NEW ELLIPSOIDAL LASER AT THE UPGRADED PITZ FACILITY

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Abstract

High brightness photoinjectors for superconducting linac-based FELs are developed, optimized and characterized at the Photo Injector Test facility at DESY in Zeuthen (PITZ). Last year the facility was significantly upgraded with a new prototype photocathode laser system capable of producing homogeneous ellipsoidal pulses. Previous simulations have shown that the corresponding pulses allow the production of high brightness electron bunches with minimized emittance. Furthermore, a new normal conducting RF gun cavity was installed with a modified two-window waveguide RF feed layout for stability and reliability tests, as required for the European XFEL. Other relevant additions to the facility include beamline modifications for improved electron beam transport through the PITZ accelerator, refinement of both the cooling and RF systems for improved parameter stability, and preparations for the installation of a plasma cell. This paper describes the facility upgrades and reports on the operational experience with the new components.

ELLIPSOIDAL LASER SYSTEM

Previously reported [1] low emittance beams were obtained using a flat-top temporal laser profile with 60 MV/m in the RF gun, and more recently new measurements have been taken with a Gaussian temporal laser profile and 53 MV/m [2]. Also recently it was found that the transverse halo of the laser must be taken into account [3]. In earlier simulations it was found that uniform ellipsoidal charge distributions with sharp charge transition boundaries would produce even higher beam quality. Furthermore, it was shown that such electron bunches are also less sensitive to machine parameter jitter [4] and therefore increase the reliability and stability - crucial parameters for single-pass FELs such as FLASH and the European XFEL.

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Naturally, a homogenous ellipsoidal photocathode laser pulse can be used to produce such charge distributions. Consequently, such a laser system has been developed for PITZ by the Institute of Applied Physics in Nizhny Novgorod, under the framework of a joint German-Russian research activity [5].

The system produces quasi-ellipsoidal laser pulses in the infrared through spectral amplitude-phase masking.

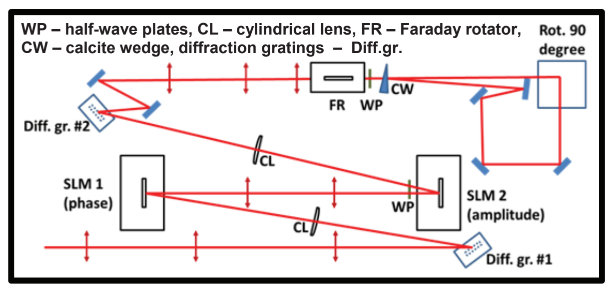

Figure 1: Schematic overview of the 3D shaper.

The shaper consists of two diffraction gratings, two Spatial Light Modulators, and various optical elements (Fig. 1). A chirped infrared laser pulse is transformed into the spectral domain with a diffraction grating and imaged onto Spatial Light Modulators (SLMs) whereupon masks such as in Fig. 2 are applied. The beam is then recombined via another grating, rotated 90º about its propagation axis, and passed back through the shaper again. This shapes the perpendicular transverse axis and produces a quasi-ellipsoidal distribution. Finally, the beam is converted from infrared to the ultraviolet via non-linear 4^{th} harmonic frequency conversion.

Simulations have been done to produce the mask in Fig. 2a) which is expected to roughly produce the quasi-ellipsoidal distribution in Fig. 2b).

Simulations have shown that these improved laser pulses have the potential to further reduce the emittance of the generated electron bunches at PITZ [4].

ISBN 978-3-95450-134-2

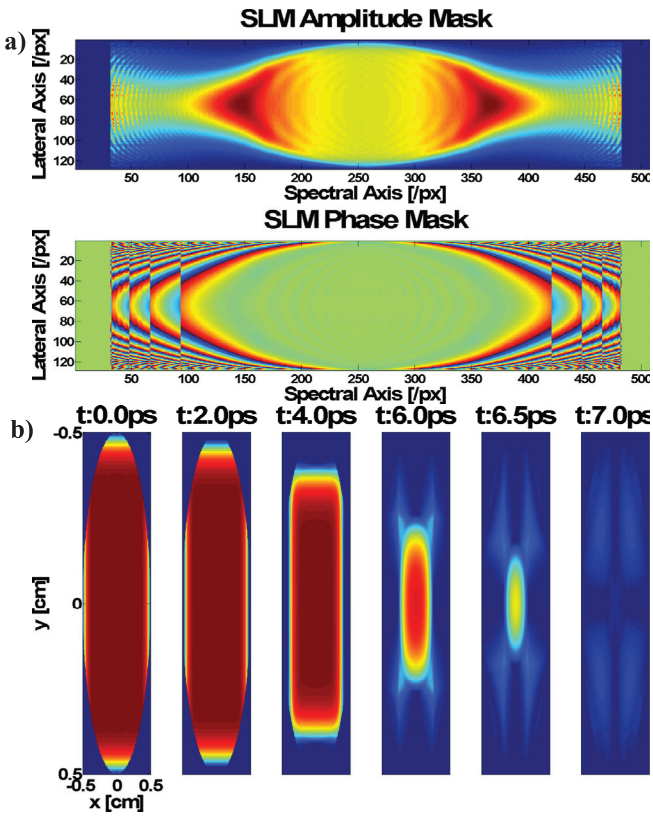

Figure 2: a) The corresponding normalized amplitude and phase masks. b) Temporal slices of a simulated quasi-ellipsoidal laser pulse. t=0 ps corresponds to the temporal center of the laser pulse.

The laser pulses are characterized by a cross-correlator coupled camera in the infrared (Fig. 3) prior to frequency conversion to the ultraviolet. Owing to the non-linarites inherent to the conversion process a UV:IR scanning cross-correlator is planned in order to fully characterize the shaped UV pulses. The first photoelectrons were produced with this system in spring and captured with a Faraday cup. The beamline and system are currently undergoing testing, commissioning, and further improvements.

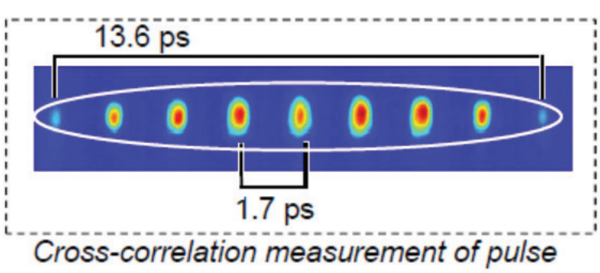

Figure 3: Cross-correlation measurement of a shaped pulse produced in the lab. Shown are ~250 fs time slices of the transverse distributions of the shaped laser pulse taken at 1.7 ps intervals throughout the entire pulse duration of 13.6 ps.

NEW GUN AND RF FEED SYSTEM

During the summer/autumn of 2014 the RF feed system and the gun at PITZ were replaced (Fig. 4). Gun 4.4 was exchanged with a Gun 4.2, while the RF feed changed from a single Thales RF window layout [6] to a double RF window-pair layout [7]. This was owing to high-load induced damage of the Thales window. Naturally, sharing of the load across two windows has reduced both the potential damage to the components and the likelihood of interruptive instances, thereby improving stability and reliability of the system.

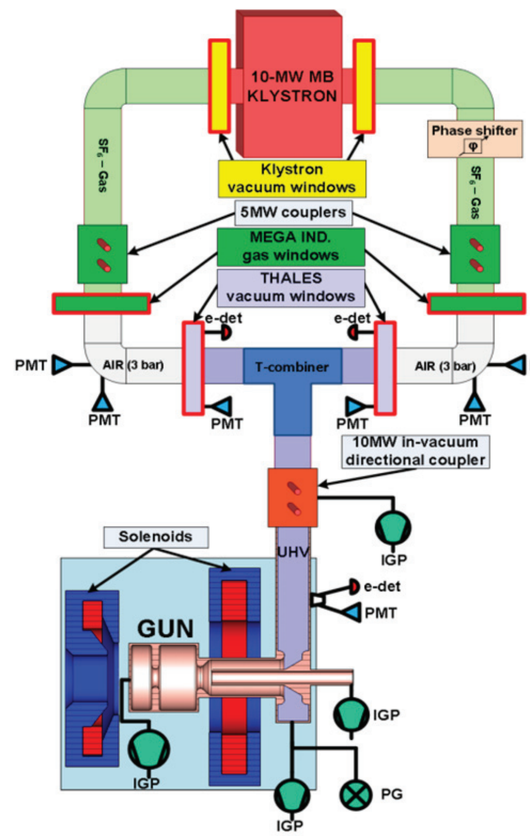

Figure 4: New gun interlock and RF distribution scheme.

However, the nominal operation target of FLASH and XFEL has not been reached owing to limitations of the gun itself. This can be attributed to the gun's troubled history [7]. Reduction of the operating power to 5 MW has shown a remarkable improvement in gun stability.

RF GUN STABILITY

One of the main tasks of PITZ is demonstration of stable operation of the RF gun at the European XFEL injector specifications. The specifications are an RMS amplitude jitter of less than 0.01% as well as an RF phase RMS jitter smaller than 0.01 deg. These challenging stability requirements have to be achieved within the RF pulse and from pulse-to-pulse.

ISBN 978-3-95450-134-2

Nominal RF pulses of 650 us flattop length at ~6.4 MW peak power in the gun cavity and 10 Hz repetition rate have to be stably supported for the European XFEL RF gun.

For the initial start-up conditions a reduced peak power of 4.5-5 MW is foreseen. A new low-level RF (LLRF) system has been implemented at PITZ since November 2014. It is based on µTCA [8] technology and imparts an increased measurement sampling rate within the RF pulse as well as extended feedback (FB) tools permitting improved regulation of the amplitude and phase of the RF gun.

Another tool to stabilize the normal conducting RF gun is the water cooling system (WCS). High temperature stability of the gun cavity is realized by heat transport control. The WCS implemented at PITZ currently has two functional modes: operation (WCS=oper) and stabilization (WCS=stab). The former actively regulates the gun's water circuit through valve-controlled mixing of cold water into the loop. Whereas, the latter employs a heat exchanger to regulate the closed warm water loop thereby reducing flow perturbations. Results of the stability measurements based on the statistical analysis of 800 subsequent RF pulses are shown in Fig. 5, where RMS phase and amplitude jitters within the RF pulse are plotted for various WCS and FB modes. These measurements have been performed for the peak RF power in the gun of 4.5 MW and 640 µs RF pulse duration.

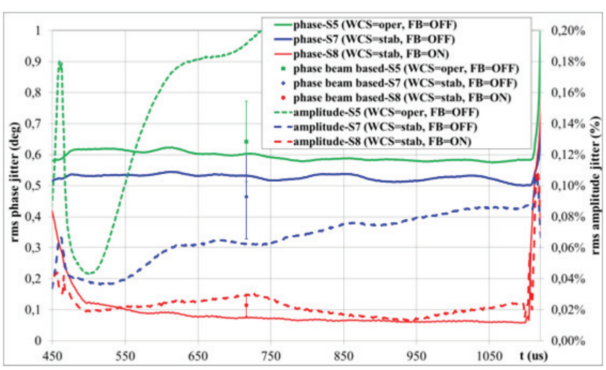

Figure 5: RF gun stability measurements. The RMS phase and amplitude jitter is plotted at left and right axis correspondingly for two regimes of the WCS and deactivated/activated LLRF feedback (measurements S5, S7 and S8). Results of the correspondent beam-based measurements are shown with markers. The horizontal position of these points corresponds to the time of the first electron bunch within the RF pulse.

As can be seen from these measurements, without feedback switching the WCS from operation mode to the stabilization mode improves the amplitude stability by a factor of 3 and the phase jitter is reduced by ~10%. Whereas, application of the LLRF feedback results in further reduction of the amplitude jitter by a factor of ~3 and significant reduction of the phase jitter (~75%). However, further improvements to the RF gun stability have to be implemented (factor 5 for the phase and factor 2 for the amplitude) in order to achieve the European XFEL injector specifications.

The RF stability measurements were cross-checked with electron beam measurements based on the fluctuations of the electron bunch charge as a function of the RF gun launch phase. The analytic approach used to fit the measured mean charge <Q> and charge fluctuations δQ assumed three independent and normally distributed sources of charge fluctuation: phase jitter, laser pulse energy fluctuations, and electronic noise of the charge measurement device (Faraday cup). It is also presumed that the temporal profile of the photocathode laser pulse is Gaussian as it was in the measurements. In order to minimize the influence of the space charge effect the space charge density at the cathode was reduced by decreasing the photocathode laser fluence. An example of the measured <Q> and δQ together with fitted curves are shown in Fig. 6. The phase RMS jitter obtained from these fits is plotted in Fig. 5.

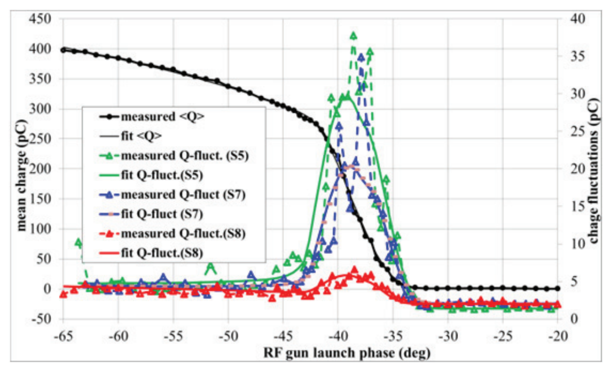

Figure 6: Beam based measurements of the RF gun stability. Measured mean charge and its analytical fit are plotted at the left axis. Charge fluctuations together with fits for three cases of WCS and FB (measurements S5, S7 and S8) are plotted at right axis.

PHOTOEMISSION STUDIES

One of the many areas of interest is the charge production behaviour of the Cs_2Te cathodes used in both FLASH and PITZ. While significant amounts of charge can be extracted from the cathodes it has been observed that the quantum efficiency (QE) of the cathode constantly decreases as a function of time (~1 year) before partially recovering (Fig. 7) [9].

ISBN 978-3-95450-134-2

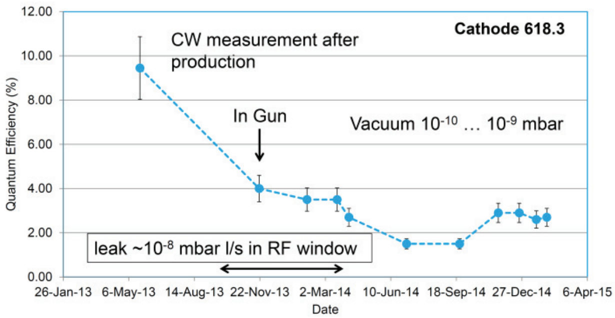

Figure 7: Quantum Efficiency of FLASH's Cs_2Te Cathode 618.3 during 2013/2014.

To investigate this behaviour one of the measurement programs embarked upon has been to map the QE over the surface of the cathode as a function of time.

It was seen that the QE consistently degrades across the entire surface of the cathode, within a period of one month, despite charge extraction occurring primarily at the centre. The evolution of existing defects and the formation of new ones can also be observed (Fig. 8). On longer time scales, on another cathode at PITZ, effects similar to those measured at FLASH have been observed.

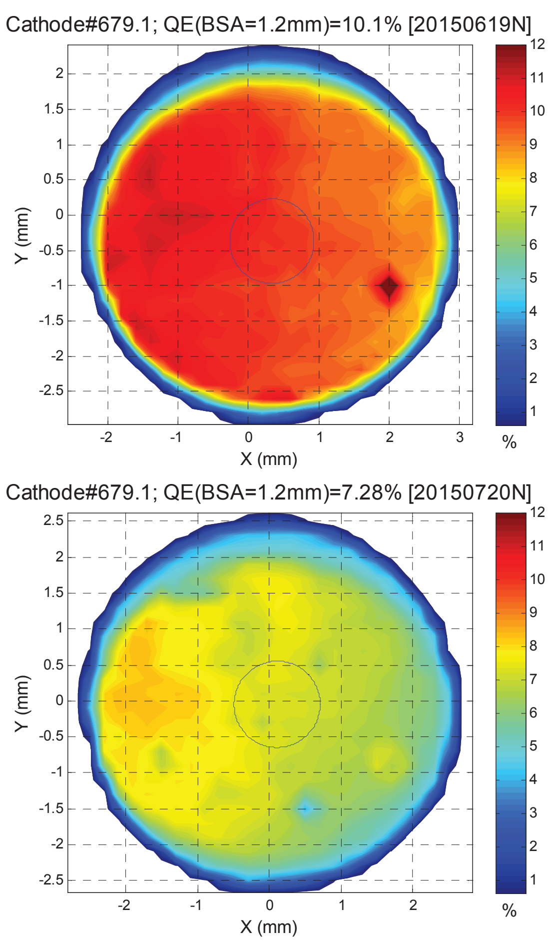

Figure 8: Evolution of cathode surface QE over one month.

Similarly, another unexplained aspect of charge extraction from the cathode was the increase of photoemission with laser pulse energy contrary to previous simulations (Fig. 9). According to simulation a uniform (flat-top) transverse laser profile, the extracted charge should saturate beyond certain laser pulse energy, corresponding to specific beam parameters and gun operating settings.

However, in reality the photocathode laser does not have a perfect flat-top transverse profile. Therefore a detailed investigative measurement program was begun to fully characterize the transverse profile of the laser and to produce a comparative set of photoemission data [3].

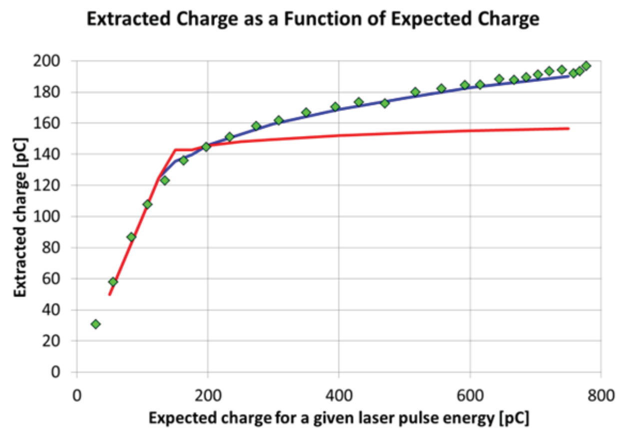

Figure 9: Extracted charge and expected charge given by simulation of a homogenous, transversely flat-top laser pulse (red) and the same distribution with a photonic halo (blue), and measurement of charge actually extracted (green).

The resulting simulations have shown that the previously observed discrepancy can be easily explained by rising Gaussian edges of the transverse laser profile generating a "halo" of charge around the core beam. Furthermore, this effect is constantly more pronounced across all gun gradients for more narrow transverse profiles where the ratio of core:halo area is decreased.

FURTHER FACILITY DEVICES

Additionally, commissioning of a transverse deflecting cavity (TDS) started in July 2015. The preliminary results are promising [10] as beam measurements are in good agreement with RF readings However, full operation of the device was limited by high reflection in the waveguide line.

A plasma cell was constructed in 2013 for doing proof of concept measurements for the AWAKE experiment at CERN [11]. The device consists of a heatpipe oven for the vaporization of lithium, Kapton foil windows to separate the volume from the beamline vacuum, and a 193nm ionizing laser to produce the plasma. The chamber has recently undergone successful mechanical, vacuum, and thermal stress tests and was placed into the beamline for the first time in July.

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SUMMARY AND OUTLOOK

Preparatory simulations were done for the new ellipsoidal photocathode laser system. This has yielded trial phase-amplitude masks which have been tested and characterized with a scanning IR cross-correlator coupled camera. Photoelectrons have been generated with the system and development is ongoing.

The RF system has shown itself to be very reliable under a two RF window-pair solution and has been operated at full XFEL RF specifications without issue. The RF system will be fully assessed with the newly manufactured gun 4.6 which is planned to be installed until the end of 2015.

The phase and amplitude regulation of the RF gun has been improved by switching the LLRF to a µTCA-based system and by further improvement of the gun's water cooling system.

Photoemission studies have been performed and it was also determined by simulation, and confirmed by experimental data, that the irregularities of the transverse laser profile on the cathode have to be fully included in simulation.

Finally, the Transverse Deflecting Structure is in the commissioning phase and is expected to deliver extended diagnostic capability and insightful experimental data. Also experiments with a plasma cell have started to do proof-of-principle experiments in the field of particle beam driven plasma wakefield acceleration.

REFERENCES

[1] M. Krasilnikov et al., Experimentally minimized beam emittance from an L-band photoinjector, PRST AB 15, 100701 (2012).

[2] G. Vashchenko et al., Emittance Measurements of the Electron Beam at PITZ for the Commissioning Phase of the European X-FEL, these proceedings (MOD04), FEL'15, Daejeon, Korea.

[3] C. Hernandez-Garcia et al., "Studies on charge production from Cs2Te photocathodes in the PITZ L-band normal conducting radio frequency photo injector," in preparation, to be submitted to Phys. Rev. ST Accel. Beams.

[4] M.Khojoyan et al., Optimization of the PITZ photo injector towards the best achievable beam quality,Proc. FEL2014, Basel, Switzerland (2014).

[5] T.Rublack, First Results Attained with the Quasi 3-D Ellipsoidal Photo Cathode Laser Pulse System at the High Brightness Photo Injector PITZ, IPAC'15, Richmond, VA, USA (2015).

[6] M.Otevrel et al., Report on Gun conditioning activities at PITZ in 2013, Proc. IPAC'14, Dresden,Germany (2014).

[7] A. Oppelt et al., Facility Upgrade at PITZ and First Operation Results, IPAC'15, Richmond, VA, USA (2015).

[8] M.Hoffmann et al., Operation of Normal Conducting RF Guns with MTCA.4, IPAC'15, Richmond, VA, USA (2015).

[9] S. Schreiber and S. Lederer, Lifetime of Cs2Te Cathodes Operated at the FLASH Facility, these proceedings (TUP042), FEL'15, Daejeon, Korea.

[10] H. Huck et al., First Results of Commissioning of the PITZ Transverse Deflecting Structure, these proceedings (MOP039), FEL'15, Daejeon, Korea.

[11] M. Gross, et al., Preparations for a plasma wakefield acceleration (PWA) experiment at PITZ, Nuclear Instruments and Methods in Physics Research A 740 (2014), pp. 74-80.

ISBN 978-3-95450-134-2