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ABSTRACT

We explore the use of the 2.2-km PEP storage ring at SLAC to drive a 40-Å free-electron laser in the self-amplified spontaneous emission configuration. Various combinations of electron-beam and undulator parameters, as well as special undulator designs, are discussed. Saturation and high peak, in-band, coherent power (460 MW) are possible with a 67-m, hybrid permanent-magnet undulator in a ring bypass. A 100-m, cusp-field undulator can achieve high average, in-band, coherent power (0.25 W) in the main ring. The existing, 25.6-m, Paladin undulator at LLNL, with the addition of optical-klystron dispersive sections, is considered for both peak and average power.

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1. Introduction

The constraint \[1\] on the transverse emittance \( \epsilon_z \) of the electron beam in a free-electron laser of wavelength \( \lambda \),

\[ \epsilon_z \leq \lambda / (2\pi), \]

becomes severe at x-ray wavelengths. For 40 Å, \( \epsilon_z \) must be below 0.64 nm \cdot rad. However, emittances close to this value have already been produced in large-circumference, high-energy, electron-positron colliders such as PEP. We shall show that it is also possible to satisfy the other FEL requirements. To avoid the need for x-ray, optical-cavity mirrors, we shall consider self-amplified spontaneous emission (SASE), in which an electron bunch with low emittance and high peak current radiates coherently in a single pass through a long undulator.

2. Characteristics of PEP

PEP, a 16-GeV electron-positron storage ring at the Stanford Linear Accelerator Center, is sketched in Fig. 1. The six long straight sections (117 m each) in PEP’s 2.2-km circumference, the high energy, low emittance, large RF voltage (up to 40 MV, allowing a large radiated power), and low bending-magnet field (0.07 T at 3.5 GeV, resulting in a low emittance) offer great potential as a synchrotron radiation source \[2\] or an FEL driver.

Instead of the 14.5 GeV typically used in collider experiments, energies as low as \( E = 3 \text{ GeV} \) offer advantages for the FEL, since \( \epsilon_z \propto E^2 \) in a storage ring. Successful beam storage has been achieved at 4.5 GeV \[3\], but lower-energy operation has not yet been tried. Low-emittance optics \[2\] have been tested, giving \( \epsilon_z = 5.3 \text{ nm} \cdot \text{rad} \) \[4\] at 7.1 GeV (compared to 30 nm \cdot rad with colliding-beam optics). Scaling this value down to 3 GeV gives an emittance only a factor of 1.5 above the FEL requirement. Because the measured vertical emittance \( \epsilon_y \) was 4\% of the horizontal, \( \epsilon_z \) could be cut in half by coupling the two dimensions.

The fractional rms energy spread \( \sigma_e \) in a storage ring, determined by synchrotron-radiation losses in the bending magnets, is proportional to beam energy and so favors low energy for the FEL. With low-emittance optics in PEP (but without wigglers) \[5\],

\[ \sigma_e = 6.6 \cdot 10^{-5} \cdot E[\text{GeV}], \]
giving an energy spread of $2 \times 10^{-4}$ at 3 GeV.

Synchrotron radiation from a wiggler increases the beam’s energy spread and changes its emittance [6]. Damping wigglers, which are placed in low or zero dispersion locations, reduce emittance:

$$\frac{\sigma_{\varepsilon_0}^2}{\sigma_{\varepsilon}^2} = \frac{1 + \sqrt{2\pi^2N_w R_0^2 K_w^2}}{1 + \frac{\pi N_w R_0 K_w^2}{\lambda_w \gamma^2}},$$  \hspace{1cm} (3)

$$\frac{\varepsilon_{\varepsilon_0}}{\varepsilon_{\varepsilon}} = \frac{1}{1 + \frac{\pi N_w R_0 K_w^2}{\lambda_w \gamma^2}}.$$  \hspace{1cm} (4)

Here $K_w$ is the dimensionless wiggler parameter; $N_w = L_w/\lambda_w$ is the number of periods of length $\lambda_w$ in a wiggler of length $L_w$; $\gamma = E/(m_e c^2)$; and $R_0$, the beam’s radius of curvature in the ring’s dipoles, is 165.5 m for PEP. If several damping wigglers are distributed around the ring, then the effect is cumulative over their total length. However, an FEL wiggler in a bypass, with the beam switched in intermittently, will not contribute to the beam’s equilibrium energy spread and emittance. For sufficiently long damping wigglers, the change in energy spread saturates but the emittance will continue to decrease with $N_w$ (until the effect saturates due to a small dispersive term neglected in Eq. (4).)

FEL gain requires a high peak current $\hat{I}$. The current in a storage ring is limited by wake fields, which cause transverse and longitudinal instabilities [7-8]. By avoiding multiple-bunch instabilities, single-bunch operation gives a higher peak current, limited by the longitudinal microwave instability. Above the instability threshold, adding charge results in lengthening of the bunch, with no increase in $\hat{I}$ [7]. Transversely, there is a similar fast blow-up, but the threshold for the longitudinal instability in PEP will be reached long before the transverse. The instability growth rates are short compared with the period of synchrotron oscillation. To estimate this limit, we use the ZAP code [9], which incorporates an extrapolation of bunch-length measurements made on the SPEAR ring and scaled to fit PEP [10-11]. For PEP’s low-emittance mode and an energy of 3 GeV, the maximum peak current is 17.6 A, much too low for an FEL.

To increase $\hat{I}$, we considered compressing the circulating bunch over a half turn [5], only when the beam is to pass into a bypass containing an FEL, thereby avoiding bunch lengthening. However, the phase-space rotation that compresses the bunch longitudinally
and so increases the peak current, is accompanied by a proportionate increase in energy spread, which may reduce the FEL gain (see below). Any margin for extra energy spread would be put to better use by arranging an equilibrium state with a higher energy spread, since the peak-current limit scales with $\sigma_z^2$. Reasonable damping-wiggler parameters ($B_w = 1.26$ T, $\lambda_w = 12$ cm and $K_w = 14.1$; with $L_w = 9$ m at 3 GeV, and $L_w = 18$ m at 3.5 and 4 GeV) can increase $\sigma_z$ by a factor of three, increasing $\dot{I}$ by nine (instead of a factor of three using bunch compression). Furthermore, the increased $\dot{I}$ is available for an FEL in a bypass or in the main ring.

The radiation damping time and the beam lifetime are of concern at the very low energy necessary for the FEL. Lifetimes of over 30 hours have been observed in PEP at 8 GeV and low current with low-emittance optics [12]. Assuming that the beam lifetime is determined by Coulomb scattering, which scales with $\gamma^{-2}$, we expect lifetimes of more than 5.7 and 4.2 hours for 3.5 and 3 GeV, respectively. These lifetimes are sufficient for FEL operation. The radiation damping times for PEP at 3 GeV, without damping wiggles and in the low-emittance mode, are $\tau_z = \tau_y = 2\tau_x = 1.02$ s. The damping wiggles described above reduce this time to $\tau_z = 0.55$ s. At 3.5 and 4 GeV, with damping wiggles, $\tau_z = 0.23$ and 0.10 s respectively. In the high peak-power, saturated, FEL design presented below, the beam is switched into a ring bypass containing the FEL once every three horizontal damping times. These relatively long times reduce the average power.

### 3. FEL Designs for PEP

The considerations above, and the formulas [13-14] for the exponential gain parameter $\rho$, the power e-folding length $L_G$, and the undulator's saturation length $L_{sat} = 4\pi\sqrt{3}L_G$ in an SASE FEL, lead (without attempting full optimizations) to the examples in Table 1. In all cases, the gain parameter includes a correction for energy spread [15],

$$\frac{\rho_{eff}}{\rho} = \exp\left[-0.136\left(\frac{\sigma_z}{\rho}\right)^2\right]$$

in the calculation of $L_G = \lambda_u/(4\pi\sqrt{3}\rho_{eff})$. We use the damping wiggles described above and assume full coupling between horizontal and vertical emittance. The low beta values (with $\beta_z = \beta_y$) require periodic refocusing along the undulator. The wavelength has been
held near 40 Å, in the "water window" between the oxygen and carbon K edges (23 and 44 Å), to permit the study of organic compounds in solution, although tuning is possible about this wavelength by adjusting the beam energy or the undulator field.

(a) A Hybrid, Permanent-Magnet Undulator

The first example seeks to obtain high peak power by minimizing $L_{sat}$, in order to reach saturation in a distance less than the 117-m length of a PEP straight section. This objective, and the scaling of $I$ and $\sigma_r$ with $\gamma$, lead to a high-field, short-period undulator with a low beam energy. A conventional, neodymium-iron, hybrid undulator, with a period $\lambda_u = 4$ cm, an undulator gap $g = 1$ cm, and $B_u = (3.44 \text{T})\exp\left[-\frac{g}{\lambda_u}\left(5.08 - 1.54\frac{g}{\lambda_u}\right)\right]$ then gives a saturation length of 67 m.

The peak, in-band, coherent x-ray power, $P_{coh}$, is 460 MW. The perturbation of the beam parameters by the saturated FEL [16], as well as the reduction in the beam lifetime by the narrow undulator gap, require placing the FEL in a bypass to the main ring. The average coherent power, $\langle P_{coh} \rangle = 28$ mW, is calculated assuming that the bunch is switched into the bypass once every third transverse damping time $\tau_z$. These powers correspond to peak and average spectral brilliances of $7 \times 10^{29}$ and $4 \times 10^{19}$ photons s$^{-1}$ mm$^{-2}$ mrad$^{-2}$ (0.1% bandwidth)$^{-1}$ respectively.

The saturation length can be reduced by using an optical klystron (OK) configuration, formed by placing a dispersive section at one [17] or more [18] points along the undulator, separated by one or two gain lengths. Fig. 2 illustrates results from a 1D simulation code, including energy spread and emittance [17]. We see that the OK gives an extra factor of 2 in power at 67 m, or the original 460 MW at 56 m. Because of the slow increase in power near saturation, the OK gives 150 MW for a length of 40 m.

(b) A Cusp-Field Undulator

The second example obtains a high time-averaged coherent power $\langle P_{coh} \rangle$ of 0.25 W by placing a weak-field, long-period undulator [19-20] in the main ring with a 100% duty cycle. This goal favors a higher $\gamma$ and a moderate $K_u$. The undulator's 100-m length (near the available 117 m) is below $L_{sat} = 300$ m, giving an output close to Renieri's limit [16].
A cusp-field undulator [21], shown in Fig. 3, is an iron-free structure consisting of two axisymmetric arrays of circular coils with parallel axes and producing a helical field on the electron orbit, which runs parallel to the coil axes. The main features of a cusp-field device are 1) sparse copper coils, convenient for periodic refocusing; 2) a simply-configured helical structure; 3) a built-in provision for orbit deflection throughout; 4) high field quality with minimal gain loss or steering due to field errors; and 5) multiple configurations due to its modular structure. It is easily configured as an optical klystron with a variable number of dispersion sections. Preliminary calculations suggest that the first 50 m of the device in Table 1 could be replaced by a 4-m dispersive section after the first $L_G$.

(c) The Paladin Undulator

This section considers using a long, existing undulator, Paladin [22], which was used with the 50-MeV ATA inc. u. cion linac at the Lawrence Livermore National Laboratory. It is a DC, iron-core, electromagnetic undulator with a length of 25.6 m, made in five 5.12-m sections, and a period of 8 cm. Fields of up to 0.32 T on axis have been attained. Here we use a 0.3-T field, giving $K_u = 2.24$ and an energy of 3 GeV. The wavelength and gain are similar to the hybrid, but $L_G$ has gone up to 6.0 m due to the longer $\lambda_u$. A length of 131 m would be needed for saturation, as curve (a) of Fig. 4 shows. Refocusing quadrupoles in the breaks between the five sections are needed to obtain the lower $\beta_x$. The measured 0.15% rms field error [23] does not reduce FEL gain [24] but periodic steering, between sections or somewhat more frequently, is required [25]. Although too short to saturate, the four gain lengths are sufficient to demonstrate exponential growth at x-ray wavelengths. The 3-cm gap permits placing Paladin on the main ring without limiting beam lifetime.

Substantial improvement is possible using an optical klystron, formed by placing dispersive sections in breaks between the Paladin sections, which are approximately one gain length apart. Fig. 4 shows the simulation results, and Table 1 gives the values for curve (c) at the true 25.6-m length. The peak power increases by over three orders of magnitude due to the optical klystron, but is still over two orders short of saturation.
The average power is restricted by Renieri's limit [16] for the case of an SASE FEL in the high-gain regime. For an approximate lower bound to this limit, we use the time-average value of one fully saturated FEL pulse every three damping times:

\[
\langle P_{\text{coh}} \rangle_{\text{max}} = \rho_{\text{eff}} \hat{I} [\text{A}] E [\text{eV}] \frac{\sqrt{2} \pi \sigma_s}{3c\tau_z}. \tag{6}
\]

For Paladin parameters, this gives 4.4 mW, slightly above the 3.3-mW time-average power calculated for Paladin in the main ring, with a 100% duty cycle, and without the OK configuration. For peak power, the Paladin OK could be in a bypass. Because Paladin is too short to saturate even with an OK, the beam could circulate through the undulator for 260 consecutive passes before damping. Alternatively, it could be in the main ring with the dispersive sections pulsed on every 3\(\tau_z\), avoiding the need for a bypass.

4. Applications

PEP's size and low emittance make it attractive for new classes of insertion devices [26] [19] and for various techniques to modulate the temporal [5] and spectral-angular structures of the electron and photon beams [27]. The resulting coherent x-rays would have novel applications. The high levels of coherent and flexibly tunable polarized light from a cusp-field undulator (or other designs [28-29]) are important in, for example, magnetic scattering experiments, whose cross sections are typically several orders of magnitude below those of electric-dipole scattering [30-31]. X-ray lithography could make significant use of coherence effects for imprinting ultra-small features [32], and for rastering the beam to produce exceptionally uniform radiation fields [19,29]. The short, extremely intense pulses from the devices described in this paper could be used for single-shot ("flash") imaging of biological samples in the water window [33], providing a possible solution to the damage problem [34] associated with x-ray imaging, while the high levels of time-averaged coherent power could generate high-quality holograms of both biological and inorganic samples [35].

References


8. B. Zotter and F. Sacherer, “Transverse Instabilities of Relativistic Particle Beams in Accelerators and Storage Rings,” ibid., 175.


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<th>Parameter</th>
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**Table 1:** Parameters for possible FELs on PEP. Column 1 describes a hybrid permanent-magnet undulator, located in a bypass and used for high peak power once every $3\tau_z$. The cusp-field undulator in column 2 is helical; the effective $K_u$ is shown. In the main ring, this device could provide high average power using a 100% duty cycle. The Paladin undulator is in column 3. Values in parentheses are for an optical-klystron configuration. For comparison, the in-band, spontaneous, coherent power is listed for a spectral bandwidth of $\lambda_u/(2L_u)$ and a photon opening angle of $\frac{1}{2}\sqrt{\lambda/L_u}$, assuming a 100% duty cycle and complete suppression of SASE. Single-bunch operation of PEP is assumed for all examples. *The number of coherent photons per pulse $N_{\text{coh}}$ is in units of photons $\cdot$ pulse$^{-1} \cdot$ (0.1% bandwidth)$^{-1}$. 
Figure Captions

1. The PEP storage ring, showing the six 117-m straight sections and the electron and positron injection beamlines from the SLAC linac. The SPEAR ring and its new 3-GeV injector (upgradable to 5 GeV) are also shown. The dashed line indicates a possible 5-GeV injection beamline for PEP.

2. Power emitted as the beam passes through the permanent-magnet hybrid undulator. (a) Without OK. (b) With one 1-m dispersion section ($B = 1$ T for 25 cm, $-1$ T for 50 cm, 1 T for 25 cm) at $z = 0.1L_{sat}$. (c) With a 1-m dispersion section at $0.1L_{sat}$, and a 0.5-m dispersion section at $0.2L_{sat}$.

3. A helical cusp-field undulator, consisting of two sets of coils displaced by $1/4$ period and oriented to provide orthogonal fields.

4. Power emitted as the beam passes through the Paladin undulator. The vertical line marks Paladin’s true length, which has been extended here to the saturation length. (a) Without OK. (b) With one 1-m dispersion section ($B = 1$ T for 25 cm, $-1$ T for 50 cm, 1 T for 25 cm) in the first break between undulator sections. (c) With a 1-m dispersion section in the first break, and a 0.25-m dispersion section in the second break.