Femtosecond X-ray Generation in the SLC Arcs

Josef Frisch, Paul Emma, Marc Ross
February 10, 2000

Short Bunches / High Currents in the SLC Arcs

In 1998 Measurements of the longitudinal wakefields, in agreement with simulations demonstrated the production of σ_z=50µm bunches in the reverse bend region of the SLC arcs with a bunch charge of $3.5\text{x}10^{10}e^-$. (K. Bane, P. Emma, M. Minty, F. Zimmermann SLAC Pub-7781).

Analysis of the data indicates that bunch lengths of σ_z=25µm, with peak currents of 15kA were produced in the “reverse bend” region of the arc.

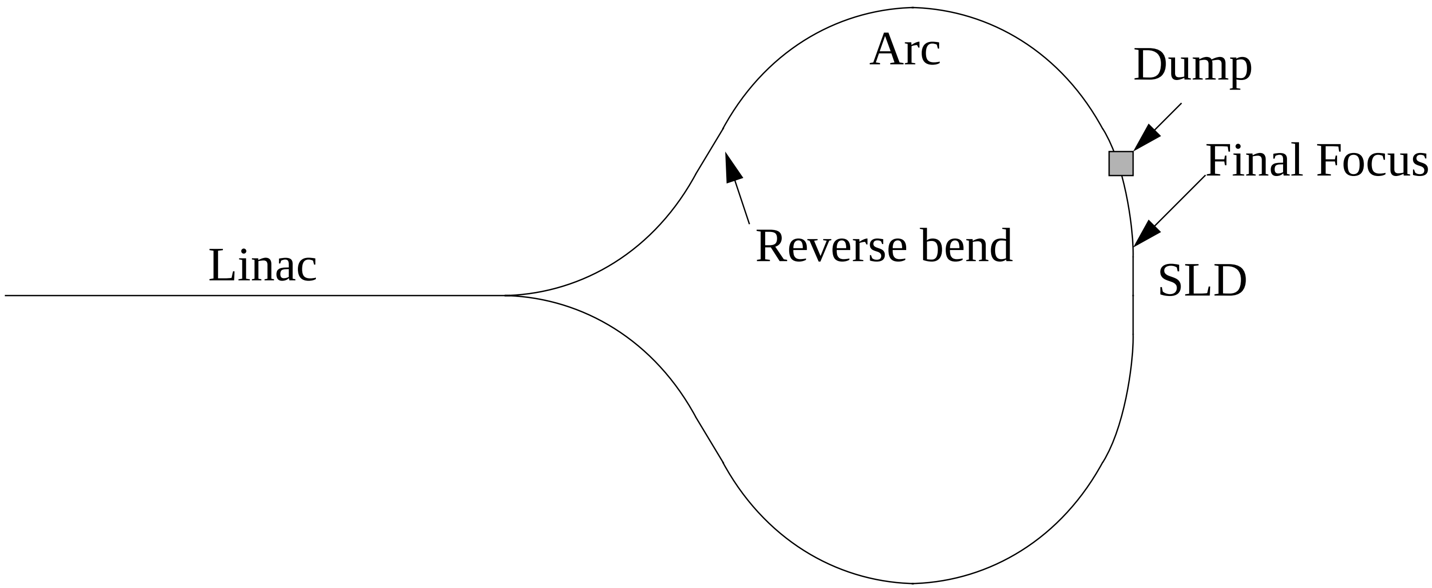
X-ray generation: With the addition of a simple undulator, ~10^{10} Photons at ~10Kev could be produced in a <200 femtosecond pulse.

Other Applications

Electron beam studies: Both NLC and LCLS use short electron bunches. Beam tests could allow study of wake field, and stability issues associated with short bunches.

Plasma / Wakefield acceleration: The high peak currents ~15 kA, could produce very high accelerating gradients.

SLC Layout



Simulations indicate that short bunches can be produced anywhere between the Reverse bend and the Final Focus. So far, the shortest simulated bunches have been in the Reverse bend region. Bunch lengths of $\sigma_z < 50\mu m$ are also possible in the Final Focus area.

With modest beamline modifications, approximately 7 Meters of space is available in the Reverse bend region. Considerably more space is available in the final focus.

Generating Short Bunches

The longitudinal wakefield in the SLC Linac generates a correlated energy spread in the beam.

This energy spread couples to the dispersion in the arc to produce compression.

The position of minimum bunch length is adjusted by operating the accelerator off crest (in our case slightly decreasing the correlated energy spread).

Simulations:

Use measured damping ring energy spread

Use chirp from operating off-peak in the accelerator (exact)

Use longitudinal wake field in the accelerator. (first order)

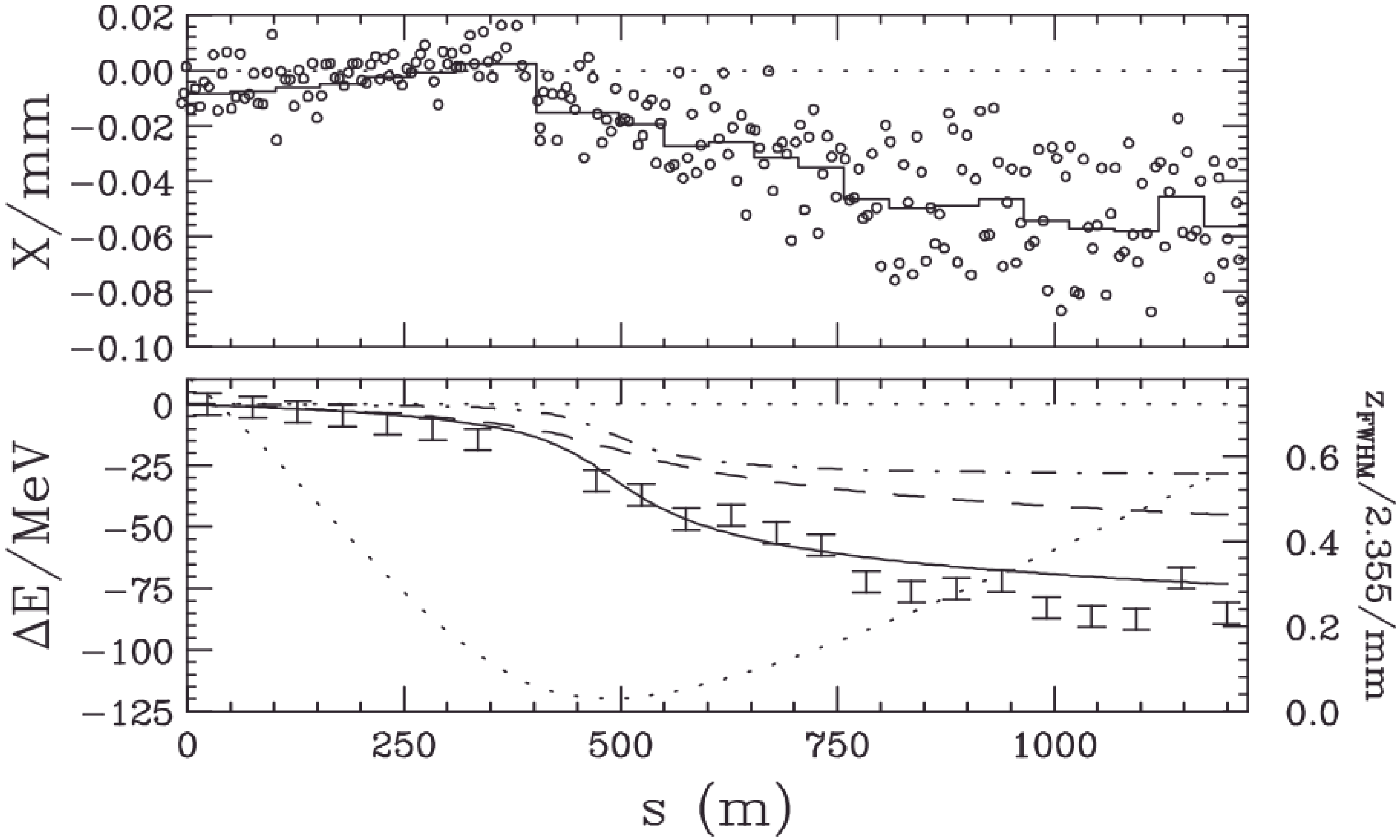
Use calculated Arc dispersion (to second order), and synchrotron radiation.

Simulation results agree with experiments (measured energy loss due to arc wakefields).

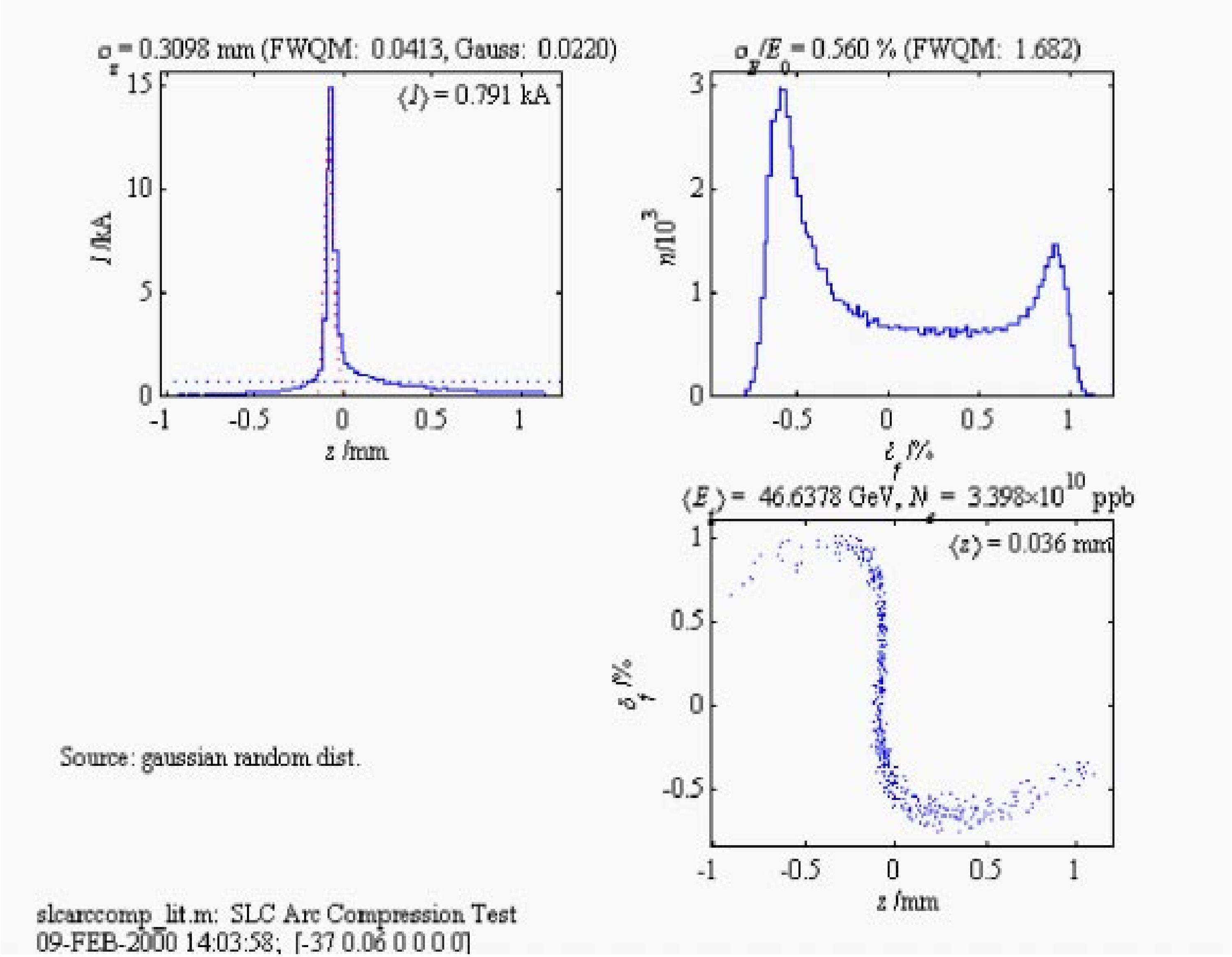
Evidence for Short Bunches in the Arcs

Orbit shift through the Arc is a measure of beam energy loss. The energy loss due to long-intudinal wakes in the arcs is consistent with a minimum bunch length of ~25µm RMS.

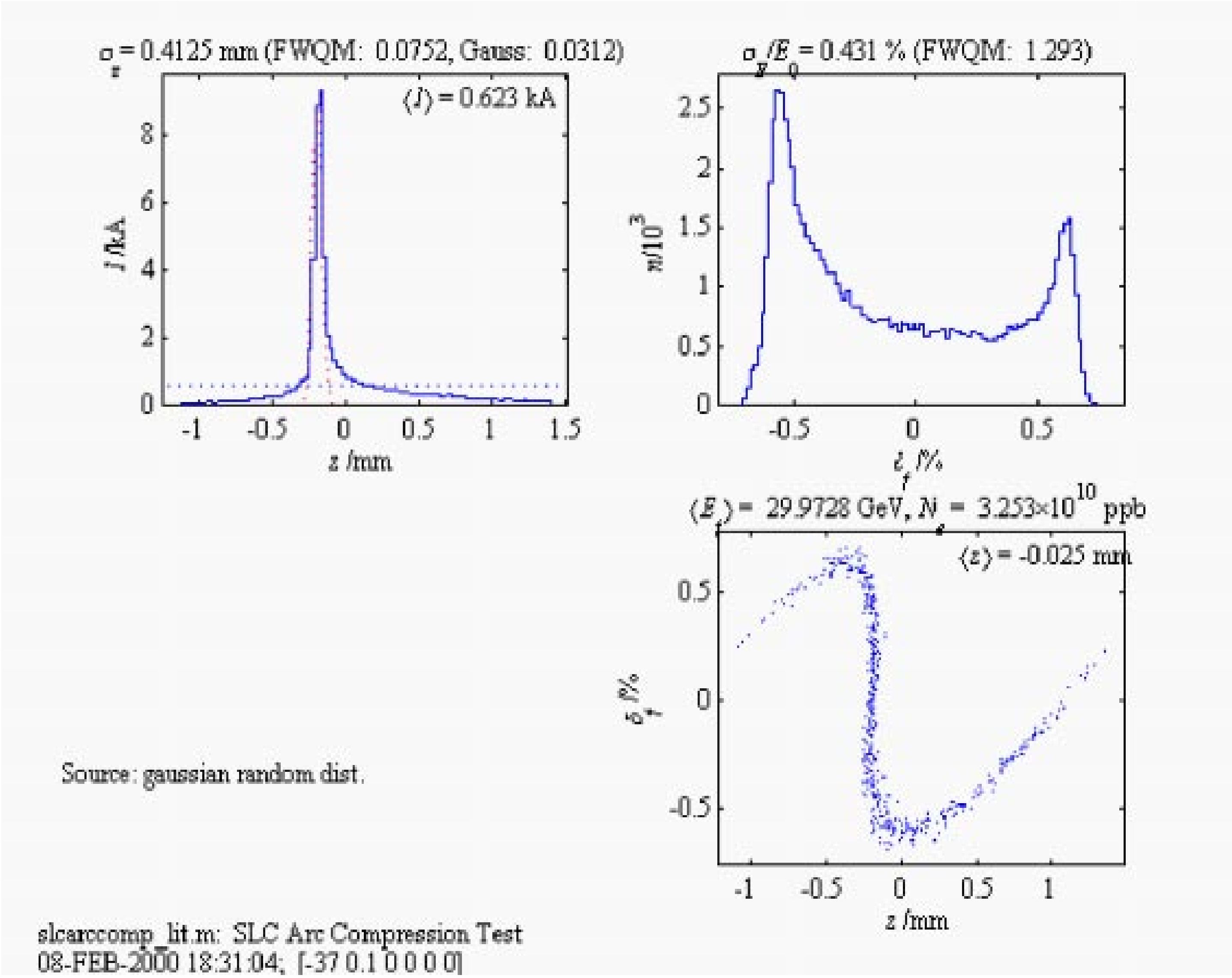
Measurements done during SLC run at $3.5x10^{10}e^{-}$, 47GeV.



Simulated bunch for 46GeV (experiment conditions)



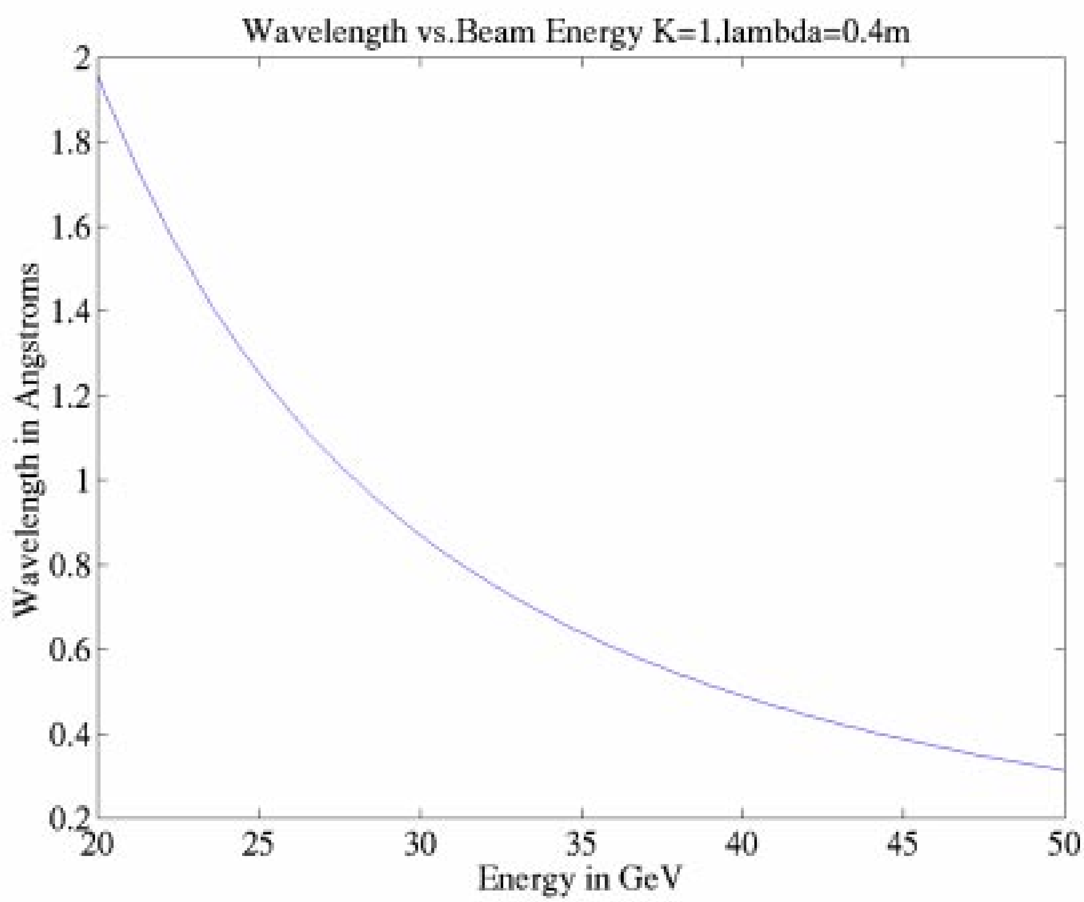
Simulated bunch for 30GeV (not optimized)



X-Ray Production: Wavelength

Undulators produce an output wavelength of $\lambda[Angstroms] = 1305.6 \frac{\lambda_u[m]}{E[GeV]^2}\left(1 + \frac{1}{2}K^2\right)$

Where λ_u is the undulator wavelength, and K is the undulator strength.



X-Ray Production: Intensity

(following H. Wiedemann in “Handbook of Accelerator Physics and Engineering”)

With N_p the number of periods in an undulator of length L, the spectral bandwidth of the radiation (in the forward direction for the fundamental) is $\Delta\lambda / \lambda = 1 / N_p$

The energy loss for an electron in a helical undulator is $E[ev] = \dfrac{0.145 E[GeV]^2 K^2 N_p}{\lambda_u}$

with approximately 60% of the energy in the fundamental for K=1.

The number of photons is proportional to N_p, K^2 (for small K)

The photons are emitted in an opening angle cone of $1/\gamma$. The photons within the $1/N_p$ bandwidth are emitted in an opening cone of $\theta_u = \dfrac{1}{\gamma}\sqrt{\dfrac{1 + K^2/2}{2N_p}}$. The photons in a bandwidth $\Delta\omega/\omega$ are $N_w = 2.86\times 10^{17} I[A] N_p \dfrac{\Delta\omega}{\omega} \dfrac{K^2}{1 + K^2/2}\left[J_0\left(\dfrac{K^2}{4 + 2K^2}\right) - J_1\left(\dfrac{K^2}{4 + 2K^2}\right)\right]^2$

The number of photons per bandwidth depends linearly on the peak current and the number of periods in the undulator, and is independent of the beam energy.

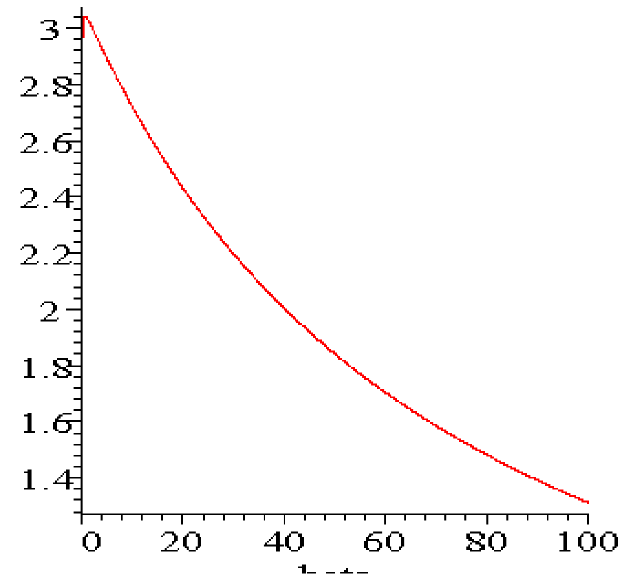
X-Ray production: Brightness

The angular spread of the X-rays adds in quadrature with the angular spread of the electron beam. $\theta = \sqrt{\theta_u^2 + \frac{\varepsilon_n}{\gamma\beta}}$ with ε_n the normalized beam emittance, β the beta function.

The effective radius of the X-ray source is the sum in quadrature of the electron beam radius, and the diffraction limit of the X-rays (small in our case): $R = \sqrt{\frac{(\beta\varepsilon_n)}{\gamma} + \frac{\lambda}{4\pi\theta_u}}$.

The brightness $B = \frac{N_w}{4\pi^2\theta^2 R^2}$ is weakly dependant on the beam beta function for our case.

Plot of brightness in units of 10^{24} photons/s/mm^2/mr^2/0.1%BW, vs. beam beta function in Meters.



System Parameters

Electron beam parameters

Beam energy	30GeV (20(?) to 46 possible (with last 10 sectors on).
Bunch charge	3.5×10^{10} e^- (output linear in charge)
Emittance ε_n	50π mm-mr round. (Flat beams may give higher brightness)
Bunch length	25µm, (75 femtoseconds) RMS (needs to be verified)
Beta function	β_x=7 meters, β_y=55 meters (easy match into the SLC Arc)
Repetition rate	10Hz, 120Hz possible

Undulator Parameters

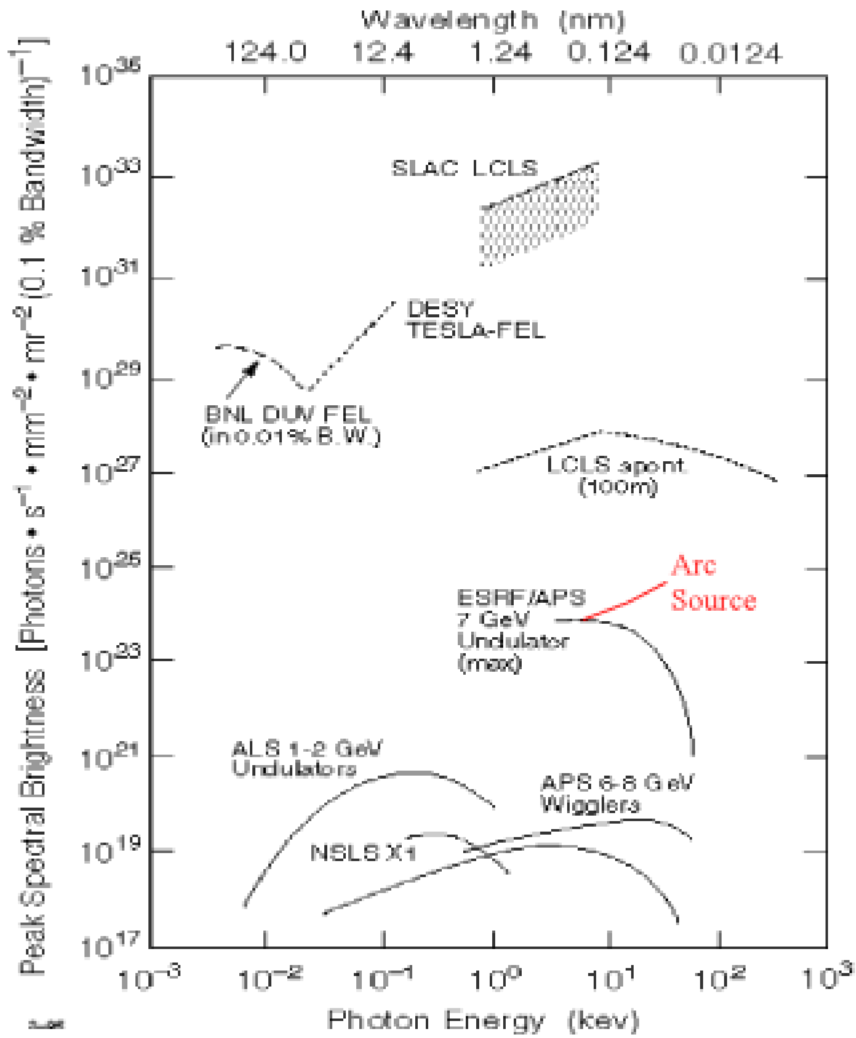
Type	Helical - electromagnetic
Wavelength	0.4 meters (chosen for center wavelength)
Length	7.5 meters (available in reverse bend)
Strength parameter "K"	1.0
B field on axis	270 Gauss (long wavelength gives low field)

Expected X-ray output

X-Ray Energy, @ 30GeV	14KeV, 0.9 A
@ 20GeV	6.3KeV, 1.9 A
@ 46GeV	33KeV, 0.37 A
Photons per pulse	$7x10^9$
Photons, 5% BW	$8x10^8$
Peak Brightness	$1.8x10^{24}$ *
Pulse Width	<200 fsec FWHM

*$\gamma\ s^{-1}\ mm^{-2}\ mr^{-2}\ (0.1\%\ Bandwidth)^{-1}$

Comparison with other Sources

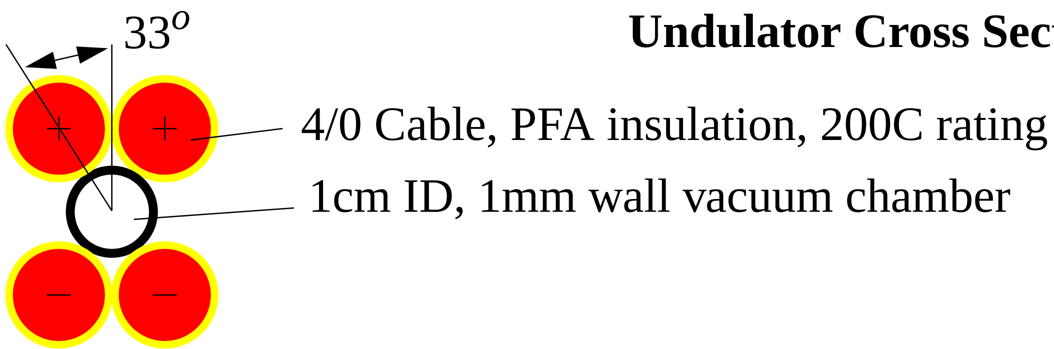


Undulator Design

Long wavelength requires a low magnetic field, allowing a very simple (low cost) undulator design

A air cooled undulator using two windings of standard power transmission cable will work.

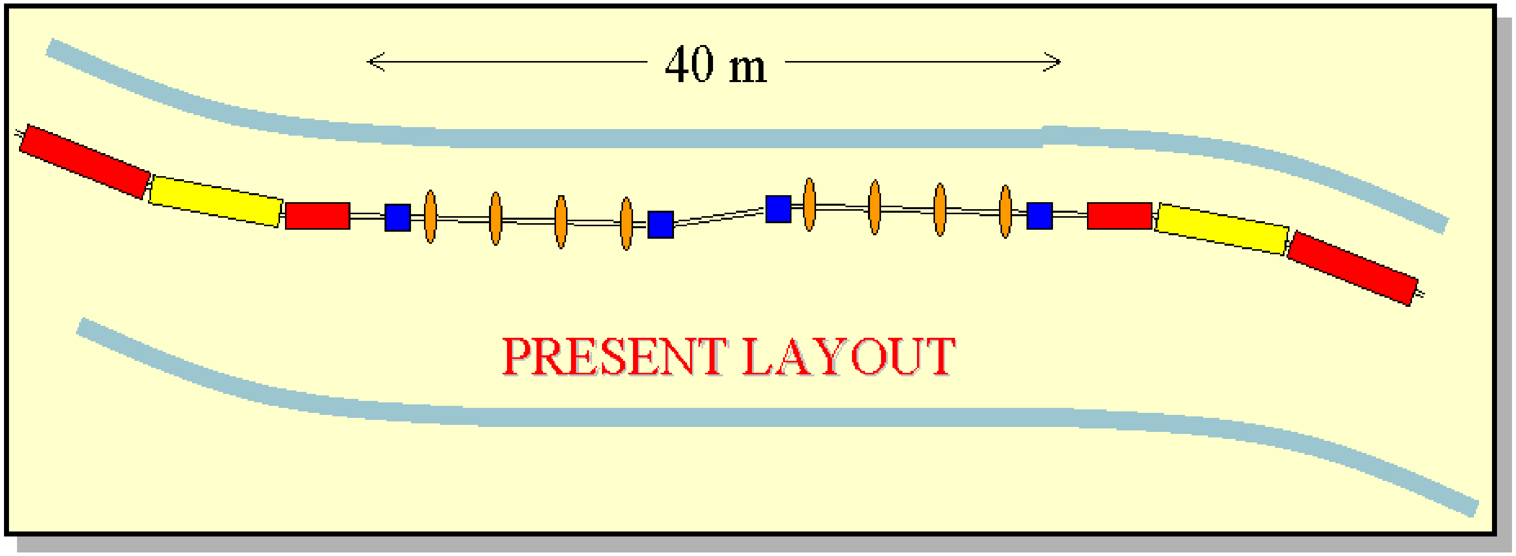
Undulator Cross Section

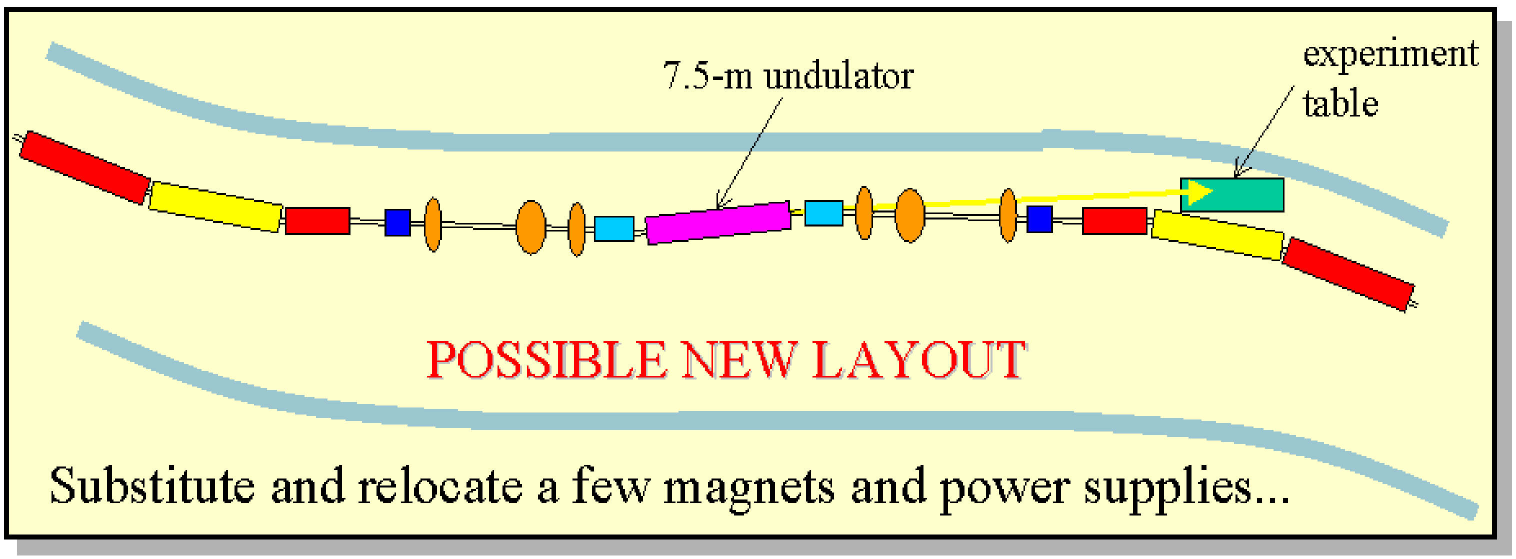


Operating Current per winding	500A, at 2.4V (+ cable loss)
Cable rating (free air, 40^{o}C ambient)	630A
Power dissipation	160W/meter, 1200W total

Water cooled designs using a single turn of magnet wire would also work.

Beam Line Modifications





Beamline Modifications:

Remove existing collimators and Skew quad
Replace four 16cm quadrupoles with four 27cm magnets from south arc
Replace four 15cm quadrupoles with two 54cm magnets from south arc
Replace inner two 50cm bends with 90cm bends from FF
Replace outer two bends with inner two
Add two new power supplies (30V, 500A)
Modify vacuum chambers
Construct X-ray extraction vacuum chamber
Modify two exit quadrupoles to allow X-ray beam clearance
Build helical undulator.
Move all magnets in X and Z.

Estimated cost is ~$400K.

Technical Issues

RF Stability: While short bunches are produced *somewhere* in the Arc for a variety of accelerator phase settings, placing the minimum length at a specific location (the reverse bend) will require RF phase stability of $<1^{o}$ S-band. A feedback based on bunch length could be used, if a suitable bunch length measurement were available.

Beam Separation / Synchrotron Backgrounds: The magnet that separates the electron beam from the photon beam will produce synchrotron light. The total synchrotron in the output angle from the undulator is comparable to the undulator power. The critical energy for the Synchrotron radiation is about 3MeV, so it should be straightforward to separate from the 10KeV X-rays.

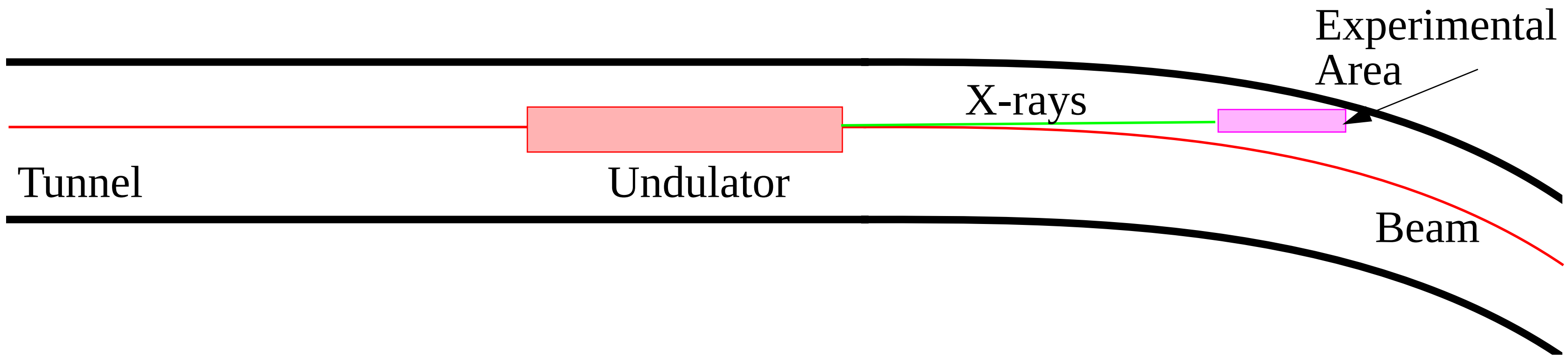
Beam Emittance: The beam emittance has not been measured under the conditions where short bunches were produced. Give our conservative emittance estimates, this should not be a problem.

Overall technical risk is low: Short bunches have already been demonstrated in this location. Since this is a spontaneous source, failure of the beam to meet the expected performance will only result in a gradual reduction in the system performance, there is no minimum required performance.

Experimental Area

This is a substantial weakness in the proposed reverse bend location

The available space is behind the Arc beamline, about 0.5M wide, ~10M long. This space is unimproved, limited accessibility, and electrical power.



Probably need to set up the X-ray experimental optics on a table, and then move the entire table into position in the Arc.

Many short pulse X-ray experiments require a (complex). femtosecond laser system. The north Arc beamline passes under an existing laser lab in building 006 (Cryo building) approximately 150 meters from the reverse bend. If necessary, a mini-penetration could be dug, and an optical beamline installed.

Note: This is not a "User Facility" Rather it is intended to allow some proof of principle experiments.

Alternate Locations

SLC Final Focus: The Final Focus tunnel provides considerably more space, however it is not clear that the pulse lengths can be made as short.

Increased space allows a 20Meter undulator (higher brightness), and increased experimental area.

The best solutions so far give a 40-60μm bunch. Further optimization may improve this.

FFTB Tunnel: This location provides much more beam space, and better utilities.

Increased space allows a 20Meter undulator (higher brightness), and increased experimental area.

Generation of short pulses would required the addition of a bunch compressor in the Linac (not modeled). **100μm appears to be the minimum bunch length.**

Interaction with LCLS installation - advantages and disadvantages.

Applications for the X-ray light - LCLS related

This system will produce X-ray pulses with similar wavelength and pulse length to the LCLS (although at 7 orders of magnitude less brightness).

Temporal Measurement: The LCLS will need to measure the pulse length and timing of the X-ray beam (or possibly the electron beam) with sub-picosecond resolution. If these techniques work at low powers, they could be tested with the Arc source.

X-ray optics development: New techniques (e.g. temporal dispersion compensation) were required for visible light optics when pulse lengths were dropped from picoseconds to femtoseconds. Similar techniques may needed to be developed for X-rays.

X-ray pulse compression: The LCLS is considering compressing the X-ray pulse with a dispersive optical system (similar to chirp pulse techniques in visible optics). The Arc source could easily provide a chirped X-ray pulse to test this technique.

User experiment development: The availability of short pulse X-rays may allow users to develop / debug parts of their experimental apparatus before the high power LCLS beam is available.

Applications for the X-ray light - Other Experiments

Until LCLS and other 4th generation light sources are operating, the Arc source could provide the shortest pulse high intensity X-rays available. While the user area is very limited in size, a variety of simple physics / chemistry experiments might be performed.

Jerry Hastings from BNL has indicated that a source of this intensity and pulse width would be useful for a variety of time resolved diffraction experiments. Note that a femtosecond laser would also bee needed for these experiments.

Tom Rabedeau from SSRL looked at the available experimental area and decided that it would be adequate for some X-ray experiments.

Electron Beam Experiments

The short bunch, high current electron beam in the reverse bend would be useful for a variety of accelerator physics and diagnostics experiments

Bunch length diagnostics: Both the NLC and LCLS expect to operate with short (σ~100μm for NLC, 5-25μm for LCLS) bunches. Instrumentation to measure short bunch lengths and timing needs to be developed.

Wakefields: Both the NLC and LCLS need to understand wakefield effects for short bunches.

Coherent Synchrotron Radiation: The short bunches and high energy will allow good measurements of CSR.

Collective damage effects: The primary source of collimator damage in the NLC appears to be high current collective effects (e.g. wall current heating). The high peak currents in the arc would allow experimental tests of these effects.

Advanced Accelerator Experiments

Plasma Wakefield Acceleration: The high electron density, 15kA, in σ_z=25μm, R_b=40X120μm bunch has an electron density $>10^{16}$ e^-/cm^3 which should allow the production of very high acceleration gradients.

High frequency structure tests: The beam could be used to test millimeter wave accelerator structures.

These accelerator tests could continue after the LCLS becomes operational and obsoletes the arc X-ray source.

Summary

Very short, σ_z=25μm, high current ~15kA bunches are believed to have been produced in the SLC Arc reverse bend.

With some relatively low cost beamline modifications, and the addition of a simple undulator, a unique short pulse, high brightness X-ray source could be constructed.

The electron beam and X-rays would be valuable for testing technologies for LCLS and NLC:

Bunch length and timing diagnostics, Femtosecond X-ray optics

The electron beam could be used for accelerator physics tests.

Wakefields, Collective beam damage, CSR

The electron beam could be used for advanced accelerator tests

Wakefield acceleration, High frequency structures.