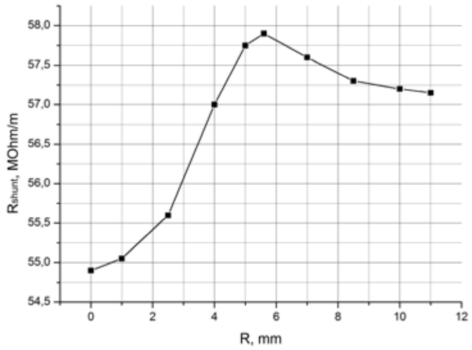

Fig.3. Dependence of R_{shunt} versus shells blending radius

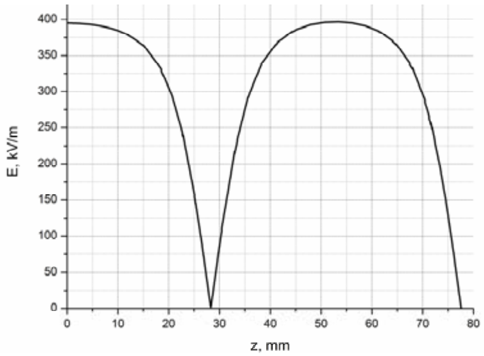

Fig.4. Accelerating field distribution along 1.6 cell structure axis

The structure's cells radiuses tuning was held to eliminate the misbalance of electromagnetic field magnitudes in cells. The accelerating field magnitude distribution along structure's longitudinal axis is shown in Fig.4 with 1 kW of input power. Mean value of structure's accelerating field, shunt impedance and Q-factor were obtained during the structure's electromagnetic characteristics investigation. They are shown in Table 1.

3. 3 CELLS AND 2 HALF-CELLS ACCELERATING STRUCTURE

First considered travelling wave structure is 3 full cells and 2 half-cells DLW accelerating structure. Half cells are located at both sides of the structure. The photocathode will be situated on the sidewall of one of them. Size of half-cells was chosen $0.5 \cdot l$ to eliminate unnecessary reflection of the signal that can appear in case of $0.6 \cdot l$ sized half cells and to make structure's tuning to the travelling wave mode more precision. The mode with $\mu = \pi/2$ phase shift per cell was chosen as the operating mode because of the high linear shunt impedance rate and maximal frequency separation between adjacent modes. The iris width, iris window's radius and shells edges rounding radius were equal for all modeled structures to make the comparison of travelling and standing wave structures more correct.

Since this structure operates at travelling wave mode the structure must include RF power output. RF input and output are connected to the half cells. As the half cells length is shorter than the supplying waveguide's smaller side, the power is fed and put out of the structure through the waveguide transitions. The output of high order modes is connected symmetrically to the RF power input and output similarly to the previous structure. Outputs of high order modes are designed in form of evanescent waveguide that replicates the power input and output with width equal to the larger side of coupling diaphragm. The general view of 3 full cells and 2 half-cells accelerating structure is shown in Fig.5.

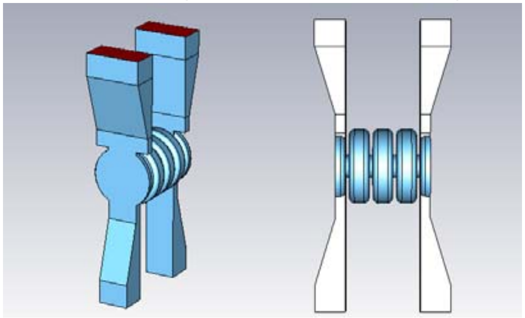

Fig.5. General view of 3 full cells and 2 half-cells accelerating system

The accelerating field magnitude distribution along the longitudinal axis of the structure is shown in Fig.6 with 1 kW of RF power fed to the port.

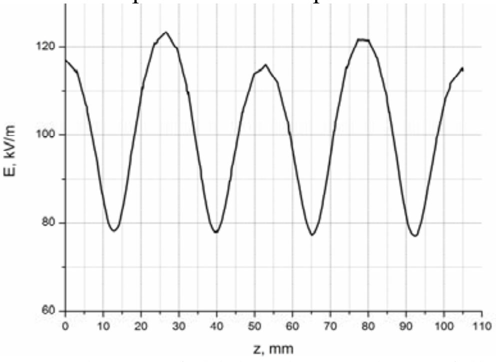

Fig.6. Accelerating field distribution along 3 full cells and 2 half-cells structure axis

The structure is tuned to the traveling wave mode. The accelerating field magnitude in adjacent cells differs from each other less then 3 % and the phase shift per each cell is 90 degrees. Mean value of the accelerating field magnitude in the structure is 103 kV/m.

4. 7 CELLS AND 2 HALF-CELLS ACCELERATING STRUCTURE

Results listed in Tabl.1 shows that the structure consisting of 3 cells and 2 half-cells appeared unable to provide the necessary level of accelerating field. That can be easily explained because the traveling wave mode have a half of amplitude of RF field achievable for standing wave. To achieve the necessary energy, the length of the structure was increased twice and therefore the system consisting of 7 cells and 2 half cells was considered (Fig.7).

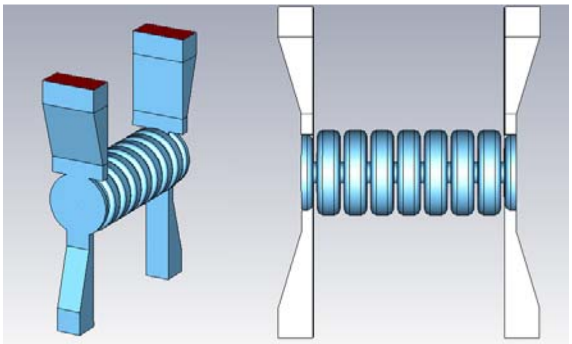

Fig.7. General view of 7 full cells and 2 half cells accelerating system

Parameters and design of this structure are identical to the 3 full cells and 2 half cells structure. All electromagnetic characteristics of the structure obtained during modeling are also listed in Tabl.1. The accelerating field distribution along of the structures longitudinal axis is shown in Fig.8 with 1 kW of power fed to the RF power input. The structure's tuning to the traveling wave mode was made analogous to 3 full cells and 2 half cells structure.

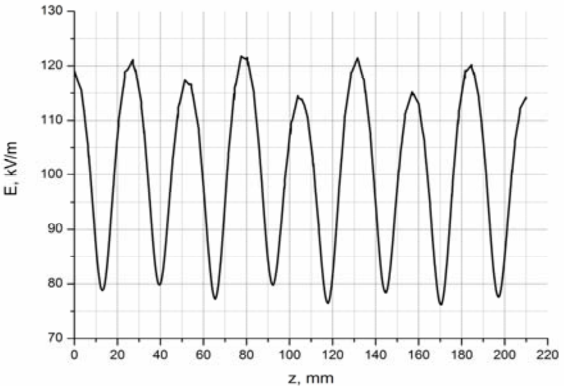

Fig.8. Accelerating field distribution along 7 full cells and 2 half-cells structure axis

5. TRAVELLING WAVE RESONATOR ACCELERATING STRUCTURE

Next improvement for travelling wave accelerating system that allows providing of higher level of electromagnetic fields is to convert 7 full cells and 2 half-cells system into travelling wave resonator (TWR). It can be useful as the short current pulses accelerating structure. The general view of TWR accelerating system is shown in Fig.9.

The accelerating system of photoinjector can be designed as the part of TWR ring. The power is fed to the structure due to the directional coupler. If the length of the TWR circuit equals the full number of generator wavelengths, the magnitude of electromagnetic fields in TWR reaches its maximum and magnitude of the wave incoming to the load from the ring turns to minimum. This is similar to the concepts and expressions for the cavity resonators. The difference is that in the TWR storage ring the wave is travelling instead of standing wave in resonators and part of the wave that is not spread in the ring doesn't reflect back to generator but comes to the coupled load. The generator works on the coupled load all the time indeed. The MW power pulse compression can be achieved using TWR.

The optimal operation regime of the structure is the critical mode. In this regime part of RF power is fed into the accelerating system through the directional coupler and compensates the power resistance losses in the resonator's sidewalls. If the structures reflecting coefficient α_T is insignificant, electrical field magnitude in storage ring may be many times more than the magnitude of feeding wave. It can be noted that the wave coming to the matched load consists of two waves in the opposite phases: one from the TWR circuit, another from the generator.

The directional coupler with narrow or wide side coupling represents the connection of two waveguides by coupling windows with space shift of quarter wavelength between the windows irradiating in the opposite directions of jointed waveguide. The directional coupler computation including the receiving of required transfer coefficient in the forward direction of jointed waveguide C simultaneously keeping transfer coefficient in the opposite direction of jointed waveguide $|P|$ below the certain level. The directivity coefficient is also significant characteristic that is determined by the expression:

$$D = 10\lg\frac{C}{|P|}. \qquad (2)$$

Here D is the directivity coefficient of the directional coupler, C – transfer coefficient in the forward direction of jointed waveguide, P – transfer coefficient in the opposite direction of jointed waveguide.

Taking into account part of the signal branching in the opposite direction and intensity attenuation factor, expression for the magnitude of electrical field traveling in TWR storage ring can be written down this way:

$$b_4 = \pm j\frac{1}{\sqrt{1-e^{-2\alpha_T}}}\frac{C}{|P|}a_1. \qquad (3)$$

Here a_1 – RF generator signal intensity magnitude, α_T – TWR ring signal intensity attenuation factor, b_4 – TWR ring electrical field intensity magnitude [4].

The magnitude of wave coming to the coupled load is not zero for any value of transition coefficient that differs from $\sqrt{1-e^{-2\alpha_T}}$. The wave is coming from the ring to the coupled load is summarized in the phase with wave coming from generator in case of undercoupled resonator and in opposite phases in case of overcoupled resonator.

The TWR accelerating system tuning is primarily consists of connecting power input and output ports of the system: waveguide bends were attached to the ports. Waveguide bends were computed to provide minimal possible reflections on the operating frequency. Reflection coefficient of modeled waveguide bends is S_{11} = -32.8 dB.

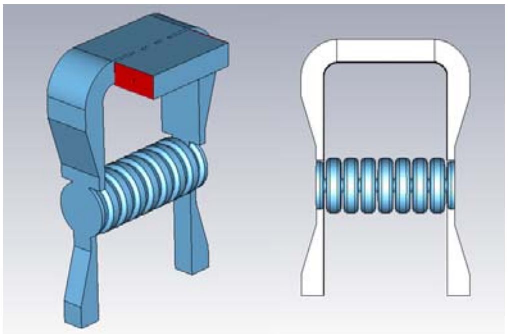

Fig.9. General view of TWR accelerating system

The TWR tuning to provide full number of wavelengths filling the ring length was made by varying the distance between waveguide bends and waveguide transitions. As a result of tuning the length of the TWR fits five wavelengths.

The structure's reflection coefficient equals to S_{11}=1.43 %, the transition coefficient taking into account power losses in copper sidewalls of the structure equals to S_{21}=96.1 %. Thus the transition coefficient of directional coupler must be equal to 3.9 % for the critical coupling mode of TWR with directional coupler.

Three coupling window model was applied to provide high directivity level of the directional coupler (Fig.10). The multiplying of coupling windows number doesn't improve to the directivity coefficient. The waveguide coupling was done by using of the rectangular coupling windows located on the narrow waveguide side to eliminate of the possible electrical breakdown of waveguide due to small window's sizes. Each coupling window has corners rounding radius of half spacing between the waveguides. The transition coefficient of directional coupler is $S_{41} = C$ = 3.9 % that equals to the TWR ring decay coefficient at the 6.5 mm coupling window width, sidewall width between waveguides is 4 mm. Sidewalls width hasn't got sufficiently impact to the directivity coefficient. The transfer coefficient in the opposite direction of TWR ring equals $S_{31} = P$ = -53 dB. Thus the directivity coefficient of the directional coupler is D = 12.4 dB.

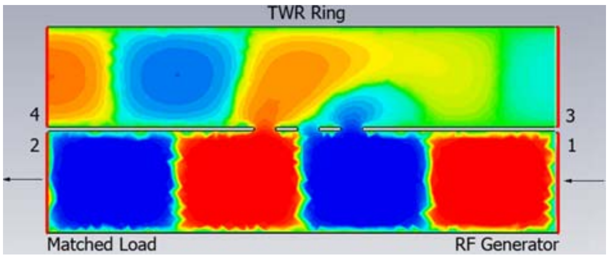

Fig.10. Electrical field distribution in directional coupler

The magnitude of electromagnetic field can be increased three times using TWR comparatively to the ordinary 7 cells and 2 half-cells accelerating structure (or necessary RF power can be decreased 9 times) at given values of the transition coefficient of directional coupler, the directionality and the decay factor of TWR ring, under the assumption of equation (3) for the strength of electromagnetic field in TWR ring. The mean value of accelerating field magnitude in case of 1 kW input power equals to 321.9 kV/m (Tabl.1).

6. ELECTRON BEAM DYNAMICS INVESTIGATION

The beam dynamics simulation in designed accelerating structures was done using BEAMDULAC-BL code designed in research laboratory DINUS of NRNU MEPhI [5]. The electron beam dynamics can be simulated taking into account the beam loading effect and Coulomb field influence using this code version. The simulation was done for beam having typical parameters for photoinjector: beam pulse charge Q = 0.1 nC, beam pulse current I = 5 A, injection energy W_{inj}= 10 keV, beam radius r= 200 μm. The main aim of investigation was to define the value of acceleration field magnitude which will provide acceleration of the electron bunch to the energy of 1 MeV.

Table 1

Main characteristics of the models

Parameters	1.6 cell	3 cells and 2 half-cells	7 cells and 2 half-cells	TWR
Operating mode	π	π/2	π/2	π/2
Structure length, mm	77.6	105	210	210
E_{mean}, kV/m (1 kW input power)	312.3	103.8	107.3	321.9
Q-factor	16530	9290	10800	10800
R_{shunt}, MOhm/m	57.9	49.1	54.9	54.9

Table 2

Results of beam dynamics simulation in designed models (output beam energy 1 MeV)

Parameters	1.6 cell	3 cells and 2 half-cells	7 cells and 2 half-cells	TWR
$E_0\lambda / \sqrt{P}$	1037	345	367	1102
E, MV/m	10.4	9.1	6.5	6.9
P, MW	1.5	20.0	4.0	0.5

Results of beam dynamics investigation shows that the 1.6 cell DLW structure cam provide electron beam acceleration to the energy of 1 MeV with 1.5 MW RF power fed to the system. This result is in the good agreement with experimental data obtained in accelerating centers. The accelerating structure based on 3 full cells and 2 half cells can provide the beam acceleration to 1 MeV with 10 MW of RF power, 7 full cells and 2 half-cells structure – with 4 MW of RF power. The TWR accelerating system shows best results – only 500 kW of RF power is necessary.

The beam transverse emittance is shown in Fig.11 in front end (red) and in output (blue) of TWR structure. It is clear that beam size preservation can be realized in accelerator. It should be reminded that the “pencil” and high brightness beam is necessary for Cherenkov THz generator.

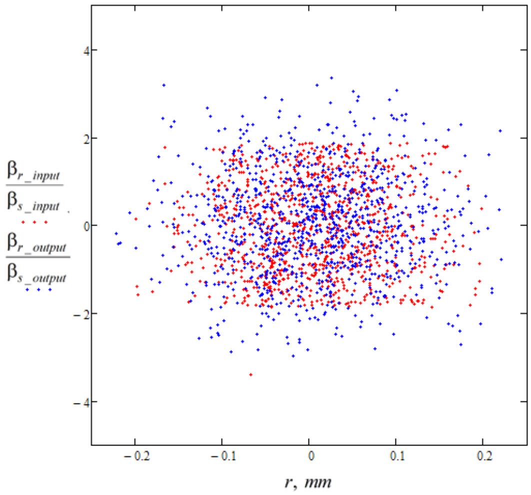

Fig.11. Transverse emittance of the electron bunch in the input (red dots) and in the output (blue dots) of the photoinjector

CONCLUSIONS

Electromagnetic models of ps band photoinjector were simulated and the analysis of electromagnetic characteristics of such models was done. It was shown that the accelerating system based on TWR with 7 cells and 2 half-cells can provides the accelerating field level comparable to 1.6 cells standing wave system with close values of input power. It allows the accelerating field magnitude decreasing and can decrease the possibility of electrical breakdown in the system. The electron beam dynamics analysis shows that the TWR accelerating system provides beam acceleration to required energy with lowest RF power comparatively all other structures and beam quality preservation can be realized.

REFERENCES

1. A.V. Smirnov. A High Performance, FIR Radiator Based on a Laser Driven E-Gun, ISBN 978-1-60456-720-5, 2008.
2. D.T. Palmer, et al. SLAC–PUB–7420, May 1997.
3. A. Anisimov, et al. // *Proc. of RuPAC-2010*, p.328.
4. J.L. Altman. Microwave circuits. Van Nostrand Co., 1964.
5. T.V. Bondarenko, et al. // *Proc. of HB 2010*, p.123.

Статья поступила в редакцию 23.09.2011 г.

УСКОРЯЮЩАЯ СИСТЕМА ФОТОИНЖЕКТОРА ДЛЯ ГЕНЕРАТОРА МОЩНОГО ИЗЛУЧЕНИЯ ТЕРАГЕРЦОВОГО ДИАПАЗОНА

Т.В. Бондаренко, С.М. Полозов

Для генерации мощного электромагнитного излучения терагерцового диапазона частот может быть использована схема, в которой излучение генерируется коротким монохроматическим сгустком электронов, пролетающим по диэлектрическому или гофрированному капилляру. Короткий сгусток электронов может быть сгенерирован с использованием фотоинжектора. В работе описывается разработка модели ускоряющей системы фотоинжектора десятисантиметрового диапазона частот для такого источника и проводится анализ динамики пучка электронов в такой структуре. Целью работы является разработка оптимальной модели, обеспечивающей максимальную эффективность и большую величину ускоряющего поля при минимальной мощности питания. Для этого были рассмотрены варианты ускоряющей системы, основанной на круглом диафрагмированном волноводе (КДВ) различных конфигураций: 1,6 ячейки КДВ, 3 целых ячейки и 2 полуячейки КДВ. Для рассмотрения возможности увеличения электрической прочности системы и снижения требований к источнику ВЧ-питания, рассмотрены модели с 7 целыми ячейками и 2 полуячейками КДВ и модель резонатора бегущей волны с 7 целыми ячейками и 2 полуячейками. Представлены результаты анализа электродинамических характеристик резонансных моделей ускоряющих структур и структур с вводами мощности. Приведены результаты исследования динамики пучка электронов в структурах.

ПРИСКОРЮЮЧА СИСТЕМА ФОТОІНЖЕКТОРА ДЛЯ ГЕНЕРАТОРА ПОТУЖНОГО ВИПРОМІНЮВАННЯ ТЕРАГЕРЦОВОГО ДІАПАЗОНУ

Т.В. Бондаренко, С.М. Полозов

Для генерації потужного електромагнітного випромінювання терагерцового діапазону частот може бути використана схема, в якій випромінювання генерується коротким монохроматичним згустком електронів, які пролітають по діелектричному або гофрованому капіляру. Короткий згусток електронів може бути згенерований з використанням фотоінжектора. У роботі описується розробка моделі прискорюючої системи фотоінжектора десятисантиметрового діапазону частот для такого джерела і проводиться аналіз динаміки пучка електронів у такій структурі. Метою роботи є розробка оптимальної моделі, що забезпечує максимальну ефективність і велику величину прискорюючого поля при мінімальній потужності живлення. Для цього були розглянуті варіанти прискорюючої системи, заснованої на круглому діафрагмованому хвилеводі (КДХ) різних конфігурацій: 1,6 комірки КДХ, 3 цілих комірки та 2 напівкомірки КДХ. Для розгляду можливості збільшення електричної міцності системи і зниження вимог до джерела ВЧ-живлення, розглянуті моделі з 7 цілими комірками і 2 напівкомірками КДХ і модель резонатора біглої хвилі з 7 цілими комірками і 2 напівкомірками. Представлені результати аналізу електродинамічних характеристик резонансних моделей прискорюючих структур і структур з введеннями потужності. Наведено результати дослідження динаміки пучка електронів в структурах.