SLAC-PUB-10003
June 2003

Measurements of Transverse Emittance Growth due to Coherent Synchrotron Radiation in the SLAC SPPS Bunch Compressor Chicane

P. Emma, F.-J. Decker, P. Krejcik, C.L. O'Connell, M. Woodley
SLAC, Stanford, CA 94309, USA*
H. Schlarb, F. Stulle, *DESY*, 22603 Hamburg, Germany

Abstract

A four-dipole bunch compressor chicane has recently been installed in the SLAC linac at 9 GeV and is capable of compressing a 3.4-nC electron bunch to an rms length of 50 microns, resulting in a peak current of nearly 10 kA [1]. The electron bunch is extracted from a damping ring with normalized horizontal emittance of ~ 30 μm. We present preliminary measurements of the initial and final emittance in the chicane and compare these to 1D and 3D calculations of the effects of coherent synchrotron radiation (CSR).

INTRODUCTION

A four-dipole bunch compressor chicane was installed in sector-10 of the SLAC linac in October of 2002 [2]. The new chicane is located at the 1-km point in the 3-km linac, at 9 GeV, in order not to interfere with present PEP-II operations. The electron bunch is extracted from a damping ring which is followed by an existing ring-to-linac (RTL) bunch compressor beamline at 1.2 GeV. The 3.4-nC bunch is compressed from 6-mm rms in the ring to 1.2-mm in the RTL, and then further compressed in the new chicane to as short as 50-μm rms (9-kA peak current).

The existing FFTB (final focus test beam) beamline, which follows the 3-km linac, has been adjusted to produce another stage of compression, for a possible final bunch length of 12 μm rms, or 30 kA of peak current. The very short bunch (80 fsec FWHM) will be used to produce high-brightness spontaneous x-rays at 28 GeV in a 2.5-m long undulator. This sub-picosecond photon source (SPPS) [3], will be commissioned in June of 2003. The chicane compressor also enhances FFTB plasma-wakefield experiments by increasing the accelerating gradient a factor of ~ 36 [4].

Finally, the new compressor provides an opportunity for machine R&D toward the linac coherent light source (LCLS) project [5], especially by allowing measurements of transverse emittance growth possibly induced by CSR.

With the large bend-plane emittance from the damping ring, and limited time, the data collected is not yet exhaustive, but does provide an upper limit to the measured CSR emittance growth. Since few CSR emittance growth measurements exist at present, these results are published in their preliminary state. Future measurements should ultimately be more conclusive and more comprehensive.

* Work supported by U.S. Department of Energy, contract DE-AC03-76SF00515.

Table 1: Chicane and beam parameters [2].

parameter	**symbol**	**value**	**unit**
Bunch charge	Ne	3.0-3.4	nC
e^- energy	E_0	9.00	GeV
rms corr. energy spread	σ_E/E_0	1.55	%
init. rms bunch length	σ_{s_0}	1.15	mm
final rms bunch length	σ_{s_f}	50	μm
x norm. emittance	$\gamma\epsilon_x$	27-45	μm
momentum compaction	R_{56}	-76	mm
bend angle per dipole	$\|\theta\|$	97	mrad
bend magnet length	L_B	1.80	m
drift from bend-1 to 2	ΔL	2.80	m
drift from bend-2 to 3	ΔL_c	1.50	m
peak dispersion	η_{pk}	449	mm
initial x beta-func.	β_x	56.3	m
initial x alpha-func.	α_x	3.29	

CSR CALCULATIONS

The chicane is shown in Fig. 1 with symbol values listed in Table 1. Bending is in the horizontal (x) plane, and a limited aperture constrains the R_{56} adjustment to just $\pm 5\%$ (no changes made here). The simulated longitudinal phase space at chicane entrance and exit is shown in Fig. 2 (bunch head at $s < 0$), with the total CSR-induced relative energy variation along the bunch at lower right. The final rms bunch length is 74 μm, but the rms is dominated by tails and the core bunch length is FWHM/$2.355 \approx 36$ μm.

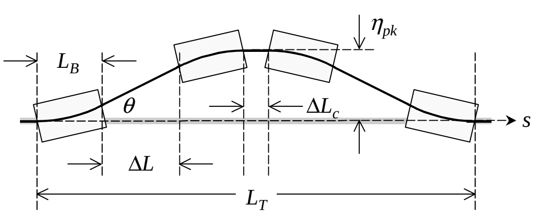

Figure 1: SPPS chicane at 9 GeV ($L_T \approx 14.3$m).

The CSR-wakefield alters each particle's energy as it passes through the chicane, generating x-kicks which become projected (bunch-length integrated) emittance growth in the bend-plane. A 1D line-charge transient field calculation, which is based on references [6, 7], is used here to generate these plots and evaluate the emittance growth. In the code, bends and drift sections are split 20 times each and the evolving non-gaussian temporal beam distribution is continually re-binned in 500 slices at each step, with

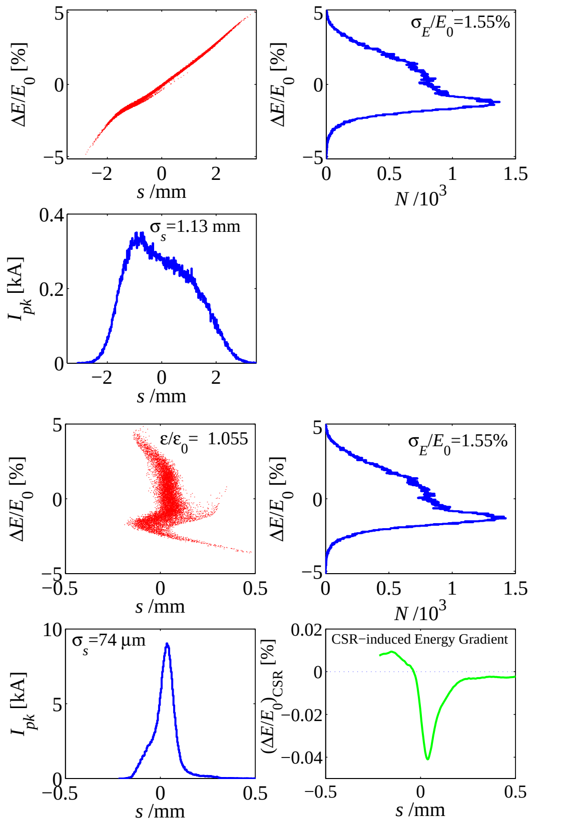

Figure 2: Simulated longitudinal phase space before (top 3-plots) and after chicane (bottom 4-plots) at 9 GeV.

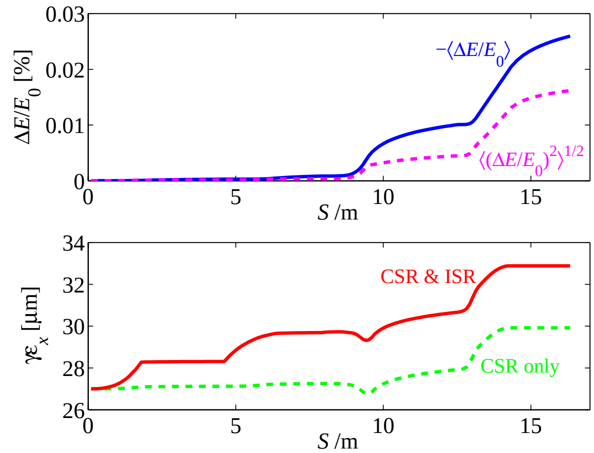

Figure 3: Simulated CSR-induced relative energy loss (top-solid), rms relative energy spread (top-dash), and bend-plane emittance along chicane, with (solid) and without ISR effect (dash) at 3.4 nC.

2×10^5 macro-particles. The macro-particles are taken from a previous 2^{nd}-order tracking run, using *Elegant* [8], through the entire RTL beamline and the 1-km of SLAC linac leading up to the chicane, including the longitudinal wakefield of the linac structures and 2nd-order optics. The emittance growth in the chicane has also been calculated using the 3D CSR code *TraFiC*^{4} [9], which includes transverse effects and agrees reasonably well with the 1D code. With a vacuum chamber full-height of 13-mm, shielding effects are not important for $\sigma_s \lesssim 100$ μm.

A calculation (1D) of the CSR-induced energy spread, energy loss, and the normalized projected horizontal emittance is shown evolving along the chicane in Fig. 3, using the phase space of Fig. 2. The larger of the two emittance curves includes incoherent synchrotron radiation (ISR) in the chicane. The calculation shows the emittance is expected to grow from $\gamma\epsilon_x = 27$ μm to 30 μm (10% increase) due to CSR alone at 3.4 nC, and up to 33 μm (22% increase) when also including ISR at 9 GeV. The CSR-induced rms energy spread is $< 0.02\%$, including a 2-m long drift section after the chicane.

BUNCH LENGTH MEASUREMENTS

The bunch length after the chicane is measured using a 2.4-m long S-band (2856 MHz) transverse rf vertical-deflecting structure located at 28.5 GeV [10]. An off-axis screen is placed downstream of the structure ($\sim$ 60 m) by $\Delta\psi_y \approx \pi/2$, vertical betatron phase advance. A pulsed horizontal magnet is used to kick the vertically-streaked beam onto the screen. The absolute bunch length is calculated from the vertical beam size by using data from both zero-crossing rf phases as well as the rf-off setting. This 3-point measurement with parabolic fit allows for a finite vertical emittance and for initially tilted (pitched) beams, possibly induced by upstream transverse wakefields.

The transverse deflector is powered by a single 50-MW klystron and applies up to 22 MV (at crest phase) allowing 10-20% resolution (at zero-crossing phase) of a 50-μm rms bunch length. A calibration is made by scanning the beam position vertically across the span of the screen, varying rf phase a few degrees around the zero-crossing. The calibration, in screen-pixels per S-band degree of phase change, allows direct conversion of beam size, in pixels, to bunch length in degrees S-band (or psec). Therefore, no apriori calibration is needed, except the rf phase shifter, and this is separately scanned $\pm\pi$ reading a nearby BPM to ensure the phase calibration is accurate to better than 1%. The minimum measured **RMS** bunch length is from 50 to 70 μm.

The bunch length is independently verified by measuring the longitudinal wakefield energy loss of the compressed bunch across 1872 meters of SLAC rf structures [11]. For a 50-μm rms bunch length and 3 nC of charge, the wakefield energy loss at the end of the linac is nearly 250 MeV (1%) which is easily measured using an end-of-linac BPM with $|\eta_x| \approx 85$ mm (the chicane CSR energy loss should be only $\sim 0.01\%$ at 28 GeV). It is a simple matter to adjust the pre-chicane rf phase until this energy-loss is maximized, resulting in a minimum post-chicane bunch length. These wake-loss scans with rf phase are a routine diagnostic and are in good agreement with tracking calculations. They further verify the minimum bunch length at 50-60 μm rms.

EMITTANCE MEASUREMENTS

Horizontal emittance measurements are made using four consecutive wire scanners (well used over last 10 yrs), all of which are located within 80 m of the chicane. The four wires (x rms beam sizes from 100 to 300 μm) allow some redundancy for the 3-parameter measurement of ϵ_x, β_x, and α_x. The beam sizes are taken from asymmetric gaussian fits, which allow for reasonably distorted beams. A profile measurement requires 50 pulses at 10-30 Hz, or 2-5 seconds plus some overhead. One emittance measurement requires about 2 minutes. Figure 4 shows two measured x-profiles with asymmetric gaussian fits. The narrower profile is with chicane off, and the wider is chicane on. The asymmetries are fairly insensitive to the bunch length (i.e., CSR power) in both the tracking and the measurements. No simultaneous vertical emittance measurements were made.

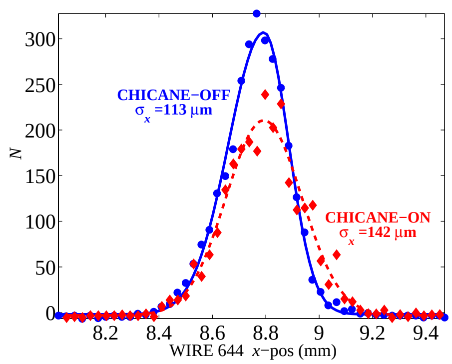

Figure 4: Measured x-profiles (points) on one of four wire-scanners with asymmetric gaussian fits, for chicane-ON (dash-red) and chicane-OFF (solid-blue).

The emittance measurements are precise to a level of about 4%, over periods $<$ 1 hour, but the linac is quite sensitive to changes in charge, rf phase, and trajectory. This makes controlled changes of the compression difficult without altering the initial emittance prior to the chicane. For these reasons we present data taken only at the minimum bunch length, and as a control, with the chicane switched completely off. The data were taken on two separate days (Feb. 5 and May 4, 2003) at 3.0 nC and 3.4 nC, respectively. The 3.4-nC data has a smaller initial emittance achieved by coupling the damping ring tunes.

Efforts were also made to correct all x-dispersion errors after the chicane. Tight quality control was placed on field quality of the dipole magnets [2], and two weak 'tweaker' quadrupole magnets were located inside the chicane and used to empirically correct the x-dispersion by minimizing the measured emittance to a precision of $\Delta\epsilon_x/\epsilon_x \approx 1\%$. In addition, impedance effects inside the chicane beam-pipe were minimized, including copper plating [2].

Figure 5 shows two sets of x-emittance measurements made downstream of the chicane on two separate days, each time with "chicane-ON" and also "chicane-OFF", at 3.0 nC (Feb. 5) and 3.4 nC (May 4). The "tracking" values

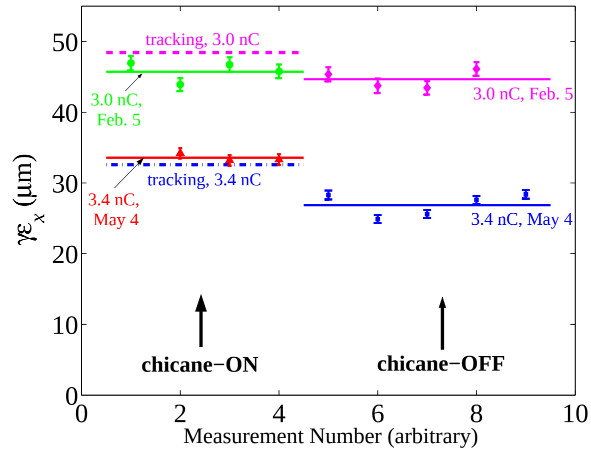

Figure 5: Emittance measurements with chicane ON and OFF at 3.0 nC (Feb. 5) and 3.4 nC (May 4). Tracking results, including ISR, are shown for both 3.0 nC (dash) and 3.4 nC (dash-dot) at $\sigma_s \approx 50$ μm.

(including CSR and ISR) are also shown (for both days) at 3.0 nC (dash) and 3.4 nC (dash-dot) and $\sigma_s \approx 50$ μm. These are calculated by tracking with the average "chicane-OFF" measured emittance as an input. With 3.4 nC, the mean "chicane-OFF" emittance is $\langle\gamma\epsilon_{x_0}\rangle \approx 26.9 \pm 0.7$ μm and the tracking result after the chicane is: $\gamma\epsilon_x = 32.9$ μm. The "chicane-ON" measurements at 3.4 nC have a mean value of $\langle\gamma\epsilon_x\rangle \approx 33.6 \pm 0.3$ μm, which is in reasonable agreement with tracking. Measurements (not shown) were also also made of the β_x and α_x functions and confirm, within a few percent, the values in Table 1.

CONCLUSIONS

The observed bend-plane emittance growth after the SPPS chicane, with a 50-μm rms bunch length and up to 3.4 nC of charge, is reasonably consistent with 1D and 3D CSR tracking calculations and sets a clear upper limit on the scale of the effect. Measurements will continue and might be improved in the future by using a larger β_x in the final bend to amplify the relative growth, and perhaps a 6-GeV chicane energy to remove ISR effects.

REFERENCES

[1] P. Krejcik et al., PAC'03, Portland, OR, USA, May 2003.

[2] L. Bentson, et al., EPAC'02, Paris, Fr., June 2002.

[3] P. Emma et al., PAC'01, Chicago, IL, June 2001.

[4] M. Hogan et al., PAC'03, Portland, OR, USA, May 2003.

[5] *LCLS CDR*, SLAC Report No. SLAC-R-593, 2002.

[6] E. L. Saldin et al., TESLA-FEL 96-14, Nov. 1996.

[7] G. Stupakov, P. Emma, EPAC'02, Paris, France, June, 2002.

[8] M. Borland, APS LS-287, Sep. 2000.

[9] M. Dohlus et al., FEL'97, Bejing, China, Aug. 1997.

[10] R. Akre et al., EPAC'02, Paris, France, June 2002.

[11] K. Bane et al., PAC'03, Portland, OR, USA, May 2003.