PHOTOCATHODE DRIVE LASER FOR SWISSFEL

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Abstract

For high brigthness photocathode RF gun, high quality laser pulses must be used to generate the photocurrent. Transverse uniformity and longitudinal laser flat top profile are predicted to improve the electron beam brightness. Moreover the laser stability and its sub-ps synchronicity respect to accelerating field are essential for stable and reliable operation. Finally the intrinsic emittance, which is the ultimate limit for the beam emittance, could be tuned by varying the laser photon energy. For this purpose, we developed a mJ frequency tripled Ti:sapphire laser, tunable within 260-283 nm range. Dependence of the intrinsic emittance and of the quantum efficiency with the photon energy has been measured and compared to theory for various metallic photocathode. In this paper the R&D activities aiming at the photocathode laser for the future SwissFEL project are reported.

INTRODUCTION

In the framework of the SwissFEL project at the Paul Scherrer Institute, laser-driven electron RF and DC guns are under development in order to generate the beam brightness required to drive the free electron laser [1-3]. In fact, the design of SwissFEL is based on photocathode electron source which approaches the limit of the intrinsic photocathode emittance. Since modern linear accelerators are able to preserve the electron beam emittance throughout acceleration [4], it becomes important to extract electrons from a cathode with the lowest possible emittance. This motivated an intense R&D on laser and photocathode. In this paper we report the photocathode drive laser performances and the experimental measurement on electron bunch intrinsic emittance.

The space charge emittance of the beam could be minimized by modifying the 3 dimensional laser distribution. The generation of cylindrical hard edge charge distribution is predicted to be helpful for effective emittance compensation [5]. This requires the independent control of the laser time shape at sub ps resolution, and the transverse top hat laser profile at the cathode.

Moreover, the intrinsic emittance and the quantum efficiency of metal photocathode could be optimized through the photon energy tuning. This requirement motivated the development of a tunable wavelength laser source able to deliver UV photons with energy spanning over 330 meV (260-283 nm).

Finally, the electron beam properties depend on the stability of the laser source. Low time jitter respect to the RF systems is necessary to extract the electron at stable optimized accelerating phase. Small laser energy fluctuations and pointing stability are needed to have steady beam working point.

In this paper we present the laser systems under development at PSI aiming at addressing the above requirements. A broadband Ti:Sa system (PULSAR by Amplitude Technologies) is used for wavelength tuning to study the emission properties of several photocathodes. Beside, a Nd:YLF laser (JAGUAR by Time-bandwidth) is used for the initial commissioning of the RF gun photoinjector and to test transverse beam spot manipulation.

INTRINSIC EMITTANCE MEASUREMENT

The PULSAR laser system is based on Ti:sapphire oscillator with is injected into a regenerative amplifier after pre-amplification and temporal stretching [6]. Two additional multipass amplification stages yield 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.

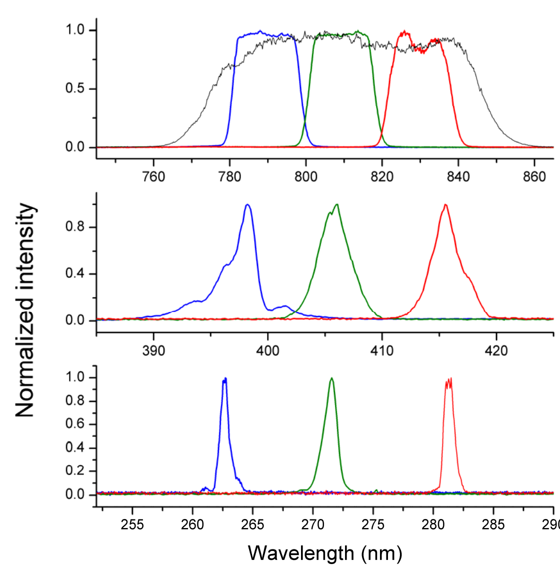

Figure 1: Example of spectra obtainable at the fundamental wavelength and at the laser harmonics.

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

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Dazzler and a Mazzler [7] located in the amplifier chain are used to actively control the spectral bandwidth and central wavelength of the amplified pulse.

Our scheme has the potential to overcome spectral narrowing of conventional Ti:sa amplifiers and allows for amplification up to 90 nm bandwidth FWHM. The Mazzler add wavelength-dependent losses compensate the laser gain curve in order to achieve a constant gain over large spectrum. For driving the photocathode, however, pulse spectra of 15-25 nm (FWHM) is sufficient for the shaping purposes. Wavelength selection is performed by the Dazzler. The amplifier allows for continuous variation of the central wavelength within a range of 760-840 nm with a spectral width between 25 nm to 90 nm (upper curve Fig.1).

Wavelength-tunability has been demonstrated also for the second and the third harmonics as well (Fig. 1 central and lower plots). Frequency-conversion from the near-IR to the UV is done by second harmonic generation in a β-barium borate (BBO) crystal (type I, 0.5 mm) and subsequent sum-frequency generation in a second BBO crystal (type I, 0.5 mm).

The central laser wavelength (i.e. the laser photon energy) is varied to produce low-emittance electrons in our low emittance gun test stand [3].

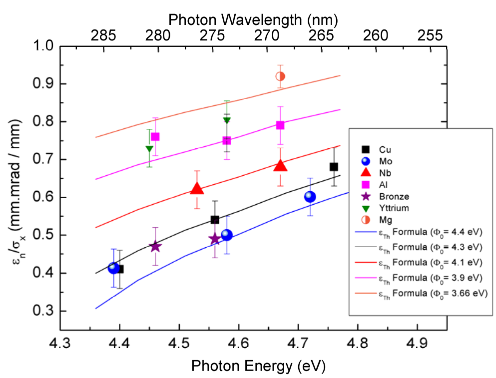

Figure 2: Intrinsic emittance for different metals as function of the laser wavelengths.

Photo-emitted electrons are characterized by a kinetic energy $E_{kin}=h\nu-\phi_{eff}$, and a intrinsic emittance $\varepsilon_{th} \propto E_{kin}^{1/2}$ arising from the mismatch of the photon energy hν and the cathode effective 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 at low charge, for different cathode materials at different wavelengths in order to reach lowest intrinsic emittance. The figure 2 summarized the result obtained and the comparison with the theory (solid curve) [8].

The emittance measurements were done at 6 MeV in a pulsed diode gun with an RF booster cavity (1.5 GHz), for detail see [3]. 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 photo-emitted from the cathode using Gaussian-like UV pulse of $\sigma_{t,laser}$= 4 ps rms.

Two different techniques, namely the pepperpot and solenoid scan methods have been applied for measuring the intrinsic emittance. Both techniques allow emittance measurements at very low charge (<1 pC) to avoid space-charge induced emittance growth.

The results depicted in the figure 2 are in good agreement with the theoretical prediction and match the work function reported in the literature. Cu, Mo and bronze cathode presents similar intrinsic emittance and, therefore, almost identical work functions. The intrinsic emittance for low work function metal, such as Al or Nb is higher. For this metal even longer wavelength would be required to reduce the emittance to the value Cu and Mo.

The intrinsic emittance has been measured also for the copper cathode in the SwissFEL test injector [2]. The recorded emittance as function of the laser spot size is plotted in figure 3. The measurement has been carried out using the JAGUAR laser at wavelength of 262 nm. The beam size has been varied through different diameter apertures. The experimental conditions are characterized RF phase set for minimizing the energy spread, solenoid field of 175.9 mT, accelerating field of 50 MV/m, beam energy 7.1 MeV, βγ=13.9. The charge density has been kept constant for the different spot size at 0.42 pC/mm^2 . The emittance has been calculated over the 100% beam charge.

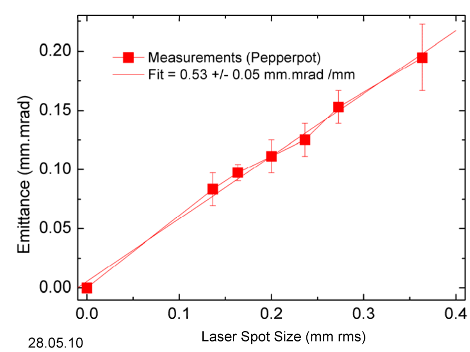

Figure 3: Electron beam emittance vs laser size measured at the SwissFEL RF gun.

The measured intrinsic emittance obtained in the RF gun, including the error bar, is consistent with the value measured for the same wavelength in the DC gun test stand [3].

Reducing the photon energy not only lowers the intrinsic emittance but also the quantum efficiency (QE). Figure 4 shows the measured QE versus the laser wavelength at normal incidence for the above cited metals [8]. The QE is determined by measuring in the DC gun the laser energy at the vacuum viewport entrance assuming the losses from this position to the cathode being ~10 %. For QE measurement the laser energy was increased to measure charge above 20 pC with both the wall current monitor and integrator charge transformer at 1 m and 2 m distance from the cathode respectively in the

DC gun test stand. Illumination of copper at λ=262 nm provides the maximum 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 Al, while Mo shows almost an order of magnitude lower QE of 3.0×10^{-6} ($\pm0.6\times10^{-6}$) than Cu.

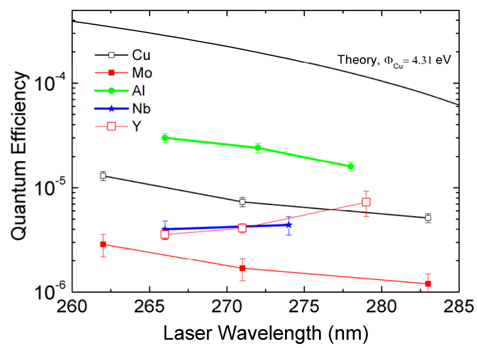

Figure 4: Quantum efficiency for several metals at different wavelengths.

The change of quantum efficiency versus 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. On the other hand the laser wavelength tuning is the key to further reduce intrinsic emittance of electron photoinjector.

LASER PERFORMANCES STUDIES

The Nd:YLF laser is a turn-key fully remote-controllable and almost maintenance-free source, ideal for the commissioning of SwissFEL test injector. The system consists of a diode pumped laser oscillator and a diode pumped regenerative amplifier. The laser pulses are frequency quadrupled by two non-linear crystals for generating 200 uJ pulses at 262 nm with a repetition rate up to 100 Hz. As shown in the figure 5, the laser beam is then focused into 50 cm long 300 microns diameter fused silica capillary. This is used to filter out the high order spatial mode and to generate an almost TEM_{00} laser distribution. The efficiency of the capillary is larger than 75%. An overfilled circular aperture is used to produce almost top hat profile. A motorized linear stage is used to insert several apertures between 1.8 to 4 mm diameters.

The beam is then imaged through an evacuated transfer line to the photocathode placed 9 meter away. The imaging system consists of a lens with focal 1.75 cm which produces a demagnification of a factor 2.75.

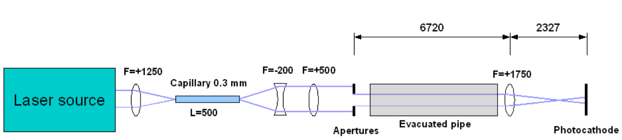

Figure 5: Schematic of the optical transport to the photocathode RF gun.

A typical laser spot recorded at the virtual cathode with 3 mm aperture, shows hard edge circular shape, figure 6. The pointing stability at the virtual cathode has been also measured for the same aperture. The jitter over 30 minutes is 5.5 µm rms in the horizontal plane and 3.6 µm rms in the vertical. For long term laser position stabilization a dedicated piezo-driven active system is under development.

The system is equipped with a motorized half wave-plate before the harmonic generation for slow adjustment of the pulse energy. For fine and fast charge feedback a second half wave-plate and a beam splitter polarized is used in the UV. The energy jitter recorded at the input gun viewport integrated over 10 minute is 0.5% rms. Long term energy variation is compensated by the feedback system.

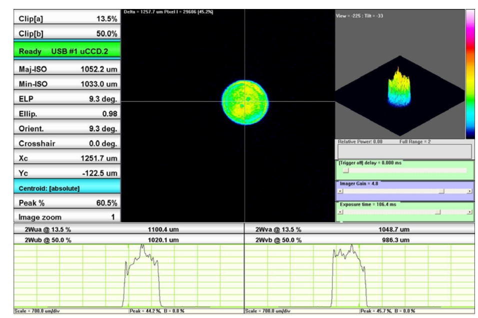

Figure 6: Laser profile at the virtual cathode for RF gun.

The laser oscillator cavity is kept at a fixed length in order to generate pulse exactly at 83.275 MHz, the 36th sub-harmonic of the RF frequency. The active feedback PLL (phase lock loop) allows then to generate laser pulse at a precise phase of the accelerating field. Spectral domain phase noise measurement indicates a time jitter for the JAGUAR laser of 300 fs rms over 10Hz-10MHz. The measurements have been performed using a large bandwidth photodiode at the oscillator exit. The electrical signal has been properly filtered and amplified to reach sufficient level a 3 GHz. The phase noise spectrum was acquired by an Agilent SSA 5052A. The analysis of the phase noise spectrum indicates the minimum achievable time jitter is limited by the PLL electronic phase detection. A new synchronization unit is under development at PSI to address the problem. Similar measurement has been conducted on the PULSAR laser system. The synchronization PLL gives better performances with a recorded relative time jitter of 44 fs rms over the bandwidth between 10 Hz to 10 MHz.

The UV pulse time intensity from the Jaguar laser has been measured by scanning cross-correlation. The cross-correlation is obtained by difference frequency generation between the UV pulse generated by the JAGUAR and the 100 fs, 800 nm pulse delivered by the Ti:Sa system. The reconstructed UV jaguar profile is reported in the figure 7. The shape is Gaussian like and the average duration is 6.3 ps FWHM with a standard deviation of 0.4 ps. For the measurement two lasers are synchronized to the injector master clock. The jitter between the two lasers affected the cross-correlation and contributed with an overall error of 0.3 ps rms. A modification of the experimental setup could be used to realize a balance cross-correlator to estimate the relative jitter between the two lasers.

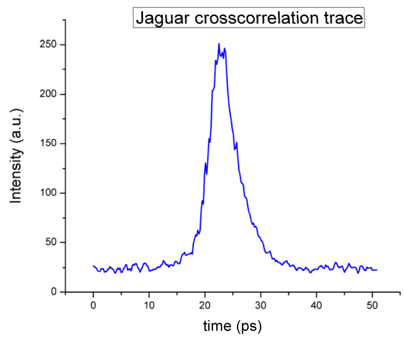

Figure 7: Cross-correlation trace of the Jaguar UV pulse

The laser performances are summarized in table 1. The Jaguar has been extensively used for the SwissFEL injector commissioning. The Pulsar has been used mainly for R&D and intrinsic emittance studies.

Table 1: Laser specifications at the cathode.

Parameter	JAGUAR	PULSAR
Energy UV 3 mm aperture	50 µJ	40 µJ
Energy fluctuations	0.5 % (over 10 min.)	0.7 % *after THG (over 10 min)
Wavelength	262 nm	263-282 nm
Spot	Circular	Circular
Spot diameter	0.65-2 mm	0.65-2 mm
Pulse duration	6.5 ps FWHM	0.2-10 ps
Laser oscillator to RF time jitter	300 fs rms	44 fs rms
Horizontal pointing stability	5.5 µm rms (over 30 min)	---------------
Vertical pointing stability	3.6 µm rms (over 30 min)	---------------

Further reduction of beam emittance is expected by applying flat top sharp edges laser temporal intensity. The generation of such a shape is under investigation using the large bandwidth delivered by the Ti:Sa system. It can be achieved by optical frequency manipulation and by time domain techniques. The spectral amplitude and phase of the UV broadband PULSAR pulses are modified by an UV Dazzler in order to achieve the desired square pulses. The pulse length can be independently adjusted by prism-based high efficiency UV stretcher. The preliminary results are very encouraging, but the maximum pulse energy attainable is limited to few ten of µJ by two photons absorption in the UV Dazzler [6, 7].

The time domain pulse shaping is realized by cascading several birefringent α-cut BBO. These crystals allow the generation of proper spaced identical replicas which, overlapping, can approximate the desired flat top intensity. This passive shaper is relatively simple and is characterized by high efficiency.

CONCLUSIONS

In this paper we report the R&D activities conducted on the photocathode laser systems for the future SwissFEL machine. The successful development of a tunable wavelength laser allows measuring the intrinsic emittance for several metal cathodes as function of the wavelength. The results are in good agreement with the theoretical prediction. The possibility to vary the energy of the photons impinging on the photocathode is promising path to achieve of the lowest beam emittance and, at the same time, preserve reasonable quantum efficiency. The Ti:Sa system will allow also the temporal pulse shaping. The Nd:YLF laser consented the successful commissioning of the SwissFEL phtoinjector. The laser proved to be stable, maintenance-free and remote-controlled system. These features make the Nd:YLF laser a good candidate for the SwissFEL photocathode drive laser. The only clear limitations of the source are in the pulse shaping capabilities. Nevertheless, other FEL facilities are reconsidering the machine working point and adopting a Gaussian laser time shape [9].

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