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LOW GAIN FEL OSCILLATOR OPTION FOR PETRA IV

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Abstract

Next generation synchrotron storage rings will have electron beam density approaching that necessary for driving an XFEL. It falls short of the quality required for the high-gain x-ray regime above 1 keV, mainly due to the large energy spread and small peak current, but is sufficient to reach low-gain regime. Here we show that integration of an XFELO insertion is feasible within the PETRA IV upgrade project.

INTRODUCTION

The new generation of storage rings reduce their emittance by one or two orders of magnitude, producing high electron densities. Their potential to drive XFELs has attracted attention, and a high gain XFEL option for PETRA upgrade was studied in [1, 2], with the conclusion that only soft x-ray photon energies are reachable, and the impact on the ring design and on the beam dynamics is significant. After the PETRA IV upgrade project started, it became clear that, on one hand, a more ambitious emittance is aimed at (down to 10 pm rad, while only a moderate reduction down to 250 pm rad was assumed in [1]), but on other, that the low emittance is incompatible with a high bunch charge. Since then the conceptual design of the PETRA IV reference lattice has been perfomed [3],and the infuence of collective effects on beam dynamics estimated. The microwave and TMCI instabilities limit the bunch current to approx. 1 mA per bunch, taking the bunch lengthening with the third harmonic cavity into account. At this bunch charge level the intra-beam scattering already blows up the emittance by a factor of 3 to 4. So, the collective effects create an obstacle to achieving peak currents sufficient for high-gain XFEL operation in the interesting wavelength range of 10 keV and above. At the same time it bacame clear that operating an insertion that would lead to an energy spead deterioration above about 50% would be incompatible with many high brightness experiments, thus an FEL insertion should be operated in a bypass with a significantly reduced duty cycle. Moreover, the high gain FEL in the exponential regime lacks full coherence and suffers from fluctuations of output power. All this reduces the appeal of a high gain FEL insertion and this option has not been pursued further.

A different path to the ring FEL is the oscillator. Some first FELs were oscillators ([4–7]), i.e. they relied on a photon storage cavity pumped by radiation from electrons repeatedly traversing it. Since metallic mirror reflectivity drops sharply at UV wavelength, such mirrors can not be used for x-rays. However, with Bragg crystal optics ([8, 9]) such cavities could be constructed, and several design studies are now available. Diamond is a good candidate for the crystal due to its mechanical properties and thermal stability. Low emittance high-repetition electron beams such as that of LCLS-II or European XFEL are required to pump the oscillator ([10–12]), and such beams are now becoming available. The ultimate storage ring would provide beams of similar quality, however with a larger relative energy spread (it is typically labout 0.1% in rings, at equilibrium, and 0.01% in linacs for XFELs). The negative effect of the large energy spread can be mitigated with a transverse-gradient undulator (TGU, [13]). In such an undulator the resonant wavelength

$$\lambda = \frac{l_w}{2\gamma^2}\left(1 + \frac{K(x_\beta + \eta\sigma_\eta)^2}{2}\right) \quad (1)$$

is kept constant for particles with energy deviations by correlating the undulator parameter K with the electron energy via dispersive offset. Here l_w is the undulator period, $K(x) = \frac{eB(x)l_w}{2\pi m_e c}$ the position-dependent undulator parameter, x_β is the betatron oscillation coordinate, η the horizontal dispersion and σ_η the relative energy deviation of the particle. With such an undulator the XFELO was shown to be theoretically feasible at a USR ([14–16]). Such device could produce fully coherent radiation in the hard x-ray in approx. 2 keV to 25 keV spectral range with meV bandwidth.

In the following section we follow [16] and show that a similar FEL gain can be achieved with projected PETRA IV beam parameters. The path to integrating the insertion into the ring optics is then sketched.

POTENTIAL OF A RING XFELO AT PETRA

PETRA IV is an upgrade of the PETRA III machine as will have the circumference of 2304 m, the electron beam energy of 6 GeV, the emittance in the 10 to 30 pm range, the bunch length of 10-50 ps depending on the RF system parameters, and the total beam current of 200 mA; 30 beam lines, in two halls plus extensions. Four of the long straight sections will be partially used to accomodate up to 10 m long IDs adjacent to the arc. Four 108 m long and four 64 m long straight sections will be present in the ring. We assume that one pf the shorter straights can be used for a long insertion as shown in Figure 1. We assume that a shorter straight section (64 m long) can be taken and that the practical limitation for the undulator length is about 30-40 m.

Further, the parameters for the PETRA IV operation mode suitable to drive an XFELO are shown in Table 1. In the same table the parameters used in [16] are shown for comparison. In the following the key differences are summarized. The undulator period of 16 mm seems too aggressive to us, a 18 mm device was adopted. A total length of 40 m could be

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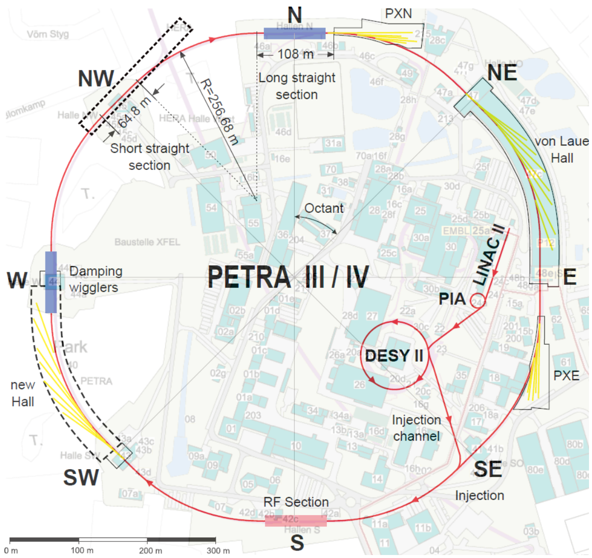

Figure 1: PETRA ring layout. The damping wiggler are shown in the present configuration.

feasible but a 30 m devices could be accomodated in a simple way with the help of optioc shown later. The emittance of $\epsilon_x = \epsilon_y = 5pm$ could be reached for PETRA IV, however only with a special damping wiggler configuration (which might not be desirable for high brightness experiments), and neglecting imperfections. Moreover, for PEP-X it is assumed that 100% coupling could be achieved e.g. by working on a resonance, which requitres a special optics setup. We asume a more conservative emittance of $\epsilon_x = \epsilon_y = 10pm$. The peak current of 40 A was calculated assumimng 0.065 mA per bunch, a 50 MHz main and a 1.5 GHz third harmonic RF system. The beam emittance and the energy spread are interdependent and depend strongly on the damping wiggler or user ID parameters. One scenario is shown in Figure 2.

Table 1: Beam Parameters for the XFELO Mode, 14.4 keV Wavelength

Parameter	**PETRA IV**	**PEP-X** [16]
Beam energy (GeV)	6	6
Emittance x,y (pm)	10, 10	5, 5
Bunch length, rms (ps)	5	2
Enegy spread (ppm)	1.4	1.0
Peak current (A)	40	20
Bunch spacing (ns)	6	6.6
Undulator period (mm)	20	16
Undulator parameter K	0.8	1.0
Undulator length (m)	30	40
$\beta^\star$ (m)	20	7.7

The gain formula adapted from [16] is [1]

[1] we could not reproduce Eq. (1) from [16] and the formula is adapted to match with Figure 2 ibid.

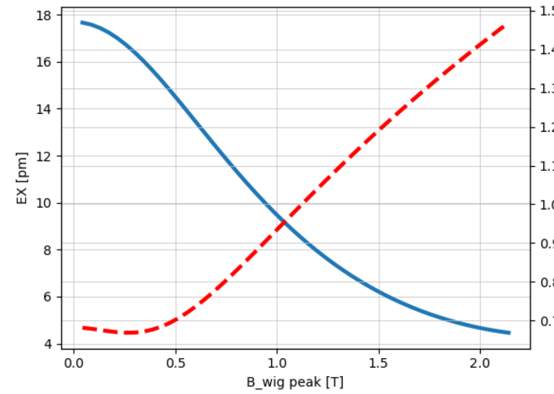

Figure 2: Effect of undulators/damping wigglers with zero dispersion at the ID (no canting), reference lattice, 24 mm period undulators of 5 m length.

$$G \approx \frac{1.53\pi^3\gamma\lambda}{l_w}\frac{K^2[JJ]^2}{1+K^2/2}\frac{N_w/\sigma_\eta}{D/\sigma_x + (5.46N_w)^2\sigma_x/D} \quad (2)$$

where D is the dispersion, σ_x the beam size, N_w the number of undulator periods and $[JJ]$ the usual coupling factor. The gain for different operation scenarios is shown in Figure 3. In all cases the gain of more than 0.3 could be achieved for dispersion in the 8-13 cm range.

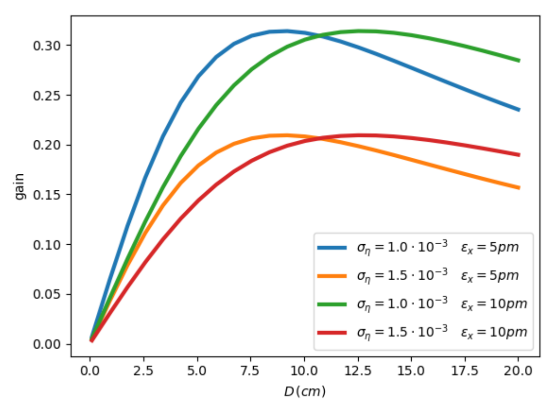

Figure 3: Gain vs. dispersion for several beam parameter scenarios.

An optical solution providing a constant dispersion in a 30 m long non-segmented undulator is shown in Figure 4. A four-magnet bump where the outermost magnets are fast kickers and the innermost two magnets could have time-independent field creates a constant dispersion in a bypass line. A bending angle of 15 mrad results in the disperion of about 13 cm. The dispersion value can be adapted by varying the kicker angles or the spacing between teh kicker and the following bending magnet. A triplet is placed outside of the four-bunp which makes it possible to vary the beta function

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and the waist and the dispersion independently. The total insertion length matches the 64 long straight section length.

The storage ring beam dynamics is decoupled from XFELO by using fresh electron bunches with a frequency matched to the cavity round-trip time, and then letting the bunches damp when every one of them is used. With bunches of 40 A peak current and 500 MHz RF system, we could fill about 1300 buckets in the ring with 6ns bunch spacing staying well below the limit of 200 mA total current. With cavity round trip times of $\approx$ 300 ns and the damping times order of 10 ms , this will result is the duty cycle of about 1% of each bunch is damped for three τ_{damp} before retirning to the XFELO.

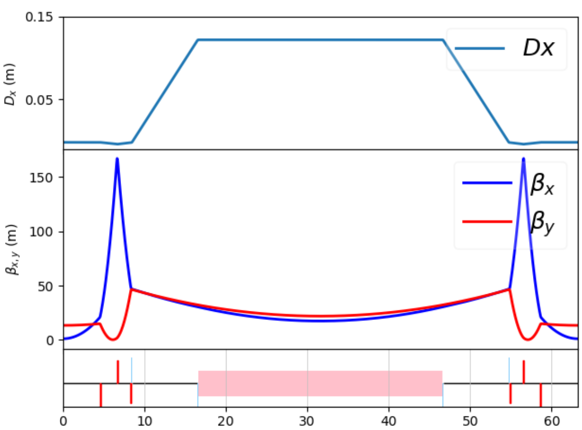

Figure 4: Sketch of a possible bypass optics.

CONCLUSION AND OUTLOOK

In this work we showed that a bypass insertion with a constant dispersion which could accomodate a TGU can be installed at PETRA IV. The TGU and beam parameters are good enough to assure the XFELO gain of $\gtrsim 0.3$, which according to [16] would result in the outcoupled power of the order of 1 MW and the bandwith of 10^{-7} (note that an expression for the maximum output power for an FEL oscillaotor found in the literature $P_{out} = \frac{\Gamma_{out}}{\Gamma_{out}+\Gamma_{loss}} \frac{P_{e-beam}}{2.4N_w}$ where Γ_{loss} and Γ_{out} stand for cavity losses and outcoupling estimate the output power at about 100 MW, a probable overestimation). We are however aware of severe issues related to the thermal effects on the cavity and b) the uncertainty in the duty cycle (related to the number of turns for which the bunch is damped in the machine before being put back into the XFELO), which is itself a function of the output power. Both these effects are to be studied in more detail before a reliable estimate of the performance can be given.

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