DESIGN AND CALIBRATION OF AN EMITTANCE MONITOR FOR THE PSI XFEL PROJECT

Volker Schlott, Åke Andersson, Miroslaw Dach, Simon Leemann, Martin Rohrer, Andreas Streun,
Paul Scherrer Institute, CH-5232 Villigen, Switzerland

Abstract

The Paul Scherrer Institute (PSI) intends to realize a compact X-ray Free Electron Laser (XFEL) based on the development of a high brightness, high current electron source. Field emitter arrays (FEA) in combination with high gradient acceleration promise a substantial reduction of transverse emittances by up to one order of magnitude compared to existing electron sources for XFELs. The acceleration concept and the main beam parameters will be demonstrated in a 250 MeV injector LINAC project. A flexible, high resolution emittance meter based on the pepperpot measurement technique has thus been designed to characterize this low emittance beam. The realization of this monitor and the calibration procedure will be presented.

THE LOW EMITTANCE GUN PROJECT AND THE ROAD TO THE PSI XFEL

A feasibility study to explore the options for an economic Free Electron Laser (FEL) facility in the hard X-ray regime with a target wavelength of 1 Å has been initiated at PSI [1]. Since the FEL radiation wavelength depends only linearly on the electron beam emittance, while it scales quadratically with beam energy, the main focus of activities in the present phase of the PSI XFEL project is directed towards the generation of a low emittance electron beam. In this context, a novel electron source – the so called low emittance gun (LEG) – is under development. It should provide sufficient peak current and up to one order of magnitude higher transverse brightness compared as to state-of-the-art RF photo-cathode guns. The LEG Test Facility starts operation with a conventional photo-cathode laser gun and concentrates during its first phase on the investigation of high gradient pulsed diode acceleration (up to 1 MV/m over 200 ns) [2] followed by a combined fundamental and 3rd harmonic RF cavity [3]. Particle tracking indicates that the combination of DC and RF acceleration provides emittance preservation and sufficient linearization of the longitudinal phase space, which eases bunch compression in order to reach the peak currents required for the XFEL project. A diagnostics section has been designed to allow the full characterization of the electron beam with its main focus on the determination and optimization of transverse emittances and energy spread as critical beam parameters. In parallel to the demonstration of this novel acceleration concept, PSI investigates the properties of laser-induced field emission from single ZrC tips [4] and gated Mo field emitter arrays [4] as possible cathode materials promising normalized beam emittances as low as 0.05 mm mrad [5].

There are two test facilities to be realized at PSI until the end of the year 2010 and before starting with the actual XFEL facility. The LEG test stand is presently being set-up for demonstrating the performance of the novel high brightness electron source. The validity of the acceleration concept (including ballistic and magnetic bunch compression) shall be demonstrated in the 250 MeV XFEL injector test facility. More information on the PSI XFEL Project and its new developments including a full set of beam parameters can be found in [6].

THE LEG TEST FACILITY

A mechanical drawing and the schematic overview of the LEG test facility is shown in the upper part of figure 1. For the expected range of beam currents (0.1 - 5.5 A), the smallest transverse emittances will be reached over a length of 0.5 m. The corresponding beam envelopes are shown in the lower part of figure 1.

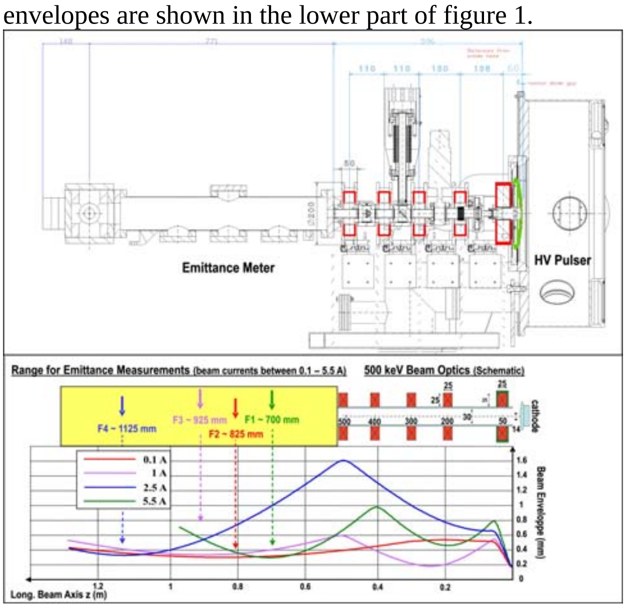

Figure 1: Mechanical drawing of 1st phase of LEG test facility (upper part). Optics simulations for expected beam current range showing beam envelopes at locations of smallest transverse emittances (lower part). The measuring rage of the emittance monitor is indicated in yellow.

The electron beam will be generated by a commercial Nd:VAN laser (Duettino from TimeBandwidth company) providing 20 µJ pulse energy at 266 nm (frequency tripled) and up to 10 Hz repetition rate at pulse widths between 15 and 40 ps (FWHM). With a copper cathode (QE ~ 10^{-5}), beam charges of only 40 pC will be accelerated by the high voltage (500 kV) pulser. An upgrade of the laser system for generating the PSI XFEL design current of 5.5 A (200 pC beam charge) is foreseen for the next phase of the facility when the two frequency (fundamental and 3rd harmonic) RF cavity will also be installed, providing acceleration up to 4 MeV.

In the 1st phase of the LEG test facility the high gradient pulsed diode acceleration will be tested. In case of an optimized gun geometry and accelerating gradients of > 250 MV/m, normalized transverse emittances as low as 50 nmrad and beam sizes in the order of 0.7 mm (FWHM) are predicted by beam dynamics simulations using Homdyn [7] and the particle-in-cell code CAPONE [8]. Linear space charge forces can be compensated over a wide range of beam currents (0.1 – 5.5 A) by using a total of 5 solenoid magnets.

DESIGN CRITERIA FOR THE LEG EMITTANCE MONITOR

As indicated in the previous paragraph, the LEG test facility will be operated in different phases over a wide range of beam currents and beam energies, requiring the highest possible flexibility from the beam diagnostics devices. For the 500 keV and 1 MeV cases (beam optics shown in the lower part of figure 1) the emittance monitor needs to cover a measuring range of at least 0.5 m length. At the same time, it should be as compact as possible, since further use in the 250 MeV XFEL injector test facility might be required for cathode material studies.

The well known “pepperpot” measurement appears most suited for determining the transverse emittance of a space charge dominated, low energy electron beam. While an exhaustive elaboration of the measurement principle is given in [9], only a short and simplistic explanation of the technique is given in the following using the notation indicated in figure 2.

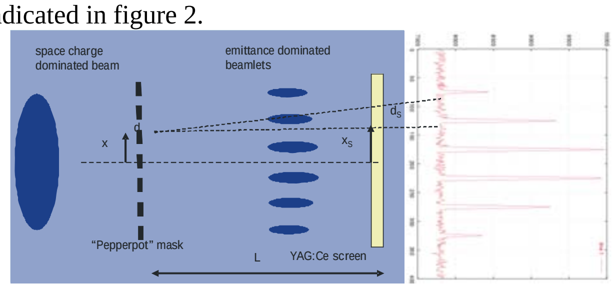

Figure 2: Illustration of “pepperpot” measuring principle.

A space charge dominated beam is converted in a set of emittance dominated beamlets after passing the “pepperpot” holes. The beamlets are visualized on a screen, which is placed at a distance L behind the “peppepot” mask. The corresponding beam profiles on the screen provide information of the angular beam distribution at the location of the “peppepot”. A broadening of the beamlets is a measure of the uncorrelated beam divergence, while the beamlet position with respect to the centre of gravity is a measure for the correlated beam divergence. The RMS beam emittance can be determined by considering the second moments of the average values of x and x’ to

$$\varepsilon_{RMS} = 4 \cdot \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2} ,$$

where <x> is the RMS distance of the optical / central axis to the “pepperpot” holes and <x’> is the RMS slope of the particles’ paths with respect to the optical / central axis, given by $(x_S - x)/L$.

“Pepperpot Mask” and Scintillation Screen

A tungsten “pepperpot” mask of 5 mm diameter, with 150 μm hole spacing and 20 μm hole diameter has been fabricated by laser beam machining. The mask thickness of 0.5 mm stops electrons with energies up to 4 MeV and should thus provide sufficient background suppression. A photograph of the “peperpot” mask is shown in the inlet of figure 3. YAG:Ce and LuAG:Ce (Lutetium Aluminium Garnet) have been selected as scintillation materials to visualize the electron beamlets, which are passing through the “pepperpot” holes. Both, YAG and LuAG are high density materials allowing the production of very thin freestanding screens. Their predominant emission in the green spectral range (535 – 550 nm) is well matched to the maximum sensitivity of CCD cameras. For least scattering of electrons in the material and highest spatial resolution, screen thicknesses of 50 μm at 5 mm diameter have been chosen.

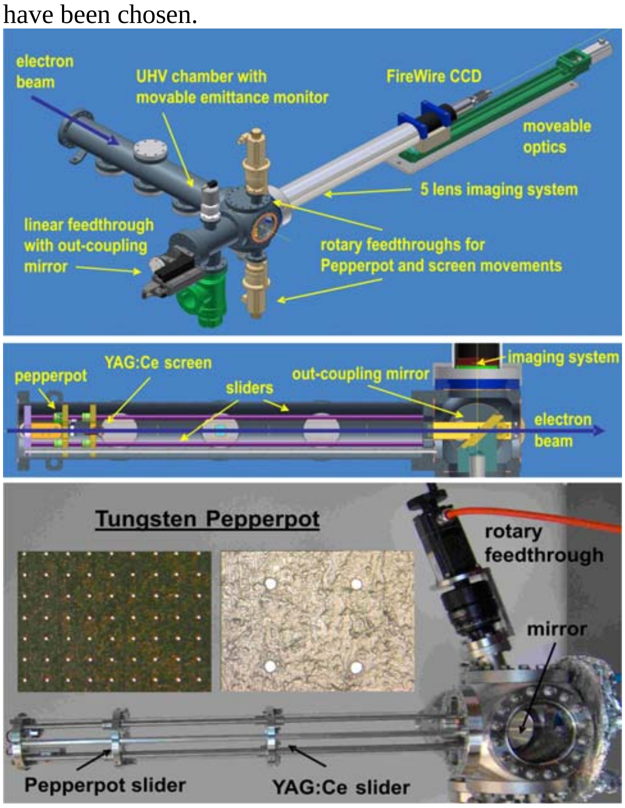

Figure 3: Schematic drawing of emittance monitor and imaging system (top), cross section of UHV part showing the sliders for the “pepperpot” and scintillation screen (middle), photograph of the emittance monitor (without UHV chamber) and “pepperpot mask” (bottom)

Mechanics and Imaging System

Both, "pepperpot" mask and scintillation screen are mounted on stainless steel sliders inside of a 900 mm long DN100CF UHV chamber. Cable winches, which are driven by a pair of rotary feedthroughs and deflection rollers at back end of the monitor, allow travel of the sliders along the entire length of the UHV chamber. In this way, "pepperpot" and scintillation screen can be moved at any location along the emittance monitor and the distance between both can be freely selected depending on the divergence of the electron beam. "Pepperpot" mask and scintillation screen can both be moved out of the beam, when reaching a "parking position" at the front end of the UHV chamber. An out-coupling mirror (90 mm in diameter, λ/20 planarity) at the back end of the monitor deflects the transmitted light from the scintillation screen under an angle of 90° out of the UHV chamber. An objective consisting of 5 lenses with 100 mm diameter and a focal length of 800 mm images the beamlets onto a 12bit IEEE1394 (FireWire) B/W CCD camera (Flea by Point Grey Research company) with 4.65 µm x 4.65 µm pixel size and 1024 by 768 pixels. This 1:1 imaging system has a theoretical resolution of 100 lp/mm at 550 nm wavelength (10% bandwidth). Objective and CCD camera are mounted on a motorized linear stage in order to keep the focal distance of 800 mm between scintillation screen and image plane.

CALIBRATION OF THE OPTICAL SYSTEM – POINT SPREAD FUNCTION

Since the optical system dominates the ultimate resolution of the emittance measurement, the so called "Point Spread Function" (PSF) was experimentally determined. The PSF is defined as the 2-dimensional intensity distribution in the image plane, produced by a point source in the source plane. It therefore includes all possible diluting contributions – namely diffraction effects, optical aberrations as well as CCD pixel resolution, readout noise, vibrations and others. A schematic overview of the experimental set-up is shown in figure 4.

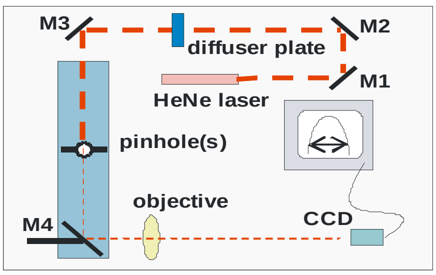

Figure 4: Schematic overview of the measuring set-up for determining the PSF of the emittance monitor.

Pinholes of different diameters (5 µm to 50 µm) were illuminated from the back side by a HeNe laser. The collimated laser beam passed a diffuser plate and the light intensity was reduced by a set of neutral density filters in order to prevent saturation of the CCD camera. The imaging system of the emittance monitor was focused on the pinhole plane and the image sizes were analyzed by fitting the 2-dimensional beam distributions.

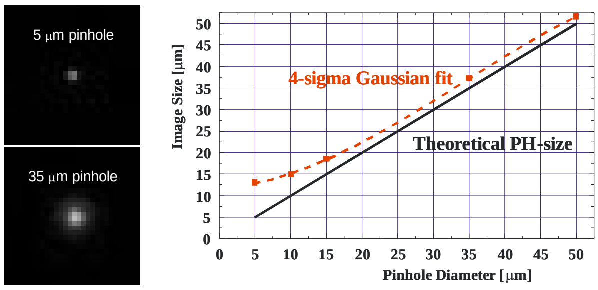

Figure 5: Pinhole images (left side) and measured PSF of the emittance monitor's imaging system (right side)

Figure 5 shows the relation between the known pinhole diameters (still 10% uncertainty might be considered) and the measured image sizes. Since the recorded 2-dimensional beam distribution does not resample the rectangular pinhole shape and changes with increasing pinhole diameter, the 4-sigma value of a Gaussian fit (95% of the data points) was taken as the image size. The image size threshold, which indicates the PSF of the optical system, was extrapolated to 11.8 µm, a value, which agrees very well with the theoretical resolution of the imaging system, which was calculated to 100 lp/mm using ray tracing. A similar online calibration option for the emittance monitor imaging system will be installed in the LEG test facility in order to cross check its resolution in case of electron beam emittance measurements.

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