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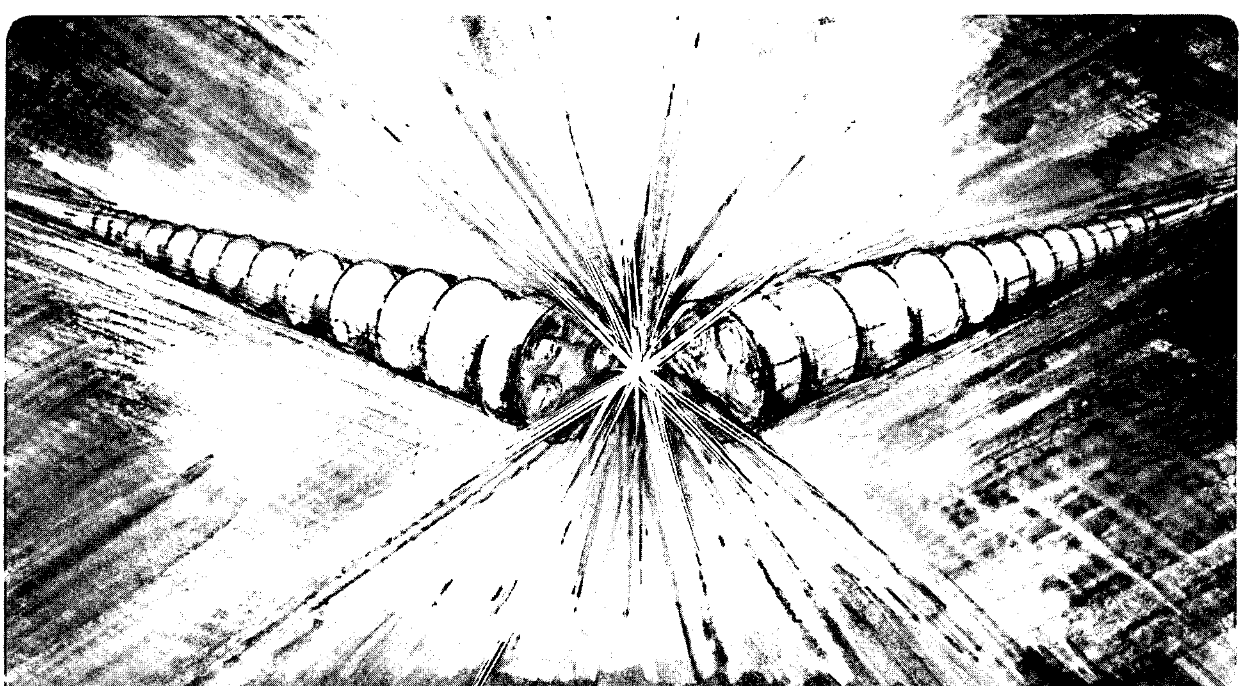

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CONCEPTS, FEATURES, AND DESIGN OF A SIXTEEN-TO-FOUR BEAM COMBINER FOR ILSE*

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Abstract

Sixteen intense parallel ion beams are to be transversely combined into four by dispersionless double bends. Emittance growth due to electrostatic energy redistribution and to the geometry is evaluated. Most bending elements are electric, and alternate with AG electrostatic quadrupoles similar to those upstream. The final elements are magnetic, combining focusing and "unbending". Electrode shapes and pulsed-current arrays (having very small clearances), and mechanical and electric features of the combiner, and described.

Introduction

Studies of induction linacs as ignition drivers for inertial-confinement fusion power plants show that many parallel ion beams are desirable at lower energies but that after some acceleration fewer beams are less costly. Therefore, we want to study and demonstrate tranverse combining of ion beams. This process will inevitably increase total transverse emittance, which must not grow too much to meet target spot focusing requirements. Beam loss, which is inefficient and could cause much trouble, must also be minimized. The beams are intense; transverse space charge force cancels most of the strong external quadrupole (AG) focusing which would produce a single-particle phase advance of 60° to 85° per period. There is no experience in the efficient combining of such beams.

Design of the ILSE (Induction Linac Systems Experiment) facility (see adjacent papers M11, M12, M14) has been strongly influenced by the requirement for a beam-combining experiment. An injector, previously specified (paper M10), will provide a four-by-four square array of sixteen C^+ beams at 2 Mev with a lattice spacing of 7.03 cm. They are accelerated to about 3.2 Mev (bunch head) and 4.8 MeV (bunch tail), with linearly varying velocity "tilt" of about 20% from head to tail, while being contained transversely by AG electrostatic quadrupole fields. Groups of four adjacent beams are then combined into four final beams, emerging at the corners of a 14-cm square into four channels for magnetic quadrupole focusing and further acceleration.

Combiner Requirements

Each group of four beams to be combined must have their axes displaced by double bends to new positions parallel to the original ones but closer together, providing a closely packed pattern of four beams which become one on leaving the combiner. These double-bend systems must be dispersionless to accommodate the velocity tilt. The dipole bending-field regions must alternate with quadrupole regions to continue the upstream focusing so as to avoid beam expansion from diminished containment. To minimize emittance growth (transverse phase space density dilution) these beams must be brought as close together as possible, which requires very thin septa between them at the final stage. Further, because of the characteristic "shape throbbing" of AG-focused beams, as these beams converge at small angles they tend to get in each other's way. To deal with this, combined-function elements are needed at the end which superpose the final focusing quadrupole fields and the final "unbending" dipole fields rather than arranging them in tandem. The design, described below, to meet these requirements is based on K-V beam distributions plus a minimal allowance for more realistic beam "shoulders", with the expectation that aberrant ions in more distant (and hopefully very faint) halos can be scraped off in a judicious manner.

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Emittance Growth[1]

When four close-packed original beams emerge from the combiner into a common focusing channel, the spaces between them fill with particles, forming a single elliptical beam. In accelerators with beams of negligible space charge (e.g., high energy physics accelerators), single particle orbit motion due to the external focusing forces would fill these spaces, causing the cross section of the beam to increase and thereby raising the emittance. In heavy ion fusion accelerators, however, the large repulsive space charge forces between particles cause them to move into the gaps between beams on a much shorter time scale. The decrease in electrostatic field energy stored in the beam due to this decrease in charge density becomes transverse kinetic energy. Thus there is a second increase in the emittance, due to the increase in transverse temperature, that is not seen in accelerators with less intense beams.

The growth in transverse emittance due to combining is important to consider when designing a heavy ion fusion power plant driver, since the transverse emittance at the end of the accelerator limits the minimum radius of the spot to which the beam can be focused. Present calculations and source characteristics imply that the emittance can be allowed to grow between the source and the target by a factor of 10 to 100 in a driver, before the ability to focus the entire beam on the target is compromised. Our calculations indicate that the overall emittance growth expected is sufficiently small that at least one combining operation can be considered for a heavy ion fusion driver.

Computer simulations and analytical estimates have been used to calculate the emittance growth expected from the ILSE combiner and from a combiner in a driver. These show that the ILSE combiner models a driver well in that the magnitude of the emittance growth expected and the influence of space charge forces on the emittance growth are similar to the case of the driver. Fig. 1 shows analytical results for four-to-one beam combining at ILSE and at driver parameters. Though the computer simulations include the major effects to be found in a combiner, including a self-consistent calculation of the space charge forces, they cannot model exactly the influence of either image forces due to nearby conductors or aberrations of the external focusing and bending fields on the beams. Moreover, the spacing of the actual beams as they emerge from the combiner can only be estimated until the combiner hardware is built and tested and a beam propagated through it. This spacing is crucial in determining emittance growth.

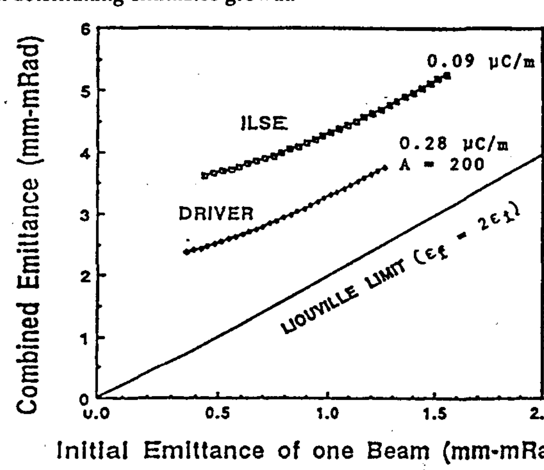

Fig.1 Emittance (4 x rms) growths for 3 mm beam-edge spacing, from methods of Ref. (1).

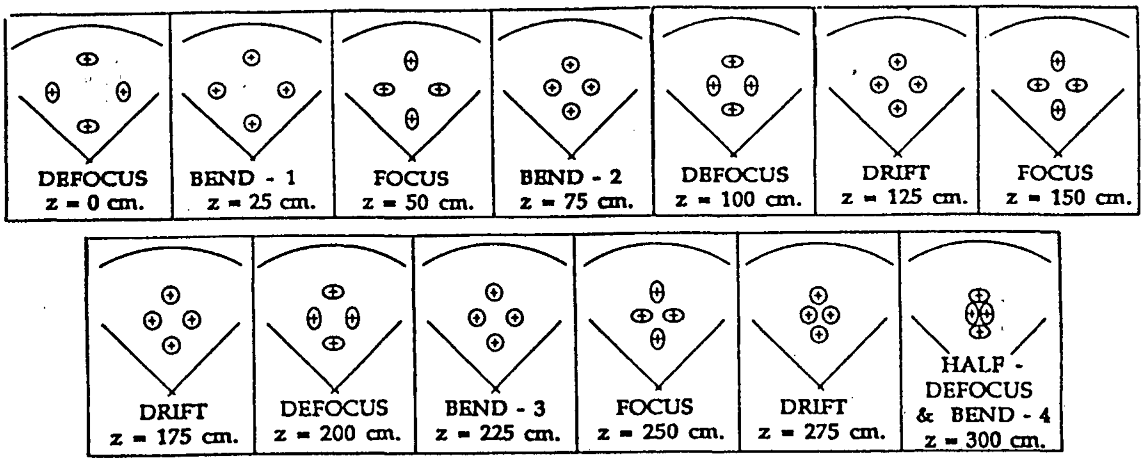

Fig. 3 Successive beam spacings and cross-section shapes in one quadrant.

Description of the Design

In the ILSE combiner each beam's axis is displaced by a double-bend system comprising, in sequence: full bend, full unbend, drift, drift, half bend, drift, and half unbend (see Fig. 2). These regions alternate with the quadrupoles of a focus-drift-defocus-drift (FODO) lattice with 50 cm half-period and single-particle phase advance of 60° per period. The combiner length is three full periods, or 3 m. All dipole and quadrupole fields are electrostatic except the final combined-function units mentioned above, which have pulsed magnetic fields. The succession of beam spacings and cross-section shapes for one quadrant of the sixteen-beam pattern is shown in Fig. 3.

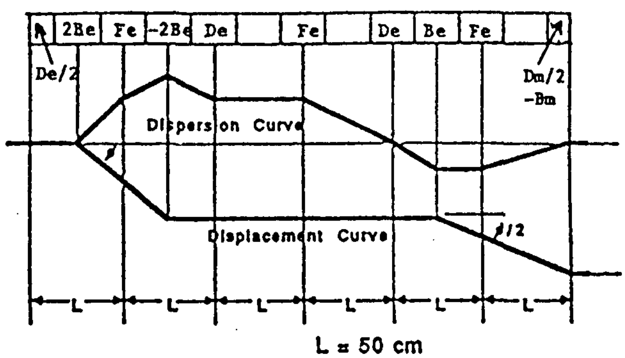

Fig. 2 Displacement and dispersion curves.

The velocity tilt imparted to the ion bunch by the upstream accelerating section causes the ion bunch head and tail to be deflected by differing amounts in the dipole fields. This dispersion must be accommodated within the combiner by sizing the beam apertures to avoid beam scraping of the head and tail of the bunch. The most notable feature of this design, however, is that the bend/unbend sequence is arranged in conjunction with the quadrupoles to minimize final beam dispersion. It has been possible to produce a collimated final beam pattern with no significant positional or angular dispersion. Bunch head, tail, and center all exit with the same displacement (in linear approximation) from the original beam axis, as shown by the dispersion curve in Fig. 2.

The final element must unbend the converging beams at the last moment to produce a set of parallel exiting beams. Furthermore, in order to produce an optimal close-packed exiting beam pattern (last section, Fig. 3), the beam cross sections must attain maximum eccentricity at the same time that they are being unbent from their converging trajectories. Since maximum eccentricity occurs at the midpoint of an ordinary focusing quadrupole, the final element must be a special half-length quadrupole, combined with the superimposed dipole field.

Combiner Hardware

The actual ion beam bend angles in the combiner are small (about 45 milliradians, or 2.6 degrees). Constant cross sections are used and a beam-clearance allowance is maintained. Two-dimensional field calculations have been used to examine quantitatively the field nonuniformities resulting from postulated electrode geometries and voltages. In this process, a harmonic expansion is fitted to the values of the field potential at a reference beam radius. The desired pure quadrupole and dipole fields correspond to the lowest order terms of the expression, and the coefficients for the unwanted higher order terms give a quantitative measure of field quality.

Working within the spatial constraints of the converging beams, it has been possible to devise electrode geometries that limit the unwanted higher order field components to a few percent of the fundamental quadrupole or dipole component. This task becomes increasingly difficult as one progresses through the combiner, and one or two auxiliary electrodes at intermediate voltages are used to shape the fields in the last six elements. Fig. 4 illustrates such a quadrupole design for the central region of the combiner and shows the corresponding field analysis, and Fig. 5 illustrates the rounded-rectangle electrodes needed to produce the bending fields.

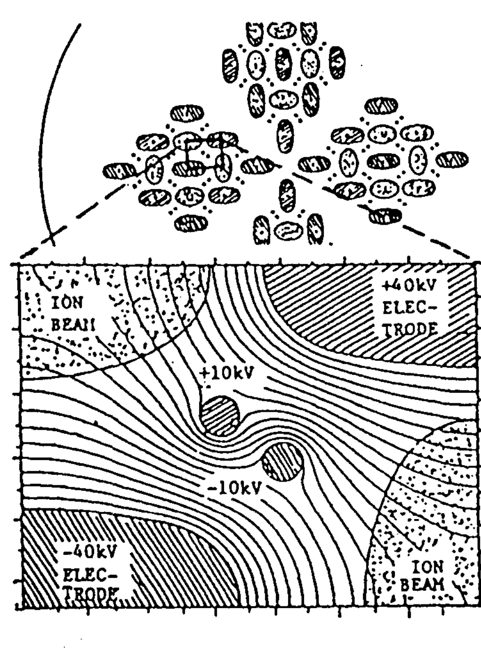

Fig. 4 Quadrupole electrodes and equipotentials.

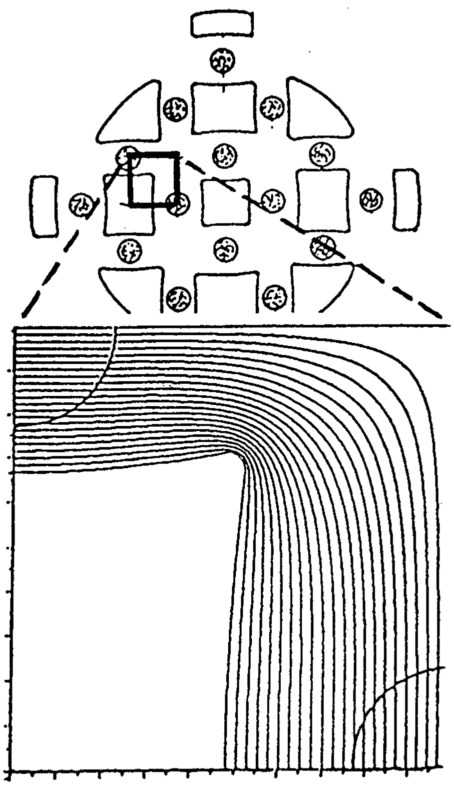

Fig. 5 Dipole electrodes and equipotentials.

Individual electrodes will be shaped from solid stainless steel using computer-controlled machining and hand-lapping. Electrodes are mounted to base plates and thence to vacuum-vessel segments. A coordinate measuring machine will be required for proper bench alignment of these components relative to fixed reference surfaces on the outside of the vessel segments.

The final combined function elements must superimpose the required quadrupole and dipole fields. The combiner design dictates that these elements be short, with an effective length of 8.3 cm. Beam-to-beam spacing at this point is that of the smallest feasible close-packed pattern, and is nominally 3 mm. While it is possible to create the required electrostatic fields for this element with a number of very small electrodes at varying voltages, this is not favored because of the anticipated difficulty of maintaining the required voltages in the presence of minor beam scraping. Instead, a magnetic quadrupole/dipole design is used that positions only electrical winding conductors and minimal iron core material in the thin septum areas between the beams (see Fig. 6). Although scraping of beam halos will take place at the septa between beams, 5 mm of additional beam clearance is provided on the outboard sides of each aperture. This clearance will accommodate the beam entry angle, the rounder entry cross section, beam dispersion, field nonuniformities near the wall, beam halo, and the ± 0.1-mm (± 0.004-in.) alignment tolerance. It will also allow experiments with small converging exit angles.

Pulsed magnets and laminated iron cores within ILSE's vacuum chamber create two problems: First, the laminated structure has a very large confined surface area, and represents a high vacuum pumping load. This is minimized by spacing the individual iron laminations to provide pump-out space between them. A one-third iron density ratio is adequate for the calculated magnetic fluxes, except in the thin septum areas, where additional laminations are used. Second, the pulsed operation of the magnet windings will generate a heat load within the vacuum chamber. Although the low duty cycle (1 millisecond every 12 seconds) produces an average power dissipation of only 8 watts, the magnet is in a vacuum environment, which will cause its temperature to rise significantly with extended use. If radiation were the only heat transfer mechanism, a calculated temperature rise of 27°C would result. With a heat sink design for conductive heat transfer to the vessel wall, an approximate 5°C temperature rise is calculated. However, to minimize thermal distortions and their detrimental effects on the alignment of the element, a simple water cooling system is planned.

Beam diagnostic instrumentation will be located before, after, and within the combiner section, allowing emittance measurements with a movable slit and a beam profiling harp diagnostic. Each drift region has a diagnostic access port with grounded beam-aperture plates and accurately located diagnostic track mounts. The diagnostic ports also allow for auxiliary beam-steering dipoles, if necessary.

The 11 electrostatic quadrupole and dipole assemblies in the combiner section will each use an adjustable bipolar 50-kV dc power supply with voltage sustaining capacitors. In six of the 11 assemblies, auxiliary electrodes running at intermediate voltages are used for field shaping. An external resistive voltage-divider circuit with sustaining capacitors will be used to provide the required auxiliary voltages without need for additional power supplies. The final four magnet assemblies will require 16 separate pulsed power supplies of about 200 V and 100 A for individual control of the dipole fields.

Distributed vacuum pumping access is provided by 8-inch diameter pumping ports at each of the seven diagnostic-port box sections, with two additional 10-inch pumping ports located in the circular sections of the vessel structure.

<u>Reference</u>

1. C. M. Celata, A. Faltens, David L. Judd, L. Smith, and M. G. Tiefenback, Proceedings of 1987 IEEE Particle Accelerator Conference, p. 1167 (1987).

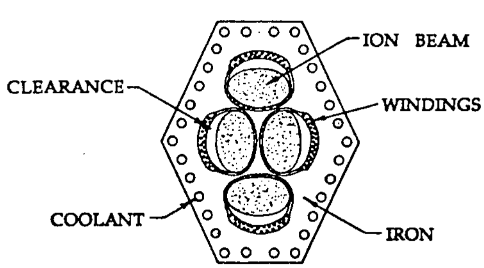

Fig. 6 Combined-function pulsed magnetic module.

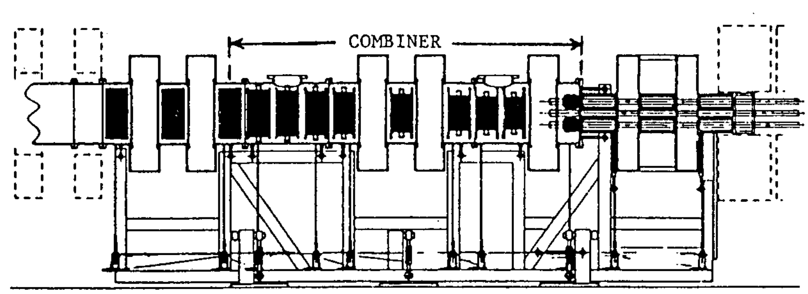

Fig. 7 Combiner side view showing diagnostic access boxes in drifts.