Presented at 2003 Particle Accelerator Conference, 5/12/200-—5/16/2003, Portland, OR, USA

SLAC-PUB-9858

COMMISSIONING OF THE SPPS LINAC BUNCH COMPRESSOR

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Abstract

First results and beam measurements are presented for the recently installed linac bunch compressor chicane. The new bunch compressor produces ultra-short electron bunches for the Sub-Picosecond Photon Source (SPPS) and for test beams such as the E164 Plasma Wakefield experiment. This paper will give an overview of the first experiences with tuning and optimizing the compressor together with a description of the beam diagnostics and beam measurements. These measurements form the basis for further detailed study of emittance growth effects such as CSR and wakefields in a previously unmeasured regime of ultra-short bunch lengths.

INTRODUCTION

The SPPS project was conceived [1] to create extremely short bunches in the SLAC linac using a four-dipole bunch compressor chicane [2] located at the 1/3rd point along the linac. The chicane was installed in the linac in the summer of 2002 and beam commissioning began in November 2002. The short bunches are to be used in a number of experiments in the Final Focus Test Beam line (FFTB), and in addition provide a rich opportunity for machine studies in this new regime of accelerator physics [3]. The first experiments to utilize the high energy-density beam include the E164 Plasma Wakefield Experiment [4] in which the strength of the beam-plasma interaction is expected to scale approximately with the inverse of the bunch length squared. A 2.5 m long undulator has also been installed in the FFTB to generate short-pulse X-rays for SPPS experiments.

The short bunches are produced in the linac in a three stage bunch compression process beginning with electron beams extracted from the North Damping Ring (NDR), shown in figure 1. The 3 nC, 6 mm long bunch from the NDR is compressed to 1.16 mm in the Ring To Linac (RTL) beamline compressor. The wakefields in the linac combined with accelerating the beam off-crest by −19.5° give the beam an energy chirp, or correlated energy spread of $\sigma_E/E_0 = 1.6\%$ rms at the $E_0 = 9$ GeV entrance to the chicane in sector 10 of the linac. The momentum compaction, R_{56} = -76 mm, of the 14.3 m long chicane, made up of four 1.8 m long, 1.6 T dipole magnets, rotates the bunch in longitudinal phase space to give a final bunch length of 50 μm rms.

The short bunch generates strong wakefields in the linac downstream of the chicane which create a further correlated energy spread of $\sigma_E/E_0 = 1.5\%$ rms in the $E_0 =$ 28.5 GeV beam at the end of the linac. The transport optics of the FFTB will be tuned for a momentum compaction, R_{56} = 2 mm, for the forthcoming SPPS experiments to give a final compressed bunch length of 12 μm rms, resulting in a peak current of 30 kA. In this paper we focus on the operation of the new linac bunch compressor.

MODE OF OPERATION

Successful production of short bunches for multiple experimental programs necessitates sharing the beam pulses in the linac with PEP II operation. The linac is operated at 30 Hz to provide 9 GeV electrons and 3 GeV positrons, via the damping rings, for PEP II injection. A third electron bunch is accelerated to 23.5 GeV to produce positrons from a target located in sector 19 of the linac. A fourth bunch of electrons is available as a test beam and can be transported to the end of the linac to the FFTB line

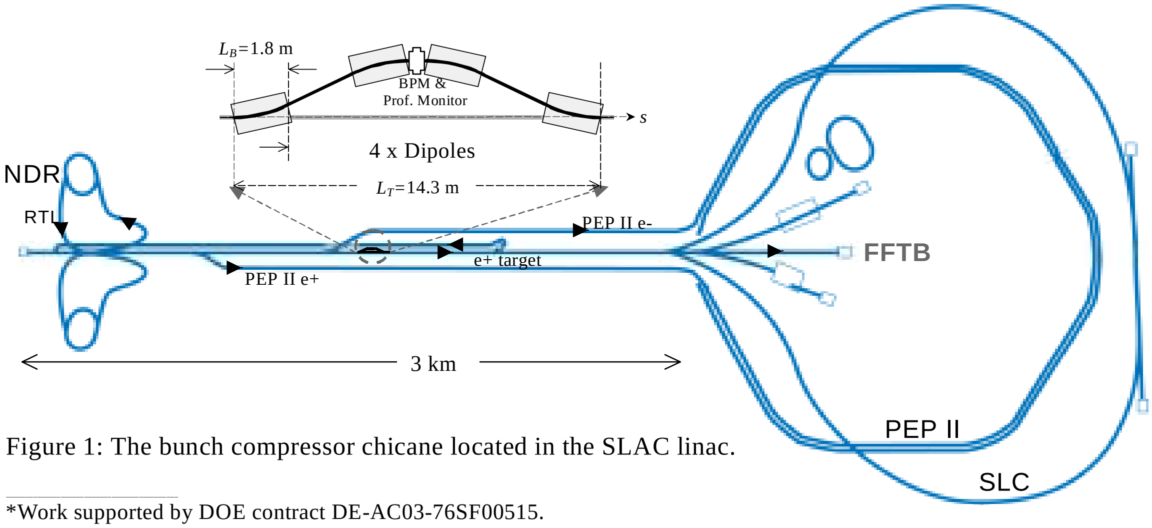

Figure 1: The bunch compressor chicane located in the SLAC linac.

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*Work supported by DOE contract DE-AC03-76SF00515.

at 10 Hz, dropping down to 1 Hz during PEP II fills. The bulk of the klystrons in the final 1/3rd of the linac are not powered, except for a few tubes to provide energy control in a feedback system, so the 28.5 GeV test beam coasts through most of this section of the linac.

Only the test beam and the "scavenger" beam for positron production are transported through the sector 10 chicane. The two beam pulses can be individually controlled for bunch compression by pulsed control of both the RTL compressor RF amplitude and the RF phase at which the bunch is launched into the linac from the NDR. The linac can be set up to leave the scavenger beam uncompressed while the test beam is tuned to give the desired bunch length for experiments in the FFTB. The chicane does introduce a fixed path length difference relative to the straight ahead beams which requires a compensating change of 130° S-band in the downstream klystron phases and positron arrival time in the South Damping Ring (SDR).

The chicane magnets are powered by a 100 kW dc supply, which remains on for both the PEP II and Test Beam programs. An automated procedure was created for switching the linac state in the event that the chicane is turned off for straight ahead beam operation.

Although the chicane has a generous energy acceptance of $\Delta E/E_0 = \pm 17\%$, there is a Machine Protection System (MPS) to prevent pulses with large energy errors from damaging the vacuum chamber. The MPS comprises beam loss monitors and toroid beam current comparators at the chicane entrance and exit which lower the repetition rate of the scavenger and test beams until the fault is cleared.

BEAM TUNING

The minimum bunch length has been optimized for a charge of 2.1×10^{10} electrons per bunch, such that the wakefield contribution to the energy chirp produces the most linearly correlated energy spread in the bunch. The desired magnitude of the correlated energy spread is produced by accelerating the beam −19.5° from crest in sectors 2 through 6 in the linac. Sectors 7 and 8 are not powered during PEP II operation and the energy at the chicane is kept constant with a sector 9 energy feedback loop to hold the beam in the middle of the magnet aperture. A BPM placed at the peak dispersion location in the chicane where $\eta_x = 45$ cm allows the energy to be measured with a relative accuracy of 0.01% and is utilized in the energy feedback loop. The feedback loop [5] controls the phase of a pair of orthogonally phased klystrons to correct the energy without altering the average beam phase.

The beam energy measured by the feedback loop is a convenient way to calibrate the relative phase of the klystrons with respect to the RF crest, allowing the beam phase to be accurately set at the desired value of −19.5°.

A retractable profile monitor installed adjacent to the high-dispersion BPM in the chicane allows the energy spread of the beam to be measured by digitizing the video image of the beam on the screen and measuring the width of the spot. The energy spread at the end of the linac is measured on a profile monitor in the FFTB beam dump.

Two techniques are used for the tuning of the bunch length. One is a fast, relative measurement of bunch length changes for tuning purposes and the second uses a semi-invasive technique for an absolute determination of the bunch length.

Wake loss scans of bunch length

At the very short bunch lengths produced by the chicane the longitudinal wakes, or beam loading, over the remaining length of the linac, cause a significant energy loss that can be easily resolved at the energy dispersive locations at the end of the linac. The longitudinal wakes in the S-band accelerating structure have been extensively modeled and these measurements have provided a unique opportunity to validate the theory at such short bunch lengths [6].

The bunch length can be varied by scanning the phase of the klystrons upstream of the chicane (sectors 2–6). The energy feedback using the chicane BPM keeps the energy constant at the chicane during the phase scan so that any change in energy measured at the end of the linac will only be due to influences downstream of the chicane. The energy feedback at the end of the linac provides a convenient tool for measuring the energy change at a dispersive BPM. Figure 2 illustrates the measured energy change as a function of linac phase, showing a distinct minimum at a phase where the bunch length is minimized.

The exact phase at which the minimum occurs is dependant on the RTL compressor RF amplitude and on the bunch charge. The wake loss scan can also be used to find the optimum RTL compressor amplitude for a given setting of the linac phase. For a given compressor amplitude the predicted energy loss versus linac phase is compared to the measured energy loss in figure 2.

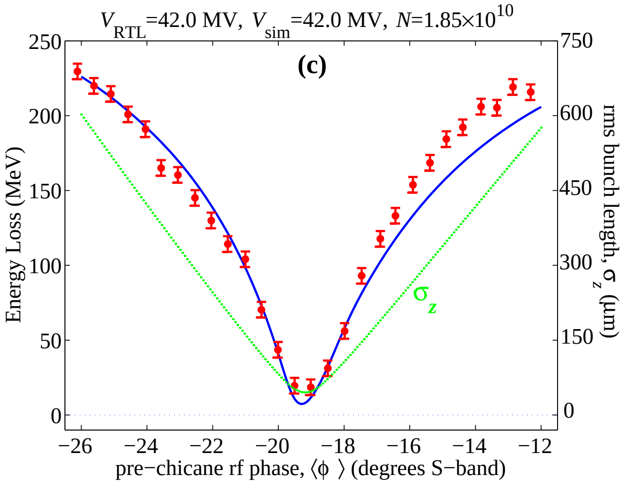

Figure 2: Energy measurement (points) and theory (solid) at end-of-linac shows maximum loss at the RF phase corresponding to minimum bunch length. Simulated rms bunch length (dashed) is also shown on right scale.

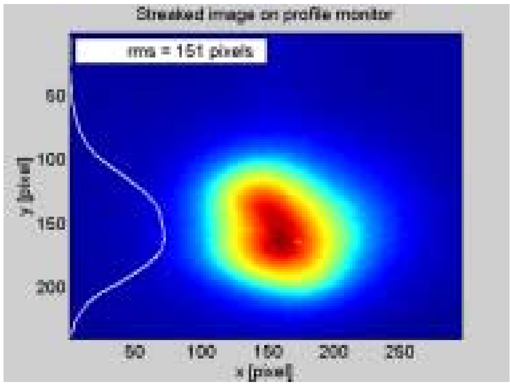

Figure 3: Profile of the beam streaked by the RF deflecting cavity.

RF transverse deflecting cavity measurement

The bunch length is measured with a 2.4 m long S-band RF transverse deflecting cavity [7] located near the end of the linac in sector 29. A deflection amplitude of 22 MV is achieved with an input power of 25 MW to the structure, which vertically streaks the beam across a profile monitor, shown in figure 3. The maximum resolving power of around 20 μm is obtained with the bunch at the zero-phase crossing of the RF, when there is no net deflection. The absolute calibration of the spot size on the screen to units of bunch length is obtained by offsetting the phase of the cavity and measuring the deflection of the beam centroid on the screen in pixels per degree S-band.

The bunch length is deduced from measuring the beam size at the screen for both settings of the zero-phase crossing and a third measurement with the cavity off. An automated procedure that relies on an orbit feedback to maintain the cavity phase accurately at the zero-crossing has been developed for measuring the bunch length. The rms width of the streaked beam profile is often biased by tails in the beam distribution so a Gaussian fit is used to give a bunch length for the core of the beam. The rms width calculated from a double-asymmetric Gaussian fit is better suited to the non-Gaussian profiles, but it is more sensitive to pulse-to-pulse variations in the beam distribution.

The vertical beam size squared measured at the three cavity settings is fitted to a quadratic function,

$$\sigma_y^2 = A\phi_{rf}^2 + B$$

shown in figure 4, and together with the screen calibration *C* [pixels/deg. S-band] yields the bunch length

$$\sigma_z = \lambda_{rf}\sqrt{A}\Big/4C$$

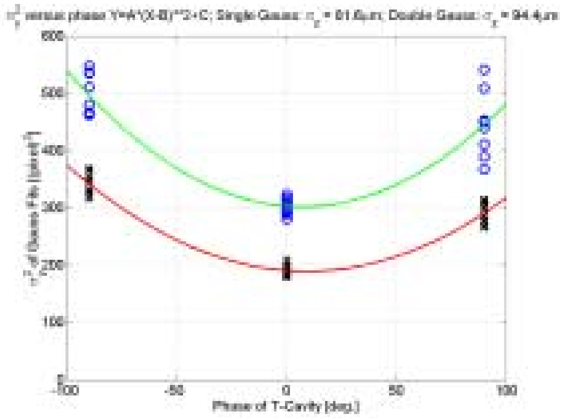

Figure 3 Vertical size squared of the streaked beam versus RF phase of the deflecting cavity using Gaussian fits (lower) and double-asymmetric Gaussian fits (upper).

Bunch lengths in the range 50–100 μm rms have been measured in the linac with this technique for a bunch charge of 3 nC.

Transverse emittance

Emittances of $\gamma\varepsilon_x$ = 40 and $\gamma\varepsilon_y$ = 5 microns have been achieved for the compressed bunch at the end of the linac using the damping ring and linac diagnostic and tuning techniques developed for SLC. The small bunch length in the chicane, particularly in the final bend magnet can result in some emittance growth through coherent synchrotron radiation (CSR). A horizontal emittance growth of 22% has been measured with the chicane on relative to the chicane off. This is consistent with the predicted growth using theoretical models and particle tracking codes [8], where about half the growth is attributed to CSR and the other half to incoherent synchrotron radiation (ISR). These results help provide an upper limit for the expected, larger relative emittance growth in the LCLS and other short bunch machines.

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