EXPERIMENTAL OPTIMIZATION OF THE CATHODE LASER TEMPORAL PROFILE*

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Abstract

Producing a flat-top temporal intensity profile for the cathode laser pulse is a key issue for the XFEL photo injector. The photo injector test facility at DESY in Zeuthen (PITZ) serves as a test bench for FEL photo injectors. The PITZ cathode laser contains a pulse shaper to produce flat-top temporal pulse profiles. Based on birefringent filters the pulse shaper includes four degrees of freedom to achieve a pulse profile with parameters closer to the required XFEL photo injector specifications (20 ps FWHM, 2 ps rise/fall time). A procedure for experimental temporal laser profile optimization is presented in this paper. The laser profile is measured using a streak camera. The five parameters - pulse length (FWHM), rise and fall time as well as flat-top modulation period and depth which are obtained from a flat-top fit of the measured profile - are used in the profile evaluation. Using results of beam dynamics simulations for various cathode laser profiles a single value of the goal function – the expected emittance growth due to measured imperfections of the profile - can be obtained. The procedure of the goal function minimization has been implemented and tested at PITZ.

INTRODUCTION

A projected normalized beam emittance of ~0.9 mm mrad from the photo injector is the key requirement to fulfill the XFEL specifications [1]. In order to achieve such a challenging performance of the electron source a cathode laser with temporal flat-top profile having 20 ps FWHM and ≤ 2 ps rise and fall time has to be used.

A pulse shaper based on the birefringent filter is currently in use at PITZ to produce a flat-top cathode laser temporal profile. The laser temporal distribution deviates from the goal flat-top (20 ps FWHM, 2 ps rise/fall time) profile. The main reason for this is the limited fluorescence bandwidth of the amplifying medium (Neodymium-doped Yttrium-Lithium Fluoride, Nd:YLF) used in the laser system.

In order to study the impact of the laser temporal profile imperfections onto the quality of the electron beam in the photo injector corresponding beam dynamics simulations have been performed. A procedure for the evaluation of the experimentally obtained laser shape has been developed based on results of beam dynamics simulations. An algorithm for the pulse shaper optimization is proposed.

LASER PULSE SHAPER AT PITZ

The laser system and the temporal pulse shaper [2] operated at PITZ were developed at the Max-Born-Institute (MBI) in Berlin. The laser produces pulse trains up to 800 µs length with a single pulse separation of 1 µs and a pulse train repetition rate of up to 10 Hz.

An IR Gaussian laser pulse (wavelength 1047 nm) is generated by the mode locked pulse train oscillator (PTO) [3], followed by the pulse shaper and six stages of diode pumped Nd:YLF amplifiers. Two nonlinear crystals are used to convert the IR laser pulse into its fourth harmonics (UV, wavelength 262 nm). A pulse shaper based on birefringent filters is currently in use at PITZ, its schematics is shown in Fig.1.

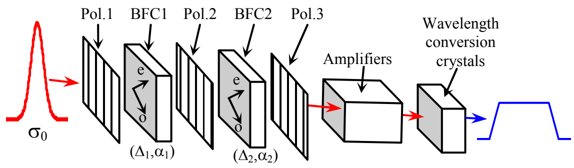

Figure 1: Schematics of pulse shaping elements.

The pulse shaper is composed of a stack of birefringent crystals (BFC1, BFC2) interspersed with polarizers (Pol.1,2,3). High birefringence of the crystals provides a phase shift between ordinary and extraordinary waves $\Delta = 2\pi(n_e(\lambda) - n_o(\lambda))d/\lambda$, where n_o and n_e are the refractive indices for ordinary and extraordinary waves in the crystal of thickness d, $\lambda = 1047nm$ is the laser wavelength. σ_o is the rms pulse duration of the initial Gaussian pulse. By adjusting the orientation of the crystals (α_1, α_2) and tuning the phase shifts (Δ_1, Δ_2) a temporal profile of the output pulse close to a flat-top can be achieved. The limited fluorescence bandwidth of the used laser medium Nd:YLF significantly modifies the pulse shape during the amplification process and restricts the rise and fall time of the output pulse to 4…5 ps. In addition, modulations in the flat-top area of the output pulse arise. Streak-camera measurements [4] show a typical modulation depth of ~10-20%. These modulations can be reduced at the cost of increased rise and fall time. The effects of the amplifier and wavelength conversion stages are significant and need to be studied in more detail. Electron beam dynamics simulations have been involved in order to find a proper compromise between modulation depth and rise/fall time of the laser pulse.

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BEAM DYNAMICS SIMULATIONS

ASTRA [5] beam dynamics simulations have been performed in order to establish a figure of merit for experimentally obtained cathode laser temporal profiles. Four main factors have been considered: pulse length (FWHM), rise/fall time, frequency and depth of the flat-top modulation.

The optimized setup of the XFEL photo injector [1] has been used to simulate the influence of the cathode laser temporal profile imperfections. The nominal flat-top distribution with 20 ps FWHM and 2 ps rise/fall time has been considered as the baseline for the comparison. A homogeneous transverse cathode laser profile with rms size of 0.4 mm has been used for the simulations. Electron bunch properties at the distance z = 15 m from the photo cathode are simulated by ASTRA, the beam is generated by a 1.5-cell L-band RF gun with 60 MV/m at the photo cathode and accelerated by the first module (8 TESLA cavities) up to an energy of ~150 MeV. The projected normalized beam emittance as a function of rise/fall time is shown in Fig.2a. The dependence of the transverse and longitudinal emittance is shown in Fig.2b as a function of the pulse length (FWHM). The transverse projected emittance is lower for longer laser pulses due to reduced transverse space charge effect, especially during emission from the photo cathode. The drawback is the increased longitudinal emittance, which is a consequence not only of the increased bunch length but also a result of the increased contribution of the longitudinal nonlinearity of the RF field.

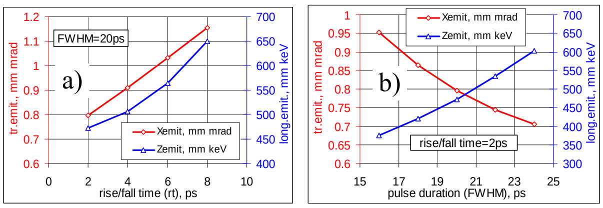

Figure 2. The beam projected transverse normalized emittance and longitudinal emittance at z=15 m. a) vs. rise/fall time of the photo cathode laser pulse; b) vs. photo cathode pulse duration (FWHM of the flat-top).

The impact of the flat-top modulation is illustrated in Fig.3, where the transverse and longitudinal emittance is shown as a function of modulation depth *m* for various modulation periods $T_n = 18\,ps/(n+0.5)$ (n=1, 2, 3, 8). Typical intensity distributions used to simulate the flat-top modulation are shown in Fig.4a. It should be noticed that these modulation frequencies are lower than those which can be critical in bunch compression schemes (which are out of the scope of this work).

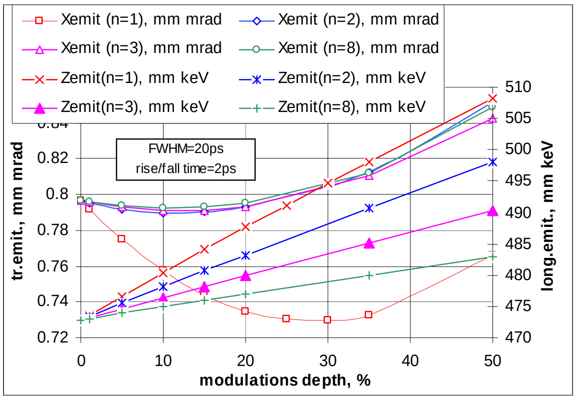

Figure 3: Simulated projected normalized transverse and longitudinal emittance vs. flat-top modulation depth *m* for various modulation frequencies (n is the number of the modulation half-wavelength on the flat-top).

For higher modulation frequency (n ≥ 2) a shallow minimum of the emittance for ~10% modulation depth is caused by the modification of the space charge force due to the modulation of the electron longitudinal phase space. On the other hand the laser intensity modulation results in a modulation of the longitudinal phase space of the electron beam and, therefore, in the longitudinal emittance growth.

A goal function for the experimental cathode laser profile optimization can be modelled now by a combination of imperfection factors: rise (*rt*) and fall time (*ft*), pulse length (*FWHM*) and modulation parameters (*n* and *m*):

$$\Phi = \sqrt{\Phi_{rt}(rt)\Phi_{rt}(ft)} \cdot \Phi_l(FWHM) \cdot \Phi_{\mathrm{mod}}(n,m)\,. \quad (1)$$

Based on simulation results these factors can be approximated as expected transverse emittance growth due to the corresponding laser shape imperfection:

$$\Phi_{rt}(x) = 1 + 0.008\cdot(x-2)$$

$$\Phi_l(x) = \begin{cases} 1 - 0.039\cdot(x-20) + 0.003\cdot(x-20)^2, \text{if } x < 20 \\ 1 + 0.061\cdot(x-20) + 0.002\cdot(x-20)^2, \text{if } x > 20 \end{cases} \quad (2)$$

$$\Phi_{\mathrm{mod}}(n,m) = \begin{cases} 1 - 0.059\cdot m + 0.0001\cdot m^2, \text{if n} = 1 \\ 1 - 0.0011\cdot m + 0.00005\cdot m^2, \text{if n} > 2 \end{cases}$$

In order to keep the minimum of the Φ_l at FWHM=20 ps, a relative longitudinal emittance growth has been used for FWHM > 20 ps.

MEASUREMENTS OF THE TEMPORAL LASER PROFILE AT PITZ

The temporal profile of the cathode laser is measured by use of a streak-camera [4] at PITZ. In order to evaluate the measured profile, a flat-top fit procedure (Fig.4b) has been developed. It yields the parameters of the flat-top laser profile (*rt*,*ft*,*FWHM*,*n*,*m*), which when being applied in (2), delivers a single value of the goal function (1). The physical meaning of this value is the expected emittance growth due to imperfections of the measured laser temporal profile.

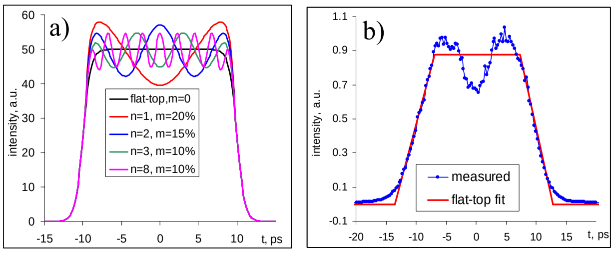

Figure 4. Cathode laser temporal profiles: a) used in beam dynamics simulations; b) measured at PITZ with a streak camera.

OPTIMIZATION OF THE TEMPORAL LASER PROFILE

Four pulse shaper parameters are available at PITZ for the tuning of the cathode laser temporal profile: rotation angles of both birefringent crystals (α_1, α_2) and their temperatures (T_1, T_2), by means of those one can vary the effective thickness (Δ_1 , Δ_2) and, therefore, the corresponding phase shifts.

In order to illustrate the complexity of the optimization procedure a contour plot of the measured goal function (1) vs. rotation angles (α_1, α_2) (for fixed temperatures (T_1, T_2)) is shown in Fig.5.

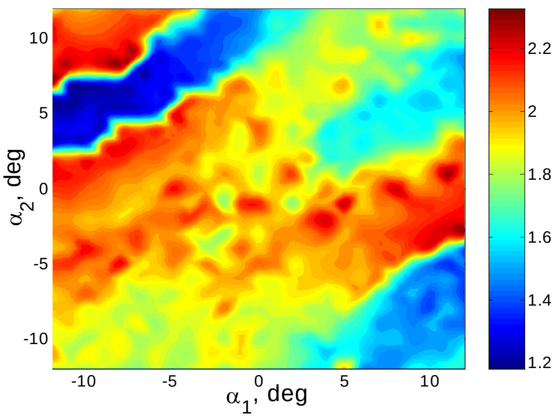

Figure 5. Contour plot o the goal function, based on measured cathode laser temporal profiles vs. rotation angles of birefringent crystals while their temperatures (phase shifts) being kept constant.

It can be clearly seen that even in the 2-dimensional cross section of the 4-dimensional parameter space there are several local minima. This makes the procedure of the laser temporal profile optimization rather sensitive to the initial parameter set. A staged strategy for the laser temporal profile optimization has been chosen: the goal function has been minimized by the simplex method [6] in the 4-parameter space (α_1, α_2 , T_1, T_2), but the initial simplex has been randomly seeded. The area of the parameter search has been smoothly restricted (to the physical parameter ranges) by applying corresponding penalty functions. At each step of the optimization three laser profile measurements have been performed in order to avoid random fluctuations. The optimization procedure and results of two trials are shown in Fig.6.

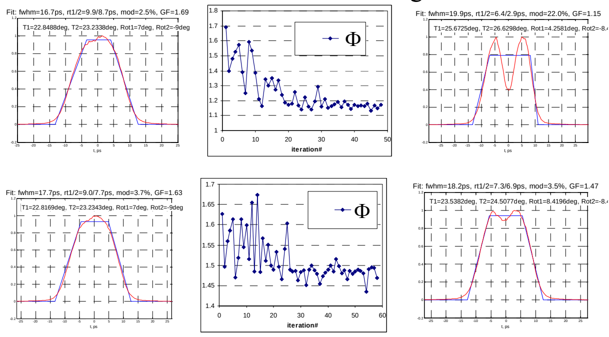

Figure 6. Optimization of the cathode laser temporal profile: left plots - initial measured distributions (the best from the randomly seeded series); middle plots – goal function evolution vs. optimization step, right plots – final measured distributions of the laser intensity.

One can see that the final profile in the upper row has comparatively short rise/fall time, but the modulation of the flat-top is rather large. In contrary, the second row represents the optimization results with small modulation at the price of increased rise/fall time.

CONCLUSIONS

A procedure for the optimization of the photo cathode laser temporal profile has been developed. It is based on the tuning of 4 parameters of a pulse shaper, based on birefringent filters. The flat-top profile evaluation is based on beam dynamics simulations for the beam emittance of the electron beam in a photo injector. The optimization is complicated by complexity of the goal function relief, which makes the search strongly dependent on the initial parameter set of the pulse shaper.

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