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Electron guns at the Budker Institute of Nuclear Physics SB RAS: prospects for the use of photocathodes with nanosecond and subpicosecond laser drivers

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Abstract. **The problem of producing high-current electron beams with relatively small lateral sizes and small velocity spread is more than a hundred years old. The continuous improvement of near-ultraviolet electromagnetic radiation sources (lasers with harmonics generators) allows significantly improving the parameters of existing electron guns. This paper discusses some problems in the development of electron guns with photocathodes and considers possible ways of using laser photocathodes in the electron guns designed at the Budker INP SB RAS.**

Keywords: electron gun, photoinjector, photocathode, laser

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1. Introduction

Production of short electron bunches is one of the oldest problems in accelerator technology. Its first solution was the invention of a triode — an electron tube with a control grid. Bunches of shorter duration were produced in microwave generators — in klystrons and their predecessors. The problem became even more topical when microwave electromagnetic waves were applied to accelerate electrons in linear and cyclic accelerators. In spite of this, cathode-grid units and a klystron buncher, which modulates the energies of particles passing through an alternating-voltage accelerating gap, were and are still used for producing subnanosecond bunches. To make the picture complete, mention should be made of a seldom-used device with a transverse microwave beam sweep and a collimating slit — a beam chopper.

There was no way of applying the photoeffect to produce short electron pulses until the advent of short light pulses, which are nonexistent in nature. The radiation power P of interest is rather high. To be specific, putting the quantum yield $\eta = 0.1$, the photon energy $h\nu = 5$ eV (ultraviolet radiation), and the current $I = 1$ A, we obtain $P = Ih\nu/(e\eta) = 50$ W. Longitudinal mode-locked lasers made it possible to obtain periodic subnanosecond pulses. Developed more recently were titanium–sapphire (Ti : sapphire) lasers to make available high-power pico- and femtosecond pulses. The laser parameters are being continuously improved. This opens up fresh possibilities for producing electron guns with photocathodes. In particular, use can be made of low-quantum-yield photocathodes operating in the poor vacuum conditions of real electron guns.

2. Emittance and brightness of electron beams

Let us recall some information about charged particle beams (see, for instance, books [1, 2]). For definiteness, we will consider electrons. The term electron bunch will be applied in

reference to an electron ensemble with a relatively low spread in coordinates and momenta. The deviations in coordinates x, y, and z from some particle selected as the reference one are normally much smaller than the characteristic dimensions of the system (than, for instance, the aperture of the electron optical channel), and the spread in momentum is much smaller than the modulus p_0 of the reference particle momentum. The direction of the reference particle momentum is usually taken as the z-axis, which is called the longitudinal coordinate axis, while the reference particle position is taken as the origin. Then, x and y are the transverse coordinates, and the small ratios p_x/p_0 and p_y/p_0 are approximately equal to the angles between the z-axis and the trajectory projections onto the xz and yz planes, respectively. For a variable describing the longitudinal motion, it is convenient to take not the longitudinal momentum p_z itself but what remains of it after subtraction of p_0. The smallness of particle coordinates in the phase space permits, to a first approximation, representing the motion of particles as a linear transformation of their coordinates. Then, the particle distribution is conveniently characterized by second-order moments, for instance, by the squares of rms sizes $\langle x^2\rangle$, $\langle y^2\rangle$, and $\langle z^2\rangle$.

When the particle motion is described by Hamilton equations, the so-called skew-scalar product of six-dimensional vectors $(\mathbf{r}, \mathbf{p})$ — that is, the bilinear form $\mathbf{p}_1\mathbf{r}_2 - \mathbf{p}_2\mathbf{r}_1$ or the sum of the areas of parallelograms in the (x, p_x), (y, p_y), and $(z, p_z - p_0)$ planes with vertexes at the origin and at the points representing the particles, is conserved for any pair of particles. The matrices of the linear transformations conserving the skew-scalar product are termed symplectic (compare with orthogonal matrices, which describe the rotational transformation conserving ordinary scalar products). The symplectic matrix determinants are equal to unity (Liouville theorem), and the determinant of the second-moment matrix is therefore conserved. In the simplest cases of independent degrees of freedom, the determinant of the second-moment matrix is equal to the product of three determinants of the form

$$\det\left\langle\begin{pmatrix} x \\ p_x \end{pmatrix}(x, p_x)\right\rangle = \begin{vmatrix} \langle x^2\rangle & \langle xp_x\rangle \\ \langle xp_x\rangle & \langle p_x^2\rangle \end{vmatrix} = \langle x^2\rangle\langle p_x^2\rangle - \langle xp_x\rangle^2 .$$

The quantity characterizing the area occupied by electrons in the (x, p_x) phase plane is defined as

$$\varepsilon_x = \frac{1}{mc}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle xp_x\rangle^2}\,, \tag{1}$$

where m is the particle mass, and c is the speed of light, and is called the normalized root-mean-square emittance (for the x degree of freedom). A 'good' electron beam has a low emittance.

Another electron beam characteristic of practical importance is its brightness B, which may be defined as the normalized current density in the four-dimensional transverse phase space. The brightness is expressed in terms of the normalized root-mean-square emittance as

$$B = \frac{I}{(2\pi)^2\,\varepsilon_x\varepsilon_y}\,, \tag{2}$$

where I is the beam current. For instance, for a flat round cathode with a temperature T, $\langle p_x^2\rangle = \langle p_y^2\rangle = mk_\mathrm{B}T$ and

$$B = \frac{j}{\pi}\,\frac{mc^2}{k_\mathrm{B}T}\,, \tag{3}$$

where k_B is the Boltzmann constant, and $j = I/(4\pi\sqrt{\langle x^2\rangle\langle y^2\rangle})$ is the cathode current density.

For an unlimited cathode emission, the current density is bounded by the fact that the field produced by the electrons that have already escaped from the cathode decelerates the outgoing electrons. In the static case, this effect is described by the Child–Langmuir law. For a photocathode illuminated by picosecond pulses, the electron bunches are disk-shaped with a surface charge density σ, and they induce a decelerating field $4\pi\sigma$ on the photocathode surface. Therefore, the first electrons of a bunch are accelerated by some field E_0, and the last ones by the field $E_0 - 4\pi\sigma$. This requires the fulfillment of the condition $\sigma \ll E_0/(4\pi)$ to obtain sufficiently low emittance, energy spread, and bunch length. For instance, at $E_0 = 100$ MV m^{-1}, one has $\sigma \ll 1$ nC mm^{-2}. This signifies that obtaining a bunch of charge 1 nC requires that the illuminated spot area be significantly greater than 1 mm^2. Let, for instance, the illuminated circle have a radius $a = 2$ mm. Then, $\varepsilon_{x,y} > (\langle x^2\rangle\langle p_x^2\rangle)^{1/2}/(mc) = [k_\mathrm{B}T/(mc^2)]^{1/2}\,a/2$, which yields a figure of 0.3×10^{-6} m at room temperature. The inequality sign in this estimate appears, because the mutual electron repulsion and the aberrations of focusing increase the emittance. Furthermore, the transverse momentum spread of photoelectrons may exceed the temperature spread.

In many cases, the electron beam should consist of separate bunches rather than be continuous. In particular, this is necessary to accelerate particles in a high-frequency field. Therefore, the electron emission has to be turned on and off promptly. The most developed way to do so is to use a control grid, which is employed in electron tubes. A negative (relative to the cathode) voltage is applied across the grid to interrupt the current from the cathode. In this way, it is possible to obtain bunches approximately 1 ns or longer in duration. Shorter bunches are produced with cathodes placed in radiofrequency (for instance, 3-GHz) cavities. The electric field extracts the electrons from the cathode and accelerates them during a significant part of the field variation period. That is why the electrons that escape the resonator vary in energy, which depends on the instant of time when they escape the cathode. If the electrons from a relatively narrow energy range were separated out, they would make up bunches shorter than 0.1 ns. In doing so, the majority of electrons are lost, and the charge of such a bunch is therefore small (on the order of 10 pC). To overcome the limitations of the above-mentioned current modulation techniques, advantage can be taken of the photoeffect. In particular, when the cathode is irradiated by pico- or femtosecond laser pulses, the resultant electron bunches are of a corresponding duration. The power of modern lasers is high enough to obtain bunches with a significant (on the order of 1 nC) charge even for a low electron yield, for instance, simply due to irradiation of the copper inner wall of the radiofrequency cavity.

3. Some electron guns of the Budker Institute of Nuclear Physics SB RAS

In this section, we describe some of the electron guns developed and used at the Budker Institute of Nuclear Physics (INP) SB RAS.

3.1 Electron guns of the accelerator-recuperator of the Novosibirsk free-electron laser

The *Novosibirsk free-electron laser* (FEL) facility [3] employs an electrostatic gun. A voltage of up to 300 kV from a rectifier

is applied across a high-voltage terminal via a cable. The cathode-grid unit of a GS-34 high-frequency electron tube serves as the electron source. A constant blanking voltage and 1-ns long gating pulses with an amplitude of up to 50 V are applied to the unit. The pulse repetition rate can be varied from zero to 22 MHz. The highest bunch charge is 1.5 nC. The bunches outgoing from the electron gun are next accelerated in resonators operating at frequency $f =$ 180 MHz.

The pulse duration $\Delta t = 1$ ns is too long, because it entails a relative energy spread $(\pi f \Delta t)^2/2$ of about 20%. Thus, so-called klystron bunching of electrons is carried out prior to their acceleration. The electrons in the middle of the bunch pass through the gap of an accelerating radiofrequency cavity (often called the bunching cavity) at the instant of time the accelerating field is equal to zero. In this case, the earlier-arriving front electrons are slightly decelerated. and the rear ones are slightly accelerated. In the transit from the bunching cavity to the main accelerating structure, the rear particles set closer to the front ones and the bunches shorten to an acceptable duration of about 0.2 ns. The electron injector of the Novosibirsk FEL, which comprises the electrostatic gun, the bunching cavity, and a pair of accelerating cavities, is illustrated in Fig. 1.

The typical value of the measured normalized electron emittance equals 20 μm. This figure is by an order of magnitude greater than the corresponding thermal emittance, which is attributable to the nonuniformity of the electric field caused by a presence of the grid and the bunch charge. Furthermore, chromatic aberrations appear in the bunching in the drift gap due to the energy difference between the front and rear particles and the short bunch produces a nonlinear defocusing field.

In the routine operating mode, the average electron current amounts to about 10 mA. To raise the average current (and, hence, the power of the Novosibirsk FEL), a radiofrequency (RF) electron gun was developed [4] (Fig. 2).

The cathode-grid unit, just as in the electrostatic gun described above, is mounted on the rear wall of a radio-frequency cavity excited at a frequency of 90 MHz. The gun is installed on a test bench. The average current achieved with the gun amounts to over 100 mA for an electron energy of about 300 keV.

The application of ultraviolet radiation in the form of pulses approximately 1 ns in duration following at a repetition rate of about 10 MHz would permit the cathode–grid units of the above guns to be promptly replaced by photocathodes and next permit fabricating an RF gun optimized for operation with the photocathode. This may be beneficial not only for shortening the electron bunches and lowering their emittance, but also for suppressing the so-called halo — electrons with large coordinate and momentum deviations, which are lost in the course of acceleration and raise the ionizing radiation intensity in the accelerator hall. Since the vacuum conditions in these and evidently all other relatively high-current guns are rather poor and high-efficiency photocathodes operate only in an ultrahigh vacuum, there is good reason to try employing low-efficiency photocathodes. For instance, for a quantum efficiency of 3×10^{-5} (copper for a radiation wavelength of 253 nm [5]), to obtain bunches with a charge of 1.5 nC requires pulses with an energy of 0.2 mJ. Since in this case the average radiation power would be on the order of several kilowatts, use can be made of heat-resistant materials (tungsten, graphite, etc.).

Figure 1. (Color online.) Electron injector. From left to right: electron gun (blue tank), diagnostic gap, bunching cavity, drift gap wherein bunching occurs, and two accelerating cavities.

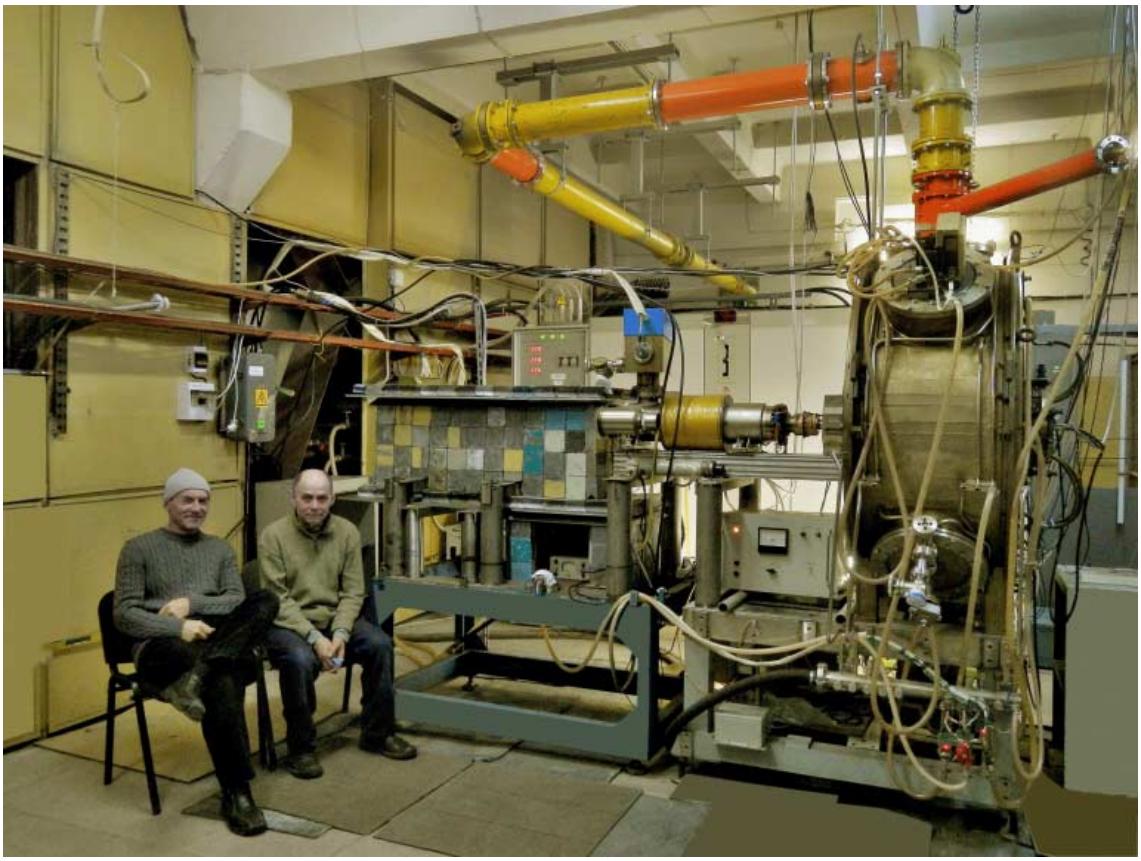

Figure 2. V N Volkov, E I Kolobanov, and a radiofrequency electron gun (the large cylindrical cavity at the right) on a test bench.

3.2 Pulsed radiofrequency gun

Figure 3 shows a pulsed radiofrequency gun with an operating frequency of 3 GHz. Since in guns of this type the near-cathode field ranges up to 100 MV m^{-1} and electrons experience rapid acceleration, it was precisely these guns that were capable of producing electron bunches with a low (a few tenths of a micrometer) normalized emittance for a relatively high (up to 1 nC) charge [6].

Figure 3. Pulsed radiofrequency gun with a coaxial input. The output opening is in the foreground. At the left and right are rectangular flanges for a feed waveguide and a vacuum pump. In the background are two radiofrequency cavities. The rear wall of the farthest cavity serves as a photocathode.

The electron energy at the output of the gun being described is about 3 MeV. It is planned to employ it for exploring wake field acceleration and development of a facility intended for electron diffractometry of fast processes. Wakefield acceleration requires bunches with a high charge (up to 2 nC), which calls for ultraviolet radiation pulses with an energy on the order of 1 mJ and a duration of less than 10 ps. Fast electron diffractometry requires subpicosecond bunches with a charge of up to 10 pC (the charge is limited by mutual electron repulsion), i.e., radiation pulses with an energy of about 2 μJ.

3.3 Electron gun of a linear induction accelerator

The Budker INP SB RAS developed a unique linear induction accelerator (LIA) [7, 8] with a low (for a current of 2 kA) normalized emittance (5 mm). The duration of electron bunches is on the order of 100 ns. The cathode unit structure is depicted in Fig. 4. It employs a dispenser hot cathode 190 mm in diameter.

Replacing the hot cathode with a photocathode would reduce emittance and modulate the electron beam current. Taking again the quantum yield equal to 3×10^{-5}, we arrive at the conclusion that this requires the UV radiation power of about 300 MW, which corresponds to the energy of 30 J for a pulse duration of 100 ns. The source of such radiation could be a neodymium laser with frequency conversion to the fourth harmonic or an excimer laser.

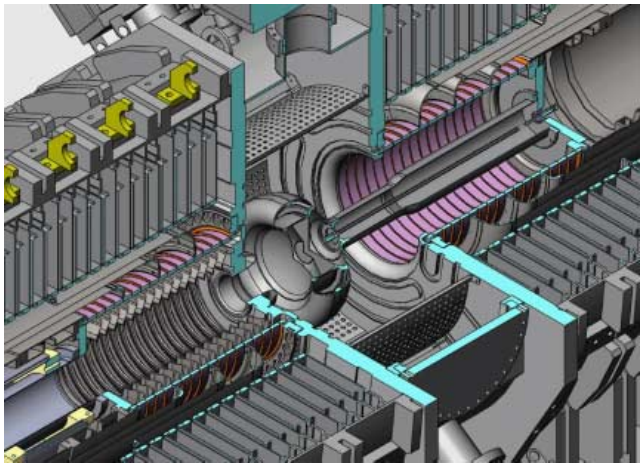

Figure 4. Cathode unit structure. The spherical cathode is fit to the cathode leg, which passes through the sectioned high-voltage insulator.

4. Conclusion

We have tried to demonstrate the promise of photocathodes by the example of electron guns at the Budker INP SB RAS accelerators. The state-of-the-art in laser engineering permits undertaking the corresponding developments. Furthermore, the parameters of lasers will substantially improve over the several years it takes to make the corresponding experimental facilities. The proposed work would result in a significant improvement in existing and projected electron accelerators.

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References

1. Chao A W, Tigner M (Eds) *Handbook of Accelerator Physics and Engineering* (River Edge, NJ: World Scientific, 1999)
2. Wiedemann H *Particle Accelerator Physics* 3rd ed. (Berlin: Springer-Verlag, 2007)
3. Kulipanov G N et al. *IEEE Trans. Terahertz Sci. Technol.* **5** 798 (2015)
4. Volkov V N et al. *Phys. Part. Nucl. Lett.* **13** 796 (2016); *Pis'ma Fiz. Elem. Chastits At. Yad.* **13** 1244 (2016)
5. Akre R et al. *Phys. Rev. ST Accel. Beams* **11** 030703 (2008)
6. Dowell D H et al. *ICFA Beam Dynamics Newslett.* (46) 162 (2008); http://www-bd.fnal.gov/icfabd/Newsletter46.pdf
7. Starostenko D A et al. *Phys. Part. Nucl. Lett.* **11** 660 (2014); *Pis'ma Pis'ma Fiz. Elem. Chastits At. Yad.* **11** 1022 (2014)
8. Starostenko D A et al. *Phys. Part. Nucl. Lett.* **13** 962 (2016); *Pis'ma Pis'ma Fiz. Elem. Chastits At. Yad.* **13** 1500 (2016)