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FEL Trajectory Analysis for the VISA Experiment*

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Abstract

The Visual to Infrared SASE Amplifier (VISA) [1] FEL is designed to achieve saturation at radiation wavelengths between 800 and 600 nm with a 4-m pure permanent magnet undulator. The undulator comprises four 99-cm segments each of which has four FODO focusing cells superposed on the beam by means of permanent magnets in the gap alongside the beam. Each segment will also have two beam position monitors and two sets of x-y dipole correctors. The trajectory walk-off in each segment will be reduced to a value smaller than the rms beam radius by means of magnet sorting, precise fabrication, and post-fabrication shimming and trim magnets. However, this leaves possible inter-segment alignment errors.

A trajectory analysis code has been used in combination with the FRED3D [2] FEL code to simulate the effect of the shimming procedure and segment alignment errors on the electron beam trajectory and to determine the sensitivity of the FEL gain process to trajectory errors. The paper describes the technique used to establish tolerances for the segment alignment.

1 INTRODUCTION

The Visible to Infrared SASE Amplifier (VISA) experiment [1], proposed by a collaboration of several institutions in the United States, is designed to provide a complete test of the Self-Amplified-Spontaneous-Emission (SASE) Free-Electron-Laser (FEL) theory in the wavelength region between 600 to 800 nm. The experiment will be carried out at the Accelerator Test Facility (ATF) at the Brookhaven National Laboratory (BNL). The ATF linac will be upgraded for this experiment to reach the required electron energies of up to 85 MeV. The present schedule for the experiment aims to obtain a complete set of data by Spring 1999.

2 SYSTEM DESCRIPTION

The VISA undulator comprises four 99-cm segments of arrays of pure permanent magnet blocks with a period length of 1.8 cm. Pairs of small permanent magnet dipoles of opposite orientation are arranged alongside the undulator, to provide an array of alternating gradient quadrupole fields (FODO Lattice), that can maintain an average β-function of 30 cm at 600 nm and 27 cm at 800 nm. The FODO cell length is 24.75 cm (one quarter of a segment length), a compromise between a requirement for small β-funtions and practical considerations. The magnet positions are not adjustable.

Table 1: Basic VISA FEL Parameters.

Electron Beam Parameters:	
Electron Energy	72.6-83.8 MeV
Norm. Electron Beam Emittance	2 mm mrad
Peak Current	200 A
RMS Bunch Length	428 μm
RMS Beam Radius	62-60 μm
Uncorrelated Energy Spread	0.18-0.15 %
Undulator Parameters:	
Undulator Period	1.8 cm
Peak Magnetic Field	0.75 T
Resonant Wavelength	600-800 nm
FEL Parameters:	
FEL Parameter ρ (1D)	$88\text{-}77 \times 10^{-4}$
Rayleigh Length	30-38 mm
Power Gain Length	17.1-19.1 cm
Error Free Saturation Length	3.4-3.8 m
Quadrupole Focusing (FODO Lattice):	
Cell Length	24.75 cm
Quadrupole Length	9 cm
Quadrupole Gradient	33.3 T/m
Ave β-function	0.27-0.30 m
Electron Trajectory Correction:	
Steering Coil Separation (Center)	0.5 m
Number of Steering Coils each plane	2 /m
Max. Correction Field	50 G
Effective field length	20 cm
Max. Kick Angle	4.1-3.6 mrad
Number of Crystal Monitors (BPMS)	2 /m

Mechanical and magnetic errors of the undulator that remain after sorting and installation will be corrected by magnet measurements and shimming. The magnet measurements will use a pulsed stretched wire system [3, 4], which reads the electron trajectory directly. It is expected that the random walkoff of the trajectory over the length of two segments can be kept below the rms beam radius.

When the undulator segments are measured and shimmed, the positions of tooling fixtures mounted on them will be recorded, and these positions will be used to align the segments into position. The crucial task in this process is relating the position of the pulsed wire used to find the focusing axis to these fiducials. It is the main subject of this paper to determine tolerances for this alignment process.

During operation, the beam position is measured with intercepting YAG crystal beam position monitors. The beam spot on the YAG crystal is transferred out of the undulator by a periscope and imaged with a video camera. The position of

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the beam is measured relative to a reticle that is projected onto the camera. Beam position monitors are located at the 25 and 50 cm points of each segment.

The beam position is corrected with a pair of trim coils in each plane. Kick angles of up to about 4 mrad are achievable.

3 CORRECTION STRATEGY

Trajectory correction studies have been performed to determine the number of BPMs required per quadrupole and to evaluate the effectiveness of various steering methods. Simulated e^- trajectories are generated which include 50 μm rms random quadrupole magnet and BPM misalignments for the cases of one BPM per quadrupole, one BPM per 2 quadrupoles, and one BPM per 4 quadrupoles. A weighted steering is performed using a dipole corrector well upstream of each BPM. The trajectories are then used in the FRED3D code to test their impact on FEL gain (see description below). Only the trajectories produced with the sparse case of one BPM per 4 quadrupoles show significant impact on FEL gain. The first two cases are superior, but they are also technically impractical, requiring 32 and 16 total BPMs, respectively, over the 4-m undulator. The third, more practical, case of 8 total BPMs is only acceptable if post-fabrication shimming of the undulator magnets is done based on alignment measurements of the quadrupole centers using a pulsed stretched wire [3, 4]. With this method, alignment of the quadrupoles can be achieved to a level of 5-10 μm which justifies the chosen layout of one BPM per 4 quadrupoles (2 BPMs per 99-cm undulator segment).

In this configuration, however, beam-based alignment, as proposed for the LCLS undulator [5], is difficult to apply to the VISA undulator. Its sparse number of BPMs per quadrupole, finite BPM resolution, and the limited energy stability of its focussing array negate the usefulness of this method. The alignment tolerances therefore must be prescribed carefully and their impact on FEL gain fully evaluated. To this end, a trajectory simulation code is linked to FEL gain calculations to test the prescribed alignment tolerances and steering algorithms.

4 TRAJECTORY SIMULATIONS

FEL dynamics does not significantly affect the transverse electron trajectory. To test the impact of various alignment errors, a computer code was written which generates electron trajectories through the undulator. The code includes misalignments of the BPMs and undulator segments, the 5-10 μm misalignments of the quadrupoles within the segment, and a weighted steering algorithm. The simulated errors included in the code are summarized below. Each effect is applied independently to the horizontal and vertical planes.

INTERNAL SEGMENT ERRORS: Each 99-cm undulator segment includes misalignments of its 8 quadrupole magnets which approximately replicates the trajectory produced by the pulsed wire alignment. The e^- trajectory is randomly distorted but bounded by ± 50 μm (i.e. the trajectory does not increase as a random walk).

EXTERNAL SEGMENT ERRORS: Each rigid segment is randomly misaligned (gaussian) at both ends by 50-150 μm rms as described below.

RANDOM BPM MISALIGNMENT: Each BPM is randomly misaligned (gaussian) by 50 μm rms.

WEIGHTED STEERING ALGORITHM: BPM readbacks and associated corrector changes are simultaneously minimized, in a least squares sense, so that unnecessarily large corrections are not applied.

No incoming trajectory launch errors are included here. It is expected that such effects are correctable by using steering elements and mutually aligned BPMs which are upstream of the undulator. Several different rms misalignments and random seeds are used to create various steered e^- trajectories which are then fed into the FRED3D code via undulator dipole errors (x and y).

5 FEL SIMULATIONS

5.1 *Description*

The effect of trajectory errors on FEL performance has been studied using the monochromatic FEL simulation code FRED3D [2]. FRED3D simulates the interaction between the electron beam and the optical field in the wiggler of an FEL amplifier. The effects of pole-to-pole errors in the wiggler magnetic field on the centroid motion of the electron beam and on relative electron-to-radiation phase are included: in each half-period, a transverse momentum increment corresponding to the magnetic field error at that magnetic pole is added to the motion of each particle.

The deviation of the transverse trajectory from a straight line reduces the overlap between the electron and photon beams and causes de-phasing of the electrons with respect to the FEL ponderomotive potential wells. The field errors are normally chosen from a truncated Gaussian distribution. Recently, the code has been modified by its author [6] to accept a list of pairs of pole errors.

5.2 *Evaluation*

Each simulated e^- trajectory is converted to a set of undulator dipole errors which replicates both the horizontal and vertical trajectories. In this conversion, the β-function through the undulator is taken as a constant since FRED3D requires a constant focussing gradient. A file describing the set of relative dipole errors is read into FRED3D where the original simulated trajectory is reproduced.

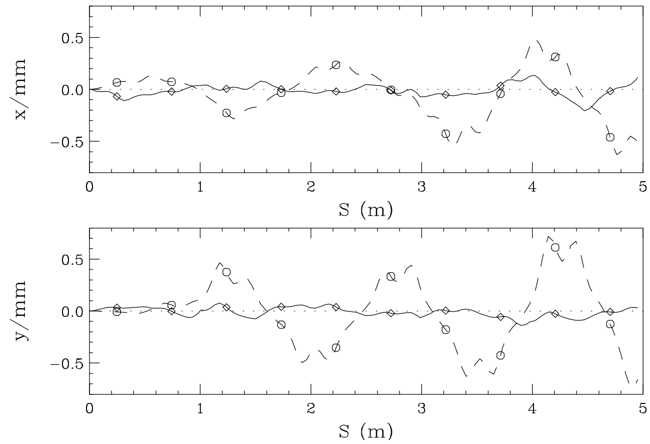

Figure 1: Horizontal and vertical e$^-$ trajectory through the VISA undulator before (*dashed*, $\sigma_x = 238$, $\sigma_y = 331$ μm) and after (*solid*, $\sigma_x = 59$, $\sigma_y = 45$ μm) steering for 50 μm BPM and external segment misalignments.

Three different random seeds are used per amplitude of misalignment. External segment misalignments of 50, 100, and 150 μm rms plus a constant random BPM error of 50 μm rms are used, for a total of 9 different tested trajectories. Fig. 1 shows an example horizontal and vertical trajectory, both before and after the weighted steering is applied, for random external segment and BPM misalignments of 50 μm rms. The small, bounded internal quadrupole misalignments are also included. The simulations use a 4.95-m undulator (i.e. one additional segment) so that the saturation length can be calculated well past the 4-m point.

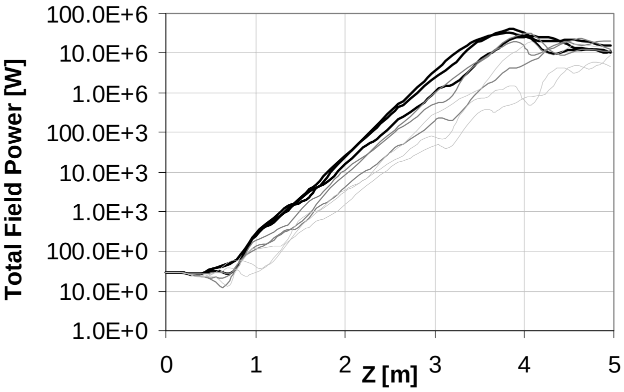

Figure 2: Predicted development of the peak radiation power of a typical VISA radiation pulse for 3 different segment alignment tolerances and 3 different random seeds. Curves from the same segment misalignments are plotted with the same pen: dark: 50 μm, medium: 100 μm, light: 150 μm.

Each trajectory is used in the FRED3D FEL code to determine the new saturation length. Figure 2 displays the predicted development of the peak radiation power for the nine different trajectories. Fig. 3 shows the saturation length and saturation power for the 9 trajectories, plotted versus the net horizontal and vertical rms of each trajectory, $\sigma_{x,y}$, defined as $\sigma_{x,y} = \sqrt{(\sigma_x^2 + \sigma_y^2)/2}$, where σ_x and σ_y are the rms amplitude of the horizontal and vertical trajectories.

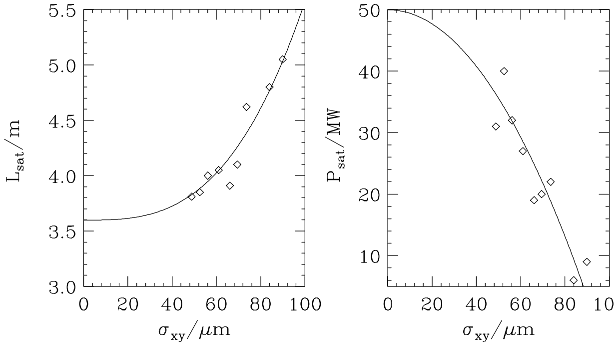

Figure 3: Saturation length, L_{sat}, and power, P_{sat}, versus combined x and y rms amplitude of e$^-$ trajectories. The solid line is a polynomial fit to the data.

The data are fitted to empirical polynomials ($L_{sat} = L_0 + a\sigma_{x,y}^3$, $P_{sat} = P_0 - b\sigma_{x,y}^2$) which are forced through $L_0 = 3.6$ m and $P_0 = 50$ MW, respectively, at $\sigma_{x,y} = 0$. The results show that random external segment and BPM misalignments should both be <50 μm rms in order that saturation occurs at a length less than 4 m.

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7 REFERENCES

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