A SCALED BEAM-COMBINING EXPERIMENT FOR HEAVY ION INERTIAL FUSION

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Abstract

Transverse beam combining is a cost-saving option employed in many designs for induction linac heavy ion fusion drivers. The resultant transverse emittance increase, due predominantly to anharmonic space charge forces, must be kept minimal so that the beam remains focusable at the target. A prototype combining experiment has been built and preliminary results are presented. Four sources each produce up to 4.8 mA Cs^+ beams at 160 keV. Focusing upstream of the merge consists of four quadrupoles and a final combined-function element (quadrupole & dipole). All lattice elements of the prototype are electrostatic. Due to the small distance between beams near the merge (~ 3-4 mm), the electrodes here are a cage of small rods, each at different voltage.

1 MOTIVATION

Transverse beam combining is an important cost-saving feature of standard driver designs for heavy ion fusion. At the low-energy end of a driver, electrostatic quadrupoles are used to focus each beam of the multiple-beam array. Voltage breakdown and economic considerations dictate a small aperture for these quadrupoles, and thus a large number of beams. At higher energies it is more economical to accelerate fewer fatter beams through large-aperture magnetic quadrupoles. Thus, transverse beam combining should be implemented at about 100 MeV.

Since space charge contributes significantly to the beam dynamics for these intense beams, the interactions between particles during merging serve as a source of emittance growth, along with the usual "phase space filling" seen, for instance, in beam stacking in storage rings. As shown in previous work[1], transverse emittance growth is minimized by packing the beams as tightly as possible. The experimental challenge is to position the beams with sufficient accuracy to allow tight packing, and to keep them focused as their centroids converge while preserving low emittance.

2 DESCRIPTION OF THE EXPERIMENT

At Lawrence Berkeley National Laboratory an experiment to demonstrate 4-to-1 transverse beam combining has been built on the old MBE-4 accelerator[2]. The MBE-4 apparatus is used mainly to provide a long transport channel; the "beam combiner" is new. The combiner, consisting of a Cs^+ source, 160 keV diode, and focusing transport channel for each of the four beams, replaces the old MBE-4 diode and matching system. The beamlines (including the sources and diodes) converge with angle of 6° relative to the combiner centerline. A computer-aided design (CAD) view of one of the combiner elements is shown in Fig. 1. Four electrostatic quadrupoles, followed by an electrostatic combined-function (quadrupole and dipole) element, are used to focus each beam and straighten its trajectory so that the beams emerge from the combiner almost parallel to the centerline of the MBE-4 transport channel. The design configuration for the beam cross sections as they emerge from the combiner is shown in Fig. 2. As can be seen, the cross section is x-y asymmetric to allow for good packing of the elliptical beams. After the combiner the merged beam is transported (without acceleration) and diagnosed in the remaining 30 lattice periods of one channel of MBE-4. Further description of the experimental setup is found in ref. [3] and [4].

Quadrupole and dipole fields in QD5 are produced by surrounding the beams with a "wire cage" of 71 1-mm diameter tungsten rods at a spacing of ~1 mm, approximately parallel to the beam path. The voltage on each rod is set according to the desired Dirichlet boundary condition, resulting in voltage differences of up to 1.5 kV from rod to rod.

Beam steering is accomplished with sources mounted on gimbals which allow them to rotate about their centers, followed by articulation in x and y of Q2. Both operations can be done in vacuum. Since the beams emerge from the combiner separated by about 4 mm, their clearance from the rods within the wire cage is only about a millimeter near the exit of the cage. Thus, steering must be correct to the sub-millimeter level.

3 PRELIMINARY RESULTS AND FUTURE PLANS

The combiner focusing elements have been fabricated and are operational. Most of the ions is transmitted through the wire cage with no evidence of voltage breakdown.

The experiment has begun to produce results, and this first round of measurements are providing guidance for beam steering adjustments and other modifications that are underway. What follows is a description of what we have measured to date and implications for future measurements.

The beam current from the four diodes has been measured with Faraday cups in place of the Q2 quadrupole array. Each beam is within ±2% of the design value of

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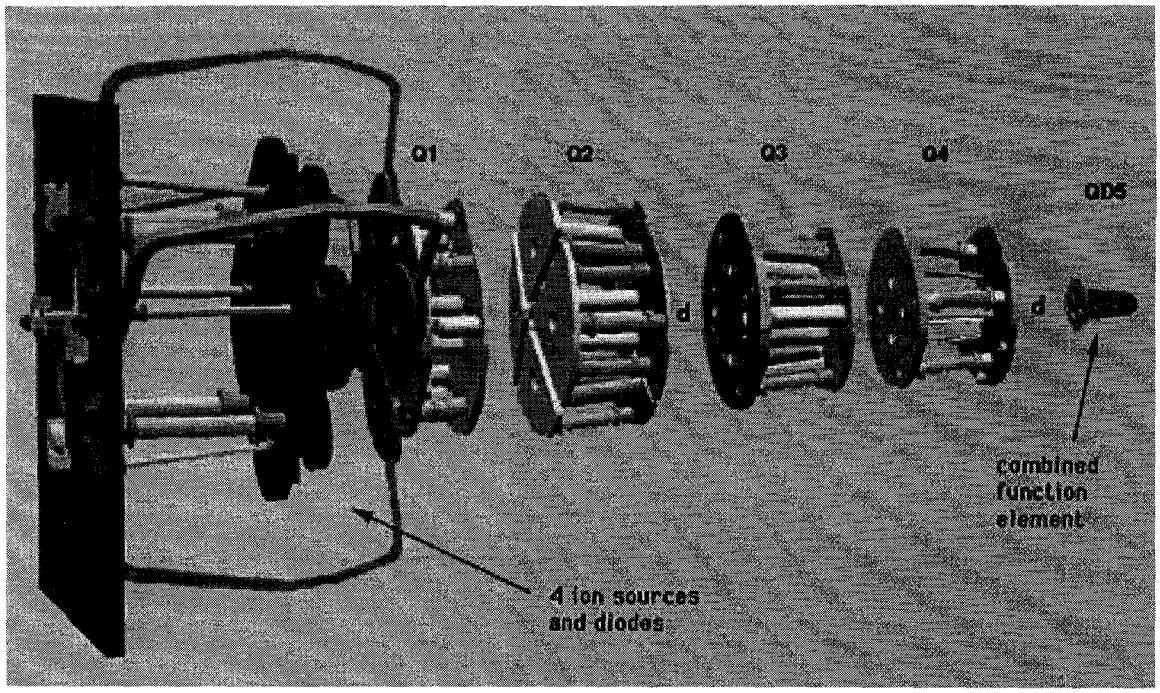

Figure 1. A CAD view of the lattice elements of the combiner apparatus. Diagnostics are at locations marked "d". The first four elements (Q1-Q4) are electrostatic quadrupoles. Each of the quadrupoles of Q2 are separately articulable. QD5 is the combined-function dipole and quadrupole. The distance from the source emitting surfaces to the end of the wire cage is ~108 cm. Downstream of QD5 the beams emerge into a 31 period transport lattice (Q7 - Q67).

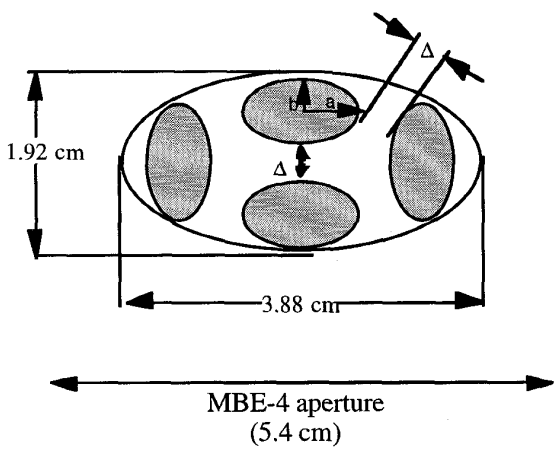

Figure 2: Design configuration of four beams as they emerge from the combiner. Beam semimajor and semiminor axes are 6.5 and 3.7 mm. Δ=4 mm.

4.75mA. This spread is consistent with the fabrication tolerances of the diode.

An aperturing mask between each diode exit and Q1 is designed to vary the current of the beams, allowing the study of merged beam phase space as a function of initial current. Phase space measurements show an unexpected, large convergence angle and a non-uniform beam profile, precluding properly matching the beam downstream. It appears that this problem is associated with secondary electron production and consequent perturbation of the ion beam properties due to the space charge of the electrons. Calculations are underway that will aid the design of a modified aperturing mask -- possibly incorporating added electric or magnetic fields -- to satisfactorily reduce the influence of secondary electrons on the ion beams.

2D and 3D particle-in-cell (PIC) simulations are used to help interpret the data. The simulations are described elsewhere in these proceedings [5]. The phase space measured at the first diagnostic station is in good agreement with the 2D PIC. Data at the second diagnostic location, just upstream of the wire cage, shows distortions in phase space that are also well reproduced by the 2D (and 3D) PIC simulation. This level of agreement lends confidence to the accuracy of the PIC simulation of this experiment and validates its use as an interpretive tool.

The third diagnostic station is located one quadrupole doublet downstream (after Q7) of the wire cage. Measurements of the merged beam current there indicate that most of the ions are transported through the wire cage (~70%). A phase space measurement of the merged beams at that location is compared to the 2D PIC simulation in Figure 3. There is rough agreement, and indications of misalignments of individual beams whose corrections are now being undertaken using the remotely articulable sources and Q2 array. Figure 3 also shows that the beams are relatively distinct and separated in phase space at this location, and are expected to remain so for several more lattice periods before the phase space

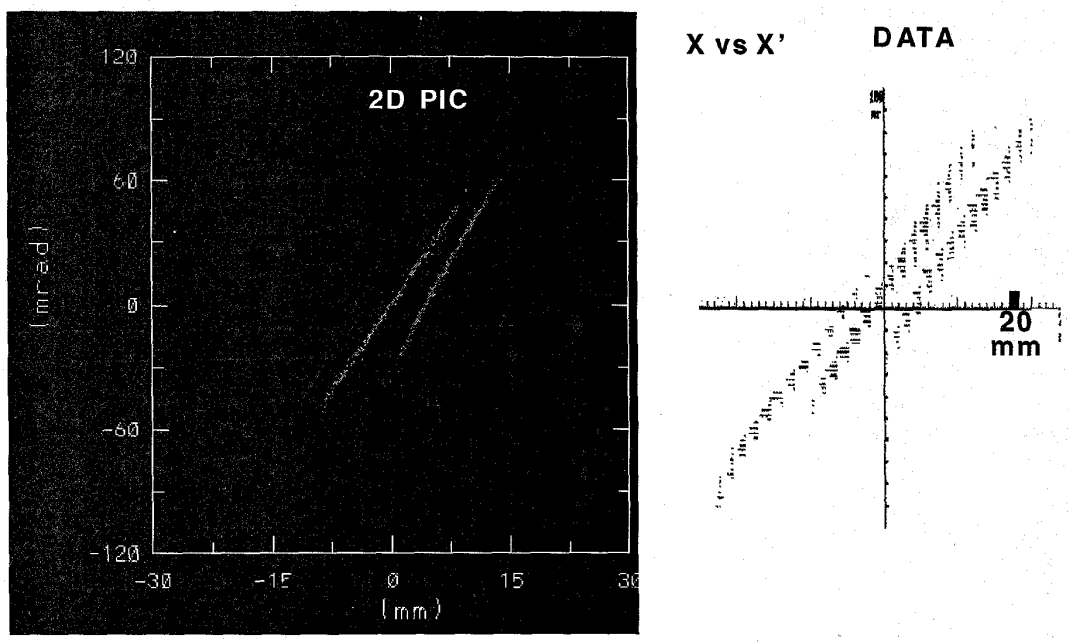

Figure 3: 2D PIC simulation of the merged beams compared to the phase space measured in the experiment at the third diagnostic location, or one quad doublet downstream of the wire cage. In this horizontal phase space, two of the four beams are at the middle. For the data, the length of the horizontal bars indicates the signal amplitude at the right edge of each bar. Table 1 shows the experimental parameters for the measurements and simulation.

TABLE 1: Experimental parameters for the data presented in this paper.

Initial current, one beam	4.8 mA
Ion kinetic energy	160 keV
beam edge radius (diode exit)	3.7 mm
beam edge convergence angle	-12 mr
Voltage of Q1	-5.032 kV
Voltage of Q2	-4.747 kV
Voltage of Q3	-4.867 kV
Voltage of Q4	-3.075 kV
Voltage of QD5	±3.800 kV
Voltage of Q6	-11.976 kV
Voltage of Q7	-17.361 kV
Voltage of Q8	-16.026 kV
Voltage of Q9	-14.207 kV
Voltages of Q10-67	-14.600 kV
Pressure in combiner	$<4\times10^{-6}$ Torr

becomes thoroughly mixed. This makes matching the beams to the downstream lattice a complicated function of the properties of each beam at the merge point and thus requires tight coupling of the experiment to simulation tools. Faraday cup measurements after Q17 show further beam loss. Along with capacitively coupled signals from electrostatic quadrupoles (sensitive to beam ions striking the quadrupole electrodes) the measurements are consistent with beam loss locations predicted by the 2D simulation.

The distinctness of the beams over several lattice periods downstream of the merge point leaves open the possibility of reducing the empty space between beams with non-linear correction elements.

Upcoming experimental efforts will include steering the beams and correcting the observed misalignments. The matching solution to the downstream lattice will be refined. Following the modification of the aperturing system, merging measurements with lower initial currents will be carried out.

4 ACKNOWLEDGEMENTS

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REFERENCES

[1] C.M. Celata et al., Proc. of 1987 Part. Acc. Conf., Washington, D.C., 2 (1987), 1167.
[2] Thomas J. Fessenden, et al., Proc. of the 1987 Part. Acc. Conf., Washington, D.C., 2 (1987), 898.
[3] C.M. Celata et al., Proceedings of the 1995 Part. Acc. Conf., p. 3220.
[4] C.M. Celata et al., Fusion Eng. and Design, V32-33 (1996) 219.
[5] W.M. Fawley et al., "Numerical Simulation Studies of the LBNL Heavy-Ion Beam Combiner Experiment", these proceedings.