WAVELENGTH-TUNABLE UV LASER FOR ELECTRON BEAM GENERATION WITH LOW INTRINSIC EMITTANCE

C.P. Hauri, R. Ganter, B. Beutner, H.H. Braun, C. Gough, R. Ischebeck, F. Le Pimpec, M.L. Paraliev, M. Pedrozzi, C. Ruchert, T. Schietinger, B. Steffen, A. Trisorio, C. Vicario
Paul Scherrer Institute, Villigen PSI, Switzerland

Abstract

We developed a powerful UV laser at a central wavelength varying from 260-283 nm. The laser system based on a frequency-trippled Ti:sapphire amplifier delivers mJ pulse energy within a duration of 1-10 ps (fwhm) with 1.5 nm spectral width (fwhm). The system is used to explore thermal emittance and quantum efficiency dependence on photon energy from metallic photocathodes. With pepperpot and solenoid scan technique we have measured the predicted theoretical limit for thermal emittance at room temperature (0.4 mm.mrad/mm rms laser spot size at 283 nm) for metallic photocathodes.

MOTIVATION

In the framework of the SwissFEL project at Paul Scherrer Institute an electron gun test facility [1] has been built in order to study new schemes for reducing electron beam emittance from the source. The design of SwissFEL Free Electron laser at Paul Scherrer Institut is based on a laser-driven photocathode electron source with a low emittance of <0.4 mm.mrad. Since modern linear accelerators preserve the electron beam emittance throughout acceleration [2] it becomes important to extract electrons from a cathode with the lowest possible emittance.

The intrinsic emittance at the surface of a cathode can be expressed analytically as [3]:

$$\varepsilon_{\mathrm{int}\,r} = \sigma_r \sqrt{\frac{\hbar\varpi - (\Phi_0 - \sqrt{e^3 F / 4\pi\varepsilon_0})}{3mc^2}} \quad (1)$$

with σ_r the laser spot size (rms), $\hbar\omega$ the laser photon energy, Φ_0 the work function of the cathode material, F the effective surface electric field, mc^2 and e the electron rest mass energy and charge respectively. Note that intrinsic effects are neglected (T=0). Equation (1) suggests two approaches for reduction of the intrinsic emittance ε_{intr} at the cathode surface. First, by reducing emitting area size σ_r or second, by matching the photon energy $\hbar\omega$ to the effective work function Φ_{eff}. The effective work function Φ_{eff} is the material work function lowered by the Schottky term ($\Phi_{eff}=\Phi_0-(e^3F/4\pi\varepsilon_0)^{1/2}$). With the wavelength tunable laser source it becomes possible to vary the energy of the photons in order to match the potential barrier height modified by the Schottky effect. A drop in quantum efficiency (QE) is expected when one approaches the limit where the photon energy compensate the effective work function [3]. Here, we present results on the reduction of the intrinsic emittance by tuning the laser wavelength illuminating the cathode. We performed simultaneous measurements of emittance and QE when varying the laser wavelength for different photocathode materials such as Mo, Nb, Al and Cu. The key element for this experiment is a powerful wavelength-tunable frequency-trippled high-power laser system.

LASER SYSTEM

The laser system (Fig. 1) is based on Ti:sapphire oscillator with is injected into a regenerative amplifier after pre-amplification and temporal stretching. Two additional multipass amplification stages yield a pulse energy of 17 mJ at a 100 Hz repetition rate after compression. Six identical Q-switched, frequency-doubled Nd:YAG pump lasers (Centurion, Quantel Inc.) have been chosen to pump the various amplifier stages with a total pump power of 120 mJ.

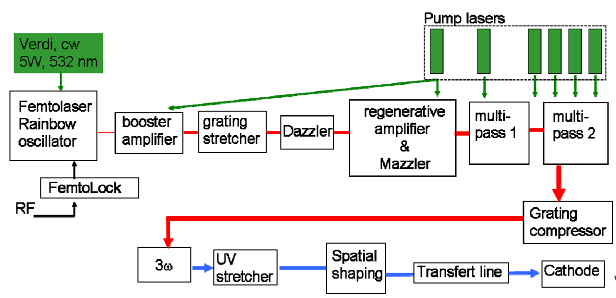

Figure 1: Amplifier layout with 3rd harmonic generation.

Conventional Ti:sapphire amplifiers provide a typical spectral bandwidth of about 40 nm (FWHM) or less and do not allow for wavelength tuning. In our system a Dazzler and a Mazzler [4] located in the regenerative cavity is used to control the spectral bandwidth of the amplified pulse and to helps to overcome such bandwidth-limiting effects. Our scheme has the potential to overcome spectral narrowing of conventional Ti:sapphire amplifiers and allows for broadband amplification up to 90 nm bandwidth (FWHM, Fig. 2). The Mazzler introduces a wavelength dependent loss inversely to the Ti:sapphire gain curve in order to achieve a flattening of the net gain over a large spectral range (blue curve). For driving the photocathode, however, pulse spectra of 15-25 nm (FWHM) at the fundamental wavelength are sufficient. Wavelength selection is performed by the Dazzler. The current amplifier scheme allows for contiuous variation of the central wavelelngth within a range of 760-840 nm with a spectral width of 25 nm.

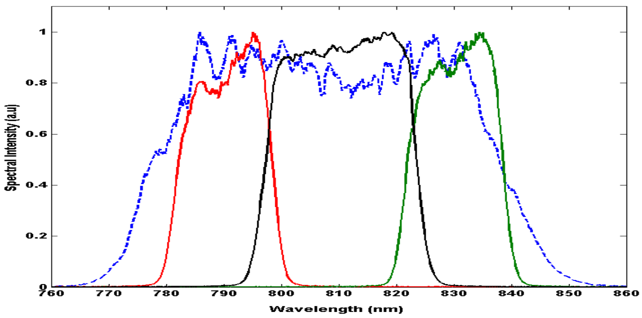

Figure 2: Broadband amplification with spectral gain filter (blue).

Wavelength-tunability could also be demonstrated for the third harmonic (Fig. 3). Frequency-conversion from the near-IR to the UV is done by second harmonic generation (SHG) in a β-barium borate (BBO) crystal (type I, 0.5 mm, φ=29.2°, ϕ=90°) and subsequent sum-frequency generation (SFG) in a second BBO crystal (type I, 0.5 mm, φ=42°, ϕ=90°). Such a control on the central laser wavelength (i.e. the laser photon energy) turned out to be helpful to produce low-emittance electrons in our low emittance gun test stand.

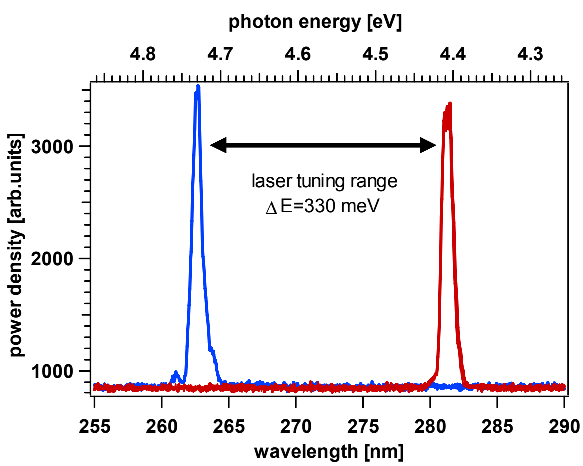

Figure 3: Wavelength tuning range of the frequency-trippled Ti:sapphire laser.

Electrons leaving the metal surface by photo-emission have a kinetic energy $E_{kin}=\hbar\omega-\phi_{eff}$, and thus a thermal emittance $\varepsilon_{th} \propto E_{kin}^{1/2}$ arising from the mismatch of the photon energy $\hbar\omega$ and the cathode work function ϕ_{eff}. The total emittance can therefore be reduced by adapting the laser photon energy to the net work function of the cathode material. Emittance measurements have been performed for different cathode materials at different laser wavelengths in order to reach lowest intrinsic emittance.

EMITTANCE MEASUREMENTS

All the emittance measurements were done at 6 MeV in a pulsed diode gun with an rf booster cavity (1.5 GHz). An overview of the accelerator beam line is shown in figure 4. The distance cathode to anode is 6 mm and negative voltage pulses of 300 kV amplitude and 200 ns full width half maximum (FWHM) duration are applied to the diode.

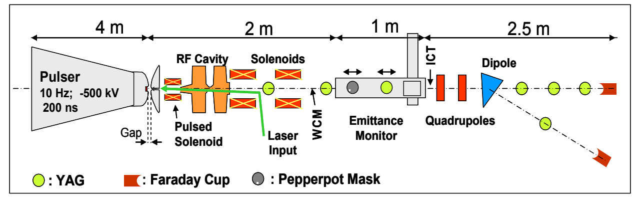

Figure 4: Schematic of the Diode-RF gun and the 4 MeV accelrator beam line with diagnostics

The metallic photo-cathode is inserted in a so-called hollow geometry (insert is recessed in regard to the holding lips) so that the electric field gradient on the cathode surface is 25 MV/m. This induces a reduction of work function by the Schottky effect of 0.23eV. Electrons are extracted from the cathode by photoemission using UV laser pulses with a Gaussian-like longitudinal profile of $\sigma_{t,laser}$= 4 ps rms. They leave the diode through a 2 mm diameter hole in the anode and are accelerated in the rf cavity to energies of up to 6 MeV.

Two different techniques, namely the pepperpot and solenoid scan method has been applied for measuring transverse emittance. Both techniques allow emittance measurements at very low charge (<1 pC). This is an important difference to previously published intrinsic emittance measurements.

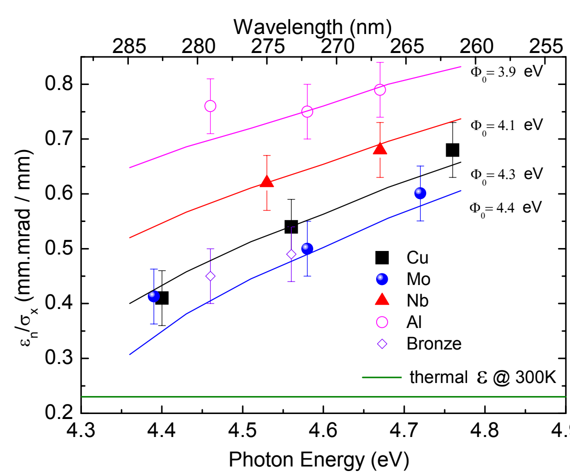

Figure 5: Normalized intrinsic emittance/mm for different cathode materials versus photon laser energy with theoretical curves according to eq (1).

Low charge emittance measurements allow for accurate determination of intrinsic emittance due to elimination of space-charge induced emittance degradation.

Normalized emittance characterization have been performed for different materials and at different laser wavelength, Measurements performed on metallic cathodes (Cu, Mo, Nb[1] and Al) are depicted in Fig. 5 together with theoretical predictions for different work functions (solid lines) according to Eq 1. Compared to copper, molybdenum presents similar emittance values suggesting an almost identical work function which is in agreement with literature [5].

For materials with a smaller work function than copper such as aluminum or niobium higher intrinsic emittance values are expected. This is confirmed on Fig. 5 where best fits to Eq. 1 are obtained for Φ_0^{Al} = 3.9 eV for aluminum and Φ_0^{Nb} =4.1 eV for niobium. These values are close to work functions reported in the literature [6] (4.2 eV for Al, 4.3 eV for Nb).

The lowest UV photon energy provided by our laser system (4.4 eV, Fig. 3) matches almost exactly the work functions of Cu and Mo (Φ_0^{Cu}~4.3 eV, Φ_0^{Mo}~4.35eV). However, a significant energy mismatch is present for Al and Nb which leads to an increase of uncorrelated kinetic energy of the electrons released from the cathode into the vacuum. For a given laser wavelength, we have measured an emittance increase of 50% for Al and 30% for Nb in comparison to intrinsic emittance of copper. Naturally, an extension of the laser wavelength tuning range would again give the possibility to reduce emittance for those metals.

While matching the photon energy to the work function of the cathode material lowers the intrinsic emittance it is expected from theory that the quantum efficiency drops for lower laser photon energies (i.e. λ_c>262 nm) [7] . Figure 6 shows the measured variation of QE with the laser for the above cited metals. The QE is determined by measuring the laser energy at the vacuum viewport entrance taking into account the losses from this position to the cathode (~10 %). For QE determination the laser energy was increased to measure charge above 20 pC with both the WCM and ICT at 1 m and 2 m distance from the cathode respectively. Illumination of copper at λ=262 nm provides a quantum efficiency of 1×10^{-5} ($\pm1\times10^{-6}$) for a cathode surface field of 25 MV/m. Higher QE of up to 2.0×10^{-5} ($\pm2\times10^{-6}$) was found for aluminum while Molybdenum shows almost an order of magnitude lower QE of 3.0×10^{-6} ($\pm0.6\times10^{-6}$) than Cu.

In fact, the change of quantum efficiency in dependence of laser wavelength was measured to vary by a factor of ≤2.5 over the explored wavelength range. Such QE at longer laser wavelength is still acceptable for electron guns and laser wavelength tuning seems the key to further reduce intrinsic emittance of conventional electron guns.

[1] (110) single crystal

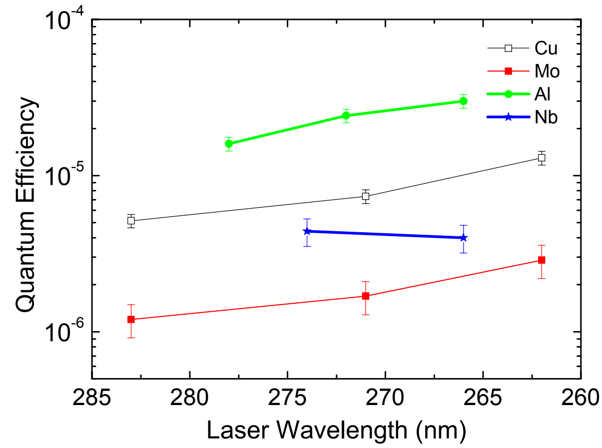

Figure 6: Quantum efficiency measurements for various cathode material at different laser wavelengths.

CONCLUSIONS

We presented the design and performance of a Ti:sapphire laser system offering wavelength tuneability within a range of 263-282 nm. Such a wavelength-tunable UV laser system has the potential to produce a low emittance electron beam at the gun since the residual kinetic energy of the electrons ejected into vacuum is reduced by matching the photon energy to the cathode work function. We studied the impact of laser wavelength tuning on the emittance and quantum efficiency of metallic cathodes and could demonstrate an efficient reduction of the intrinsic emittance. By adapting the laser photon energy to the effective work function of the cathode material, the projected emittance per mm laser spot size was reduced by 40 % to 0.41 mm.mrad/mm for a polycrystalline copper cathode while QE dropped only by 60 %. The measured high QE at longer wavelengths is definitely advantageous for applications demanding low emittance and would be an ideal electron source for compact FELs and energy recovering linear accelerators.

REFERENCES

[1] R. Ganter et al. "Commissioning of a Diode/RF Photogun Combination,"Proc. FEL2009, Liverpool, UK, pp 317-320
[2] Y. Ding et al. PRL 102, 254801 (2009)
[3] Dowell et al. Phys. Rev. STAB 9, 063502 (2006)
[4] www.fastlite.com
[5] Eastman, Phys. Rev. B 2, 1-2 (1970)
[6] Handbook of Chemistry and Physics, edited by D.R. Lite (2010)
[7] K.L. Jensen et al. J. Appl. Phys. 102, 074902 (2007)