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Experimental optimization of the 6-dimentional electron beam emittance at the NSLS SDL

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ABSTRACT

Experimental optimization of the 6-dimensional electron beam emittance generated by a Magnesium (Mg) photocathode RF gun is presented in this report. A new electron beam optimization algorithm for a low charge (<100 pC) beam was experimentally demonstrated; where the electron beam velocity bunching inside the RF gun plays a critical role, and the transverse emittance as a function of the laser-RF timing jitter was experimentally characterized for the first time. A 20 pC electron beam was optimized to have a normalized slice emittance of 0.15 mm mrad and a longitudinal projected emittance of 3.9 ps keV. Furthermore, the upper limit of the measured thermal emittance—0.5 mm mrad per mm of the rms laser size, is about 50% lower than the theoretical prediction for a Mg cathode (Qian et al., 2010) [1].

1. Introduction

The success of the Linac Coherent Light Source (LCLS) has brought inspiration to the development of X-ray free-electron lasers (XFEL) around the world, and better than expected electron beam brightness has led to more aggressive XFEL designs [2–7]. One of the inspirations is the change of the XFEL electron beam from the conventional design of a high charge ($\sim$1 nC) to the empirical optimization of a modest charge ($\sim$0.25 nC) [2–4]. Due to the smaller collective effects, such as space charge and coherent synchrotron radiation (CSR), both transverse and longitudinal emittance are improved for the 0.25 nC beam leading to a higher electron beam brightness than the electron beam with the nominal 1 nC charge. This idea has been extended to operating a photoinjector in the regime of even lower charge (1–20 pC), which is expected to enable production of $\sim$1 fs electron pulses with $\sim$0.1 mm mrad normalized transverse emittance, and enable the generation of an ultrashort or potentially fully coherent Self-Amplified Spontaneous-Emission (SASE) XFEL [3,8,9].

With the growing interest in low charge FELs, it is necessary to revisit the photoinjector optimization algorithm in the low charge regime, where the beam optimization strategy for both emittance compensation and bunch compression is expected to be different from the high charge mode. For example, with the reduction of the space charge effect, the transverse emittance could be dominated by the thermal and RF emittances, so minimization of the RF induced emittance is very important for achieving an ultralow emittance. The bunch compression of a low charge beam could be simplified by the combination of velocity bunching together with a single chicane compression resulting in an ultrashort electron beam ($\sim$1 fs) [3,8–10].

In this paper, we present a systematic 6-D emittance study of the high-brightness electron beams from a Mg photocathode RF gun at the Source Development Laboratory (SDL) of the National Synchrotron Light Source (NSLS) [11]. A new electron beam optimization algorithm for the low charge regime ($\sim$20 pC) was experimentally demonstrated. Experimental results show that velocity bunching in the gun is important not only for bunch compression, but also for optimization of both the transverse and longitudinal emittances [10]. The rest of this paper is organized as follows: a brief description of the SDL facility and operation experience with Mg cathode are discussed in section II. The experimental results for the low charge emittance optimization are presented in the section III. We also present the first experimental observation of emittance growth caused by the laser-RF timing jitter.

2. Experimental setup and Mg photocathode performance

The experiments reported here were performed at the NSLS SDL [11]. The NSLS SDL is a laser and linac facility featuring a high-brightness electron source; a 4-magnet chicane bunch compressor and an S-band SLAC type traveling wave linac. The high-brightness electron source is an S-band BNL-type photocathode RF gun with a Mg cathode. The photocathode drive laser

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is a frequency tripled (4.66 eV) Ti:Sapphire laser based on chirped pulse amplification (CPA).

Fig. 1 is the schematic layout of the SDL experimental setup for the QE and emittance studies. The SDL injection system consists of a photocathode RF gun, a solenoid magnet, UV optics and electron beam diagnostics. The photocathode RF gun operating with the normally incident UV light generates a 5 MeV electron beam, which is then focused by the solenoid magnet. The main electron beam diagnostic is a beam profile monitor (BPM) with a YAG screen; the 0.25 mm thick YAG screen is positioned perpendicular to the electron beam and is followed by a 45° metal mirror. The mirror reflects the electron beam image on to a CCD camera. The metal mirror is electrically isolated so it also functions as a Faraday cup for beam charge measurements. To minimize the space charge effect, the emittance of the photoelectron beam is characterized after the electron beam is accelerated by two sections of the linac (*T*1 and *T*2) to an energy of ~70 MeV. The emittance measurement is done using the standard quad-scan technique [12]: a quadruple triplet followed by a YAG screen BPM. During the transverse emittance study, the chicane and the down-stream linac sections *T*3–*T*5 were turned off.

Inside the SDL photoinjector is a Mg cathode, which is friction welded into a copper substrate, and has been generating photoelectrons since 2004. The QE of the SDL Mg cathode with a 266 nm UV laser is 0.2% [1], which is the highest value reported for a metal cathode [13]. Due to the active chemical properties of Mg, the contamination formed on the cathode surface degrades the QE over time. To keep the QE in routine operation above 0.01%, the photocathode laser is also used for cathode cleaning [14]. During the cathode cleaning, the RF gun vacuum is used as an in-situ monitor of how much of the surface layer is removed. To achieve effective cleaning without damaging the cathode, the intensity of the 100 μm (rms spot size) UV laser, is adjusted until the vacuum increases from the static value of $\sim 4 \times 10^{-10}$ to $\sim 8 \times 10^{-10}$ Torr. After a good cathode cleaning, the Mg QE typically improves by an order of magnitude and goes above 0.1%. QE value higher than 0.1% usually lasts for 1–2 weeks, and then stabilizes on the level of 0.06% for months, and finally drops to 0.01% gradually. Fig. 2 plots the QE history of the Mg cathode in the calander year 2009; it shows that the QE in routine operation was always higher than 0.01%, and the interval between cathode cleanings varied from 2 to 6 months depending on the gun vacuum and experimental requirements.

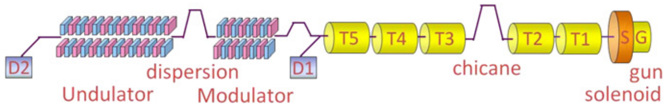

Fig. 1. Schematic of the experimental setup for the QE and emittance studies at the NSLS SDL (distances and sizes are not in proportion).

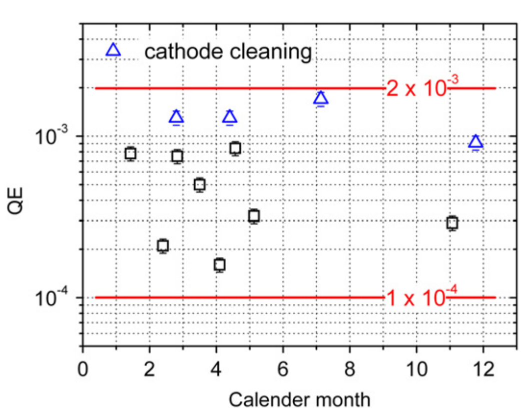

Fig. 2. Mg cathode QE history in the calendar year 2009.

3. Experimental optimization of the 6-dimensional emittance

The experimental procedures of emittance optimization for a 20 pC beam are presented in this section. We then discuss the experimental studies of the laser-RF timing jitter and the resolution of the emittance measurement technique. We concluded this section with a discussion on the thermal emittance of the Mg cathode.

Generally speaking, the transverse emittance of the electron beam generated by a photocathode RF gun can be categorized in three parts: thermal emittance, RF emittance and space charge emittance. The thermal emittance is mainly determined by the photoemission process. The transverse and longitudinal emittances induced by the RF effects are [15]:

$$\varepsilon_x^{rf} = \frac{\alpha k^3 \sigma_x^2 \sigma_Z^2}{\sqrt{2}} \tag{1}$$

$$\varepsilon_z^{rf} = \sqrt{3}(\gamma - 1)k^2 \sigma_z^3 \tag{2}$$

where $\alpha = eE_0/2mc^2k$ is the normalized field strength, k is the RF wavenumber, σ_x and σ_z are the transverse and longitudinal beam sizes at the RF gun exit, respectively. Eqs. (1) and (2) show that the bunch length compression in the gun could lead to a reduction in both transverse and longitudinal RF emittance.

We first investigated the emittance as a function of the electron beam charge. Fig. 3 shows that the transverse emittance decreases as the charge is reduced with all other parameters fixed, such as laser spot size and RF gun phase. We would like to point out that the operating parameters used in Fig. 3 are not fully optimized. In order to control the emittance measurement error better than 10%, we choose a charge of 20 pC for further optimization; 20 pC will also allow us to make direct comparison with the results from the LCLS [3].

Emittance induced by the linear space charge forces can be removed by emittance compensation [16] while emittance due to the nonlinear forces remains. Previous studies show that a uniform 3-Dimensional ellipsoid [17] is the ideal solution to minimize the emittance growth due to the nonlinear space charge effect. In our experiment, a truncated Gaussian is used to approximate a quasi-uniform transverse laser distribution, and to linearize the transverse space charge effect. Besides laser shaping, a uniform QE over the cathode is also critical for space charge linearization [18]. Emittance growth due to the non-uniformity in QE was experimentally studied recently [1]. The vacuum based cathode cleaning

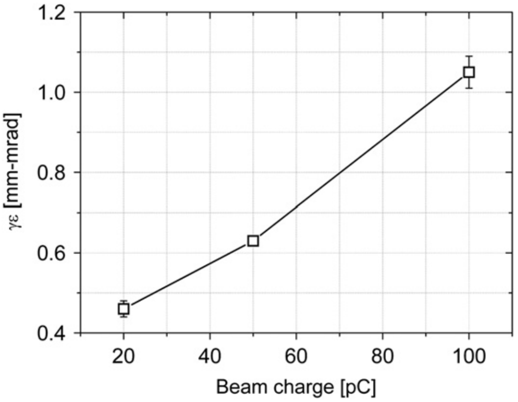

Fig. 3. Normalized transverse emittance as a function of the electron beam charge for a set of non-optimized parameters.