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Diagnostic Systems for Characterizing Electron Sources at the Photo Injector Test Facility at DESY, Zeuthen site

S. Rimjaem[1*], G. Asova[1†], J. Bähr[1], H. J. Grabosch[1], M. Hänel[1‡], L. Hakobyan[1§], Y. Ivanisenko[1], M. Khojoyan[1§], G. Klemz[1], M. Krasilnikov[1], M. Mahgoub[1], D. Malyutin[1], S. Lederer[2], A. Oppelt[1], M. Otevrel[1], B. Petrosyan[1], D. Richter[3], J. Rönsch-Schulenburg[4], A. Shapovalov[1¶], R. Spesyvtsev[1††], L. Staykov[1†], F. Stephan[1] and G. Vashchenko[1]

[1]*DESY, Platanenallee 6, Zeuthen, 15738 Germany*
[2]*DESY, Notkestraße 85, Hamburg, 22607 Germany*
[3]*Helmholtz-Zentrum Berlin, Hahn-Meitner-Platz 1, Berlin, 14109 Germany*
[4]*Universität Hamburg, Luruper Chassee 149, Hamburg, 22761 Germany*
**Corresponding author. E-mail: sakhorn.rimjaem@desy.de*
[†]*On leave from INRNE, Bulgaria,* [‡]*Currently at Siemens AG.,* [§]*On leave from YerPhI, Armenia,*
[¶]*On leave from MEPHI, Russia,* [††]*Currently at University College London, UK*

Abstract

The Photo Injector Test facility at DESY, Zeuthen site (PITZ), has been designed and built to be a test stand for photo injectors of linac based free-electron lasers. Several diagnostic systems are used to study and optimize electron sources for the Free-electron LASer in Hamburg (FLASH) and the European x-ray free-electron laser (European XFEL). Characterization and experimental results from the last run period showed that gun operation with an average RF power of 50 kW was achieved. This corresponds to a peak power level of 7 MW, >700 μs RF pulse length and a repetition rate of 10 Hz. The minimum measured geometric mean of the normalized projected rms emittance in both transverse directions was 0.89 mm-mrad for 1 nC bunch charge. This value shows that the required normalized transverse projected emittance for the photoinjector of the European XFEL can be realized at PITZ. Overview of components and diagnostics as well as some experimental results will be presented.

***Keywords*:** free-electron laser, photo injector, photocathode RF-gun, electron beam diagnostics

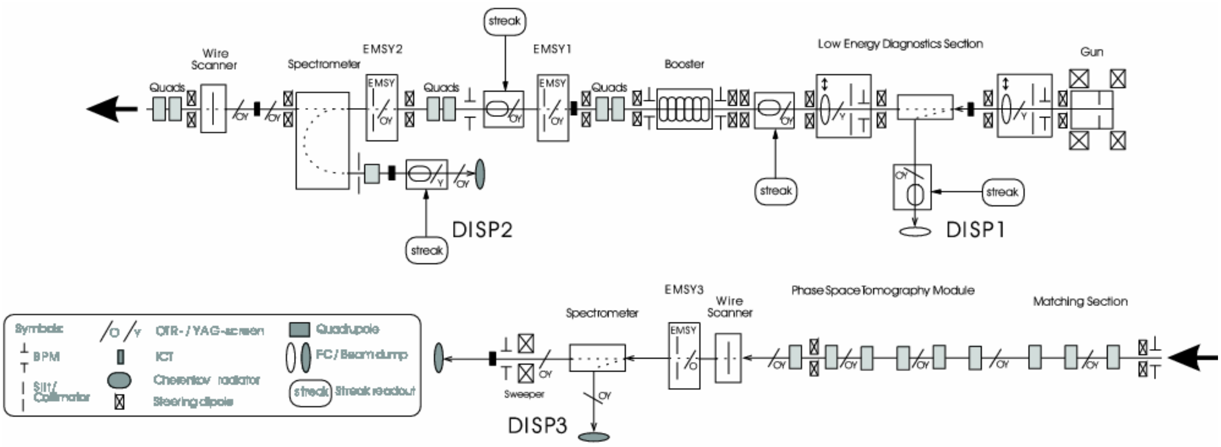

Figure 1. Schematic diagram of the current PITZ beam line including electron gun, booster cavity, dispersive arms (DISP), screen stations and emittance measurement system (EMSY) stations.

Introduction

The photoinjector development is realized as one of the most important challenges in short wavelength free-electron laser (FEL) technology. The main requirement to a FEL source is the capability to produce electron beams with high quality in both longitudinal and transverse phase space. A major goal at the Photo Injector Test facility at DESY, Zeuthen site (PITZ), is to develop, characterize and optimized electron sources for the Free-electron LASer in Hamburg (FLASH) and the European x-ray free-electron laser (European XFEL).

Slice transverse normalized emittance and slice peak current are important parameters, which define the gain of the self-amplified simulated emission (SASE) FEL process. Peak power, longitudinal bunch length or energy spread can be modified or improved later in the beam transport line before the electron beam enters the undulator. Contrary, the transverse normalized emittance has to be optimized from the injector source since it cannot be improved further after the photoinjector exit. The required transverse slice emittance for a bunch charge of 1 nC at the undulator entrance for the European XFEL is 1.4 mm-mrad. This value can safety be met with a normalized projected transverse emittance at the photoinjector exit of 0.9 mm-mrad. Therefore, optimization of the normalized transverse emittance is a major goal for research activities at PITZ. The European XFEL also requires electron beams with a duty factor of 32500 pulses per second, which means 1 nC micropulses at 5 MHz in 650 μs pulse trains and a repetition rate of 10 Hz. Production of this high duty cycle electron beams is also another goal of PITZ.

Setup and Beam Parameters

The current PITZ setup (Fig. 1) consists of a 1.6 cell normal conducting resonant frequency (RF) gun with a Cs_2Te photocathode driven by a Yb:YAG photocathode laser system, a normal conducting booster cavity for post acceleration and several diagnostic systems to characterize the electron beam properties. The gun and the booster are operated with separated L-band (1.3 GHz) RF power systems.

The gun is surrounded by the main and bucking solenoid magnets for space charge compensation [1]. Conditioning results in the run period 2008-2009 showed that the gun could be operated with an RF average power of more than 50 kW corresponding to a peak power of more than 7 MW in >700 μs flat-top RF pulse length at a repetition rate of 10 Hz [2]. The maximum accelerating gradient at the cathode is about 60 MV/m resulting in a maximum momentum gain of ~6.8 MeV/c.

A new Yb:YAG laser system was developed by Max-Born-Institute (MBI) and is installed at PITZ since 2008. It has the ability to generate UV laser pulse trains of up to 800 micropulses with a spacing of 1 μs between the pulses. This laser system can produce a temporal flat-top shape with a maximum length of 24 ps FWHM and rise and fall time as short as 2 ps. It is possible to adjust the pulse length between 2-24 ps to investigate the influence of the pulse length on electron beam properties. Details of this new laser system were described in reference [3].

In the 2008-2009 setup [4], the booster cavity was a normal conducting nine-cell copper resonator. It was built as a prototype for the TESLA super conducting accelerating cavities [1]. Standard operation parameters of the booster have been 70 μs pulse length and ~2 MW peak power at 10 Hz repetition rate. These operating conditions resulted in a momentum gain of ~8 MeV/c.

In the 2009-2010 shutdown period, a new gun cavity with the same design and cleaning procedure as the previous one has been installed as a new electron source at PITZ. In order to study the conservation of small emittance beams along the beam transport line after the booster acceleration, the TESLA type booster cavity was replaced by a new cut disk structure (CDS) booster, which can provide higher energy gain and does not degrade the beam quality. Conditioning and studying of the operating conditions of this new booster cavity are ongoing.

Beam Diagnostics at PITZ

Beam bunch charge

The electron bunch charge is measured using either integrating current transformers (ICT) or Faraday cups. The ICT is a non-destructive device but it has resolution limitations on measuring small bunch charges. The Faraday cup can be used to measure very small charges but also stops the beam at the measuring position. The choice of using ICT or Faraday cup depends on the measurement purpose.

Beam size, shape and position

Several screen stations equipped with CCD cameras have been installed along the beam transport line and are used to monitor beam size, beam shape and beam position. Each screen station consists of scintillating screens: Ce-doped Yttrium Aluminum Garnet (YAG) powder coated and/or optical transition radiation (OTR) screens. Two wire scanners and a new screen station using CVD diamond have been installed in the upgraded beam line for monitoring long pulse trains.

Moreover, several beam position monitors (BPM) have been installed and are used to observe the beam transverse position relative to the central trajectory. Compared to the screens, this device is a non-destructive beam position monitor.

Beam momentum and longitudinal phase space

To investigate the longitudinal phase space, beam momentum and momentum spread distributions are measured at spectrometers using a combination of a dipole magnet and an observation screen downstream. The complete longitudinal phase space is measured by analyzing Cherenkov light coming from the momentum spectrum using a streak camera.

There are three dispersive arms in the current PITZ setup. The first dispersive arm (DISP1) consists of a 60^o dipole magnet and a screen station downstream to measure momentum of electron beam exiting from the gun. Usually, an aerogel is used as the source for Cherenkov radiation to measure longitudinal phase space distributions.

The second dispersive arm (DISP2) is used to measure momentum, momentum spread, longitudinal phase space and the transverse slice emittance after the beam is accelerated by the booster [5]. It combines a 180^o dipole magnet, which simplifies the reconstruction of the momentum measurements, a slit at the exit of the dipole for slice emittance measurements and two screen stations. The first screen station is used to measure momentum distributions and longitudinal phase space of beams with momentum up to 40 MeV/c. The second one is used for the measurement of horizontal slice emittance [5, 6].

Currently, the third dispersive arm (DISP3) at the end of the beam line is capable to measure beams with maximum momentum up to only 16 MeV/c [1]. In spring 2011, a new dispersive arm will be installed. It is designed for measurements of electron beam momentum up to 40 MeV/c, high resolution slice momentum spread and vertical slice emittance. In order to allow measurements with electron beams for European XFEL parameters (3250 pulses and a repetition rate of 10 Hz), a huge beam dump is required after this section. Due to a space limitation, three dipole magnets will be used to transport electron beams to the dump of the main beam line. Simulation results suggest that a longitudinal slice momentum spread as small as 1 keV/c can be measured using this dispersive arm together with a transverse RF deflecting cavity [7].

Emittance and transverse phase space

Transverse projected emittance and phase space are measured using a single slit scan technique at the emittance measurement system (EMSY stations). Details of these devices and the measurement procedure were described in the references [1, 8]. The normalized transverse projected rms emittance is calculated from

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

where $\beta\gamma$ is the Lorentz factor corresponding to beam momentum, $<x^2>$ and $<x'^2>$ are the second central moments of the electron beam and divergence distributions in the transverse phase space obtained from the slit scan, x' is the angle of the single electron trajectory with respect to the whole beam trajectory and σ_x is the rms beam size measured at the slit position. The factor $\sigma_x(<x>)^{-1/2}$ is applied to correct for possible sensitivity limitation of low intensity beamlets and is always larger than one.

The slice transverse emittance can be investigated by measuring the transverse emittance of the electron beam at different longitudinal positions along the bunch. Currently, horizontal slice transverse emittance can be measured at the second screen station in the DISP2 using the technique described in references [5, 6]. The vertical transverse slice emittance will be measured at PITZ with the second screen station in the new dispersive arm (DISP3).

A phase space tomography section was installed at PITZ in 2010 for more detailed analysis of the transverse phase space distribution. This section consists of three FODO cells and four screen stations [9]. The FODO cell is a pair of quadrupole magnets with a drift space in between providing a focusing-drift-defocusing-drift structure. With correct matching from quadrupole magnets upstream and the proper geometry of the FODO cells with correct quadrupole magnetic field strengths, a phase advance of 45^o between each screen station is provided. The measurement procedure using this section is currently under commissioning.

Results and Discussion

Measurement results for longitudinal phase space

Momentum and longitudinal phase space were measured in the 2008-2009 run period at two locations; DISP1 and DISP2. Experimental results show that the maximum mean momentum achieved from the gun was ~6.7 MeV/c with a momentum spread of around 10-20 keV/c for an accelerating gradient at the cathode of 60 MV/m and the phase of maximum mean momentum gain (on-crest). After acceleration by the TESLA booster cavity, a maximum mean momentum of ~14.8 MeV/c was achieved with a spread of about 150 keV/c. A measurement of the longitudinal phase space at the first screen station in DISP2 [10] shown in Fig. 2 was performed for a gun gradient of 60 MV/m at the cathode and on-crest phase. The booster phase was set to -10^o off-crest.

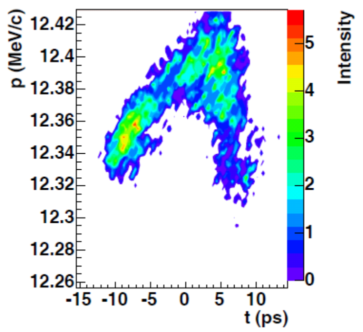

Figure 2. Example of measured longitudinal phase space distribution for electron beam with mean momentum of ~12.4 MeV/c [10].

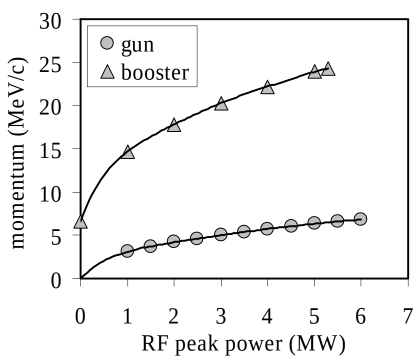

Figure 3. Measured momentum of the electron beam as a function of the RF peak power.

For the current PITZ setup, measurements of the maximum mean momentum of electron beam after the gun and the booster acceleration were performed for different RF peak powers and the results are shown in Fig. 3. The maximum mean momentum gain from the gun and the booster are 6.8 and 17.7 MeV/c. In these measurements the gun and the booster phase were set to be at the on-crest phase. The RF power in the gun was set to the maximum value for the momentum measurements after the booster acceleration.

Measurement results for transverse phase space

Transverse projected emittance was measured for different bunch charges and different rms laser spot sizes using the single slit scan technique at 5.74 m downstream the cathode (EMSY1). The solenoid field was scanned to define the minimum emittance point for each laser spot size on the cathode. Emittance optimizations for the setup in 2008-2009 were performed using a flat-top laser pulse length of 20-25 ps FWHM and 2-4 ps rise/fall time. The gun gradient was 60 MV/m at the cathode and the phase was adjusted to obtain the minimum emittance value ($+6^o$ off-crest). The booster phase was at on-crest.

Optimizations for 1 nC bunch charge showed that at the minimum emittance point a horizontal projected emittance (ε_x) of 0.721±0.013 mm-mrad and a vertical projected emittance (ε_y) of 1.089±0.020 mm-mrad were measured for a 100% rms phase space. The minimum rms geometric mean emittance in both transverse directions $\varepsilon_{xy} = (\varepsilon_x \varepsilon_y)^{1/2}$ was obtained as 0.886±0.011 mm-mrad [11]. The measured horizontal and vertical phase space at this point are illustrated in Fig. 4. Optimization results of the normalized projected emittance as a function of the rms laser spot size for different bunch charges are shown in Fig. 5.

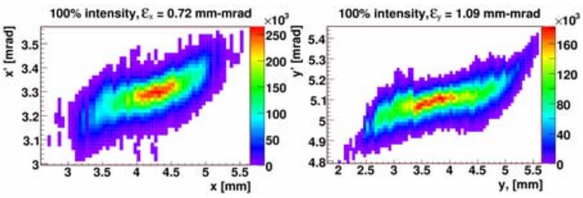

Figure 4. Measured horizontal (left) and vertical (right) transverse phase space distributions for minimum emittance point of 1 nC bunch charge.

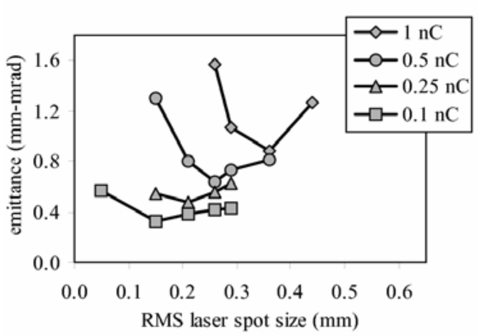

Figure 5. Measured normalized geometric mean emittance (ε_{xy}) as function of the rms laser spot size for bunch charges of 1, 0.5, 0.25 and 0.1 nC. All emittance results are for 100% rms values.

Conclusions and Outlook

Measurement results of the PITZ setup in 2008-2009 demonstrated electron beam parameters as required for the European XFEL, especially for the RF average power (≥50 kW) in the gun and the normalized transverse projected emittance (0.89 mm-mrad). Currently, this successful characterized gun cavity is used as the electron source at FLASH. The PITZ beam line was upgraded in the shutdown period in 2009-2010. Characterization of the new RF gun together with the new booster cavity is ongoing.

To have more powerful tools in phase space analysis, a transverse RF deflecting cavity will be installed in spring 2011 together with the new third dispersive arm. Electron beams will get a time dependent vertical deflection when traveling through this cavity. This leads to a correlation between longitudinal coordinate and transverse position. Transverse and longitudinal phase space of the deflected electron bunches can be measured in the tomography section and in the new dispersive arm. This will provide the possibilities to study the slice momentum spread with high resolution and the vertical slice emittance as well as properties of electron bunches along the train when including further kicker magnets.

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