HIGH BRIGHTNESS PHOTO INJECTOR UPGRADE AND EXPERIMENTAL OPTIMIZATION AT PITZ

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Abstract

The Photo Injector Test facility at DESY in Zeuthen (PITZ) develops and optimizes electron sources for linac driven free electron lasers like FLASH and the European XFEL. The PITZ photo injector was upgraded in 2010. A new RF gun cavity with significantly improved RF regulation and a new Cut Disc Structure (CDS) booster have been installed and conditioned. The main goal of PITZ is to demonstrate a small electron beam emittance by tuning several main parameters of the injector - photo cathode laser pulse, RF gun with solenoids and booster cavity parameters. Slit scan technique is used to measure the transverse phase space of the electron beam and the projected normalized emittance. The photo injector is capable of pulse train production which can be measured with dedicated diagnostics. This enables optimization of the beam emittance for a wide range of bunch charges from tens of pC to several nC while keeping high resolution of beam measurements. The results of the experimental optimization will be presented yielding a new benchmark of photo injector performance.

INTRODUCTION

A high brightness electron source is a key issue for the successful operation of linac based Free Electron Lasers (FELs). Major goals of the Photo Injector Test facility at DESY location Zeuthen (PITZ) are experimental optimization of the high brightness electron source and detailed studies of the photo injector physics.

The current PITZ setup consists of a 1.6-cell L-band normal conducting copper gun cavity amended with main and bucking solenoids to focus electron beams and counteract space charge forces. A Cs_2Te photocathode together with the photo cathode laser system is capable to produce long trains of electron bunches with individual charge up to several nC. Electron bunches with maximum longitudinal mean momentum of ~6.8 MeV/c generated by the gun are being further accelerated up to ~25 MeV/c by a booster cavity. A large number of systems for different type of electron beam diagnostics is integrated in the PITZ beam line including bunch charge, beam trajectory, transverse and longitudinal phase space measurements. The main focus is on the minimization of the beam projected emittance at different levels of bunch charge. Experimental results obtained from the 2008-2009 run period showed that the electron beam performance to reach the transverse projected emittance required for the European XFEL photo injector was achieved. One of the main factors limiting further photo injector improvement was found to be the RF gun launch phase stability [1].

PITZ UPGRADE

The PITZ upgrade in 2010 included efforts to improve the phase stability by installation of a 10-MW in-vacuum RF coupler enabling efficient feedback control of the phase jitter. The new gun (cavity prototype 4.1) has been installed and successfully conditioned at PITZ using an upgraded RF system [2]. Another major upgrade was the replacement of the old TESLA booster by a new CDS cavity [3]. Several important innovations in beam diagnostic systems have been implemented including improvements in the nominal slit scan technique used for the transverse phase space measurements [9] as well as installation and commissioning of a phase space tomography module [5].

10 MW In-Vacuum Coupler

The PITZ RF-gun is fed by a 10-MW klystron via two waveguides coupled by a vacuum T-combiner. Currently only vacuum windows for nominal peak power up to 5MW are available for L-band RF systems with the required specifications on peak and average power levels. Two such windows are installed right before the T-combiner. To measure amplitude and phase of the RF signals in the waveguides before their mixing in the T-combiner a pair of directional couplers (so-called 5-MW couplers) to measure forward and reflected waves is installed before each vacuum window [6]. Until 2010 the control on the RF feed at PITZ was realized based on signals from these two pairs of directional couplers. Possible cross-talk of the two 5-MW couplers under circumstances of not well-defined gun resonance conditions made the task of the LLRF feedback extremely complicated.

In order to be able to measure the forward and reflected power required for amplitude and phase stabilization, a 10-MW in-vacuum directional coupler was developed and

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produced by Mega Industries LLC [7]. The 10-MW coupler is installed after the T–combiner as close to the gun as possible. Besides direct monitoring of the RF phase, beam based measurements have been performed [6, 8]. The RF gun phase rms jitter before installation of the 10-MW in-vacuum directional coupler was in the order of 2…2.5 deg (or 10...15 deg peak-to-peak) [9]. After the upgrade feedback became available resulting in significant improvement of the phase stability; the rms phase jitter is now ~0.2…0.3 deg [8]. Besides increasing the shot-to-shot phase stability the 10-MW coupler enabled the control of the phase profile within the pulse train. Before the upgrade a typical phase slope of ~125 deg/ms was observed. The emittance measurements at PITZ require a pulse train operation in order to keep optimum signal quality of the observed beam and beamlets. The above mentioned slope resulted in a substantial smearing of the observed images of pulse trains. The upgrade implied an almost zero slope (or negligible fluctuations of the slope around zero) and therefore an integration of more identical electron bunches within a pulse train.

CDS Booster

The previous booster based on a normal conducting TESLA cavity had significant drawbacks, such as a not well-known field profile, rather short acceleration range, restricted peak and average gradient due to poor cooling. The CDS booster is specially designed and produced for PITZ; it is ~ 40% longer and much more flexible in peak and average power [3]. These significantly improved characteristics are required for consistent electron beam characterization for a wide range of machine parameters, especially for long pulse train operation. Currently the CDS booster is operated with RF pulses of up to 0.7 ms length at a repetition rate of 10 Hz. The peak power of up to 5.5 MW yields an electron beam momentum gain of ~18 MeV/c [4]. Pick-up antennas in the cavity provide reliable information on the RF field amplitude and phase. Up to now only feed forward is applied in the booster, works on the feedback are ongoing.

Emittance Measurement Procedure

The slit mask technique is the nominal method to reconstruct the transverse phase space and to measure the projected emittance [1, 4, 9]. The local beam divergence is measured using a 1 mm thick Tungsten slit with a 10 µm opening. The space charge dominated beam is cut into emittance dominated beamlets which are to be measured 2.64 m downstream of the slit mask location. To obtain more details of the transverse phase space a single slit scan is being used, where beamlets are recorded continuously while a slit mask is slowly being moved across the electron beam (with a typical speed of ~0.1…0.5 mm/s). With an electron bunch train repetition rate of 10 Hz typically up to several hundreds of beamlets are used in the phase space reconstruction.

Due to small intensities at the tails of the phase space distribution (or because of their large divergence) corresponding beamlets cannot be measured with sufficient accuracy. To correct this effect a concept of 2D scaled emittance [1, 4, 9] is used. For more details on the emittance measurement procedure see [10].

The transverse phase space of the electron beam can also be measured using the tomography module [5]. First experience with tomographic reconstruction of the transverse phase space at PITZ is reported in [11].

Time resolved measurements of the transverse emittance are enabled by operating the booster off-crest and performing emittance measurements in the following dispersive arm using a linear energy chirp [12]. The time resolution of this method is ~4ps for an electron beam with ~20..25 ps length (FWHM). Significant improvement of the time resolution can be achieved by using a transverse deflecting cavity. The system for the transverse deflector is currently under installation at PITZ, the expected time resolution is ~0.5 ps [13].

PHOTO INJECTOR OPTIMIZATION

Several photo injector parameters have to be optimized in order to minimize the transverse emittance of the electron beam. For a given bunch charge the transverse spot size of the photo cathode laser and the RF gun launch phase have to be adjusted. The most sensitive parameter for the emittance optimization is the main solenoid current. It has to be tuned for each machine settings.

Photo Cathode Laser

The photo cathode laser system is developed by the Max-Born-Institute (MBI, Berlin) and is capable to produce laser pulses with a flat-top temporal profile of ~ 20…22 ps FWHM and rise/fall times of ~2 ps [14]. Typical laser temporal profiles are shown in Fig. 1, where results of measurements using an optical sampling system (OSS) obtained during emittance optimization at different levels of bunch charge are depicted. The slight variation of profiles is mainly due to a long term drift of the laser system. The temporal profile of the laser has been usually monitored once per day, small fine readjustments were performed in order to minimize rise and fall time while keeping the modulation of the flat-top reasonably small.

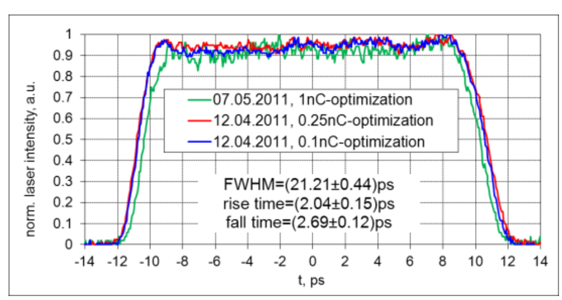

Figure 1: Temporal profiles of a photo cathode laser pulse. Each profile corresponds to the measured emittance optimum for a given bunch charge.

Transverse laser shaping is realized by imaging of a so-called beam shaping aperture (BSA) with variable diameter onto the cathode. A radial homogeneous distribution served usually as a goal for the transverse profile tuning.

The laser optic transport line was also upgraded in terms of better BSA imaging. Two typical transverse distributions of laser intensity are shown in Fig. 2.

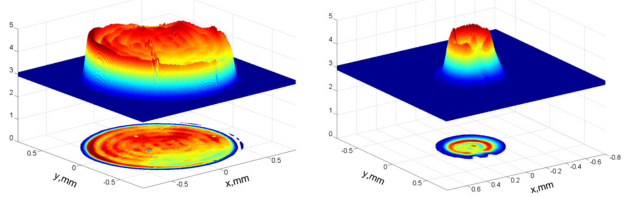

Figure 2: Laser transverse distribution at the photo cathode: obtained using a BSA diameter of 1.2 mm (left plot, rms sizes are σ_x=0.30 mm and σ_y=0.29 mm) and of 0.5 mm (right plot, σ_x=0.13 mm, σ_y=0.12 mm).

Experimental Emittance Optimization

Standard optimization implies variation of the spot size of the cathode laser and of the RF gun phase. For each optimization step a scan of the main solenoid was performed in order to obtain a minimum value of the geometric mean of horizontal and vertical emittance $\varepsilon_{xy}=(\varepsilon_x\varepsilon_y)^{1/2}$. The CDS booster was kept at the maximum available gradient, its phase was always tuned to be at the phase of the maximum mean momentum gain.

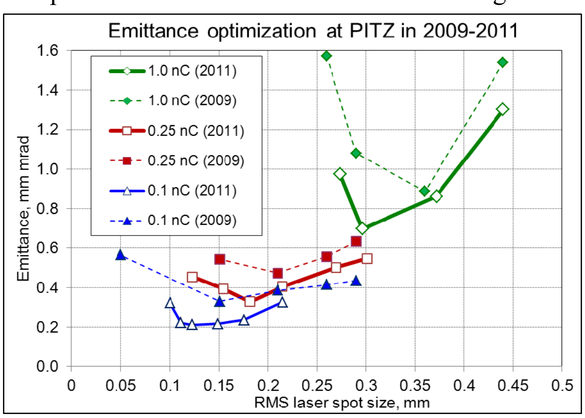

Figure 3: Measured geometric mean emittance as a function of the rms laser spot size for various bunch charges. Results of 2009 are shown with dashed lines.

The beam emittance was optimized for bunch charges of 1; 0.5; 0.25 and 0.1 nC in 2009 [1]. In 2011 the photo injector was re-optimized for bunch charges of 1; 0.25 and 0.1 nC [4]. Besides this the beam emittance was optimized for a 2 nC [15] and 0.02 nC bunch charge [4, 10]. Results of the emittance optimization are shown in Fig. 3 where best xy-emittance values obtained in 2011 for various bunch charges are plotted vs. rms spot size of the laser at the cathode. To illustrate the improvement of the photo injector performance after the above mentioned upgrade corresponding curves from 2009 are plotted as well. Significant improvement of the RF gun phase stability is the largest contribution to the improvement in emittance. The emittance improved by ~20% for 1 nC, ~30% for 0.25 nC and ~35% for 0.1 nC w.r.t. corresponding numbers obtained in 2009. Larger emittance improvement for lower charges is also a result of the RF gun phase slope correction within a pulse train as pulse trains with several hundred pulses are used for these measurements.

CONCLUSION

The facility upgrade at PITZ resulted in significant improvement of the photo injector performance. The reduction of the RF gun phase jitter of about one order of magnitude by implementation of a 10-MW directional coupler and a new feedback and phase slope control yielded together with other machine improvements a more than 20% reduction of the emittance compared to 2009.

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