EMITTANCE OPTIMIZATION FOR DIFFERENT BUNCH CHARGES WITH UPGRADED SETUP AT PITZ

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Abstract

The Photo Injector Test facility at DESY, Zeuthen site, (PITZ) has the aim to develop and optimize high brightness electron sources for free electron lasers like FLASH and the European XFEL. Photo electrons emitted from the $\mathrm{Cs_2Te}$ cathode are accelerated by a 1.6-cell L-band RF gun cavity operated at $60\,\mathrm{MV/m}$ maximum accelerating gradient at the cathode. Cylindrically shaped laser pulses with a flat-top temporal profile of about $20\,\mathrm{ps}$ FWHM and $2\,\mathrm{ps}$ rise and fall time are used to produce electron beams with extremely low emittance. The PITZ beam line was upgraded in 2010. The new gun cavity (prototype number 4.1) was installed January 2010. The new booster cavity (CDS) with well-defined field distribution was installed in July 2010. The diagnostic system for characterization of the laser hitting the photocathode was upgraded in October 2010. Emittance measurements results for different charges: $2\,\mathrm{nC}$, $1\,\mathrm{nC}$, $0.25\,\mathrm{nC}$, $0.1\,\mathrm{nC}$ and $0.02\,\mathrm{nC}$, will be presented. The optimization was done for different parameters, e.g. gun solenoid current, gun phase, laser spot size on the cathode, booster gradient.

INTRODUCTION

Linac based free-electron lasers like FLASH and the European XFEL require electron beams of high quality with small normalized projected transverse emittance. Research activities at PITZ include development, production, characterization, and optimization of photo injectors to satisfy the requirements of the European XFEL and FLASH [1, 2]. For the production of coherent light in such free-electron lasers the Self Amplified Spontaneous Emission (SASE) process is used. The wavelength and brightness of the electromagnetic radiation emitted during this process is amongst others defined by peak current, energy spread, and transverse projected emittance of the electron beam. The transverse slice emittance is formed during the emission process at the cathode in the RF gun, and cannot be improved after the electron beam leaves the injector. The XFEL project requires a normalized transverse projected emittance of less than $0.9\,\mathrm{mm\,mrad}$ for $1\,\mathrm{nC}$ bunch charge [2]. Production of electron beams with such small transverse projected emittance is the main task of PITZ. Starting from November 2009 a significant part of the facility was upgraded [3].

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EMITTANCE MEASUREMENT PROCEDURE

Transverse projected emittance is measured at PITZ by using the single slit scan technique [4]. The local divergence of the beam is estimated by cutting the electron beam into thin slices ($10\,\mu\mathrm{m}$) and measuring their transverse distribution after propagation in a drift space. In order to reconstruct the transverse phase space, beamlet images are recorded continuously while the slit is being slowly moved across the beam. The transverse distribution of the beam is measured at the position of the slit to correct for intensity losses. The beam profile at the position of slit and beamlet profiles on the observation screen are recorded with a 12 bit CCD camera. The camera gain is set by the operator to use the full dynamic range of the camera. Reasonable signal level can be achieved by tuning camera gain and number of electron bunches integrated in a pulse train. The transverse projected emittance is calculated by using following formula [4]:

$$\varepsilon_x = \beta\gamma \frac{\sigma_x}{\sqrt{\langle x^2 \rangle}} \sqrt{\langle x^2 \rangle \cdot \langle x'^2 \rangle - \langle x x' \rangle^2} \qquad (1)$$

where $\langle x^2 \rangle$ and $\langle x^{'2} \rangle$ are the second central moments of the beam in the trace space obtained from the slit scan, and $x^{'} = p_x/p_z$, σ_x is the rms beam size measured at the position of the slit, and $\beta\gamma$ is a Lorenz factor measured using the dispersive section.

BEAM DYNAMIC SIMULATIONS

For the beam dynamics simulations ASTRA was used [5]. The transverse phase space has been optimized for $1\,\mathrm{nC}$ bunches. To produce them, a cathode laser pulse with flat-top temporal profile ($22\,\mathrm{ps}$ FWHM and $2\,\mathrm{ps}$ rise/fall time) was used. The transverse laser distribution was assumed to be radially uniform with variable diameter. The gun gradient was optimized to get a measured beam mean momentum $6.9\,\mathrm{MeV/c}$ after the gun. The booster gradient was also tuned to get a measured beam mean momentum after the booster of $24.9\,\mathrm{MeV/c}$. The multiparameter photo injector optimization yielded a minimum rms projected emittance of $0.6\,\mathrm{mm\,mrad}$ obtained for an rms laser spot size at the cathode $\sigma_{\mathrm{xy}} = 0.4\,\mathrm{mm}$, gun phase $\phi_{\mathrm{gun}} = -1.1\,\mathrm{deg}$ with respect to maximum mean momentum gain phase (MMMG phase), gun gradient $\mathrm{E_{gun}} = 60.6\,\mathrm{MeV/m}$, booster gradient $\mathrm{E_{booster}} = 20.6\,\mathrm{MV/m}$, booster phase $\phi_{\mathrm{booster}} = 0\,\mathrm{deg}$ (MMMG phase) and solenoid peak field $\mathrm{B_z} = -0.22808\,\mathrm{T}$. In order to study the sensitivity of the obtained minimum emittance to various machine parameters, parameter scans have been performed. Results are shown in Fig. 1 and 2.

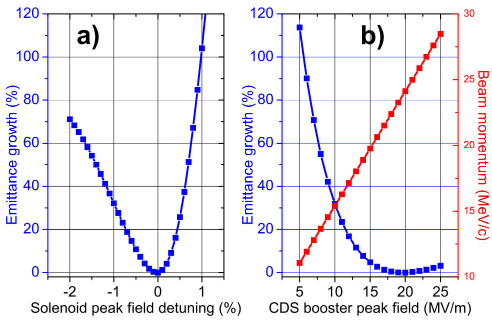

Figure 1: Emittance growth from main solenoid current and booster accelerating gradient.

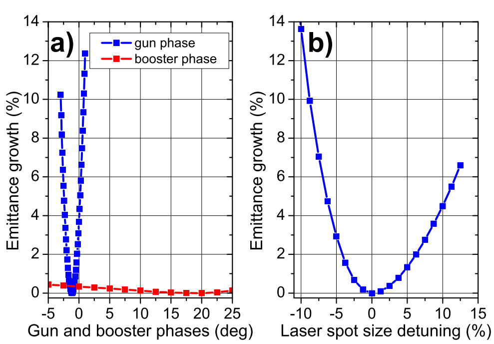

Figure 2: Emittance growth from gun, booster phases and laser spot size detuning.

As an example, a detuning of the main solenoid peak field by 0.5% only results in a 10% emittance growth (Fig. 1a). With a nominal solenoid current of $392\,\mathrm{A}$, this translates in a sensitivity of $2\,\mathrm{A}$. Therefore, the solenoid current step size for emittance optimization should be smaller than $2\,\mathrm{A}$. Emittance growth dependencies on the gun launch phase (Fig. 2a) and the laser rms spot size (Fig. 2b) are weaker than on the solenoid peak field, but the impact of these parameters is still significant. The emittance dependence on the booster gradient (Fig. 1b) is rather flat for a beam momentum larger than $22\,\mathrm{MeV/c}$. The booster launch phase formal optimization results in the optimum phase of $+20\,\mathrm{deg}$ with respect to on-crest phase, but due to a significant momentum spread at this phase it will be extremely hard to measure this emittance minimum using the slit scan method. Moreover the simulated emittance growth is very small within a wide range of the booster phase and the on-crest phase is of practical interest.

EMITTANCE MEASUREMENTS

Taking into account simulation results, the dependence of emittance on main solenoid current, rms laser spot size on the cathode, and gun accelerating phase were in the focus of experimental studies at PITZ. For all measurements the temporal profile of the cathode laser pulse was kept to be flat top with $\mathrm{FWHM} \approx 20\,\mathrm{ps}$ and $\sim 2\,\mathrm{ps}$ rise and fall time [6].

Emittance vs. RMS Laser Spot Size on the Cathode

Emittance have been measured for different bunch charges depending on the rms laser spot size at the cathode. For each charge parameters optimization was performed. For all measurements gun and booster were operated at maximum gradient. Phases of the gun and booster were tuned to get maximum mean momentum gain of the electron beam after acceleration. This yields a mean beam momentum after booster acceleration of $24.9\,\mathrm{MeV/c}$. For each bunch charge the emittance optimization for various laser spot size at the cathode has been performed. The minimum emittance values chosen from the solenoid scan depending on the laser transverse size at the cathode obtained from experimental optimization are presented in Fig. 3. The minimum measured emittance value for $1\,\mathrm{nC}$ bunch

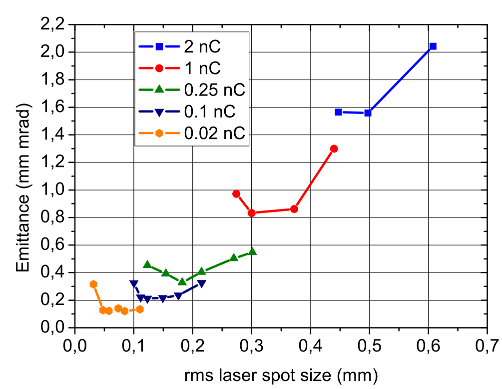

Figure 3: Emittance measurements for different charges.

charge was obtained for a rms laser spot size at the cathode of $0.3\,\mathrm{mm}$ and gives the geometrical mean emittance of $0.83\,\mathrm{mm\,mrad}$ which satisfies the European XFEL requirements. The minimum emittance values obtained for 2, 0.25, 0.1, and $0.02\,\mathrm{nC}$ charges are 1.56, 0.33, 0.21, and $0.12\,\mathrm{mm\,mrad}$ respectively.

Emittance vs. Main Solenoid Current

Measured emittances for the optimum laser spot size on the cathode are shown in Fig. 4 as a function of the main solenoid current for various bunch charges: 2, 1, 0.25, 0.1 and $0.02\,\mathrm{nC}$.

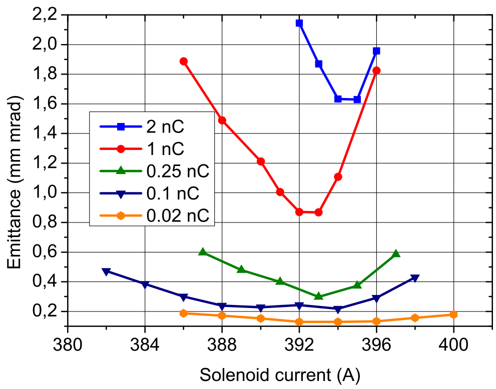

Figure 4: Emittance dependence on solenoid current.

Emittance vs. Gun Phase

Emittance dependence on the gun launch phase was measured for $1\,\mathrm{nC}$ bunch charge. The rms laser spot size at the cathode was fixed to $0.3\,\mathrm{mm}$. The mean momentum of the electron beam was $24.9\,\mathrm{MeV/c}$ during these measurements. The gun phase was varied with respect to the MMMG phase. For each gun phase the booster phase was tuned to the MMMG phase. For each gun phase a gun solenoid scan was performed and minimum emittance values are presented on Fig. 5.

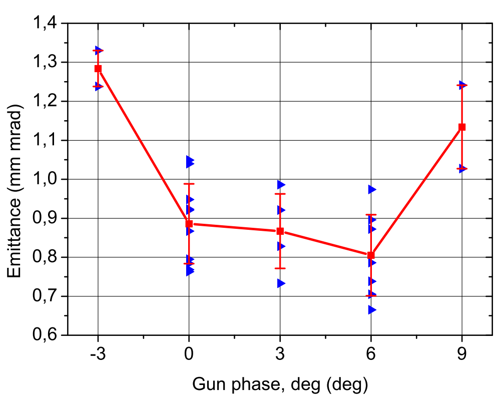

Figure 5: Emittance dependence on the gun phase: blue dots - measurement data, red connected dots - average value for a given phase.

Emittance vs. Booster Gradient

Emittance as a function of the booster gradient was measured for an rms laser spot size on the cathode of $0.3\,\mathrm{mm}$ and $1\,\mathrm{nC}$ bunch charge. The gun and booster were operated at MMMG phases for these studies. The results are presented in Fig. 6. The experimentally obtained curve shows similar behavior than simulations (Fig. 1b).

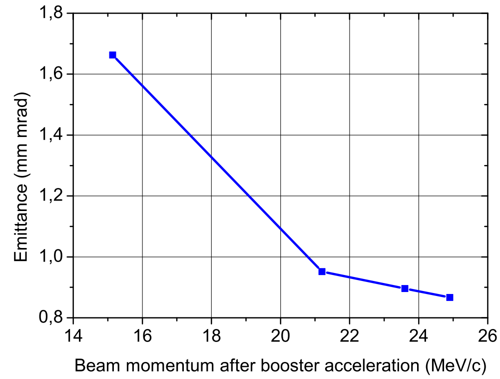

Figure 6: Emittance dependence on booster gradient for an rms laser spot size on the cathode of $0.3\,\mathrm{mm}$ and $1\,\mathrm{nC}$ bunch charge.

SUMMARY

The transverse projected emittance was optimized at PITZ for a wide range of bunch charges. The obtained emittance values satisfy the requirements for the European XFEL photo injector. Detailed studies of the emittance dependencies on different machine parameters including gun launch phase, laser spot size, and booster gradient were performed.

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