Longitudinal Kinetic Energy Spread from Focusing in Charged Particle Beams*

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Abstract

A charged particle beam can be given a longitudinal kinetic energy spread through focusing by magnetic solenoid lenses. Measurements of energy spread are reported and are compared with the results of computer simulations, which include several known sources of energy spread. These sources are discussed. The results of the measurements and the simulations agree, giving energy spreads which are two orders of magnitude larger than the initial thermal energy spread.

I. INTRODUCTION

Longitudinal kinetic energy spread can place limits on the operation of free electron lasers, the bunching of beams for heavy ion inertial fusion, radial focusing in accelerators, and other applications. The radial focusing of a beam by a magnetic solenoid lens creates energy spread in several ways, some of which are reversible and some of which are in practice irreversible. A reversible spread results from the linear focusing of a laminar beam; energy spreads which are in practice irreversible result from lens spherical aberrations and thermal motion of particles in the lens magnetic fields. Interparticle collisions can also cause an irreversible energy spread. We have measured the longitudinal energy spread of a 2.5-keV, 36-mA electron beam in a periodic channel, and we have done computer simulations of the same channel which include several known sources of energy spread.

Linear focusing of a laminar beam by a magnetic solenoid lens creates a reversible energy spread when the beam is focused to a waist radius which differs from the waist radius before the lens. Since a magnetic field changes only the directions of particle velocities, the change in radial potential energy with a change in waist radius is accompanied by an equal and opposite change in longitudinal kinetic energy. Lens spherical aberrations create additional energy spread, as particles at larger radii are focused more strongly. It has been shown [1] that the inclusion of nonlinearities of up to third order can result in a highly nonuniform density profile, and that particles near the edge of a laminar beam can be given enough energy to cross the axis. Any such change in transverse energy in a magnetic lens must be accompanied by an equal and opposite change in longitudinal energy. Initial transverse thermal velocities also play an important role in particle motion through a lens. In our case, even though the beam is space-charge dominated, initial transverse thermal velocities contribute significantly to the evolution of particles as they move through the lens magnetic fields, resulting in changes in the longitudinal kinetic energy which are much larger than the original transverse thermal energy.

II. EXPERIMENTAL RESULTS

The experimental setup consists of a short pulse electron beam injector [2] and a 5-m long periodic solenoid focusing channel [3]; the measurements of energy spread were made at 3.8-m along the channel. The electron beam is generated by a gridded electron gun with a generalized perveance of 4.3×10^{-3}. The channel, between the gun and the point of measurement, consists of three matching lenses followed by 24 channel lenses with a period of .136-m. The measurements were made with a parallel retarding grid energy analyzer. The first measurement was on a slightly mismatched beam, with a radius varying from 7.5-mm to 12-mm in the channel, a phase advance per period without space charge $\sigma_0=53^\circ$, and a space charge tune depression of .14. The second was on a mismatched beam with $\sigma_0=88^\circ$, a space charge tune depression of .22 and a radius varying from 4-mm to 8-mm in the periodic channel. The beam envelopes for the first and second measurements, obtained from the simulations, are shown in Figs. 1a and 1b, respectively.

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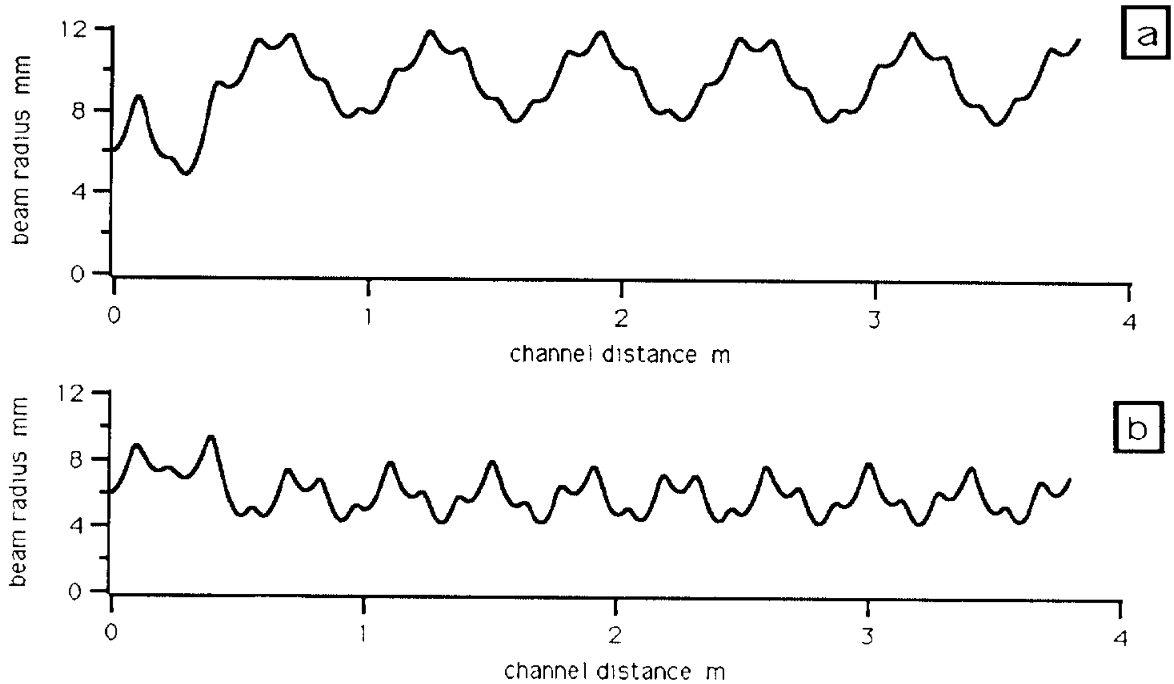

Fig. 1 Beam envelopes obtained from the simulations for the first (a) and second (b) cases. (a) has a tune depression of .13 with σ_0=53°; (b) has a tune depression of .22 with σ_0=88°.

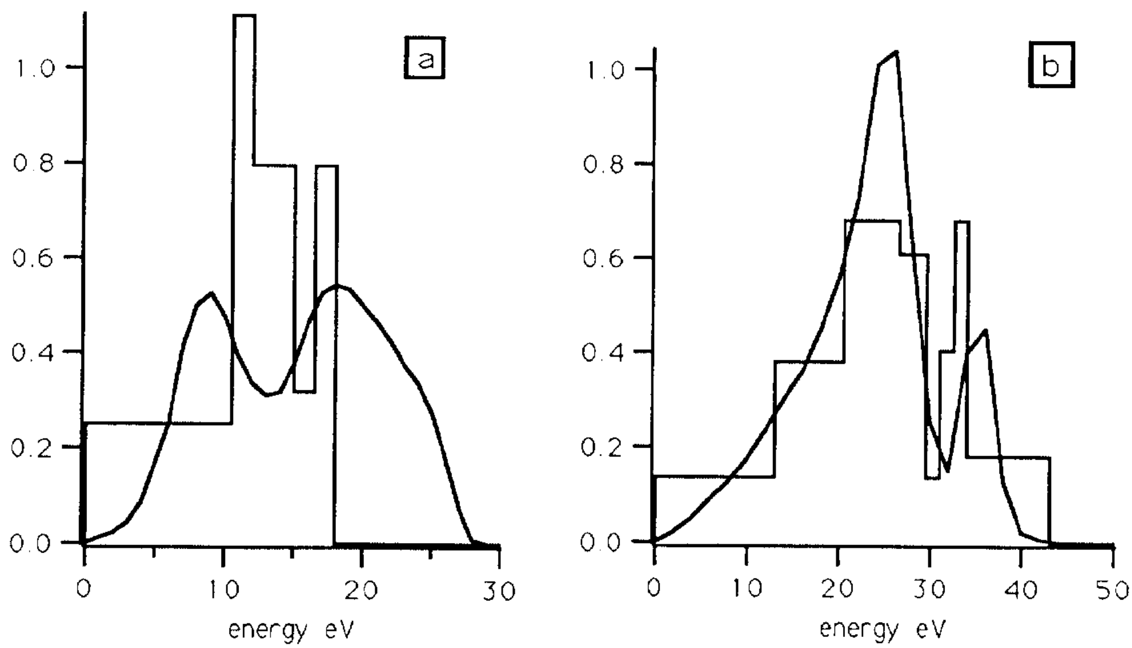

Fig. 2 Distributions in longitudinal kinetic energy for the first (a) and second (b) cases. The bar graphs are the experimental results. The solid lines are the simulation results. The zero points on the horizontal axes are set arbitrarily.

The measured energy distributions for the first and second cases are shown by the bar graphs in Figs 2a and 2b, respectively. The first has a full-width at half-maximum of about 10-eV; the second, with stronger focusing, has a FWHM of about 20-eV. The initial thermal FWHM energy spread is about .2-eV for both cases.

The zero point in Figs. 2a and 2b is arbitrarily set near one end of the distribution. Small variations in the alignment of the energy analyzer with respect to the direction of beam propagation do not change the measured energy distribution but do change the measurements of total energy. The beam energy at the end of the channel therefore cannot be found accurately with the parallel grid energy analyzer (the simulations show a drop in average longitudinal kinetic energy of about 30-eV, or slightly more than 1%, for both cases).

III. SIMULATION RESULTS

The basis for the computer simulation has previously been described [1]. It includes variations in the density profile and nonlinearities in the equations of motion of up to third order. The simulation calculates the evolution of the space charge field resulting from the motions of concentric rings of charge, assuming that the beam and the channel have circular symmetry. For this application we have added individual particles with transverse thermal velocities. The evolution of the particles is determined from the lens fields and from the calculated space charge field. Since the space charge field is found from the concentric rings of charge, the simulation is able to follow individual particle motions without having to calculate their interactions with each other. The distribution in longitudinal kinetic energy is found by keeping track of the longitudinal velocity of each particle throughout the channel. The resulting energy spreads are shown by the solid lines in Figs. 2a and 2b, corresponding to the first and second measurements, respectively.

IV. DISCUSSION

The energy distributions found from the measurements and the simulations in both cases differ from Gaussian distributions in that they have depressions near the center. This means simply that there is a particular energy range near the center of the distribution which few particles occupy. We do not yet have a physical explanation for this.

A source of longitudinal energy spread which is not included in the simulations is interparticle collisions. When a beam is accelerated from the cathode the longitudinal temperature becomes negligible compared with the transverse temperature. Coulomb collisions then redistribute the thermal velocities toward an isotropic equilibrium temperature, resulting in an increase in longitudinal energy spread. Ichimaru and Rosenbluth [4] have calculated this relaxation rate for a single-component plasma. While the time for relaxation to an isotropic temperature is much longer than the beam travel time, this effect can still produce a significant longitudinal energy spread in a relatively short distance. A more detailed discussion of this can be found elsewhere [5]. The FWHM energy spreads for the first and second cases are found to be 5-eV and 7-eV, respectively. Both give an increase of between 5% and 15% in the FWHM energy spread from the simulations. When compared with the results of the measurements, this difference is too small to conclude that transverse thermal collisions are contributing to axial energy spread in the beam. Work is in progress at the University of Maryland on an experiment in which thermal collisions are the dominant source of energy spread.

V. SUMMARY

Longitudinal kinetic energy spread induced by the focusing of an electron beam by magnetic solenoid lenses has been measured and simulated. Good agreement between the theory and experiment has been found.

VI. REFERENCES

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