THE STUDY OF FOCUS-DEPENDENT DARK CURRENT FOR AREAL RF PHOTOGUN

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Abstract

AREAL (Advanced Research Electron Accelerator Laboratory) is a laser driven photocathode RF gun based electron linear accelerator project aimed to produce ultra-short bunches with small emittance. As the first phase of the project an electron RF gun was accomplished, providing short electron pulses with 5 MeV energy, which are used for ultrafast irradiation experiments in life and materials sciences [1]. For such experiments an exact calculation of the absorbed dose and electron bunch peak current is one of important conditions. The presence of a dark current in electron gun affects the electron emission from photocathode, the exact absorbed dose calculation, and in general, harms the machine performance. One of the possibilities to avoid the presence of a dark current in the experimental area is to use the energy difference between "on-phase" electron beam and "spread over RF pulse" dark current. Based on the energy difference the influence of focusing solenoid strength on each pulse will be different. In this paper the estimation of dark current amount, produced in the electron gun, the ways to avoid its influence on experiments are discussed. The dark current measurements are compared with the simulation results. The electron beam separation from a dark current is discussed.

INTRODUCTION

AREAL is a laser driven RF photogun electron linear accelerator. The main purpose of AREAL accelerator [2, 3] is the generation of electron bunches with 5-20 MeV energy, small emittance and sub-picosecond pulse duration for advanced researches in the fields of accelerator technology, new radiation sources and applications in life and materials sciences. In the first phase of project implementation an electron beam with energy up to 5 MeV is produced in the RF photogun section with a 1.5 cell S-band cavity. The experimental set-up of AREAL facility is shown in Fig. 1.

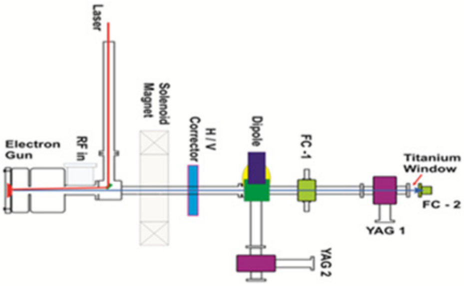

Figure 1: Schematic layout of AREAL setup (phase 1).

The beam parameters for two nominal operation modes are presented in Table 1.

The photoelectrons are emitted by illuminating metallic (copper) cathode with a high energy ultrafast UV laser pulse of 0.4-8 psec duration. While photoemitted electrons are generated by the laser pulse, having about the same pulse duration due to a short response time (about 10 fsec) of cathode material, a dark current is emitted along the entire RF pulse length. Due to high electric field and long field emission time, the total charge of dark current can be comparable to the beam charge. The dark current forms the so-called "non-desirable tail" of the bunch, which worsens the electron beam quality, impairs emittance and energy spread measurements. A large dark current may produce a parasitic radiation, causing wrong dose calculations and undesirable irradiation effects during radiation experiments. By the usage of solenoid magnet and spectrometer we have studied the main beam separation possibility to minimize the dark current influence on experimental conditions.

Table 1: Operating Parameters of the Electron Beam

	Single Bunch	**Multi Bunch**
Number of Bunches	1	16
Energy (MeV)	5	5
Bunch Charge (pC)	300	10-15
Transv. Profile (x/y) (mm) rms	1.5/1.6	0.65/0.55
Norm. transv. emit. (mm-mrad)	<0.3	<0.3
Pulse length FWHM (ps)	0.5-8	0.5-1
Pulse rep. rate (Hz)	1-50	1-50

DARK CURRENT SOURCE AND SIMULATION

For some materials the presence of an electric field, more than 10 kV/m near the surface, leads to electron field emission. Field-emitted electrons are the main source of a dark current [4,5] in RF guns. In AREAL gun cavity, filled with 6 MW of RF power, a high electric field of about 110 MV/m near the cathode surface is used to accelerate the electrons emitted from the photocathode. The average voltage obtained in gun cavity is in order of 5 MV. In an electron gun the presence of high accelerating RF field leads to a significant amount of field electron emission. The major part of electrons is emitted from the cathode and its surroundings, because of maximal electric field being located at it. Part of the field-

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emitted electrons, due to RF phase synchronization, can be accelerated by an electric field along with the "main" beam.

The field emission current *I* can be described by the modified Fowler-Nordheim (F-N) relationship [6, 7]

$$I=S\frac{C*(\beta E_0)^{2.5}}{\Phi}\exp(-B\frac{\Phi^{1.5}}{\beta E_0}), \qquad (1)$$

$$C=\frac{2\sqrt{2}}{3\pi}*\frac{A}{\sqrt{B*\Phi^{1.5}}},$$

where E_0 is the amplitude of the sinusoidal macroscopic surface field in V/m, Φ is the work function of the emitting material in eV, β is the field enhancement factor and S is the effective emitting area (m^2). The constants A and B are given as $A=1.54*10^{-6}$ and $B=6.83*10^{9}$. The slope of F-N plot linear fit (Fig. 2) is used to calculate the field enhancement factor [6]. For copper photocathode the work function is 4.8 eV. Thus, using Eq. (1), we calculated the field enhancement factor $\beta=98$:

$$\beta=\frac{6.83*10^3*\Phi^{1.5}}{k_2}, \qquad (2)$$

where k_2 is the slope of the fit.

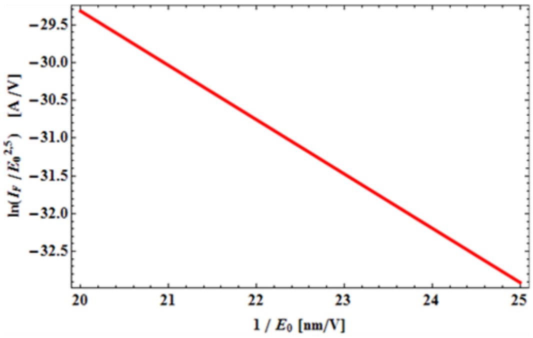

Figure 2: The Fowler-Nordheim plots for the enhancement factor determination components.

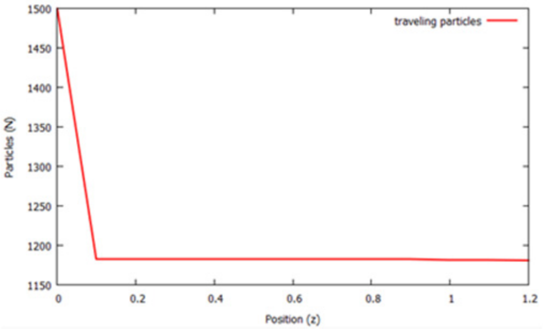

Figure 3: Simulation of dark current transmission along the facility by ASTRA.

To model the transmission of the dark current along the accelerator we used ASTRA tracking code [8]. In simulation the dark current was assumed to be emitted mostly from the cathode, its surrounding area and cavity irises. The electrons, starting from cathode area, are accelerated downstream to Faraday Cup (FC1 in Fig. 1), where real measurements can be performed. By comparing the measured charge with simulation results, one can reproduce the total dark current amount emitted in the gun. The simulation has shown that about 21% of particles do not reach FC1 and most of them are lost already in the first half-cell of gun resonator. The result of dark current transmission is presented in Fig. 3.

According to the obtained results, we observed that a considerable amount of dark current is transported through the RF gun, which is added to the "main" beam.

DARK CURRENT MEASUREMENTS

To estimate the dark current impact on absorbed dose calculations for the experiments, dark current measurements have been carried out at experimental stations, using Faraday Cups (Figure 1). The beam charge and dark current were measured at FC1 located on straight beam pass and at FC2 at the spectrometer arm. The maximum of the transported dark current was focused into FC, using the solenoid magnet. For 3 µs RF pulse length, 3.3 MW RF power and 6.5 A solenoid current, the measured maximum charge of dark current at the straight arm was 390 pC (Fig. 4).

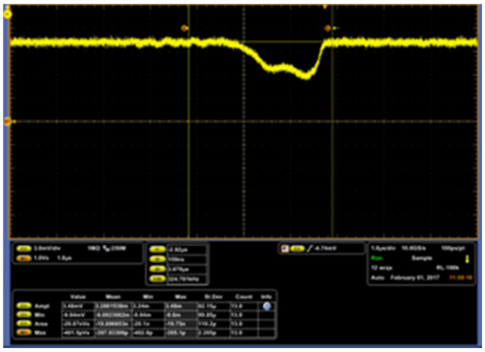

Figure 4: Dark current charge measured at FC1.

The main sources of dark current emission are gun resonator cell irises and the surroundings of photocathode. The accelerating longitudinal component of the RF field has its maximum on gun axis. Since the electrons, emitted from irises, are quite off from RF axis, they are more influenced by the radial component of the electric field, leading to additional focusing of the dark current.

Dark current measurements were carried out for several nominal operating regimes to estimate the influence of dark current on experiments. Charge measurements at FC1 were performed for different solenoid currents and several values of the RF power (Fig. 5). The results have shown that the dark current charge could be comparable to the "main" electron beam charge. The maximum charge of the dark current was measured ~491 pC with 3.8 MW RF power and 5 A of solenoid current. The increase of solenoid current to a value, focusing the "main" beam, is decreasing the dark current charge about twice (Fig. 5).

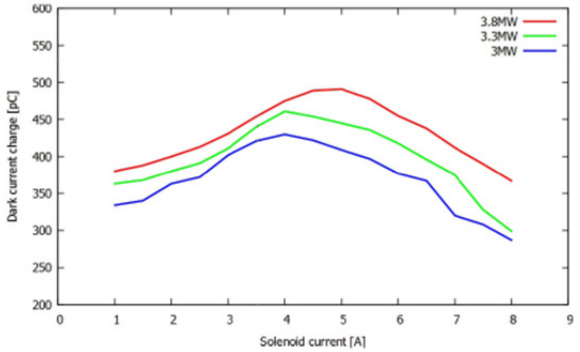

Figure 5: Dark current charge as a function of solenoid current measured for several RF power values.

To measure the dark current mean energy and transported charge after spectrometer dipole, the YAG-2 screen and FC2 are used. For the experimental setup, corresponding to beam energy of 3.2 MeV and optimal solenoid current of 8.2 A, the beam and dark current profiles were recorded using YAG-2 screen (Fig.6).

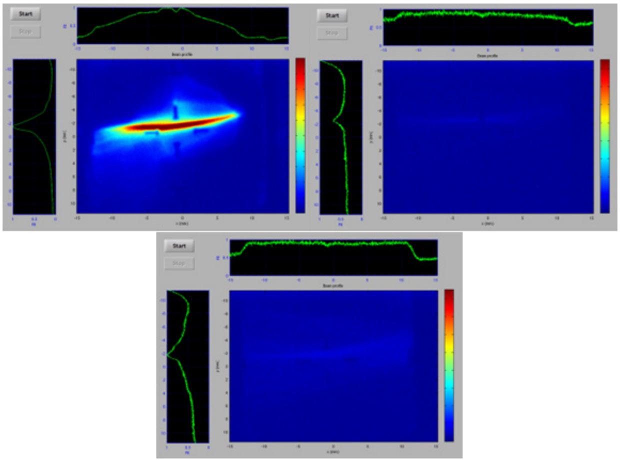

Figure 6: Accelerated beam (left) and dark current (right) images at YAG screen for the nominal experimental set-up. The profile of maximum dark current focused at YAG-2 screen for non-experimental conditions (bottom).

The maximum dark current image at YAG screen has been recorded by decreasing the solenoid current from 8.2 to 5.9 A and the dipole current from 3.5 to 2.5 A (Fig. 6 bottom). The measured dark current energy threshold is 2.4÷2.9 MeV, the average energy of dark current electrons is about 2.6 MeV. Since the dark current is emitted along the entire length of RF pulse, some electrons can reach the energy of the main beam, which is seen in Fig. 6 (left).

To estimate the dark current contribution to the absorbed dose at irradiated target, charge measurements at experimental point have been done using FC2. According to the measurements, the dark current contribution, for nominal experimental conditions, is at the level of FC scope signal noise (Fig. 7 left). Due to a large difference between the beam and dark current charges, the measurements on the same scale of the scope were impossible. Thus, the cut signal of beam charge with dark current scale is presented in Fig. 7 (right). Because of being on the noise level the dark contribution is counted as a noise in a level of 0.1 % of measured beam charge signal.

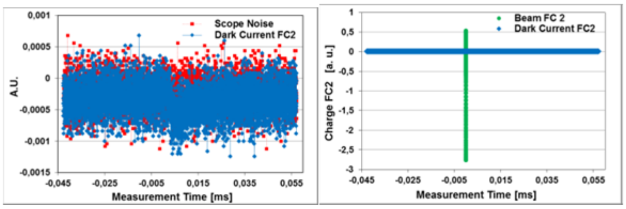

Figure 7: Left: dark current charge (blue) and the FC scope signal noise (red). Right: the cut signal of beam charge (green) and dark current (blue) with the same scope scale.

CONCLUSION

To provide "pure" electron beam for irradiation experiments, measurements and simulation of dark current, emitted in the electron gun, have been performed. The dark current charge maximum dependence on solenoid field for several RF power settings has been studied. The solenoid current and the spectrometer dipole field were optimized to minimize dark current contribution during the experimental sample irradiation. For nominal experimental conditions, the dark current contribution to experiments at the spectrometer arm was at the level of 0.1 %, with respect to the main beam.

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