LONGITUDINAL PHASE SPACE DYNAMICS WITH NOVEL DIAGNOSTIC TECHNIQUES AT FACET*

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Abstract

FACET produces high energy electron beams for Plasma Wakefield Acceleration (PWFA) experiments. The high energy density beams are created by chirping the electron beam with accelerating sections and compressing the beam in magnetic chicanes. Precise control of the longitudinal beam profile is needed for the drive-witness bunch PWFA experiments currently underway at FACET. We discuss the simulations, controls, and diagnostics used to achieve FACET's unique longitudinal phase space.

INTRODUCTION

FACET is a unique accelerator facility designed to produce high energy, high peak current electron bunches [?]. FACET leverages 2 km of accelerating structures from the original SLAC linac to produce a high energy electron beam (typically 20.35 GeV). In addition, FACET has three bunch compressors distributed throughout the linac that allow for precise control of the longitudinal beam profile. FACET is capable of delivering 30 μm long bunches containing 3.2 nC of charge. Diagnosing short bunches is challenging because traditional techniques like streak cameras do not have the required resolution. In addition to producing short bunches with high peak current, FACET can also provide "drive-witness" beams for use in beam driven Plasma Wakefield Acceleration experiments (PWFA). The driver contains roughly 1 nC of charge and has a 30 μm long bunch length. The witness contains about 0.5 nC of charge, is approximately 10 μm long, and trails the drive bunch by 100 μm. Precise diagnosis of this type of bunch profile is required for monoenergetic PWFA experiments.

OVERVIEW OF FACET

FACET can be thought of as a set of grouped components that shape the longitudinal profile and energy spectrum of the beam. Figure **??** is a schematic of FACET that shows the regions of the beam line which contribute to the longitudinal phase space.

* Work supported [optional: in part] by the U.S. Department of Energy under contract number DE-AC02-76SF00515.

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Damping Ring

The damping ring accepts a high charge, high emittance, 1.19 GeV beam from the injector and produces a $10.0 \times 1.0 mm$·mrad beam via the synchrotron radiation damping mechanism. The beam bunch length and energy spread out of the damping ring are primarily functions of the beam charge and RF voltage in the ring. The bunch length is measured using synchrotron radiation produced by the beam in the ring which is optically transported to a Hamamatsu C5680 streak camera and compared with the results of previous studies [?]. The bunch length is roughly 7 mm out of the damping ring for a 3.2 nC bunch. The uncorrelated beam energy spread of the beam out of the ring is less than 0.1% and weakly influences beam dynamics in the linac.

Ring-to-Linac

The Ring-to-Linac (RTL) is a high dispersion transport line with an RF compressor cavity that provides a correlated head-tail energy spread, or chirp, to the beam. The magnetic compression parameter R_{56} for the RTL is 60 cm. The compressor is typically run at 40 MV, resulting in a 1% chirp. The bunch length at the end of the RTL is between 500 μm and 1 mm and strongly influences the longitudinal dynamics in the linac. The amplitude of the compressor klystron is an important parameter for tuning the bunch length in the linac.

Linac Sections 2 through 10

There are 809.5 m of s-band cavity structures in linac sections 2 through 10 (LI02-LI10). The beam is accelerated to 9 GeV in this region of FACET. The bunch length does not change in LI02-LI10. There are two effects that influence the beam chirp in this region. The first is the effective phase of the klystrons. In order to minimize emittance growth in the linac, we employ a "staggered chirp" klystron phasing by first accelerating the beam on crest and then increasing the phase in each sector of the linac. This results in an effective LI02-LI10 phase of -20 degrees. In the SLAC convention, negative degrees are ahead of crest, so the tail has higher energy than the head of the beam. The second influence on beam chirp are longitudinal wakefields in the cavities. The wakefields have been measured and are a weak effect compared to LI02-LI10 phase for bunch lengths longer than 500 μm [?].

ISBN 978-3-95450-122-9

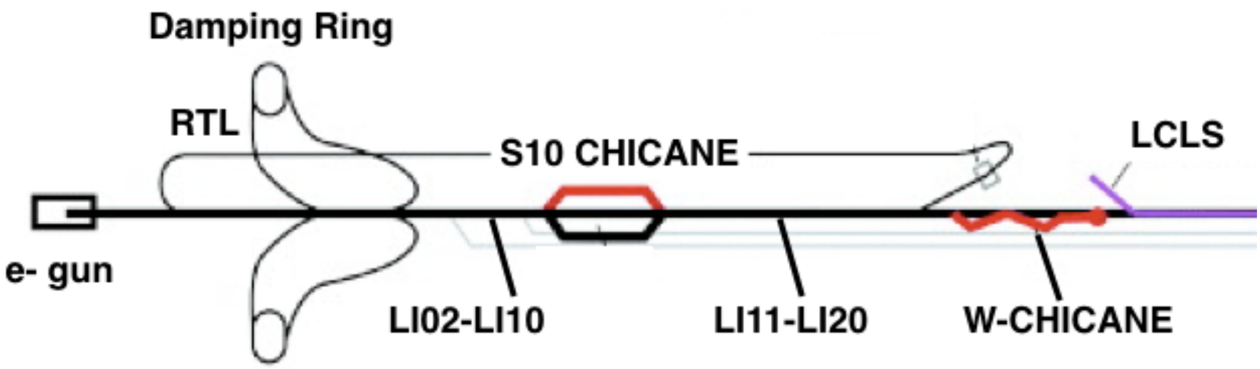

Figure 1: Schematic of the FACET beamline.

Sector 10 Chicane

There is a four-bend chicane at the end of linac sector 10 that compresses the beam from $\sim 500\ \mu$m to $\sim 50\ \mu$m. The R_{56} for the chicane is -7.5 cm and is never changed. The compression in this chicane is controlled solely by the chirp applied to the beam in LI02-LI10. As a result, the LI02-LI10 effective phase is another key tuning parameter.

Linac Sections 11 through 20

There are 848 m of s-band cavity structures in linac sections 11 through 20 (LI11-LI20). The beam is accelerated to 20.35 GeV in this region and the bunch length does not change. The beam is accelerated on crest, so there is no contribution to chirp from klystron phase. On the other hand, the longitudinal wakefield is very strong for bunch lengths shorter than 100 μm and provide a head tail chirp of roughly 2% in this region of FACET. The longitudinal wakefield decelerates particles in the tail of the bunch, so the head has higher energy than the tail in this case.

Sector 20 W-Chicane

FACET employs a unique “W-Chicane” with positive R_{56} for final bunch compression. The R_{56} can be varied from 0 to 10 mm to achieve different bunch compressions and profiles. Maximum bunch compression is typically achieved for $R_{56} = 5$ mm. In addition, the beam energy spread is large enough that the second order compression T_{566} also plays a role. T_{566} is about 0.1 m for $R_{56} = 5$ mm. The compression in the chicane is adjusted to produce different bunch profiles, but never in an “on-the-fly” manner. For this reason, the sector 20 R_{56} is not considered a tuning parameter.

BUNCH LENGTH DIAGNOSTICS

A number of bunch length diagnostics are employed at FACET, including beam streaking with an x-band transverse deflecting cavity (TCAV), pyrometer measurements of OTR radiation, autocorrelation of THz OTR radiation, Fourier transform of Smith-Purcell radiation, and bunch profile inference from the measured energy spectrum. Of these techniques, only the Smith-Purcell measurement and energy spectrum measurement are capable of providing non-destructive, shot-by-shot measurement of the bunch profile, and only the energy spectrum measurement is performed regularly.

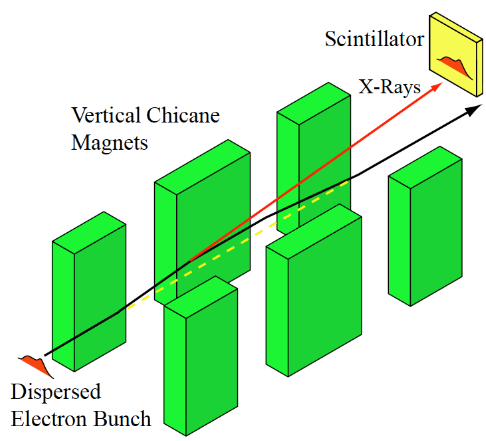

Figure 2: Illustration of the energy spectrum measurement.

Non-destructive Energy Spectrum Measurement

The non-destructive measurement is achieved by passing the dispersed beam in the final section of the W-Chicane through a vertical half-period wiggler magnet. This technique was pioneered at SLAC at the SLC and employed in the FFTB [?] [?]. The dispersed beam radiates x-rays as it passes through the wiggler. The x-rays are intercepted by a scintillating YAG:Ce crystal just above the beam orbit. Figure **??** illustrate the experimental set up. The beam particles radiate 250 keV of energy on average, a negligible amount compared to the 20.35 GeV mean beam energy.

Bunch Profile Inference

The bunch profile can be inferred from the energy spectrum by comparing the measured energy spectrum to the energy spectrum simulated with the 2D longitudinal particle tracking code LiTrack [**?**]. LiTrack is a fast code which can simulate 200k particles through the entire FACET linac in a fraction of a second. An upgrade was made to the longitudinal wakefield code that improved the speed of the calculation by a factor of 50. LiTrack outputs an energy spectrum and bunch profile for each run. The simulated energy spectrum and measured energy spectrum are compared using a weighted χ^2 residual. If the spectra match, the corresponding bunch profile is inferred. This technique relies on a one-to-one correspondence of bunch profiles with energy spectra. For long bunches, the energy spectrum tends to be narrow and gaussian. In this case, the technique fails. For short bunches, the energy spectrum is wide, non-gaussian, and uniquely encodes the effect of klystron phases and longitudinal wakefields in the linac. At FACET, we are primarily interested in short bunch profiles, so this technique is almost always successful.

The inferred bunch profile has been compared to other bunch length measurements, specifically the TCAV, and found to be in general agreement. This validates the method. Unfortunately, we do not know *apriori* the simulation parameters needed to produce a matched energy spectrum. There are systematic phase drifts throughout the linac that are not reported by the kylstron phase readbacks. Other devices, like the compressor klystron, are known to be miscalibrated. In general, a large, multidimensional parameter scan in LiTrack is required to determine the correct machine parameters. This scan can be time-intensive, despite LiTrack's fast run time.

Flight Simulation with Extremum Seeking

We employ a novel technique to provide a real-time estimate of the bunch profile using a generic controls algorithm called Extremum Seeking (ES) [**?**]. The ES algorithm inputs a cost to be minimized and outputs a correction to the parameters of the system. In our case, the cost is the χ^2 residual between the measured and simulated spectra, and the system parameters are the inputs to LiTrack. ES can minimize the cost by varying an arbitrary number or parameters simultaneously. We simulate FACET with fourteen free parameters in code package called LiTrackES.

The ES algorithm and LiTrack are initialized with parameters that are assumed to be close to the real machine parameters. In general, the initial guess does not provide an accurate estimate of the measured energy spectrum, but ES evolves the simulation parameters to find the match. On average, it takes about 500 iterations of the algorithm (roughly 5 minutes) to find a match. Once a match is found, ES stabilizes the system so that it remains locked to the measured energy spectrum. We adjust the gain of the ES algorithm so that it is sensitive to machine drift and not shot-to-shot fluctuations.

Results with LiTrackES

LiTrackES was employed during a four hour run where we adjusted the machine parameters to change the bunch profile. Simultaneous measurements were taken with the TCAV, pyrometer, THz autocorrelator, and Smith-Purcell device. LiTrackES was found to be in agreement with the TCAV and pyrometer. At this moment, we do not have results from the THz autocorrelation or Smith-Purcell measurement. The obvious advantage of LiTrackES over the other methods was that LiTrackES provided real time bunch profile. The pyrometer is sensitive to peak current rather than bunch profile and the TCAV cannot be used every shot. The results of the run are shown in Figure **??**.

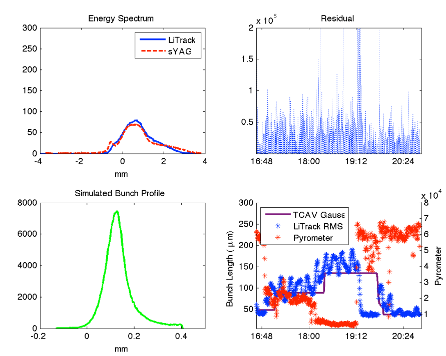

Figure 3: Comparison of LiTrackES with TCAV and Pyrometer over a four hour period. Note that the pyrometer varies inversely with bunch length.

CONCLUSION AND FUTURE WORK

LiTrack with the Extremum Seeking algorithm has successfully provided a real-time estimate of the bunch profile at FACET. LiTrackES currently operates in a passive mode, adjusting a virtual machine to match the real machine. Alternatively LiTrackES can be used as an active feedback, adjusting machine parameters in real time to produce a stable bunch profile. It can also be used to tune the machine to minimize the bunch length or match to a two-bunch profile for plasma wakefield experiments.

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ISBN 978-3-95450-122-9