PHOTOCATHODE LASER WAVELENGTH-TUNING FOR THERMAL EMITTANCE AND QUANTUM EFFICIENCY STUDIES

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Abstract

The SwissFEL compact accelerator design is based on extremely low emittance electron beam from an RF photoinjector. Proper temporal and spatial shaping of the photocathode drive laser is employed to reduce the space charge emittance contribution. However, the ultimate limit for the beam quality is the thermal emittance, which depends on the excess energy of the emitted photoelectrons. By varying the photocathode laser wavelength it is possible to reduce the thermal emittance. For this purpose, we applied a tunable Ti:sapphire laser and an optical parametric amplifier which allow to scan the wavelength between 250 and 305 nm. The system permits to study the thermal emittance and the quantum efficiency evolution as function of the laser wavelength for the copper photocathode in the RF gun of the SwissFEL injector test facility. The results are presented and discussed.

INTRODUCTION AND MOTIVATIONS

The Paul Scherrer Institute (PSI) is building an X-ray Free Electron Laser (FEL) user facility, which aims to deliver ultrashort coherent photon pulses with wavelengths ranging between 0.1 and 0.7 nm by the year 2017 [1]. For cost and space reasons the driving accelerator is foreseen with relatively modest final energy, thus calling for very low emittance. In preparation of SwissFEL, PSI is commissioning a 250 MeV photo-injector (SITF), which intends to demonstrate the generation of high-brightness electron beams and serves as a realistic test bed for crucial components for SwissFEL [2].

Modern linear accelerators demonstrated that it is feasible to preserve the electron beam emittance throughout acceleration. It becomes therefore important to generate the electron bunch at the source with the lowest possible emittance. Its growth due to the linear space charge forces is effectively counteracted by emittance compensation scheme. The photocathode drive lasers employ typically spatial and temporal pulse shaping in order to compensate the emittance dilution due to nonlinear space charge effect. Therefore the thermal or intrinsic emittance becomes a realistic limit for the beam quality. This parameter is a measure of the temperature of the electrons emitted from the cathode and it depends on the excess of energy of the photoelectrons in vacuum. Thermal emittance is function of the cathode material and surface quality, the accelerating electric field and laser wavelength.

The value of the intrinsic emittance is linked directly to the quantum efficiency (QE) of the photocathode (number of emitted electrons per incident photons). In the presented work we characterize the intrinsic emittance and the QE in RF gun while varying the laser wavelength. Similar studies are reported for photocathodes in DC gun [3]. The intrinsic emittance, ε_{in} can be written as [4]:

$$\varepsilon_{in}(\omega) = \sigma_L \sqrt{\frac{\hbar\omega - \Phi_{eff}}{3mc^2}} \qquad (1)$$

with ω the laser wavelength, $\hbar\omega$ the photon energy, σ_L the rms laser spot size and Φ_{eff} the effective work function of the copper cathode including the Schottky effect. The Schottky term accounts for the reduction of potential barrier due to the applied electric field on the cathode surface. The total emittance can be reduced by adapting the laser photon energy to the net work function of the cathode. A decrease in quantum efficiency (QE) is expected when the laser photon energy approaches the effective work function. The QE can be expressed as [4]:

$$QE(\omega) \approx K \cdot \left(\hbar\omega - \Phi_{eff}\right)^2 \qquad (2)$$

K takes into account the reflection of the laser at the cathode surface and the probability of the emission process. From equations 1 and 2 it is clear that lower ε_{in} can be obtained at the price of also lower QE.

For the design of high brightness accelerator a trade-off between the maximum acceptable intrinsic emittance and the quantum efficiency need to be established. The lower QE calls for higher energy and more complex drive laser with consequent worsening of system stability and ability control the photon beam tridimensional shape.

EXPERIMENTAL SETUP

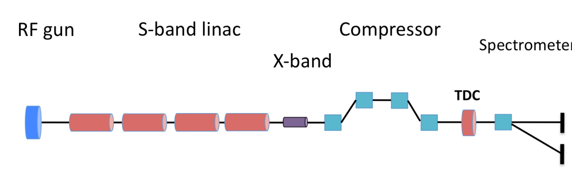

Figure 1: Layout of the swissFEL injector test facility.

The presented studies were conducted at the SwissFEL Injector Test Facility. The machine is based on a 3 GHz RF gun driven by a deep-UV laser on a copper cathode. The layout is depicted in Figure 1 and more details can be

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found in [1]. The photoelectrons are accelerated up to 250 MeV energy by four S-band cavities. In the last two structures the bunch is accelerated off-crest to apply an energy chirp. After linearization in an X-band and the compression in a magnetic chicane the electron beam 6D properties are measured in the diagnostic section. Here the Transverse Deflecting Cavity (TDC) allows for slice parameters reconstruction. The high-energy spectrometer is located at the end of the machine before the beam dump.

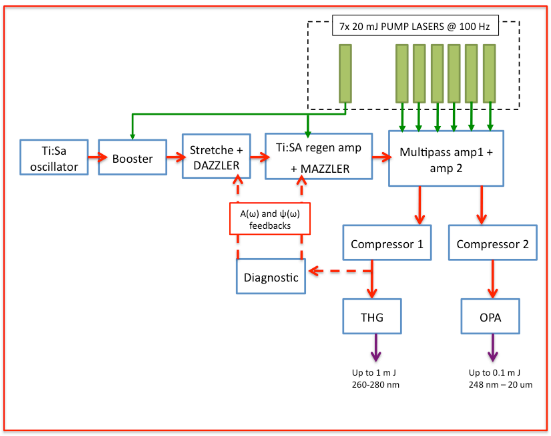

Figure 2: Layout of the swissFEL photocathode drive laser.

The laser system is based on Ti:sapphire oscillator and chirped pulse amplifier, Figure 2. The amplifier consists of a booster followed by a regenerative and two multipass amplifiers [5]. Seven identical Q-switched, frequency-doubled Nd:YAG pump lasers pump the amplifiers with a total energy of 120 mJ. The final pulse energy after compression is 20 mJ with a typical stability of 0.54 % RMS (4.4% P-P) over 5 minutes. The system is equipped with two compressors to pump independently the third harmonic generation (THG) and a white-light continuum optical parametric amplifier (OPA). Conventional Ti:sapphire amplifier do not allow for wavelength tuning. In our system, the DAZZLER and the MAZZLER programmable spectral filters [5] can be used to actively control the spectral width and the central wavelength of the laser pulse. The amplifier permits continuous adjustment within 760-840 nm with a typical spectral width used in the operation of 35 nm and 55 fs pulse. The THG is realized by sum frequency generation of the fundamental and the second harmonic. The pulse energy in the deep-UV reaches 1 mJ with pulse-to-pulse stability of 0.7% RMS (5.6% P-P). The unique architecture of the Ti:Sa laser system offers wavelength tunability in the fundamental, as well as in the second and third harmonic. Wavelength between 262 to 280 nm can be delivered to the cathode. Downstream the THG, flat top temporal shape is produced in pulse stacking crystals. A series of circular apertures on the laser beam, provide top-hat beam on the cathode with diameter varying from 50 μm to 1 mm. The OPA allows adjusting the deep-UV spectrum outside the tunability range of the Ti:sapphire. The output energy in the deep-UV reaches 0.1 mJ with pulse-to-pulse stability of <5% RMS. At the OPA, the pulse duration is shorter than 100 fs, therefore additional stretching in dispersive glass serves to lengthen the pulse duration to about 1 ps. This pulse is used only for QE measurements, while for the intrinsic emittance studies are conducted with the10 ps flat-top pulse out of the THG and pulse stacking setup.

The ε_{in} and QE studies are performed on a polycrystalline oxygen-free copper photocathode plug. The cathode has been used at SITF since January 2011. The surface was diamond milled with final peak to valley roughness of 3 nm. Prior to the installation the photocathode plug was baked out at 250 °C.

The intrinsic emittance was measured at the linac exit at 250 MeV for low beam charge. ε_{in} is determined as slice emittance of the central slice of low charge similar to the technique reported in literature [6]. Preliminary studies were done for different wavelengths and laser beam sizes. The laser diameter was controlled through different apertures while keeping constant surface charge density. The experimental conditions are characterized by RF phase set for minimizing the energy spread, solenoid field of 175.9 mT and accelerating field of 50 MV/m.

QUANTUM EFFICIENCY MEASUREMENTS

Figure 3 shows the emitted charge as function of the laser pulse energy for several wavelengths.

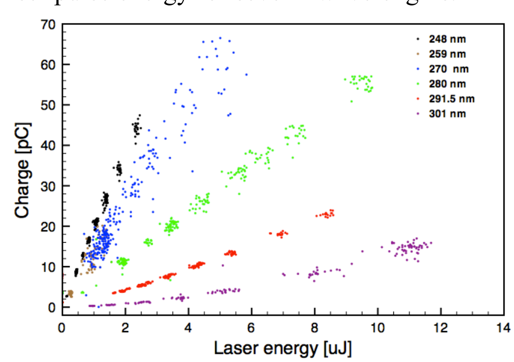

Figure 3: Charge versus laser energy for different photocathode laser wavelength.

Using the OPA, the laser spectrum was tuned between 248 and 301 nm (corresponding to photon energy from 4.1 to 5 eV). Ultra-broadband dielectric optics were employed in the optical transport to the RF gun. The largest laser aperture giving 1 mm laser diameter at the cathode, were used to avoid space charge induced saturation. The laser pulse duration was set to about 1 ps. For the experiment the gun field was regulated at the nominal phase, which corresponds to an accelerating field of 50 MV/m (nominal phase 38 deg and maximum electric field at the cathode of 85 MV/m). The charge was measured by means of calibrated beam position monitor.

As expected from the theory, the emitted charge is significantly increased as the difference between laser photon energy and work function grows. The QE ranges

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more than one order of magnitude from $5*10^{-6}$ to $1.5*10^{-4}$ electrons per incident photons. The curves indicate linear dependence and absence of saturation.

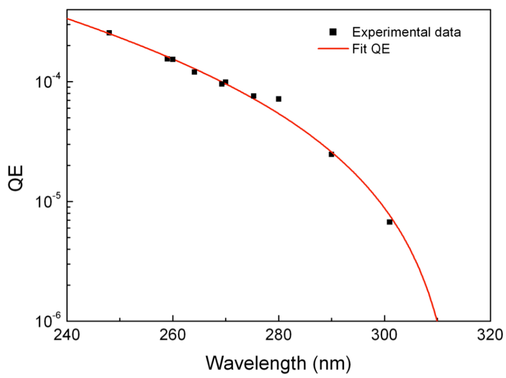

Figure 4: Quantum efficiency as function of photocathode laser wavelength and photon energy.

In Figure 4 the experimental QE data are compared with a quadratic fit as expected from the theory, equation 2. The fit intercepts quite well the experimental data. The effective work function turns out to be 3.93 eV. The Schottky barrier reduction calculated as in [4] for flat surface gives a photocathode work function of 4.2 eV. This value is slightly lower respect to value of 4.3 eV reported for copper in [3]. More detailed studies are foreseen to explain this discrepancy.

EMITTANCE MEASUREMENTS

Similar to [6] the intrinsic emittance is assumed to be equal to the minimum of the slice emittance at the linac exit for low charge electron bunch. The measurement was done at the exit of the linac with typical energy of 250 MeV. More details on the slice emittance measurement and reconstruction procedure can be found in reference [7]. For ε_{in} measurement the laser wavelengths were tuned using the DAZZLER and MAZZLER programmable filters and the THG. The OPA, in fact, turned out to be not suitable for reliable intrinsic emittance determination. In fact the low output energy paired to the high amplitude fluctuation (5% rms) and the strong spatial dis-uniformities hindered stable machine operation and careful intrinsic emittance quantification.

Two approaches were used for ε_{in} measurement. First the laser beam size at the photocathode was kept constant while changing the photon energy. In the second approach, ε_{in} is measured for different laser beam size and fixed wavelength.

The results of wavelength tuning at fixed laser size are reported in Figure 5. The experimental parameters are charge of 1 pC, laser rms size of 50 μm (density of 13 pC/mm^2) and 10 ps flat top laser pulse obtained by pulse stacking.

With the DAZZLER and MAZZLER filters the fundamental spectrum was adjusted in order to vary the THG wavelength 261 to 275 nm (the corresponding spectra are shown in the inset of Figure 5). The ε_{in} varies from 600 to 745 nm/mm. Slice emittance as low as 30 nm

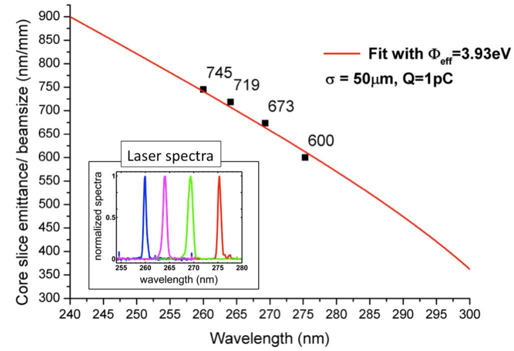

Figure 5: Intrinsic emittance for different photocathode laser wavelength and 50 um laser diameter.

were measured. The experimental data are well fit assuming an effective work function of 3.93 eV in agreement with the value to fit the QE in Figure 4.

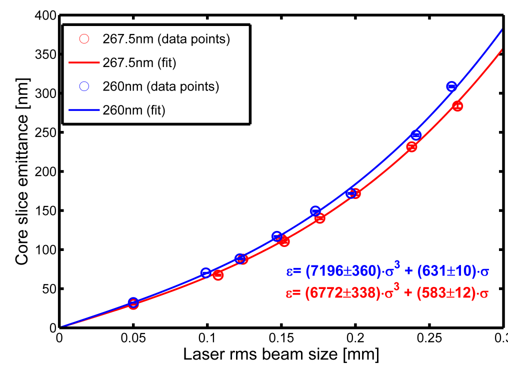

Figure 6: Intrinsic emittance as function of the laser rms spot size measured at 260 and 267.5 nm. The experimental points are displayed with third order polynomial fit.

The measured intrinsic emittance as function of the rms laser size for 260 and 267.5 nm is shown in Figure 6. For all the measurements, the charge density was kept at 30 pC/mm^2 with pulse duration of 10 ps FWHM.

For both the photon energies the measured dependence is nonlinear, as it would expected from equation 1. The ε_{in} data are instead well described by sum of a linear and third order fit. The nonlinearity could be explained by residual effect of the space charge. Extrapolating to the limit of zero beam size the intrinsic emittance corresponds to 585 and 626 nm for 266.5 and 260 nm respectively. This value is lower than the value estimated in Figure 5 suggesting that some additional emittance dilution effect affects the first measurements. Further studies are required to fully understand the experimental results.

CONCLUSION

At the SwissFEL injector test facility the effect of laser wavelength were studied for low charge electron bunch. We report for the first time measurement of quantum efficiency and intrinsic emittance in for a copper photocathode in a RF gun, for laser photon energies

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ranging from 4.1 to 5 eV. Preliminary measurements allow determining the effective work function of copper cathode in RF gun. This value permits to fit well the experimental data for the QE and the intrinsic emittance. Unexpected nonlinear dependence between the intrinsic emittance and the laser size is observed. Further studies are in progress to understand the experimental outcomes.

ACKNOWLEDGMENT

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