EXPERIMENTAL OPTIMIZATION AND CHARACTERIZATION OF ELECTRON BEAMS FOR GENERATING IR/THz SASE FEL RADIATION WITH PITZ

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Abstract

The Photo Injector Test facility at DESY, Zeuthen site (PITZ), develops high brightness electron sources for modern linac-based Free Electron Lasers (FELs). The PITZ accelerator can also be considered as a suitable machine for the development of an IR/THz source prototype for pump-probe experiments at the European XFEL. One of the interesting options for the IR/THz generation with PITZ is to generate the radiation by means of a SASE FEL using an uncompressed electron beam with bunch length of a few 10 ps and a peak current of ~200 A. In this paper, results of experimental optimizations and characterizations, including transverse phase space, slice transverse emittance and longitudinal phase space, of electron beams with bunch charges of 4 nC are presented and discussed. The measurements were done with beam momenta of 15 MeV/c and 22 MeV/c. Results of IR/THz SASE FEL calculations by using the GENESIS1.3 code based on the measured beam parameters are also presented.

INTRODUCTION

The Photo Injector Test facility at DESY, Zeuthen site (PITZ) has been established to develop, study and optimize high brightness electron sources for modern linac-based short-wavelength Free-Electron Lasers (FELs) like FLASH [1] and the European XFEL [2]. The photocathode (PC) laser systems at PITZ are able to produce various temporal pulse shapes: Gaussian, flat-top and quasi-3D ellipsoidal [3–5]. The electron bunch charge can be varied from a few pC to 5 nC and the beam can be accelerated up to ~22 MeV/c.

The concept of generating IR/THz radiation by electron bunches from a linear accelerator for pump and probe experiments at the European XFEL was presented in [6]. PITZ has been considered as an ideal machine for the development of such IR/THz source. IR/THz generation from PITZ has been studied by 2 methods: Self-Amplified Spontaneous Emission (SASE) FEL and Coherent Transition Radiation (CTR) as presented in [7] and [8], respectively.

In [7], start-to-end (S2E) simulations of the THz SASE FEL from a PITZ-like accelerator for radiation wavelengths of 20 µm and 100 µm were performed by using the ASTRA [9] and the GENESIS1.3 [10] codes. An APPLE-II undulator with a period length of 40 mm was used as the radiator. The electron beams with bunch charges of 4 nC and beam momenta of 15 and 22 MeV/c were used to generate radiation wavelengths of 100 µm and 20 µm, respectively. The results show that a radiation peak power of at least 90 MW can be achieved within an undulator length of 6 m.

In order to demonstrate that such electron beams with the required parameters for SASE FEL radiation can be obtained from the PITZ accelerator, experimental optimization and characterization of electron beams with bunch charges of 4 nC for such purpose were performed. The experiments were done for 2 cases of beam momenta, 15 and 22 MeV/c as used in the S2E simulations. First, transverse projected emittances were measured and optimized. Then, parameters of the optimized beams including current profile, slice transverse emittance and slice momentum spread were measured. The results from ASTRA simulations are also presented alongside with the measurement results. Finally, the SASE FEL radiation based on the measured beam parameters were calculated by using the GENESIS1.3 code.

OPTIMIZATION AND CHARACTERIZATION OF 4 nC ELECTRON BEAMS

The layout of the PITZ beamline including an extension for simulation studies of IR/THz SASE FEL at the end of the beamline is shown in Fig. 1. The layout consists of a 1.6-cell L-band photocathode RF gun surrounded by main and bucking solenoids, a CDS booster, a TDS cavity, screen stations, quadrupole and dipole magnets and an APPLE-II type undulator which is assumed to be placed at the end of the beamline. LEDA, HEDA1 and HEDA2 sections are used for electron beam momentum and longitudinal phase space (LPS) measurements.

Machine and some measured beam parameters used in this work are listed in Table 1. The PC laser with Gaussian temporal shape was used for electron beam generation. The RF gun phase was adjusted for the maximum mean momentum measured by LEDA. The booster phase was adjusted for the minimum momentum spread measured by HEDA1.

Optimization of Transverse Projected Emittance

The transverse projected emittance is measured using the single slit-scan technique [11]. The emittance measurement system (EMSY) consists of slit masks with an opening gap

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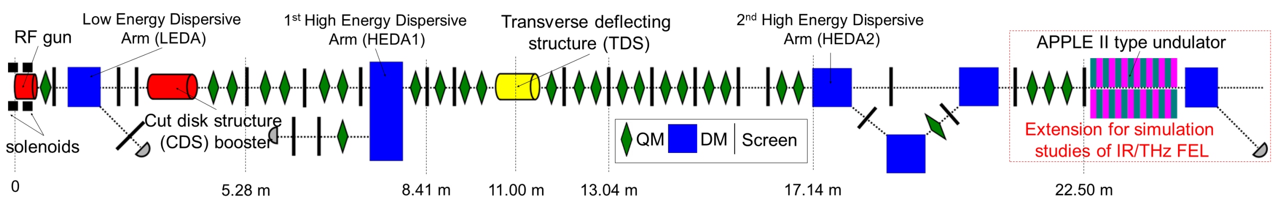

Figure 1: Layout of the PITZ beamline including extension for an IR/THz FEL for simulation studies. Here QM, DM and screen represent quadrupole magnets, dipole magnets and screen stations for monitoring of beam transverse profiles, respectively. The numbers represent the distance from the photocathode location (Z = 0).

Table 1: Machine and Electron Beam Parameters

Parameter	
PC laser pulse duration	~11 ps FWHM
PC laser diameter on the cathode	3.7 mm
Peak E-field in the gun	60.5 MV/m
Peak E-field in the booster	9.8 and 17.2 MV/m
Bunch charge	4 nC
Beam momentum after the gun	6.5 MeV/c
Beam momentum after the booster	15 and 22 MeV/c

of 10 μm and a beamlet collecting screen located at distances of Z = 5.28 m and Z = 8.41 m, respectively. More details of the measurement and the analysis procedures can be founded in [11].

First step, the optimization for minimizing the projected transverse emittance was done by measuring emittance as a function of the main solenoid current (I_m). Then, I_m was fixed at the value that delivers the smallest value of geometrical mean of emittance in both transverse planes. However, the optimized horizontal and vertical emittances are not symmetric. This asymmetry is possible caused by kicking from multipole fields inside the gun cavity system as investigated in [12]. Therefore, the second step optimization was to use the quadrupole magnets installed at the gun exit to symmetrize the optimized horizontal and vertical emittances from the first step.

The experimental results of projected emittance optimizations are summarized in Table 2 together with the results from ASTRA simulations using corresponding machine conditions. The measurement results of the 15MeV/c case show a strong x-y asymmetry which cannot be improved even when the gun quadrupole magnets were used.

The discrepancy between measured emittance values and those from the ASTRA simulations for the same laser diameter on the cathode was already observed in [11, 13], especially for the bunch charge above 250 pC. This difference is increasing with the bunch charge and becomes more significant for the 4 nC case. A main reason for this discrepancy is that mechanisms of the space charge dominated photoemission are more complex than those implemented in the ASTRA code. Another reason is that the asymmetry kick in the gun region is not fully compensated by the gun quadrupole magnets [12].

Table 2: Optimized Transverse Normalized Projected Emittance of the 4 nC Beams

	$\varepsilon_{n,x}$ [μm]	$\varepsilon_{n,y}$ [μm]
15 MeV/c ASTRA	4.92	4.92
15 MeV/c measurement	7.13	11.05
22 MeV/c ASTRA	4.44	4.44
22 MeV/c measurement	6.26	6.86

Current Profile Measurement

The current profiles of the optimized beam are measured by using the TDS. The screen located at Z = 13.04 m is used for monitoring the streaked beam. The principle and procedure of current profile measurement at PITZ are described in [14].

The measured current profiles and those from the ASTRA simulations are presented in Figure 2. Both simulation profiles show peak current of about 160 A and bunch duration of about 25 ps FWHM. The measured profile of 15 MeV/c case is quite close to the one from the simulation while the measured profile of the 22 MeV/c case is a bit shorter than the others. The reason of this difference is still not fully understood and under investigation.

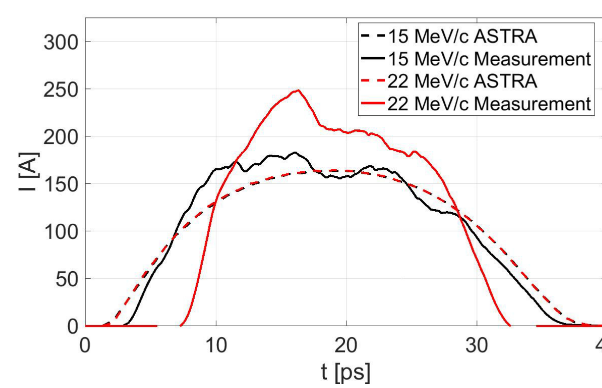

Figure 2: Beam current profiles of the optimized 4 nC beams. Note that the profiles from ASTRA are for the beams at Z = 5.28 m.

Evaluation of Slice Emittance

Slice emittance is evaluated by using the quadrupole scan technique [15, 16]. The quadrupole doublet right before the TDS is used for the measurement. The experimental setup is similar to one used for the bunch current profile measurement. Linear transport matrix approach was applied

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to obtain slice emittance values. Note that space charge effects were not taken into account for the Twiss parameters determination.

Profiles of the evaluated slice emittance at Z = 5.28 m are shown in Fig. 3 together with corresponding ASTRA simulations. The evaluated experimental values are significantly higher than those expected from the simulations. This difference can also be explained by the reasons similar to those used for the projected emittance discrepancy. Another important cause is that significant space charge effects are neglected in the slice emittance reconstruction from the quadrupole scan. It is responsible for the uncertainty of the obtained experimental emittance values. Investigations to quantify these factors and to improve the measurement procedure are ongoing.

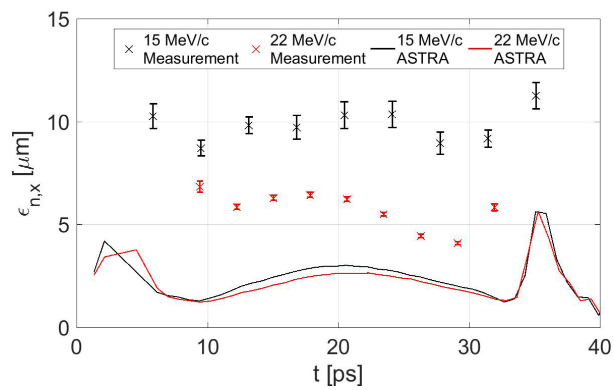

Figure 3: Horizontal slice emittance of the optimized beams at Z = 5.28 m. The error bars only include statistical errors.

Evaluation of Slice Momentum Spread

The longitudinal phase space (LPS) is measured by transporting the streaked beam from the TDS downstream to HEDA2. By using the TDS together with the first dipole magnet, the current profile and the momentum distribution of the beam can be shown simultaneously on the first monitoring screen in HEDA2. Then the slice momentum spread can be derived from the measured LPS.

The average evaluated slice momentum spreads are about 29 and 47 keV/c for the beam momenta of 15 and 22 MeV/c, respectively. While the average simulated slice momentum spreads of the beams at Z = 5.28 m are about 4 keV/c for both beam momenta. A major cause of this extreme difference could be limitations of the measurement resolution. The values of beam projected emittance are quite high. They limit transverse focusability of the beams and therefore the minimum achievable momentum resolution [17]. Imperfections of the beam transport could cause beam dispersions and spoil the beam momentum spread. TDS induced energy spread can also contribute to the discrepancy [18].

The measurement resolution can be improved by carefully optimizing the beam transport and further optimizing the beam projected emittance.

SASE FEL CALCULATION

The GENESIS1.3 code is used for simulations of the SASE FEL radiation. An APPLE-II undulator in helical mode [19] with period length of 40 mm is used as the radiator. The simulations were performed for two cases of radiation: 20 µm using 22 MeV/c beam and 100 µm using 15 MeV/c beam. We assumed that the measured and simulated beam profiles from previous sections are those at the undulator entrance. The Twiss parameters of the beams were assumed to be matched for beam transport along the undulator.

Figure 4 presents the results of the simulated FEL peak power along the undulator. The values of saturation power, saturation length and pulse energy at the saturation point for each case are listed in Table 3. An interesting point is that the emittance has a little impact on the saturation characteristics which corresponds to the analysis of the FEL parameter space in [7].

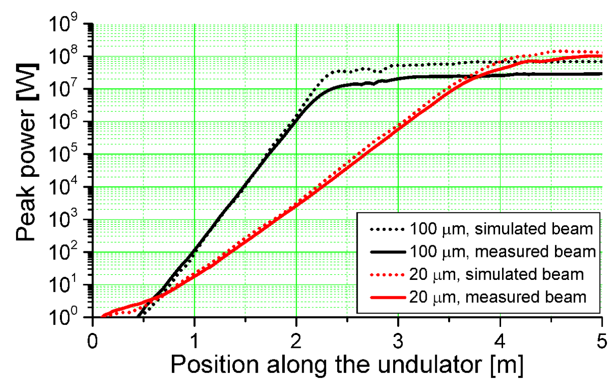

Figure 4: Simulated FEL peak powers along the undulator axis.

Table 3: Simulated FEL saturation power (P_{sat}), saturation length (L_{sat}) and pulse energy (E_{sat}).

	P_{sat}[MW]	L_{sat}[m]	E_{sat}[µJ]
100 µm, sim.beam	67	3.74	650
100 µm, meas.beam	29	4.16	390
20 µm, sim.beam	143	4.60	570
20 µm, meas.beam	101	4.92	480

SUMMARY AND OUTLOOK

Experimental optimization and characterization of 4 nC electron beams were done at PITZ including time-resolved measurements. SASE FEL simulations based on the measured beam profiles were performed for the radiation wavelengths of 20 µm and 100 µm. The results show that a radiation peak power in the order of 10^7-10^8 W can be achieved within a saturation length up to 5 m.

Experiments using a flattop photocathode laser are planned to be performed. Measurement procedures of the electron beams, especially for the slice emittance and slice momentum spread, still have to be improved for more reliable and accurate results.

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