Potential of a longitudinally focusing insertion for a storage ring X-ray FEL.

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Abstract

In present work we investigate the potential of a longitudinally focusing device to compress bunches passing an undulator for a synchrotron storage ring. If integrated into a storage ring similar to PETRAIII such device could potentially produce continuous $\sim$1ps pulses of photons in the $\text{nm}$ 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.

Keywords: Synchrotron Radiation

1. Introduction

Low gain FELs with wavelength down to $\sim$200$\text{nm}$ (6eV) have been in operation at storage rings using optical cavities\cite{refs}. Short wavelength FELs presently use linacs as drivers since they provide necessary electron beam quality. X-ray FELs such as LCLS, European XFEL or SWISS FEL are now in operation or under construction worldwide. They use linacs as drivers to assure beam qualities necessary for a SASE process at those wavelengths. For a typical wavelength (1KeV-30KeV) the European XFEL requires emittances below $10^{-9}$, energy spreads $\sim 1\text{MeV}$ and peak currents of several $kA$ at electron beam energies up to 17.5$\text{GeV}$. The saturation length (for basic definitions in the FEL theory see e.g. \cite{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 PETRAIII (see Tab. \ref{tab: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. \cite{2} and references therein) An insertion device with longitudinal focusing (of crab cavity type, discussed e.g. in \cite{3}) 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. \ref{fig:1}. It could be used as an insertion or as a bypass subject to space availability. In the following some simulation studies for the possibility of integrating such an insertion into PETRAIII are presented. All calculations are performed with xcode\cite{4}.

Table 1: PETRAIII beam parameters\cite{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        | $10^{-3}$ (6MeV) |
| Bunch charge         | 20 nC       |
| Bunch length         | 44ps or 13mm |
| Peak current         | 170A        |
| Longitudinal damping time | 10msec    |

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2. Possibility of an FEL insertion device at PETRAIII

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) 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 PETRAIII. Neglecting collective self-interactions and diffusion is neglected the insertion has no theoretical footprint on longitudinal beam dynamics. The beam compressor parameters which were used in calculations corresponding to PETRAIII beam parameters are shown in Tab. 2. 800MHz cavity was chosen for demonstration since it has the wavelength longer than the electron beam size. 1.3GHz 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 Fig. 3). The system length with undulator is of the order of 200m. No optimization has been performed so far wrt. length, RF power, potential for using storage ring arcs etc., so this number could be sufficiently improved.

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

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

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

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 beam compressor parameters which were used in calculations corresponding to PETRAIII beam parameters are shown in Tab. 2. 800MHz cavity was chosen for demonstration since it has the wavelength longer than the electron beam size. 1.3GHz 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 Fig. 3). The system length with undulator is of the order of 200m. No optimization has been performed so far wrt. length, RF power, potential for using storage ring arcs etc., so this number could be sufficiently improved.

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

Table 2: Possible parameters of a 20mm soft x-ray undulator.

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

Table 3: Parameters of a 68mm soft x-ray undulator of European XFEL type (for \( 6\)GeV electron beam).

An obvious 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 12GHz cavities the length can be reduced to a few meters only. However the bunch length at PETRAIII is longer than the RF wavelength for frequencies about \( \geq 1 \)GHz. One can still achieve compression in that case, but it would result in a specific current shape. 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 Tab. 4).

Table 4: Parameters of the bunch compressor and decompressor used in simulations with 20x compression for nominal bunch length.

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

Table 5: Parameters of the bunch compressor and decompressor with 50x compression for short bunch operation.

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

Undulator. The radiation wavelength is

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

(4)

And the Pierce parameter is

$$\rho = \frac{1}{\gamma} \left( \frac{K A J \lambda l_w}{8 \pi \sigma_p} \right)^2 \frac{I}{I_A} \frac{1}{I_A} = 17kA$$

(5)

gain length

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

(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 $\sqrt{2}L$ where $L$ is the period length. E.g. 4m FODO optics will require short undulators of $\sim 1m$ length with quadrupoles between them. Power estimates assuming 0.02mm and 0.068mm period undulators are presented in Fig. 2-4.

Figure 2: Steady state SASE simulations for $E_{\gamma} = 1266eV$, $K=5.0$, 50x compression

Figure 3: Steady state SASE simulations for $E_{\gamma} = 335eV$, $K=10.0$, 50x compression

Figure 4: Steady state SASE simulations for $E_{\gamma} = 100eV$, $l_w = 0.068$, $K=10.0$, 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 qualities. Synchrotron radiation induces bunch diffusion, mostly in the longitudinal phase space. Such
Figure 5: 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 800MHz cavity. Current profiles before (blue dashed line) and after (solid blue line) are shown.

Figure 6: Simulated longitudinal phase space at the entrance (green) and after the bunch compressor (red) with 12GHz cavity. Current profiles before (blue dashed line) and after (solid blue line) are shown.

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. A major limiting factor in FELs is the coherent synchrotron radiation [6]. In the design discussed the bunch length (1ps) is 5-6 orders of magnitude longer than the critical wavelength of the bending magnet radiation (2-20KeV for 0.1-1T 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

\[
g(\lambda) = N \left| \int_{0}^{\infty} n(z) \exp\left(2\pi iz/\lambda\right) dz \right|^2
\]

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

3. CONCLUSION AND OUTSTANDING R&D NEEDS

Figure 7: Effect of 1000 iterations of a map of type ?? on a distribution with no momentum spread, with 1% random noise, normalized coordinates.

Figure 8: Steady state SASE simulations for \(E_{\gamma} = 335\text{eV}, K=10, 50x\) compression assuming \(\beta = 4m\) optics equalizing vertical and horizontal emittance is possible.

Following issues need to be further addressed.
Figure 9: Steady state SASE simulations for $E_e = 335\text{eV}$, $
abla = 10$, 20x compression assuming $\beta = 4\text{m}$ optics equalizing vertical and horizontal emittance and bunch shortening down to 4ps is possible.

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

ii. Another possible effect is the longitudinal phase space dilution due to nonlinearity of space rotation during compression and decompression in combination with diffusion or mismatching of RF phases, voltages, or $R_{56}$. A calculation for 1000 iterations assuming 1% random perturbation to the one-pass map (Figure 7) suggests that the effect should not play a role if the compressor and decompressor pair is tuned properly.

iii. 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 $\langle \beta \rangle = 4\text{m}$. 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 between the vertical and the horizontal (see Fig. 8) plane or possibly by an asymmetric low-$\beta_x$ optics. The energy spread after the first focusing RF cavity is significant (5%). This will require very large momentum acceptance optics in the insertion. All these questions require separate R&D.

With proper optimization of the layout for the X-ray wavelength of interest to experiments, and assuming short bunch operation ($\sim$4ps) of a storage ring, operation of $\sim$100m long insertion device with longitudinal focusing as an FEL in the present

or next generation of light sources producing ps photon pulses of high peak power seems theoretically possible.

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