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An X-ray Free Electron Laser Driven by an Ultimate Storage Ring*

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INTRODUCTION

There is a worldwide interest in developing so-called ultimate storage ring (USR) light sources having electron emittances near the X-ray diffraction limit that would provide spectral brightness one or two orders of magnitude higher than present-day, 3rd generation sources and very large coherent flux in the multi-keV photon energy range [1]. At the same time, there is a growing scientific interest in X-ray FEL sources that can provide a continuous train of evenly spaced, low peak power, coherent photon pulses at repetition rates of above 1 kHz, unlike the bursts of much higher frequency pulses that can be provided by linac-based FELs pulsed with repetition rates of order 100 Hz or less. These CW sources would enable dynamic imaging of materials undergoing transitions in millisecond or less time scales would open up the development of new non-line spectroscopic techniques that could lead to a better understanding of electronic and nuclear dynamics in materials.

In this paper, we explore a concept for implementing a high repetition rate, low peak brightness soft X-ray FEL on a diffraction limited ultimate storage ring. Such a USR source, as illustrated in Fig. 1, would have the practical advantage of serving a large number of users on many “normal” (spontaneous radiation) beam lines as well as an FEL user community, making it an extremely powerful resource for synchrotron radiation science.

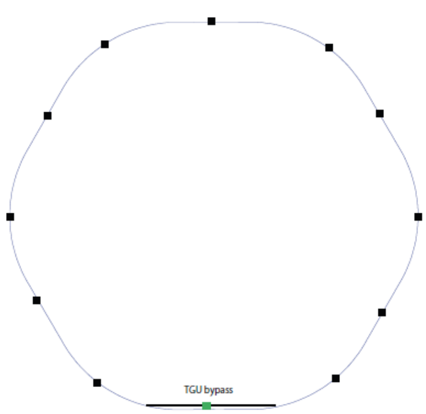

Figure 1: *A layout of PEP-X to drive a soft x-ray FEL in a 120-meter bypass. Most electron bunches (represented by squares in black color) are stored in the ring while a bunch (in green) is wiggling and lasing in transverse gradient undulators. The lased bunch is injected back into the ring and recycled in three damping times to be lased again in the bypass.*

STORAGE RING

Designing a storage ring having a natural emittance of order10 pm-rad, the diffraction-limited emittance for 10 keV X-rays, that has adequate dynamic aperture for reasonable lifetime and that can accommodate off-axis top-up injection is extremely challenging. Recently, we found a simple solution of such a lattice [2] based on fourth-order achromats. Each achromat, consisting of eight 7-bend achromatic cells, is designed to minimize the nonlinear effects of the high-order resonances. Some key parameters of the lattice are tabulated in Table 1.

Table 1: Main parameters of PEP-X as a conventional ring-based synchrotron light source or a driver of a free electron laser in a bypass.

Parameter	PEP-X(USR)	PEP-X(FEL)
Beam energy [GeV]	4.5	4.5
Circumference [m]	2200	2200
Current [mA]	200	10
Bunch Charge [nC]	0.5	0.75
Emittance, x/y [pm-rad]	12/12	160/1.6
Energy Spread [10^{-3}]	1.25	1.55
Bunch length [mm]	3.0	0.3
RF Voltage [MV]	8.3	282
RF Frequency [MHz]	476	1428
Damping time [ms]	18	18

The basic principle for driving an FEL in a USR is to periodically switch a stored electron bunch into a bypass that contains the FEL undulator. Provided the electron bunch has small enough emittance, high enough peak current, and small enough energy spread, it will generate SASE FEL radiation and the bunch will incur a relatively large energy spread and micro bunching in the process. Before this bunch can be used in the FEL again, the induced energy spread must damp down and the bunching wash out, which it will do once it is back in the storage ring for a sufficient amount of time. While this bunch is damping down, another bunch can be switched into the bypass for lasing. The repetition rate is then given by the number of bunches in the ring and the amount of time needed to restore the bunches.

Although the electron beam in the PEP-X machine described in [2] reaches a diffraction-limited transverse emittance for hard X-rays, it is not bright enough to drive a conventional FEL due to its low peak current and relatively large energy spread. To achieve the desired peak current of 300 A or more, we must shorten the bunch and increase the bunch charge as summarized in Table 1. The electron energy spread is 1.55×10^{-3}, which is about

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the same order as that of the FEL parameter ρ. As discussed below, to overcome this problem, we propose to apply a transverse gradient undualtor concept together with a properly dispersed beam in the PEP-X FEL beamline.

To shorten the electron bunch, we have to either decrease the momentum compaction factor or increase the RF focusing. We chose the latter because of its much higher threshold for longitudinal instability induced by coherent synchrotron radiation (CSR) in bending magnets [3]. Moreover, by tripling the RF frequency from the conventional 500 MHz used in many light sources to 1.5 GHz, we make the focusing more efficient. This frequency choice allows us to utilize the advance of the development of superconducting RF (SCRF) cavities for the CEBAF upgrade project [4]. For a reduction of ten in bunch length, we need approximately 300 MV of SCRF cavities operating in CW mode in the storage ring. This voltage can be provided by three cryomodules similar to those used in the CEBAF upgrades.

An undesirable consequence of the shortened bunch is the enhancement of intra-beam scattering (IBS). The increased emittances and energy spread due to IBS in a bunch having up to 0.75-nC charge seems tolerable. A more serious concern is the beam induced high order modes (HOMs) generated by so many cavities. In particular, the modes could drive transverse multi-bunch instability and limit the number of bunches in the ring. An estimate of the threshold was made using the measured values of the HOM in the CEBAF cavities [5]. The result showed that we can keep 100 bunches stable assuming a suitable bunch-by-bunch feedback system will be used. These bunches could drive a FEL with a repetition rate of 10 kHz assuming that three damping times are required for a lased bunch to be restore to its equilibrium state.

FREE ELECTRON LASER

The concept of using a "transverse gradient wiggler (undulator)" (TGU) was proposed about three decades ago as a way to overcome electron energy spread in FEL oscillators [6]. More recently the use of TGUs has been suggested for high-gain FELs in laser-plasma accelerators [7]. The idea is illustrated in Fig. 2. By canting the magnetic poles, one can generate a linear y dependence of the horizontal undulator field so that

$$\frac{\Delta K}{K_0} = \alpha y \,. \qquad (1)$$

Consider dispersing the electron beam vertically according to its energy such that $y = \eta\Delta\gamma/\gamma$. By choosing the dispersion function

$$\eta = \frac{2+K_0^2}{\alpha K_0^2} \,. \qquad (2)$$

and keeping it constant in the TGU, the change in the electron's energy is now exactly compensated by the change in the magnetic field so that every electron satisfies the resonant condition in the undulator.

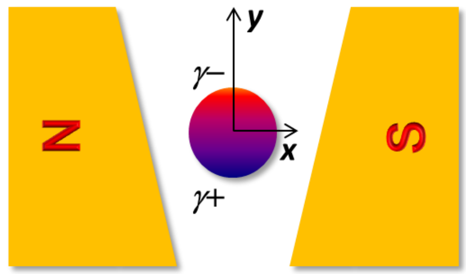

Figure 2: Transverse gradient undulator by canting the magnetic poles. Each pole is canted by an angle ϕ with respect to the yz plane. The higher energy electrons are dispersed to the higher field region (negative y) compared to the lower energy electrons to match

Table 2: FEL parameters for PEP-X.

Parameter	Value	Unit
Undulator period	3	cm
Undulator K_0	3.7	
Undulator length	100	m
Transverse gradient	33	m^{-1}
Dispersion	3.5	cm
Avg. beta in x	16	m
Avg. beta in y	75	m
Peak current	300	A
FEL wavelength	1.5	nm
FEL peak power	200	MW
FEL pulse energy	0.2	mJ
FEL repetition rate	10	kHz

Note here that the undulator is rotated 90 degrees compared with a horizontal undulator; hence the electron wiggles vertically. In this way, we can take advantage of an achievable small emittance in the vertical plane in the storage ring. As shown in Table 1, we set 1% coupling of the emittance between x and y, which makes a flat beam with the vertical size much smaller than the horizontal size. By introducing a vertical dispersion, we finally make an almost round beam inside the undulator, but the electron energy is correlated with the y dimension. No quadrupole is used in the TGU undulator section. In the vertical plane, the focusing due to the TGU undulator is so weak that its betatron wavelength is much longer than the total length of the undulator and therefore the dispersion is approximately a constant.

To evaluate FEL performace, the FEL simulation code Genesis [8] has been modified for the TGU purpose. The dispersed beam is prepared separately and imported into Genesis. The main undulator and beam parameters used in the simulations can be found in Table 2.

Figure 3 shows an example of the FEL power gain curve at 1.5 nm wavelength using a hybrid permanent magnet TGU undualtor. The FEL saturates before 100 m, with its power above 200 MW. This gives 0.2 mJ pulse energy assuming 1-ps pulse length. By using a superconducting undulator, which has the advantage of the combination of smaller period, larger magnetic field and higher transverse gradient, we expect to achieve a shorter saturation length at this wavelength or at an even shorter wavelength.

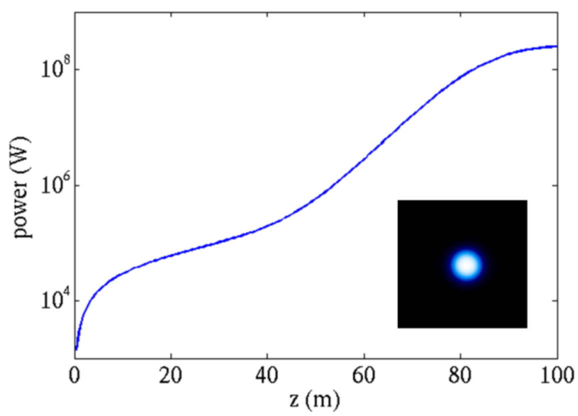

Figure 3: Simulated FEL power gain curve using a TGU. The FEL wavelength length is 1.5 nm in this example. A transversely coherent mode can be clearly seen at the end of undulator.

SUMMARY

We proposed a design of a diffraction limited storage ring light source, or "ultimate storage ring", that can be built in the PEP tunnel. The 4.5-GeV design achieves horizontal and vertical electron emittances that are at the diffraction limit for multi-keV X-rays. Secondly, based on the USR design, we presented a recent study of reducing the bunch length to 1ps using many superconducting RF cavities at a higher frequency. Finally, we introduced transverse gradient undulators and showed an application of FEL lasing in soft X-Ray region in a bypass with a repetition rate of 10 kHz.

Aside from the ultimate storage ring, the lasing scheme relies on SCRF and TGU technologies. For SCRF, we plan to improve the design of the cavities used for the CEBAF upgrades and further damp down the HOM in the cavities. Currently, we are considering to build a prototype of an improved cavity and to test it with electron beam in the SPEAR3 ring. Similarly, for TGU, we envision to design and build a prototype and then have a beam test at NLCTA.

Another important issue to be addressed is the low current limit of 10 mA, which is a serious drawback for other users of the USR. Obviously, a way to overcome it is to lower the HOM in the cavities and therefore to raise the threshold of the beam current.

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