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WAKEFIELD EFFECTS IN THE ADVANCED PHOTON SOURCE LINAC*

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Abstract

A free-electron laser (FEL) based on self-amplified spontaneous emission (SASE) is currently under commission at the Advanced Photon Source (APS).

The APS SASE FEL [1] requires a high-brightness, low-emittance, and low-energy spread beam. A photocathode rf gun coupled to the APS linac is the source of the beam. Transverse wakefields generated by misalignments of the accelerating structures can degrade the beam emittance and result in large transverse trajectory errors. Effects due to random consecutive-cell misalignments, alignment errors of the accelerator components, and long-wavelength distortions on a given structure are studied by simulation. The highest emittance dilution comes from alignment errors (steps) between the rf structures. Also, the large centroid excursions cause large beam losses. It is shown that trajectory corrections help reduce emittance growth and mitigate particle losses. The linac rf-structure misalignment tolerance has been set at 350 μm rms [2]. The emittance dilution of a 5-mm-rad beam due to step errors of the order of 500 μm rms can be reduced to less than 1% by trajectory correction alone. Various means to reduce emittance dilution by closed bumps are also investigated.

1 INTRODUCTION

The APS linear accelerator provides the beam for the APS SASE FEL. The electron beam requirements are small normalized emittance, low energy spread, and high peak current. In addition there are tight requirements on the beam stability. Longitudinal and transverse wakefields affect strongly the beam emittance and trajectory. In this paper, we address the effects on the beam quality due to transverse wakefields generated by accelerating structure misalignments. We used the program 'elegant' [3] to simulate effects of random misalignments between two consecutive cells of a given accelerating structure, alignment errors between two consecutive structures, and long-wave distortions over a single structure.

The APS linear accelerator is about 50 m long, divided into five sections designated by L1,...,L5. There are thirteen SLAC-type S-band 3-m-long traveling-wave accelerating structures. The photoinjector, L1, consists of a photocathode gun and one accelerating structure. The photoinjector delivers a 0.5- to 1.0-nC beam at about 43 MeV. L2 consists of four accelerating structures driven by a single SLEDed 35-MW klystron. L3 contains a bunch compression system that will provide higher bunch peak current; it is presently being commissioned. In our simulations, L3 is a drift space. L4 and L5 have a total of eight accelerating structures, each section consisting of four SLEDed waveguides. A 20-m-long transport line follows the linac proper. The complete linac can deliver a maximum of 650 MeV.

2 LOW-ENERGY-LINAC SIMULATIONS

In the simulations, the accelerating structures are approximated by periodic, cylindrically symmetric, disk-loaded structures of period 3.5 cm. The transverse wakefield is restricted to the dipole mode and depends linearly on the transverse displacement of the exciting charge. To determine the source of alignment or construction errors that most affected the beam-emittance dilution, we used an idealized six-dimensional particle distribution, perfectly symmetric, of 0.001 standard momentum deviation, 1 ps long, and mean energy 43 MeV. In these initial studies, we limited the tracking to L2, the first section after the photoinjector, where the energy is no greater than 250 MeV and the effects from wakefields are most damaging, since the resultant perturbing force is inversely proportional to the beam energy. In the absence of longitudinal wakefields, the beam is accelerated on the rf wave crest. In general, 10,000 macroparticles and, where applicable, ten to thirty sets of random numbers were used in the simulations. We varied the beam peak current from 100 to 500 A, the normalized transverse emittance (ε_N), from 1 to 5 mm mrad, random step-misalignments between two consecutive accelerating structures (Δ), and random misalignments between two consecutive cells of the same structure (δ), both errors in the range of 0.5 to 2.0 mm rms.

For $\Delta > 0.5$ mm rms we observed significant particle losses, which were fairly independent of the initial emittance and caused by the large wakefield-induced transverse oscillations. To obtain a meaningful measure of the emittance growth, we consequently assumed an iris aperture of 1 m, effectively ignoring losses. Without aperture restrictions, a beam at 500 A (peak current) with step misalignments of 2.0 mm rms can have trajectory distortions up to 10 cm. The large aperture does not affect the wakefield calculations since 'elegant' uses a Green's function method to calculate the wakefields with a pre-

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selected Green's function that is independent of the particular aperture used in the tracking.

Figure 1 shows the horizontal emittance growth versus step misalignments for a beam of 1 mm mrad initial emittance and three different values of peak current. In the figure, the vertical axis shows the mean normalized emittance, averaged over ten seeds. The emittance spreads are large and are omitted for clarity.

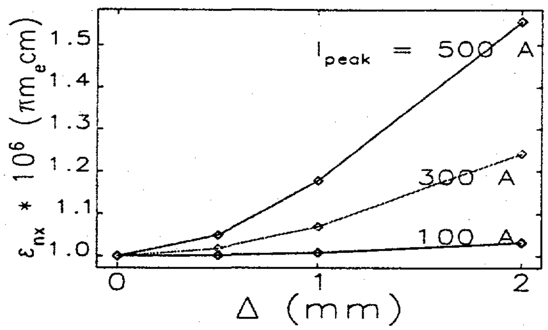

Figure 1: Emittance growth versus random step misalignments, averaged over ten seeds.

In Figure 2 we compare the horizontal normalized emittance growth versus distance along L2 for two types of misalignment at the 2-mm-rms level. The initial emittance is 5 mm mrad and the peak current is 500 A.

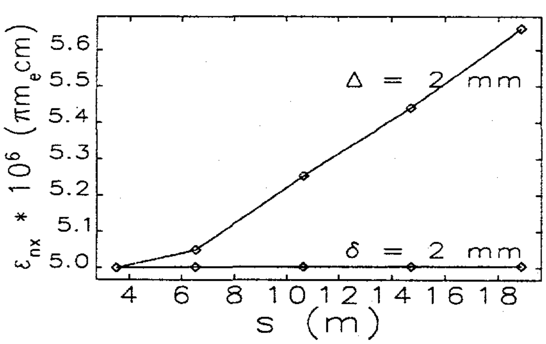

Figure 2: Emittance growth versus consecutive cell misalignments (δ) and consecutive structures (Δ).

For a fixed peak current, the incremental emittance growth, defined as the final average value minus the initial value, is fairly independent of the initial beam emittance. For the same type of error, e.g., Δ-step errors, the emittance grows linearly with the current. As expected, for a fixed current and initial ε_N, the emittance grows exponentially with random error levels [3], as can be seen in Figure 1.

We also examined effects from cell-to-cell distortions, which follow a sinusoidal distribution. We simulated sinusoidal distributions of wavelengths half, equal to, and double the length of the accelerating structure, and of various amplitudes. For low amplitude values there was no significant emittance dilution. A 6-m-long, 2-mm amplitude distortion results in 3% dilution, compared to, for instance, 50% average dilution for Δ-step misalignments of 2-mm-rms error, at the same beam peak current of 500 A.

3 LOW- TO HIGH-ENERGY LINAC

In April 2000, the APS linac was upgraded to provide the FEL requirements of high beam quality and stability. A bunch compressor was designed [2], and the entire linac lattice was changed to accommodate the future compressor components and requirements. Several lattice configurations were modeled for different acceleration gradients and beam currents. As described in [2], effects of longitudinal wakefields such as beam loading were minimized by proper phasing of the rf voltage along the linac. The betatron functions were kept low and of similar magnitude in both planes. We examined these configurations for their sensitivity to accelerating structure misalignments (Δ-steps) and the consequent effects on the beam-centroid motion and emittance distortion.

3.1 Uncorrected Trajectory

In all simulations referred to in this section, tracking extends from the end of the photoinjector to the end of the post-linac transport line, ending at the first screen of a three-screen emittance measurement section, which is our reference point for emittance growth and final beam parameters. The input beam distribution is obtained from a typical PARMELA simulation from the photocathode gun to the end of the first accelerating structure, and filtered to 93% of the beam, corresponding to 2.43 mm and bunch length of 1.8 nanoseconds. The initial normalized transverse emittances are about 4.8 mm mrad in both planes. In general, 11,000 macroparticles were tracked, and ten seeds were sampled for each error level. The following results refer to a configuration that accelerates a beam containing 160 A of peak current from 43 MeV to 135 MeV in the L2 section to the beam final energy of 217 MeV in L4. The energy remains constant in L5. Figure 3 shows the final emittance growth versus Δ-steps, averaged over ten seeds. In the figure, squares indicate the final normalized horizontal emittance, before trajectory corrections. For Δ=1.0 mm-rms, they represent 86% emittance growth.

3.2 Corrected Trajectory

From L2 to L5, the beam is focused by thirty large-bore quadrupoles placed around the accelerating structures, and by seven quadrupoles in the transport line. Each accelerating structure is flanked by bipolar dipole correctors. In Figure 3, the pluses depict the horizontal emittance growth after trajectory correction. With trajectory correction, there is less than 1% dilution for misalignments up to 0.5 mm rms. For higher errors, the average growth is reduced to 2-6%. There are residual trajectory oscillations that are not reduced by further iterations of the correction algorithm. In all cases, the required corrector strengths are well within their current limits' specifications.

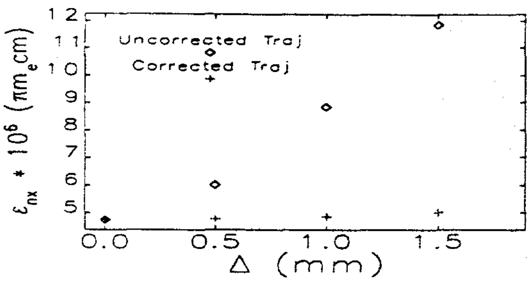

Figure 3: Emittance growth versus step misalignments before and after trajectory correction.

3.3 Emittance Bumps

Strategically placed local trajectory oscillations can help reduce emittance growth [4]. This technique, known as the "ε-bump technique," induces additional trajectory excursions to cancel the effects of those caused from other sources, such as transverse wakefields. By minimizing the beam oscillations at the end of L2 with a four-magnet closed bump and then minimizing the oscillations at the end of L5, also with a four-magnet bump, we can reduce the final growth to about 1%. In Figure 4(a) we show the beam-centroid displacements before and after application of the ε-bumps, depicted by continuous and dashed lines, respectively. The plots are drawn for a typical seed and for step misalignments of 1.5-mm rms. Figure 4(b) depicts the corresponding emittance growths. The results shown were obtained without prior trajectory correction, which would have reduced the beam oscillations.

4 SUMMARY

Emittance growth due to transverse wakefields arising from accelerating structure misalignments can be quite large. Without trajectory correction, for a beam carrying 0.8 nC and peak current of 160 A, an initial emittance of 5 mm mrad can reach 6 mm mrad for random steps misalignments of 0.5 mm rms. At higher error strengths, there are considerable particle losses due mainly to the beam large trajectory excursions. Trajectory correction helps reduce the emittance growth by more than 20%. Carefully placed ε-bumps can also reduce the final emittance. In April 2000, the APS linac was completely realigned, with the accelerating structures alignment tolerance set to 350 μm. Within these specifications, the transversal emittance growth due to accelerating structure misalignments alone could be kept to less than 1%.

ACKNOWLEDGMENTS

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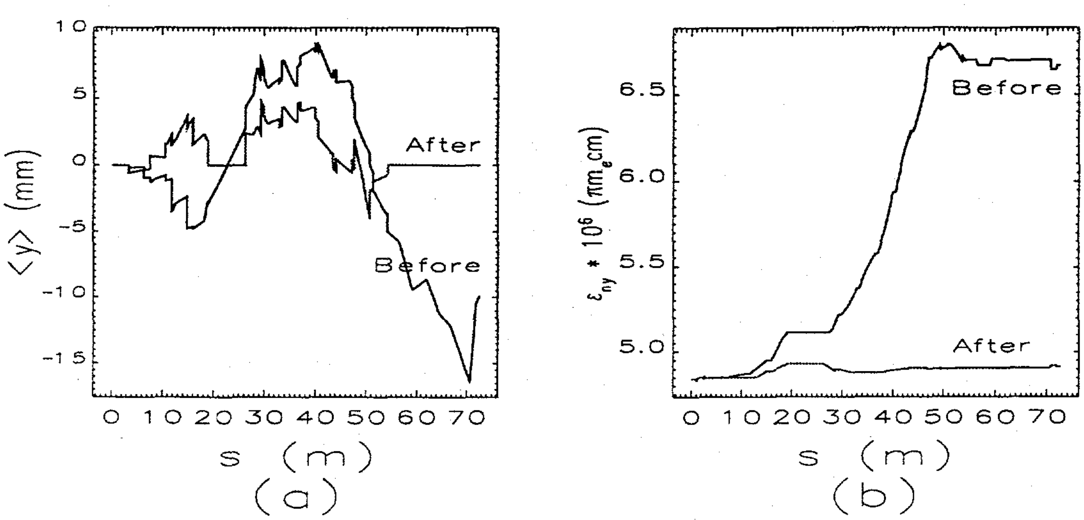

Figure 4: Trajectories (a) and emittances (b) before and after application of "ε-bumps."