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PITZ EXPERIMENTAL OPTIMIZATION FOR THE AIMED CATHODE GRADIENT OF A SUPERCONDUCTING CW RF GUN

M. Krasilnikov*, P. Boonpornprasert, Y. Chen, G. Georgiev, J. Good, M. Gross, P. Huang, I. Isaev, C. Koschitzki, S. Lal, X.-K. Li, O. Lishilin, G. Loisch, D. Melkumyan, R. Niemczyk, A. Oppelt, H. Qian, H. Shaker, G. Shu, F. Stephan, G. Vashchenko, DESY, Zeuthen, Germany
M. Dohlus, E. Vogel, DESY, Hamburg, Germany

Abstract

A continuous wave (CW) mode operation of the European X-ray Free-Electron Laser (XFEL) is under considerations for a future upgrade. Therefore, a superconducting radio frequency (SRF) CW gun is under experimental development at DESY in Hamburg. Beam dynamics simulations for this setup have been done assuming 100 pC bunch charge and a maximum electric field at the photocathode of 40 MV/m. Experimental studies for these parameters using a normal conducting RF photogun have been performed at the Photo Injector Test facility at DESY in Zeuthen (PITZ). The beam transverse emittance was minimized by optimizing the main photo injector parameters in order to demonstrate the feasibility of generating electron beams with a beam quality required for successful CW operation of the European XFEL for conditions similar to the SRF gun setup.

INTRODUCTION

For successful CW operation of modern XFEL facilities the electron source should combine high average power and peak beam brightness sufficiently high for proper lasing. A high cathode gradient in the gun is one of the important factors to achieve high phase space density of the generated electron beams. However due to the CW requirements (high average power) on the electron source the peak RF power (gradient) in the RF gun is limited and is typically lower than in the case of pulsed guns. An SRF CW L-band gun is under experimental development at DESY in Hamburg [1]. A maximum electric field at the photocathode of 40 MV/m is considered for the operation of this gun in the CW mode of the European XFEL. Beam dynamics simulations for the SRF photo injector (CW SRF PI) setup have been done for 100 pC bunch charge generated with Gaussian photocathode laser pulses. Optimization of the projected normalized emittance yielded 0.45 mm mrad. In order to demonstrate this brightness the normal conducting PITZ photo injector has been tuned to the proposed conditions, namely 40 MV/m maximum electric field at the cathode and bunch charge of 100 pC. Results of experimental studies at PITZ supplied with corresponding beam dynamics simulations are compared with the optimized SRF CW photo injector setup.

LAYOUTS OF PHOTO INJECTORS

One essential difference between PITZ and the SRF gun setup is the location of the main solenoid. Due to the superconducting environment a focusing solenoid has to be separated from the SRF gun cavity and located downstream. For the normal conducting PITZ RF gun cavity the main solenoid is located closer to the cathode plane and its field overlaps with RF fields of the L-band PITZ gun cavity. Axial distributions of RF and solenoid fields are shown in Fig. 1 for both setups.

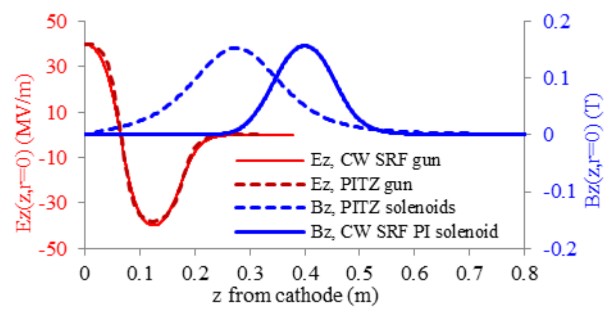

Figure 1: Axial distributions of RF electric fields (amplitudes $E_z(z, r = 0)$) and longitudinal magnetic field of solenoids ($B_z(z, r = 0)$) for SRF and PITZ guns.

BEAM DYNAMICS SIMULATIONS

Beam dynamics optimization for the CW SRF PI setup were performed using ASTRA [2] for 100 pC bunches applying photocathode laser pulses with a Gaussian temporal profile of 4 ps RMS duration. A module with 8 TESLA cavities (with 14.5 MeV energy gain per cavity) was applied to accelerate the beam up to 120 MeV. RF phase of the gun, strength of the solenoid (corresponding field profiles shown in Fig. 1) and laser transverse spot size were optimized to minimize a transverse emittance at the injector exit. Beam dynamics simulations for the PITZ setup were performed for parameters compromising between assumed CW SRF PI simulations and currently available parameters in experiment. Photocathode pulses with Gaussian temporal profile with 2.6 ps RMS duration (35% shorter than in the CW SRF PI simulations) were applied. The gun with maximum RF field of 40 MV/m at the photocathode and launch phase at the maximum mean momentum gain (MMMG) was used. The CDS booster [3] accelerates the beam up to ~17 MeV which is comparable with 1st cavity in cryomodule acceleration in the CW SRF PI case. The photocathode laser spot size and the main solenoid peak field were tuned in order to minimize projected normalized RMS emittance at z=5.27 m, the standard location of emittance measurements at PITZ.

Optimized simulated transverse RMS beam size and

* mikhail.krasilnikov@desy.de

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emittance along both photo injectors are shown in Fig. 2 (top plot). Corresponding beam energy and RMS bunch length are shown in the bottom plot. The transverse RMS emittance expected from the PITZ injector is lower mainly due to the optimized position of its main solenoid (z=0.276 m in Fig. 1). Because of the above mentioned limitations of the superconducting environment for the CW SRF PI setup the solenoid is separated from the gun cavity and centred at z=0.4 m.

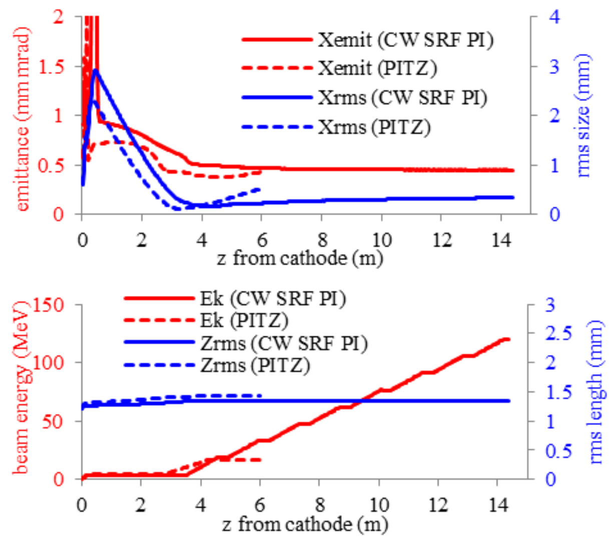

Figure 2: Simulated beam parameters along the beam line. Top: transverse RMS beam size and normalized transverse emittance. Bottom: mean beam energy and RMS bunch length.

Simulated optimized transverse phase space and beam slice parameters at the exit of the injector are shown in Fig. 3 for both setups.

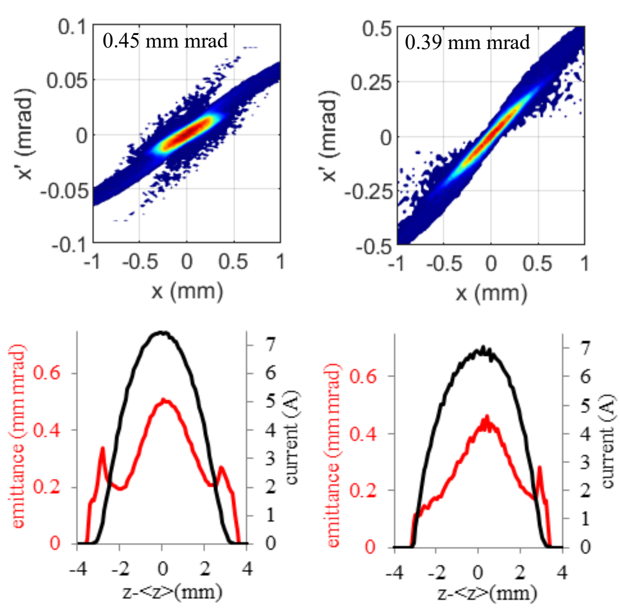

Figure 3: Beam parameters at the photo injector exit: left column – CW SRF PI, right column - PITZ. Top row: transverse phase space; bottom row: slice emittance and beam current profiles.

EXPERIMENTAL PITZ OPTIMIZATION

PITZ has been used to experimentally characterize the electron source performance for a parameter space close to the simulated optimum CW SRF PI setup.

Photocathode Laser

The photocathode laser system was operated with temporal Gaussian pulses with ~6 ps FWHM. A corresponding laser pulse temporal profile measurement using a cross-correlator (OSS – Optical Sampling System) is shown in Fig. 4 (left). Transverse shaping of the laser illuminating the photocathode is realized using variable aperture (the so-called Beam Shaping Aperture – BSA). The laser transverse distribution was monitored using a dedicated UV-sensitive CCD camera (Fig. 4, right). Inhomogeneity of the core and presence of radial halo are clearly seen and related to features of the laser system and imperfections of the optical transport beam line.

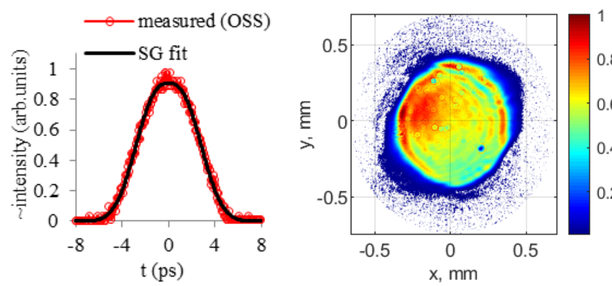

Figure 4: Left: Photocathode laser pulse temporal profile measured with OSS supplied with a Super Gaussian (SG) fit $SG \propto \exp\{-0.5 \cdot |t/2.6|^{2.59}\}$. Right: Transverse distribution of the laser intensity for the BSA diameter of 0.8 mm: laser RMS sizes: $\sigma_{x/y}^{laser} = 0.196/0.200$ mm.

RF Gun

The RF power in the gun (PITZ Gun4.2 prototype) was adjusted to yield a maximum electric field of 40 MV/m at the photocathode. This corresponds to a peak RF power in the gun cavity of 2.78 MW. The launch RF phase was tuned to the MMMG. Corresponding phase scan for the mean momentum and RMS momentum spread is shown in Fig. 5 (left). The momentum distribution for the MMMG phase is shown in the right plot.

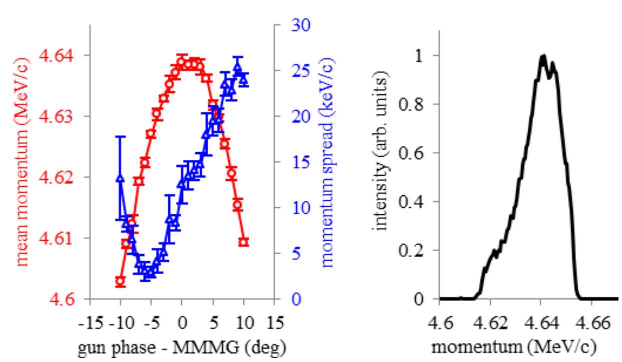

Figure 5: Left: gun RF phase scan for beam momentum. Right: beam momentum distribution after the gun at the MMMG phase, $\langle p_z \rangle = 4.64$ MeV/c, $\sigma_{p_z} = 10$ keV/c.

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Further electron beam acceleration was realized using the CDS booster which was operated on-crest at the peak power of ~2.3 MW, resulting in a final beam mean momentum of ~17.6 MeV/c.

Emittance Measurements

Beam transverse normalized RMS emittance was optimized at the first emittance measurement station (EMSY1) located z=5.27 m downstream of the photocathode. The single slit scan technique [3] was applied to measure the horizontal and vertical phase space of the 100 pC electron beam. The laser spot size (BSA diameter) was varied from 0.6 mm to 1.3 mm with a step of 0.1 mm. For each laser spot size, a main solenoid scan was performed to measure horizontal and vertical emittances. For the main solenoid current of 274 A gun quadrupoles [4] were optimized in order to obtain an electron beam distribution at the YAG screen (EMSY1) as round and symmetric as possible. Results of the experimental optimization are presented in Fig. 6 where emittance is shown as a function of the laser spot diameter together with ASTRA simulations. For comparison the results for the CW SRF setup are shown as well. Error bars of the measured curves include estimations on the emittance measurement uncertainty due to the intrinsic charge cut of the slit scan technique. PITZ emittance simulations have been performed with two laser transverse distributions: radially homogeneous and applying core and halo (C+H) model [5] deduced from the measured laser profile (see Fig. 4, right). Simulations for a BSA smaller than 0.7 mm revealed a regime of strong space charge dominated emission from the photocathode. Beam dynamics simulations for this regime show significant discrepancies with experimental observations. This problem is known [5] and under investigations.

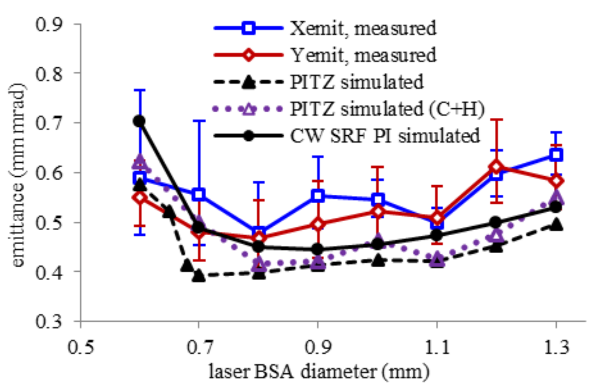

Figure 6: Normalized RMS emittance as a function of the laser Beam Shaping Aperture (BSA) diameter: measured at PITZ and simulated for PITZ and CW SRF PI setups.

Typical results of a basic emittance optimization measurement – emittance as a function of the main solenoid current – are shown in Fig. 7 for BSA=0.8 mm (see right plot in Fig. 4 for the laser transverse distribution). Simulated curves for the PITZ setup are shown as well. Both simulated curves are shifted by +4 A w.r.t. the measured curves for better comparison of the beam size and emittance dependencies on the main solenoid current. This discrepancy as well as vertical regular offset between simulated and measured emittance curves is a part of the above mentioned problem [5]. Measured horizontal and vertical phase spaces for the optimum solenoid current value (274 A) are shown in Fig. 8. Corresponding measured RMS normalized horizontal and vertical emittance values are $\varepsilon_{x,n} = (0.479 \pm 0.006_{stat})$ mm mrad and $\varepsilon_{y,n} = (0.468 \pm 0.005_{stat})$ mm rad. These values are in a reasonable agreement with simulation results within systematic limitations of emittance measurements.

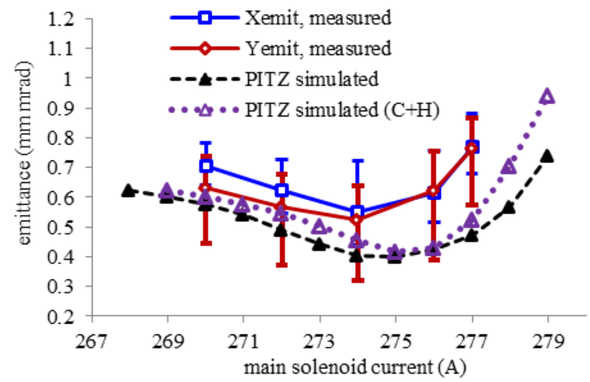

Figure 7: Normalized RMS emittance as a function of the main solenoid current together with ASTRA simulations for the PITZ setup.

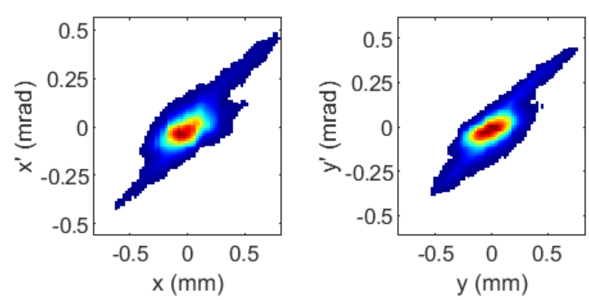

Figure 8: Horizontal (left) and vertical (right) transverse phase space measured for the optimum main solenoid current of 274 A.

CONCLUSION

Beam dynamics simulations for a CW SRF photo injector of the European XFEL have been performed assuming a peak RF electric field of 40 MV/m at the photocathode and 100 pC bunch charge generated by Gaussian photocathode laser pulses with 4 ps RMS duration yielding optimum emittance values of ~0.45 mm mrad. Experimental studies for this parameter space have been done at PITZ with Gaussian laser pulses with 2.6 ps RMS duration and yielded measured emittance values of ~0.5 mm mrad which is by ~0.1 mm mrad higher than the minimum expected from the corresponding PITZ simulations. The difference in optimized emittance between PITZ and CW SRF photo injector setups is mainly related to the main solenoid position w.r.t. the gun cavity and to the difference in the photocathode laser pulse duration.

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