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A Proposal for Femtosecond X-ray Generation in the SLC Collider Arcs*

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Abstract

The high-energy electron beam from the SLAC linac, in conjunction with the bunch compression of the existing SLC collider arcs, provides the opportunity for an extremely short pulse spontaneous emission x-ray source with high brightness. Experiments at the SLC have already demonstrated peak currents of 10 kA at 46 GeV [i]. The addition of a relatively simple undulator in the 'reverse-bend' section of the north arc can generate x-ray radiation of wavelength <1 Å with peak brightness higher than any existing source. This could be used for testing x-ray diagnostics and to gain experience with short pulse x-ray experiments as a precursor to high brightness experiments with the Linac Coherent Light Source (LCLS). In addition, experiments with a short electron bunch, relevant to the LCLS and the Next Linear Collider (NLC) projects, might be carried out.

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Introduction

In 1998, measurements [i] in the SLC north collider arc, confirmed that peak currents of nearly 10kA, and bunch lengths less than 50 μm rms are possible. This 50-GeV electron beam could be used to produce an extremely short pulse spontaneous emission x-ray source with good brightness. Possible applications are in testing x-ray diagnostics and to gain experience with short pulse x-ray experiments as a precursor to high brightness experiments with the LCLS. The addition of a simple undulator and extraction optics to this existing beamline is expected to be of relatively low cost. In addition, the availability of very short pulse electron beams may be useful for LCLS and NLC related wakefield and diagnostics experiments.

1 The Existing Beamline

The experiments of reference [i] have demonstrated the availability of a high charge, short electron bunch in the 'reverse-bend' section of the north collider arc of the Stanford Linear Collider (SLC). The north (or electron) arc is 1.2 km in length with a 280-meter bend radius and is depicted in the SLC-layout of Fig. 1.

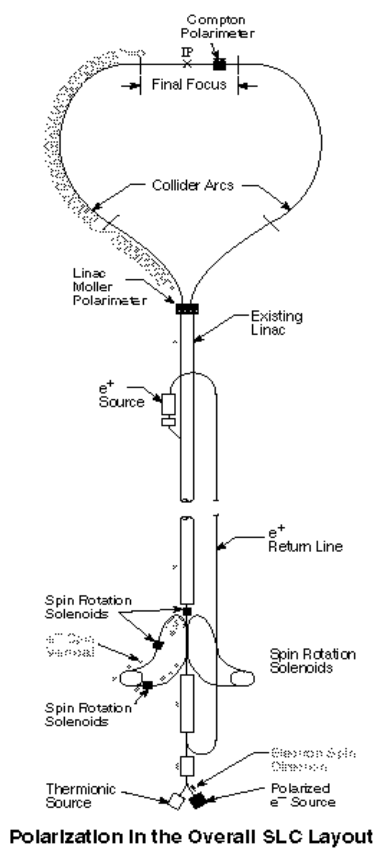

Fig. 1. SLC layout with collider arcs at top. The reverse-bend section of the north arc is at the inflection point of the left-side arc, near the "Collider Arcs" left-indicating arrow.

The reverse-bend section is at the one-third point in the arc, spans about 40 meters, and includes some electron beam optics, which might be modified to include an undulator. The existing magnet configuration in the reverse-bend provides a 5.5-meter long dispersion free space. An undulator might be added here with beam separation optics installed downstream. Alternately, the beamline might be rearranged using additional magnets (probably readily available from other unused SLC systems) to provide space for a 10-20-meter long undulator, which could produce substantially higher brightness x-rays. The straight-ahead x-rays could be used for testing on a small table mounted next to the beamline in the tunnel. The modified beamline could also include space for micro-bunch diagnostics and for wakefield experiments.

2 The Electron Beam

The nominal SLC electron energy in the reverse-bend is $E_e \approx 46$ GeV with $N_e \approx 4\times10^{10}$ electrons in a single bunch (6.4 nC). We assume that the arc can be adjusted for operation between 20 and 50 GeV, although 42 GeV is the lowest energy that has been tested to date. The damped rms normalized emittance typical in SLC round-beam operations is $ge_{x,y} \approx 30$ mm-mrad (or $e_{x,y} \approx 0.33$ nm at 46 GeV). It is also possible to run in a flat-beam mode with $ge_x \approx 50$ mm-mrad and $ge_y \approx 10$ mm-mrad. To be conservative here, and to allow for the unusually high energy spread in the arc (SLC $\times3$) necessary for compression, we will assume round beam emittances of $ge_{x,y} \approx 50$ mm-mrad.

As demonstrated experimentally in reference [i], by chirping the 0.8-mm rms electron bunch length in the SLAC linac with 0.6 % rms correlated energy spread, the arc will compress the bunch to 50 *m*m rms or less (180 fsec) at the reverse-bend location. Further calculations suggest that this compression can approach 20 *m*m rms (70 fsec) in the beam core. Fig. 2 shows particle tracking of the longitudinal phase space coordinates to the reverse-bend, including linac wakefields, arc compression to second order, and the incoherent energy spread generated in the arc by synchrotron radiation.

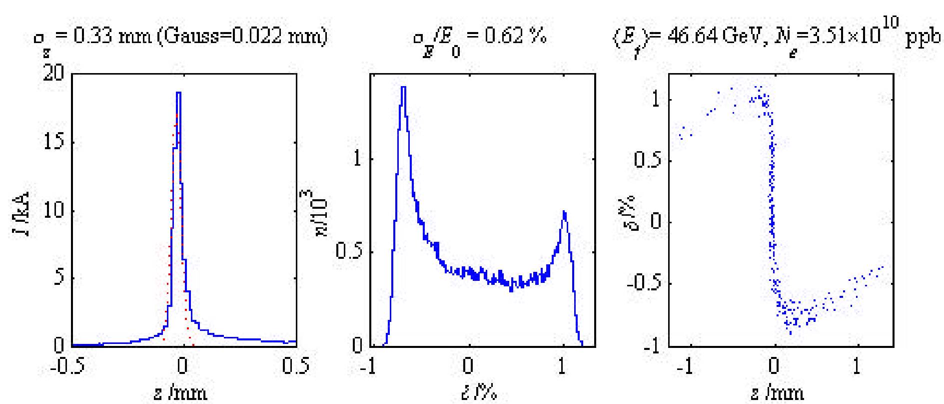

Fig. 2. Tracking of longitudinal phase space up to the reverse-bend. The bunch population is 3.5×10^{10}, the bunch length is 22 *m*m rms (gaussian fit) and the rms energy spread is 0.6 % at 46 GeV.

With a 280-meter bend radius, the effects of coherent synchrotron radiation in the arc should be well shielded by the 1-cm ID aluminum vacuum chamber for bunch lengths as small as 25 μm rms. Note, however, that no experimental confirmation of the electron beam emittance was done *simultaneously* with the experiments of reference [i].

3 Alternate Location

The undulator could also be installed in the existing Final Focus Test Beam (FFTB) tunnel, where the proposed LCLS undulator will reside. The advantages of this location are that it is more suitable for experimental work, and might integrate well with the development of experimental areas for the LCLS. The very short bunches, however, have not yet been demonstrated in the FFTB. The system would either need to run with the SLC-standard 0.8-mm bunch length, or possibly a complex bunch compression system would need to be added upstream. Such a compressor system would only be compatible with the LCLS if the RF photo-injector, with its small longitudinal emittance, were also installed. This becomes a large-scale installation. With its long and gentle bending, there is no better-suited high-energy electron compressor than the existing arc.

4 Radiation Wavelength

In the following, we design for an x-ray energy range of 6.5-40 keV (or 2-0.3 Å for 20-50 GeV electrons). This covers a region of interest for x-ray experiments, and is readily attainable with reasonable undulator parameters. Depending on the design chosen, roughly 10^{10} x-ray photons should be available, with $>10^7$ in a 0.1 % bandwidth (BW) delivered in a 180 fsec rms pulse (see Table 2 below). The overall peak brightness is of the order 10^{24} photons/s/mm^2/mrad^2/0.1% BW. Specific cases are outlined in Table 2.

5 Undulator

For purposes of illustration, we outline a very conservative, low cost undulator design, which might easily fit into the available space. The low field (<300 Gauss) requirement of a long period undulator makes a helical electromagnet reasonable. One design option is to use two pairs of approximately 1-cm diameter conductor wrapped around a 1-cm pipe to produce an undulator with period l = 40 cm and K = 1. The undulator parameter, K, is related to its period and field [ii] by

$$K \approx 93.4 \cdot B[\mathrm{T}] \cdot l[\mathrm{m}] \ , \qquad (1)$$

and the photon energy, E_p, in terms of the electron energy, E_e, is given by

$$E_p[eV] \approx 9.50 \frac{E_e[\mathrm{G}eV]^2}{l[\mathrm{m}]\left(1+K^2/2\right)} \ . \qquad (2)$$

The magnetic field on axis for a bifilar helical undulator is given by [iii]

$$B = 2m_0 \frac{I}{l}\left[p \frac{d}{l} K_0\left(p \frac{d}{l}\right) + K_1\left(p \frac{d}{l}\right)\right] , \quad (3)$$

where d is the diameter of the helix, K_0 and K_1 are modified Bessel functions and I is the conductor current. Since we are using two bifilar windings, we must take into account the angle between the windings, which reduces the field to 0.84 times the single bifilar winding field at the same total current. The conductor size is chosen based on its current rating. An operating current of 500 A per conductor is within the rating of a 4/0 cable. Table 1 lists some possible undulator parameters.

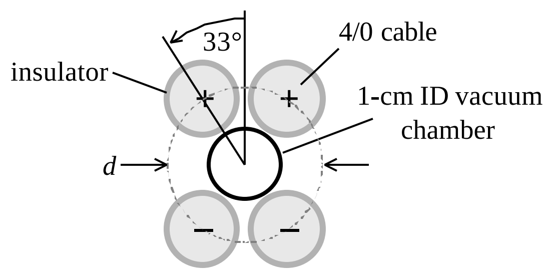

Fig. 3. Cross-section of simple, helical undulator.

Table 1. Possible undulator parameters for a long-period, helical electromagnet with no iron.

Parameter	symbol	value	unit
Undulator period	l	40	cm
Undulator length	L	5-20	m
Number of undulator periods	N_p	12-50	
Undulator parameter	K	1	
Photon energy at 50 GeV (maximum)	E_{p1}	39.5	keV
Photon energy at 46 GeV (nominal SLC)	E_{p2}	33.5	keV
Photon energy at 28 GeV (B-Factory compatible)	E_{p3}	12.4	keV
Photon energy at 20 GeV (estimated minimum)	E_{p4}	6.3	keV
Undulator beam pipe inner diameter		1	cm
Conductor circle diameter (includes insulation)	d	2.6	cm
Magnetic field on axis	B	270	Gauss
Conductor current (each)	I	500	A
Number of windings per direction		2	
Cable conductor diameter		11.68	mm
Cable insulation (PFA)		1.14	mm
Cable current rating (air, 40° C ambient)		630	A
Undulator power dissipation per meter		160	W/m

6 Background Radiation

The arc bends are considerably stronger than the undulator and will produce significant synchrotron radiation. The energy loss per particle in the arcs corresponds to 1.4 GeV over the net 270°-bend angle at 50 GeV. In a 1/*g* angle, this corresponds to 3 keV per electron. This is similar to the energy loss in the undulator. The critical energy in the arc is approximately 1 MeV. This energy is sufficiently higher than the undulator radiation that it should easily be filtered with a glancing incidence mirror. At lower electron energies, the critical energy and the total synchrotron power decrease.

7 Beam Separation

The x-ray beam must be separated from the high-energy electron beam through some as yet undetermined beamline modification. The floor coordinates of the reverse-bend beamline are shown in Fig. 4. Design work is underway to increase the orientation angle and available space for the undulator in order that the photon beam clears the downstream arc magnets, which are 15 cm wide. The existing orientation will only provide 4.5 cm which would direct the photon beam into the face of the next arc magnet (at *s* = 40 m in the figure). The electron beam might then be transferred through the remaining arc to an existing 10-Hz limited beam dump, or all the way through the SLC collider hall to the nominal 120-Hz dump. The DC power supply of the arc requires ~1 MW at 46 GeV.

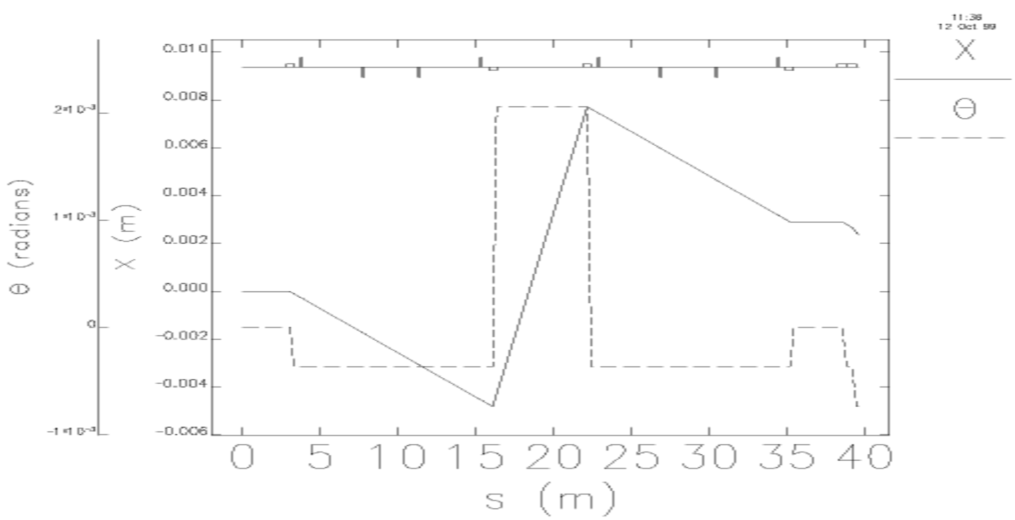

Fig. 4. Floor coordinates (solid) and beamline angle (dash) of the existing reverse-bend section. Quadrupole and dipole magnets are indicated at top. The undulator location is centered between the two center dipoles (small boxes). The 2-mrad central angle needs to be increased to ~8 mrad.

8 Brightness

This source should have a peak brightness comparable to, or higher than any existing x-ray source, and with a pulse length of a few-hundred femtoseconds. Based on the LCLS Design Study Report [iv], the highest peak brightness sources in this wavelength range are the ESRF and the APS with <10^{24} photons/s/mm^2/mrad^2/0.1% BW. The *average* brightness for the SLC-based source will, however, be very low due to the low repetition rate (10-120 Hz).

The mean energy loss of an electron in a planar undulator of length *L*, is

$$\Delta E[eV] \approx 0.0726 \cdot E_e[\mathrm{Ge}V]^2 \cdot K^2 \frac{L[\mathrm{m}]}{l[\mathrm{m}]^2} \ , \tag{4}$$

with twice this loss generated in a helical undulator. For an undulator with $K = 1$, the fraction of energy in the fundamental mode is ~60 % [ii]. With the photon energy given in Eq. (2), it is apparent that the number of photons produced is independent of beam energy, linear in undulator length and inversely proportional to undulator period.

The photons are emitted in an opening angle cone of $1/g$. With N_p undulator periods, the number of photons within the $1/N_p$-bandwidth is in an opening angle of [ii]

$$q_u = \frac{1}{g}\sqrt{\frac{1+K^2/2}{2N_p}} \ . \tag{5}$$

The total photon flux per bandwidth, $\Delta w/w$, in this cone is

$$N_w \approx 2\times 1.43\cdot 10^{17} \cdot I_{pk}[A] N_p \frac{\Delta w}{w} \frac{K^2}{1+K^2/2}[J_0(x) - J_1(x)]^2 \ , \tag{6}$$

with $x \equiv K^2/(4 + 2K^2)$. The leading factor of two in Eq. (6) is for a helical undulator, J_0 and J_1 are Bessel functions and I_{pk} is the peak electron current. This flux is independent of electron energy and, for a fixed period, is linear in undulator length.

When the effects of the electron beam emittance are included, the opening angle of the x-ray radiation increases to

$$q_x = \sqrt{q_u^2 + \left(\frac{e_N}{g R_b}\right)^2} \ , \tag{7}$$

where e_N is the normalized rms electron beam emittance, and $R_b = (ße_N/?)^{1/2}$ is its rms transverse size. The effective source size of the x-ray radiation is

$$R_x = \sqrt{R_b^2 + \frac{l_r}{4p q_u}} \ , \tag{8}$$

where l_r is the radiation wavelength, and the second term is the diffraction limit (small for our conditions).

The total peak brightness is then

$$B_{pk} = \frac{N_w}{4p^2 q_x^2 R_x^2} \ , \tag{9}$$

with $4p$ converting rms to area. The output brightness is a fairly weak function of electron beam size, for reasonable beam sizes, as shown in Fig. 5, where peak brightness is plotted against the beta function of the electron beam for a 46-GeV beam, 5-meter undulator and e_N = 50 mm-mrad. Table 2 lists some x-ray beam parameters for various undulator lengths, where a mean beta function of 50 m is used (reverse-bend nominal).

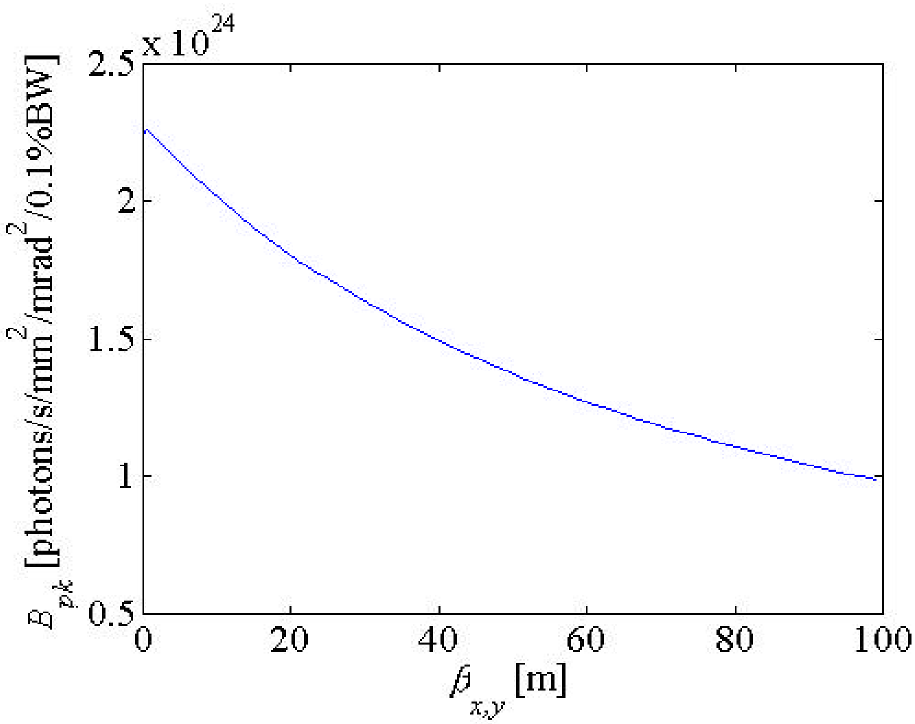

Fig. 5. Peak brightness as a function of the mean beta function of the electron beam ($b_x = b_y$).

If the undulator is installed in the FFTB tunnel with no bunch compression, the pulse length increases by a factor of ten and the brightness decreases by a factor of ten. All other parameters remain unchanged. If the optimistic arc compression is used, with 25-*m*m rms bunch length, the pulse length becomes 80 fsec and the brightness increases by a factor of two.

Table 2. X-ray parameters for a 5-, 10- and 20-meter long undulator with $K = 1$, and ? = 40 cm, and an e^- bunch with $N_e = 3.5\times10^{10}$ ppb, $ß_{x,y} = 50$ m, $e_N = 50$ mm-mrad, and $s_z = 50$ μm.

Undulator length ⇒		5 m	10 m	20 m
Total fundamental photons		0.5×10^{10}	1.0×10^{10}	2.0×10^{10}
Number of photons per 0.1% BW		1.3×10^{7}	2.6×10^{7}	5.2×10^{7}
X-ray energy for E_e = 20-50 GeV	keV	6.3-39	6.3-39	6.3-39
Pulse length (rms)	fsec	180	180	180
Bandwidth	%	8	4	2
Peak brightness (E_e = 28 GeV)	*	0.4×10^{24}	1.1×10^{24}	2.7×10^{24}
Peak brightness (E_e = 46 GeV)	*	1.4×10^{24}	3.5×10^{24}	8.1×10^{24}
Average brightness (46 GeV, 120 Hz)	*	0.7×10^{14}	1.8×10^{14}	4.0×10^{14}

* photons/sec/mm^2/mrad^2/0.1% BW

The calculations above are based on a fairly conservative electron beam parameter set. If we use more optimistic numbers for the electron beam quality, such as $N_e = 4\times10^{10}$ ppb, $E_e = 46$ GeV, $e_N = 30$ mm-mrad, $s_z = 20$ mm and a 20-meter long undulator, the peak brightness increases to 58.0×10^{24} photons/s/mm^2/mrad^2/0.1% BW. For this electron beam, but using a 4-cm period, 20-meter undulator with K ˜ 5.3, the radiation wavelength is unchanged and the brightness increases to 1×10^{27} photons/s/mm^2/mrad^2/0.1% BW; almost equal in brightness to that of LCLS spontaneous radiation.

9 Conclusions

The high peak current already demonstrated in the SLC arcs, combined with a simple, low cost undulator, could provide a high brightness, sub-picosecond x-ray source at energies of 6-40 keV. This source would be valuable for LCLS component and diagnostic testing, and for other experiments requiring short pulse x-rays. The most conservative parameter set indicates a peak brightness higher than the brightest existing sources in the 1-Å wavelength range. Optimistic parameter sets suggest a factor of 50 increase in peak brightness over the brightest existing sources, with a factor of 1000 possible if a more costly linear undulator is used. With the existing SLAC linac and arc, this source might be brought on-line relatively quickly and at reasonable cost.

10 References

[i] K. Bane, P. Emma, M. Minty, F. Zimmermann, *Measurements of Longitudinal Wakefields in the SLC Collider Arcs*, SLAC-PUB-7781; Presented at the 1st Asian Particle Accelerator Conference (APAC-98), Tsukuba, Japan, March 23-27, 1998.

[ii] A.W. Chao, M. Tigner, *Handbook of Accelerator Physics and Engineering*, World Scientific, 1999.

[iii] R. Waynant, M. Ediger, *Electro-Optics Handbook*, McGraw-Hill, 1994.

[iv] *LCLS Design Study Report*, SLAC-R-521, April 1998.