

RF PHOTOINJECTOR AND RADIATING STRUCTURE FOR HIGH-POWER THz RADIATION SOURCE

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Abstract

Sources of high-power electromagnetic radiation in THz band are becoming promising as a new method of a low activation introscopy. Research and development of accelerating RF photoinjector and radiating system for THz radiation source are reported. The photoinjector is based on disk loaded waveguide (DLW). Two different designs of accelerating structure were modelled: widespread 1.6 cell of DLW structure and travelling wave resonator structure (TWR). The resonant models of these structures and the structures with power ports were designed. Electrodynamics characteristics and electric field distribution for all models were acquired. Results of picoseconds photoelectron beam dynamics in simulated structures are reported. Designs of decelerating structures exciting Cherenkov radiation are based on corrugated metal channel or metal channel coated with dielectric. Analysis of radiation intensity and frequency band are presented.

INTRODUCTION

THz radiation is nowadays becoming promising in solving such vital problems as national security, biomedicine and in manufacturing processes control. In national security issue THz radiation can be used in introscopy systems. The definition of the weapons, explosives, drugs and fissionable materials is the main aim of introscopy. The introscopy of cargo transport is much more complicated objective than passenger introscopy issue. The gamma, electron or neutron facilities are used in introscopy system including cargo introscopy at present. The compact electron or ion gun or accelerator is the basic element of such facilities. The main difficulty is the fact that it is necessary to use an electron linear accelerator (LINAC) which can derive the beam with 3-5 times energy variation. LINACs of this type are utterly complex facilities. All of gamma, electron or neutron facilities have a number of disadvantages as needs of environmental shielding and cargo activation.

High-power THz radiation source based on photoinjector and decelerating capillary channel is now one of the most discussable compact facilities providing monochromatic THz radiation of power high enough to be used for cargo introscopy [1].

Facility is based on two main parts: accelerating structure and decelerating radiating channel. Capillary is placed right after the accelerating structures and is made of copper with either dielectric coated inner surface or corrugated surface.

ACCELERATING STRUCTURES

1.6 cell DLW structure

Accelerating structure consists of two accelerators connected sequentially: 1.6 cell DLW and 9 cell TWR structure. First part of facility accelerating system is 1.6 cell standing wave accelerating structure (figure 1). This accelerating structure by itself comes artlessly as a photoinjector part of the accelerating system.

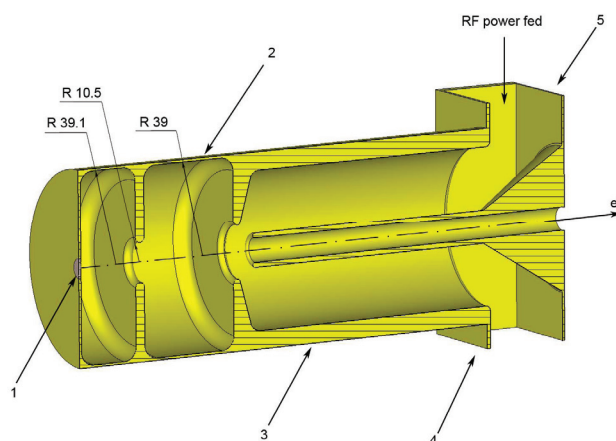


Figure 1. 1.6 accelerating structure: 1 – photocathode, 2 – resonator, 3 – coaxial wave type transformer, 4 – vacuum port, 5 – power input.

This accelerating structure operates on π mode and S-band frequency 2856 MHz ($\lambda=105$ mm). 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. First cell length is 0.6 of full-sized cell to obtain maximum field amplitude in the center of the photocathode arranged in the cell's sidewall. 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 RF power input is organized by S-band standard rectangular waveguide with the coaxial coupler. RF power is fed into the structure through only one of the connected waveguides; another is used for structure field symmetry and will be applied for vacuum and other accompanying connections. This scheme provides high level of field symmetry in the system that leads to better quality of the accelerated beam.

This type of wave transformer differs from recently used RF power inputs in photoinjectors like ones in BNL Guns [2]. That type was exploiting the scheme of power

input through the coupling diaphragm directly into the full-sized cell of the structure in this wise fill cell was a wave transformer.

TWR structure

Travelling wave resonator is a type of ordinary linear accelerator structure with some additions. Basically the accelerating wave propagating in acceleration structure is travelling wave type but the trait that makes this system a resonator is energy recuperation coming out of interlocking RF power input with output and feeding power with directional coupler (figure 2). If the length of the TWR circuit is devisable to the generator wavelength, 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 [3].

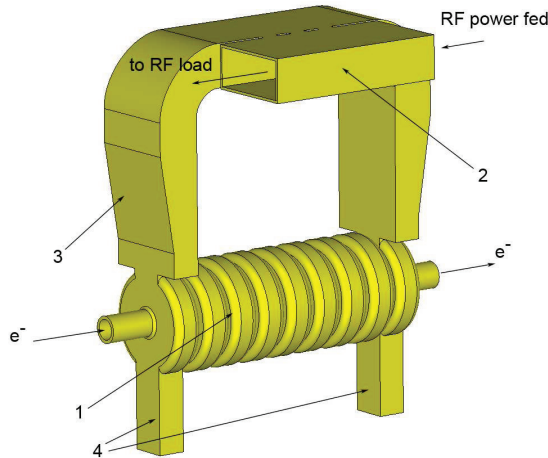


Figure 2. Travelling wave resonator structure: 1 – accelerating structure, 2 – directional coupler, 3 – TWR ring, 4 – vacuum ports.

TWR is based on 9 cell travelling wave S-band structure with $\pi/2$ operating mode. 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. In this case the part of power that is not branched into the TWR ring is summed with the one from generator in the opposite phase and gives the minimal magnitude signal coming to the load. Two main parameters determining efficiency of TWR are the circuit power attenuation factor and the directivity factor of the directional coupler.

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. Directional coupler computation included receiving of required transfer coefficient in the forward direction of jointed waveguide C and simultaneously keeping transfer coefficient in the opposite direction of jointed waveguide $|\Gamma|$ below the certain level.

Three coupling window model was applied to provide high directivity level of directional coupler. Enlarging the number of coupling windows doesn't improve the directivity coefficient.

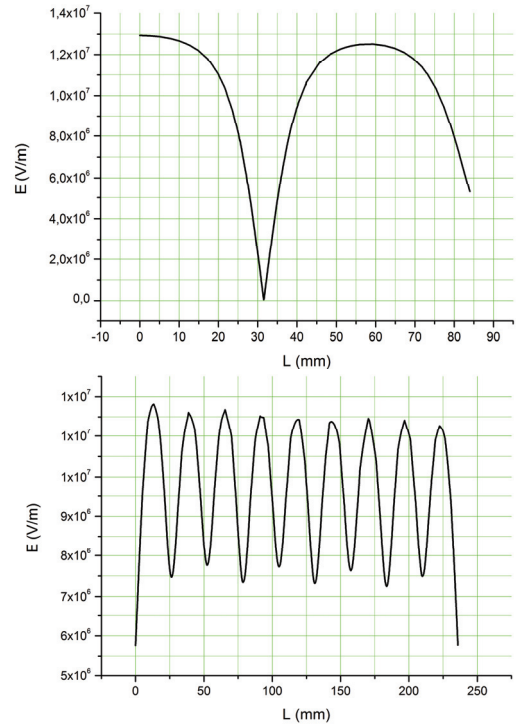


Figure 3. Electrical field magnitude plots at 1 MW power fed for 1.6 cell structure (upper) and for TWR structure (lower)

Taking into account part of the signal branching in the opposite direction and intensity attenuation factor, expression for the magnitude of electrical field spreading in TWR storage ring for critical mode can be written as:

$$A_{TWR} = \pm j \frac{1}{\sqrt{1 - e^{-2\alpha_r}}} \frac{C - |\Gamma|}{C} A_{input}, \quad (1)$$

here A_{TWR} - TWR circuit electrical field intensity magnitude, α_r - TWR ring signal intensity attenuation factor, A_{input} - RF generator signal intensity magnitude.

In considered case transition coefficient of directional coupler $C=3.9\%$ that equals to TWR ring decay coefficient at the 14 mm coupling window width, sidewall width between waveguides is 4 mm. Sidewalls width doesn't have much impact on directivity coefficient but ought to be wide enough to provide coupler ruggedness. Transfer coefficient in the opposite direction of TWR ring equals $\Gamma=-48\text{dB}$. Thus directivity coefficient of directional coupler is $D=23\text{dB}$. Using the formula (1) power in TWR multiplies 9 times vs. input power level.

BEAM DYNAMICS

Beam dynamics simulation in designed accelerating structures was done using BEAMDULAC-BL code

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designed in laboratory DINUS of NRNU MEPhI [4]. The simulation was done with the following beam parameters: injection energy $W_{inj}=5$ eV, feeding RF power $P=2.5$ MW, beam pulse current $I=5$ A, beam pulse charge $Q=1$ nC. Photoelectron beam initial radius is $r=200$ μm that corresponds to the laser spot of the same size focused on the cathode surface. This beam parameters values are similar to most of photoinjectors. The first accelerating section is fed by 1.5 MW and the second by 1 MW power.

The results of photoinjector beam dynamics investigation shows that at this value of RF power fed beam bunch can be accelerated to the energy of 1 MeV. The further acceleration of the beam in TWR section resulted in 5 MeV beam energy that meet the requirements for the beam in THz generation process.

Pencil-shaped and high brightness beam is necessary for Cherenkov THz generator to achieve that beam size preservation can be realized in accelerator using longitudinal magnet field focusing.

CHAPILLARY CHANNEL

Two types of channels could be used for generation of Cherenkov radiation: the conducting (metal) capillary coated by dielectric inside (see Fig. 4a) and the corrugated channel or grating surface also (Fig. 4b). The inner channel radius $d/2$ should be comparable to the wavelength, i.e. should be about 0.1 – 1 mm. The structure period t (the distance between of diaphragms) in the second case should also be comparable to the wavelength.

The main idea of using the capillary channel as a source for radiation lies in a principle of Cherenkov radiation. The phase velocity of the wave propagating inside the capillary channel is less than the electron beam velocity. So the beam propagating in such structure would induce the radiation with the frequency dependent on the channel dimensions.

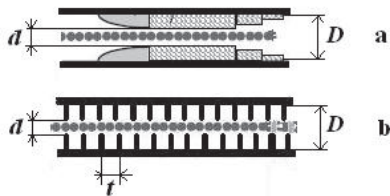


Figure 4. The conducting (metal) capillary coated inside by dielectric (a) and the corrugated channel or grating surface (b).

Different approaches can be estimated for achieving the induced power in the accelerated structures. One of the ideas is based on using the form-factor concept [5]. The decelerating structure parameters such as shunt impedance, Q-factor and group velocity are numerically investigated in terms of TM₀₁ wave excited inside of the capillary. Then radiated power can be founded using the formula for the case of short burst mode when pulse repetition time is much longer than the beam length:

$$P = \frac{\omega}{4} \frac{r}{Q} \left| v_{group} \right| \cdot \left| \frac{q\Phi}{1 - \beta_{group} / \beta} \right|^2, \quad (2)$$

where ω - radiation resonant frequency, r - channel shunt impedance, Q - channel quality factor, q - bunch charge Φ - bunch form-factor, v_{group}, β_{group} - absolute and relative group velocity of the channel. For considered capillary channels Q is about 2000, β_{group} - 0.8 and r is around $3 \cdot 10^4$.

Another concept was discussed by Bolotovskiy [6]. In this concept beam energy loss for the Cherenkov radiation is described by the force acting on the moving charge by the induced fields. Electron beam is presented as a point charge because beam sizes are smaller than induced radiation wavelength. The corrugated channel in this concept is presented as a small disk loaded. This method doesn't take in the account beam form factor.

Both cases show alike results for power radiated by the beam propagating in the channels. The goal was to achieve the radiation with 1 THz frequency. Channel length for both designs was 2 cm. Dielectric channel dimensions are: 300 μm channel radius and 30 μm teflon thickness. In case of corrugated channel transverse sizes appears to be smaller: 100 μm cell radius, 80 μm diaphragm radius. For the stated above beam parameters the radiated power appears to be around 50 kW in the case of dielectric coated channel and 20 kW in case of corrugated channel in case of 1 nC beam charge and 5 MeV beam energy.

CONCLUSION

RF photoinjector and decelerating system were investigated for high-power THz generator. RF photoinjector is based on two accelerating sections: 1.6 cell standing wave structure with coaxial power input and travelling wave section based on travelling wave resonator. Both are fed by S-band 2.5 MW magnetron. First is used to emit photoelectrons and to accelerate bunch to 1 MeV. Second is used for further acceleration to 5 MeV.

Decelerating channel can be based on two main concepts: corrugated metal channel and dielectric covered channel. Both are applicable for achieving high radiation power rates.

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