Simulation of a Radio-Frequency Photogun for the Generation of Ultrashort Beams


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Abstract—A radio-frequency photogun for the generation of ultrashort electron beams to be used in fast electron diffractoscopy, wakefield acceleration experiments, and the design of accelerating structures of the millimeter range is modeled. The beam parameters at the photogun output needed for each type of experiment are determined. The general outline of the photogun is given, its electrodynamic parameters are calculated, and the accelerating field distribution is obtained. The particle dynamics is analyzed in the context of the required output beam parameters. The optimal initial beam characteristics and field amplitudes are chosen. A conclusion is made regarding the obtained beam parameters.

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INTRODUCTION

Multipurpose accelerator facilities based on ultrashort-beam sources for various applications in accelerator physics and other fields are currently being designed in several research laboratories around the world [1–3]. A radio-frequency (RF) photogun often serves as the key element of such sources. The principle of its operation is as follows: an electron beam is produced at a photocathode subjected to laser irradiation and is accelerated in the electromagnetic field of cavities. This beam generation method has several specific features.

1. The beam length is set by the laser pulse duration. Pulses emitted by modern lasers may be as short as several tens of femtoseconds [4].

2. The initial size of the laser spot at the photocathode affects the beam emittance (effectively defines its initial value).

3. The influence of the space charge may be minimized by enhancing the acceleration gradient, which depends both on the input RF power and the initial acceleration phase [5], in the gun itself.

4. The optimal RF power input provides an opportunity to suppress the influence of transverse electromagnetic forces acting on a charge due to the disturbance of axial symmetry of the system [5].

5. The beam charge depends on the photocathode type and the laser parameters (energy per pulse, wave-length). Different photocathode types and varying laser parameters provide access to a wide range of beam charges (from 100 fC to several nanocoulombs) [6, 7].

The present study is focused on modeling the radio-frequency photogun of the S range at the Budker Institute of Nuclear Physics. This gun is to be used as a beam source for various applications, including electron diffractoscopy studies of fast processes, plasma wakefield acceleration experiments, and generation of electron beams for the excitation of electromagnetic fields of the millimeter range. Widely different beam parameters are needed in these applications. The beam charge and its initial length depend largely on the photocathode properties, the energy of the laser pulse, and its duration. However, such characteristics as the end length of the beam, its emittance, energy, angular divergence, transverse size, etc., are defined primarily by the particle dynamics and the RF photogun properties. The beam parameters needed for each application and the beam dynamics are calculated below (with the characteristics of the photocathode and the laser system factored out). The design of the RF photogun is also outlined. Although lasers with a pulse duration of several tens of femtoseconds are already available [4], the initial beam length was set to several picoseconds so as to enable the use of simpler and cheaper lasers.
1. CALCULATION OF THE PARAMETERS OF THE RF PHOTOGUN BEAM

Fast electron diffractoscopy allows one to study processes within a sample with a temporal resolution finer than a thermal vibration of molecules [8–10]. A pump source is used to excite a dynamic process in the material, and the study itself involves the analysis of a diffraction pattern produced by an ultrashort electron beam (probe source) directed at the sample. This pattern emerges if Wulff–Bragg’s condition

\[ n\lambda = 2d \sin \theta \]  

(1)

is satisfied [11]. Here, \( n = 1, 2, 3, \ldots \) is the diffraction order; \( \lambda \) is the de Broglie wavelength for an electron; \( d \) is the crystal lattice period; and \( \theta \) is the Bragg angle. If this condition is fulfilled, electrons are scattered from lattice sites by angle \( 2\theta \) and form a diffraction pattern in the detecting plane. The properties of this pattern provide information regarding the structure of the crystal lattice, its parameters, and the processes occurring within it.

The beam length for a fast diffractoscopy system is set by the temporal resolution of the studied processes (typically <1 ps [8–10]). The beam energy should correspond to such a de Broglie wavelength that satisfies condition (1). The number of electrons in a beam should be sufficient for detection with a CCD camera; at the same time, the charge should be as small as feasible (so as to suppress Coulomb forces).

The angular divergence of particles in a beam for electron diffractoscopy may be estimated as follows. Figure 1 shows the diagram of electron propagation through the crystal lattice. The particles scattered from lattice sites are deflected by double Bragg angle \( 2\theta \) and end up in the position with radius \( R \). The particles with angular spread \( \pm \alpha \) are also deflected by angle \( \theta \), but end up in the positions with radii \( R_{1,2} \). If we assume that angles \( 2\theta \) and \( \alpha \) are small, \( R_1 = 2L\theta \), \( R_2 = L(2\theta + \alpha) \), and \( \Delta R = R_2 - R_1 = 2\alpha L \). In order for the diffraction pattern to be clearly discernible, ring radius \( R \) should be at least an order of magnitude larger than ring width blurring \( \Delta R \) induced by the angular spread (i.e., \( R/\Delta R \approx \theta/\alpha \approx 10 \)). It follows from Wulff–Bragg’s condition (1) at a small \( \theta \) that \( \lambda \approx 2d\theta \). Then, \( R/\Delta R \approx \theta/\alpha \approx \lambda/(2\alpha d) \approx 10 \), and \( \alpha \sim \lambda/(2d) \). The de Broglie wavelength for electrons is \( \lambda = h/p \), where \( h \) is the Planck constant and \( p \) is the particle momentum. At an energy of 4 MeV, \( \lambda = 0.3 \) pm. Thus, we obtain \( \alpha \sim 0.1 \) mrad for a typical lattice period of 2 Å.

In view of the above, the following beam parameters are optimal for a diffractoscopy system: a length of 100–200 fs, an energy of 3–5 MeV, a charge of 2–0.1 pC, and an angular divergence of 0.1 mrad, and a repetition rate of \( \geq 10 \) Hz.

An electron beam shorter than 1 ps may be produced using either a rather expensive laser or an additional buncher [12]. In the latter case, a correlated energy spread in the beam is needed; the efficiency of bunching depends strongly on the linearity of this energy spread of particles. In view of this, a beam length of several picoseconds is the optimal initial one for RF structures of the 5 range. This allows us to identify the needed beam parameters at the photogun output (given that the mean beam energy remains unchanged after bunching): a length of \( \sim 2 \) ps, an energy of 3–5 MeV, a charge of 2–0.1 pC, and an angular divergence of 0.1 mrad.

In the case of plasma wakefield acceleration [13, 14], beam length \( \sigma_z \), needed to produce a plasma wave is defined by the Langmuir wavelength [15, 16]:

\[ \sigma_z \sim \frac{c}{\omega_p} \]  

(2)

where \( c \) is the speed of light in vacuum, \( \omega_p = \sqrt{4\pi n_e e^2/m} \) is the plasma wavelength, \( n_e \) is the plasma density, and \( e \) and \( m \) are the charge and the mass of an electron. A plasma density of at least \( \sim 10^{15} \) cm\(^{-3} \) is needed to produce an electric field intensity of several gigavolts per meter. According to (2), the characteristic beam length is then \( \sigma_z \sim 0.2 \) mm (\( \sigma_z \sim 0.6 \) ps). The beam charge required for build-up of plasma oscillations to the maximum amplitude (defined by nonlinear wave breaking) is equal to the charge of plasma electrons within a volume of \( (c/\omega_p)^3 \) (i.e., \( q \sim n_e \sigma_z^2 \sim 1 \) nC). The needed beam emittance depends on the depth of the wakefield potential well in plasma and on the particle energy. Therefore, it is defined by the subsequent accelerator rather than by an RF photogun.

The beam from the VEPP-5 injection complex at the Budker Institute of Nuclear Physics [17, 18] with