

BEAM SHAPING AND COMPRESSION SCHEME FOR THE UCLA NEPTUNE LABORATORY*

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Abstract

We have recently added a dispersionless translating section to the UCLA Neptune linear accelerator beamline. This new section of beamline will serve as a venue for beam shaping and compression experiments using the 14MeV electron beam produced by the UCLA Neptune PWT linac and newly installed photoinjector. An examination of the first and second-order optics indicates that when certain nonlinear effects are minimized through the use of sextupole magnets, the longitudinal dispersion is dominated by a negative R_{56} which, for an appropriately chirped initial beam, can be used to create a ramped beam of a few picosecond duration that would be ideal for driving large amplitude wake fields in a plasma and producing high transformer ratios. The beamline is now in operation. Preliminary data indicate that the beamline optics are well-predicted by simulation and that sextupoles can be used successfully to eliminate nonlinear horizontal dispersion. Future experiments are planned for measuring beam compression (using CTR autocorrelation) and doing longitudinal phase space tomography (using a transverse deflecting cavity).

INTRODUCTION

Recently, a scheme was proposed [1] for the creation of a beam which approximates an asymmetrical "doorstep" current profile using first and second order beam optics. The proposed method takes advantage of the RF curvature in the longitudinal phase space distribution of a positively chirped (i.e. back-of-crest) driving beam. Under a pure negative R_{56} compression of the longitudinal phase space (i.e. with negligible higher order contributions), such a phase space distribution results in a ramp-shaped current profile of a few picosecond to sub-picosecond duration, which is ideal for use as a driving beam for large amplitude plasma wake-fields with high transformer ratios [2,3].

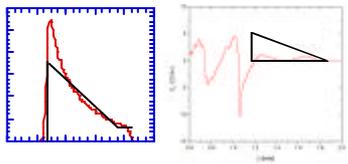


Figure 1. Plots showing the longitudinal phase space (a) and density profile (b) of a ramped beam produced by negative R_{56} compression, as well as a PIC simulation (c) of the wake field produced by such a beam in a plasma of density $2 \times 10^{16} \text{ cm}^{-3}$.

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The simulated longitudinal phase space for such a beam is shown in Fig. 1(a). The current profile associated with the phase space in Fig. 1(a), and a comparison of it to the optimized "doorstep" current profile, are shown in Fig. 1(b). The wake fields produced by this beam distribution, shown in Fig. 1(c), were obtained from a particle-in-cell simulation of a proposed wake field accelerator experiment for the ORION project at the Stanford Linear Accelerator Laboratory. The *S-Bahn*, a new section of beamline installed at the UCLA Neptune laboratory in the Fall of 2002 has been designed, using sextupoles to cancel nonlinear effects, to produce a nearly linear negative R_{56} compression capable of creating a ramped beam of the sort shown in Fig. 1. A diagram of this beamline is shown in Fig. 2.

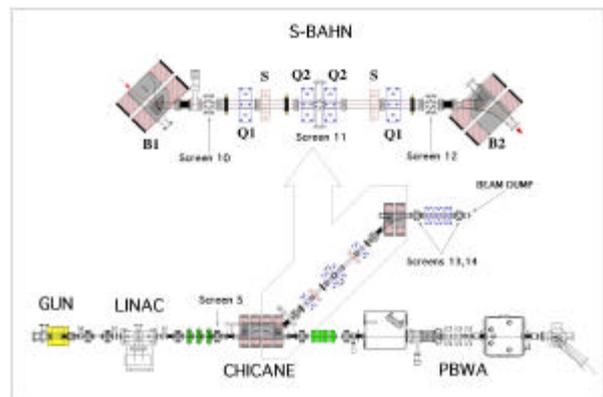


Figure 2. UCLA Neptune beamline with S-Bahn.

BACKGROUND

The *S-Bahn* beamline is a dispersionless translating section exhibiting a widely used geometry known as a "dogleg." The two pairs of bending dipoles (B1 and B2) are separated by symmetrically positioned focusing optics (Q1 and Q2) and sextupole magnets (S1 and S2) for performing nonlinear corrections. Pursuant to the discussion of reference [1], the optics of this device are optimized under the conditions that (1) the quadrupole field settings be symmetric about the midpoint, (2) the beamline be operated in a nondispersive mode, and (3) there be a focus at the midpoint (Screen 11 in Fig. 2). If satisfied, the aforementioned conditions ensure that transverse emittance growth is minimized and that the beam size is well-controlled. In addition, elimination of the horizontal dispersion to linear order was shown to predictably determine the (negative) value of the longitudinal dispersion element (R_{56}) of the transport matrix, which is the primary mechanism for compression.

Compression requires that an RF curvature and momentum chirp be imposed upon the beam's distribution in the longitudinal phase plane by injecting it into the linac off-crest. When acted upon by a negative longitudinal dispersion (R_{56}), a beam with a positive momentum chirp (i.e. injected back-of-crest) will experience a rotation in the trace space plane of the longitudinal coordinate z and the fractional momentum error δ . This transformation results in a net longitudinal compression of the beam and a hook-shaped distribution of the sort shown in Fig. 1 (a) which has a ramped density profile.

This mechanism is dependent upon the z phase space transformation being *linear*. However, since a beam injected off-crest tends to have a larger energy spread, the longitudinal dispersion may be expected to contain significant nonlinear contributions from terms proportional to various powers of the momentum error. For the beamline geometry and RMS energy spread particular to the Neptune S-Bahn, these nonlinearities are dominated by the second order transport matrix elements T_{566} and to a lesser degree by T_{561} and T_{562} . The longitudinal transport equation to second order is therefore approximated by

$$z = z_0 + R_{56}\mathbf{d} + T_{566}\mathbf{d}^2 + T_{561}x_0\mathbf{d} + T_{562}x_0'\mathbf{d} \quad (1)$$

Analytical calculations and simulations using the codes PARMELA and ELEGANT predict that the dominant T_{566} contribution can be eliminated and the other two reduced by a factor of approximately one-half by effective use of sextupoles. To this end, two sextupole magnets (labeled S in Fig. 2) have been included in the S-Bahn lattice.

RECENT EXPERIMENTAL RESULTS

Between recent shutdowns of the Neptune laboratory for RF work (January-February) and for installation of a new magnesium cathode photoinjector (April 2003), several runs were performed for the purposes of determining the running parameters and upstream optics for proper matching of the beam into the S-Bahn, and for optimizing the optics of the S-Bahn for operation in a nondispersive mode suitable for negative R_{56} compression.

The various conditions on the S-Bahn optics discussed above constrain the allowed transverse Twiss parameters and emittance of the beam entering the dogleg section. In particular, the normalized emittance should be less than 10 mm mrad, the beta function should be relatively large (at least 1m) and the beam should be highly convergent at the entrance to the first bend (B1). However, various technical and spatial constraints required that the upstream optics be operated in a mode with somewhat smaller beta functions and larger emittance. The empirical values for the Twiss parameters and normalized emittance obtained from quadrupole scans are shown in Table 1.

Table 1: Empirical Parameters

Parameter	Value	Location
Q_{beam}	35.4 ± 3.8 pC	Faraday Cup
U (Energy)	11.5 MeV	Screen 10
σ_{δ}	< 0.5%	
α_0	-0.94 ± 0.43	Upstream Quads
β_0	0.77 ± 0.43 m	Upstream Quads
$\epsilon_{N,0}$	6.03 ± 1.8 mm mrad	Upstream Quads

Since no diagnostic is currently in place for measuring beam compression, the linac phase was set to minimize energy spread rather than to produce a chirped beam. Previous measurements have indicated an energy spread of less than 0.5% under these operating conditions. A stable nondispersive operating point was determined empirically by observing the beam on the six profile monitors (Screens 5, 10-14 in Fig. 2). The horizontal dispersion function η (or R_{16}) was minimized by observing the beam centroid position at the S-Bahn midpoint (Screen 11) under a variation of the fields of all magnetic elements on the dogleg (B1, B2, Q1, Q2) by a fractional offset ζ from those field values corresponding to the desired operating configuration. For a beam of constant central energy, the resultant shift in the centroid position is the same as that which would be observed due to a change in the central momentum by the same fractional amount and is given to second order in ζ by

$$\Delta x_{\text{cen}} = R_{16}\mathbf{z} + T_{166}\mathbf{z}^2 + O(\mathbf{z}^3) \quad (2)$$

Consequently, the first and second order horizontal dispersion terms R_{16} and T_{166} can be obtained by fitting the measured centroid position data to a quadratic in ζ . The values of T_{166} at the exit of the S-Bahn (Screen 13) obtained by this method are shown in Table 2 at three different settings of the sextupole field strength. Simulation values from the transport code ELEGANT [4] are provided for comparison.

Table 2. Measured vs. Simulated Dispersion Values

Sextupole (T/m ²)	T_{166} (m) Experiment	T_{166} (m) Simulation
0.00	2.59 ± 0.59	2.54
22.4	0.23 ± 0.77	0.67
32.9	-1.27 ± 0.93	-2.07

The R_{16} for all three cases has the same simulated value of -0.013 m, to be compared with the measured value of -0.009 ± 0.015 m. Experimental errors listed correspond to 95% confidence level. The T_{166} values match to within 20% relative error for the case where the sextupoles are turned off. The larger discrepancies for the sextupole-corrected cases are due in part to the fact that the sextupole magnets have not yet been characterized and the

field values listed are those predicted by RADIA simulations of their field profiles.

The input beam for the ELEGANT simulation was obtained by modeling the gun and linac using the particle transport code PARMELA and matching the simulated output beam to the empirical values of emittance, energy, Twiss parameters, and energy spread in Table 1. The magnetic field parameters used in ELEGANT were set to match the experimental running conditions as closely as possible, given the available calibration information for the various magnetic elements on the beam line. The transverse beam profiles predicted at the locations of the six profile monitors are shown in Fig. 3.

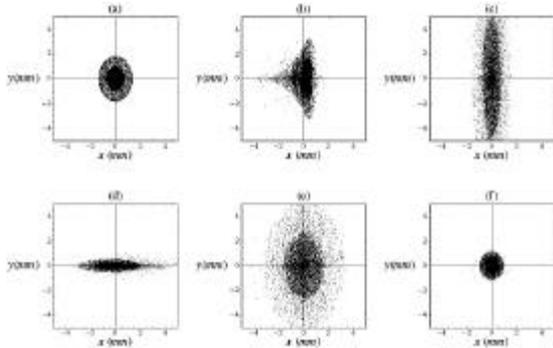


Figure 3. Beam profiles from ELEGANT simulations at locations corresponding to the six profile monitors labeled in Fig. 2: (a) Screen 5, (b) Screen 10, (c) Screen 11, (d) Screen 12, (e) Screen 13, (f) Screen 14.

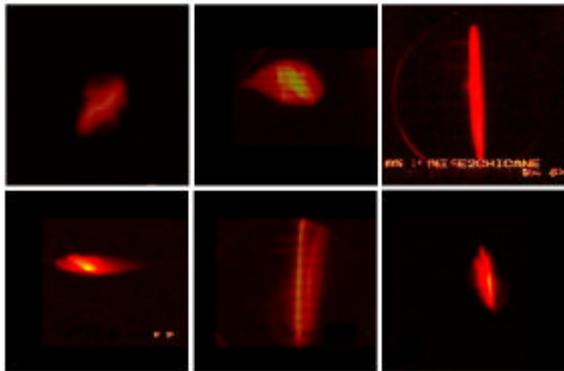


Figure 4. Matrix of images from the six profile monitors corresponding to the locations in Fig. 3.

The ELEGANT simulation successfully reproduces the experimentally observed root mean square (RMS) beam sizes on all six screens to within 30%, with the exception of screen 14, where the vertical beam size is underestimated by 70%. For a visual comparison, images of the beam captured on the various screens are shown in Fig. 4. The scales and positions of the images within the matrix correspond with those of the plots in Fig. 3.

In order to judge the suitability of this operating point for negative R_{56} compression, the ELEGANT simulation was rerun using the same lattice file but with a chirped

input beam of 1.8% RMS energy spread (obtained by setting the linac phase in the PARMELA simulation to 20° back-of-crest) and with the sextupole field strengths set appropriately for cancellation of nonlinear longitudinal dispersion (T_{566}). Plots of the longitudinal trace space and density profile of the simulated beam are shown in Fig. 5. The density profile shows a ramped beam of the sort indicated in Fig. 1 as being an ideal drive beam for plasma wake-field experiments.

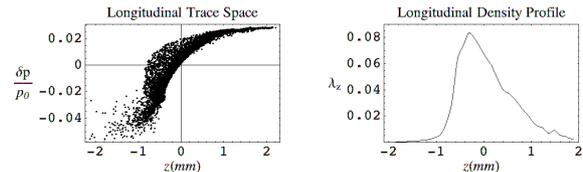


Figure 5. Ramped beam as predicted by ELEGANT simulation for the operating parameters of the present experiment.

CONCLUSIONS

The preliminary results reported above indicate that the UCLA Neptune S-Bahn beamline has been successfully operated in a configuration in which the measured beam sizes and nonlinear *horizontal* dispersion are in good agreement with simulation. The same simulation results also predict a ramped beam at the output of the S-Bahn, indicating that this would be a suitable operating point for negative R_{56} beam compression.

Following the installation and conditioning of the new Neptune photoinjector (currently in progress), coherent transition radiation (CTR) interferometry will be used to measure the final bunch length of the beam. In addition, a transverse mode deflecting cavity is currently being developed as a tool for experimental verification of beam shaping. This diagnostic method imposes upon the beam a time-dependent transverse momentum kick that is proportional to longitudinal position within the bunch. The beam's distribution in the longitudinal phase space is thereby deflected transversely so that it can be observed on a simple profile monitor [5-7].

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