

# Coherent X-Rays from PEP\*

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## Abstract

This paper explores the use of a large-circumference, high-energy, electron-positron collider such as PEP to drive a free-electron laser (FEL), producing high levels of coherent power at short wavelengths. We consider Self-Amplified Spontaneous Emission (SASE), in which electron bunches with low emittance, high peak current and small energy spread radiate coherently in a single pass through a long undulator. As the electron beam passes down the undulator, its interaction with the increasingly intense spontaneous radiation causes a bunch density modulation at the optical wavelength, resulting in stimulated emission and exponential growth of coherent power in a single pass. The need for optical-cavity mirrors, which place a lower limit on the wavelength of a conventional FEL oscillator, is avoided.

We explore various combinations of electron-beam and undulator parameters, as well as special undulator designs and optical klystrons (OK), to reach high average or peak coherent power at wavelengths around 40 Å by achieving significant exponential gain or full saturation. Examples are presented for devices that achieve high peak coherent power (up to about 400 MW) with lower average coherent power (about 20 mW) and other devices which produce a few watts of average coherent power.

## I. INTRODUCTION

The relevant features of PEP are the long straight sections (117 m) in its 2.2-km circumference, the large RF voltage (up to 40 MV), and the low bending-magnet field (0.07 T at 3.5 GeV). The electron-beam emittance required for an FEL is given by  $\epsilon_x \leq \lambda / (2\pi)$ . At 40 Å, the requirement of 0.64 nm-rad can be reached by operating PEP at 3 — 4 GeV, a fraction of its 16-GeV maximum energy, with low-emittance optics, and with extra emittance reduction from damping wigglers and/or the long FEL undulator itself. Radiation produced by damping wigglers and the FEL undulator reduces the damping time, facilitating operation of PEP at low energy.

## II. CHARACTERISTICS OF PEP

Instead of the 14.5 GeV typically used in collider experiments, the FEL requires energies as low as 3 GeV, taking advantage of the fact that the transverse emittance scales quadratically with energy in a storage ring. Successful beam storage has been achieved at 4.5 GeV [1], but lower-energy operation has not yet been tried. Low-emittance optics [2] have been tested, giving  $\epsilon_x = 5.3$  nm·rad [3] at 7.1 GeV (compared to 30 nm·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. The measured vertical emittance was 4% of the horizontal. Thus the horizontal emittance

could be cut in half by coupling the two dimensions. The fractional rms energy spread  $\sigma_\epsilon$  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. Without damping wigglers [4],  $\sigma_\epsilon = 6.6 \cdot 10^{-5} \cdot E$  [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 [5]. Damping wigglers, in low or zero dispersion locations, reduce emittance but increase energy spread.

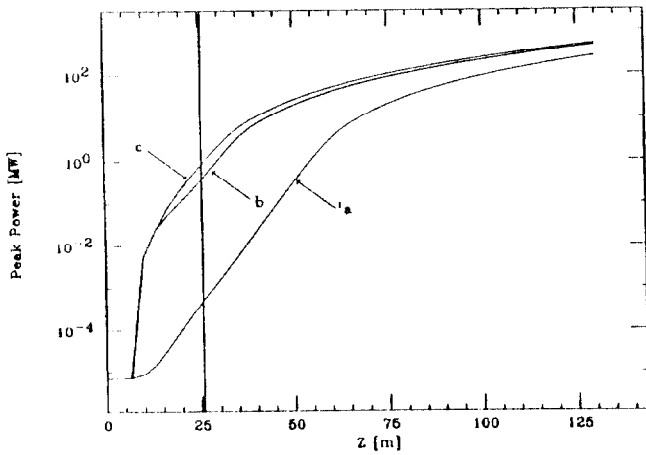
FEL gain requires a high peak current,  $I_p$ . The peak single-bunch current in a storage ring is limited by the microwave instability. Adding charge results in lengthening of the bunch, with no increase in  $I_p$ . Transversely, there is a similar fast blow-up. The instability growth rates are short compared with the period of synchrotron oscillation. The threshold for the longitudinal instability in PEP will be reached long before the transverse. To estimate this limit, we use the ZAP code [6] and an extrapolation of bunch-length measurements made on the SPEAR ring and scaled to fit PEP data [7-8]. For PEP's low-emittance mode and an energy of 3 GeV, this gives a maximum peak current of 17.6 A.

To increase this peak current, we considered compressing the circulating bunch over a half turn [2,4], in order to reach a high peak current only when the beam passes through the FEL, thereby avoiding bunch-lengthening instabilities. However, the phase-space rotation that compresses the bunch longitudinally and so increases the peak current, is accompanied by an increase in energy spread by the same factor. If the FEL gain is not close to the energy-spread limit (see below), then the half-turn compression would be helpful. However, this tolerance 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  $\sigma_\epsilon^2$ . Reasonable damping-wiggler parameters ( $B_w = 1.26$  T,  $\lambda_w = 12$  cm,  $K = 14.1$ , and  $L_w = 9$  m at 3 GeV, or  $L_w = 18$  m at 3.5 and 4 GeV) can increase the energy spread by a factor of three, increasing the peak current attainable by nine. For the same increase in energy spread, bunch compression would gain only a factor of three in peak current.

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 [9]. Assuming that the beam lifetime is determined by Coulomb scattering, which scales with the inverse square of the beam energy, 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 wigglers and in the low emittance mode, are  $\tau_{x,y} = 1.02$  s and  $\tau_s = 0.51$  s. With the damping

**Table 1:** Parameters for various FEL's on PEP. Lines 1-4 describe conventional permanent-magnet undulators, located in a bypass and used once every  $3\tau_x$ . A 100% duty cycle is assumed in lines 5-7 (but see text for line 6). The Paladin undulator is in lines 5 and 6, without and with an optical klystron configuration, respectively. The cusp-field undulator in line 7 is helical; the effective K is shown. Single-bunch operation of all undulators is assumed.

$E$ GeV	$\lambda$ Å	$\lambda_u$ cm	$g$ cm	$B_u$ T	$K$	$\epsilon_z$ Å-rad	$\beta_x$ m	$z_R$ m	$\sigma_\epsilon$ $10^{-4}$	$I_p$ A	$\rho$ $10^{-4}$	$\rho_{\text{eff}}$ $10^{-4}$	$L_G$ m	$L_u$ m	$\tau_x$ ms	$\sigma_s$ mm	$P_p^{\text{coh}}$ MW	$P_{\text{av}}^{\text{coh}}$ mW	$P_p^{\text{spon}}$ MW	$P_{\text{av}}^{\text{spon}}$ mW
3.0	35.8	3.70	1.0	0.98	3.37	1.96	8.5	5.8	6.3	144	7.0	4.1	4.1	89	550	3.3	180	4	70	1.2
3.5	37.9	4.00	1.0	1.06	3.97	2.05	5.5	3.7	7.2	219	9.1	6.0	3.1	67	230	4.2	460	28	130	5.1
3.0	36.2	2.85	0.5	1.48	3.94	1.96	8.0	5.5	6.3	144	6.6	3.7	3.6	77	550	3.3	160	3	140	2.3
3.5	37.8	3.10	0.5	1.58	4.57	2.05	5.0	3.4	7.2	219	8.7	5.5	2.6	57	230	4.2	420	26	240	9.7
3.0	40.7	8.00	3.0	0.30	2.24	1.96	9.1	6.2	6.3	144	8.7	6.1	6.0	25.6	550	3.3	879W	3.3	1.9	7.1W
3.0	40.7	8.00	3.0	0.30	2.24	1.96	9.1	6.2	6.3	144	8.7	6.1	N/A	25.6	550	3.3	1.0	3.7W	6.8	26W
4.0	37.9	27.0	N/A	0.034	1.2	2.71	15.0	13.5	7.4	327	11.8	9.0	13.9	100	100	5.1	0.043	250	1.5	3.5W



**Figure 1:** 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.

wigglers described above, they are reduced to  $\tau_{x,y} = 0.55$  s and  $\tau_s = 0.23$  s.

### III. FEL DESIGNS FOR PEP

#### A. Conventional Permanent Magnet Undulators

These considerations, and the formulas [10-12] for the exponential gain parameter  $\rho$ , the power e-folding length  $L_G = \lambda_u / (4\pi\sqrt{3}\rho)$ , and the undulator length for saturation of  $L_{\text{sat}} = \lambda_u / \rho$  in an SASE FEL, lead (without attempting a full optimization) to the first four examples in Table 1. In all cases, the wavelength has been held near 37 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.

The first four examples use neodymium-iron hybrid undulators with  $B_u$  [T] =  $3.44 \exp[-(g/\lambda_u)(5.08 - 1.54g/\lambda_u)]$ , periods of 2.85 to 4 cm, and saturation lengths of 57 to 89 m. The undulator lengths  $L_{\text{sat}}$  and  $L_G$  were calculated using  $\rho_{\text{eff}}$ ,

which includes the correction for energy spread [13],

$$\frac{\rho_{\text{eff}}}{\rho} = \frac{\exp[-0.136(\sigma_\epsilon/\rho)^2]}{1 + 0.64(\sigma_\epsilon/\rho)^2}. \quad (1)$$

We use the damping wigglers described above and assume full coupling between horizontal and vertical emittance. The lower beta values (with  $\beta_x = \beta_y$ ) will require periodic refocusing along the undulator.

The peak coherent x-ray power,  $P_p^{\text{coh}}$ , ranges from 160 to 460 MW. Perturbation of the beam parameters by the saturated FEL [14], as well as the reduction in beam lifetime by the narrow undulator gap, require placing these FEL's in a bypass to the main ring. The average coherent power,  $P_{\text{av}}^{\text{coh}}$ , is calculated assuming that the bunch is switched into the bypass once every three transverse damping times  $\tau_x$ . The 460 MW case has a peak and average spectral brilliance of  $4 \times 10^{29}$  and  $2.3 \times 10^{19}$  photons  $\cdot$  s $^{-1}$   $\cdot$  mm $^{-2}$   $\cdot$  mrad $^{-2}$   $\cdot$  (0.1%bandwidth) $^{-1}$  respectively. Total peak and average spontaneous powers are also given in Table 1. Comparisons of these with the coherent power should take their significantly larger bandwidths ( $\approx 100\%$ ) and opening angles ( $1/\gamma$ ) into account. To indicate how in-band levels of spontaneous coherent power would compare to the amplified levels listed in the table, calculations for the first four devices (assuming a 100% duty cycle and complete suppression of SASE) yield 140, 100, 141, 107 W peak, and 0.52, 0.5, 0.52, 0.51 mW average, respectively. These figures are for a spectral bandwidth of  $\lambda_u/2L_u$  and an opening angle of  $\approx \frac{1}{2}\sqrt{\lambda/L_u}$ .

#### B. The Paladin Undulator with an Optical Klystron

The long undulators discussed above would be expensive and difficult to build. Here we consider using a long, existing undulator. The Paladin undulator [15] was used at the Lawrence Livermore National Laboratory for FEL experiments with the 50-MeV ATA induction linac. It is a DC iron-core electromagnetic undulator with a length  $L_u$  of 25.6 m, made in five 5.12-m sections, and a period  $\lambda_u$  of 8 cm. Fields  $B_u$  of up to 0.32 T have been attained. Here we use a 0.3-T field, giving a  $K$  of 2.24. The fifth line of Table 1 shows the result, using the same 3-GeV parameters as before. The wavelength,  $\lambda = 40.7$  Å, and gain,  $\rho = 8.7 \times 10^{-4}$ , are similar to the previous cases, but the power gain length has gone up to 6.0 m due to the longer undulator period. A length of 131 m would be needed for saturation, as curve (a) of Fig. 1 shows. Refocusing quadrupoles in the breaks

between the five sections are needed to obtain the lower  $\beta_x$ . Although too short to saturate, the existing four gain lengths are sufficient to demonstrate exponential growth at x-ray wavelengths. Because Paladin's gap is 3 cm, it could be placed on the main PEP ring, rather than a bypass, without limiting beam lifetime.

An optical klystron (OK), formed by placing dispersive sections in one [16] or more [17] of the breaks between the Paladin sections, can improve substantially on this result. The calculations of Table 1 use a 1D simulation code, including energy spread and emittance [16], to find the increase in output power obtained by inserting dispersive sections in the first one or two section breaks, which are approximately one gain length apart (see Fig. 1). Line 6 of 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 impressive, with the assumption of a 100% duty cycle (undulator in the main ring); this exceeds the Renieri limit [14], and further work will be required to find optimal dispersion parameters for average power. For maximum peak power, the dispersive section can be pulsed on, avoiding the need for a bypass.

The second dispersive section brings the FEL to saturation slightly more quickly, but contributes only a factor of 2 in the 25.6-m length of the actual device. The increasing energy modulation of the beam as it travels requires less dispersion in successive sections. The parameters are not fully optimized, but demonstrate decreasing benefit from successive dispersion sections. Longer sections or a third section would overbunch and decrease the output.

### C. The Cusp-Field Undulator

Several alternative approaches to insertion device design for PEP based on weak-field, long-period undulators have been introduced in recent years [18-19]. These focus on the maximization of time-averaged (as opposed to peak) coherent power through a single-pass device. A "Cusp-Field" undulator [20-21] of this class has been explored by one of us (R.T.). It is an iron-free structure consisting of two axisymmetric arrays of circular coils with displaced parallel axes 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) a sparse copper coil construction, whose long period facilitates the use of refocusing elements along its length; 2) a simply-configured helical structure; and 3) a built-in provision for orbit deflection along the entire undulator length, allowing continuous control of coherence gain, including switching in and out of the FEL mode in one orbital period. It is expected that the field quality of this structure should be very high, and that its versatile selection of field configurations will enable a wide range of x-ray research, including systematic studies of coherence growth and modulation in particle beams, to be performed.

A cusp-field device appears suitable for use as an unsaturated SASE undulator (see last line of Table 1). The power gain  $g$  for the indicated 100m may be calculated with the formula [22]  $g \approx 0.11 \exp(\lambda_u/L_g)$ . For the parameters shown, the length required for full saturation would be 300 m, corresponding to a peak coherent power of 1.2 GW. Note the

rather high value of average coherent power, due to the 100 % duty cycle in a steady state mode. At the listed levels of peak coherent output power, the perturbation of PEP's beam is estimated to be still negligible, whereas operation at levels an order of magnitude higher would begin reducing the coherent power gain due to increasing beam energy spread. The calculations done here followed those of Renieri [14].

Due to its modular structure, the cusp-field undulator is particularly suited for being configured as an optical klystron with a flexible number of modulation/dispersion sections. This would permit the systematic study of OK configurations ranging from a minimum of one dispersion section to the recently-proposed "distributed-OK" structure [17]. Calculations based on the parameters in Table 1 [16] indicate that the first 50 meters of the device could be replaced by one 14 meter gain length + 4 meters of dispersion, and that two or more such sections would enable gain saturation to be attained in less than 100 m. For equal numbers of gain lengths in the OK mode, the net power gain attained by the cusp-field device would be about twice as much as Paladin's (see Fig. 1), based on the ratio of their operating peak currents, energies, and effective gain parameters  $\rho_{eff}$ .

## IV. REFERENCES

1. M. Donald et al., LEP Note 553 (1986).
2. A Bienenstock, G. Brown, H. Wiedemann, and H. Winick, *Rev. Sci. Instr.* **60**, 1393 (1989).
3. M. Borland and M. Donald, *Proc. IEEE Part. Acc. Conf.*, Chicago, IL, March 1989.
4. A. Hofmann, SSRL ACD Note 39, Nov. 1986.
5. H. Wiedemann, *NMI A266*, 24 (1988).
6. M.S. Zisman, S. Chattopadhyay, and J.J. Bisognano, "ZAP User's Manual," LBL 21270, 1986.
7. A. Chao and J. Gareyte, *SPEAR 197*, PEP 224 (1976).
8. M. Month, *SPEAR 198*, PEP 227 (1976).
9. G. Brown et al., *Proc. 1987 IEEE Part. Accel. Conf.*, **461-663**, (1987).
10. C. Pellegrini, *NMI A272*, 364 (1988).
11. J. Bisognano et al., *Part. Acc.* **18**, 223 (1986).
12. M. Cornacchia et al., *Nucl. Instrum. Methods A250*, 57 (1986).
13. G. Dattoli et al., *Nuovo Cimento 11D*, 393 (1989).
14. A. Renieri, *IEEE Trans. Nucl. Sci.* **26(3)**, 3827 (1979).
15. G.A. Deis et al., *Proc. 10th Int. Conf. Magnet Technology*, Boston, MA, Sept. 1987.
16. J. Gallardo, C. Pellegrini, *Optics Commun.* **77**, 45 (1990).
17. V. N. Litvinenko, INP, submitted.
18. R. Tatchyn, *Proc. Workshop on PEP as an SR Source*, SSRL, 10/21-21/87, 97-113.
19. R. Coisson, *Rev. Sci. Instr.* **60(7)**, 1426(1989).
20. T. Cremer and R. Tatchyn, unpublished.
21. R. Tatchyn, T. Cremer, P. Csonka, *SR-90 Synchrotron Radiation Conference*, Moscow, (1990).
22. A. Jackson et al., *SPIE Proceedings 582*, 131(1985).

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