EMITTANCE GROWTH CAUSED BY BENDS IN THE LOS ALAMOS FREE-ELECTRON LASER ENERGY RECOVERY EXPERIMENT*

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Abstract

Experimentally transporting the beam from the wiggler to the decelerators in the energy recovery experiment (ERX) at the Los Alamos National Laboratory free-electron laser was more difficult than expected because of the large initial emittance in the beam. This emittance was apparently caused in an early 60° achromatic bend. To get this beam through subsequent bends without wall interception, the quadrupole focusing had to be changed from the design amount; as a result, the emittance grew further. This paper discusses various mechanisms for this emittance growth in the 60° bend, including effects caused by path changes in the bend resulting from wake-field-induced energy changes of particles in the beam and examines emittance filters, ranging from a simple aperture near a beam crossover to more complicated telescope schemes designed to regain the original emittance before the 60° bend.

Introduction

The ERX at the Los Alamos free-electron laser (FEL) studied the possibility of recovering energy by directing the electron beam to a series of decelerators,[1] after the beam caused lasing in the wiggler. These decelerators would recover a large amount of the beam's energy, which was not used in lasing. The decelerators and accelerators would be driven jointly through a bridge coupler;[2] if the recovered energy exceeded the ohmic losses in the decelerators, it could succeed in partially driving the accelerators, thereby increasing the overall electronic efficiency of the lasing significantly. In the experiment performed, the average beam current was so low that, in fact, the rf losses in the decelerators were greater than the recovered energy; thus the experiment only served as a proof-of-principle test.

Because the coupling scheme was designed for low losses, the accelerators and decelerators were placed close to one another, resulting in a folded beamline (Fig. 1). After the wiggler, the beam enters a 180° bend with two coupled pairs of quadrupole singlets tuned to make it isochronous (and thus achromatic). Later, the beam enters a 60° bend with one coupled pair of quadrupole singlets to make it also isochronous. Then, the beam goes through a matching section of four singlets and enters the decelerators. Simulations using the particle tracking code PARMELA show that if the unnormalized beam emittance is greater than 20 π·mm·mrad, the four quadrupole singlets cannot satisfactorily match the beam. Emittance is defined as the area of the transverse phase-space contour containing 90% of the beam.

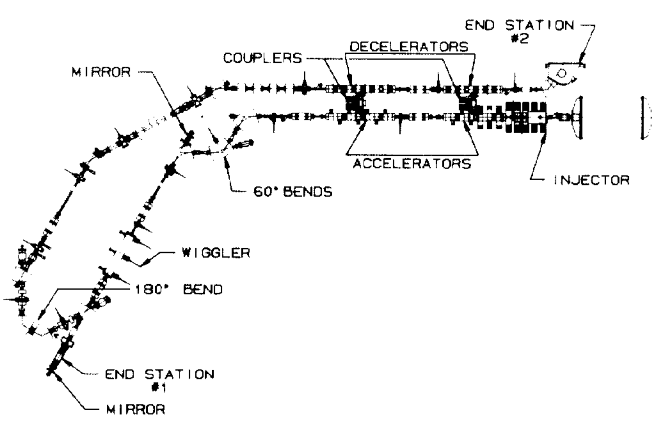

Fig. 1. ERX beamline.

Simulations show that the current transport through the beamline depends critically upon the beam's emittance. For beams with emittances greater than 3 π·mm·mrad at the entrance to the 180° bend, the beam will grow sufficiently in the bend to start scraping along the beam walls. Thus, the quadrupole pairs have to be varied from their isochronous (and achromatic) settings to regain 100% beam transmission. Because the bend is no longer achromatic, the beam's emittance begins to grow in the bend. As the initial beam emittance is increased to 4 π·mm·mrad, the emittance at the end of the bend grows to 14 π·mm·mrad, and as the initial emittance is increased further, the final emittance quickly grows to the point that the beam cannot be matched into the decelerators. More fundamentally, a large initial emittance is undesirable because it degrades the lasing.

Initial PARMELA simulations of the beamline to the start of the 180° bend indicated emittances of only 3 π·mm·mrad. In the same position, however, the actual beam had emittances of up to 15 π·mm·mrad with high-beam current, resulting in beam blowup in the decelerators. By decoupling and retuning the quadrupole singlets, we matched the beam into the decelerators and achieved successful energy recovery.[1] The majority of the unexpected emittance growth measured at the 180° bend apparently took place in the 60° achromatic bend, possibly caused by

- misalignment and asymmetries in the bend,
- energy-independent, radial space-charge forces in the bend,[3] and
- path deviations in the bend caused by particle-energy changes from wake fields.

Mechanisms for Emittance Growth

Misalignments or Asymmetries in the Bend

The achromatic 60° bend, shown in Fig. 2, is fairly insensitive to small changes in its layout. The following list describes the emittance growth resulting from various misalignments. The labels D1, D2, and D3 refer to the first, second, and third magnets in Fig. 2, respectively. The number in parentheses after a magnet label refers to the angle it actually bends the beam. For example, D1(60) means that the first magnet bends the beam 60°. The last

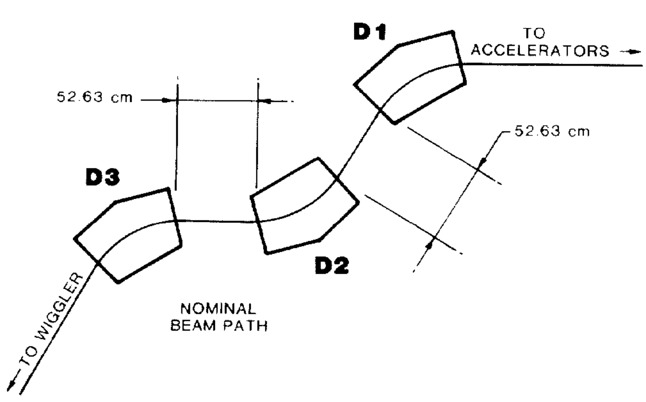

Fig. 2. Design of 60° achromatic bend. All edge angles are 17°. Path length in the dipoles is 50 cm.

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three entries in the table refer to the cases in which the dipoles are cocked so the beam is bent out of the plane of the beamline (Fig. 2). These calculations, using PARMELA, were done with a beam of initial emittance 1.5 π·mm·rad. The magnitude of all the errors reported here is suspected to be much larger than the actual misalignments.

Error	Change in Emittance (π·mm·mrad)
Both beam drifts are 2.5 cm longer	0.03
First beam drift is 2.5 cm longer	0.40
D1(59), D2(58), D3(59)	0.35
D1(59), D2(60), D3(61)	1.42
D1(60), D2(59), D3(59)	1.18
D1(59), D2(59), D3(60)	1.34
First dipole rotated 1° clockwise	1.10
Second dipole rotated 1° clockwise	1.61
Third dipole rotated 1° clockwise	1.40
First dipole raised 5° out of plane	1.26
Second dipole raised 5° out of plane	1.10
Third dipole raised 5° out of plane	1.12

Although some of these growths represent a large percentage of the initial beam emittance, they only increase the overall emittance to about 5 π·mm·mrad. These increases probably add in quadrature, and they are independent of the original beam emittance.

Energy-Independent, Radial Space-Charge Force

An electron bunch, which is being bent, feels a radial force in a dipole field, caused by the difference in the curl part of the space-charge vector-potential equation when the A_z term (linear motion) is replaced by an A_r term (circular motion).[3] This extra term appears in the magnetic field as

$$\vec{B} = \vec{B}_{usual} + \hat{z}\,\frac{1}{r}\,A_\theta \ ,$$

which results in an energy-independent radial force. The term $\vec{B}_{usual}$ is simply the usual magnetic field found in linear motion. The emittance growth caused by this effect scales linearly with beam width, peak current, and with the angle of deflection. By including this force in PARMELA simulations of the 60° achromatic bend, its effect can be estimated.

Case	Initial Emittance (π·mm·mrad)	Final Emittance (π·mm·mrad)
Beam not focused in bend	2	7
Beam focused in bend	3	2

The beam is focused with a quadrupole triplet located roughly 1 m in front of the start of the bend. The beam is about 1.75 cm in diameter without focusing and about 0.3 cm in diameter with focusing. The initial emittance is greater in the focused case because the radial space-charge forces are greater with a smaller beam. In the simulations, roughly one-quarter of the particles were scraped in the bend, which accounts for the drop in the emittance in the second case.

These simulations were for a peak current of 200 A (measured right after the bend), which is similar to the peak currents actually seen. The radial space-charge force appears to be too small to account for most of the emittance growth in the bend.

Longitudinal Wake-Field Effects.

Although transverse wake-field effects may be important, they are smaller than the effects of the longitudinal wake fields in the 60° achromatic bend. Simply stated, the longitudinal wake field changes the path of the particles because their energy has now changed. If this change occurs in the middle of the bend, because of a scraper, the beam box to beam pipe transitions, or the beam pipe bellows between the dipoles, then the bend is no longer achromatic. In Fig. 3, we see the effect of depressing one particle's energy at the center of the bend. The particle is displaced from its unperturbed position at the exit of the third magnet and its exit trajectory is not parallel to the unperturbed trajectory. For the case in Fig. 3, the particle experiences a 1% energy depression at the center of the bend and, as a result, is translated 3 mm transversely and exits at a relative angle of 0.6°. This translation and rotation is linear with respect to the energy depression of the particle; with a 1/2% energy depression, I expect to see a 1.5-mm translation and a 0.3° rotation. There is a crossover of all the perturbed and unperturbed trajectories located 28 cm from the exit plane of the last magnet. When averaged over all the particles and their different energy losses, there is a range of particle displacements and rotations, which is an emittance growth.

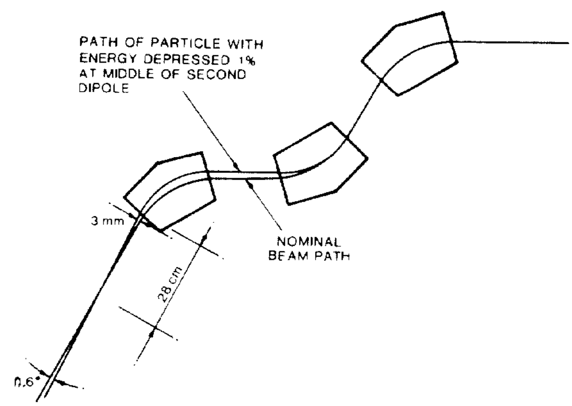

Fig. 3. Comparison of trajectories in the 60° achromatic bend of a nominal particle and one whose energy is depressed 1% at the middle of the bend. The trajectories form a focus 28 cm after the last pole face. The figure is not to scale.

Knowing the magnitudes of these translations and rotations allows me to determine how beam size affects emittance growth. For example, with a 1% energy depression, one can calculate what happens to a beam with an initial emittance of 2 π·mm·mrad and various diameters. If the beam diameter is large (1.7 cm), then the divergence of any particle, given by the emittance divided by the radius initially can vary up to 0.6 mrad (±0.3 mrad). If the beam trajectory is altered by 3 mm and 30 mrad, then the final beam size is roughly the same, but now a particle's divergence can vary over 30 mrad, so the emittance has grown by a factor of 50.

Toward the other extreme, if I start with a very small cross-section beam (0.06 mm in diam), then a particle's divergence is limited to 60 mrad. If the beam passes through the bend and the particles have their trajectories altered in the same way, then the opposite happens. The beam divergence does not change much, but the beam size becomes 3 mm, resulting again in an emittance growth of a factor of 50. An intermediate case, with a beam size in the middle, (3-mm diam) leads to less emittance growth. Now the beam divergence is limited to about 2 mrad. The 3-mm translation and 30-mrad rotation yield an emittance growth of about 30 π·mm·mrad, a factor of 15. Using PARMELA to simulate this effect, I come up with the following list, which agrees well with the above simple picture:

Case	Initial Emittance (π·mm·mrad)	Final Emittance (π·mm·mrad)
Energy depression, 1% (unfocused)	2	76
Energy depression, 1% (focused)	3	15
Energy depression, 1/2% (unfocused)	2	39
Energy depression, 1/2% (focused)	3	8

The beam cannot be focused to less than 3 mm at the entrance of the bend because of the great distance (about 1 m) between the focusing quadrupole triplet and the start of the bend. As before, particles are scraped going around the bend, and because there is almost a uniform distribution of particles with energy depressions between none and the full 1%, the 90% emittance contours should be somewhat lower than the earlier estimates.

These calculations are for a single source of wake-field generation; in particular, they are for a scraper in the middle of the second 60° magnet. Preliminary calculations using wake fields from the beam-box transitions in the magnets show very similar results.

The measured beam size is about 1 cm and the observed emittance is 16-20 π·mm·mrad. This emittance corresponds to an energy depression of about 0.4%, which is consistent with wake-field calculations of the beam-box transitions. Energy diagnostics show energy depressions as large as 3%, but the diagnostics are farther downstream, and the depression is caused, in part, by wake fields in the region after the bend.

Use of Filters to Eliminate Emittance Growth

A simple aperture is a good emittance filter. A quadrupole triplet can produce a beam waist either in front, at, or behind an aperture. The effectiveness of emittance filtering is measured by the ratio of the initial to final beam brightness, which is proportional to the beam current divided by the total transverse emittance. In Fig. 4, this ratio is plotted for the three different focusing situations as a function of beam transmission. The plot shows that very satisfactory emittance filtering is possible if one can tolerate a fair amount of beam interception. Of course, emittance filtering only removes particles that might interact unfavorably with the light in the wiggler and cannot increase the actual number of electrons that are interacting correctly.

In the actual FEL experiment, the 60° bend is used to rotate the electron beam into coincidence with the optical axis of the laser mirrors. Hence, the aperture used for emittance filtering must be large enough to permit the laser light to pass through without eclipsing. An acceptable design* is shown in Fig. 5. The first quadrupole is used for the filtering. The aperture is in Position C in Fig. 4, and Curve C shows the brightness enhancement as a function of beam transmission. PARMELA simulations of this exact geometry agree with Curve C because they do not take into account any nonlinearity in the quadrupole fields.

Conclusion

I have examined several causes for emittance growth in the beamline up to the decelerators. The growth is a cascade effect that starts from an initial emittance growth in the 60° bends. This poor quality beam can only be transmitted through the 180° bend by mistuning its quadrupoles away from an achromatic setting. This mistuning results in further emittance growth. I suspect

*R. W. Warren, Los Alamos National Laboratory, private communication, August 1986.

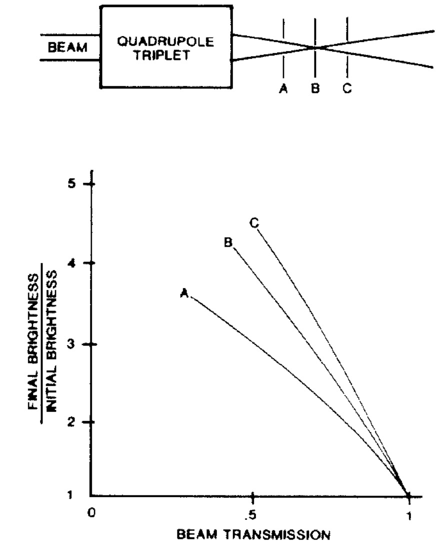

Fig. 4. Emittance filtering with a simple aperture: (A) before beam crossover; (B) at beam crossover; (C) after beam crossover. Brightness enhancement is plotted against amount of beam transmitted through the aperture.

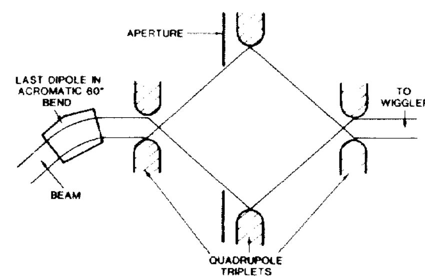

Fig. 5. Telescoping emittance filter.

that the initial emittance growth is caused by longitudinal wake-field effects in the 60° bend from either a scraper at the middle of the bend or the beam-box to beam-pipe transitions. The longitudinal wake fields create a variable energy depression on some of the electrons, and these electrons then take different paths inside the 60° bend. As a result, the bend is no longer achromatic. A wake-field energy depression of 0.4% inside the bend would account for the emittance growth observed in the experiment. This amount of energy depression is consistent with that actually seen using energy-spread diagnostics. A complicated telescoping emittance filter may then be used to regain the earlier brightness at a cost of some of the beam transmission.

Acknowledgment

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