Experiment to Measure Ramped Electron Bunches at the UCLA Neptune Laboratory Using a Transverse Deflecting Cavity[1]

R. J. England*, D. Alesini†, B. O'Shea*, J. B. Rosenzweig* and G. Travish*

**UCLA Dept. Physics and Astronomy, Los Angeles, CA 90095*
†INFN Laboratori Nazionali di Frascati, Frascati, Italy

Abstract. A proof of principle experiment is underway at the UCLA Neptune laboratory to test the concept of generating linearly ramped relativistic electron bunches (rising in density from head to tail followed by a sharp cutoff) by using a sextupole-corrected dogleg section as a bunch compressor. Bunches with this structure have been predicted to be ideal for use as a plasma wakefield drive beam. The diagnostic being developed to measure the time profile of the beam is an X-Band (9.6 GHz) deflecting cavity. The recently completed cavity is a 9-cell standing wave structure operating in a TM_{110}-like mode, designed to measure the temporal structure of the 2 to 10 ps, 14 MeV electron bunches generated by the Neptune S-band photoinjector and plane-wave transformer (PWT) accelerator beamline, with 50 fs resolution. We discuss the experimental plan for the ramped bunch experiment and present preliminary data related to the tuning and operation of the deflecting cavity.

INTRODUCTION

A technique for generating relativistic electron bunches with ramp-shaped current profiles has recently been proposed [1], and an experiment to test this technique is in progress at the UCLA Neptune linear accelerator laboratory. Techniques for generating electron bunches having a ramped (i.e. triangular) current profile that rises gradually from head to tail, followed by a sharp drop, are of potential interest to the plasma wakefield accelerator (PWFA) community. This type of bunch profile approximates the "doorstep" profile which linear plasma theory [2] and recent 2D simulations [3] predict to be the ideal shape for the current profile of the beam used to drive the accelerating wakefields in a PWFA, as it maximizes the energy transfer from the drive beam to the trailing witness bunch (a process quantified in terms of a parameter called the transformer ratio, defined by $R = E_+/E_-$ where E_+ is the peak accelerating field behind the bunch and E_- is the peak decelerating field within the bunch).

The proposed method for generating the ramped bunches is discussed in detail in Ref. [1]. In short, the technique requires injecting an electron bunch with a positive energy chirp (i.e. particles at the head of the bunch are at higher energy) into a dogleg, or dispersionless translating section, which serves as a bunch compressor. When the beamline

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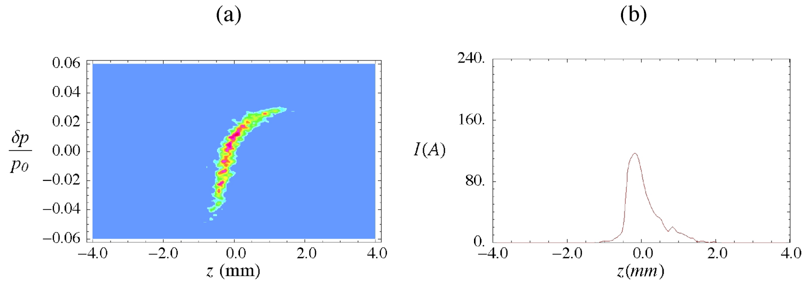

FIGURE 1. Parmela simulation showing (a) longitudinal phase space and (b) current profile of a ramp-shaped beam produced by the UCLA Neptune linear accelerator and dogleg compressor.

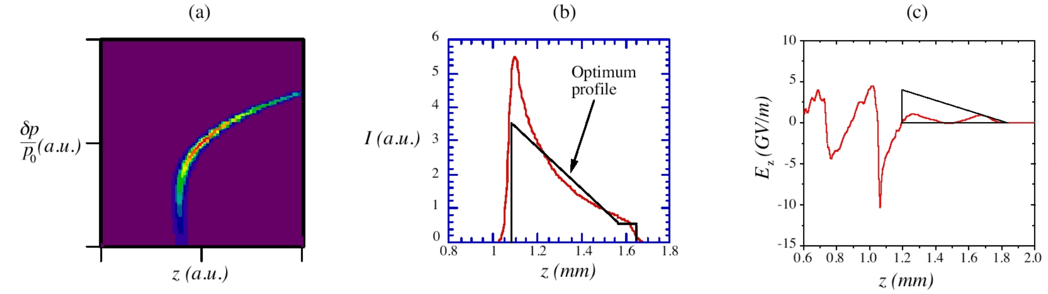

FIGURE 2. Plots of (a) the longitudinal phase space of an artificially generated ramped beam designed to resemble that of Fig. 1, (b) the corresponding current profile (in red) superimposed with the "doorstep" profile (in black), and (c) the wakefield produced by this beam in a 2D PIC simulation.

optics are properly tuned, and second order nonlinear effects are minimized by use of sextupole magnets, simulations and analytical calculations predict that the negative first order longitudinal dispersion of such a beamline will produce a nearly linear compression of the beam, resulting in a "hook-shaped" distribution in the longitudinal phase space. An image of such a phase space, obtained from a simulation of the Neptune photoinjector and dogleg compressor using the particle transport code PARMELA, is shown in Fig. 1(a). As seen in Fig. 1(b) the resulting current profile is similar to a triangular ramp.

Figure 2(a) shows the longitudinal phase space from a PARMELA simulation which has been artificially manipulated to resemble that of Fig. 1(a). The corresponding current profile is superimposed with the ideal "doorstep" profile in Fig. 2(b). Figure 2(c) shows the results of a 2D particle-in-cell (PIC) simulation where a 6 nC beam with the current profile in (b) was injected into a plasma with $10^{16} cm^{-3}$ density, producing 10 GV/m wake fields with a transformer ratio of $R = 11$, indicating that beams with this shape can in principle produce transformer ratios which exceed the traditional limit of $R = 2$ for symmetrically shaped beams.

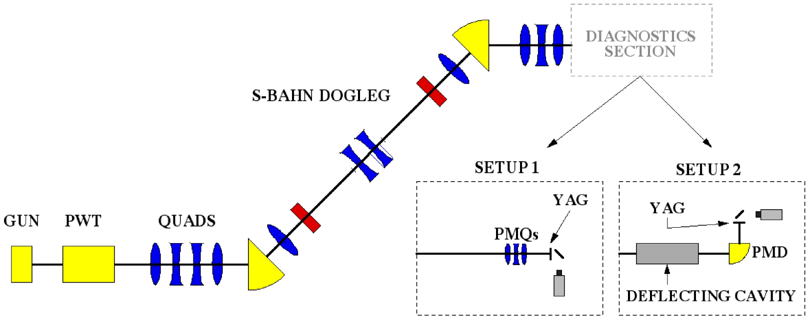

FIGURE 3. Cartoon representation of the experimental beamline and diagnostics section.

EXPERIMENTAL SETUP

As part of an ongoing experiment at the UCLA Neptune laboratory, we will attempt to directly measure the ramped current profile of the 300 pC, 12-14 MeV electron bunches generated by the 1.6-cell S-Band photoinjector and plane wave transformer (PWT) accelerator, following compression in the dogleg section (dubbed 'S-Bahn' after a train line in Germany). A cartoon drawing of the experimental beamline is shown in Fig. 3, with quadrupole magnets represented by blue lenses, dipoles by yellow wedges, and sextupole magnets by red rectangles. A recently constructed diagnostics section is designed to accommodate two alternate setups, labelled 1 and 2 in Fig. 3. Setup 1 involves the use of permanent magnet quadrupoles to obtain a tightly focused high-brightness beam. That experiment will be conducted after the Setup 2 experiments are completed and is discussed in Ref. [4]. The arrangement shown in Setup 2, which will be the focus of this paper, involves the use a recently installed deflecting mode cavity to measure the current profile of the electron beam. A 90-degree permanent magnet dipole spectrometer (shown as a small yellow wedge in Fig. 3) has been constructed and will be inserted after the deflecting cavity in order to attempt a reconstruction of the longitudinal phase space of the beam.

DEFLECTING CAVITY DESIGN AND TUNING

The idea of using a deflecting cavity to resolve the temporal structure of electron bunches is an old one [5], but one which has enjoyed renewed interest [6, 7]. Such a device operates in an electromagnetic dipole mode, which imparts a transverse momentum kick to passing electrons, producing a correlation between the longitudinal and transverse coordinates within the beam. This permits the temporal structure of the beam to be reconstructed from the image on a simple profile monitor downstream. The final transverse RMS beam size along the deflecting axis after a drift L following the cavity is given by $\sigma^2 = \sigma_0^2 + \sigma_{def}^2$ where σ_0 is the spot size with the deflecting cavity turned off and σ_{def} is the contribution due to the deflection, given by $\sigma_{def} = (2e\sigma_z L\pi f V_0)/(cU)$, where σ_z is the RMS bunch length, f is the RF frequency, V_0 is the deflecting voltage, and U is the beam energy [8].

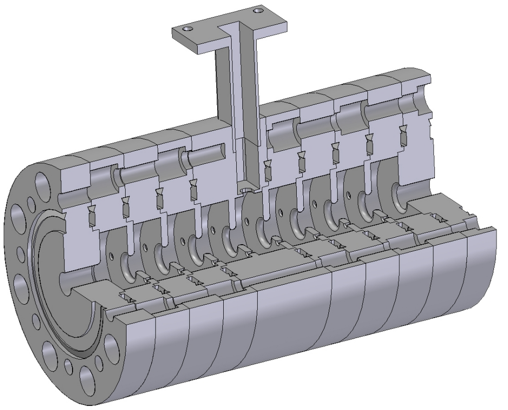

FIGURE 4. CAD drawing of the deflecting cavity with cutaway section.

The deflecting cavity for the Neptune experiment is a 9-cell standing wave structure operating in a TM_{110}-like dipole mode with a π phase advance per cell. It operates with up to 70 kW of peak input RF power, which is provided by an X-band klystron at a resonant frequency of 9.59616 GHz. The structure was designed and constructed at UCLA, and preliminary studies were done at UCLA in collaboration with INFN Laboratori Nazionali di Frascati. The final version of the cavity is made of Glid-Cop (AL-15) with a modular structure that permits the cells to be mated together via conflat style vacuum flanges with o-rings between them. This design effectively eliminates the need for brazing, except on the input power coupler. A cutaway CAD drawing of the assembled cavity is shown in Fig. 4. The input power coupler is attached to the center cell. Although in principle the choice of input coupler location determines the polarization of the electromagnetic standing wave in the cavity, slight asymmetries due to machining errors in the individual cells can produce a small cell-to-cell rotation of the polarization vector. To eliminate this effect, symmetrically placed holes were machined on either side of the irises between the cells. These holes couple to the undesired polarization mode and shift its frequency so that only the desired polarization is excited by the input RF power.

The cavity was designed to be resonant at a frequency higher than the design frequency by 4 to 6 MHz and to be slightly undercoupled at room temperature, so that fine tuning could be accomplished by using a temperature controlled PID feedback loop. The field flatness was measured by the bead pull technique, using a conducting (aluminum) bead, the results of which are shown in Fig. 5(a). Note that the square root has been taken of the measured frequency shift (with the negative square root of the absolute value for negative values), so that the positive and negative going peaks are proportional to the magnetic and electric field magnitudes respectively at the location of the bead. The corresponding resonance (at room temperature) is shown in Fig. 5(b). The cavity was found to be properly tuned at a temperature of 66 C, where the power reflectance of the π mode was found to be $S_{11} = -35dB$, with a coupling coefficient of $\beta = 1.036$.

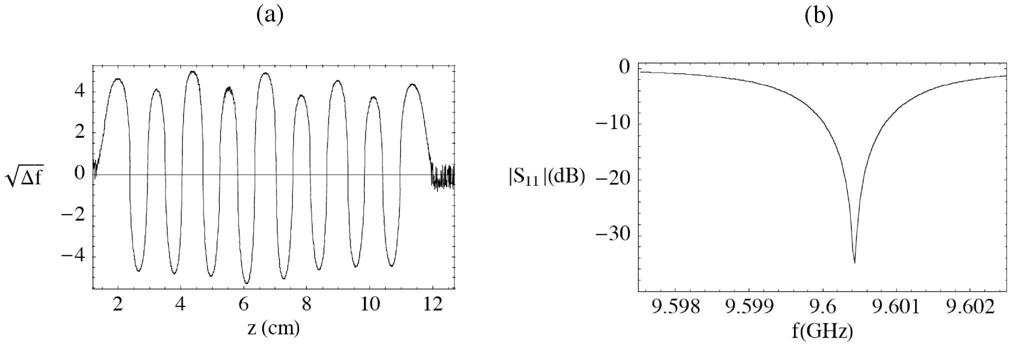

FIGURE 5. Plots showing (a) bead pull data using an aluminum bead and (b) the resonance of the π mode at room temperature.

RECENT RESULTS

The deflecting cavity was recently installed on the Neptune beamline and tested with high power RF. Figure 6(a) shows the measured input power for three different levels of attenuation. The three corresponding reflected power traces are shown in Fig. 6(b). Breakdown was not observed to be a problem at any of the achievable levels of input power (up to 70 kW). Prior to a scheduled beamline shutdown to upgrade the photoinjector cathode and address various maintenance issues, a run was conducted where the unchirped electron beam was successfully propagated through the cavity and streaked images of the longitudinal beam profile were obtained. Figure 7(a) shows the beam's transverse profile as observed on a profile monitor 30 cm downstream of the cavity with the cavity turned off. A problem with the phase-locked oscillator used to generate the low-level X-band RF signal and maintain its phase with respect to the electron beam arrival time resulted in 100% phase jitter. Consequently the cavity was only phased correctly on approximately 1 out of 20 shots. A streaked beam image from one such shot is shown in Fig. 7(b). In this streak, the beam had an energy of 12.5 MeV and a charge of approximately 100 pC. The input power to the cavity was 42.7 kW, corresponding to a deflecting voltage of 490 kV, with a transverse shunt impedance of 5.6 MΩ.

The time profile of the bunch, reconstructed from the streak in Fig. 7(b) is shown in Fig. 7(c). The reconstruction was done by mapping the vertical axis in (b) to the time axis in (c) according to the relation

$$\Delta t = -\Delta y \frac{p_0 \lambda}{e V_0 2\pi L} \tag{1}$$

where Δt is the temporal displacement of a particle from the beam centroid Δy is the vertical deflection of the particle at the screen, p_0 is the momentum of the beam, λ is the X-band RF wavelength, V_0 is the deflecting voltage, and L is the drift length from the cavity to the screen. This relation is valid when the beam is injected at the zero crossing of the RF, and ignores the finite width of the beam when the deflector is turned off. The latter assumption produces an inherent distortion in the reconstructed profile, which

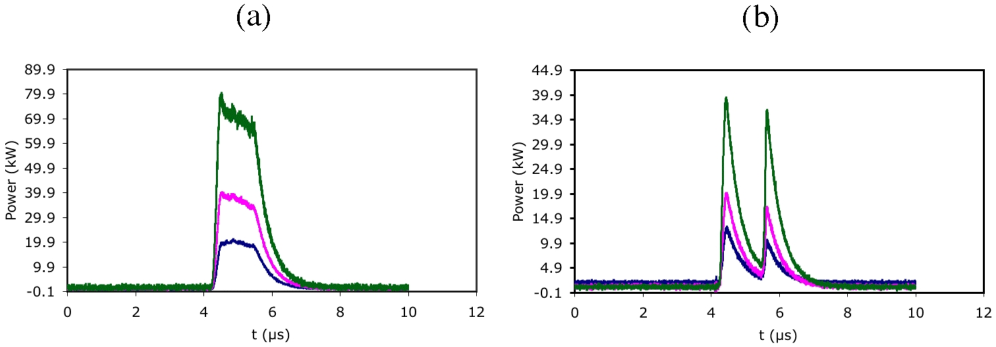

FIGURE 6. Plots showing (a) forward and (b) reflected power at three different levels of attenuation.

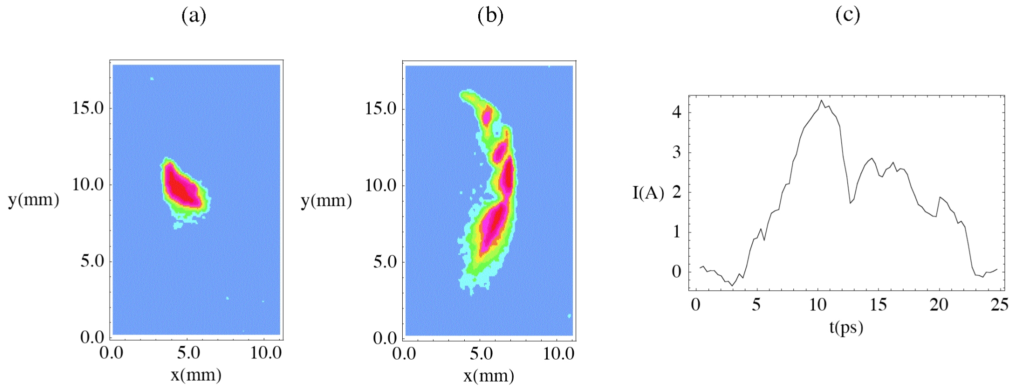

FIGURE 7. Plots showing transverse beam profiles (a) with the deflector turned off, (b) with the deflector on at 44 kW input power, and (c) the beam's current profile reconstructed from (b).

is unavoidable since there is no way to correlate the deflected positions of individual particles with their transverse coordinates when the cavity is turned off. This error is minimized, however, by making the undeflected spot size as small as possible. Both the streaked image and the reconstruction in Fig. 7 indicate the presence of a modulation of the electron beam. The slight curvature of the streaked image is possibly due to some misalignment of the beam trajectory with respect to the cavity axis. This and other effects will be examined in detail in future beam runs. Since the beam shown in Fig. 7 was injected on-crest in the linac it represents the status of the uncompressed bunch, prior to any bunch shaping. The observed longitudinal modulation is consistent with previous observations made of the beam's energy spectrum, which showed a similar modulation in energy when the pulse was chirped. The suspected cause of the modulation is an incorrect matching of the bandwidth of the 100 ps (full width half-max) drive laser pulse from the Coherent YAG laser system to the grating compressor used to reduce the pulse duration by a factor of five. Subsequent adjustments to the laser system, aided by use of a second harmonic generation autocorrelator, have been made in order to correct this problem.

CONCLUSIONS

The ramped electron bunch experiment at the UCLA Neptune laboratory is now well underway. The primary diagnostic device for measuring the current profile of such bunches, an X-band 9-cell standing wave π-mode deflecting cavity, has been installed and tested and appears to be capable of successfully producing streaked images of the electron bunches. The cavity does not exhibit signs of breakdown at the relevant input peak power levels (up to 70 kW). Future experiments, including extensive streaking of chirped pulses and implementation of a permanent magnet dipole after the deflecting cavity to permit a tomographic reconstruction of the longitudinal phase space distribution, will commence in the next few weeks. These efforts will occur following several upgrades to the photoinjector system and beamline, which are currently in progress, including replacement of the photocathode, adjustment of the drive laser system to reduce the modulation seen in Fig. 7, and repair of the X-band oscillator to reduce the phase jitter.

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