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Production of quasi ellipsoidal laser pulses for next generation high brightness photoinjectors ☆

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A R T I C L E I N F O

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A B S T R A C T

The use of high brightness electron beams in Free Electron Laser (FEL) applications is of increasing importance. One of the most promising methods to generate such beams is the usage of shaped photocathode laser pulses. It has already demonstrated that temporal and transverse flat-top laser pulses can produce very low emittance beams [1]. Nevertheless, based on beam simulations further improvements can be achieved using quasi-ellipsoidal laser pulses, e.g. 30% reduction in transverse projected emittance at 1 nC bunch charge.

In a collaboration between DESY, the Institute of Applied Physics of the Russian Academy of Science (IAP RAS) in Nizhny Novgorod and the Joint Institute of Nuclear Research (JINR) in Dubna such a laser system capable of producing trains of laser pulses with a quasi-ellipsoidal distribution, has been developed. The prototype of the system was installed at the Photo Injector Test facility at DESY in Zeuthen (PITZ) and is currently in the commissioning phase.

In the following, the laser system will be introduced, the procedure of pulse shaping will be described and the last experimental results will be shown.

1. Introduction

A major task in optimization of modern free-electron lasers (FELs) is minimization of the electron bunch emittance and maximizing their brightness. One of the most promising methods to reach that goal is the transverse and longitudinal photocathode laser pulse shaping [2].

At PITZ such pulse shaping to improve the electron beam brightness and emittance has been done for a long time. In order to realize this, a laser system was developed at the Max-Born-Institute in Berlin. The system is capable of producing longitudinal flat-top laser pulses with short rising and falling times [3].

Further enhancement of the electron beam can be obtained using quasi ellipsoidal laser pulses. This is a result of simulations done at PITZ. For generating trains of laser pulses with μs separation, such quasi ellipsoidal shaped laser pulses have never been produced before, as such it was necessary to develop a unique laser system at IAP. The shaping unit consists of two spatial light modulators (SLMs).

2. Beam dynamics simulations with ASTRA code

Shaping of the photocathode laser pulses plays a significant role in the optimizations of the electron beam quality, especially the slice emittance. Beam dynamics simulations comparing different longitudinal and transversal laser pulse shapes have been performed at PITZ using ASTRA code [ASTRA]. A detailed description of the simulations has been published elsewhere [4,5]. Here, only the main results of the simulations are presented.

In Fig. 1 the results of slice emittance simulations for electron bunches with 1 nC bunch charge are shown. It can be seen that an average slice emittance reduction of about 50% can be expected using (quasi) ellipsoidal laser pulses instead of cylindrical transverse shaped laser pulses with a temporal Gaussian or flat-top profile. Additionally, the slice emittance profile is significantly modified while the ellipsoidal laser pulses are applied.

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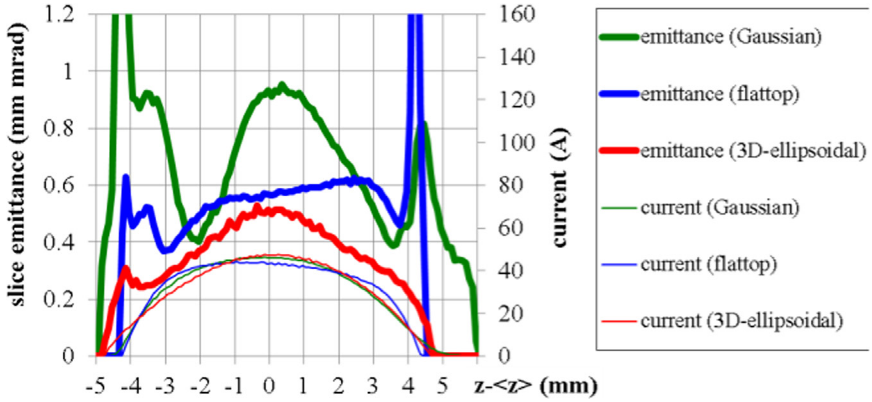

Fig. 1. Simulated slice emittance for 1 nC bunch charges using different photocathode laser pulse shapes.

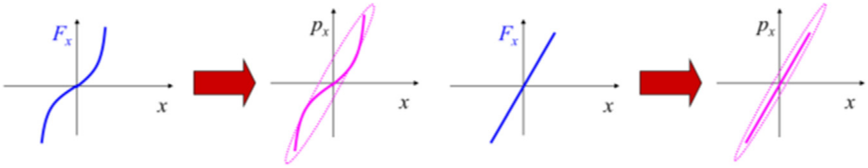

Fig. 2. Space charge impact of Gaussian/flat-top (left) respectively quasi ellipsoidal (right) photocathode laser pulses on transverse emittance (phase space).

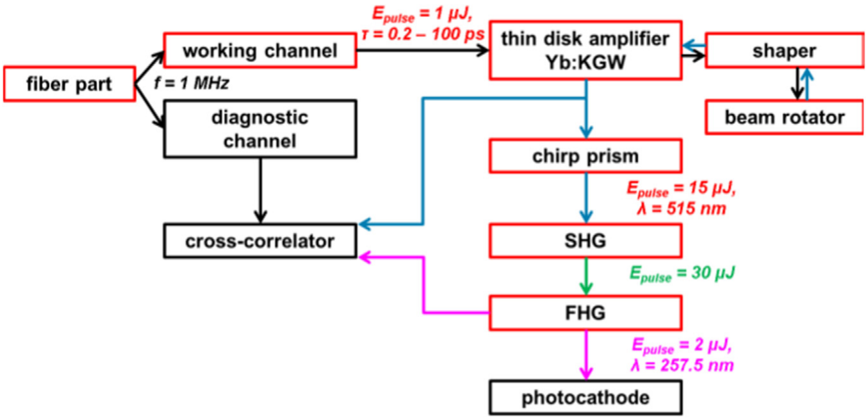

Fig. 3. Schematic setup of quasi ellipsoidal laser system.

Significant linearization of the transverse space charge force by applying the ellipsoidal photocathode laser pulse is illustrated in Fig. 2. The strong charge density gradient for the Gaussian pulses (left plot in Fig. 2) results in rather strong nonlinearity of the Lorenz force and, therefore, in the uncorrelated phase space distortion. The space charge distribution of the quasi-ellipsoidal bunch is more linear (right plot in Fig. 2), which corresponds to the more linear transverse phase space and a significantly smaller emittance.

Besides the transverse phase space, more linear longitudinal phase space has been simulated for the quasi-ellipsoidal bunches. This enables more flexibility in the subsequent bunch compression in a linac based FEL accelerators.

3. Ellipsoidal photocathode laser system

Motivated by the simulations, a laser system capable of producing trains of quasi ellipsoidal laser pulses was developed at IAP RAS in collaboration with JINR. Since the beginning of 2015 this laser system has been under commissioning at PITZ. Here, further developments of the laser system are addressed to get the system into reliable long term operation at the L-band RF gun with a Cs_2Te photocathode at PITZ. All works are done in close collaboration with IAP. The overall setup of the laser system is shown in Fig. 3.

The actual laser system consists of a fiber laser with a dual-output. This allows providing two independent laser beams with similar characteristics. The wavelength of the beams is 1030 nm, the pulse length is about 150 fs and the repetition rate is 45 MHz. The frequency is later on reduced to 1 MHz. One of the beams is used for the photocathode laser beam path (working channel) and the other one for the cross-correlation beam path, providing the sample pulses (diagnostic channel).

The fiber laser system also comprises a fiber-based pulse stretcher, a preamplifier and a system for pulse train (macropulse) formation.

To provide a precise tuning of the laser pulse timing with respect to the RF phase, which is crucial for a stable operation of the photo injector, a rough and a fine tuning of the frequency is possible. The rough adjustment can be done by the control of the temperature of the laser fiber. A piezo ceramic cylinder is integrated inside the optical fiber coil of the oscillator to enable the fine tuning.

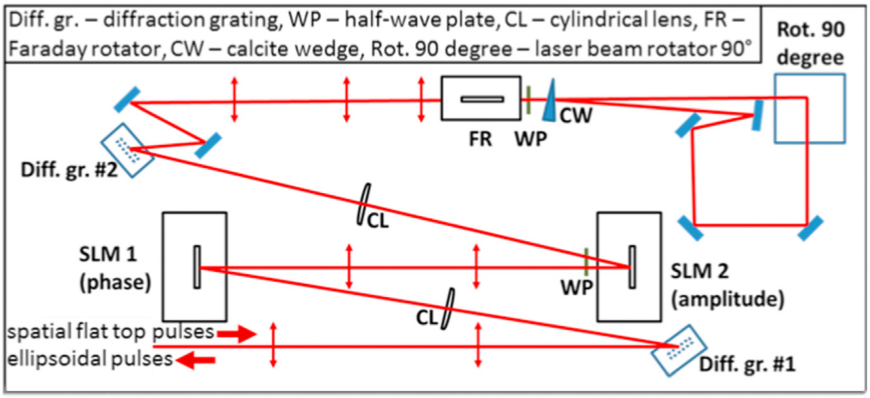

Fig. 4. Setup of pulse shaper unit.

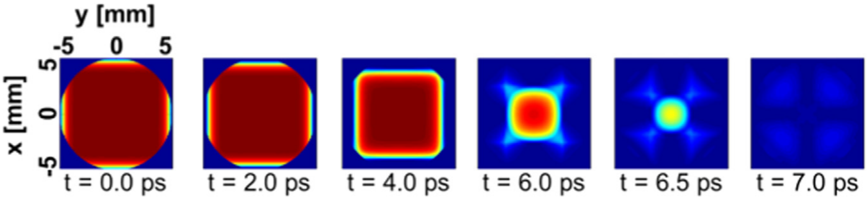

Fig. 5. Simulated ideal quasi ellipsoidal laser pulses passing the shaping unit two times (rotated by 90°).

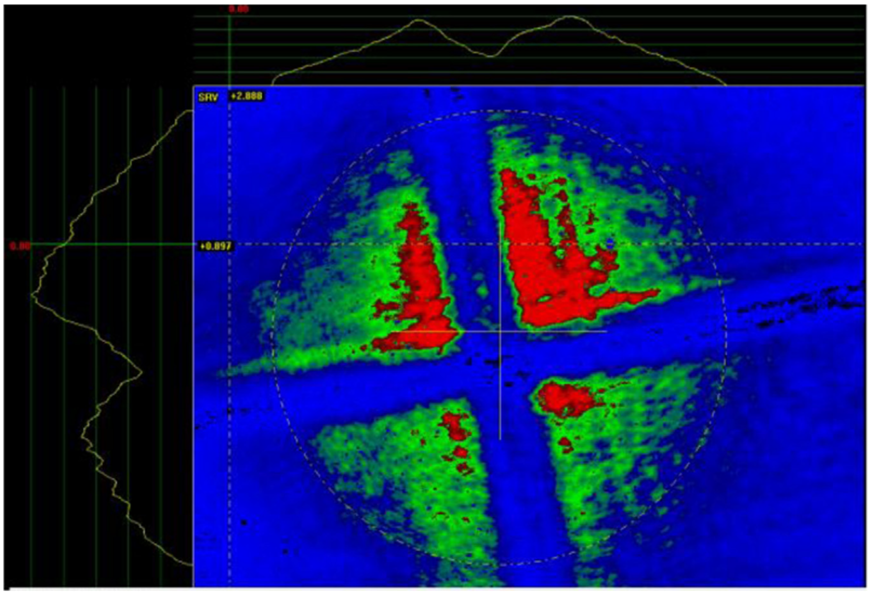

Fig. 6. Laser pulses imaged – by help of wire cross – onto the virtual cathode of PITZ laser beam line.

The laser pulses coming from the working channel are first stretched to some ps pulse length and then sent through a pinhole. The size of the pinhole is adjusted in a way that only the more or less flat part-in terms of intensity-in the middle of the transverse Gaussian laser beam is transmitted. The part of the pulses with a high intensity gradient is thereby cut away. The pinhole position is also used as the first image plane of the system.

The quasi flat-top laser pulses are then transported to a multi-pass (10 passes up to now) Yb:KGW disc amplifier. As pump source a 960 nm LDM 2000-100 (Laserline GmbH) CW laser is used.

In the next step the amplified laser pulses are shaped both temporally and spatially. This is realized by a scheme based on two liquid crystal based spatial light modulators (currently SLM HES 6010 NIR by Holoeye Photonics AG). The principal set-up of the 3-D pulse shaper is shown in Fig. 4.

The pulse shaper is based on a zero dispersion optical compressor. Initially the (chirped) laser pulses are diffracted at a grating. This results in a wavelength separation and thereby a transformation of the temporal into a spatial distribution. By imaging the laser pulses afterwards onto the first SLM the phase of defined temporal and spatial fractions can be modulated. In a second step the polarization of the laser beam is rotated by 45° and again imaged onto the second SLM. In conjunction with the polarization the individual liquid crystals of the SLM acts now as amplitude modulators.

After the phase and amplitude masking a second diffraction grating transforms the wavelength components back into the temporal axis.

As a single pass through the pulse shaper only forms the laser profile in one spatial dimension, the laser pulses are rotated after the pulse shaper unit by 90° and then returned back through the pulse shaper unit a second time. This allows a pulse shaping in x- and y-direction.

In Fig. 5 simulations of shaped laser pulses, using the described pulse shaper setup, are shown. From left to right the pulse shape and intensity distribution can be seen. The $t=0$ ps is defined at the temporal center of the laser pulse.

It can be seen that the edges of the laser pulses are not perfectly round outside the temporal center of the laser pulses. This behavior can be reduced by including further SLMs at bisecting angles, e.g. rotating 3 times by an angle of 45°.

Finally, frequency conversion is achieved with LBO and BBO crystals.

The cross-correlation technique is used for beam diagnostics, both in IR (before frequency conversion) and UV. For this, a high-speed delay line is implemented, which allows measurement of the spatial and temporal profile of the laser pulses with high precision. A full description of the cross-correlator can be found elsewhere [6,7].

4. Experimental status

The new laser system has been integrated into the existing (photocathode laser) transport structure and preliminary photoelectrons have been generated successfully.

A wire cross was placed in the final image plane of the new laser and then transported onto the virtual cathode of the PITZ laser beam line (Fig. 6).

Due to difficulties concerning the synchronization of the SLMs with the facility's gating trigger, no emittance measurements have been carried out to date. A few technical solutions are under consideration to solve this issue.

5. Conclusion

Based on simulations a change from cylindrical pulses with Gaussian or flat-top temporal profiles to quasi ellipsoidal laser pulses can significantly reduce the emittance of electron bunches generated by a photoinjector.

Motivated by these simulations a laser system capable of creating such quasi ellipsoidal laser pulses has been developed and installed at PITZ. A full integration of the laser system into the PITZ environment has been completed and first electrons have been generated using the new photocathode laser system.

After the first tests some difficulties, e.g. synchronization of SLMs with RF timing, have been discovered, solutions have been found and will be realized soon.

Meanwhile, stability and reliability tests of the laser system will be done. First emittance measurements are planned in 2016.

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