FIRST RESULTS ATTAINED WITH THE QUASI 3-D ELLIPSOIDAL PHOTO CATHODE LASER PULSE SYSTEM AT THE HIGH BRIGHTNESS PHOTO INJECTOR PITZ*

T. Rublack[#], J. Good, M. Khojoyan, M. Krasilnikov, F. Stephan,
DESY Zeuthen, Zeuthen, Germany,
I. Hartl, S. Schreiber, DESY Hamburg, Hamburg, Germany,
A. Andrianov, E. Gacheva, E. Khazanov, S. Mironov,
A. Potemkin, V. V. Zelenogorskii, IAP/RAS, Nizhny Novgorod, Russia
E. Syresin, JINR, Dubna, Moscow Region, Russia

Abstract

A demand on modern high brightness photo injectors required for a successful operation of linac-based free electron lasers is the possibility to generate beams with minimized beam emittance. A major way to optimize this parameter is the operation of photo cathode laser systems generating shaped laser pulses. Up to now flat-top laser pulses have been used at PITZ to achieve this goal.

As a next step in the optimization of photo injectors operated in the space charge dominated regime, the implementation of a photo cathode laser system capable to produce quasi 3-D ellipsoidal laser pulses had been considered as a result of beam dynamics simulations. That show a significant improvement in electron beam emittance compared to conventional cylindrical pulses.

The Institute of Applied Physics (IAP RAS, Nizhny Novgorod, Russia) has developed such a photocathode laser system in collaboration with the Joint Institute of Nuclear Research (JINR, Dubna, Russia) and the Photo Injector Test facility at DESY, Zeuthen site (PITZ). The laser pulse shaping is realized using spatial light modulators. The laser system is capable of pulse train generation. Just recently the delivery of the laser system and the implementation of it into the existing laser beam line at PITZ were finished. First electrons generated by the new laser system have been generated shortly after that. Although emittance measurements have not performed yet, the work presented there is a first significant step towards experimental investigation of the advantages of quasi 3-D ellipsoidal photo cathode laser pulses.

In this contribution the overall setup, working principles and the actual progress of the development as well as first results of electron beam generation will be reported.

INTRODUCTION

Ultrafast spectroscopy in the range of a few femtoseconds or even shorter as an instrument to investigate the behaviour of very fast processes, e.g. thermal excitation of molecules, has become a very popular instrument in various scientific research fields.

Wavelengths in the XUV are necessary for a lot of these experiments [1]. Such beams can be provided by linac-based Free-Electron Lasers (FELs) such as the Free-electron LASer in Hamburg (FLASH) and the European X-ray Free-Electron Laser (European XFEL).

FELs like these two operate on the basis of the Self Amplified Spontaneous Emission (SASE) process [2], which requires an extremely high space charge density of the radiating electron bunches. Therefore, requirements such as high peak current, low energy spread, and small transverse emittance of the electron beam are inevitable. The latter property cannot be improved in the linac and thus the emittance must be minimized in the photo injector.

One of the main possibilities to achieve this requirement is the shaping of the photo cathode laser pulses. By utilizing spatial cylindrical laser pulses with a temporal flat-top instead of Gaussian profile, a significant reduction of the transverse emittance of space charge dominated beams can be achieved.

While at most FELs the Gaussian laser pulse profile is used as the standard, at PITZ a flat-top temporal profile is used by default. Using this shaped laser pulses measurements of the normalized transverse projected beam, emittance between 0.7 and 0.9 mm mrad for electron beams of 1 nC bunch charge have been obtained [3].

To improve this emittance value, simulations with different kinds of laser pulse shapes were performed. As a result it could be shown by several simulations that the next step towards further reduction of the emittance is the use of 3-D ellipsoidal photo cathode laser pulses [4,5].

Laser systems capable of generating such laser pulses for trains of microbunches are currently not available. Therefore, a prototype was developed, constructed and recently installed at PITZ.

BEAM DYNAMICS SIMULATIONS

Beam dynamics simulations have been used to study the influence of different laser beam shapes on the electron beam quality. Therefore, three different types of laser shapes were investigated: 1) spatially cylindrical

*Work supported by the German Federal Ministry of education and Research, project 05K10CHE “Development and experimental test of a laser system for producing quasi 3D ellipsoidal laser pulses”, Helmholtz Joint Research Groups, project HRJRG-400 and RFBR grant 13-02-91323.
#Tino.Rublack@desy.de

laser beam with a temporal Gaussian profile, which is currently used as the standard profile at most

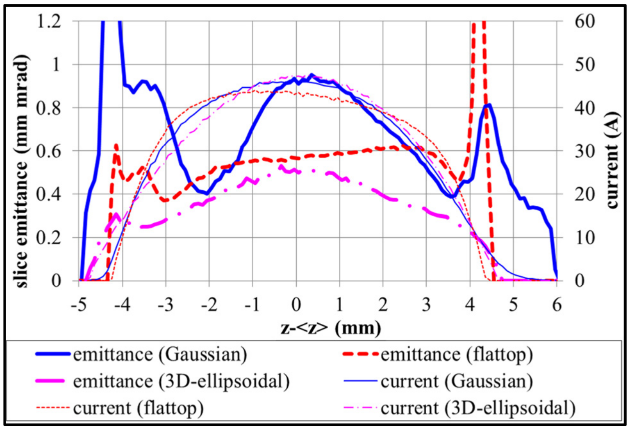

Figure 1: Beam dynamics simulation of electron bunches for photo cathode laser pulses with flat-top, Gaussian and 3-D ellipsoidal temporal profiles; normalized transverse slice emittance ε_{slice} distribution along the electron bunch.

FELs, 2) spatially cylindrical laser beam with a temporal flat-top profile as used at PITZ and 3) temporal-spatial ellipsoidal laser pulses. The simulations were based on the former PITZ photo injector layout [6]. In the simulations a photo cathode laser beam with a $\sigma_{x,y}$ of about 0.4 mm rms was assumed, the electron beam charge was always 1 nC and the simulations were evaluated at a distance of 5.74 m from the photo cathode.

The results of these simulations are shown in Fig 1 and Table 1.

Table 1: Values of Normalized Transverse Projected Emittance ε_{proj} and Normalized Average Slice Emittance $<\varepsilon_{slice}>$ corresponding to Fig. 1.

Parameter	Cathode laser pulse profile		
	flat-top	Gaussian	3-D ellipsoid
ε_{proj} [mm mrad]	0.63	1.05	0.43
$\langle\varepsilon_{slice}\rangle$ [mm mrad]	0.55	0.72	0.40

3-D ELLIPSOIDAL PHOTOCATHODE LASER SYSTEM SETUP

A novel laser system capable of producing quasi 3-D ellipsoidal laser pulse trains at a wavelength of 257 nm has been developed at the IAP in collaboration with JINR and was installed at PITZ. First photo electrons have been generated just recently.

The laser system is made of four main parts: dual-output fiber laser, diode pumped Yb:KGW disk amplifier, pulse shaper and frequency conversion unit. In addition there are several characterization components at different positions within the beam path.

The dual-output fiber laser consists of an oscillator, which generates laser pulses at a wavelength of ~1030 nm with pulse duration of about 150 fs at a repetition rate of 45 MHz, a fiber-based pulse stretcher, a preamplifier, and a system for pulse train (macropulse) formation.

The generated beam is split into two beams at the output of the fiber laser. Both beams are then amplified with separate fiber amplifiers. While the beam coming out of the primary output is used to illuminate the photo cathode later on, the second beam is used for beam characterization, namely as diagnostic pulse source for a scanning cross-correlator.

After the fiber laser, the (Gaussian) beam of the primary output is send through a pinhole to cut out quasi-spatial flat-top laser pulses from the middle part – the part were the intensity gradient is "low" - of the pulse. These pulses are then amplified using a multi-pass Yb:KGW disk amplifier [7].

The amplified laser pulses are then shaped both temporarily and spatially. This is realized by a scheme based on Spatial Light Modulators (SLMs). The principle scheme of the 3-D pulse shaping unit is shown in Fig. 2.

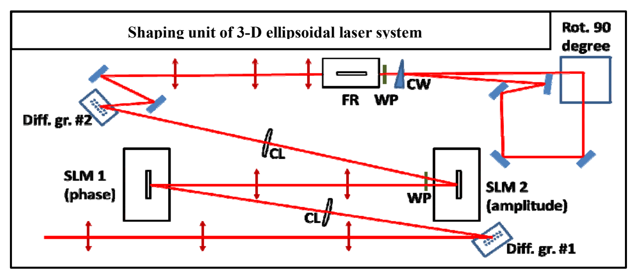

Figure 2: Setup of the 3-D pulse shaper; SLM – spatial light modulator, Diff. gr. – diffraction grating, WP – half-wave plate, CL – cylindrical lens, FR – Faraday rotator, CW – calcite wedge, Rot. 90 degree – laser beam rotator 90°.

The pulse shaper is based on a zero dispersion optical compressor. Among other things the shaping unit consists of two diffraction gratings, two cylindrical lenses, and two liquid crystal based SLMs (HES 6010 NIR SLM; Holoeye Photonics AG). The spatial light modulators are positioned at the focal planes of both cylindrical lenses, which images one with diffraction grating onto the other in the meridian plane.

While the first SLM manipulates the phase of the laser pulse the second one becomes an amplitude modulator. Therefore, the laser beam polarization is rotated after the first SLM by 45 degree using a half wave plate. As mentioned before, the pulse shaper only works in one plane. Therefore, the laser beam passes the shaping unit twice, rotated by 90 degree.

Laser beam shaping is done at a wavelength of 1030 nm. In order to produce photo electrons using a Cs_2Te photo cathode (PITZ standard), (4th harmonic) frequency conversion of the laser pulses are done afterwards, using frequency conversion crystals (LBO and BBO).

Knowledge and control of the spatial and temporal pulse shape are crucial for the operation of the laser system. The observation of the spatial pulse shape is done by a fast CCD camera. The intensity of the laser pulses is measured with a photodiode. Taking into account that both, spatial profile and intensity are time dependent this measurements cannot be done for an entire laser pulse, but have to be done at different times within one pulse. Therefore, the characterization of the 3-D shaped laser pulses is done using the scanning cross-correlator technique (Fig. 3) [8].

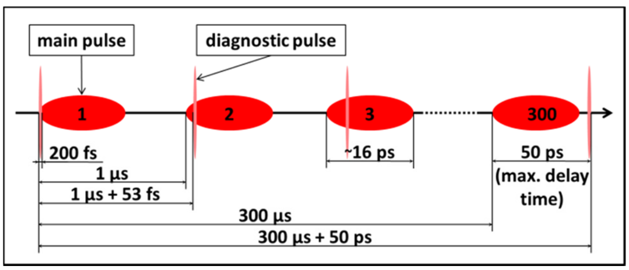

Figure 3: Time scheme of the scanning cross-correlator used for 3-D laser pulse diagnostics.

As mentioned earlier the used diagnostic pulse is generated within the fiber laser. Within the beam path of the diagnostic laser pulses a high-speed delay line is implemented. This makes it possible to shift the temporal position of the diagnostic pulses compared to the one of the main pulses. A BBO crystal at the intersection of both pulses is used to generate a frequency converted third beam. This beam is highly intensity sensitive (nonlinear) related to the main pulse (the diagnostic laser pulse intensity is fixed), and therefore allows measuring the spatial and temporal profile of the spatial and temporal shaped micropulses with a high precision [8].

Up to now, only initial tests have been done using the scanning cross-correlator technique with the new laser system capable of producing quasi 3-D ellipsoidal laser pulses. The characterization was done after pulse shaping but before harmonic generation. Pulse duration of the laser pulses has been about 16 ps zero-to-zero at a repetition rate of 1 MHz for the (currently) 300 micropulses within a macropulse and a macropulse repetition rate of 10 Hz. Figure 4 shows the result of a measurement done at IAP. Time step between each image (temporal slice) is about 1.7 ps (optimum resolution possible is about 200 fs).

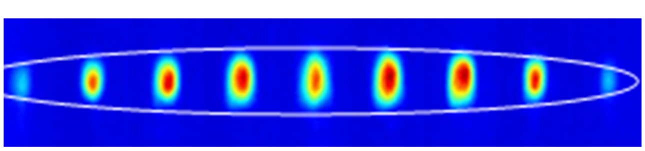

Figure 4: Scanning cross-correlator measurements of spatial and temporal shaped laser pulses (before harmonics generation), ~ 1.7 ps time steps between images.

FIRST PHOTO ELECTRONS

A short time ago the installation and commissioning of the laser system, as well as the implementation of the laser system into the existing laser transport beam line was completed. First tests started quite recently. The system is not tuned to optimized operation, nevertheless was it possible to generate and measure 50 pC electron bunches at PITZ produced with the new laser (Fig. 5).

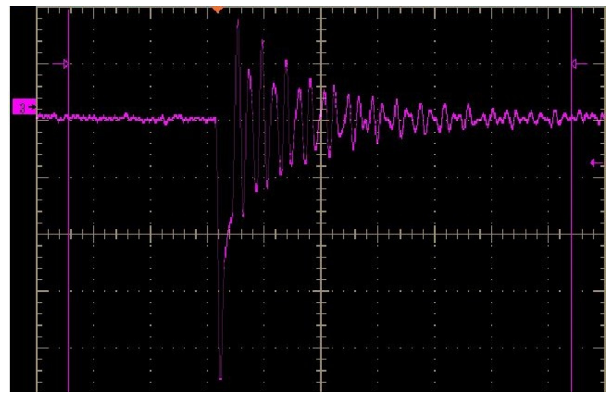

Figure 5: Charge measurement (Faraday cup) of electron bunch generated by new laser system; bunch charge about 50 pC.

An image of the laser beam measured at a virtual cathode (VC2), which is at an equivalent distance to the real photo cathode, is shown in Fig. 6.

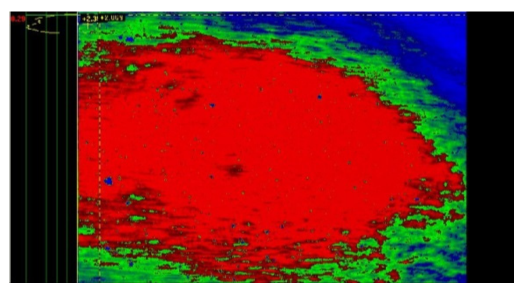

Figure 6: CCD-camera measurement of laser pulses generated with new laser system at virtual cathode (VC2).

As can be seen the size of the laser pulse is very large and the shape is not optimal. Nevertheless, it is an important step for further development and optimization of the laser system.

CONCLUSION

Simulations have shown a significant emittance reduction of space charge dominated beams using 3-D ellipsoidal laser pulses instead of a Gaussian or a flat-top temporal profile pulses. Such a laser system was developed at IAP and is now installed at PITZ. It was shown that first electron bunches with about 50 pC bunch charge have been generated. Higher bunch charges are expected maximizing laser pulse energy and optimizing focusing the beam on the photo cathode. Further steps in optimization of the laser system are planned.

REFERENCES

[1] T.W.J. Dzelzainis et al., “Emission Spectroscopy from an XUV Laser Irradiated Solid Target”, X-Ray Lasers 2008, Springer Proceedings in Physics, Vol. 130, p. 549 (2009).

[2] P. Schmueser et al., *Ultraviolet and Soft X-Ray Free-Electron Lasers: Introduction to Physical Principles, Experimental Results, Technological Challenges*, (Berlin Heidelberg: Springer, 2008).

[3] M. Krasilnikov et al., “Experimentally minimized beam emittance from an L-band photoinjector”, Physical Review Special Topics – Accelerators and Beams 15, 100701 (2012).

[4] C. Limborg-Deprey and P.R. Bolton, “Optimum electron distribution for space charge dominated beams in photoinjectors”, Nuclear Instruments and Methods in Physics Research, A557, p. 106 (2006).

[5] M. Khojoyan et al., “Beam dynamics optimization for the high brightness PITZ photo injector using 3D ellipsoidal cathode laser pulses”, TUPSO36, Proceedings of the 35th International Free Electron Laser Conference, Manhattan, USA, 2013.

[6] M. Khojoyan et al., “Studies on the Application of the 3D Ellipsoidal Cathode Laser Pulses at PITZ”, THPRO043, Proc. IPAC2014, Dresden, Germany, http://jacow.org/.

[7] E. Gacheva et al., ”Disk Yb:KGW amplifier of profiled pulses of laser driver for electron photoinjector”, Opt. Express 23, p. 9627 (2015).

[8] V. V Zelenogorskii et al., "Scanning cross-correlator for monitoring uniform 3D ellipsoidal laser beams”, Quantum Electron 44(1), p. 76 (2014).