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DARK CURRENT STUDIES AT RELATIVISTIC ELECTRON GUN FOR ATOMIC EXPLORATION – REGAE

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Abstract

In this paper dark current studies which have been performed at REGAE are presented. The data are analyzed and interpreted in terms of the Fowler-Nordheim field emission theory. The dark current increased after a vacuum accident, which gave the opportunity to document the reconditioning of the cavity. A correlation of field enhancement factor and effective emission area is found.

INTRODUCTION

Relativistic electron diffraction is a tool to explore structural dynamics of matter. The scattering cross section is several orders of magnitude higher for electrons than for X-rays so that only a small number of electrons is required to achieve comparable results. However, the required electron beam quality is extraordinary. To study e.g. proteins a coherence length of 30 nm is required which translates into a transverse emittance of 5 nm at a spot size of 0.4 mm. In addition short bunch lengths down to 10 fs and a temporal stability of the same order are required in order to study chemical reactions or phase transitions in pump-probe experiments. These are challenging parameters for an electron source, which can only be reached at a low bunch charge of about 100 fC.

Recently a photocathode electron gun called REGAE (Relativistic Electron Gun for Atomic Exploration) [1] has been commissioned at DESY with the goal to produce electron bunches as required for electron diffraction [2, 3]. REGAE employs a photocathode S-band rf gun. Operation at high accelerating fields provides means to suppress space charge induced emittance growth, in turn high fields increase field emission and lead thus to a higher dark current. The contrast of photo emitted to field emitted electrons plays an essential role for the quality of the recorded patterns. Minimization of this detrimental contribution requires to study the generation and propagation of dark current.

While the photo emitted electrons are generated in short pulses (< 100 fs), dark current is emitted throughout the length of the rf pulse with low charge per rf bucket and integrates up on the detector. The relevant parameter for the image quality is hence the integrated dark charge. The main source of dark current is the back plane of the rf gun, where both the field and the capture efficiency for field emitted electrons is highest. Differences in the beam parameters as e.g. energy and charge per bunch lead to differences in the beam optics of the photo emitted electrons as compared to field emitted electrons; space charge effects are for example negligible for dark current electrons. Thus a large fraction of field emitted electrons are lost during the beam transport to the detector. Dark current collimators are a means to increase these losses, however, a fraction of the dark current overlaps with the beam in phase space such that it can't be removed by collimators. A minimization of the field emission in the gun in addition to an efficient collimation is hence necessary. The following discussion concentrates on the generation of the dark current. For the measurements the dark current is focused onto a Faraday cup and no collimators are used, a conclusion on the actual back ground contribution in the detector plane cannot be drawn.

The measured dark charge in an actual setup depends on many parameters which may be sorted into three groups: the operation state, the conditioning state and the preparation state of the setup. The operation state covers parameters as rf gradient and pulse length, focusing conditions and beam apertures. Even for a constant operation state the measured dark charge is, however, not constant, because field emission depends on the surface characteristics in the high field regions of the cavity which can change during operation. Geometrical irregularities as e.g. dust particles with sharp edges provoke field emission due to local field enhancement. But the current drawn through the emitter during field emission leads also to heating of the emitter which can destroy it. Thus field emission can be reduced during high gradient operation. A general reduction of the field emission requires a careful preparation of the gun cavity. Smooth surfaces without scratches are general requirements for cavities operating at high gradients. In addition the cavity needs to be cleaned prior to installation in order to remove dust particles. (Complemented by mounting under clean room conditions.) The gun in operation at REGAE has been cleaned by Dry Ice Cleaning (DIC) [4, 5], a technique which has been used before for rf guns operating at 1.3 GHz for FLASH and PITZ, where a dark current reduction by more than a factor of 10 could be demonstrated [6]. For REGAE no measurements of an uncleaned gun are available for comparison. Due to the dependence of the dark current on the operational and conditioning state it is in general also difficult to compare measurements made at different facilities. Moreover, published data concerning dark current for S-band guns are very limited. In Fig.1 a measurement of dark charge versus gradient at REGAE is shown. For this and all measurements following below a fixed focusing setting (i.e. independent of the gradient) is chosen, which roughly maximizes the dark charge measured on a Faraday cup 2 m downstream of the gun. The rf pulse length is 4.8 μs. For comparison in [7] a dark charge of 0.6 nC at 120 MV/m gradient and 2 μs rf pulse length is reported. Measurements presented in [8] with 2.5 μs taken as effective emission time (as REGAE) result in about 11 pC at 74 MV/m.

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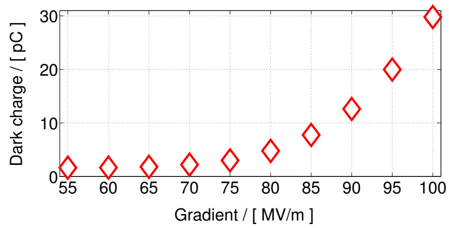

Figure 1: Measured dark charge vs. gradient for a 4.8μs long rf pulse at REGAE.

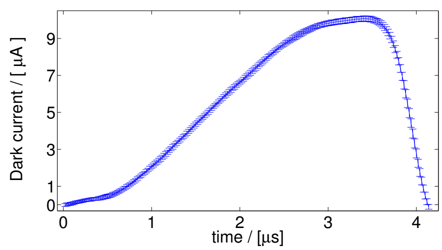

Figure 2: Dark current sample trace at a gradient of 75 MV/m. Average of 200 shots, the error bars display the standard deviation of the measurements.

MEASUREMENT AND DATA ANALYSIS

Charge measurements at REGAE are performed with Faraday cups or a cavity monitor [9]. At the diagnostics station downstream of the buncher cavity a Faraday cup is equipped with an amplifier which enables dark current measurements. Hardware and electronics are described in detail in [9]. Fig. 2 shows a typical measurement of a dark current trace. Here 200 shots are averaged, the error bars represent the standard deviation of these 200 shots. Rms deviations are small despite the fact that they include the overall effect of all errors like machine instabilities, statistical behavior of field emission and noise of the measurement device and digitization electronics as well as amplifier noise.

Fowler-Nordheim plots [10] have been created to see whether the measured dark current depends on the field strength as expected from field emission theory. The field emitted current for an alternating field can be expressed as [11]:

$$\bar{I}_F = \frac{5.7 \times 10^{-12} \times 10^{4.52\phi^{-0.5}} A_e (\beta E_0)^{2.5}}{\phi^{1.75}}$$

$$\times exp\left(-\frac{6.53 \times 10^9 \times \phi^{1.5}}{\beta E_0}\right)$$

where E_0 is the amplitude of the sinusoidal macroscopic surface field in V/m, β is the enhancement factor and $\bar{I}_F$ is the average field emitted current in amperes from an emitting area A_e in m^2. In a semilogarithmic plot of $\bar{I}_F/E^{2.5}$ versus $1/E$ the data should yield a straight line with β derived from the slope as:

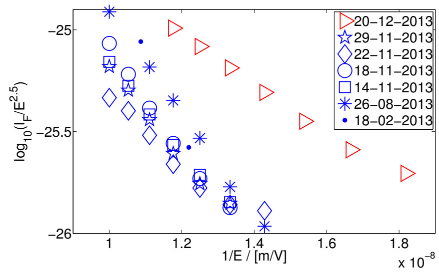

Figure 3: Fowler-Nordheim plot for the period before the vacuum problem. A first measurement result after the vacuum accident is added for comparison.

$$\frac{d\left(log_{10}\bar{I}_F/E^{2.5}\right)}{d\,(1/E)} = -\frac{2.84 \times 10^9 \phi^{1.5}}{\beta}$$

A_e can then be deduced from the offset of the line.

MEASUREMENT RESULTS

REGAE was commissioned in 2012 and is delivering electron beams for diffraction experiments since [2]. Dark charge measurement were performed from Feb. 2013 on. In Dec. 2013 an rf-probe developed a small vacuum leak in which course the dark current increased considerably. The vacuum level went up to 10^{-8} mbar only. We assume hence that no particulates had been produced due to the leak and that the gas flow was also too small to relocate particulates inside of the cavity. The increased level of dark current appears hence to be related to surface adsorbates. The accident gave an opportunity to document the reconditioning of the cavity after the vacuum leak had been fixed.

In Fig. 3 results are shown for the period before the vacuum leak appeared plus one measurement after the vacuum leak had developed. Note that different cathodes (Cs_2Te, Mo, Au) had been used during this and also during the following periods. Different cathodes show somewhat different dark current levels but are not fundamentally different. Moreover, variations of the work function in the Fowler-Nordheim formula lead only to small variations of the field enhancement factor and effective area. Since it is not clear whether the dark charge is coming from the cathode itself or from the surrounding back plane of the cavity the work function of copper was used (4.6 eV) for the analyses of the measurements.

Except for the lowest dark current levels, where the precision of the measurements is limited, the data follow in general nicely a straight line in the Fowler-Nordheim plots, i.e. no anomalous behavior was found. Results for the periods during and after the vacuum problem show a similar quality with varying slopes and offsets as will be discussed below. The derived field enhancement factor and effective area can

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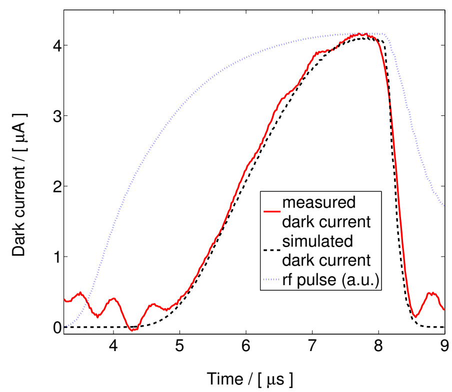

Figure 4: Measured and calculated dark current within an rf pulse. The dark current pulse appears to be delayed and shortened as compared to the rf pulse.

be used to calculate the temporal development of the dark current pulse as shown in Fig. 4. Here the measured rf field has been combined with the corresponding parameters from the Fowler-Nordheim analysis. As pointed out in [12] the dark current pulse appears to be delayed and shortened as compared to the rf pulse. This is due to the exponential dependence of the dark current and in full agreement with the field emission model. The ratio of integrated dark charge to the maximal dark current defines an effective dark current pulse length, which yields 2.5 μs for our case. We operate the rf with a 1 μs short flat-top to allow the rf feedback systems to adjust. Reducing the pulse length by this 1 μs from 4.8 to 3.8 μs would hence lead to a 40% reduction of the dark charge.

Field enhancement factors β and effective emitter areas A_e for dark current measurements taken before, and after the vacuum event are collected in Fig. 5. All data are found to follow two distinct exponential-like curves. High field enhancement factors coincide with small effective emitter areas A_e and vice versa. A similar kind of anti-correlation has been reported previously in [13]. A statistical interpretation of the data implies that a small number of emitters with high field enhancement factor dominate the measurements when the cavity is not well conditioned. During the conditioning the emitters with high β disappear first and emitters with lower field enhancement factor become dominant. At the same time the total effective area of the dark current emitters increases. The curves displayed in Fig. 5 can hence be understood as representations of the distribution function of the emitters active in the gun cavity. We assume that the curves represent the preparation state of the cavity, while an actual measurement of the dark current relates much more to the conditioning state of the cavity. The measurements show that the preparation state of the cavity has been degraded by the vacuum event and the previously achieved dark current levels cannot be fully recovered (for identical conditioning states). It requires however more data, possibly also from other setups, to consolidate this interpretation.

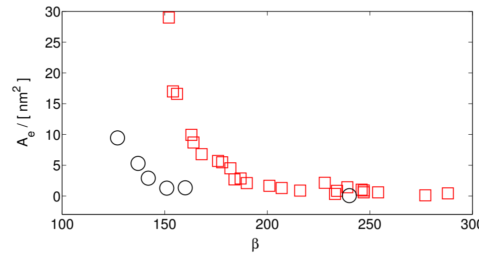

Figure 5: Compilation of field enhancement factors β and effective emitter area A_e for dark current measurements at REGAE. Circles are for the time before the vacuum problem appeared, squares show results after the vacuum problem had been fixed. All results are found to follow two exponential like curves.

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