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PRELIMINARY ON-TABLE AND PHOTOELECTRON RESULTS FROM THE PITZ QUASI-ELLIPSOIDAL PHOTOCATHODE LASER SYSTEM

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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). Simulations have previously shown that homogenous ellipsoidal photocathode laser pulses allow the production of high brightness electron bunches with minimized emittance.

Correspondingly, a new prototype photocathode laser system capable of producing quasi-ellipsoidal laser pulses was installed last year and brought into active electron beam operation at the start of this year.

Several electron beam measurements have been made with pulse shaping. It was possible to show a beam quality improvement equivalent to that of conventional beam shaping techniques such as pulse stacking and beam shaping apertures. Further improvements were constrained due to a number of systematic limitations which are to be addressed in the redesign currently under construction.

INTRODUCTION

Low-emittance beams have been obtained using a flat-top temporal laser profile with 60 MV/m gradient in the RF gun [1], more recently with a Gaussian temporal laser profile and 53 MV/m [2]. 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 should also be less sensitive to machine parameter jitter [3] and therefore increase the reliability and stability – crucial parameters for single-pass FELs such as FLASH and the European XFEL.

QUASI-ELLIPSOIDAL PHOTOCATHODE LASER SYSTEM

Naturally, a homogenous ellipsoidal photocathode laser pulse is a first approximation 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 [4].

The system produces quasi-ellipsoidal laser pulses in the infrared through spatio-spectral amplitude masking of chirped Gaussian laser pulses.

The shaper is implemented by locating a modulator at the at the Fourier plane of a 4f - zero-dispersion stretcher-compressor. In this case the modulator is a Spatial Light Modulator (SLM) to act as an amplitude mask in the transverse-temporal domains (Fig. 1).

The pulses are passed through the shaping unit, rotated 90° about their propagation axis before being passed back through the shaper, and are then coupled out for frequency conversion to the ultraviolet.

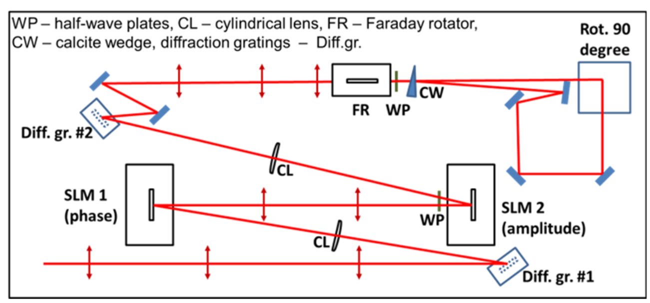

Figure 1: Schematic overview of the 3D shaper (phase mask currently omitted).

A number of diagnostic tools are implemented to characterize the laser pulses. The temporal envelope of the laser pulses is characterized by cross-correlator coupled cameras in the both the infrared, prior to frequency conversion, and in the ultraviolet afterwards. Furthermore, a slit-scanning spectrometer is used to acquire spectrographs of the pulses and reconstruct their profiles.

Finally, the laser is coupled into a shared laser transport beamline. A uTCA-based feedback loop is used to ensure synchronization to the RF systems which permitted the first electron beam quality measurements with the new laser system at PITZ.

SIMULATIONS

Simulations were done using the ASTRA [5] code to compare and contrast various pulse distributions (Fig. 2) for the 9.5 ps FWHM pulse durations which are currently available. These were done for the operating parameters of 0.5 nC bunch charge, 6.5 MeV/c momentum in the gun, and 22.3 MeV/c after the CDS booster.

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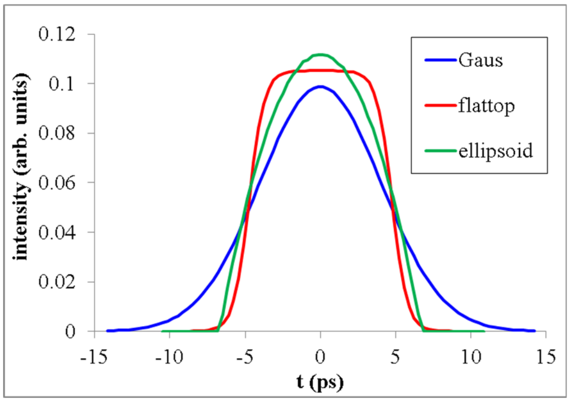

Figure 2: Used pulse profiles for the three types of photocathode pulse envelopes.

For these parameters, and of three shapes of the photocathode laser all with 9.5 ps FWHM, the minimized emittance for the EMSY station located 5.277 m downstream of the gun was found (Table 1).

Table 1: ASTRA Simulation Results

Pulse shape→	cylindrical		ellipsoid
Temporal profile→	Gaussian	Flattop	
Projected normalized emittance [mm·mrad]	0.80	0.64	0.35
Average slice emittance [mm·mrad]	0.49	0.57	0.33
Bunch length (rms) [mm]	1.44	1.20	1.34
Peak current [A]	35.4	39.5	37.8
Longitudinal emittance [mm keV]	34	22	12.5

ELECTRON BEAM MEASUREMENTS

Preliminary electron beam measurements with the new photocathode laser system utilized a “truncated” beam owing to the imperfect transport of the laser to the cathode resulting in a large transverse spot size on the cathode. This could be observed with a camera (VC2) placed at a virtual plane with an optically equivalent distance to that of the real beam path. As the new photocathode laser system “piggybacks” onto the already existing laser transport beamline it was possible to achieve the desired dimensions by cropping the beam with the pre-existing Beam Shaping Aperture (BSA) in the tunnel. The diameter was then set to 1.2 mm (Fig. 3).

A SLM mask was manually fitted by observation of the IR cross-correlation to obtain a 10-12 ps FWHM distribution as a first approximation. The unusual shape of the temporal envelope can be explained by the laser spectrum, shown in Fig. 4.

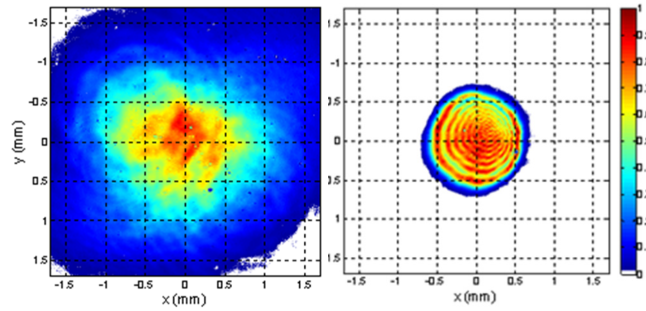

Figure 3: Transverse laser profile at a virtual cathode plane without (left) and with (right) a beam shaping aperture.

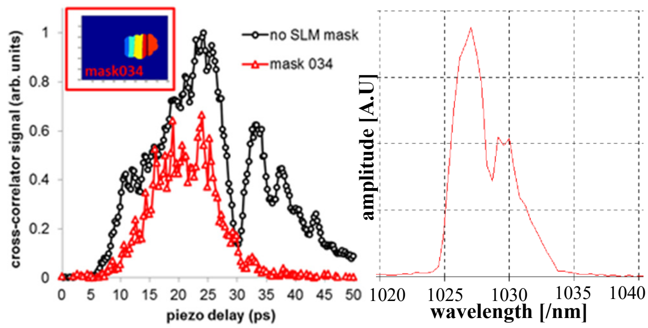

Figure 4: Laser temporal envelope obtained by infrared cross-correlation (left), and the laser spectrum (right).

The emittance of the generated electron beam was measured, under the machine parameters given in the simulation section, as a function of solenoid current in comparison to the simulations above. The measured beam emittance is shown in Fig. 5 together with the rms beam sizes as a function of main solenoid current.

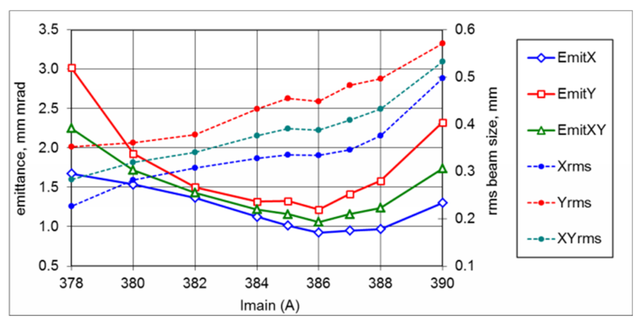

Figure 5: Measured electron bunch emittance and spot size as a function of main solenoid current.

The normalized transverse emittance at the optimum solenoid current (386 A/225 mT) was found to be ε_{nx} = 0.93 mm mrad, ε_{ny} = 1.22 mm mrad, and a geometric mean of ε_{nxy} = 1.06 mm mrad.

These values are on par with measurements undertaken for the nominal flat-top photocathode laser pulses. The beam was also observed on a transverse deflecting cavity and seen to have a close-to parabolic current density (Fig. 6) and a roughly ellipsoidal shape on the temporal-transverse x coordinate plane (Fig. 6 insert).

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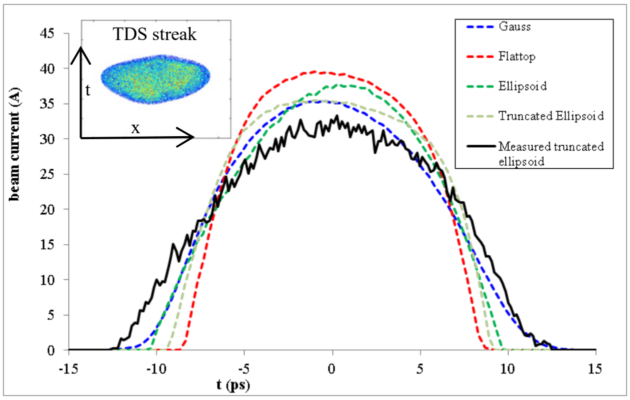

Figure 6: Measured beam current profile with a TDS compared to simulated profiles for various laser pulse envelopes.

The measurements do not meet the theoretical values predicted by simulation (Table 1) due to limited spectral quality, beam stability and transport issues. As can be seen in Fig. 4, the pulse spectrum is masked very short due to the absorption band slightly off-center in the spectrum. This also results in even shorter pulses after frequency conversion than in simulation. The long-term stability suffers due to poor opto-mechanical stability which leads to drifting throughout the system. Finally, piggybacking the laser onto the pre-existing laser transport designed for magnification brings issues because the new laser system prefers demagnification. The transversely cut laser distribution on the photocathode is far from the optimal case studied in simulation.

REDESIGN

Through operation of the laser a number of systematic limitations have been identified and are foreseen to be corrected with a simplified redesign centred around a single high-power, oscillator-amplifier laser system. The new system is a 1 MHz solid-state Yb:KGW Pharos laser from Light Conversion capable of producing 20 µJ chirped laser pulses whose energy inversely scales with decreasing repetition rate up to 200 µJ.

This system is seen to be the backbone of a linear, highly robust, stable, and flexible laser pulse shaping system based on the same zero-dispersion stretcher-compressor concept as the old design with two independent, high resolution shaping units utilizing the maximum chip area on dichroic Hamamatsu SLMs for each spatio-spectral plane.

A significant reduction in optical path length and the number of optical elements was achieved and the inclusion of detectors for on-line parasitic observation at every stage was included, as shown in Fig. 7. The linear scheme also simplifies troubleshooting and alignment.

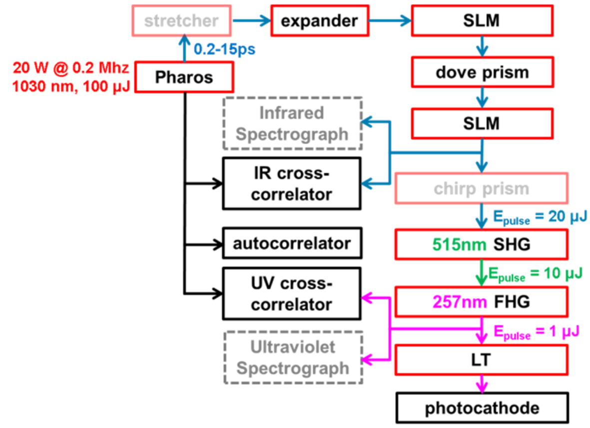

Figure 7: Schematic overview of the new photocathode laser system under construction.

CONCLUSION

Owing to the implementation of uTCA-based synchronization system in the last year it became possible to generate photoelectron bunches with modulated three-dimensional profiles and measure their beam properties.

These photoelectron bunches have displayed improved properties in relation to that of unshaped pulses, and a quality on par with conventional pulse shaping techniques. Several systematic limitations prevented realization of photocathode laser pulses with the desired beam shape.

A redesign of the laser system was done based on a commercial, high power oscillator-amplifier laser while keeping the concept of the pulse shaper. It is expected that this should solve most of the systematic limitations in the near future.

It is anticipated with the simplified redesign based around a single-stage photonic source that most of the systematic limitations shall be eliminated in the near future.

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