Title
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Publication Date
1993-05-01

LBL-33803
UC-419

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Presented at the International Symposium on Heavy Ion Inertial Fusion, Frascati, Italy, May 25–28, 1993, and to be published in the Proceedings

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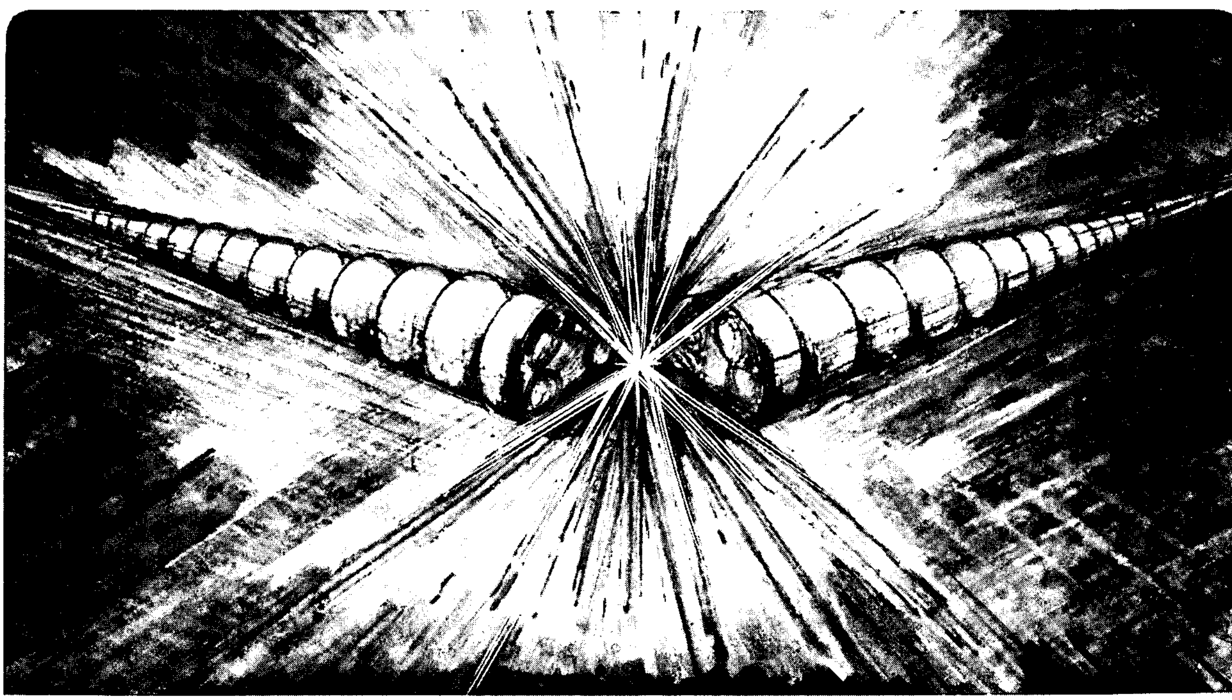
May 1993



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

LBL-33803
UC-419
HIFAN-582

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Submitted to the International Symposium on Heavy Ion
Inertial Fusion, Frascati, Italy, May 25-28, 1993

*This work was supported by the Office of Energy Research, Office of Fusion Energy, U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

Transverse Beam Combiner for ILSE*

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Abstract

Previous Heavy Ion Fusion driver system studies suggest that transverse beam combining significantly reduces driver cost. In a combiner, several beams are brought together to a common transport channel which accommodates the increased line charge density. Combining intense beams increases the transverse emittance mainly due to the heating of the beam by space charge forces as the non-uniform original beam configuration becomes more uniform. The combiner itself introduces additional aberrations, which are small for the present design. Those aberrations are due to the reduced available space for the focusing electrodes and reduced clearance from the beamlets to the surrounding electrodes, thereby generating field aberrations and larger image forces. These aberrations can also lead to particle loss. We have studied a particular design of the proposed Induction Linac System Experiment (ILSE) combiner which is a first-order achromat that tolerates a rather large fractional head-to-tail momentum tilt of ±10%. Using a 2-D particle-in-cell code we have found that ~7% of particles are lost in the combiner. The emittance growth after the combiner is large enough so that the emittance growth due to combiner aberrations is unimportant. The scaled projection to a driver shows the growth is small enough to be tolerated. At present, methods of improving combiner design to reduce particle loss and to minimize emittance growth are being studied.

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*Work supported by the Director, Office of the Energy Research, Office of Fusion Energy, U.S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

PACS #: 41.75.Ak

I. INTRODUCTION

Many parallel beams are desirable in the a low energy electrostatic focussing section of an induction linac driver. As the beams accelerate, the focusing system can handle more current and it becomes economically advantageous to accelerate fewer beams using magnetic focusing. At the electrostatic-to-magnetic crossover point the beams may be combined in groups of four or more.

The transverse emittance grows when beams are combined. For beams with significant space charge, there is an extra increase of emittance due to electrostatic energy decrease as the current density profile of the combined beam evolves towards uniform, in addition to the normal effective phase space increase dut to the incomplete filling at the combining point.

As the beams are brought together in a combiner, the various abberations such as geometric, choromatic and focusing field ones cause further, although small, increase of the emittance. Chromatic abberation can be controlled by employing a first order achromatic design of the combiner. Further optimization is obtained from the cancellation of the second and third order chromatic abberation at the higher energy by selecting design energy somewhat lower than the one in the middle of the beam pulse. As the separation distance among the beams becomes less, the focusing electrode geometry deviates from the ideal one which cause the field abberation inducing particle loss at the later stage of the combiner.

In section 2, the emittance increase in the combining process is discussed. A specific ILSE combiner design is described in section 3, followed by the nunerical simulation results (section 4). A concluding summary is given in section 5.

II. EMITTANCE INCREASE FROM MERGING

The rms phase space volume is larger than the one actually occupied by the beams themselves as the beams are combined. This geometric dilution can be calculated at the merging point for a four-to-one symmetric combining assuming elliptic phase space for each beamlets as follows:

$$\varepsilon_f^2 = [(\frac{a^2+b^2}{2}) + 2d^2][\frac{\varepsilon_i^2}{2}(\frac{a^2+b^2}{a^2b^2}) + 2\delta p^2 + \frac{1}{2}(a'^2+b'^2)] - [\frac{1}{2}(aa' + bb') + 2\, \mathbf{d}\, \delta \mathbf{p}]^2$$

Since the initial beam emittace (ε_i) is assumed to be small, the angle of the centroid ($\delta\mathbf{p}$) and the slope of the envelope (a' and b') at the merging point should be minimized. This serves as one of the design constraints. When these conditions are met, the remaining geometric emittance increase due to the beam displacement (**d**) is small compared to the space charge contribution of given in next section . The actual geometric dilution is larger than that of the above for a phase space geometry other than ellipse.

For an intense beam, further increase in normalized emittance (ε_n) occurs due to the equilibrization of the current profile in the merging process, which can be calculated from the emittance equation:[1]

$$\delta\varepsilon_n{}^2 = Q\, R^2\, \delta f$$

where $Q = \dfrac{\lambda q e}{4\pi\varepsilon_o \gamma m c^2}$, λ = line charge density, R is the envelope radius of the merged beam, and δf is a dimensionless profile factor depending on the beamlet arrangement and spacing. For the 4-to-1 symmetric combination in a uniform focusing channel, δf is given by

$$\delta f = -\frac{3}{4} + \log\{\frac{1}{4}\,[2(\frac{d}{a})^2 + 1]^2\,(\frac{a}{d})^3\}$$

where **d** is the beamlet displacement from the center and **a** is the envelope radius of a upstream beamlet.

The emittance due to the space charge is moderately dependent on the beam separation when **d** is comparable to **a**, and even at zero separation there is a significant growth resulting from spatial non-uniformity. In addition, the above emittance equation indicates that the normalized emittance increase is independent of the beam kinetic energy at the merge point, hence the scaling to a driver only depends on the square root of the mass ratio for a beam of given line charge density. Good agreement of this formula with particle-in-cell (PIC) computations in a A-G focusing system is observed, although the above equation is only approximate for the non-uniform focusing channel.

At a reasonable beam edge-to-edge separation of 5 mm, the total emittance growth is expected to be of ~ 1 $\times 10^{-5}$ m-rad for a ILSE combiner of $q = 1$, $\lambda = 1$ μC/m, and mass of A = 39 amu. For a driver of A = 200 amu with the same line charge density, the growth is reduced by a factor of $\sqrt{5}$. For a reasonable combiner/merge scenario, the space charge force is dominant contribution to the emittance growth and the final emittance after the merging is insensitive to the geometric phase space dilution.

III. ILSE COMBINER

Since the total system length of ILSE is much less than that of a driver, the head-to-tail velocity tilt on the beam is generally large by a factor of several in the combiner. In order to handle this large velocity tilt in a combiner, a first order achromatic design is considered so that the beam centroid will come out of the combiner with small (less than 1 mm) offset from the design orbit. However, since the typical momentum tilt is as large as ± 10 % of the beam velocity, the second and third order aberrations are not small. The full second order correction including the chromatic and geometric aberrations is possible in principle, however, the number of elements used is unrealistically large. In addition, the second and third order aberrations tends to cancel at higher energy than the design value and the chromatic aberration from the design orbit can be made small by choosing the design energy to be somewhat less than the average beam energy.

Following the combiner, a matching section is used to make a smooth transition to the magnetic transport channel. Exact matching over the entire bunch length of the merged beam is not possible due to the velocity tilt.

The combiner consists of seven quadrupoles and the four bends, with last bend being a combined function element design to give both the required bend strength and the focusing force for a smooth transition to the merge zone with its layout of quadrupoles for the matching to the subsequent accelerator section.

As the beamlets are brought together in a combiner, the transverse spacing between the electrode becomes smaller and field distortions from an ideal harmonic field occurs. The field aberration of the present design is reasonably small giving a few percent particle loss, and an improved electrode design to reduce the field aberration is underway.

Figure 1 shows the dispersion curve and the actual controid displacement for a given first order achromat design. Although the centroid deviation is as large as 5 mm in the middle of the combiner, the final value is less than 1.0 mm if the fractional beam energy variation is within $0.9 < \frac{E}{E_o} < 1.3$. This odd choice of the energy variation is due to the fact that the second and third order aberration cancel at a higher energy than the design point E_o.

Although the chromatic aberration seems to be controllable, the effects of a large deviation from the design orbit inside of the combiner, such as interaction with images and the field aberrations, must be calculated and considered in a combiner design.

As the beamlets are brought together the space available for the electrodes become very restricted, and the ratio of the electrode radius to the aperture radius deviates from the ideal one for the elimination of the dodecapole aberration (magic ratio of 8/7). It is straight forward to calculate the three dimensional field decomposition of a realistic quadrupole geometry using the capacity matrix technique [2], and it is found that the dodecapole aberration field strength at the beam edge is about 2 % for the first few quadrupoles after the first bend and becomes as large as 6 % at the end. Further calculations show that the total aberration field strength is no more than twice of the above values.

IV. TEST BY SIMULATION

A new two-dimensional PIC code HIBEAM (closely related to the previously employed code SHIFTXY of I. Haber [3]) has been developed to test the various combiner designs with the realistic boundary condition which include a self-consistent representation of the field from the electrodes as well as the space charge. Some of the three-dimensional effects can be added by superposing external multipole field components, although this is not completely self-consistent. In the drift section the boundary condition of a large conducting cylinder surrounding the entire system and representing the vacuum wall is used rather than free boundary condition.

Since the merging process of a intense beam is violent and the increase of the emittance is rather large, the final emittance is insensitive to the initial conditions such as emittance of the beamlet. Thus small perturbation from the image charge and other small imperfections would normally be unimportant. However, with the field aberrations induce moderate particle loss of ~7 % with large phase space distortion inside of the combiner.

The best description of the whole merging process can be seen in a color movies of the transverse dynamics, where each of the beamlets is represented by its own color. The simulation shows that the merging process to an equilibrium state is rather slow due to the collisionless nature of the beams. On the other hand, the emittance growth takes place on the rather short time scale of one beam plasma period.

V. Summary

Computer simulations and analytical estimates have been used to calculate the emittance growth expected from an example ILSE combiner and from a typical combiner in a driver. The merging process after the combiner itself is conceptually well understood and the details of the combiner itself have been emphasized. The chromatic aberration with large velocity tilt of ±10 % can be tolerated with minimum displacement of the centroid from the design orbit when a first order achromatic design is used. The field aberrations due to compact design cause distortion on the phase space and result in a reasonably small particle loss in the particular design considered.

A better design of the combiner to reduce the particle loss is underway. An alternative combiner design using combined function elements is also under consideration. When a combiner consisting of ideal quadrupoles is introduced, tolerable particle loss, perhaps less than a couple of percent, is expected due to the image charge on the electrode.

VI. REFERENCES

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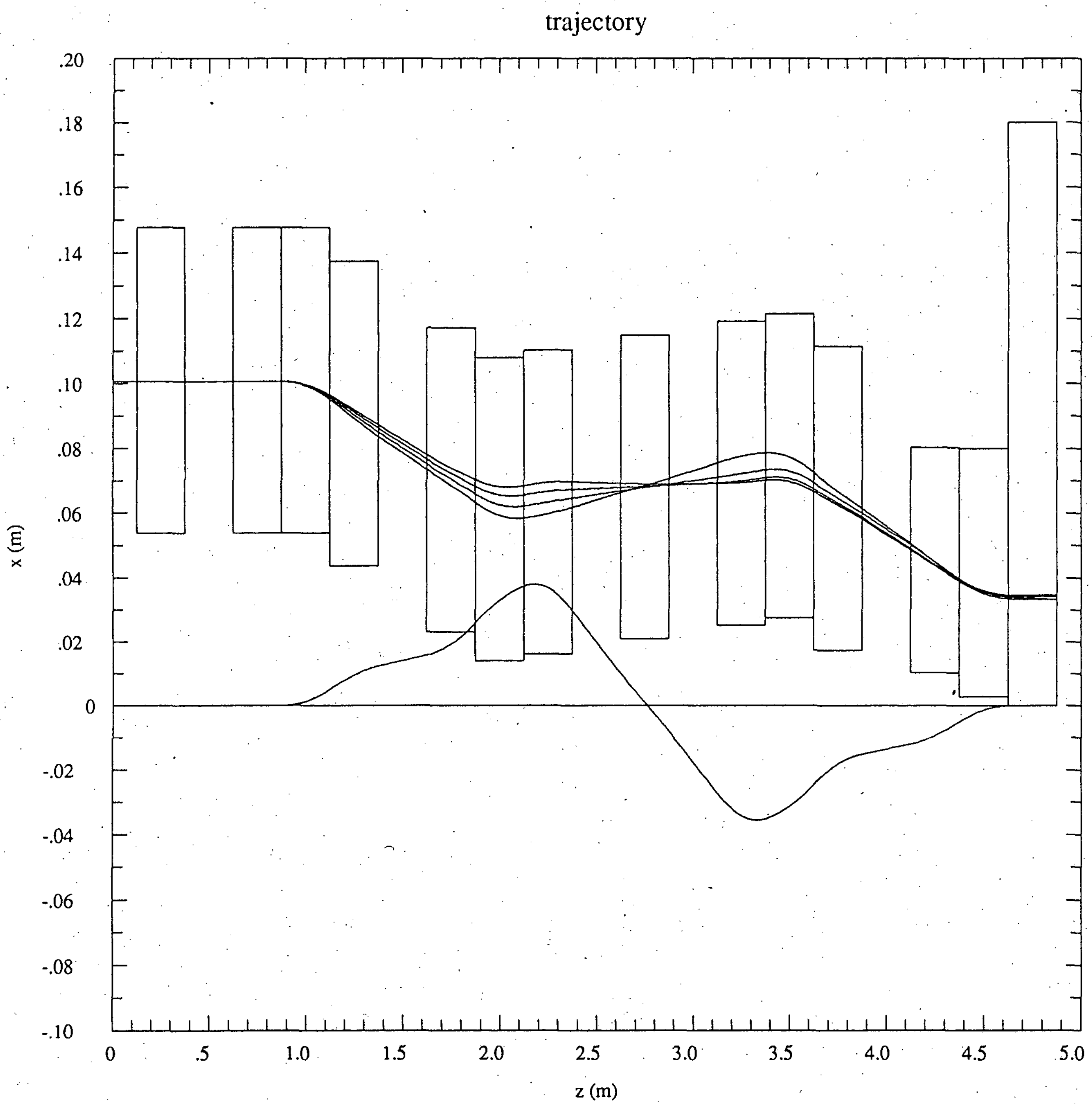
[2] M. Berz, W. Fawley, and K. Hahn, Nucl. Inst. and Meth., A 307 (1991) 1.

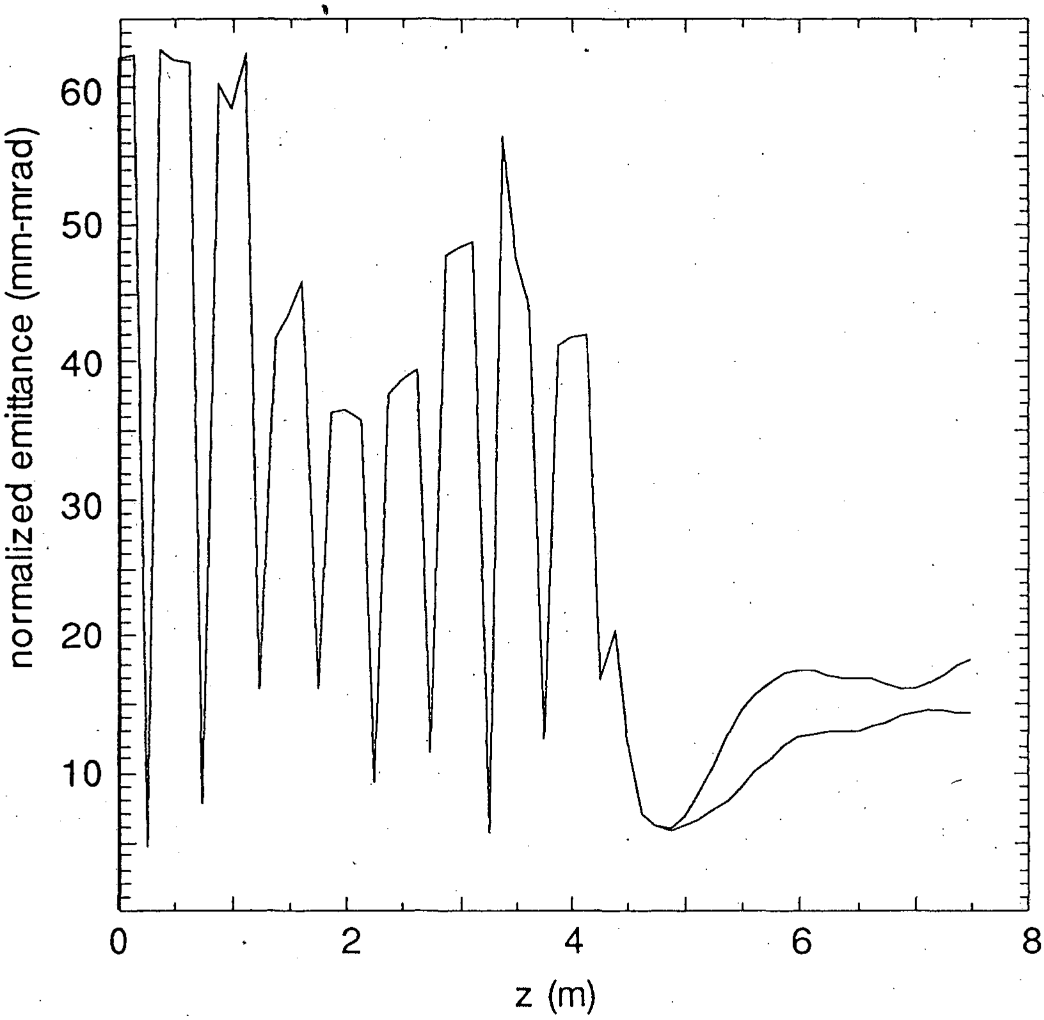
[3] I. Haber, Proc. 1984 INS International Symposium on Heavy Ion Accelerators and their Applications to Inertial Fusion, p. 451 (Institute for Nuclear Study, Tokyo)

Figure caption

Fig-1. ILSE combiner design. The botton curve represents the dispersion of the first order achromat system. The upper curves are the actual centroid orbits, for the fractional beam energy of variation of 0.9-1.2.

Fig-2. Time history of the normalized emittance of the 4-to-1 symmetric combination. The large variation of the emittance in the combiner is the controllable geometric dilution, and the final emittance is rather independent of this.


trajectory
x (m)
z (m)
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
-.02
-.04
-.06
-.08
-.10
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0



normalized emittance (mm-mrad)
60
50
40
30
20
10
0
2
4
6
8
z (m)

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