BEAM DYNAMICS OF THE 250 MEV PSI XFEL INJECTOR

T. Schietinger, A. Adelmann, R.J. Bakker, C. Kraus, K. Li, A. Oppelt, B. Oswald,
M. Pedrozzi, J.-Y. Raguin, F. Stulle, A.F. Wrulich, PSI, CH-5232 Villigen, Switzerland
Ji Qiang, LBNL, Berkeley, CA 94720, U.S.A.

Abstract

The PSI XFEL project aims at developing a pulsed high-brightness, high-current electron source which is one of the prerequisites of a cost-effective high-power laser-like X-ray light source. Creating an ultra low emittance beam is a great challenge, transporting, i.e., accelerating and compressing it is equally difficult. We present a 3D start-to-end simulation of our planned 250 MeV injector facility. The injector consists of a photocathode with pulsed DC acceleration followed by a two-cell standing-wave L-band cavity that leads into a ballistic bunching section. After some further velocity bunching in an L-band structure the electron beam enters several S-band structures which accelerate it up to the final energy of 250 MeV. An X-band RF structure prepares the beam for the following bunch compressor in which the target peak current of 350 A is reached. The target value of the slice emittance is 0.1 mm mrad, necessitating precise beam dynamics simulations. For the 3D simulations we use IMPACT-T, a time domain parallel particle tracking code, in which the self fields are treated in the electrostatic approximation. We discuss various issues such as projected and slice emittance preservation and shed light on some of the differences between an envelope and the 3D model.

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 between 0.2 (at 1 Å) and 10 (at 100 Å) $\times 10^{12}$ 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 based on a 6-GeV S-band main linac of very high brightness. The first 250 MeV are crucial to achieve the required low emittance, since space charge effects have strongest impact at low energy. The PSI XFEL project tackles this challenge with an innovative strategy based on

1. a low-emittance gun (scaled photocathode, or, at a later stage, field emitter array),
2. very fast acceleration right after the emission by way of a pulsed diode generating a 250 MeV/m field, and
3. a three-fold compression scheme employing ballistic, velocity and magnetic bunch compression.

While standard methods are sufficient beyond 250 MeV to further transport and accelerate the beam, the proposed techniques to be used up to that point need to be tested in practice. For this reason, we plan to build a 250 MeV injector test facility in the period 2008–2011. The layout of this machine has been designed according to the emittance compensation technique, i.e., space charge forces are carefully balanced against the natural evolution of the emittance. A computational tool similar to HOMDYN [1] ("beam envelope tracker" or "BET") was used for this first design. The significance of space charge effects, however, calls for a validation with a full 3D particle tracking code.

MACHINE LAYOUT

A schematic overview of the injector is given in Fig. 1. The machine starts with a photocathode which is irradiated by a pulsed laser. The emitted electrons are accelerated by a strong longitudinal electrical field (0.5–1 MV across a 4 mm gap), which is pulsed and synchronized with the laser. This *high gradient acceleration* is needed to inhibit beam blow-up by space charge forces. The bunch length (FWHM) at the diode exit is 40 ps (or about 20° at 1.5 GHz), the bunch charge is 200 pC, resulting in a 5.5 A peak current. To reach the current required for the operation of a FEL, this bunch length must be drastically reduced in the following sections. A pulsed solenoid focuses the beam into the first RF component, a two-cell capture cavity run at two frequencies, 1.499 GHz (fundamental mode) and 4.497 GHz (3^{rd} harmonic mode). Besides accelerating the bunch to about 3.5 MeV, the combination of the two modes prepares the bunch for *ballistic compression* in the ensuing drift by introducing a carefully tuned velocity difference between the head and the tail of the bunch. The beam's transverse dimensions in this drift space are controlled by four consecutive solenoids. After the ballistic compression the bunch length is down to about 9 ps (equivalent to 25 A peak current). Further *velocity bunching* occurs in a 40-cell L-band (1.499 GHz) traveling-wave structure operated in $2\pi/3$ mode, in which the electrons are accelerated to 30 MeV. *Main acceleration* (for the injector) is furnished by a booster linac consisting of four 120-cell S-band (2.997 GHz) traveling-wave structures. Besides accelerating the beam to about 280 MeV, at which point space charge effects become less dominant, this section also adjusts the energy chirp of the bunch, which allows the tuning of the bunch compression further downstream and, in the full FEL machine, the compensation of the wake-field induced energy spread generated in the main FEL linac. The last RF component in the injector design is a 12-GHz cavity (X-band, 4^{th} harmonic of S-band). Its pur-

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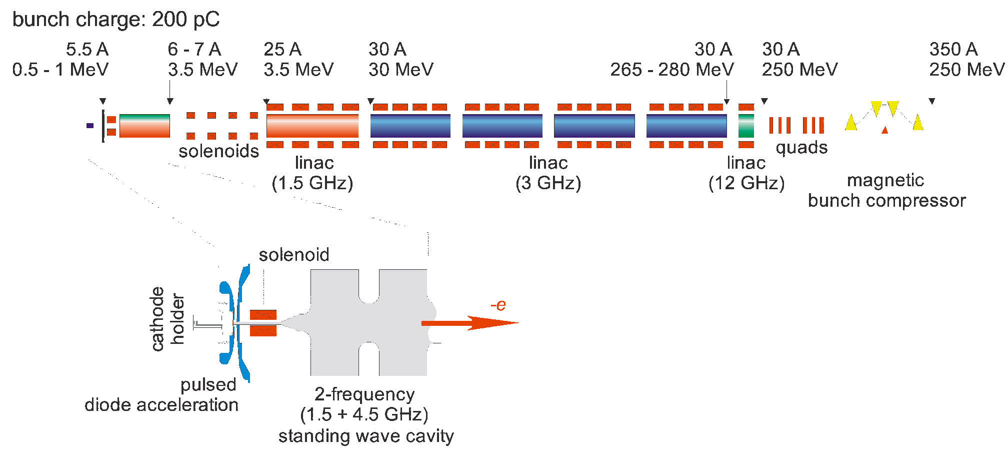

Figure 1: Overview of the 250 MeV linac (top) with a detailed sketch of the first accelerating elements (bottom). Target beam currents and energies along the machine are indicated.

pose is to compensate for the non-linearity of the bunch's energy profile accumulated in the main linac. In this *profile linearization* section, the electrons are decelerated to 250 MeV, the final injector energy. All along the linac solenoids surrounding the cavities are used to control the transverse beam size. Final bunch compression to a bunch length of 0.63 ps (350 A peak current) is achieved with a conventional magnetic dipole chicane following the X-band cavity. Two quadrupole triplets in front of the dipole section can be used optionally to correct the beam.

SIMULATION TOOL

While the preliminary design of the machine was done with a the HOMDYN-like envelope tracking code BET with fast turn-around, the significance of space charge effects call for a validation by a 3D particle tracking code. In addition, high statistics is needed for the study of slice emittances, where only a fraction $< 10\%$ of the bunch is considered. A well established code that fulfills these requirements is IMPACT-T [2], a parallel time-dependent particle-in-cell code. It uses a space charge solver based on an integrated Greens function and a set of easily adjustable beamline elements to compute trajectories of macroparticles in 3D space. Running in parallel on a distributed memory cluster it can handle the large particle numbers needed for detailed slice emittance studies. For our injector studies, we track 2×10^6 particles on a $32\times32\times128$ mesh.

In IMPACT-T, beamline elements are described by field maps, i.e., equally spaced samplings of the fields, which are then internally interpolated. The field maps for our setup were produced with Poisson/Superfish [3]. The traveling-wave structures are described by Fourier coefficients of the longitudinal electrical on-axis field. From these the longitudinal and radial electrical fields and the transverse magnetic field can be calculated [4]. The Fourier coefficients are computed from the on-axis field as obtained with Superfish. The phase of the traveling-wave structures is adjusted for 30° off-crest acceleration.

For the interpretation and visualization of the results we use H5Part [5], a portable high performance parallel data interface to HDF5 in conjunction with ROOT [6], an object-oriented data analysis framework developed at CERN.

Gun Simulation

Particular attention is required for the simulation of the particle gun. It represents a computational challenge since in our setup the long bunch length and the fast acceleration right after the cathode (125–250 MV/m field) mean that while the electrons of the bunch tail are still waiting to be emitted by the cathode, the head of the bunch has already been accelerated to 1 MeV energy! Consequently, there is no common rest frame for the entire bunch to perform the computation of the self-fields. One way around this problem consists in binning the particles according to their energy at each time steps. In the solution we have adopted, a 40-ps bunch is emitted into the diode field at 1 eV energy in 380 consecutive slices. After every time-step the particles are then re-binned into 32 energy bins. The resulting phase space distributions after the diode have been found to agree quite well with those obtained with a fully consistent MAFIA simulation.

Matching Procedure

For the rest of the machine, the parameters obtained with the BET simulation are converted to IMPACT-T inputs. The beam optics (solenoid field strengths) are then adjusted such that after each component the beam sizes match in both simulations. This is important to ensure that space charge effects remain comparable between the two codes.

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RESULTS AND COMPARISON TO BEAM ENVELOPE TRACKER

As examples we show in Figs. 2 and 3 simulation results for the two most crucial parameters, emittance and bunch length, in the early stages of the injector. In each plot, we compare the results obtained with IMPACT-T to the ones from BET. For the projected emittance, good agreement is found in the two-cell cavity, but also in the traveling-wave structures outside the solenoid fields. Inside the solenoids, the IMPACT-T curves feature the characteristic emittance blow-up due to the electrons spiraling in the magnetic field (Busch theorem). This effect is not present in BET, where only bunch slices are considered. The projected emittance at the end of the S-band structure is about 0.4 mm mrad.

Also shown is slice emittance for the central 20% of the bunch. Here, BET gives considerably lower values than IMPACT-T, which in general predicts only about a factor two between slice and projected emittance. Detailed studies of the longitudinal bunch structure in the two codes are underway to understand this discrepancy.

Figure 3 illustrates the bunch compression in the two-cell cavity and the following drift. While there is good qualitative agreement between the two codes, IMPACT-T predicts somewhat less compression after the capture cavity. This could be due to a slight mismatch in phase in the two-cell cavity and is also under study at the moment.

CONCLUSION AND OUTLOOK

We have performed the first start-to-end 3D simulation of the PSI XFEL injector. The detailed simulation in general confirms our strategy for emittance preservation and bunch compression at low energy. This is work in progress—the matching between the codes still needs to be improved further, and the differences in slice emittance need to be understood.

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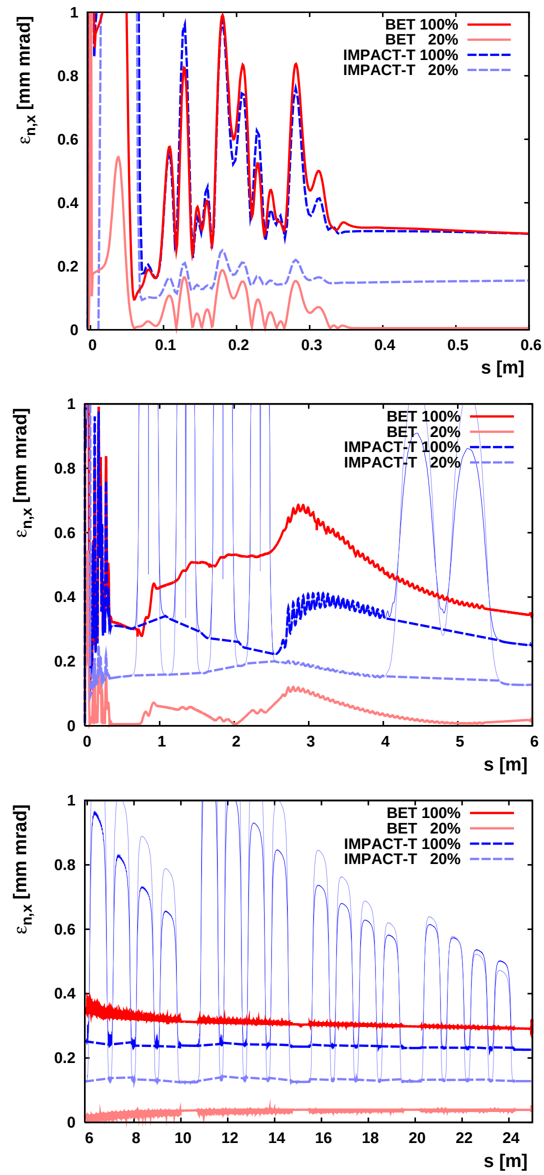

Figure 2: Projected and 20% slice emittance in the two-cell capture cavity (top), up to the end of the L-band structure (middle) and in the S-band structure (bottom).

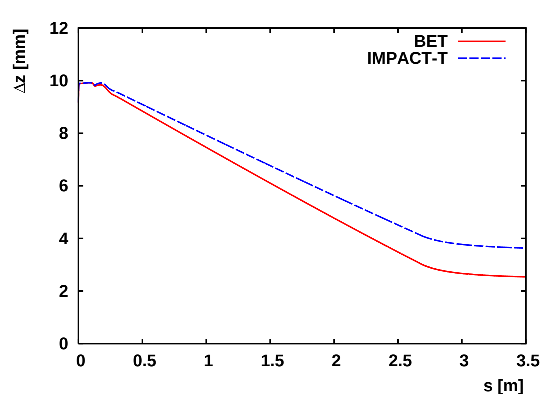

Figure 3: Evolution of bunch length in the two-cell capture cavity and the following drift space demonstrating ballistic compression.