Measurement of Time Response of Laser-Triggered GaAs Photocathode

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Abstract

An RF gun with a laser-triggered photocathode is a very attractive as an injector for linear accelerators since it can produce a low-emittance high-current electron beam with originally short pulse length. A GaAs photocathode can generate a polarized electron beam. The time response of GaAs photocathode is very important for RF gun operation if it is comparable with RF period. An experimental facility has been fabricated to measure the length of electron bunch extracted from GaAs photocathode illuminated by laser pulse of 98 ps (FWHM). The method of bunch length measurement using circular scanning in RF cavity was developed. We use 50 kV DC gun for beam extraction. The minimum measured bunch duration was 106 ± 20 ps (FWHM) for $4.5 \cdot 10^8$ electrons per pulse. In this report we describe the experimental setup and obtained results.

1 INTRODUCTION

Future electron-positron factories require a very high luminosity and, therefore, a sufficiently large number of injected particles. A laser-driven RF gun appears to be the most convenient electron source which is able to supply a very high intensity. It is planned to use a laser-driven RF gun at the injector complex for Novosibirsk Phi-factory project [1]. This electron source has several advantages:

1. An originally short bunch length, it helps to avoid a subharmonic buncher system.
2. A laser-driven RF gun can provide the required number of electrons per bunch.
3. This gun can produce a polarized electron beam.

A GaAs photocathode satisfies all the requirements for the electron beam:

- A very high current densities - up to 800 A/cm^2.
- High quantum efficiency - up to 20%.
- High degree of polarization (80%).
- Reasonable life time - up to few weeks.

Several problems still need to be solved. The returned electrons bombardment is one of it. The absence of returned electrons can be guaranteed when the emission duration is less then a quarter of RF period. The emission duration upper limit is 50ps width at 10% level for RF 2856 MHz. The time response measurements for GaAs photocathode is presented in this paper.

2 EXPERIMENTAL SETUP

The GaAs photocathode (p-doped by Zn, $10^{19} cm^{-3}$) is prepared in NEA condition by depositing Cs and O_2 at its surface with a standard procedure [2]. When activation has been accomplished, the cathode is fastened to the DC gun by manipulator (see Fig.1). This procedure allows to carry out activation in a separate chamber and avoid the problems connected with a sparking due to Cs covering of the high voltage insulator surface.

The cathode is negatively biased with a voltage ranging within 0-50 kV. The diameter of the laser spot on the cathode is 2 mm, and gun perveance is $1.5 \cdot 10^{-3} \frac{A}{kV^{3/2}}$. Photoemission is excited by two lasers: a CW 75 mW Ar^+ for activation, and a pulsed (532 nm) Nd:YLF laser injected by CW Mode-Locked Nd:YLF laser. A pulsed laser provides the 98 ps wide (FWHM), 1.5 mJ laser pulse with a 10 Hz repetition rate. We use an autocorrelator for a control of a laser pulse duration (FWHM) with 10 ps accuracy.

We suggested, realized and experimentally tested the device for length measurement of electron bunch , emitted by GaAs photocathode. The main idea of the method

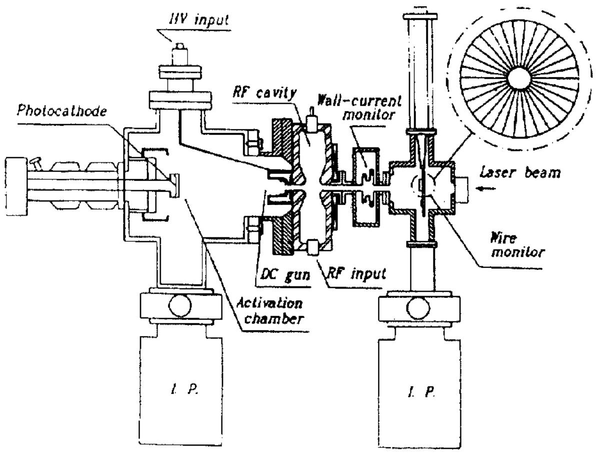

Figure 1: Experimental setup.

is circular scanning of electron beam travelling in rotating magnetic field of RF cavity. The electrons passing through the cavity along its axis experience transverse deflection, which direction depends on the longitudinal position of electron in the bunch. As a result longitudinal position of electron transformed to angular position in the plain orthogonal to the axis.

The circular deflection of electron beam in the cavity is performed by transverse magnetic field of TM_{110} mode with circular polarization. Circular polarization is provided by exciting of two orthogonal modes shifted on $\frac{\pi}{2}$ in phase.

The maximum deflection is reached when transit angle is equal to $\frac{\pi}{2}$. In this case beam with duration $\Delta\tau$ sweeps in the plain orthogonal to the axis an arc of circumference with sizes:

$$R = \frac{eH_0\lambda \cdot L}{\pi\gamma mc^2}$$

$$\Delta\Theta = w \cdot \Delta\tau$$

where λ is RF wavelength, w - frequency and H_0 is an ampl. of magnetic field. We can determine the beam duration $\Delta\tau$ by measuring the angular size $\Delta\Theta$. Let us consider the main sources of error in this procedure.

1. The final size of the beam. If the beam has final transverse size d on the detector then its duration can be determined with uncertainty $\delta\tau$:

$$\frac{\delta\tau}{T} = \frac{d}{2\pi R} \tag{1}$$

where T is period of RF

2. The energy distribution in the beam produces the uncertainty :

$$\frac{\delta\tau}{T} = \frac{1}{4} \cdot \frac{1}{2 + \frac{3U}{W_0} + \left(\frac{U}{W_0}\right)^2} \cdot \frac{\delta U}{U} \tag{2}$$

where U is accelerating voltage, $W_0 = 511$ keV.

3. If orthogonal modes have difference in amplitude δH and phase shift differs from $\frac{\pi}{2}$ to $\delta\phi$, then polarization of resulting magnetic field is elliptical. In this case the error in determination of bunch duration depends on the bunch duration and azimuth of bunch center of mass but doesn't exceed :

$$\frac{\delta\tau}{T} \leq \sqrt{\left(\frac{\delta H}{H_0}\right)^2 + (\delta\phi)^2} \tag{3}$$

Cavity was optimized to get maximum deflection of the beam with 50KV energy for given input RF power. The resonant frequency is 2.46GHz, measured unloaded quality factor is 17000. The cavity has two orthogonal loops for RF power input and two piston tuners for adjustment of resonant frequency of each mode in the range 0.5 MHz. Pulsed magnetron is used as the source of RF power. Its power and frequency can be controlled in some range by amplitude of anode pulse from modulator. The maximum power is 1.5 kW. The stable operation of magnetron is provided by ferrite circulator which decouples magnetron from resonant load. The adjustment of cavity is performed by using 15 ns or continuous electron beam. If polarization is circular, electron beam draws a full circle on the detector surface and makes a uniform charge distribution on the channels of 2π-detector (see Fig.1).

The 2π-detector is a set of 30 tantalum sectors perpendicular to the beam axis with a hole for laser beam in the center. Each sector acts as a Faraday cup to collect the electrons of the bunch. The maximum resolution of this instrument is 400/30=13.3 ps, and normal electronic noise value is 10^6 electrons per each channel. The summarized contribution for all described above error factors ((1),(2),(3)) does not exceed 20 ps value.

For a total charge control we use a Faraday cup and a wall-current monitor.

3 EXPERIMENTAL RESULTS

Fig. 2 (a,b,c) shows the time dependence of an electron bunch current at the 2π-detector for different energies. Fig. 2 (a,b,c) contains the Lorentz-shape solid curves:

$$I = I_{max} \cdot \frac{\delta^2}{\delta^2 + (t - t_0)^2} \tag{4}$$

fitted to the experimental points, where δ is a half of FWHM bunch duration, t_0 is a position of a current maximum. The laser pulse parameters remain the same for all three energy values.

The significant lengthening of the electron bunch with the energy decreasing is coming from following:

At first, from the lengthening in the gun. The bunch duration at the anode plain in the space charge regime is very close to the time of flight through the gun gap for electron:

$$\tau = d \cdot \sqrt{\frac{2m}{eU}} \tag{5}$$

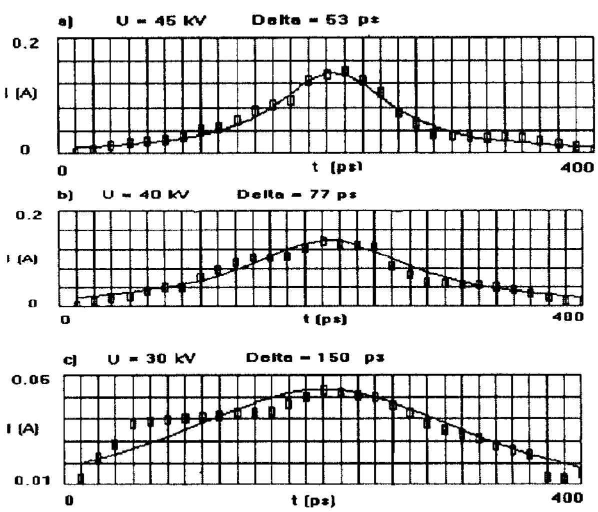

Figure 2: Shape of an electron bunch current at different energies: 45 keV (a), 40 keV (b), 30 keV (c) and at the same laser pulse parameters.

where d is an effective gun gap, $U$is a voltage on an effective gun gap. It is true only if the emission duration is shorter then the time of flight (5). In the opposite case, when the emission duration is longer then the time of flight, the bunch length at the anode plain is determined by the emission duration. The next reason of bunch lengthening is connected with a decreasing of the maximum extracted current, due to a gun voltage decreasing. It means that the part of the laser pulse, which can saturate the gun, becomes longer and longer.

Let us note, that the bunch length for 45 keV, $7.0 \cdot 10^8 e^-$, 98 ps FWHM emission duration electron bunch, taking from PARMELA simulation for gun geometry is equal to 100 ps. It is very close to the original laser pulse FWHM duration (98 ps) and to the measured bunch duration (106 ps) FWHM (see Fig. 2(a)). According to this results, the bunch lengthening due to GaAs time response does not exceed the total measurement error: 20+10=30 ps.

The dependencies of the total charge in the bunch upon the energy and the number of photons are presented in Fig. 3(a,b) respectively. We use a set of calibrated glasses to decrease the number of photons in the laser pulse and a Faraday cup to measure the bunch charge. Here we suggest a very simple model to explain such kind of dependencies. Let us assume that the emission ability pulse has a Lorentz shape, (4) and electron gun cannot extract all charge due to the space charge limit. In this case the top of emission ability pulse will be cut at the level:

$$I = p \cdot U^{3/2} \tag{6}$$

here $p = 0.0015 \frac{A}{kV^{3/2}}$ for our gun. And the total charge in the pulse cut is

$$Q = 2\delta I_{max}(\frac{\pi}{2} - atan(\frac{t}{\delta})) + 2tpU^{3/2},$$

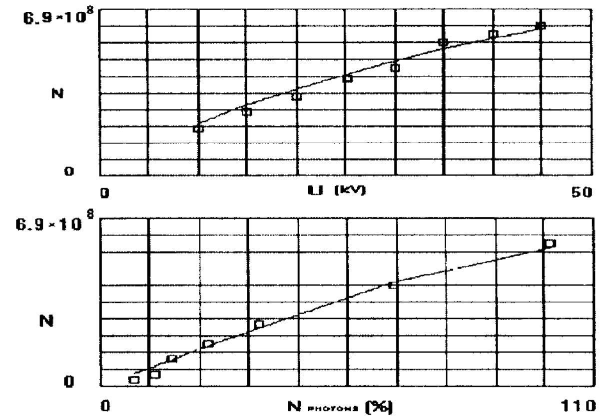

Figure 3: Total number of electrons in the bunch as a function of bunch energy (a) and number of photons in laser pulse (b).

$$t = \delta \sqrt{\frac{I_{max}}{pU^{3/2}} - 1} \tag{7}$$

The solid curve in Fig.3(a) is the result of calculation using (7).

The bunch charge measurements for different number of photons in the laser pulse are presented in Fig. 3(b). The solid curve is calculated using (4) with constant U, but for different I_{max}. This model contains three parameters: δ - a duration of emission ability, we put δ equal to 49 ps - a half of the FWHM laser pulse duration, $p = 0.0015 \frac{A}{kV^{3/2}}$ is the calculated perveance of our gun and I_{max} - max. emission ability, which is equal to 700 mA.

This model is very sensitive to the emission ability pulse shape. For example, it is not possible to make a good fitting with Gaussian emission ability pulse shape. A good matching of this model with experimental results gives us another confirmation of the small bunch lengthening (less then 30 ps) due to GaAs time response.

4 CONCLUSION

According to data obtained in this experiment a thick GaAs photocathode has a low time response. We provide an upper limit for the lengthening of the electron bunch due to GaAs time response at the level of 30 ps. We hope that this result will bring some optimism to people who choose a GaAs photocathode as an electron source for RF gun.

5 REFERENCES

[1] A.V.Novokhatski, A.V.Aleksandrov, A.A.Kulakov, P.V.Logatchov, L.Tecchio. A laser-driven gun for electron-positron factories. NIM A 340(1994) p.237-240, North-Holland.

[2] D.T.Pierce, R.J.Celotta, G.-C.Wang, W.N.Unertl, A.Galejs, C.E.Kuyatt and S.R.Mielczarek; Rev. Sci. Instrum. 51 (1980) 478.