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Development of photoinjector in IAP RAS

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Abstract. A photoinjector electron accelerator is being developed at the Institute of Applied Physics of the Russian Academy of Sciences, in which it is planned to implement sequential acceleration of particles up to energies of about 20 MeV. The first section of the complex, designed for an output particle energy of 3.5 MeV, can be used for experimental study of promising regimes of terahertz radiation from short electron bunches. After additional acceleration in the second section, bunches with small transverse emittance and velocity spread can be injected into a plasma accelerator cell to further increase their average energy to the GeV level and to use them as an active medium in an X-ray FEL. In addition, work is underway to study photocathodes based on diamond films.

Keywords: photoinjector, electron accelerator, photocathode, undulator radiation.

1. Introduction

Photoinjector accelerators [1, 2] make it possible to obtain dense cold electron bunches of picosecond duration with an average particle energy of several MeV and a characteristic charge from fractions of a nanocoulomb to tens of nanocoulombs. Such bunches can be used, for example, to generate high-power short terahertz pulses of undulator or cyclotron radiation [3–8], in experiments on Compton scattering of laser pulses [9], and also for injection into more energetic accelerators. A photoinjection complex [10] is being created at the IAP RAS, in which stepwise acceleration of electrons up to energies of the order of 20 MeV should be implemented while maintaining the normalized transverse bunch emittance at a level of 1 mm×mrad. This report describes the current work on the creation of accelerating and focusing systems of the accelerator, as well as on the study of new types of photocathodes based on diamond films.

2. First stage of acceleration

The first section of the accelerator is a classical version of a photoinjector with a 1.5-cell accelerating structure operating in the lowest symmetric TM-type π-mode. Photoemission of an electron bunch with a charge of up to 100 pC and a duration of about 10 ps from a copper cathode is to be provided by an ultraviolet laser pulse with a wavelength of about 260 nm. According to calculations, powering the resonator from a 5 MW klystron at a frequency of 2.45 GHz guarantees an accelerating field amplitude at the cathode of about 70 MV/m and acceleration of particles to an average energy of ~3.6 MeV. The basis of the electron optics of the photoinjector is a system of the main solenoid with a field of about 0.25 T and the bucking coil providing a zero magnetic field on the surface of the photocathode. This system is designed to ensure the compensation of the emittance growth associated with the space charge [2] and focusing of the electron beam over a length of about 1 m (Fig.1).

Also, for the experimental study of the previously proposed different regimes of undulator and cyclotron radiation [3–8], the electron-optical system should make it possible to introduce electron bunches into the region of a relatively strong axial magnetic field. In particular, to implement the negative mass regime [4–6], it is required to put the electrons on stationary trajectories (i.e., without significant excitation of cyclotron oscillations) in a combination of undulator and near-resonant guiding magnetic fields. It was shown [11] that such a problem can be solved with sufficient efficiency first by injecting particles into a longitudinal magnetic field along its converging field lines, and then by pumping forced oscillations in a smoothly increasing field of a helical undulator. Changing the tilt angle of the electron trajectories to match them with the field lines of the guiding field is provided using a lens in the form of a short magnetic coil with a maximum field of 0.4 T, located in the region of the focal waist of the electron beam at a distance of about 70 cm from the accelerating section (Fig.2). This approach makes it possible to use a magnetic field with a sufficiently sharp input and, accordingly, a solenoid with a sufficiently small radius of about 2 cm, which increases its energy efficiency. According to calculations, at a field strength of 5–8 T, the bunch radius inside the solenoid and the range of transverse oscillations in the undulator do not exceed 0.1 mm and 1 mm, respectively, which also makes it possible to use an energy-efficient small-radius undulator.

At present, all components of the first stage accelerating system have been manufactured and tested at a low power level. At the moment, work is underway to manufacture magnetic systems and assemble the accelerator.

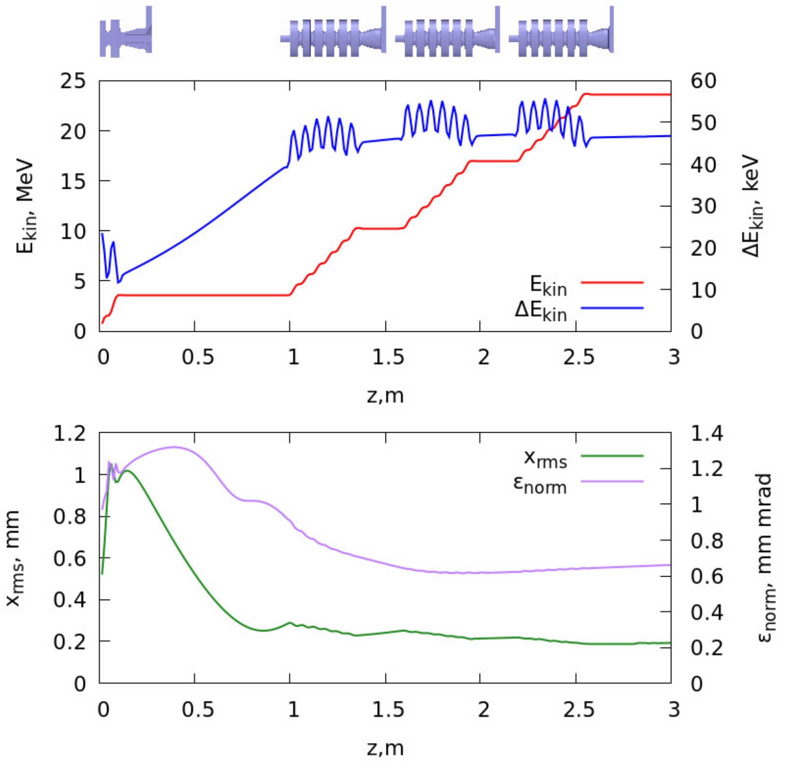

Fig.1. Evolution of electron bunch parameters during acceleration. The accelerating structure of the first stage occupies a space from 0 to 25 cm, the accelerating structures of the second stage – from 90 to 270 cm. The average particle energy (red), energy spread (blue), transverse size of the bunch (green) and transverse normalized emittance (violet) are shown.

3. Second stage of acceleration

To implement an additional increase in the average particle energy to a value of about 20 MeV, a system of accelerating sections and focusing solenoids was designed. Each accelerating section is a sequence of 6 coupled resonators powered by a microwave source at a frequency of 2.45 GHz (Fig.3). This frequency coincides with the operating frequency of the first stage of the photoinjector, which makes it possible to synchronize all the final microwave amplifiers in both stages, feeding them through controlled phase shifters from one stable low-power source of a continuous microwave signal. The working TM mode of the accelerating structure is the π-mode with antiphase field oscillations in neighboring cells. With a power of the power signal of 5 MW, the amplitude of the accelerating field in the resonators is about 35 MV/m (the time-average acceleration gradient is about 17 MeV/m), which, according to calculations, provides an increase in the energy of relativistic particles of about 6.5 MeV over a length of one section of about 40 cm. The sequential arrangement of three such sections makes it possible to achieve acceleration of a 3.5-MeV photoinjector electron bunch to an average energy of more than 20 MeV. In this case, the violation of the phase matching between the accelerated particles and the accelerating field, which occurs due to a small difference in the speed of the bunch from the speed of light, is compensated by optimizing the phase of the accelerating field between adjacent successive sections. Modeling shows that the increase in the root-mean-square energy spread in energies during the acceleration time in the second cascade for a bunch with a charge of 100 pC does not exceed 0.07% of the final particle energy, and the total energy spread, taking into account that acquired in the first cascade, is about 0.2%. In the future, it is planned to investigate the possibility of reducing these values by optimizing the system parameters.

The beginning of the first accelerating section of the second stage is located near the focal beam waist (Fig.1). To stabilize the transverse characteristics of the bunch, magnetic focusing systems in the form of solenoids surrounding each accelerating section are designed. With a magnetic field in them of about 0.1 T, they ensure that the value of the transverse normalized beam emittance is kept within 0.7 mm mrad and the transverse diameter is within 1 mm (the initial bunch diameter determined by the size of the laser spot on the cathode).

Despite the achievement of the declared characteristics of the electron beam in the calculations, before starting to fabricate the elements of the second stage, it is planned to perform a number of additional studies to optimize the accelerator scheme.

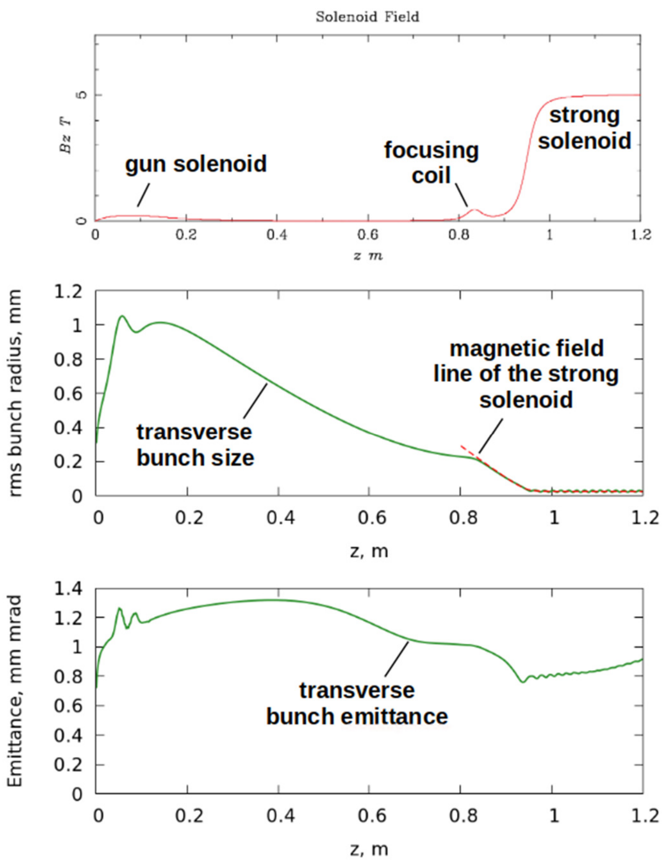

Fig.2. Calculation of the dynamics of an electron bunch in the electron-optical system of a photoinjector with injection into a strong magnetic field of 5 T. The dependence of the magnetic field on the axial coordinate, the evolution of the transverse size of the bunch and the normalized transverse emittance are shown.

4. Testing of diamond photocathodes

In parallel with the design of the accelerator, photocathodes based on CVD diamond films are being studied. Such cathodes can combine high quantum efficiency and insensitivity to vacuum quality [12, 13]. The studies are carried out using a specially designed vacuum chamber, which makes it possible to register the electric charge emitted from the cathode surface under the action of laser radiation.

Nanocrystalline diamond films were deposited in a CVD plasma microwave reactor on n-type silicon substrates 20×20×0.5 mm^3 in size. The thickness of the deposited film was about 0.5 μm. The films were grown in a mixture of hydrogen and methane, to which a gas containing a dopant, phosphine PH_3, was added in a small amount. Several samples of photocathodes were grown, the growth conditions of which differed in the content of methane, phosphine in the gas mixture, and the substrate temperature. As a result, the diamond films had different ratios of the diamond and non-diamond phases and phosphorus content. The quantum efficiency of the investigated cathodes for the laser wavelength of 266 nm varied in the range $(4–9)\times10^{-6}$, which is almost an order of magnitude higher than the measured values of the quantum efficiency of the copper photocathode. It is important that the samples were not subjected to any special treatment before being placed in a vacuum, which indicates the low sensitivity of such photocathodes to environmental conditions. Currently, work on the study of diamond photocathodes continues.

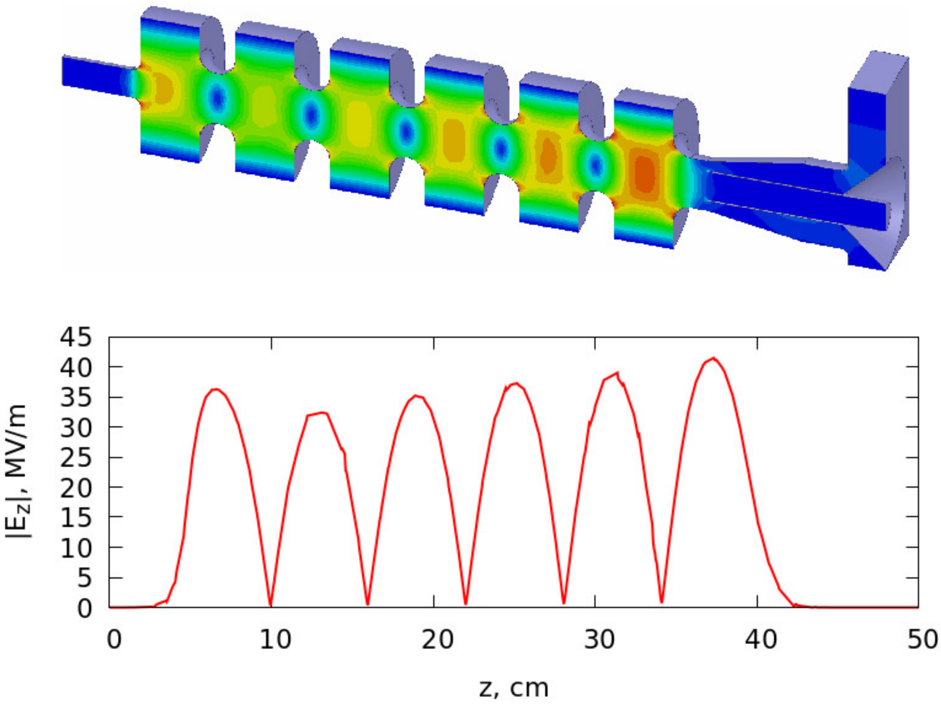

Fig.3. The accelerating structure of the second stage and the corresponding distribution of the accelerating electric field inside the cells.

5. Conclusion

The realization of the electron accelerator with the photoinjector gun is currently under the progress in the IAP RAS. The use of several accelerating sections should provide the output particle energy of up to 20 MeV. The electron-optical systems ensuring high beam quality and possibility for injecting the electron bunches into magnetic systems of prospective THz oscillators have been developed. New variants of photocathodes based on CVD diamond films are under investigation.

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6. References

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