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A 2.45 GHz PHOTOINJECTOR GUN FOR AN FEL DRIVEN BY LASER WAKEFIELD ACCELERATED BEAM*

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Abstract

The photoinjector of short electron bunches is a key element of investigations aimed on particle acceleration by pulses of the subpetawatt laser PEARL (10 J, 50-70 fs)[1]. Projected parameters of the photoinjector are the following: an electron energy of 5 MeV, charge >0.1 nC, bunch length of about 3 mm, transverse emittance no worse than 1 mm×mrad, and an energy spread no more than ~0.1%. The photoinjector is based on a 2.45-GHz klystron (model KIU-111 built by Toriy), with output power ~5 MW, pulse length ~7 μs, efficiency ~44%, power gain ~50 dB. This klystron will feed a standard 1.5-cell gun resonator with removable photocathode. The gun will be driven by a third harmonic of a Ti:Sa laser with 100-uJ energy in a picosecond pulse. The photocathode will be made of CVD diamond film which has high QE, long lifetime and is robust with respect to the vacuum conditions.

RF GUN DESIGN

The gun has classical design based on bunch acceleration in 1.5-cell cavity fed by a KIU-111 klystron, built by Toriy, operating at 2.45 GHz [2-3]. The klystron radiation is synchronized with laser system based on third harmonics of Ti:Sa laser.

Klystron

The klystron, shown in Fig. 1, generates output power up to 5 MW over a pulse duration of 7 μs. It provides 10-40% efficiency and 50 dB power gain at a frequency band of 10 MHz. Its repetition rate can reach 1 kHz. In our RF gun the repetition rate is planned to be as high as only 10 Hz. The klystron requires a 55-kV power supply supporting 250 A of current. In order to deliver the necessary 100-200 W of input RF power to klystron, we are going to use a so-called preamplifier which has been already produced.

Laser

We carried out experiments to generate 10-ps, 0.1-μJ laser pulses (at third harmonics of 1030 nm wavelength) with cylindrical and 3D ellipsoidal distributions of the intensity [4]. The system setup is shown in Fig. 2. Two methods were exploited. In both methods, the fact was used that for pulses with essential linear frequency modulation the spectra distribution follows for intensity distribution in time, and that control for spectrum shape corresponds to the control of the intensity distribution. The first method is based on using of pulse compressor with zero frequency dispersion and a programmed mirror SLM (Spatial Light Modulator). This method allowed to generate quasi-ellipsoidal laser pulses with 90° axial symmetry. The second method is based on a use on SLM matrix and the profiled volume Bragg grating. The Bragg grating was written inside ellipsoidal volume and is absent outside it at all. By means of SLM laser pulses were formed with cylindrical intensity distribution in a space and were guided to the Bragg grating. The reflected radiation also had the ellipsoidal intensity distribution in a space.

We have performed a project of an original system for synchronization of the klystron KIU-111 with the laser.

Figure 1: The klystron KIU-111.

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Figure 2: Laser system.

1.5-Cell Cavity

The accelerating cavity has axisymmetric coaxial coupler which excites the TM_{01} (π-type) mode at 2.450 GHz, shown in Fig. 3. The Q-factor in copper cavity at room temperature is more than 1.4×10^4. The klystron, producing 5 MW of RF power, allows obtaining maximum cathode field of approximately 70 MV/m. Field distribution of the operating mode is shown in Fig. 4. This mode is separated of the so-called 0-mode by 150 MHz. The coupling factor of the operating mode is close to 1.

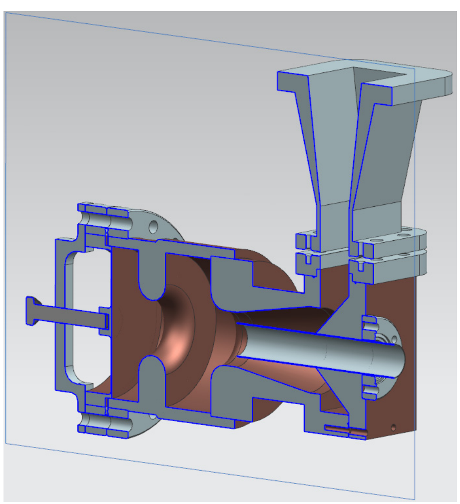

Figure 3: 1.5-cell RF cavity.

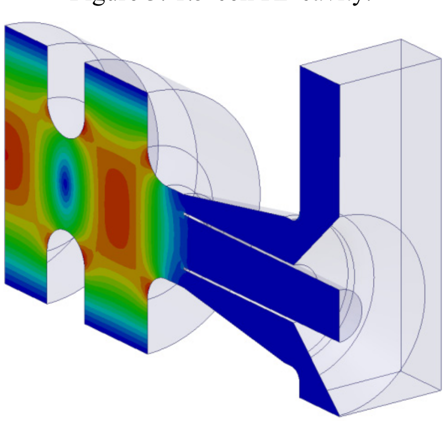

Figure 4: Field distribution in the cavity.

In Fig. 5, the reflection by the cavity is plotted. One can see that at resonant frequency (2.45 GHz) the reflection is less than -20 dB.

Transmission Line

Transmission line from the klystron to RF resonator is based on 90×45 mm^2 rectangular cross-section waveguide. It includes ferrite isolator, in order to isolate the klystron from reflection, directional couplers, and an additional window made of quartz.

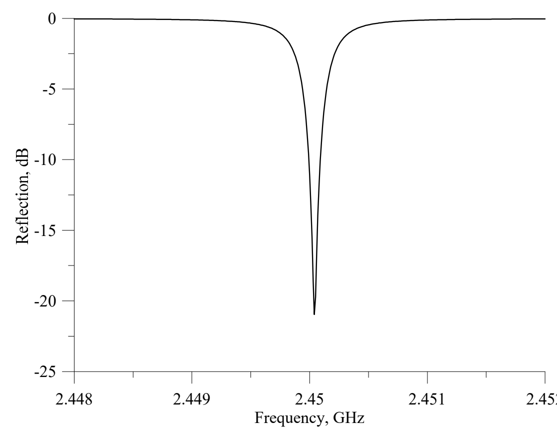

Figure 5: Reflection by the cavity.

Diamond Photocathode

Diamond photocathodes are able to provide high quantum efficiency (~10^{-3}) as well as a low sensitivity to contaminations and vacuum quality [5]. We carried out a precipitation of the nano-crystal diamond films on a surface of the molybdenum cathodes of different shapes (cylindrical and plane) by means of precipitation from gas phase (CVD). For the precipitation, the modernized plasma-chemical reactors on a base of CW gyrotron at frequency 30 GHz with power up to 12 kW and a reactor based on 2.45 GHz magnetron of 3 kW power were used. It was found out that morphology and film structure crucially depend on a particular precipitation regime that can be influent on emission cathode properties.

BEAM SIMULATIONS

Bunch dynamics was simulated using particle in cell method. Typically, total number of particles exceeded 500. A motion of each particle in given RF fields was calculated by means of relativistic equations with Coulomb fields of particles itself taken into account.

Results of calculations are illustrated by Figs. 6-8. In Fig. 6, one can see energy of the particles in dependence on distance from cathode. Because power of the klystron is limited by 5 MW, particle's energy gain does not exceed 4 MeV. The length of the first cell was chosen so that bunch arrives to the first iris at near to zero electric field. In these simulations, we assumed Gaussian laser wavebeam shape along all coordinates.

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We carried out calculations of the main solenoid as well as backing coil, which compensates the field at cathode, both operating in CW regime with DC water cooling. Magnetic field amplitude and distribution of the magnetic field of the solenoid along longitudinal coordinate were optimized in order to get minimum of transverse beam emittance. The result of the mentioned optimization is that we can reach 1.4 mm×mrad transverse emittance in accordance with the plot shown in Fig. 7, where the emittance is plotted in dependence on time elapsed since bunch injection. In Fig. 6, time t = 0.5 ns corresponds to time when the bunch has already left the second cell.

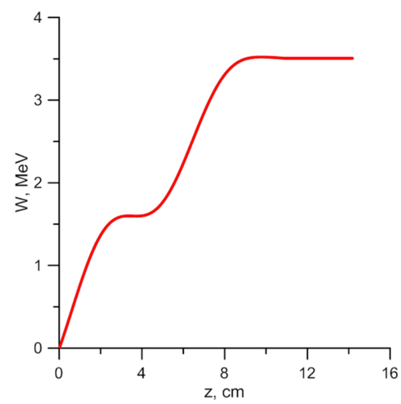

Figure 6: Energy of particles vs. distance from cathode.

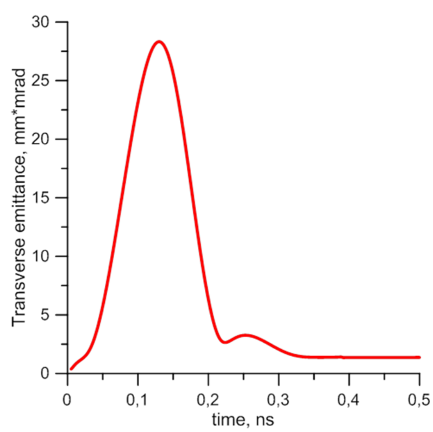

Figure 7: Transverse emittance vs. time.

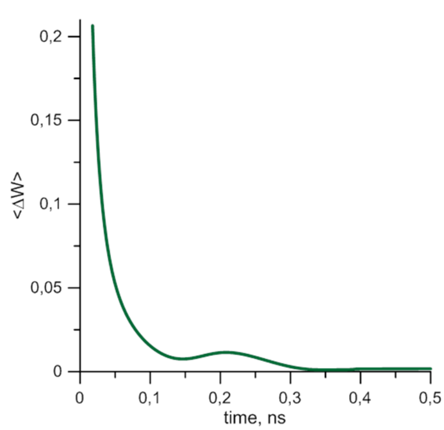

Figure 8: Normalized energy spread of particles vs. time.

For experiments on laser acceleration of electrons in a babble it is important to produce bunches with small energy spread. For our RF gun project, we optimized an injection phase in order to obtain the energy spread as small as ~0.1%. Figure 8 shows the normalized energy spread in dependence on time elapsed since bunch injection.

Key parameters of RF photoinjector (to be finally produced in 2018) are summarized in the Table 1.

Table 1: Specification of Key Parameters

Parameters	Value
Frequency	2.45 GHz
Cavity length	11.74 cm
Laser pulse duration	10 ps
Magnetic field	1.07 T
Bunch charge	100 pC
Laser spot radius at cathode	1 mm
Cathode field	70 MV/m
Injection phase	-40°
Average energy	3.5 MeV
Transverse emittance	1.4 mm×mrad
Energy spread	0.2%

CONCLUSION

Preliminary calculations show that necessary parameters of RF gun for laser wakefield acceleration experiment are achievable. Commissioning is scheduled in the fall of 2018.

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