TOWARDS A LOW EMITTANCE X-RAY FEL AT PSI

A. Oppelt*, A. Adelmann, A. Anghel, R.J. Bakker, M. Dehler, R. Ganter, C. Gough, S. Ivkovic,
F. Jenni, C. Kraus, S.C. Leemann, F. Le Pimpec, K. Li, P. Ming, B. Oswald, M. Paraliev,
M. Pedrozzi, J.-Y. Raguin, L. Rivkin, T. Schietinger, V. Schlott, L. Schulz, A. Streun, F. Stulle,
D. Vermeulen, F. Wei, A.F. Wrulich, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

Abstract

The Paul Scherrer Institute (PSI) in Switzerland is aiming to build a compact and cost-effective X-ray FEL facility for the wavelength range 0.1 – 10 nm. Based on the generation of very low emittance beams, it consists of a low-emittance electron source followed by high-gradient acceleration, and advanced accelerator technology for preserving the initial low emittance during further acceleration and bunch compression. In order to demonstrate the feasibility of the concept and the emittance preservation, a 250 MeV test facility will be built. This machine has been designed to be used as injector for the X-ray FEL at a later date. The accelerator design of the 250 MeV linac will be presented together with the status of the low emittance source and high gradient acceleration.

INTRODUCTION

In order to realize compact free electron lasers for the Angstrom wave length range, electron sources with high brilliance and ultra low emittance are required, allowing for low beam energies and short undulator length, and thus dramatically reducing the size and costs of such a project.
The proposed X-ray FEL at PSI is based on the development of new concepts that enable a substantial reduction in size and costs of the facility with respect to other existing designs.
The successful operation of such a FEL depends on the combination of high peak current, low energy spread, and high brightness of the electron beam. For the PSI-XFEL performance, in order to reach the Angstrom spectral range, a peak current of 1.5 kA, a relative energy spread around 10^{-4}, and a normalized transverse (slice) emittance as low as technically possible (i.e. $\varepsilon_n < 0.1$ mm mrad), are crucial. These stringent requirements shall be met by using new techniques, which include a low emittance source, a high gradient acceleration section, and a sophisticated bunch compression scheme.

LOW EMITTANCE SOURCE

Electrons emitted via field emission from micron sized metallic tips have an intrinsic low emittance due to the small source size. Using a double gated emitter geometry, parallel beamlets are produced from these tips. Combining the tips into a two-dimensional field emitter array (FEA), the required beam current can be reached with minor losses in emittance. Research at PSI focuses on developing suitable field emitter arrays emitting a total current of 5.5 A with an emittance of about 0.05 mm mrad. A scanning electron microscope (SEM) image of such an array, produced in-house at PSI, is shown in figure 1. Currents up to $\sim 10\mu$A per tip have been extracted from such a FEA in DC mode. The performances were studied at a 100 kV test stand [1].

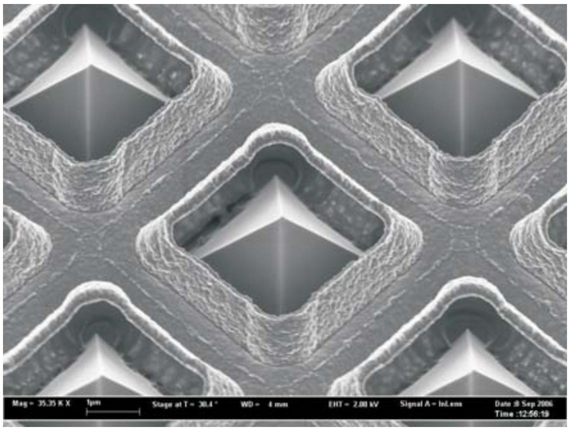

Figure 1: SEM picture of a FEA produced at PSI: the pyramidal shaped Mo tips and the gate layer are clearly visible.

Needle cathodes (single tip field emitters) are also investigated at PSI. Currents up to 470 mA were extracted from a ZrC needle via field emission (pulsed voltage, 2 ns FWHM, 30 Hz) [2]. Laser assisted field emission from needle cathodes allows increasing the extracted current further and offers the possibility of pre-bunching the electron beam. Figure 2 shows the measured current waveforms when applying different voltages (2 ns FWHM, 30 Hz) to a needle cathode in combination with laser illumination (266 nm, 6 μJ, 16 ps RMS). In this way, a peak current of 2.9 A was extracted [3]).
Since the fabrication and operation of the FEA [4] is very challenging, the option of using a conventional photo cathode is also investigated. With the proper choice of parameters (material, bunch charge, peak current), emittances of about 0.1 mm mrad should be reachable. Therefore, a Cu photo cathode will be chosen as start-up version for the injector. For both options, photo emission and field emission, the parameters were chosen equally such that the design of the following accelerator sections is not affected.

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* presenting author: anne.oppelt@psi.ch

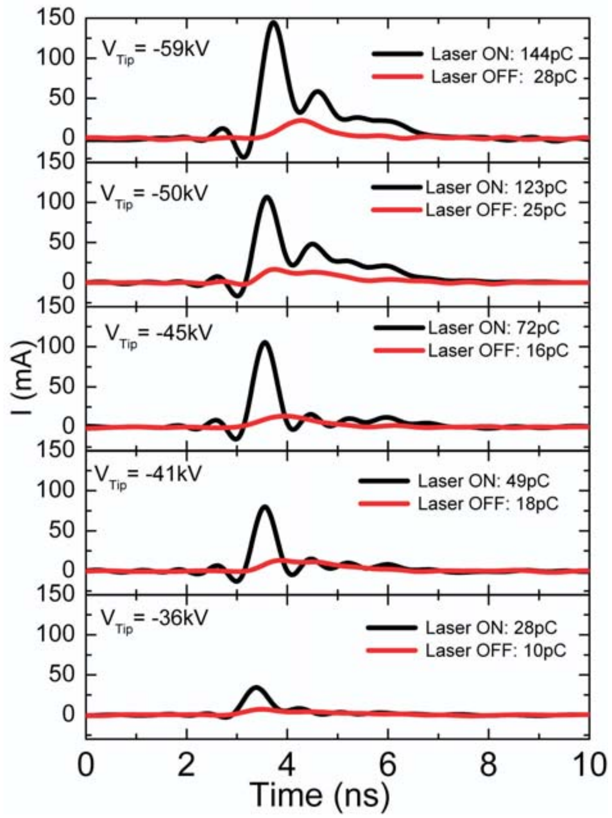

Figure 2: Effect of the laser illumination on the extracted current as function of different voltages applied to a ZrC needle cathode (see text). Note: The photo current pulses are broadened due to the low bandwidth of the oscilloscope (1 GHz).

HIGH GRADIENT ACCELERATION

In order to preserve the low initial emittance produced by the FEA, the field emitter will be operated in a pulsed diode at an accelerating gradient of 250 MV/m (1 MV pulser, 4 mm gap between cathode and anode). The development of such a high voltage pulser is ongoing at PSI. A 500 kV pulser was installed at the PSI site in summer 2007 and commissioning has started. After successfully having passed the high voltage tests, high gradient tests are scheduled and we expect beam operation by the end of the year. Figure 3 shows a photograph of this pulser in the test bunker. Some basic diagnostics for electron beam characterization at 500 keV (mainly emittance and momentum measurements) is being mounted. After demonstrating operation at 125 MV/m, this pulser will be upgraded to the final 1 MV pulser in order to realize the target acceleration gradient of 250 MV/m and produce a 1 MeV electron beam.

Figure 3: The high voltage high gradient test facility at PSI: the 500 kV pulser is installed and being commissioned.

EMITTANCE PRESERVATION AND BUNCH COMPRESSION

Even after the high gradient acceleration process, the electron beam is still fragile at 1 MeV. A concept for preserving the small emittance is therefore necessary, since space charge forces will blow up the beam emittance. Emittance conservation in the first 250 MeV of acceleration, where space charge forces dominate, is therefore a challenging task.

The low beam current (5.5 A) and bunch charge (200 pC) are beneficial to reduce the initial emittance and its dilution due to space charge forces in the low energetic region. But in order to obtain a peak current sufficient for lasing, a large bunch compression ratio of ∼270 is needed, which can be realized by controlling the longitudinal phase space. Therefore, after the high gradient section, the electron beam is accelerated off-crest in a two-frequency RF cavity [5]. The fundamental frequency (1.5 GHz) introduces thus an energy chirp which leads to ballistic bunching, while the third harmonic frequency (4.5 GHz) flattens the accelerating field and thus allows controlling the longitudinal bunch shape. In the following L-band TW structure, the RF compression is finished and the bunch length frozen, see figure 4. At this stage, the electron bunches are short enough to be further accelerated in an S-band TW structure,

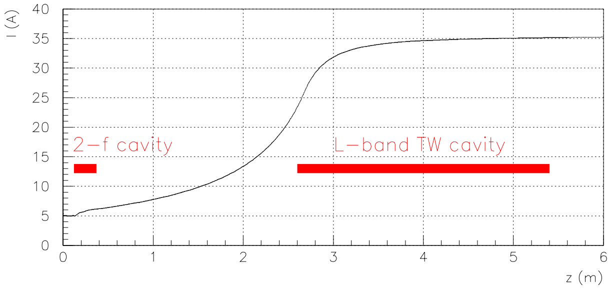

Figure 4: Effect of the two-frequency cavity: current increase due to ballistic bunching (HOMDYN calculation).

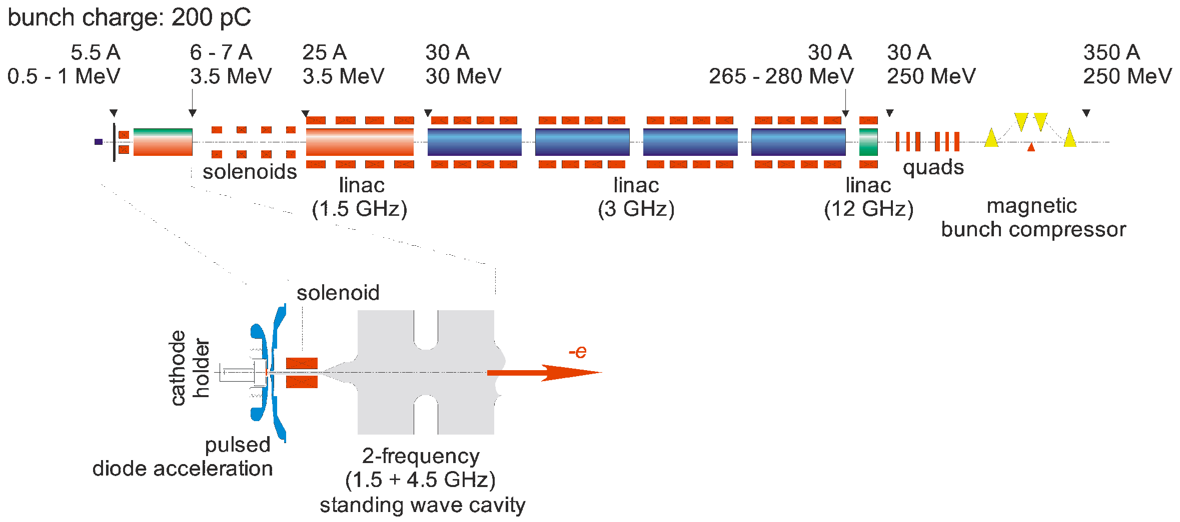

Figure 5: Layout of the 250 MeV injector facility (top) with a detailed sketch of the first accelerating elements (bottom). Target beam currents and energies along the machine are indicated.

running at 3 GHz. Afterwards, a 12 GHz harmonic cavity linearizes the phase space before further bunch compression takes place in the magnetic chicane. Here, an energy of 250 MeV and a peak current of 350 A are reached. At this stage of acceleration, space charge essentially no more influences the electron beam.

After the injector, the beam will be further accelerated to ∼6 GeV, always using normal conducting RF technology (mainly S-band). Another magnetic bunch compressor assures the peak current of 1.5 kA needed for the PSI-XFEL. At the entrance of the 30 m long undulator, a target slice emittance not larger than ε_n = 0.2 mm mrad must be realized.

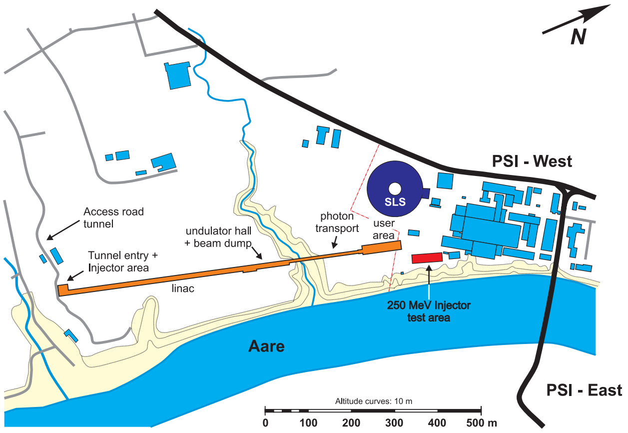

Figure 6: Site plan of the PSI-West area with the planned infrastructure for 250 MeV injector (red) and PSI-XFEL (orange).

250 MEV INJECTOR FACILITY

In order to experimentally verify the low emittance accelerator concept described above, a 250 MeV injector facility will be built and operated at PSI in the years 2008–2011. The detailed setup of the 250 MeV injector is described in [6]. Figure 5 represents a schematics of the machine and its space charge dominated beam optics.

If successful, the 250 MeV machine should then serve as injector for the cost-effective 6 GeV PSI-XFEL. The proposed installation of the 250 MeV injector building and the XFEL infrastructure on the PSI site (close to the SLS) is illustrated in figure 6.

Beam dynamics simulations of the complete 250 MeV injector facility have been done using different tools [7]: envelope tracking codes (`HOMDYN` [8], `BET` [9]) and particle codes (e.g. `IMPACT-T` [10]). The simulation results show the feasibility of the accelerator concept: bunch compression and emittance preservation can be realized. As an example, figure 7 represents the emittance growth in the accelerator calculated with `HOMDYN`. The energy distribution along the bunch as well as the current profile at the end of

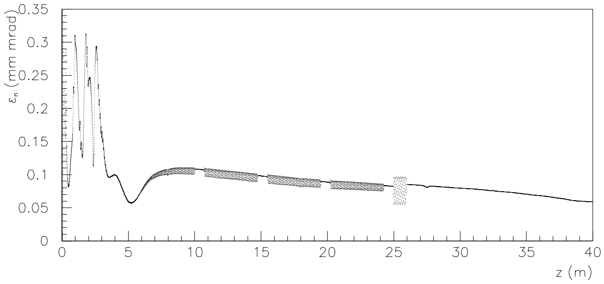

Figure 7: `HOMDYN` calculations of projected emittance growth along the 250 MeV injector.

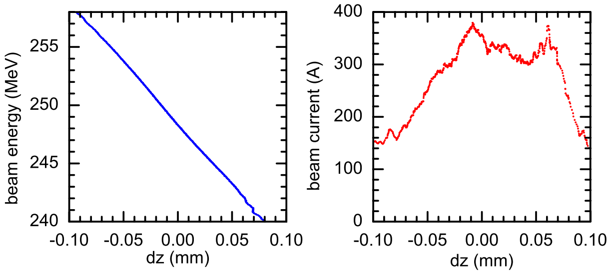

Figure 8: Slice energy distribution (left) and current profile (right) after the bunch compressor at z=40 m.

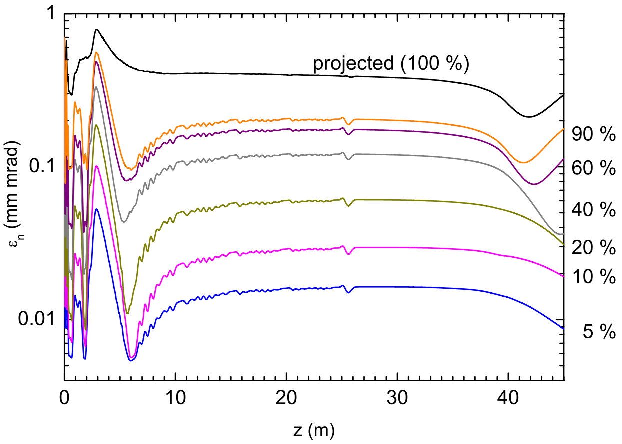

Figure 9: Slice emittance growth as calculated with `BET`.

the 250 MeV injector are presented in figure 8. Figure 9 shows slice emittances for various slice sizes as simulated with `BET` (an envelope code based on `HOMDYN`). These kind of 1D simulations are currently verified by a full 3D simulation of the 250 MeV injector [6].

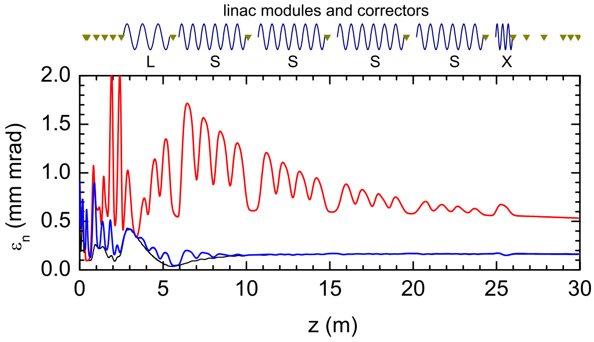

Figure 10: Misalignment studies for the 250 MeV injector: random offsets of beamline elements with $\sigma = \pm 70\mu$m result in an emittance growth due to dispersion (red), but orbit correction (blue) can bring back the emittance to the ideal value (black). On top of the plot, the accelerating structures as well as the position of the corrector coils are depicted.

In addition to beam dynamics simulations for optimizing accelerator components and beam optics, basic tolerance and alignment studies were done using the `BET` code [3]. For the first beamline elements (pulsed diode, solenoid, two-frequency cavity), the tolerance requirements are fairly stringent: according to the simulation results, relative field variations below 5×10^{-3} have to be realized. For the elements further downstream, the requirements are more relaxed.

Misalignment studies show that the beamline element positioning is not critical: beam orbit correction using steerers brings the emittance back to the ideal value (case of perfect alignment), see figure 10.

SUMMARY AND OUTLOOK

The PSI-XFEL concept is based on new technologies such as field emission, high gradient acceleration, and a two-frequency cavity, which are currently under development. In order to prove the sophisticated bunch compression scheme and the transport of low emittance beyond the space charge dominated regime, a 250 MeV injector facility will be built. Its successful operation will allow the construction of an Angstrom range cost-effective XFEL at PSI in the time period 2011 – 2016.

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