RF PHOTOGUN AND CHERENKOV DECELERATING SYSTEM FOR A HIGH POWER RADIATION SOURCE IN SUB-MM REGION

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Some results of RF photogun and Cherenkov decelerating system research and design are discussed. This R&D is providing to construct a high power pulse radiation source in sub-mm region. It is well known that the conducting capillary filled by dielectric skin can be used as a Cherenkov radiation generator. One needs very short (less than 1 mm) and high brightness electron bunch to provide the coherent radiation. The short bunch can be generated by means of a photogun. The electrons should be accelerated to the energy equal to 1…4 MeV in compact section and injected to the decelerating structure. This radiation source can be used for inspection systems or as a laboratory generator.

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1. INTRODUCTION

The problem of the introscopy is very actually at present. The detection of weapons, explosives, drags and fissionable materials is the main aim of introscopy. The introscopy of cargo transport is strongly difficult comparatively of the passenger's one. The gamma, electron or neutron facilities are used for introscopy at present including cargo introscopy. The compact electron or ion gun or accelerator is the base element of such facilities. It's necessary to have an electron linac (or two accelerators) which can derive the beam with energy variation in 3-5 times for cargo introscopy for example. This is no easily task. All of gamma, electron or neutron facilities have a number of great disadvantages as needs of the enviermental shielding and activation of the cargo.

New generation of introscopy facilities with low activation are under design now. The using of THz region radiation is one of possible methods. The radiation in sub-mm region is comletely safe as being not ionizing. But compact and effective sources in sub-mm region are absent in present. High radiation power can be generated using large accelerator (linear or synchrotron) and free electron laser (FEL) but such facilities are not compact. Traditional vacuum (as traveling wave tubes, carcinotrons. klinotrons, orotrons) and solid state (OLED, resonant tunnel diodes) generators not give power higher than 1 W.

Indeed the design of compact and effective generator is very actual aim. Such facilities can be used not only in introscopy system as well as in biology, medicine, chemistry, solid state physics, radio astronomy, homeland security, environment monitoring, spintronics, advanced spectroscopy, and plasma diagnostics [1].

2. GENERAL PRINCIPLE OF THZ RADIATION GENERATOR

The design of THz (or sub-mm) radiation source is one of possible needs of photo guns. The THz generator based on Cherenkov or Smith-Parcell was proposed early [1]. The short electron bunch with MeV energy and special decelerating system was discussed. The radiation in ps and sub-ps bands can be generated using this scheme.

The operating principle of proposed generator is based on using of the Cherenkov irradiator and undulator is not necessary here. Such generator was proposed by B.M. Bolotovskiy in 1961. The coherent Cherenkov radiation can be generated using short and well collimated electron bunches which must also have ps or sub-ps duration and 100…200 μm transverse size. Such bunch can be formed using a photo cathode and compact accelerating system providing high acceleration gradient. The laser system driving the photo gun proposed must generate short laser pulses or a series of pulses. The bunch (or bunch packet) should be accelerated to the MeV energy and injected into especial irradiating capillary channel in which electromagnetic radiation will induced. Two types of capillary channel could be used in the proposed generator. The conducting (metal) capillary coated inside by dielectric can be used. The slow-wave structure can be made as a corrugated channel or grating surface also.

The possibility of high brightness, high density bunch focusing to the sub-wavelength dimension (so called microbunch) is one of advantages of this operation principle.

The schematic layout of sub-mm pulse generator is shown in Fig.1. The main components of generator as photo cathode and laser system, accelerating system, MW power generator, capillary system will discussed in this paper. The beam dynamics in the photo gun and THz radiation generation will be studied also.

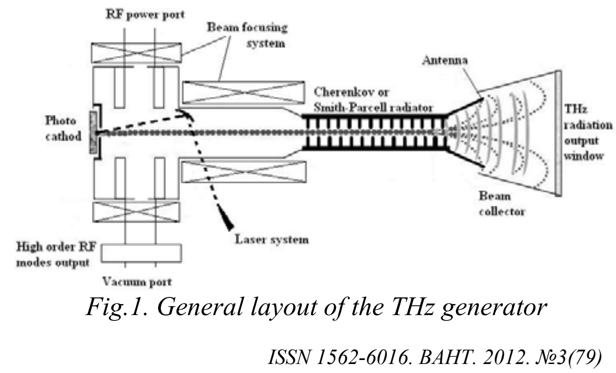

Fig.1. General layout of the THz generator

3. PHOTOCATHODE AND LASER SYSTEM

Photocathodes used in photoinjectors are commonly made from metal (as copper or magnesium). Metal photocathode is more useful because of easiness in manufacturing and mounting in cell and long lifetime.

The Me cathodes above work in UV-band of light source so the laser system must to provide UV-band 0.1…1 ps duration pulses. To achieve the desired electron energy on the exit of photocathode, pulses must also have energy of about 0.1…10 mJ. Most fitting laser systems are based on mode locked Ti:Sapphire, Ar or Nd:YLF lasers. These lasers can provide laser pulses in 710…920 nm range. The β-barium borate frequency doubler is used to shift laser operating frequency to UV-range. The pumping system is mostly based on Ar laser.

4. ACCELERATING STRUCTURE

The accelerating structures consisting of 1.6 cell of disk-loaded waveguide (DLW) (Fig.2), 3 cells and 2 half-cells of DLW, 7 cells and 2 half-cells of DLW and accelerating structure based on traveling wave resonator (TWR) based on 7 cells and 2 half-cells of DLW (Fig.3) have been considered for short electron bunch acceleration and its electrodynamics characteristics compared. The results of the study are discussed in [2] in detail. Let us represent the accelerating structures construction and main study results briefly.

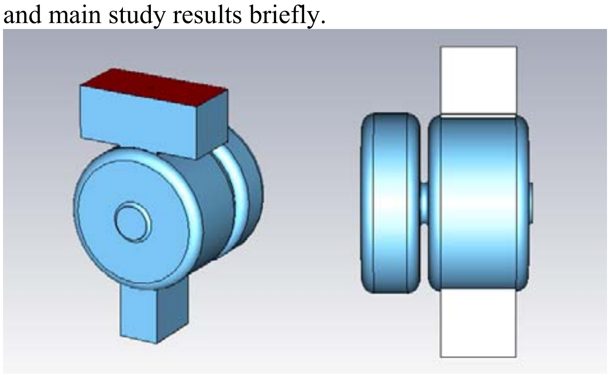

Fig.2. General view of 1.6 cell accelerating system

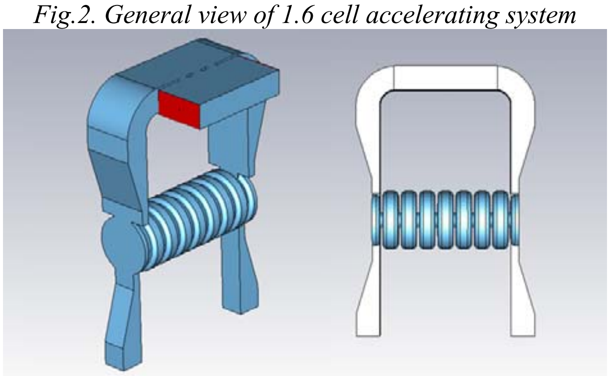

Fig.3. General view of TWR based on 7 cells and 2 half-cells accelerating system

Most widely used normal conducting accelerators are based on 1.6 cells DLW. It is operate in standing wave mode. Electromagnetic characteristics comparison of 1.6 cell structure and traveling wave structures was done to investigate the possibility of development more effective structures with lower possibility of electrical breakdown.

All accelerating structures were designed using similar construction and parameters. Structures were computed for 2856 MHz RF operating frequency. Mode with $\mu = \pi / 2$ phase shift per cell is the operating mode of 3 cells and 2 half cells, 7 full cell and 2 half cell and TWR structures because this structures are operating in traveling wave mode. The 1.6 cell structure operates in standing wave regime and $\mu = \pi$ was chosen as an operating mode. All structures are characterized with positive normal dispersion.

Resonant frequency of the structure was set 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 (up to 100 MV/m) in structures. Photocathode will be arranged in half-cell's sidewall, therefore accelerating field on the cathode endwall surface must be as high as possible. The ratio of iris window to the wavelength is set to 0.1. This value is a trade-off between the wish to get maximum amplitude of accelerating field and to exclude probable beam loss on the iris. Performance of the structures was also increased by rounding of shells edges. The rounding radius value was chosen to provide the highest possible shunt impedance and Q-factor.

Structure's power input was organized using standard S-band waveguide with 72×34 mm cross-section was attached to the structures through the coupling diaphragm. 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]. Waveguide's cross-section matches sizes of coupling diaphragm. Full cell with RF port and output of high order modes forms the wave converter for 1.6 cell structure. The wave converters are formed by half cells with attached RF ports and outputs of higher type's waves for all traveling wave structures. The wave converter is designed to minimize reflections.

RF ports are jointed with the rectangular waveguide and the power is fed to the resonator through the directional coupler in the TWR. If the electrical path length of the structure equals to the full number of wavelengths then the magnitude of the wave inside the ring is maximum and magnitude of the wave that is coming to the coupled load is minimal. The MW generator must work on the matched load all the time. The optimal operation regime of the structure is critical mode. In this regime part of RF power is fed into the accelerating system through the directional coupler and fills in the power resistance losses in the resonators sidewalls. If the structures reflecting coefficient is insignificant, the TWR electrical field magnitude is many times more than the magnitude of feeding wave.

The results of electrodynamics characteristics study of all three designed structures are shown in Table 1.

Table 1
Main characteristics of the accelerating system 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
Accelerating field on axis E_0, 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	23.3	27.2	27.2

5. BEAM DYNAMICS SIMULATION IN ACCELERATING STRUCTURES

Beam dynamics simulation in designed accelerating structures was done using BEAMDULAC-BL code designed in laboratory DINUS of NRNU MEPhI [4]. The simulation was done with the following beam parameters: injection energy $W_{inj} = 10$ keV, output energy 1 MeV, beam pulse current $I = 5$ A, beam pulse charge $Q = 0.1$ nC, beam initial radius $r = 200$ μm. This beam parameter's values are similar as most of photoinjectors. The main aim of investigation was to achieve the value of acceleration field magnitude that will provide acceleration of electron beam to 1 MeV [2], minimal energy required by high intensity sub-mm radiation source.

Beam dynamics investigation results shows that 1.6 cell DLW structure can provide electron beam acceleration to the energy 1 MeV with $P = 1.5$ MW of RF power fed to the system. This result is in the good agreement with experimental data. Accelerating structure based on 3 full cells and 2 half cells provide 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. Consideration of TWR accelerating system shows best results in accelerating electron beam to 1 MeV – with 500 kW of RF power fed into the structure.

The beam size preservation and focusing can be realized in accelerator using longitudinal magnet field. It should be reminded that sub-mm beam dimensins are necessary for Cherenkov THz generator.

Table 2
Results of beam dynamics simulation in designed models

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_0, MV/m	10.4	9.1	6.5	6.9
P, MW	1.5	20.0	4.0	0.5

6. RF GENERATOR

As it is clear from Table 2, 0.5 MW of RF power is necessary to realize 1 MeV energy gain for TWR structure and 1.5 MW for 1.6 cell standing wave photo gun. Klystrons or magnetrons produced by Federal state unitary enterprise Research & Production Corporation "Toriy" are available for this aim. The pulse magnetron MI-475 has the following characteristics: RF pulse power up to 2 MW, average power 2.5 kW, pulse duration 4 μs. This is sufficient for TWR designed. The klystron as KIU-168 can be used if the higher power is necessary: RF pulse power up to 6 MW, average power 6 kW, pulse duration 7 μs.

7. THZ RADIATION GENERATION

Two types of channels could be used to generate the radiation: the conducting (metal) capillary coated by dielectric inside (Fig.4,a) and the corrugated channel or grating surface also (Fig.4,b). The inner channel radius $d/2$ should be comparable to the wavelength, i.e. can be smaller than 1 mm. The structure period t (the distance between of diaphragms) in the second case should also be comparable to the wavelength.

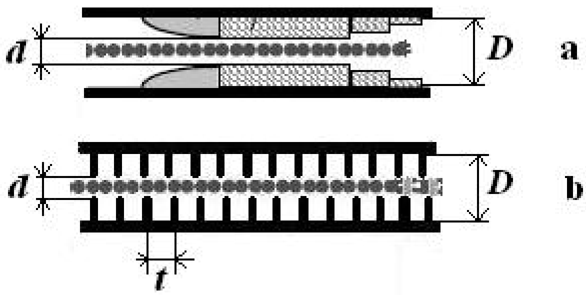

Fig.4. The conducting (metal) capillary coated inside by dielectric (a) and the corrugated channel or grating surface (b)

Presence of the channel inside dielectric in which the radiating particle moves, leads to suppression of the radiation on high frequencies. It is suppose to use a dielectric tube in practically interesting cases as a radiator. The intensity of generated radiation can be significantly increased if a high current modulated electron beam consisting of short bunches with the period of longitudinal modulation less or of the order of the radiated wave length is used. If the dielectric tube is located in a metal tube (waveguide) radiation will be limited by volume of this tube. And, as consequence, width of lines on which radiation is raised, will considerably decrease and a maximum wavelength λ_m will be limited by the critical value λ_{cr} ($\lambda_m \le \lambda_{cr}$). So the Cherenkov radiation is considered to be one of the more effective ways for THz radiation generation [1].

The other mechanism to produce THz radiation is Smith-Purcell effect. Smith-Purcell radiation arises when charged particles move near a grating or any periodical structure. The total losses for Smith-Purcell radiation might be estimated as

$$W \approx \alpha\hbar\omega_c N , \quad (1)$$

where N – number of diffraction grating elements; α – the fine structure constant ($\alpha \approx 1/137$); $\hbar$ – Planck's constant and

$$\omega_c \approx \frac{c\beta\gamma}{h} \quad (2)$$

is the cut-off frequency.

CONCLUSIONS

The scheme of high power radiation generator in sub-mm region was proposed. This radiation source is based on RF photogun and Cherenkov or Smith-Parcell decelerating system. Some results of generator components (RF photo gun and accelerating system, laser, RF power supply system) design and beam dynamics simulation were discussed.

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СВЧ-ФОТОКАТОД И ЧЕРЕНКОВСКАЯ ЗАМЕДЛЯЮЩАЯ СИСТЕМА ДЛЯ МОЩНОГО ГЕНЕРАТОРА ИЗЛУЧЕНИЯ СУБМИЛЛИМЕТРОВОГО ДИАПАЗОНА

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Рассмотрены некоторые результаты исследования и разработки СВЧ-фотокатода и черенковской замедляющей системы, предназначенных для генерации мощных импульсов излучения субмиллиметрового диапазона. Как известно, проводящий капилляр, покрытый изнутри слоем диэлектрика, может быть использован в качестве источника черенковского излучения. Для получения монохроматического излучения необходимо иметь очень короткий (меньше 1 мм) сгусток электронов, который может быть получен при использовании фотокатода. Электроны должны быть ускорены в короткой системе до энергии 1…4 МэВ и инжектированы в замедляющую систему. Такой источник излучения может быть использован в досмотровой системе или в качестве лабораторного генератора.

НВЧ-ФОТОКАТОД І ЧЕРЕНКІВСЬКА УПОВІЛЬНЮЮЧА СИСТЕМА ДЛЯ ПОТУЖНОГО ГЕНЕРАТОРА ВИПРОМІНЮВАННЯ СУБМІЛІМЕТРОВОГО ДІАПАЗОНУ

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Розглянуто деякі результати дослідження та розробки НВЧ-фотокатода і черенківської уповільнюючої системи, призначених для генерації потужних імпульсів випромінювання субміліметрового діапазону. Як відомо, проводячий капіляр, покритий зсередини шаром діелектрика, може бути використаний як джерело черенківського випромінювання. Для отримання монохроматичного випромінювання необхідно мати дуже короткий (менше 1 мм) згусток електронів, який може бути отриманий при використанні фотокатода. Електрони мають бути прискорені в короткій системі до енергії 1…4 МеВ і інжектовані в уповільнюючу систему. Таке джерело випромінювання може бути використано в оглядовій системі або в якості лабораторного генератора.