MEASUREMENTS AND MODELING AT THE PSI-XFEL 500 kV LOW-EMITTANCE ELECTRON SOURCE

T. Schietinger, A. Adelmann, Å. Andersson, M. Dietl, R. Ganter, C. Gough, C.P. Hauri, R. Ischebeck, S. Ivkovic, Y. Kim, F. Le Pimpec, S.C. Leemann, K. Li, P. Ming, A. Oppelt, M. Paraliev, M. Pedrozzi, V. Schlott, B. Steffen, A.F. Wrulich,
Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

Abstract

Paul Scherrer Institute (PSI) is presently developing a low-emittance electron source for the PSI-XFEL project. The electron gun consists of an adjustable diode configuration subject to pulses of 250 ns (FWHM) with amplitude up to 500 kV from an air-core transformer-based high-voltage pulser. The facility allows high gradient tests with different cathode configurations and emission processes (pulsed field emission and photo emission). In the first stage, the beamline consists of focusing solenoids followed by an emittance monitor. Selected beam characterization measurements from photo cathode operation driven by a 266 nm UV laser system delivering 4 μJ energy during 6.5 ps (RMS) are presented and compared to the results of 3D particle tracking simulations.

INTRODUCTION AND MOTIVATION

The goal of the PSI-XFEL project is the realization of an X-ray Free Electron Laser (FEL) operating in the wavelength range between 1 and 100 Å and producing up to 10^{12} photons per pulse at a repetition rate of 100 Hz. To keep spatial and financial requirements within reasonable limits, the project foresees a compact design featuring a 6 GeV S-band main linac. This compact layout requires a high-brightness electron beam, which in turn calls for a low-emittance source. The strategy chosen for the PSI-XFEL project consists in utilizing a high-voltage pulsed diode providing fast acceleration with a special cathode optimized for low emittance (photo cathode or field emitter array). To evaluate various configurations and materials, a test stand has been set up at PSI consisting of a pulser, a laser system and a diagnostic beamline [1]. Figure 1 gives an overview of the pulser and beamline assembly.

An important aspect of the test facility, in particular in view of the further advancement of the PSI-XFEL project, is to improve the understanding of the space charge dominated electron beam by way of simulation. Indeed, one of the objectives of the test facility is the validation of our 3D particle tracking code against observations. In this paper we present a set of measurements taken at the test facility and compare it to the result of a 3D particle simulation.

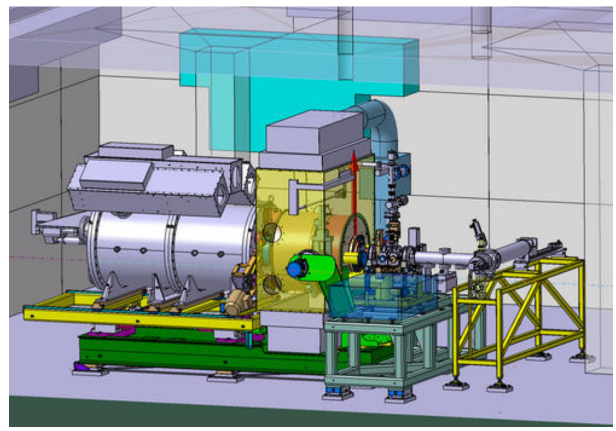

Figure 1: Schematic view of pulser (left) and diagnostic beamline, including the emittance monitor (right).

EXPERIMENTAL SETUP

The air-core transformer-based high-voltage pulser delivers pulses of 250 ns (FWHM) with amplitude up to 500 kV [2]. The diode gap between two mirror-polished electrodes is adjustable between 0 and 30 mm. Electrodes manufactured from stainless steel have been found to withstand the highest gradients and generally to offer the most stable experimental conditions for beam measurements. The measurements described here were performed with hand-polished stainless steel electrodes separated by 7 mm at a voltage of 313 kV, corresponding to a gradient of 44.7 MV/m. The chosen gradient represents a compromise between high accelerating field and stable operation with this particular set of electrodes.

The metallic cathode is illuminated by laser pulses when the applied voltage across the anode-cathode gap is at maximum. The laser light enters the electron beamline from a side viewport and is reflected towards the cathode by a 5 mm × 5 mm mirror. The mirror edge is at least 5 mm away from the electron beam axis. The laser pulses, generated by a Nd:vanadate (Nd:VAN) passively mode locked picosecond system, feature a Gaussian time profile (σ_t = 6.5 ps). The transverse profile is also Gaussian, with spatial dimensions controlled by a two-lens telescope assembly and monitored via a "virtual" cathode: a reflexion from the entrance viewport is monitored on a small optical table beside the beamline, at a distance equal to that between viewport and cathode. The maximum optical energy per pulse at the laser exit can reach about 12 µJ at laser exit and reduces to about 4 µJ at the pulser viewport entrance after ten meters of transport through an evacuated pipe and various optical components.

The diagnostic beamline includes five solenoid magnets, an emittance monitor and an additional YAG screen for transverse beam characterization upstream of the emittance monitor. A wall current monitor and a Faraday cup provide non-destructive and destructive bunch charge measurements, respectively. Only the first four solenoids were powered during the measurements described here.

The emittance monitor was specifically developed to cover the wide range of beam charges and energies [3]. Given the constraints of a space charge dominated, low-energy electron beam with possibly significant shot-to-shot fluctuations the pepper-pot measurement technique was chosen [4].

In our setup, the retractable pepper-pot mask is a laser-beam machined tungsten disk of 200 µm thickness. The 20 µm diameter holes are separated by 250 µm in both dimensions and extend over an area of 5 mm × 5 mm. An image of the beamlets is portrayed onto a 50 µm thick YAG screen, whose light is deflected by an out-coupling mirror under an angle of 90° into a telescope equipped with a firewire CCD camera. The optical resolution of the imaging system is about 10 µm. Both mask and screen are mounted on stainless steel sliders inside a 900 mm UHV chamber and can be moved individually over a distance of 600 mm along the beam axis, allowing for a wide range of experimental setups. The YAG screen of the emittance monitor can also be used for other measurements of transverse beam properties (beam envelope scans).

No longitudinal information such as beam energy and bunch length is obtained from this setup. For the simulation we assume that the electron bunch features the same Gaussian time profile as the laser pulse generating it.

BEAM MEASUREMENTS

The transverse beam sizes are defined as the root-mean-square (RMS) of the particles' horizontal and vertical positions. For the observed beam, this is approximated by the widths obtained from Gaussian fits to beam image projections. The beam profile was measured with the first YAG screen at a distance of 498 mm from the cathode, and with the movable second YAG screen at distances ranging between 790 and 960 mm from the cathode.

The transverse beam emittance is estimated from images of the beam after its passage through the pepper-pot mask. The distance between mask and screen was kept at its minimum of 30 mm, for which the precision of the emittance measurements is highest. We perform 1D analyses on the two projections of the image. The resulting histograms are divided into bins covering one beamlet each. An evaluation of the RMS emittance requires beamlet centroids and widths. While the beamlet centroid is derived from the bin centroid, its width cannot simply be obtained from the RMS of the bin distribution due to the effects of background and overlapping beamlets. We therefore use full widths at various heights to estimate both the Gaussian width and the background level of an individual beamlet, after subtraction of a global background. The error on the resulting emittance is estimated by variation of all input parameters, including the background subtraction, within their respective uncertainties. Figure 2 shows the intensity pattern of a typical pepper-pot image. The emittance was measured at distances of 750, 830 and 890 mm from the cathode, with results around 1 mm mrad (see Fig. 3).

The bunch charge was determined to be about 20.7 pC by integration of the Faraday cup signal.

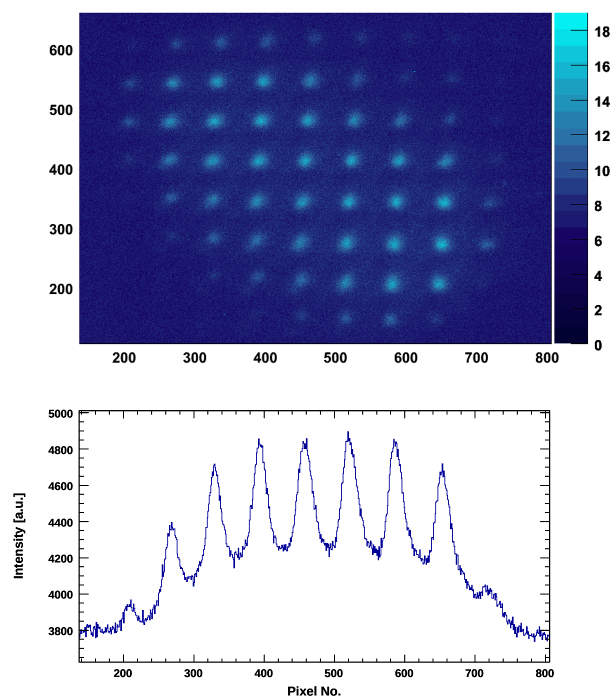

Figure 2: Detail of a typical pepper-pot raw image (top) with corresponding projection (bottom).

SIMULATION TOOL

For the 3D particle simulation we use the Object-oriented Parallel Accelerator Library (OPAL) developed at PSI [5]. OPAL-T is a parallel time-dependent particle-in-cell code that uses a space charge solver based on an integrated Green function [6] and a set of easily adjustable beamline elements to compute trajectories of macro-particles in 3D space. Running in parallel on a distributed memory cluster it can handle the large particle numbers needed for detailed slice emittance and beam halo studies.

To simulate the beam generated at our test facility we track a minimum of 10^6 particles on a 32×32×64 moving mesh. Electrons with a Gaussian spatial distribution are emitted from the cathode with a Gaussian time profile, where the widths correspond to the measured values (σ_x = 330 µm, σ_x = 370 µm). The electrons leave the cathode in parallel with 1 eV kinetic energy, i.e., no microscopic properties of the cathode are taken into account. The beamline elements (diode and solenoids) are described by field maps, i.e., equally spaced samplings of the fields, which are then internally interpolated to the particle positions. The field maps for our setup were produced with Poisson/Superfish [7]. Inside the diode field the simulation advances in time steps of 0.1 ps, whereas in the ensuing beamline the time step is 1 ps. The solver parameters were derived from convergence studies observing RMS quantities such as beam size and emittance.

For the interpretation and visualization of the results we use H5Part [8], a portable high performance parallel data interface to HDF5 in conjunction with ROOT [9], an object-oriented data analysis framework developed at CERN.

COMPARISON BETWEEN MEASUREMENTS AND SIMULATION

Small adjustments to the beam optics were necessary to match the observed beam sizes. Such adjustment is expected at some level, since the solenoid field measurements were not carried out *in situ* (in the presence of the beamline), but in an isolated environment. We found that lowering the field strengths of the first three solenoids by 5% while increasing that of the fourth by 9% brings measured and simulated beam sizes in reasonable agreement.

The emittance of the simulated beam features a prominent minimum of just above 2 mm mrad, near the waist in the region of the emittance monitor. The measured values are considerably lower, around 1 mm mrad, and their precision is insufficient to confirm the predicted minimum. Closer inspection of the simulated beam reveals a large halo in the region of the emittance monitor, the origin of which is still being studied. The large, but sparsely populated halo has a considerable effect on the RMS emittance. To exhibit the effect of the halo in the simulation we also plot the emittance as obtained considering only the central 90% particles (in the transverse plane). Figure 3 summarizes the comparison between measurements and simulation for the horizontal plane.

CONCLUSION AND OUTLOOK

We have presented a first comparison between measurements made at the 500 keV PSI low-emittance gun test facility and the results of our own 3D particle tracking code. While there is reasonable agreement for the beam envelope, further study is needed to understand the details of both measured and simulated emittances.

The test facility is currently being upgraded with a two-cell RF cavity allowing acceleration of the beam up to an energy of 4 MeV. The upgrade includes various additional diagnostic elements, in particular an energy spectrometer.

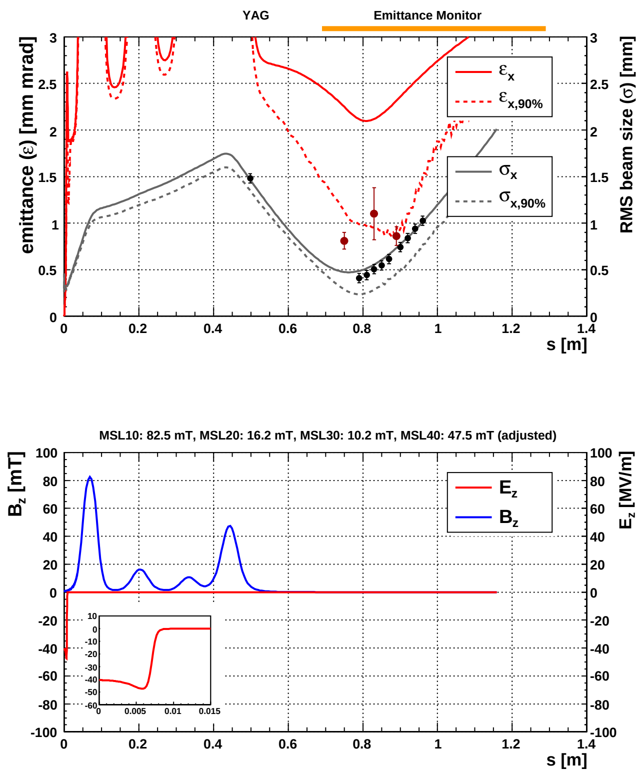

Figure 3: Top: Comparison of simulation results (solid and dashed lines) with measurements (points with error bars). See text for details. Bottom: Magnetic and electric field strengths entering the simulation drawn on the same horizontal scale.

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