PHYSICAL REVIEW E VOLUME 51, NUMBER 2 FEBRUARY 1995

Experimental study of the response time of GaAs as a photoemitter

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(Received 25 August 1994)

An experimental investigation was carried out to measure the response time of GaAs in negative electron affinity conditions as a photoemitter. During the experiment, the photocathode was excited by a short-pulse (38 ps rms) frequency-doubled Nd:YLF laser. Results show that the rms response time of GaAs is shorter than 40 ps.

PACS number(s): 29.25.Bx, 41.60.Cr

I. INTRODUCTION

Laser-driven cathodes have become increasingly important in the past ten years. In particular, photoemission from GaAs in negative electron affinity (NEA) [1] enables the production of polarized high-density electron bunches. dc guns, which accelerate electron beams emitted by a GaAs cathode, are currently operating or being proposed in some laboratories [2–4]. The acceleration imparted by rf guns would allow an enhanced electric field at the cathode, which should overcome the limitation in current density for the emitted bunches due to space-charge repulsion [5]. Moreover, the fast reaching of the relativistic regime for the electrons would also reduce the emittance growth due to space charge [6].

Designing a rf structure involves knowing the response time of the photemitting material, i.e., the width of the temporal distribution of electrons caused by an arbitrarily short laser excitation. The rems response of the electron beam should be shorter than one rf cycle by a factor of at least 20 [6]. rf guns currently operating or being developed work at frequencies lying between 0.144 and 17 GHz [7].

The response time of NEA GaAs was calculated by the diffusion equation of electrons as minority carriers in the conduction band of *p*-doped GaAs [1]. This approach considers about 1 ns for a reflection-mode cathode. Although some theoretical and experimental efforts have been made in order to evaluate the response time of transmission-mode GaAs photocathodes [8–10], no measurements, to our knowledge, have been carried out, on the response time of reflection mode, so some of the present authors developed a dedicated Monte-Carlo investigation on this parameter [11]. As a result of simulation, the rms response time τ_{GaAs} proved to be about 140 ps, which is considerably shorter than was predicted by the diffusion equation. This result encouraged us to undertake the investigation on this parameter described through this paper.

II. EXPERIMENTAL SETUP

The GaAs cathode (*p* doped with Zn, 10^{19} cm^{-3}) is prepared in NEA conditions by depositing Cs and O_2 on its surface using a standard procedure [12]. Once activation has been accomplished, the cathode is fastened to the dc gun by means of a manipulator. This allows activation to be carried out in a separate chamber and all the problems connected with the depositing of Cs on the chamber walls (which can cause sparking due to high voltage) are bypassed. The cathode can be negatively biased within a voltage range of 0–60 kV. A ceramic ring provides insulation of the cathode holder from the rest of the system, which is grounded. The dc gun is designed to deliver 5 A cw maximum current at 60 kV corresponding to a maximum gradient at the cathode's surface of 15 Mv/m. Figure 1 illustrates the layout for the experimental apparatus.

Photoemission is excited by four lasers: a cw 75 mW Ar^+, a cw 30-mW diode laser of 780 nm wavelength, a frequency-doubled Nd:YAG (532 nm), where YAG denotes yttrium aluminum garnet, producing pulses 15 ns long and a short-pulse frequency-doubled Nd:YLF (527 nm) with a power up to 1.5 mJ/pulse and 10 Hz repetition rate. The first two lasers are used to activate the GaAs source. Activation of the GaAs in NEA conditions is assured by the periodical monitoring of its quantum efficiency illuminating the cathode by the diode laser, the photons of which have an energy slightly greater than the semiconductor band gap. The Nd:YAG laser is useful for calibrating the diagnostic system, as explained later on. The short-pulse Nd:YLF is the laser used for investigating the GaAs response time. The rms pulse duration of a typical laser shot is 38±2 ps and its full spot size on the cathode surface is 2 mm. The laser-

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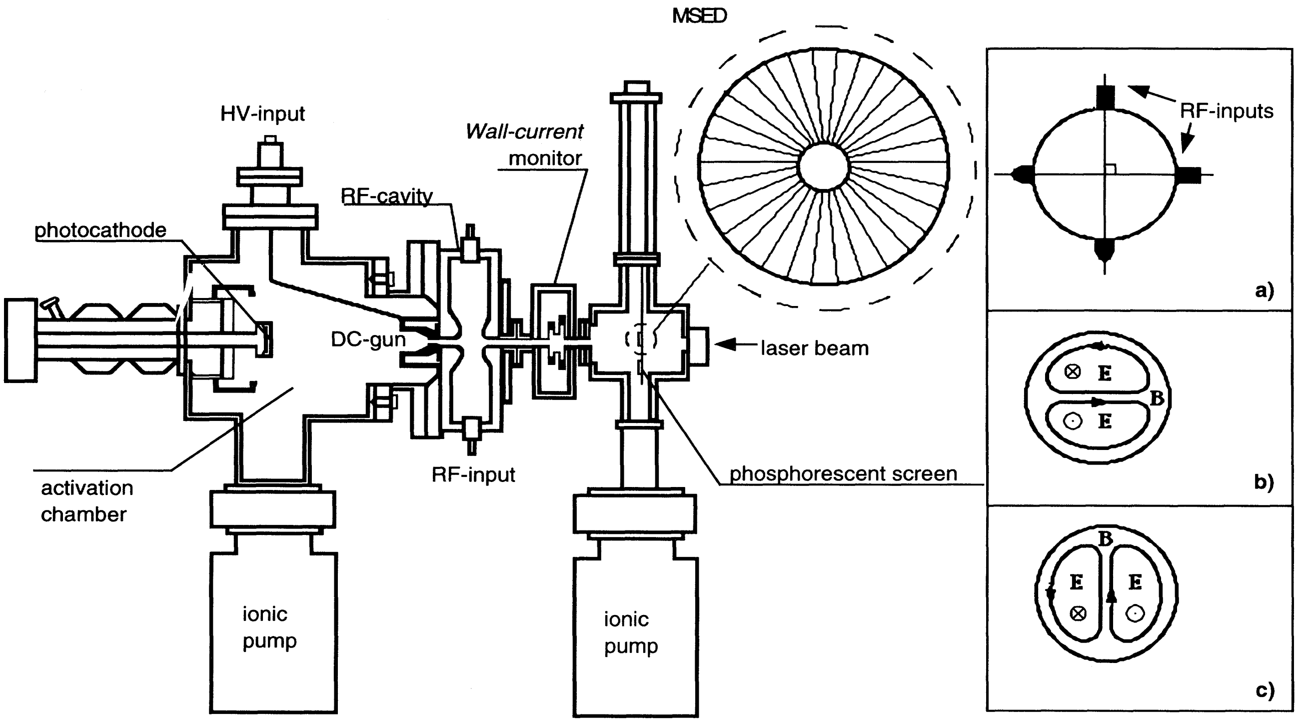

FIG. 1. Layout of the experimental apparatus. (a) Sketch of the cavity with the two power inputs; (b) electric and magnetic fields in the cavity relative to the first power input; (c) same as (b) relative to the second power input.

pulse profile was measured by means of an autocorrelator [13].

The experimental apparatus is equipped with two diagnostic devices which enable the measurement of a wide range of GaAs response times. The diagnostic devices are complementary to each other. The first is a wall-current monitor, the resolution of which is estimated to be approximately 170 ps (rms) and it was intended for measuring any long response time. In practice, the wall-current monitor was used only at the very beginning of the experiment in order to provide a rough measurement of GaAs response time [14]. The second, more accurate diagnostic device is a combination of a rf cavity and a multisector electron detector (MSED). The rf cavity operates in TM_{110} mode with two power inputs geometrically shifted in angle by $\pi/2$ rad [Fig. 1(a)] and supplied by a magnetron with a frequency of $\nu=2.465$ GHz. Figures 1(b) and 1(c) display the patterns of the electric and magnetic fields in the cavity relative to the two power inputs. When the electron beam passes through the center of the cavity, no action is exerted on the electrons by the electric field. Moreover, the two magnetic fields are shifted in phase by $\pi/2$ rad and are equally strong in amplitude. Vector composition results in a magnetic field which is constant in modulus and rotates at the frequency of the cavity. This imparts a transverse kick to the incoming electrons, the direction of which depends on the time when a single electron enters the cavity. As a result, a screen orthogonal to the beam axis would collect electrons only over an arc of a circle, provided that the total bunch length is lower than one cycle of the rf cavity (400 ps). The MSED is a series of 30 tantalum sectors perpendicular to the beam axis with a hole inside; each sector acts as a Faraday cup, collecting the electrons of the bunch. The duration of the bunch can be assessed by observing the number of sectors excited. The resolution of this instrument is estimated to be 4 ps. Electronic noise limits the minimum measurable charge collected by one sector to 10^6 electrons. A detailed description of this device can be found in Ref. [15].

The Nd:YAG laser is used to calibrate the system. External coils allow the electron beam to be driven in the

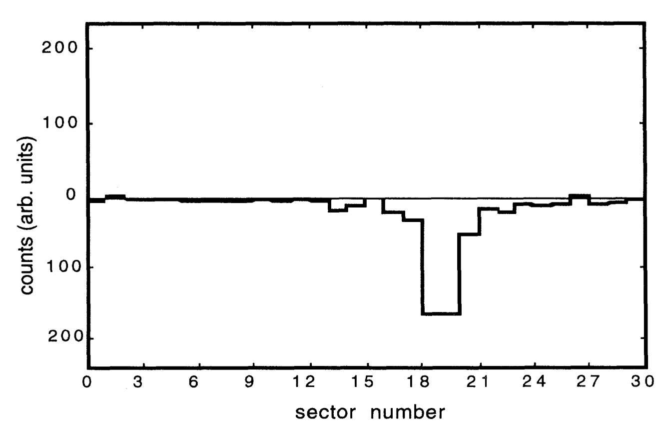

FIG. 2. With rf on the cavity off, the beam is kicked leftward. The number of sectors excited determines the resolution of the device (about 10 ps). Here the voltage is 60 kV.

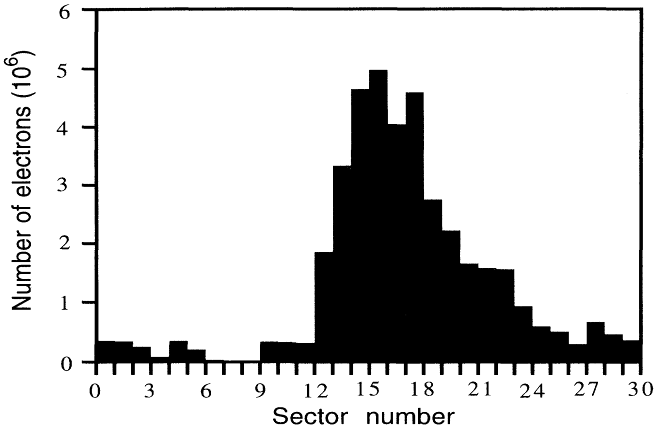

FIG. 3. Response to excitation by Nd:YLF laser at 60 kV. When the resolution of the device is accounted for, the duration of the electron bunch is $\tau_B(40\pm10)$ ps.

X-Y plane, perpendicular to the beam axis. Thus, when the rf on the cavity is off and the cathode is illuminated by the Nd:YAG laser, the beam can be centered in the detector, corresponding to the situation in which no signal is recorded by any sector. Then the rf is switched on: if the beam axis is perfectly coaxial to the hole in the detector, all sectors will record the same signal within the uncertainty of the device. This is feasible because the duration of the Nd:YAG laser pulse is much longer than one rf cycle. Of course not all sectors will record the same current if the beam is not centered; this provides confirmation of a good alignment.

Space charge causes the electron beam to suffer transverse enlargement; this effect cannot be perfectly compensated by adjusting the currents in the external coils and the accuracy of the measurements therefore exceeds the resolution of the device. In order to estimate this contribution the Nd:YLF laser is operated with the rf off. The beam is moved leftward (Fig. 2) by varying the current in the external coils. At 60 kV, three channels are excited (equating to approximately 10 ps rms); this is the accuracy of our device due to the size of the beam, determined by the laser spot and the contribution of space charge. At 30 kV the accuracy becomes better (7 ps rms) because the deflecting magnetic field is more effective and the electron bunch consequently impinges on the MSED with a larger radius, thus hitting only two sectors. The dependence on space charge was checked using the Nd:YAG laser; the much lower current density produced by this laser resulted in only one sector being excited.

TABLE I. Bunch length as calculated by the PARMELA computer code for different accelerating voltages.

	rms bunch length (ps)	
Electron gun voltage (kV)	10^8 electrons	4×10^9 electrons
30	39	55
40	39	49
45	39	46
60	39	42

As an alternative to the MSED, there is a phosphorescent screen which gives an image of what would have been the distribution of electrons on the sectors. This device only provides a qualitative check, but helps considerably in the initial setup of the device.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Measurements were carried out using the Nd:YLF laser and operating with the electron gun at different voltages, from 30 to 60 kV. Figure 3 shows a typical result of bunch length measurement at 60 kV of accelerating voltage in the gun. The whole bunch is recorded within 14 channels corresponding, after deconvolution with the accuracy of measurement, to a bunch duration of (40 ± 10) ps (rms).

In order to provide an estimate of the contribution of the space-charge effect to bunch lengthening, simulations were performed with the PARMELA computer code. The simulations take into account the electron gun geometry and the laser-pulse parameters at different bunch intensities (up to 4×10^9 electrons), and they consider a uniform emission of electrons from the photocathode. Table I shows the result of simulations. At 60 kV and at a relatively low beam intensity (10^8 electrons) the contribution of the space charge to the bunch length is negligible.

According to these results, the GaAs response time does not exceed the total measurement error. As this error relatively is high, we prefer to state only an upper limit for the response time, i.e., $\tau_{\mathrm{GaAs}} < 40$ ps.

These results suggest that a GaAs photocathode can be installed in a rf gun with a frequency of up to 1 GHz or more. Valid opportunities are also envisaged at higher frequencies.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to G. Abbrugiati, G. Balikov, M. Lishenkov, and V. Valentino for their valuable support in assembling the setup.

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