START-TO-END PARTICLE TRACKING OF THE FACET ACCELERATOR*

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Abstract

The Facility for Advanced aCcelerator Experimental Tests (FACET) consists of the first two-thirds of the SLAC two-mile linac, followed by a final focus and experimental end station. To date, wakefield-dominated emittance growth and dispersion in the linac, along with dispersive and chromatic effects in the final focus, have precluded regular, reliable operation that meets the design parameters for final spot size. In this work, a 6-D particle tracking code, Lucretia, is used to simulate the complete machine, with input parameters taken directly from saved machine configurations. Sensitivities of various machine parameters to the final spot sizes are compared with measurements taken from the real machine, and a set of tuning protocols is determined to improve regular machine operation.

INTRODUCTION

Simulation of beam dynamics by particle tracking is a powerful tool for both the design and study of particle accelerators, especially where collective and nonlinear effects contribute significantly to the final performance of the machine. Of the many software packages available for this purpose, Lucretia [1] is a natural choice for FACET. It is designed specifically for single-pass linear accelerators and is implemented completely in Matlab, which integrates nicely with the existing EPICS-Matlab-AIDA control software ecosystem at SLAC [2]. In this paper, we present a new software interface that allows non-experts to run simulations and that pulls live machine configurations directly from the control system. Further, we discuss the results of studies tracking the FACET beam with this software from extraction at the SLC North Damping Ring (NDR) to the dump at the end of the beamline.

FSIM GUI DEVELOPMENT

fSim is a Matlab graphical interface to Lucretia, with a number of features intended to simplify its use and allow physicists and operations staff who are not experts in modeling to perform meaningful simulations of realistic scenarios in a matter of minutes. It is intended as a tuning tool to allow rapid iteration between simulated machine parameters and the real accelerator.

fSim takes as input a Lucretia data structure describing the beamline elements, klystrons, power supplies and so on derived from a MAD8 design deck, which may be modified on the fly to simulate nearly any conceivable reconfiguration of the accelerator. The default input beam distribution has been generated to match previous

measurements [3] of the electron beam at extraction from the NDR, but essentially any arbitrary input distribution may be generated by the user on the basis of incoming emittance and Twiss parameters, longitudinal distribution and so on. In addition to displaying the built-in Lucretia output of diagnostic devices (BPM positions, beam distribution statistics, and so on) the user can add flags to save the entire particle distribution at any number of locations, allowing more sophisticated plotting, fitting or offline analysis.
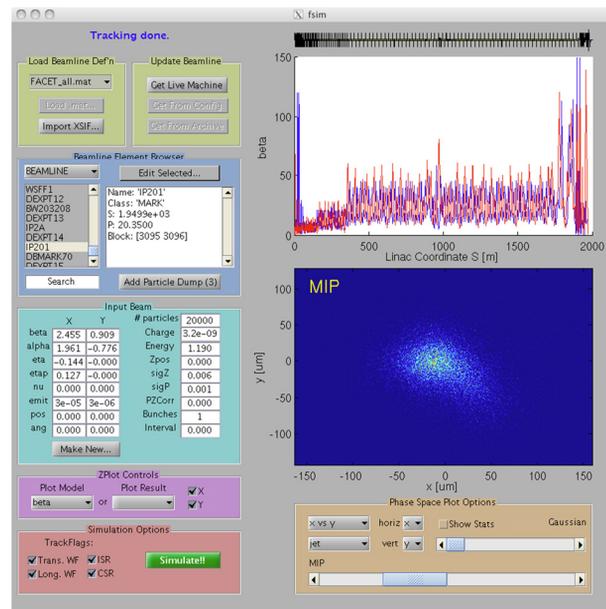
Figure 1: fSim interface with z-plot of Twiss functions and simulated beam profile at the FACET plasma IP.
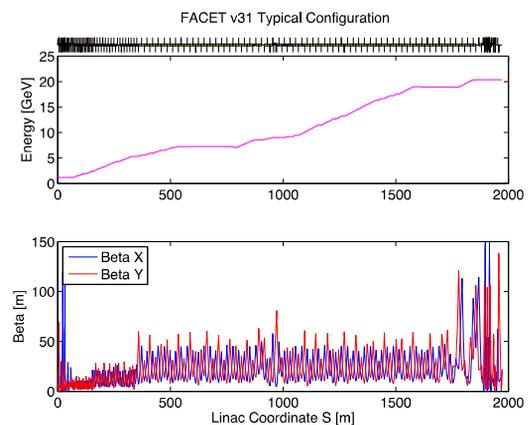
Figure 2: fSim model snapshot of accelerator state. The momentum profile (top) and Twiss functions (bottom) are calculated from control system readbacks of magnet excitation, RF amplitudes, etc.

Another useful feature is the ability to import the current or historical configuration of magnet setpoints, klystron amplitudes and phases, magnet mover positions and so on. Live values are retrieved via EPICS Channel Access or from the AIDA middle layer and are automatically input into the beamline data structure. In addition, previous machine states can be retrieved by importing values from saved configuration, or directly from EPICS Channel Archiver data. By default, certain areas of the accelerator that are used to correct for un-modeled optical errors – for example, the beta-matching section of the North Ring to Linac (NRTL) transport line – are not updated, preserving accurate beam transport.
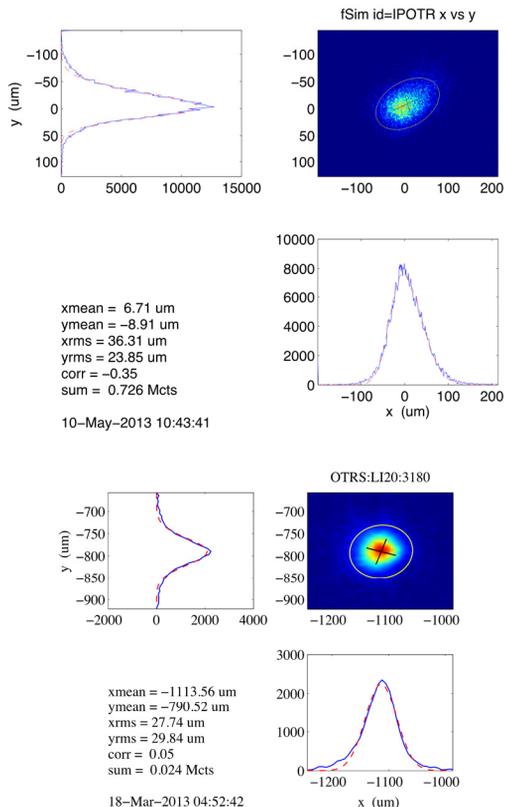
Figure 3: Simulated (top) and real (bottom) transverse beam profiles measured at the plasma IP diagnostic OTR.

Simulation of a single pass on the FACET production server takes 20-30 seconds to complete, depending on how the user has set flags for tracking wakefield contributions and synchrotron radiation losses.

FACET SIMULATION STUDIES

After the commissioning and first user run at FACET in 2012, stability and reproducibility were identified as key areas where improvements should be made.

RF Jitter Analysis

The phase and amplitude jitter of the 144 klystrons used to accelerate the FACET beam to its final energy of 20.35 GeV sets a limit on the pulse-to-pulse stability of the FACET beam. To study these effects, 200 random input pulses were simulated, each with random phase errors of 1 degree RMS applied to every klystron. The complement of active klystrons was imported from a typical machine state; transverse RF kicks were not modeled as part of this study, but could be pending a measurement of the kick for each cavity. Each pulse was tracked through the entire machine and output at the plasma wakefield oven IP.
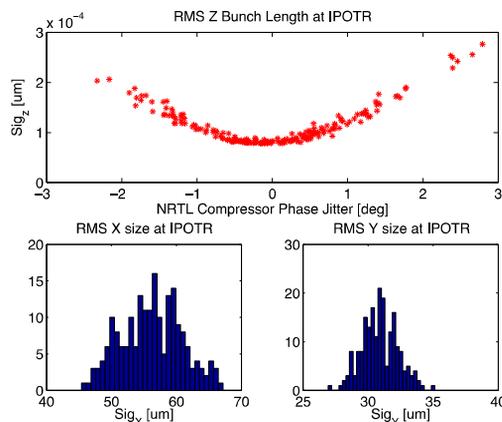
Figure 4: 200 tracked beams, each with 1 degree RMS random phase jitter applied to linac klystrons. Top: RMS bunch length at plasma IP is most sensitive to jitter in the NRTL compressor klystron. Bottom: Distribution of transverse beam sizes.

The final parameter most sensitive to the RF contribution was the final bunch length, which relies on the correct chirp contribution in the Linac Bunch Compressor Chicane (LBCC) in Sector 10. The most strongly correlated input was the NRTL compressor klystron, due to the high time-of-flight sensitivity to the beam energy in the transport line ($R_{56} \sim 0.6$ m). Work to stabilize the klystron by re-tuning the solid-state preamplifier and reducing multipacting in the load by means of additional vacuum pumping has reduced the real phase jitter to < 0.1 degree [4].

Orbit Sensitivity

Transverse emittance growth in the linac is a limiting factor in FACET's performance, especially for plasma wakefield acceleration experiments which require high charge densities at the IP. This emittance growth is largely due to head-tail instability excited by off-axis trajectories in the RF structures, and is exacerbated by the longitudinal energy chirp that provides anti-BNS damping. Typically, an empirical procedure is employed to tune down the emittance growth by optimizing the linac orbit, but this is a slow process and difficult to reproduce from day to day. Rather than steering the beam to the center of the quadrupole lattice, the solution converges to one where the wakefield contributions cancel.

Simulations were therefore undertaken to study the effect of misalignments of the RF structures to the quad

field centers. 30 different linacs were generated with random 0.1 mm RMS transverse misalignment of the disk-loaded waveguide cavities and the nominal FACET beam tracked through. Figure 5 shows the transverse emittance growth down each of these machines, with black traces for reference of the same beam with zero misalignments. Due to slight mismatch of the incoming beam, even the perfectly aligned case is not the best.

Nevertheless the results are instructive, as regardless of alignment, the tracked beams do not significantly deviate until approximately 700 m down the machine. In sectors 7-8 the emittance diverges quickly, but levels off and continues to grow linearly. This agrees nicely with operational experience, where final emittance values are typically highly sensitive to the beam orbit in this section, which is typically maintained to within a few tens of microns compared to the "gold" reference.
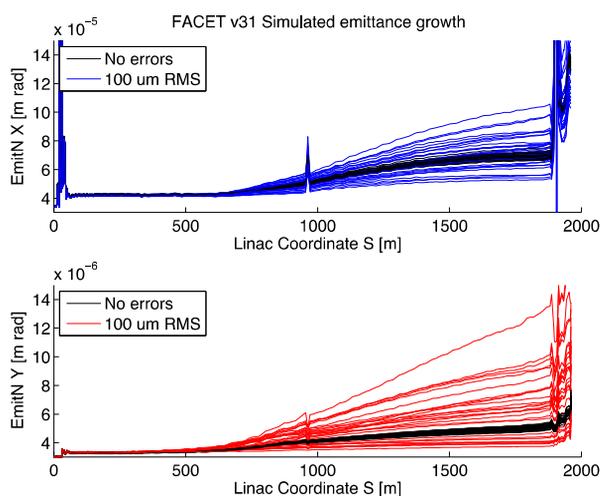
Figure 5: Effects of RF structure misalignment on horizontal (top) and vertical (bottom) normalized emittance growth in FACET. 30 beams are tracked to the dump, with random transverse offsets (0.1 mm RMS) applied to each end of the S-band accelerating structure. Results for perfectly aligned structures are plotted in black.

Table 1: Design, Typical and "best" Normalized Linac Emittance (cm-mrad) Measured at FACET. Significant Growth Particularly in the Vertical Plane is Evident Between Sectors 4 and 11

Location	Design $\varepsilon_x/\varepsilon_y$	Typical $\varepsilon_x/\varepsilon_y$	Best $\varepsilon_x/\varepsilon_y$
Sec. 2	3.0 / 0.3	3.3 / 0.33	2.9 / 0.25
Sec. 4	-- / --	4.0 / 0.35	2.5 / 0.25
Sec. 11	-- / --	7.0 / 0.8	5.5 / 0.5
Sec. 18	5.0 / 0.5	8.0 / 1.0	5.5 / 0.6

CONCLUSIONS AND FUTURE WORK

There are a number of planned additional features for the fSim software tool. These include correlation plot-style scanning of input parameters and/or automatic optimization with respect to output parameters like spot size, bunch length, etc. The next step would then be to add the inverse of the machine "get" operation and implement a "put" operation for outputting the optimized machine to the control system. Additionally, since fSim is generically written, the author hopes that other accelerators, in particular, LCLS can be modeled as well.

From the point of view of FACET accelerator physics specifically, further study of emittance growth mechanisms is needed, particularly in understanding the wakefield-dominated growth in Sectors 7-8, dispersion generation due to quadrupole misalignments, and other optical errors. Proposed ideas for suppressing the wakefield growth, such as new longitudinal chirp schemes, alignment tolerances, or lattice changes that desensitize the machine to this instability should be studied in software before implementation. Hopefully, with a new tool allowing rapid iteration between real and simulated beams, FACET performance and availability will continue to improve.

REFERENCES

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[3] R. Holtzapple, SLAC-R-0487, Ph.D. Thesis, June 1996.

[4] F. J. Decker *et al*., "Performance Improvements of the SLAC Linac for the FACET Beam", TUPWO068, these proceedings.