STORAGE RING XFEL WITH LONGITUDINAL FOCUSING

I. Agapov*, G. Geloni, European XFEL GmbH, Hamburg, Germany

Abstract

In present work we investigate the possibility of running a high gain FEL on a storage ring using a longitudinally focusing insertion to compress bunches passing an undulator. If integrated into a storage ring similar to PETRA III such device could potentially produce continuous ps pulses of photons in the nm range with peak pulse powers of tens of GW. Even without operating in FEL saturation mode the longitudinal focusing can provide means to increase the brightness and shorten the photon pulse length

INTRODUCTION

Low gain FELs with wavelength down to ~ 200 nm (6 eV) have been in operation at storage rings using optical cavities. Short wavelength FELs presently use linacs as drivers since they provide necessary electron beam quality. X-ray FELs such as LCLS, European XFEL or SwissFEL are now in operation or under construction worldwide. They use linacs as drivers to assure beam qualities necessary for a SASE process at those wavelengthes. For a typical wavelength (1 keV-30 keV) the European XFEL requires emittances below 10^6, energy spreads ~ 1 MeV and peak currents ov several kA at electron beam energies up to 17.5 GeV. The saturation length (for basic definitions in the FEL theory see e.g. [1]) roughly defines the minimum practically sensible undulator length. At European XFEL, for the shortest wavelength, achieved with the maximum electron beam energy, the saturation length can be a hundred meters, but for soft X-rays it can be as short as 30 meters depending on the wavelength and electron beam parameters. This makes it in principle possible to fit such an undulator into a storage ring. Beam parameters in latest generation light sources such as PETRA III (see Table 1) are such that for UV photons the beam quality is not far removed from that required for an FEL. For shorter wavelength saturation length becomes larger and the possibility of using the stored beam for SASE FEL directly becomes limited. The interest in shorter wavelength storage-ring based FELs has recently been growing since they could combine extreme peak brightness and coherence of an FEL with continuous operation and lower power consumption of a storage ring (see e.g. [2] and references therein). An insertion device with longitudinal focusing would consist of a compression section, SASE undulator, and a decompression section. The rest of the ring could be passed with the usual bunch length. A design sketch is presented in Fig. 1. It could be used as an insertion or as a bypass subject to space availability. This scheme is in principle similar to a crab cavity type, discussed e.g. in [3], however longitudinal phase space only is manipulated. In the following some simulation studies for the possibility of integrating such an insertion into PETRA III are presented. All calculations are performed with *Ocelot* [4].

* ilya.agapov@xfel.eu

Table 1: PETRA III Beam Parameters [5], assuming high bunch charge operation mode with 40 bunches

Parameter	Value
Beam energy	6 GeV
Circumference	2304 m
Emittance $\varepsilon_x, \varepsilon_y$	10^{-9}, 10^{-11}
Energy spread	10^{-3} (6 MeV)
Bunch charge	20 nC
Bunch length	44 ps or 13 mm
Peak current	170 A
Longitudinal damping time	10 msec

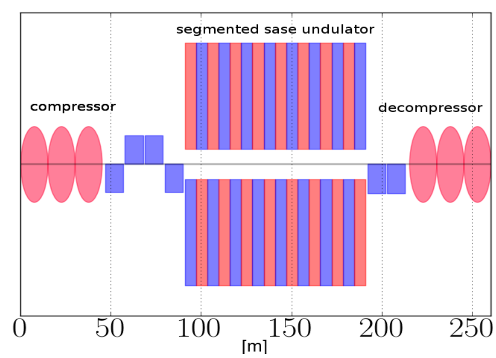

Figure 1: Insertion device layout. Going from left to right, the beam passes an RF module, a dispersive section (chicane or arc), a number of undulators, a disperive section and finally another RF module.

POSSIBILITY OF AN FEL INSERTION DEVICE AT PETRA III

Longitudinal Phase Space Focusing

In a linac-based FEL bunch compression is a key factor, but can allow for certain beam distortion as long as it preserves the lasing bunch core. For a multiturn operation the margin for such distortions is much thinner. Space charge and Coherent Synchrotron Radiation (CSR) [6] effects play much smaller role for longer bunches and higher energies, so cleaner compression and decompression can be in principle expected than for a typical linac FEL. The requirement is that no beam instabilities and distortions should appear on the time scale faster than the longitudinal damping time which is about 1000 turns for PETRA III. Neglecting collective interactions, the longitudinal phase space map for the insertion is

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$$M = M_{RF2} \cdot M_{C2} \cdot M_{C1} \cdot M_{RF1} \quad (1)$$

where the dispersive sections maps are given by matrices

$$M_{C1,C2} = \begin{pmatrix} 1 & R_{56}^{(1,2)} \\ 0 & 1 \end{pmatrix} \quad (2)$$

and the RF cavity maps are

$$M_{RF1,RF2} : \begin{pmatrix} t \\ p \end{pmatrix} \to \begin{pmatrix} t \\ p + V^{(1,2)} \sin(f_{RF} \cdot t) \end{pmatrix} \quad (3)$$

Here t and p are longitudinal coordinates usually measured in meters and relative energy units, R_{56} is the standard notation for dispersive time delay and $V^{(1,2)}$ are total RF voltages for the compressor and the decompressor. One easily checks that by choosing $R_{56}^{(1)} = -R_{56}^{(2)}$ and $V^{(1)} = -V^{(2)}$ the whole transfer map reduces to unity. So when collective self-interactions and diffusion are neglected the insertion has no theoretical footprint on longitudinal beam dynamics. The possible undulator parameters used in simulations are given in Tables 2 and 3, and the beam compressor parameters corresponding to PETRA III beam parameters are shown in Table 4 and 5. 800 MHz cavity was chosen for demonstration since it has the wavelength longer than the electron beam size. 1.3 GHz cavity of European XFEL type could also be used, but half its wavelength is shorter than the electron bunch length and the bunch tails will not be compressed fully (see Figs. 2, 3). The system length with undulator is of the order of 200 m. No optimization has been performed so far wrt. length, RF power, potentaial for using storage ring arcs etc., so this number could be sufficiently improved.

Table 2: Possible Parameters of a 20 mm Soft X-ray Undulator

Parameter	Value
Period	$l_w = 0.02m$
Field	$K = 0 - 10.0$
Radiation wavelength at 6 GeV	300 eV-17 keV
Section length	0.9 m
Optics	FODO with $\beta = 4m$

Table 3: Parameters of a 68mm Soft X-ray Undulator of European XFEL Type (for 6 GeV electron beam)

Parameter	Value
Period	$l_w = 0.068m$
Field	$K = 0 - 10.0$
Radiation wavelength at 6 GeV	100 eV-5 keV
Section length	0.9 m
Optics	FODO with $\beta = 4m$

An obvous drawback of the system is the large amount of RF power required. Since the longitudinal focusing is proportional to $V \cdot f_{RF}$ higher RF frequency will result in shortening the section length. With 12 GHz cavities the length can be reduced to a few meters only. However the bunch length at PETRA III is longer than the RF wavelength for frequencies about $\gtrsim 1GHz$. One can still achieve compression in that case, but it would result in a specific current shape 3. If low momentum compaction operation is assumed where the bunch length is shortened by a factor of say, 10, such high frequency cavities could be employed efficiently (see Table 5). Producing shorter bunches without loosing bunch current at PETRA III is however presently impossible.

Table 4: Parameters of the Bunch Compressor and Decompressor used in Simulations with 20x Compression for Nominal Bunch Length

Parameter	Value
RF frequency	800 MHz
Cavity length (at 35 MV/m gradient)	45 m x2
Chicane length	20-30 m
Dipole fields	0.2 T
R_{56} compressor	-0.15 m
R_{56} decompressor	0.1 5m

Table 5: Parameters of the Bunch Compressor and Decompressor with 50x Compression for Short Bunch Operation

Parameter	Value
RF frequency	3.9 GHz
Cavity length (at 35 MV/m gradient)	9 m x2
Chicane length	~20 m
Dipole fields	~0.2 T
R_{56} compressor	-0.15 m
R_{56} decompressor	0.15 m

Undulator

The radiation wavelength is

$$\lambda_r = \frac{l_w}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \quad (4)$$

And the Pierce parameter is

$$\rho = \frac{1}{\gamma}\left(\left(\frac{KA_{JJ}l_w}{8\pi\sigma_b}\right)^2 \frac{I}{I_A}\right)^{\frac{1}{3}} \qquad I_A = 17kA \quad (5)$$

gain length

$$L_G = l_w/(4\pi\sqrt{3}\rho) \quad (6)$$

So to increase the energy reach of a SASE FEL into the harder part of the spectrum one chooses possibly short undulator period. If using the FODO optics, decreasing the beam size is possible down to $\sqrt{2\epsilon L}$ where L is the period length. E.g. 4 m FODO optics will require short undulators of ~ 1 m length with quadrupoles between them. Power estimates assuming 0.02 mm and 0.068 mm period undulators are presented in Figs. 4-6.

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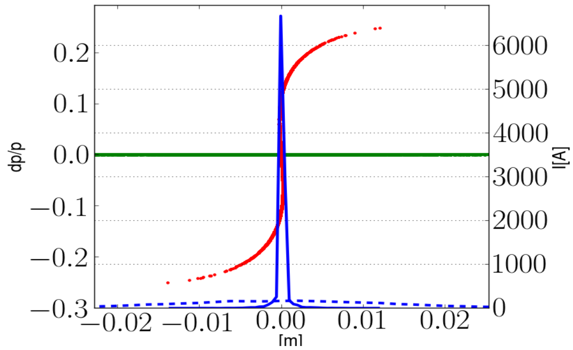

Figure 2: Simulated longitudinal phase space at the entrance (green), after the bunch compressor and at the exit (identical to the entrance phase space) of the insertion device, with 800 MHz cavity.Current profiles before (blue dashed line) and after (solid blue line) are shown.

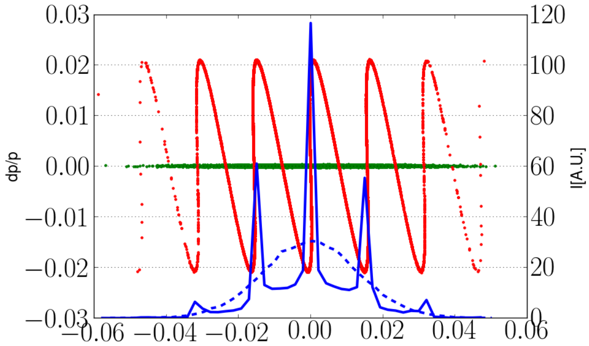

Figure 3: Simulated longitudinal phase space at the entrance (green) and after the bunch compressor (red) with 12 GHz cavity. Current profiles before (blue dashed line) and after (solid blue line) are shown.

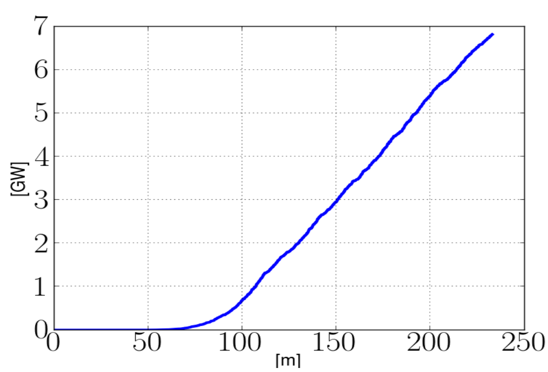

Figure 4: Steady state SASE simulations for $E_\gamma = 1266eV$, K=5.0, 50x compression.

Influence on Beam Dynamics

The feasibility question from the beam dynamics point of view reduces to the turn-to-turn preservation of beam quality. Synchrotron radiation induces bunch diffusion, mostly in the longitudinal phase space. Such diffusion is in principle a limiting factor even for linac-based FEL performance, however for the device in question the diffusion footprint is similar to that of standard ring insertion devices and is not in principle a limiting factor. Moreover, the FEL undulators can potentially be used in place of damping wigglers for reducing the emittance. The FEL-induced energy spread however is to be taken into account for more detailed studies. A major limiting factor in FELs is the coherent synchrotron radiation [6]. In the design discussed the bunch length (1 ps) is 5-6 orders of magnitude longer than the critical wavelength of the bending magnet radiation (2-20 keV for 0.1-1 T dipoles), whereas CSR manifests itself when the bunch length is comparable to the wavelength of the radiation emitted. Estimates based on taking into account the power enhancement factor

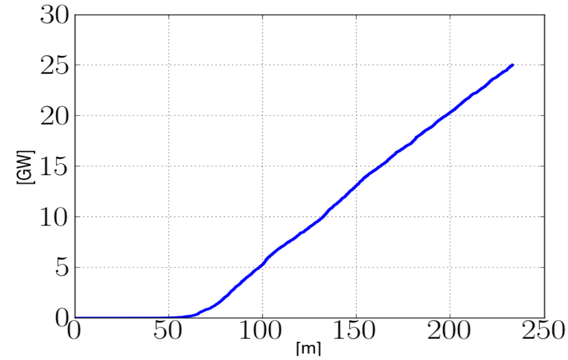

Figure 5: Steady state SASE simulations for $E_\gamma = 335eV$, K=10.0, 50x compression.

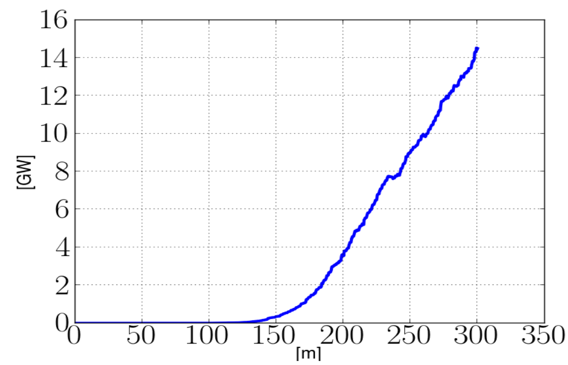

Figure 6: Steady state SASE simulations for $E_\gamma = 100eV$, $l_w = 0.068$, K=10.0, 50x compression.

$$g(\lambda) = N \left| \int_{0\infty}^{\infty} n(z) \exp(2\pi i z/\lambda) dz \right|^2 \qquad (7)$$

where N is the number of particles in the bunch, $n(z)$ the bunch form factor and λ the radiation wavelength, show negligible effect on the total emitted power of sycnchrotron radiation. Another SASE undulator effect on the beam is microbunching which is washed away in dispersive sections and should not present a problem.

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CONCLUSION AND OUTSTANDING R&D NEEDS

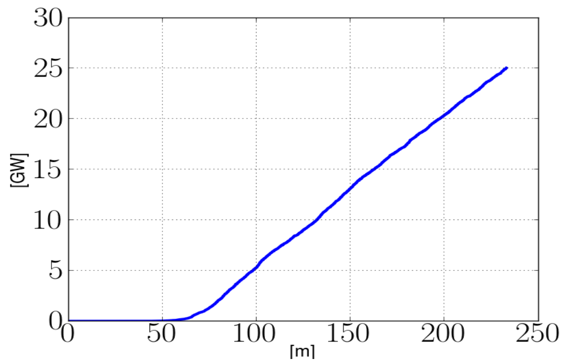

Figure 7: Steady state SASE simulations for $E_\gamma = 335eV$, K=10, 50x compression assuming $\beta = 4m$ optics equalizing vertical and horizontal emittance is possible.

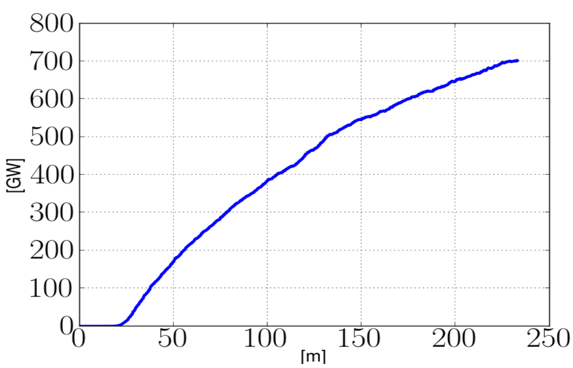

Figure 8: Steady state SASE simulations for $E_\gamma = 335eV$, K=10, 20x compression assuming $\beta = 4m$ optics equalizing vertical and horizontal emittance and bunch shortening down to 4 ps is possible.

Several issues need to be further addressed.

Although CSR should not be a limiting factor, possibilities for other instabilities need investigation.

Electron optics design has to be performed to match the existing beam transport. In this work power estimates were done based on standard FODO optics with $\langle\beta\rangle = 4m$. Due to large difference in the vertical and horizontal emittances, special optics producing round beams will improve the performance. This could be achieved by emittance exchange bewteen the vertical and the horizontal (see Fig. 7) plane or possibly by an asymmetric low-β_x optics. The energy spread after the first focusing RF cavity is significant (5%). This will require very large momentum acceptance optics in the insertion. On the other hand, the performance can be improved with a transverse gradient undulator [7]. Moreover, if same current short bunch operation (~4 ps) of a storage ring could be achieved, the performance is improved significantly (see Fig. 8).

With proper optimization of the layout for the X-ray wavelength of interest to experiments, operation of ~100 m long insertion device with longitudinal focusing as an FEL in the present or next [8] generation of light sources producing ps photon pulses of high peak power seems theoretically possible. The major problem is however due to the fact that straight sections of 100 m length are not feasible in present storage ring light sources. Thus a major step on the way to practically implementing the proposed FEL scheme is in R&D towards storing high current beams in storage rings.

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