DESIGN CONSIDERATIONS FOR A THz PUMP SOURCE AT THE SWISSFEL

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Abstract

A powerful THz source is being considered for THz pump / X-ray probe experiments at the planned SwissFEL. The source should deliver half-cycle pulses of less than 1 ps duration with a pulse energy of 100 μJ in a focal region of 1 mm^2. Design considerations and simulations for such a source fulfilling the challenging parameter combination will be presented.

MOTIVATION

The Paul Scherrer Institute (PSI) in Switzerland proposes to build a compact and cost-effective X-ray FEL facility for the wavelength range 0.1 – 7 nm, the SwissFEL. The global layout of this machine, consisting of a linear accelerator and several undulator lines, is shown in Fig. 1.
Delivering coherent, high-brightness, circularly-polarized X-rays at energies corresponding to nm wavelengths, the SwissFEL will be capable of single-shot lensless imaging of nanometer-scale objects.
The design of the SwissFEL foresees a separate source of THz radiation delivering high-energy electromagnetic pump pulses of THz bandwidth which are synchronized to the sub-ps X-ray probe pulses of the SwissFEL. The combination of THz pump and X-ray probe pulses permits real-time investigations of ultrafast magnetic interactions, as well as exploring non-ionizing heating phenomena and catalytic processes at the nm scale [1].

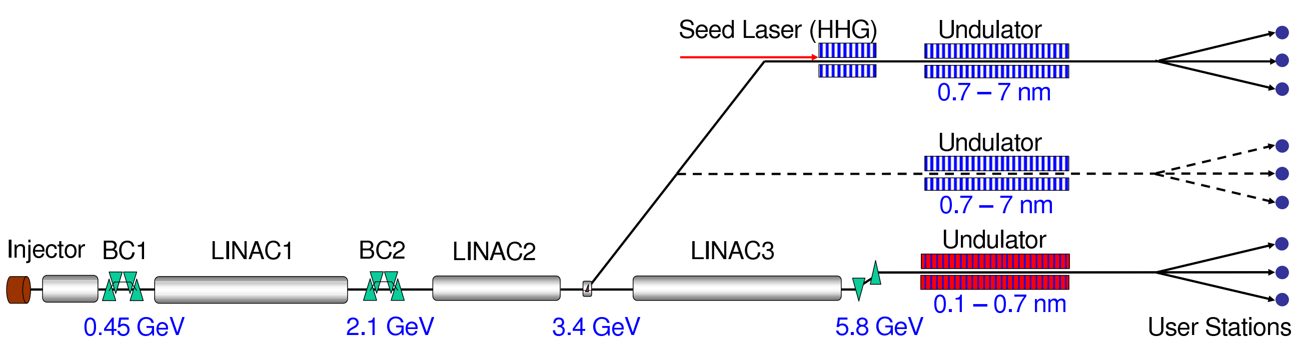

Figure 1: Schematic layout of the SwissFEL facility.

In order to allow for such experiments, the THz pump source at the SwissFEL has to fulfill the following specifications:
– A photon beam with a *pulse energy of 100 μJ and more, focused down to 1 mm^2* allows for localized heating of materials faster than the relaxation time (i.e. without heat expansion). The achieved electric field strength would be $\sim 10^8$ V/m and can be used to displace atoms in polar solids to probe structural phase transitions, ferroelectricity, etc. The magnetic field is about 0.3 T, which allows to create magnetic / spin excitations and to follow the magnetization dynamics on a ps time scale.
– A *half cycle pulse with a duration of less than 1 ps* provides unidirectional electromagentic fields that create unidirectional surface distortion or polarization, opening, for example, exciting possibilities for the detailed study of catalytic processes.
– Experiments require the arrival of the *THz pump pulse up to 1 ns prior to the X-ray probe pulse*. This is hard to realize by deriving the THz pump pulse from the FEL drive beam. Generating the THz pump signal independently from the X-ray probe signal by means of a separated THz source is therefore preferred and has the additional advantage that a very compact THz source (in particular also tunable by the users) with high electron bunch charge (compared to the $\leq$200 pC of the FEL drive beam) can be built.
Most existing THz sources do not fulfill all these specifications and hence cannot be considered as a pump source for the SwissFEL. An almost optimal THz source was demonstrated at SDL (Brookhaven) [3], even though the SDL injector is not optimized for high charge, and the generated transition radiation is difficult to focus down to a small spot size due to its radial polarization.

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BASIC CONSIDERATIONS

When passing an electron beam with the proper beam parameters through a bending magnet, synchrotron radiation (SR) in the THz range can be produced. A sketch of such a SR spectrum is shown in Fig. 2. Compared to transition radiation (TR), SR has the advantage of a well defined polarization, though its single particle emission is less efficient at long wavelength than TR. For single particle emission, the cut-off in the spectrum is given by the

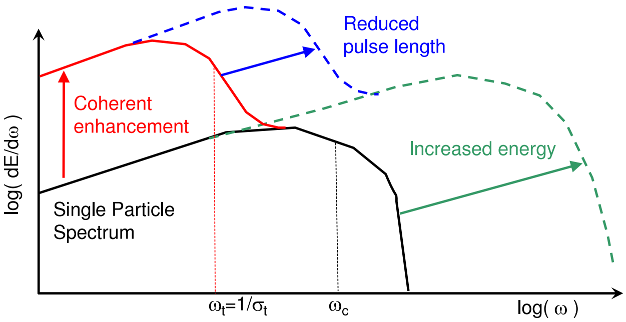

Figure 2: Sketch of the synchrotron radiation spectrum.

critical frequency[1] ω_c=$3c\gamma^3/r_{bend}$, the maximum amplitude is proportional to the electron beam energy, and the emitted energy for $\omega \ll \omega_c$ is independent of the electron beam energy. For short bunches (i.e. bunch length smaller than the wavelength of observation), multiparticle coherent enhancement occurs. The most promising approach is therefore coherent emission from a relativistic electron beam, where the radiation process in the forward direction can be described by

$$P_{total}(\omega) = P_e(\omega) \cdot |F(\omega)|^2 \cdot N^2$$

with the single-particle emission spectrum $P_e(\omega)$, the form factor F, which is the Fourier transform of the longitudinal bunch profile, and N, the number of electrons in the bunch. When considering the three terms of the equation, the radiation process can be maximized by
(i) using a particle energy high enough to guarantee that $P_e(\omega)$ is broader than the width of the form factor F;
(ii) reducing the bunch length such that the bunch emits coherently in the THz ($F\sim1$ for coherent emission, while $< |F(\omega)|^2 >= 1/N$ for incoherent emission);
(iii) increasing N, i.e. the bunch charge Q.

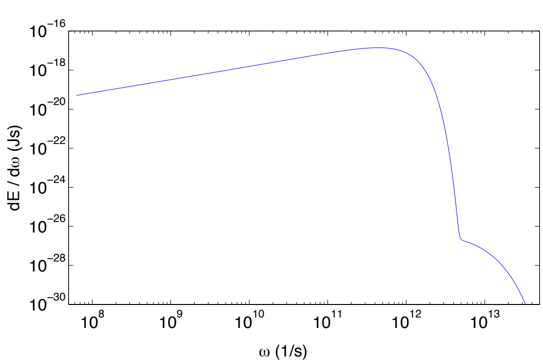

Figure 3: Expected SR spectrum from the analytical model for a 1 nC electron beam of 10 MeV with 1 ps bunch length. Bend radius: 1 m, collection angle: 100 mrad.

[1]We follow the definition of [2] for the critical frequency, beyond which there is negligible radiation. Another definition is ω_c=$3c\gamma^3/(2r_{bend})$, which gives a kind of central frequency dividing the emitted energy spectrum into two parts of equal energy content.

A generic design of a linac based THz source fulfilling the wish list would thus consists of an electron gun that generates sub-ps bunches of high charge (≥1 nC), a booster section that accelerates the bunches to >10 MeV, and a dipole magnet as radiator with $r_{bend}\sim$1 m. The design of such a source is straightforward, since emittance and energy spread have reduced impact on the emitted spectrum. The expected SR spectrum can be calculated using a simple analytical model [4] and is shown in Fig. 3. The estimated pulse energy would be $\sim$14 μJ. The performance can be increased by higher bunch charge (e.g. 5 nC) and/or shorter pulse length (requiring a bunch compressor). Higher beam energy helps collecting the radiation due to the smaller emission angle and thus reducing diffraction losses.

DESIGN SIMULATIONS

Beam simulations for the described generic setup have been done with the particle tracking program ASTRA [5]. As electron source, an S-band RF gun, originally designed for high charge operation up to 20 nC (multi-bunch) at CTF3 [6], was used to generate a 5 nC (single bunch) electron beam (laser parameters: 10 mm spot radius, 1 ps pulse length) (Fig. 4).

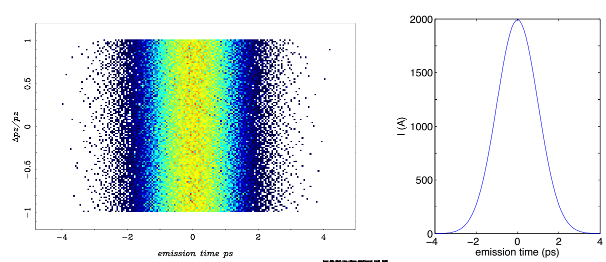

Figure 4: Longitudinal phase space at the cathode plane; σ_t=1 ps (time projection, right plot).

Due to the high charge density in the bunch, space charge forces strongly distort the longitudinal and transverse phase space during the acceleration process, although a high acceleration gradient (100-120 MV/m) is applied at the cathode and a focussing solenoid (280 mT) is placed directly after the gun, such that the magnetic field extends up to the cathode plane. Figure 5 displays the longitudinal phase space at the gun exit.

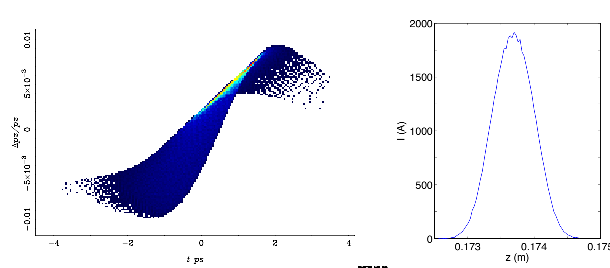

Figure 5: Longitudinal phase space after the gun.

In order to avoid further beam blow-up and bunch lengthening, an S-band booster cavity (1.25 m long, 38 cells) starting at z=0.5 m after the cathode increases the electron beam energy from about 8 MeV to 30 MeV. Since emittance is of no concern, no envelope matching was applied at the entrance of the booster cavity, thus avoiding additional space charge problems induced by strong focussing. RF focussing occurs in the booster cavity and leads to a nice beam size evolution, as shown in Fig. 6 (left). The beam size reduction after the gun indicates clearly the two regimes: solenoid focussing at the gun exit and RF focussing in the booster.

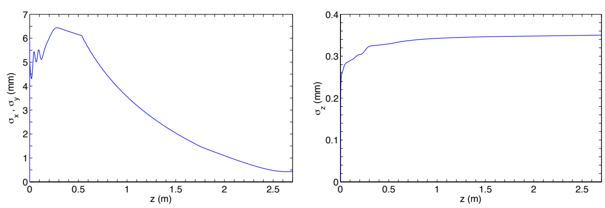

Figure 6: Beam size and bunch length development of the electron beam along the accelerator.

After the booster, the influence of space charge becomes negligible, and the phase space (Fig. 7) is frozen. The bunch length at this position is[2] 1.24 ps, or 370 μm.

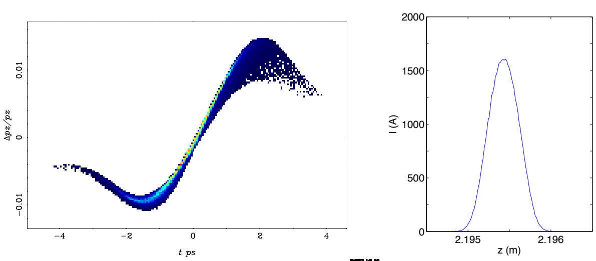

Figure 7: Longitudinal phase space after the booster.

A bunch compressor could be installed at this position, in order to shorten the pulse length: the space-charge induced energy chirp over the bunch allows for compression in a dogleg bend system with negative R_{56}. The need of shorter bunches will be discussed below.

At the moment, we assume that a radiator (bending magnet) for generating the THz radiation is placed directly after the booster (at z=2.2 m). Figure 8 displays the calculated SR spectrum when varying the bunch length or the collection angle. The strong influence of the collecting aperture on the total photon energy is explained by the fact that the radiation is collected over a larger pathlength in the bending plane.

With the parameters of the particle distributions obtained from ASTRA simulations (Q= 5 nC, E=30 MeV, σ_z=370 μm), a bending radius of 1 m, and a collecting aperture of 100 mrad (corresponding to 3 times the opening angle of

[2]Gauss fit of Fig. 7 (right). The rms value is 350 μm, see Fig. 6 (right).

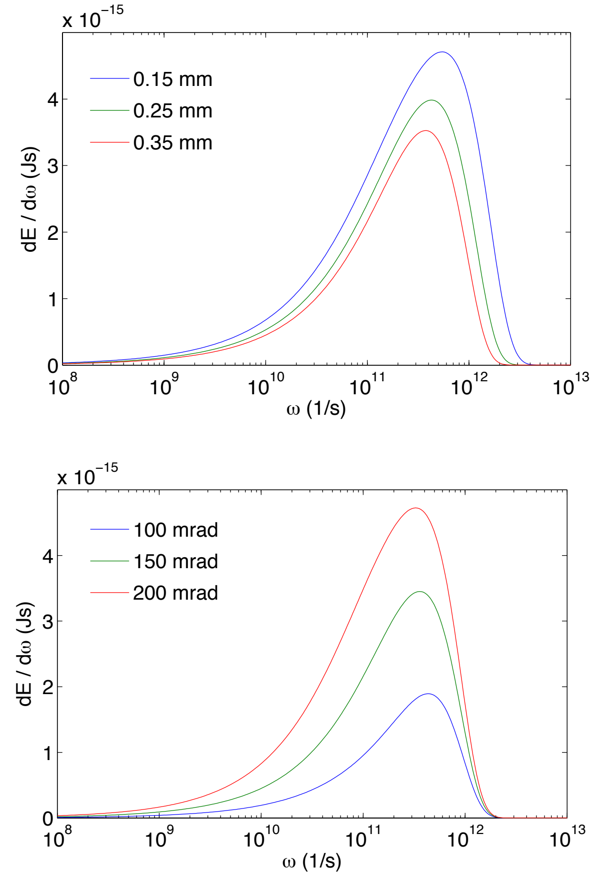

Figure 8: Synchrotron radiation spectrum from the analytical model for E=30 MeV, r_{bend}=1 m, Q=5 nC. Top: for different bunch lengths (collecton angle: 100 mrad). Bottom: for different collection angles (bunch length: 0.37 mm).

SR emission at 30 MeV), the analytical model gives a total photon pulse energy of 1.7 mJ integrated over the complete SR spectrum. However, nearly no energy is contained above 1 THz due to the strong cut-off at higher frequencies. Since only very short pulses can produce radiation in this spectral range, bunch compression must be applied. An increase of the electron beam energy does not overcome the problem, since it increases only the single particle component in the spectrum, and not the coherent part (Fig. 2) in the required range of a few THz. A detailed study of the bunch compression and possible bunch compressor setup is therefore needed.

Meanwhile, we assume that the electron bunches, produced by the presented compact linac layout, can be compressed to 100 μm. This corresponds to a compression factor of $\sim$3.5 and should be feasible. It is clear that larger bunch compression factors (e.g. a factor of 10, resulting in a bunch length of 37 μm) may cause trouble at the bunch charge used, due to increased space charge forces. Figure 9 shows the radiation spectrum in the THz range for various electron bunch lengths and two different collection angles.

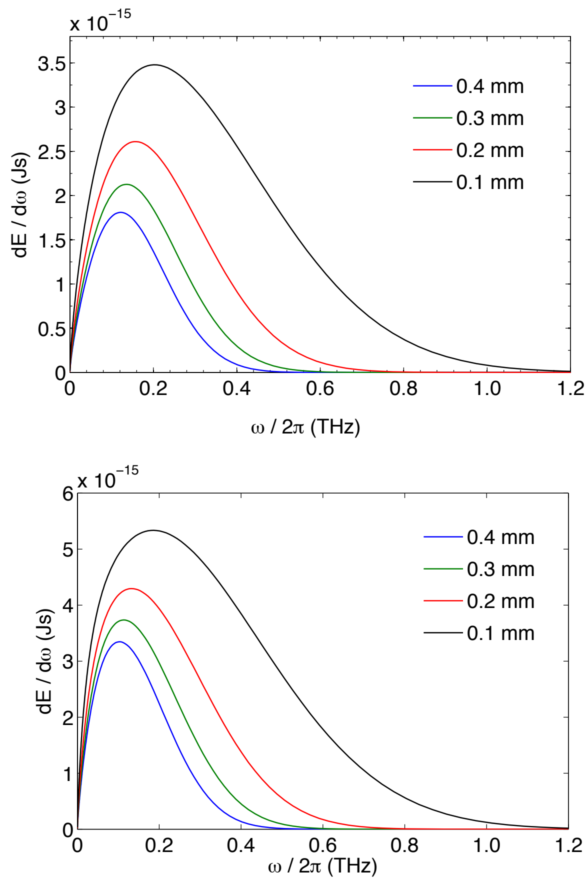

Figure 9: Synchrotron radiation spectrum from the analytical model for different electron bunch lengths. E=30 MeV, r_{bend}=1 m, Q=5 nC. Two different collection angles are assumed: 100 mrad (left) and 150 mrad (right).

Table 1: Calculated photon pulse energies for various bunch lengths and two different collection angles corresponding to Fig. 9. E=30 MeV, r_{bend}=1m, Q=5 nC. The total pulse energy as well as the energy contained above 1 THz are displayed, respectively.

bunch length (μm)	collecting aperture (mrad)	total energy (mJ)	energy >1 THz (mJ)
400	100	1.5	5e-8
300	100	2.3	5e-8
200	100	4.2	1e-7
100	100	11.0	0.08
37	100	40.0	15.0
400	150	2.7	7e-8
300	150	4.0	7e-8
200	150	6.9	2e-7
100	150	17.1	0.12
37	150	60.7	22.6

Table 1 displays the calculated photon energies, and Fig. 10 summarizes the expectations for these cases. For bunches below 100 μm, the calculated spectral distributions look very promising, and the pulse energy contained above 1 THz reaches the required 100 μJ.

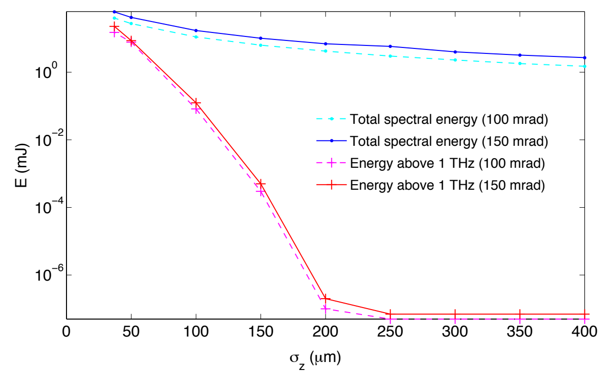

Figure 10: Photon pulse energies as a function of the electron bunch length for two different collection angles: 100 mrad (dashed lines) and 150 mrad (full lines). E=30 MeV, r_{bend}=1 m, Q=5 nC. Blue curves show the total energy contained in the spectrum, red curves show the energy contained in the spectral range above 1 THz.

SUMMARY

A synchronized THz pump source is considered for the SwissFEL in order to provide extremely powerful electromagnetic field pulses with a duration below 1 ps, for high-bandwidth excitation in ultrafast pump-probe experiments. Basic design considerations of such a compact linac based THz source have been described and the expected performances have been presented. Further beam dynamics studies are needed, e.g. a self-consistent analysis in the gun, and bunch distortions due to wake field effects. Detailed design work (e.g. for a bunch compressor) is required to provide SR radiation above 1 THz, as recently requested by potential users.

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