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ACHROMATIC BEAM COMBINER AND BEND SYSTEM FOR ILSE*

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Achromatic Beam Combiner and Bend System for ILSE*

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The lattice configuration of the beam combiner and bend system of the proposed Induction Linac System Experiment (ILSE) is described. These subsystems must transport high current ion beams with large momentum variations within a single pulse ($\Delta P/P_0 \leq \pm .1$), with minimal beam loss or emittance growth. Configurations which are achromatic through first order, including the effect of image fields have been developed. Calculations of the beam envelope and centroid motion are made with beam dynamics code HICURB, which includes strong space charge effects and chromatic effects through all orders.

Introduction

A heavy ion driver for Inertial Confinement Fusion has non-accelerating sections in which crucial beam manipulations are performed. These include the final focus system, drift compression, bends required to orient beams to the reactor configuration, and possibly beam combiners and splitters. Similar systems are to be found in both the induction linac and rf linac/storage ring approaches [1, 2]. New beam physics is involved because the operations must be carried out in the presence of strong space charge forces. In addition, a large head-to-tail velocity tilt may be present, e.g. during final compression and in the low energy phase of acceleration.

The Induction Linac Systems Experiment (ILSE), currently being designed at the Lawrence Berkeley Laboratory [3], is a comprehensive model of beam manipulations in an induction linac driver. In addition to multiple beam acceleration, experiments with four major non-accelerating components are planned. These are

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

- (1) Beam Combiner. Sixteen parallel beams are merged simultaneously in groups of four to achieve a four fold current amplification per beamlet in a single step.
- (2) A space charge dominated beamlet is transported through a 180° bend system.
- (3) Drift compression by a factor of 2 - 3 is carried out in the 180° bend and an additional straight transport channel.
- (4) Final Focus to a small spot radius ($r_s < 3$ mm) is carried out with four large aperture quadrupoles and beam neutralization.

The present paper is devoted to the conceptual design of the ILSE beam combiner and 180° bend.

180° Bend System

At the end of acceleration a single ILSE beamlet continues directly into a bend system which is intended to model the analogous driver feature. Beamlet design parameters at this point are (for C⁺)

$T = 10$ MeV	design energy
$[B\rho] = 1.58$ T-m	rigidity
$I = 3.37$ Ampere	current
$\Delta P/P_0 \leq \pm 3.9\%$	tilt
$\epsilon > 4 \times 10^{-5}$ m-r	edge emittance (unnormalized)
$Q = 2.39 \times 10^{-4}$	perveance
$\tau_p = .4$ μ s	pulse length

The value of emittance ϵ is very uncertain at present since its value depends on the as yet unknown operation of the combiner. Momentum variation of $\pm 3.9\%$ is distributed along the pulse as a systematic "tilt", varying approximately linearly with time. Since the pulse tail moves more rapidly than the pulse head (by $\sim 7.8\%$) some drift compression occurs during the bend, as it would in a driver. This is not expected to cause difficulties.

In the final phase of acceleration the lattice period length is 1.2 m, with phase advance of 72° per period. Beam edge radius is about 1.4 cm (maximum). It is desired to continue this focal structure through the bend since it is efficient for current transport in the design range and no space is consumed in matching to a new lattice. With these focal conditions and beam parameters the effective tune is about 20% of the undepressed value of 72° , therefore the beam is space charge dominated.

Several practical consideration strongly constraint the bend system layout. These are the need to tightly confine the large momentum dispersion, maintain a matched beam envelope, employ magnets of acceptable design and strength, and fit the system within a confined space. A closely packed array of dipole and quadrupoles has been devised to meet these constraints. All magnets are pulsed on a period of ~ 1 ms to avoid the bulk and cost of heat removal.

The bend system consists of twelve periods of a quadrupole FODO array interspersed with dipoles. Period length is 1.2 m and phase advance per period is 72° for the design energy of 10 MeV. The 24 dipoles are symmetrically placed between quadrupoles. They are approximately half strength in the first and last 2.5 periods and full strength (~ 1.3 T) for the 7 central periods. This arrangement produces a first order achromat with matched dispersion through the central section, and thereby results in a considerable savings in aperture. The quadrupole gradient is 17 T/m, which yields a .94 T field at the 5.5 cm vacuum aperture. Effective length (hard edge field) of all magnet is 20 cm, resulting in aspect ratio length/radius = 3.6. This value is considered very small, i.e. the fringe fields can cause a significant perturbation of the particle orbits.

Total bend system arc length is 14.4 m, and width is about 8 m, measured between entrance and exit design orbits. These values permit a reasonable fit into available laboratory space.

Actual magnet lengths in a preliminary design are 27.6 cm, leaving almost no room for diagnostics and vacuum pumping. Several alternative designs are being studied to

alleviate this problem, among which are combined function bends and quadrupoles, and slightly shorter, stronger magnets.

The 5.5 cm aperture radius is set by three factors: maximum envelope radius (1.9 cm), maximum momentum dispersion (2.0 cm), and a safety factor (1.6 cm). The extremes of dispersion occur at pulse head and tail - the central portion of the beam uses less than 50% of available aperture. It is apparent that beam head and tail are relatively more vulnerable than the pulse center to several important aberrations. These include non-linear chromatic effects, image forces, higher order multipoles and non-linear quadrupole and dipole fringe fields. It is expected that some emittance growth will result from these aberrations. The essence of the bend experiment is to measure, understand, scale and possibly control such effects.

It is desirable to make the entire bend system achromatic through first order in position and momentum. As mentioned, this is achieved with the specified layout when beam current is negligible. For finite beam current, the phase advance per period is highly depressed, so the dynamics of a single ion cannot be achromatic. This inevitable feature is not considered a problem since momentum spread at any point within the pulse is expected to be very small ($\ll 1\%$). The greater issue is the achromaticity of the coherent motion of the beam centroid for values of momentum far away from the design value. Due to the $\pm 3.9\%$ momentum tilt the centroid of the pulse head and tail are dispersed by up to two centimeters and it is desired that this motion reach a null at the bend system end. Image forces reduce the coherent tune by about 3%. To restore effective coherent tune to 72° per period (as required for achromaticity in this design) the quadrupole gradients are raised by 3%. This is clearly a current amplitude dependent feature, so a tune fix cannot work for the entire pulse.

Dispersion plots for the beam centroid are given in Figures 3 and 4 for the case $\Delta P/P_0 = (\pm 0.025, \pm 0.05)$ with and without image fields present. The beam dynamics code

HICURB [4], which includes image effects and dispersion through all orders of ΔP was employed for this study.

Beam Combiner

An option for the HIF driver is to employ electrostatic focusing at low energy ($T \leq 100$ MeV). This approach involves the parallel acceleration of a large number of beamlets ($N \sim 64$) of relatively low line charge density ($\lambda \leq .25 \mu\text{ C/m}$) and small radius ($a \leq 3$ cm.). The focusing structure is significantly cheaper than the alternative of multiple magnetic channels. As energy increases the current carrying capability of magnetic channels increases rapidly and it becomes cost effective to transport a moderate number of beamlets ($N \sim 16$) in this mode. The required four-to one merge is carried out with a special beamline subsystem called a combiner, which translates beamlets into tightly packed clusters of four each. Emittance increases significantly during the first betatron period after the merge. If beamlet orbits are parallel at the instant of merge and empty space between beamlets is minimized, then emittance growth is primarily the result of a non-linear field energy contribution [5], and total emittance growth can be as low as a factor of four. This growth is acceptable in a driver if it is not repeated in later operations.

A combiner is planned for ILSE at the 4 MeV point, which would transform the sixteen initial beamlets with line charge $.06 \mu\text{ C/m}$ into four with $.24 \mu\text{ C/m}$. This occurs just prior to the 4 beamlet magnetically focused accelerating system, although one to two periods of special magnetic focusing may be required to handle and match the newly merged beams before they are further accelerated. Beam parameters upon entrance to the combiner are (for C^+)

$T = 4.0$ MeV	
$I = .48$ A	beamlet current
$B\rho = 1.00$ T-m	rigidity
$\epsilon \leq 10^{-5}$ m - r	emittance
$Q = 1.35 \times 10^{-4}$	perveance
$\Delta P/P_0 \leq \pm .1$	momentum variation

Edge emittance ϵ is uncertain since it depends on the operation of a source and injector presently under development. The large momentum variation represents the head-to-tail tilt and is nearly linear in time. It is the consequence of acceleration at near constant line charge density. Lattice period length is 1.0 m and the matched radius maximum value is 1.44 cm. These input parameters are unchanged during transport through the combiner until the beamlets are actually merged.

The combiner consists of three lattice periods which are a FODO array of multiple (16) beam electrostatic quadrupoles. The upstream period length (1.0 m) and tune of $60^\circ/\text{period}$ are maintained. The quadrupole occupancy factor is reduced to .33 in order to make room for the required bends. A schematic of this layout is shown in Figure 3. Four bends are employed, this being the minimum number needed to translate beamlets and also be a first order achromat in position and angle. The achromatic feature is necessary, given the large momentum tilt, unless rapidly pulsed elements can be used. Bends sequentially produce inward, reverse, inward and reverse deflections, with total angle equal to zero (as desired for low emittance growth). The first three bends are electrostatic, with pole voltages in the range ± 50 kV. The last element of the combiner is a special combined function bend/quadrupole. This design appears to be essential to prevent substantial beam loss on the upstream aperture. It is the only magnet in the combiner, this choice being made to prevent high-voltage breakdown in the very confined available aperture where some particle scrapeoff is expected. Magnetic field is in the range $\sim .3 - .5$ T. Cross sections of a typical multiple beam bend and the combined function magnet are shown in Figures 4 and 5.

The design of focusing and bending elements for the combiner has proven to be a very complex task, the principal difficulty being to shape electrodes such that the desired dipole or quadrupole field is produced without generating an excessive level of higher order multipoles. These shapes must be introduced into minimal transverse space since sixteen beam channels are present. In addition, only a few distinct high voltage levels are employed, in order to minimize field distortion by their feeds. A net sideways step in the

range 3-4 cm is to be produced over the 3 m system length, but only a small fraction of space can be devoted to bends; this results in the relatively large ± 50 kV on bend electrodes. Quadrupole electrodes are similarly constrained with pole tip potentials up to $\sim \pm 50$ kV.

Conclusion

ILSE will model major non-accelerating systems of a Heavy Ion Driver. Control of large chromatic and space charge related effects are vital in both systems. Special bend and focus elements must be designed for the multiple beam combiner and 180° bend.

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Fig. 1

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Fig. 2

Schematic of Beam Combiner

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Fig. 3

BEAM COMBINER ; MULTIBEAM ELECTROSTATIC BEND

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Fig. 4

MAGNETIC BEND AND DEFOCUS QUADRUPOLE

COMBINED FUNCTION
CURRENT DOMINATED MAGNET
MINIMUM BEAM-TO-BEAM SEPERATIONS = 3 mm
MAXIMUM FIELD = .5 T
EFFECTIVE LENGTH = 8.3 cm

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Fig. 5

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