DETERMINATION OF LONGITUDINAL PHASE SPACE IN SLAC MAIN ACCELERATOR BEAMS*

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Abstract

In the E164 Experiment at the Stanford Linear Accelerator Center (SLAC), we drive plasma wakes for electron acceleration using 28.5 GeV bunches from the main accelerator. These bunches can now be made with an RMS length of 12 microns, and accurate direct measurement of their lengths is not feasible shot by shot. Instead, we use an indirect technique, measuring the energy spectrum at the end of the linac and comparing with detailed simulations of the entire machine. We simulate with LiTrack, a 2D particle tracking code developed at SLAC. Understanding the longitudinal profile allows a better understanding of acceleration in the plasma wake, as well as investigation of related effects. We discuss the method and validation of our phase space determinations.

INTRODUCTION

Knowing the longitudinal profile of the electron bunches in the E164 plasma wakefield acceleration experiment is crucial to a full understanding of the acceleration process, and also allows us to probe a series of other effects, such as field ionization thresholds and transverse instabilities. With bunches that can be as short as 12 μm, or 35 fs, the energy spectrum of the bunches is wide, with a full width of nearly 4%, and has many features which result from the complicated evolution of the longitudinal phase space down the 3 km SLAC accelerator. These features and the overall width provide distinguishing characteristics from one machine state to another. Comparison of these spectra with detailed simulations of the machine allows reconstruction of the shot-by-shot longitudinal profile. Having this information, we can then identify which particles have which energy before entering the plasma, allowing a more accurate determination of the peak gradient achieved by our plasma accelerator. Similarly, understanding the bunch profiles allows further understanding of several observed effects such as space charge field ionization of the lithium vapor.

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EXPERIMENTAL SETUP

To measure the energy spectrum of the electron beam in a non-destructive way, we installed a small chicane in a region with 8 cm of horizontal dispersion downstream of the main accelerator. This chicane deflects the electron beam vertically by about 2 mrad, and the beam radiates synchrotron radiation with a spectrum predominately in the few hundred keV range. These X-rays are intercepted by a Cerium doped YAG scintillator screen 2 m downstream of the chicane and create a visible image which is viewed by a 12 bit digitizing camera. This is adapted from a technique used at SLAC in the 1980s to measure energy spectra [1]. As the electron beam sweeps out all angles between 0 and 2 mrad, the vertical coordinate contains no information, but the horizontal changing intensity directly maps the dispersed electron beam profile. Thus the image detected by the camera can be thought of as an analog bar code identifying each machine shot. We sum the image vertically to create a spectrum curve for comparison with simulation.

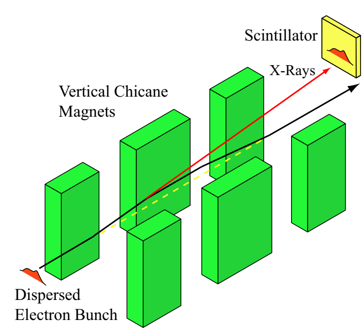

Figure 1: Schematic of the synchrotron X-Ray producing chicane in a region of horizontal dispersion.

SIMULATIONS

The simulation code for modelling the SLAC linac is called LiTrack. This particle tracking code was developed by K. Bane and P. Emma of SLAC [2]. It is a two dimensional code which takes account of wakefields, synchrotron radiation and tracks all second order terms in the particle optics. This code does not deal with discrete elements the way ELEGANT does, for example, but rather uses other programs to generate a second order matrix treatment for sections of the linac. This greatly speeds execution, and has been benchmarked for accuracy.

METHOD

Spectra for each shot of the accelerator are saved as images. We knowing the nominal values for parameters of the accelerator such as rf phases and the R_{56} values of regions with bunch compression, we then allow several of these parameters to vary slightly around the expected values and perform a series of simulations. For example, the overall phase of the rf in the linac is a quantity which typically varies by one half to one degree from nominal over the period of several minutes required to take a sequence of data. Changes of even $0.2°$ can make a measurable difference to the bunch's energy spectrum and length, so we always perform a series of simulations where this quantity is allowed to vary.

There are nine major parameters which affect the output of the simulation, but a number of them are well fixed, reducing the number of simulations we need to perform to a manageable level. Having a suite of simulations, we then compare the energy spectrum associated with each one against the actual series of observed energy spectra. Our spectra typically span a width of about 200 bins. Similar to a conventional χ^2 metric, we calculate the sum of the squares of the differences between the bins of the two data and simulations. For ease of use, we take the square root and divide by a scale factor so that the resulting fit quality numbers are typically in the range of 30 to 100.

By choosing the best simulation match to each shot, we determine the starting properties of the accelerator and the longitudinal properties of the beam as it exits the machine.

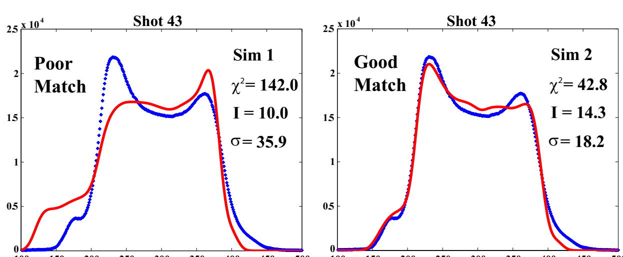

Figure 2: Example of a poor and a good fit. The only difference in the simulations is that overall rf phase changed by 0.5 degrees. Our method is sensitive to small changes.

Phase Space Output

As an example, we show the phase space coming from LiTrack for the above "Good" case. Our information allows detailed comparison with effects in the plasma.

The various adjustable LiTrack parameters listed in the lower left represent quantities such as the total beam charge, the input bunch length and asymmetries, various rf phases and amplitudes and energy collimator acceptances.

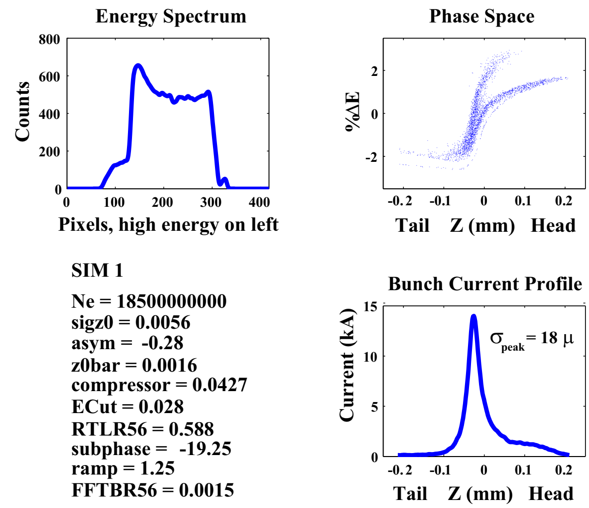

Figure 3: Simulation output showing bunch phase space.

VALIDATION

To verify that the results are reasonable and also accurate, we use several techniques. Taken as a group, they demonstrate that our method is reliable for understanding the longitudinal dynamics of our electron bunches.

Autocorrelation

We seek to corroborate our results with other indications of bunch length. One very good method is an autocorrelation measurement performed using Coherent Transition Radiation (CTR) produced by our short bunches in the Terahertz regime [3]. This gives an indication of the absolute bunch length, but not the details of the bunch distribution. As the above paper discusses, short bunches with conditions very like those shown above have been measured to have longitudinal σ of approximately 18 microns, matching the simulation result well.

Pyro Peak

The above autocorrelation measurement requires a large number of successive shots of the machine in order to build up a picture of the bunch profile, limiting its usefulness. We therefore take a signal which simply represents the total CTR power emitted by each given shot.

For a typical data run of 200 machine shots, the total bunch charge is stable to better than 5%, and all shots have the same transverse size. Therefore, only the longitudinal profile is different between successive shots. High peak current, short bunches will radiate significantly more total coherent power than longer bunches, so correlating the observed radiation power with the peak currents recovered from simulation provides a good indication that the simulations are giving correct results. See Figure 4.

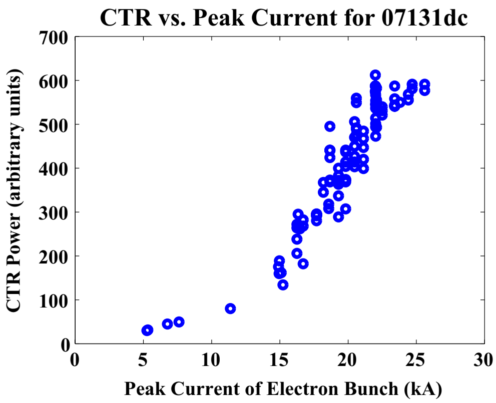

Figure 4: Peak current as determined through simulation correlates well with total measured CTR power.

Details of Energy Spectrum After Plasma

We measure the energy spectrum of the electron bunch after it passes through the plasma cell to determine the total energy gain and other parameters. A puzzling feature observed in the July 2004 data run was that many shots into the plasma had a large number of particles which appeared to transit the plasma with no deceleration. Later simulation of the incoming beam showed the reason. As can be seen in Figure 3, there is a "nose" on the beam where the current remains at a low value for a while before the main part of the electron bunch arrives. This low current lacks the associated space charge field strength to ionize lithium, so sees no plasma effect [4]. Comparison with the particle in cell code OOPIC [5] that includes field ionization effects replicates this behavior.

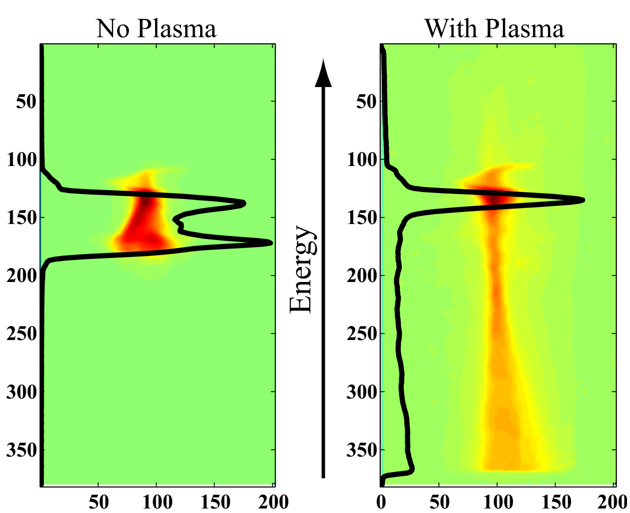

Figure 5: Spectrometer images of two shots, without and then with the plasma cell in the beam. The high energy nose cannot ionize lithium, so goes through unimpeded in both cases. Only later portions of the bunch experience the plasma effects with strong acceleration and deceleration. Vertical axis is pixels on spectrometer camera.

The large amount of charge which was not affected by the wake was at first a surprise. We ran the accelerator at slightly different conditions than had been planned, so we had not anticipated beams with the long noses that we saw. Success in using LiTrack to determine the source of the effect gives further confidence in our indirect method of understanding the beam profile.

APPLICATIONS

Knowing the phase space before the plasma allows, in particular, a more accurate determination of the gradient achieved in our plasma wakefield accelerator. As we see in referring to Figure 3, the tail of the bunch, where the accelerated particles are located, is about 4%, or 1.2 GeV lower in energy than the leading high energy particles. To see any acceleration whatsoever on our downstream spectrometer, these trailing particles must gain more than 1.2 GeV. Naively taking the difference between the highest energy accelerated particle and the highest energy of particles in the plasma off case would dramatically underestimate the magnitude of acceleration in the plasma wake [6].

CONCLUSION AND FUTURE WORK

Non-destructive measurement of the beam energy spectrum has a variety of applications. For E164, we have focused on linking the measurements with simulation to extract the longitudinal profile of the extremely short bunches produced in the SLAC main accelerator shot by shot. This allows a more accurate understanding of the field strength in our plasma wakes and will lead to knowledge of various other phenomena involved in the beam-plasma interaction.

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