Possibility of adding a slotted foil at the European XFEL

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A slotted foil can be used to generate femtosecond and sub-femtosecond X-ray pulses at the free electron facilities, and two color femtosecond pulses can be generated by inserting a double slot foil at the bunch compressor location to spoil the emittance of the electron bunch. This advanced scheme have been demonstrated experimentally at the LCLS. At the European XFEL, however, radiation losses caused by a slotted foil is a big concern for the downstream cryomodules. In this paper, we present the location chosen for the slotted foil implementation and studies on the heat load of the foil for different materials. Tracking simulation using BDSIM is prepared with the same geometry as the European XFEL layout. Simulations are on-going.

Contents

1 Introduction

Recently, scientific community has shown interest in the production of femtosecond time resolution X-ray pulses, this research tool enables studies of countless processes within the femto and sub-femto scale in different scientific disciplines including biology, medicine, chemistry, materials science, physics, astrophysics, energy research, environmental research, electronics, nanotechnology and photonics. During the last years electron accelerators have been optimized with free electron lasers (FEL) wich operates with low emittance injectors to create electron bunches, linear accelerators and electron beam optics to minimize the emittance growth during acceleration and transport, and bunch compression to generate ultrashort bunches[7].
The European XFEL international facility in Germany is aimed to provide new reasearch opportunities by using x-ray flashes to investigate ultrafast processes. With a 3.4 km of total length, the European XFEL operates with superconducting accelerator technology to provide FEL radiaton characterized by its high average brilliance in the X-ray regime combined with extreme peak intesities, femtosecond pulse duration and high degree of coherence. At present enables the acceleration of up to 27,000 electron bunches per second with an energy up to 17.5 GeV.
XFEL radiation is characterized by its ultra short pulse duration currently in the 10-100 fs regime[2], to achieve even shorter pulses a slotted-foil can be used[1] to spoil the emittance of most of the beam while leaves a narrow unspoiled slice (Figure 1).

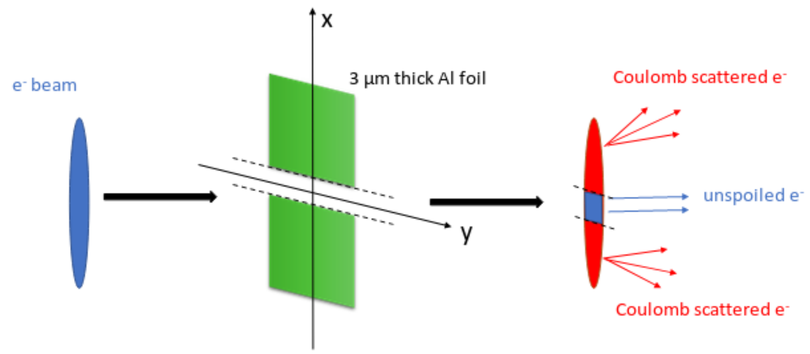


Figure 1: A schematic of the slotted foil method in one of the magnetic bunch-compressor chicane (Adapted from [3]).

The method consist of an Aluminium foil located in the path of the beam at the center of a magnetic bunch-compressor chicane. After the beam goes through the foil only the electrons with a direct path through the gap contribute to the laser pulse, while the electrons that hit the foil generates Coulomb scattering. in this configuration most of the beam will not lase due to the emittance increase, only the small unspoiled slice will lase (the fewer electrons, the shorter the resulting X-ray pulse.) producing much shorter x-ray pulses.

[1]This technique has been widely used at LCLS see [3].

In this paper we discuss preliminary results of the slotted foil performance obtained with BDSIM[5] tracking in order to study compatibility of the slotted foil technique with the European XFEL design, different scenarios of the beam loss are considered due to the insertion of slotted-foil method.

2 Concepts on FELs

2.1 Bunch compression

The generation of extremely short FEL pulses is achieved by means of longitudinal bunch compression. High peak currents of several 1000 A are needed in extreme-ultraviolet and X-ray free-electron lasers. These cannot be produced directly in the electron gun. Therefore moderately long bunches with a peak current of about 50 A are created in the source. The electrons in the linac have speeds very close to the speed of light, and the velocity differences are far too small for a trailing electron to catch up with a leading electron if the particles move on a straight line. This possibility is opened if the particles are passed through a magnetic chicane (Figure 2).

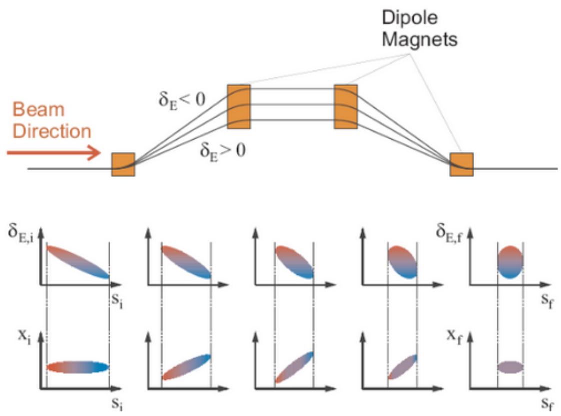


Figure 2: Bunch compression schematic. In a magnetic chicane the electrons at the tail move on a shorter orbit than those at the head.

A magnetic bunch compressor consists of two elements: an energy *modulator* and a non isochronous achromatic sections, the energy modulator provides a time-energy correlation (chirp) along the bunch length, the non isochronous section introduces an energy-dependent path length. In this way a proper tuning of the modulator parameters to provide the needed chirp along the bunch, results in compression as the bunch propagates.

2.2 Requirements on electron beam quality

A key quantity to achieve high-gain FEL is the gain length, to obtain a short gain length, the peak current in the bunch must be very high, in the order of several 1000 A for reducing the gain length. Another important parameter is small cross section of the beam, a measure of the beam size is given by the emittance ϵ, which in a roughly way can be defined as the product of radial beam size and divergence. A low emittance means that it is possible to maintain a small beam diameter over a very long distance, The third requirement is a very low energy spread within the beam. In order to achieve laser saturation the energy spread must be less than half the FEL parameter. To summarize the FEL performance is determined by the peak current, emittance and low energy spread. Low emittance and high peak current beam are required in the ondulators, so typically long beams are produced with low emittance and they are compressed later[1].

3 Location of the slotted foil

European XFEL has three magnetic chicanes the first one is located at an energy of 130 MeV, the second at an energy of 700 MeV and the third at an energy of 2400 MeV (See Figure 3).

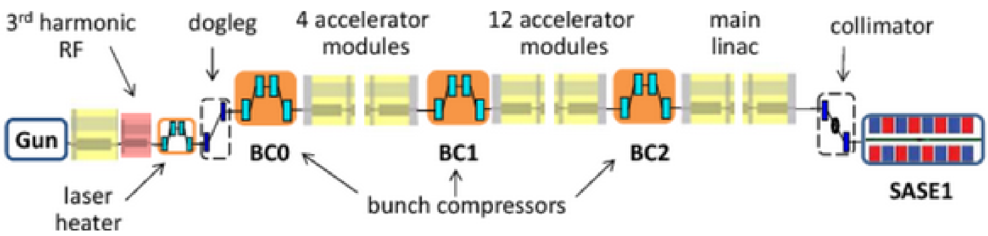


Figure 3: Schematic of the European XFEL layout.

The larger momentum dispersion (which describes the path length change for a particle with relative energy error δ), low emittance, and the larger ratio total beam size to unspoiled beam ($\frac{\sigma_\delta R_{36}}{3\sigma_y}$) in BC1 make this location the best choice for producing the shortest duration unspoiled electron pulse.

Parameter	symbol	BC0	BC1	BC2	unit
bunch charge	Q	200	200	200	pC
chicane energy	E_0	130	700	2400	MeV
chicane dispersion	η	206	480	370	mm
momentum compaction	R_{56}	60-120	50	30-100	mm
rms initial E-spread	σ_δ	1.6	0.9	0.3	%
normalized emittance	ϵ_n	0.5	0.5	0.5	μm
ratio total beam size to unspoiled beam	$\frac{\sigma_\delta R_{36}}{3\sigma_y}$	8	24	12	

Table 1: European XFEL bunch compressors comparisen and beam parameters.

The unspoiled electron pulse length can be estimated as discussed in [3],

$$\Delta\tau \approx \frac{2.35}{|\eta h|\, c}\sqrt{\eta^2\sigma_{\delta_0^2} + (1+hR_{56})^2\left[\Delta x^2/3 + \epsilon\beta\right]} \tag{1}$$

based on a simpler calculation, the pulse duration of the unspoiled portion of the electron bunch has been estimated for the three bunch compressors and BC1 is the best option for locating the slotted foil. With BC1 parameters, shown in Table 1 above, we will be able to achieve pulse duration of $\Delta\tau \approx 0.7$ fs.

4 Estimation of the energy deposition

Incident electron beam hitting the foil leads to energy deposition, the temperature increase can be determined from the beam parameters together with specific heat capacity of the foil material.
Given an electron bunch the temperature increase due to an incident beam is given by:

$$\Delta T = \frac{\Delta E'}{\rho C_p V} \tag{2}$$

where ρ is the slotted foil material density, C_p the specific heat capacity and V is the volume of the beam; the energy deposition in the foil per bunch $\Delta E'$, is calculated from the energy deposition per e^-:

$$\Delta E' = \Delta E \cdot n \tag{3}$$

where n is the number of electrons per bunch ($n = \frac{q}{e^-}$).
ΔE can be estimated with the stopping power S of the foil material(Extracted from ESTAR tables[4], see Figure 4.) as follows:

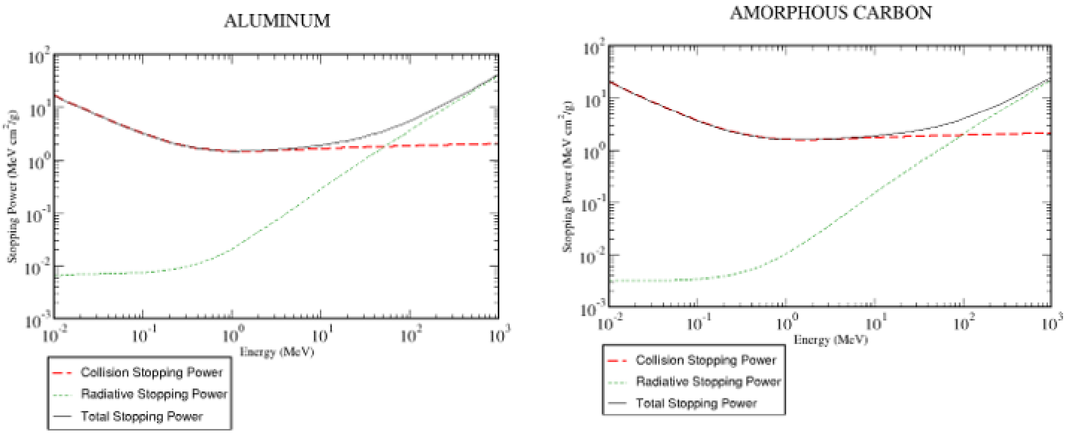
$$\Delta E = S\rho d \tag{4}$$

where d is the thickness of the material. The estimated temperature increase for the beam with transverse sizes $\sigma_x = 200$ μm and $\sigma_x = 4.8$ mm is $\Delta T = 1.52$ °C.

Parameter	symbol	value	unit
energy deposition per e^-	ΔE	3.64×10^{-15}	J
energy deposition per bunch	$\Delta E'$	4.5×10^{-7}	J
Al density	ρ	2.6989	g cm^{-3}
Al specific heat capacity	C_p	0.921	J/g°C
beam volume	V	12×10^{-7}	cm^{-3}
Al stopping power	S	2.811	MeV cm^2 /g
foil thickness	d	3×10^{-4}	cm

Table 2: Parameters considered in the temperature increase estimation.

Comparing the temperature increase and Aluminum melting point ($T_m = 660.3$°C), we can see that the foil can stand ≈ 440 bunches before reaching a temperature very close to T_m. Considering the high repetition rate of the beam at European XFEL and the estimation above we need to consider a different material being Diamond a better option because of it's high melting temperature ($T_m = 3642°$C) and density ($\rho = 3.515$ g cm^{-3}).



(a) Aluminum stopping power.

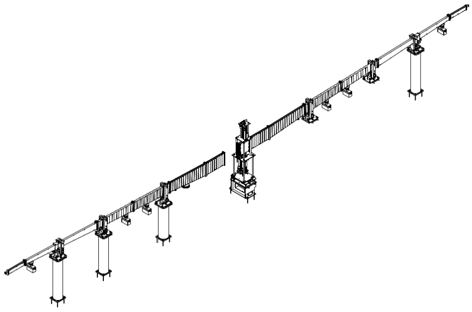
(b) Diamond stopping power.

Figure 4: Stopping power for electrons extracted from ESTAR tables.

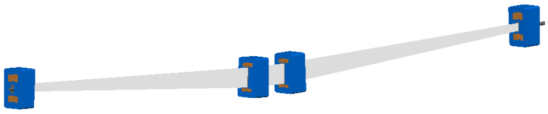
The temperature increase calculation for Diamond gives a value of $\Delta T = 1.56\ \mu°$C, which seems fairly reasonable result comparing to Aluminum, with this temperature increase the number of bunches that a Diamond foil can stand is ≈ 2334, nevertheless it is important to mention that for these estimations thermal conductivity and cooling effects are not considered yet. Also we have to simulate the beam passing through the Diamond foil to find the thickness that produces a similar dispersion to the 3μm Aluminum foil.

5 BDSIM tracking and simulation setup

BDSIM is a C++ software that utilises the Geant4 toolkit to simulate both the transport of particles in an accelerator and their interaction with the accelerator material, BDSIM uses ASCII text input with a .gmad syntax created by converting a MAD-X or MAD8 Twiss file or writing it manually, it produces output ROOT files for data analysis.
To simulate bunch compressor chicane region, it is necessary to define the beam line elements specifying the name of the component and its dimensions, include a sequence definition using defined components, specify where to record output files. The physics processes included are ionization, Bremsstrahlung radiation, Coulomb scattering and multiple scattering, To make the desired outcome happen more often the biasing factor was set up to 100 except for Bremsstrahlung which was set to 1000.
The geometry of the magnetic chicane,(i.e. beam pipes trapezoid like and middle rectangular beam pipe with the slotted foil) adapted in the BDSIM simulation was built with pyg4ometry [6](see Figure 5 (b)).



(a) Schematic of the BC1 magnetic chicane.



(b) BC1 magnetic chicane geometry built in pyg4ometry.

Figure 5: BC1 at European XFEL.

The vacuum chambers between the dipoles are made of copper and the vacuum chambers outside are made of stainless steel. The foil is intended to be Aluminum, however the foil material can be freely varied according to the performance in spoiling the beam; simulation using Diamond are being planned as well.

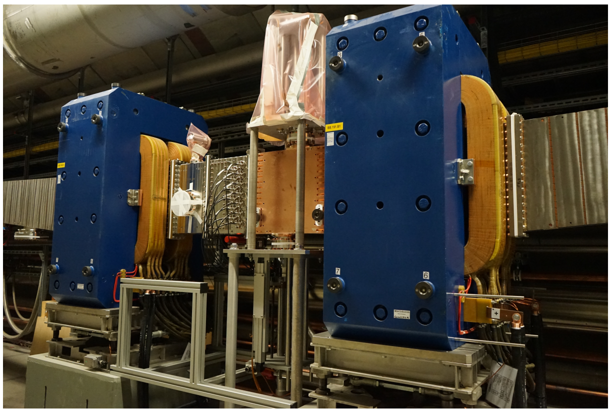


Figure 6: BC1 magnetic chicane at European XFEL.

For the proposes of this simulation the main elements to be incorporated are the dipole magnets at BC1, a rectangular beam pipe, and the foil ($\Delta x = 3\mu$m) with vertically varying size gap (Figure 7).

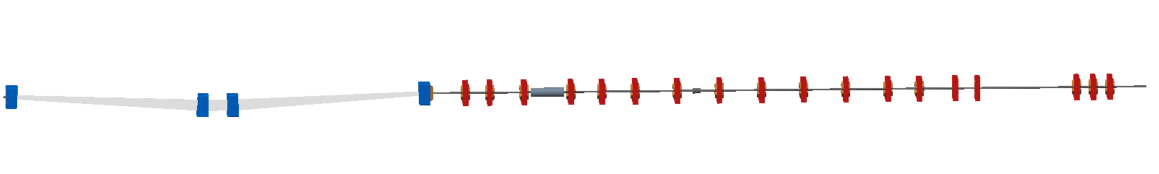
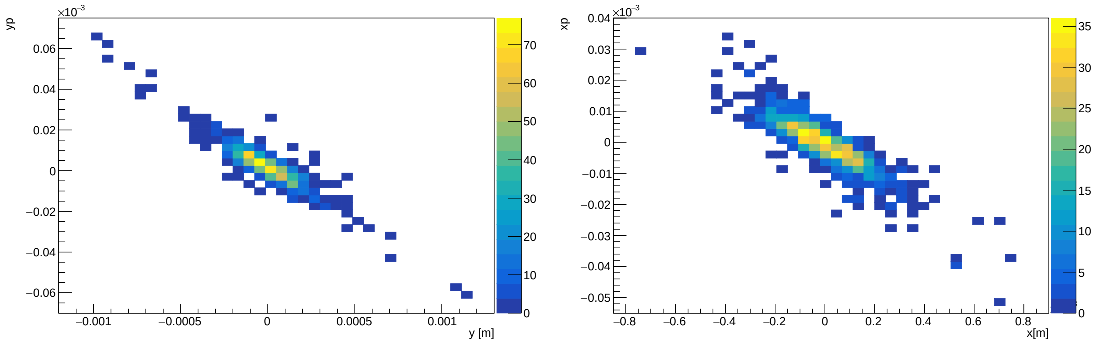


Figure 7: BC1 magnetic chicane geometry in BDSIM.

The input beam distribution follows a gaussian distribution, it was set up with the userFile option and and it was generated to start at the beginning of the first dipole (see Figure 7).
In order to test general aspects related to the geometry we performed preliminary simulations with a beam populated by $n = 1000$ electrons with $E = 700$ MeV, an Aluminum foil with 3μm thickness and a 180 μm gap. In Figure 8 it is shown the beam distribution at the beginning of the first dipole.



(a) y transverse momentum as function y coordinate.

(b) x transverse momentum as function x coordinate.

Figure 8: Beam distribution at the beginning of the first component.

In Figure 9 it is shown x transverse momentum as function of y transverse momentum at the beginning of the first dipole.

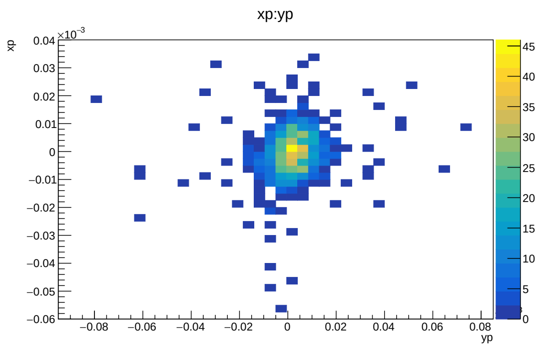


Figure 9: x vs y.

The distribution of the beam must be analyzed after the slotted foil to study the energy losses that its insertion can generate. We must also increase the number of particles of the beam to $\approx 10^7$ electrons so that we can obtain reliable results.

Conclusions and future work

Tracking simulation with slotted foil is in progress and it's worth taking care of every possible detail related to geometry to get reliable results. Simulations will be carried out in the near future to study different options (i.e. material and thickness of the foil) that guarantee a good performance of the foil technique. The optics in the BC can be further improved to shorten the pulse length.

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