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Heavy-Ion Fusion Driver Research at Berkeley and Livermore

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P. Seidl, R. Bangerter, C.M. Celata, W. Chupp, F. delaRama, S. Eylon, A. Faltens, W.M. Fawley, T.J. Fessenden, W. Ghiorso, K.D. Hahn, E. Henestroza, R. Hipple, D. Judd, S. MacLaren, C. Peters, L. Reginato, D. Vanecek, J.D. Stoker, S. Yu, J.J. Barnard, M.D. Cable, D.A. Callahan, T.V. Cianciolo, F.J. Deadrick, A. Debeling, A. Friedman, D.P. Grote, K.A. Holm, H.A. Hopkins, V.P. Karpenko, H.C. Kirbie, D.B. Longinotti, S.M. Lund, L.A. Nattrass, M.B. Nelson, M.A. Newton, T.C. Sangster, and W.M. Sharp

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Accelerator and Fusion Research Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

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Lawrence Livermore National Laboratory
Livermore, California 94550

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E.O. Lawrence Berkeley National Laboratory Berkeley, CA 94720

J.J. Barnard, M.D. Cable, D.A. Callahan, T.V. Cianciolo, F.J. Deadrick, A. Debeling*, A. Friedman, D.P. Grote, K.A. Holm, H.A. Hopkins, V.P. Karpenko, H.C. Kirbie, D.B. Longinotti, S.M. Lund, L.A. Nattrass, M.B. Nelson, M.A. Newton, T.C. Sangster, and W.M. Sharp
Lawrence Livermore National Laboratory, Livermore, CA 94550

ABSTRACT:

The Department of Energy is restructuring the U.S. fusion program to place a greater emphasis on science. As a result, we will not build the ILSE or Elise heavy ion fusion (HIF) facilities described in 1992 and 1994 conferences. Instead we are performing smaller experiments to address important scientific questions.

Accelerator technology for HIF is similar to that for other applications such as high energy physics and nuclear physics. The beam physics, however, differs from the physics encountered in most accelerators, where the pressure arising from the beam temperature (emittance) is the dominant factor determining beam size and focusing system design. In HIF, space charge is the dominant feature, leading us into a parameter regime where the beam plasma frequency becomes comparable to the betatron frequency. Our experiments address the physics of non-neutral plasmas in this novel regime. Because the beam plasma frequency is low, Particle-in-cell (PIC) simulations provide a good description of most of our experiments.

Accelerators for HIF consist of several subsystems: ion sources, injectors, matching sections, combiners, acceleration sections with electric and magnetic focusing, beam compression and bending sections, and a system to focus the beams onto the target. We are currently assembling or performing experiments to address the physics of all these subsystems. This paper will discuss experiments in injection, combining, and bending.

I. EXPERIMENTS WITH THE 2MV K^+ INJECTOR

A driver-scale, one-beam heavy ion injector has been constructed and operated at LBNL. The new injector has, as its design goals, a particle energy of 2 MV, line charge density of 0.25 μC/m (800 mA of K^+) and a normalized edge emittance <1 π-mm-mr. These design parameters are the same as in a full-scale driver. The low emittance is essential for near-ballistic final focusing onto a small target. The line charge corresponds to the optimal transportable charge in a full-scale electrostatic quadrupole channel, and the high injector energy has significant cost advantages in a fusion driver. The ultimate injector for a fusion accelerator is conceptually a replicate of this one-beam injector to many beams, with an extended pulse length of many microseconds, instead of the one to two microseconds (budget-determined) in this 2 MV injector. While the particle energy and particle current have been achieved separately in previously built injectors, the unique combination of energy, current, and emittance requirements pose a new technical challenge. Furthermore, the required beam parameters must stay constant over the entire pulse, and the injector must run reliably.

The new injector is based on an electrostatic quadrupole (ESQ) configuration[1,2]. The ion beam, after extraction from an axisymmetric diode, is injected into a lattice of electrostatic quadrupoles arranged to provide simultaneous acceleration and strong focusing. The ESQ configuration was chosen over the more conventional electrostatic aperture column primarily because of high- voltage breakdown considerations. The accelerating gradient of an ESQ can be made quite low, and the strong transverse fields sweep out secondary electrons which may initiate breakdown processes. However, the ESQ configuration has an inherent beam aberration, which must be carefully controlled to minimize emittance degradation. The key design issues center around the control of high voltage breakdown and phase-space distortions.

The injector column consists of a diode followed by four electrostatic quadrupole sections (Fig. 1). The source is a 6.7" diameter curved hot alumino-silicate source emitting K^+ ions. These sources have been shown to produce beams with temperature-limited emittances, and have long life-time and high reliability. The injector is powered by a 2-MV Marx with parallel LC and RC circuits that produce a 4-μs flat-top.

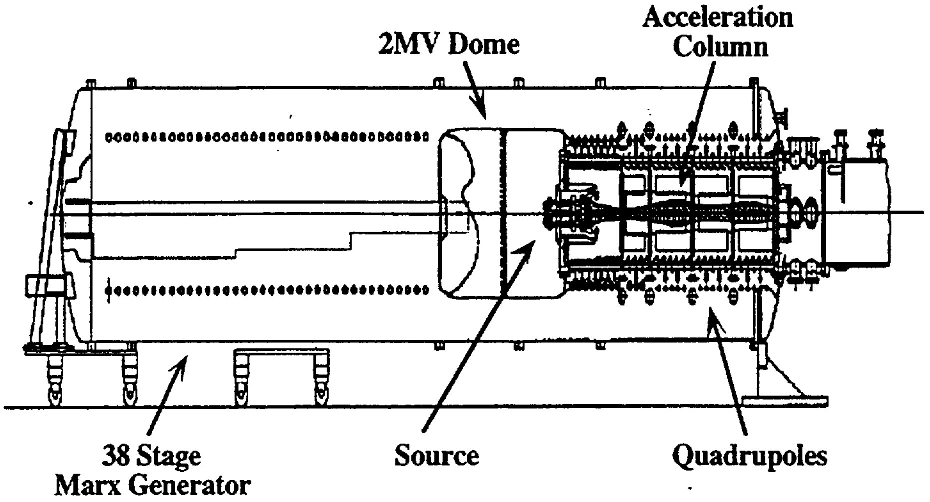

Fig.1: 2 MV injector schematic.

One key design issue is the dynamics of the space-charge dominated ion beam. A low energy ion beam in a strong electrostatic focusing channel experiences an aberration which can lead to an increase in beam emittance. The cause of this effect is that ions at a given axial location within the quadrupole channel do have variable energies, depending on their relative proximity to the electrodes. Variations in beam energy lead to a spread in betatron motion, which results in a kinematic aberration of the beam. This effect is most serious for low beam energy and strong quadrupole fields. The beam dynamics are further complicated by the facts that the interdigital geometry of the electrode package is fundamentally 3-dimensional, and that the beam is space-charge dominated. Detailed theoretical predictions required extensive 3-D PIC simulations and code developments with WARP-3D [3].

The engineering design and construction of the ESQ injector took about one year and was completed in October 1993. On the first day of operation, a K^+ beam in excess of the design parameters of 2 MV and 800 mA was produced. The current was measured for a range of Marx and pulser voltages, and the agreement with code predictions was excellent. The highest energy and current achieved thus far is 2.3 MV and 950 mA of K^+, or 15% above the design goals. We have not yet attempted to push the injector to its limit of performance.

The transverse emittance was measured with a double-slit scanner. Over a broad range of parameters, the measured normalized edge emittance was less than 1 π mm-mr. As the current is increased, phase-space distortions are enhanced, as predicted by theory and simulations.

We have successfully “fine-tuned” the extraction pulser and Marx voltage to the point where the exiting beam is flat to less than ±0.2% over 1 μs. Variations in emittance and the beam envelope over the pulse duration are minimal.

II. BEAM COMBINING

Transverse beam combining is an important cost-saving feature of standard driver designs for HIF. 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, larger-diameter beams through large-aperture magnetic quadrupoles. Analysis indicates that transverse beam combining is best implemented at about 100 MeV.

Since space charge dominates 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 [4], transverse emittance growth is minimized by packing the beams as tightly as possible. Near the merge point the small space between beams makes it difficult to insert focusing structures with good field quality. The experimental challenge is to position the beams with sufficient accuracy to allow tight packing, and to keep them focused as their centroids converge.

II.1 Description of the Experiment

At LBNL, an experiment to demonstrate 4-to-1 transverse beam combining is underway [5]. The combiner consists of a Cs^+ source, 200 keV diode, and focusing transport channel for each of the four beams. The beamlines converge with an angle of 6° relative to the combiner centerline (Fig. 2). 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. The design configuration for the beam cross sections as they emerge from the combiner is x-y asymmetric to allow for good packing of the elliptical beams. After the combiner the merged beam will be transported and diagnosed through 30 lattice periods.

Due to length restrictions, matching of the beam from the cylindrically symmetric diode to the alternating gradient transport channel is done in the combiner, rather than in a separate matching system. For the same reason, the need for initial dipoles (that would bend the trajectories of the beams towards a common axis in a driver) has been removed by aiming the sources toward a common point of convergence. The first three combiner quadrupoles consist of circular electrodes, with the ratio of electrode radius to aperture set to minimize the lowest order 2D nonlinear field component -- the dodecapole. At the fourth quadrupole, the space between beams is too small for cylindrical electrodes, so hyperbolic electrodes have been designed which both shield the beams from each other and produce minimal field nonlinearity.

The small spacing between the beams at the downstream end of the fifth lattice element does not allow adequate space for large electrodes. Quadrupole and dipole fields are instead produced by surrounding the beams with an elliptical "squirrel cage" of tungsten rods,. The rods have a spacing of ~1 mm, and are nearly parallel to the beam path. The voltage on each rod is set so that the rods approximate the correct Dirichlet boundary condition. Since the beams emerge from the combiner separated by about 4 mm, their clearance from the rods within the squirrel cage is only about ~1.5 mm near the exit of the cage. Thus, beam alignment must be correct to the sub-millimeter level.

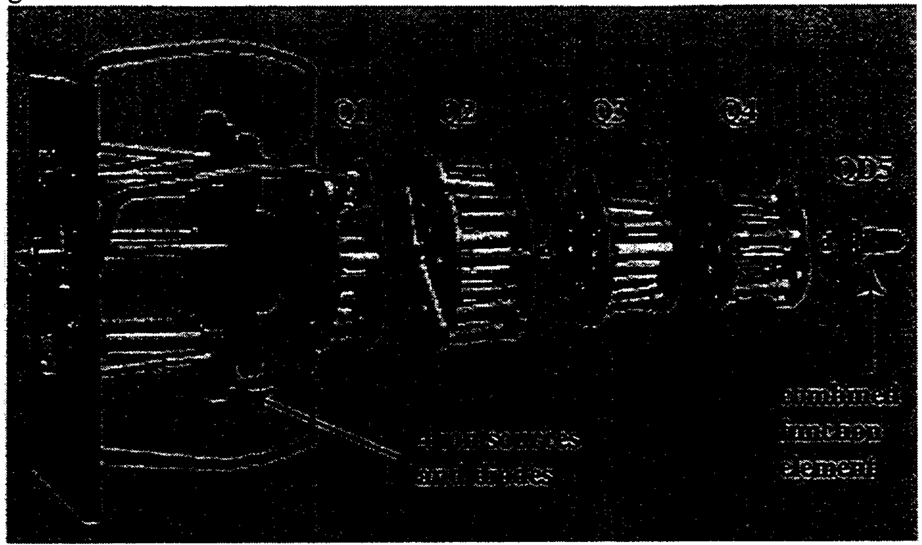

FIG. 2: Schematic of the combiner experiment (d=diagnostic location).

II.2 Simulation Results and Status of the Experiment

Experiments and simulations of the current carrying capacity of MBE-4 have indicated that the MBE-4 channel can transport a low-emittance (unmerged), 20-mA beam with only a few percent beam loss. This implies that beam merging experiments of four, ~4 mA beams could be possible with relatively little beam loss. Following this result, transport through the entire combiner, with both merging and subsequent transport of the merged beam has been simulated using the 2D electrostatic PIC code HIBEAM. Results further substantiated the practical nature of the design.

Image effects of the electrodes of the first four quadrupoles, field aberrations in the squirrel cage, phase space filling, and the conversion of electrostatic potential energy of the beams to transverse thermal energy during the merging process all increase the emittance. Beam loss is negligible. The simulations demonstrate that this experiment is, like a driver, in the regime where both space-charge and phase-space filling determine the final emittance growth. Because of the relatively large spaces between the small beams in this experiment, the emittance growth is proportionately bigger than it would be in a driver, where the much larger beams are expected to have approximately the same separation. Simulations have shown adequately low emittance growth for the driver.

At present all components of the combiner have been fabricated, aligned and installed. At the time of this writing, experiments are underway to measure the distribution function of the beams at the entrance to the squirrel cage for detailed comparison to the simulations above. Later, the effect of the combiner on one beam will measured, followed by four-beam merging experiments.

III. EXPERIMENTS IN BENDING AND RECIRCULATION

A recirculating induction accelerator (recirculator) potentially offers reduced cost relative to a "conventional" linac because the accelerating and focusing elements are re-used many times in a single target shot. The overall accelerator length is reduced (to about 3.6 km in the "C-design" recirculator of Ref. [6], and possibly less), and the accelerating cores are smaller and are not driven so close to saturation because it is not necessary to accelerate the beam at the maximum possible rate. The recirculator designs considered to date employ greater axial pulse compression than is typically assumed for linac designs, with a smaller number of longer beams used initially, and do not employ beam combining. Current research on recirculator drivers has centered on multi-ring designs, with each ring augmenting the beam's energy by an order of magnitude over ~100 laps. Relative to a "conventional" linac, the length is reduced by a factor of order 2-3, but the beam path length increases to perhaps ~200 km. Hybrid designs (with a recirculator at the low-energy end) are also possible.

The beam dynamics issues which must be resolved before a recirculating driver can be built include centroid control, longitudinal beam confinement, acceleration schedule, avoidance of phase-space dilution in bends, and insertion/extraction of the beam into/out of the rings. As described below, these can be addressed at reduced scale in a small prototype recirculator. The waveform generators in a driver must supply variable accelerating pulses at ~100 kHz repetition frequencies, and accurate time-varying dipole fields with good energy recovery. These requirements are challenging, but advances in solid-state power electronics should make it possible to meet them through a technology development program. Collisional interactions can drive beam or gas ions into the walls of the beam pipe, and so cause the desorption of wall material. This material will interact with the beam on its next pass. Thus, and because of the long path length, a high vacuum of 10^{-10} to 10^{-11} torr is especially important. There remain uncertainties in some of the relevant cross sections; many of these can be resolved through experiments on existing accelerator facilities.

III.1 Experimental program

LLNL, in collaboration with LBNL, is currently developing a small prototype heavy-ion, recirculating induction accelerator. This "small recirculator" is intended to explore, in a scaled manner, the physics and technology issues involved in constructing a full scale recirculating driver. The small recirculator will be assembled and operated as a series of experiments over several years' time. Over the past year a linear transport experiment using permanent-magnet quadrupoles was carried out; The next major experiment will be a study of beam transport around a bend (initially without acceleration). In the later experiments, the machine will be operated in a full recirculating mode with a variety of beam manipulations, requiring sophisticated pulsed-power waveform synthesis.

The small recirculator will have a circumference of 14.4 meters, a 3.5 cm aperture radius for the beam focusing and bending elements, and a half-lattice period (HLP) of 36 cm. The beam will be transversely focused by permanent magnet quadrupoles with a field of ~0.3 T at the pipe wall, and will be bent with electric dipole deflector plates. The quadrupoles and dipoles will each occupy about 30% of the axial lattice length, and the full ring will consist of 40 HLP's, including two large-aperture quadrupole magnets through which the beam will be inserted and extracted. The K^+ beam will be accelerated from an initial particle kinetic energy of 80 keV to 320 keV over 15 laps by 34 induction cores. The current will increase from 2 mA to 8 mA, with half of the current amplification from halving the length of the bunch, the other half from doubling the velocity. The phase advance of the betatron motion of the ions in the ring will range from $\sigma_0 = 78°$ to 45° per lattice period in the absence of beam space charge, and from $\sigma = 16°$ to 12° in its presence. The average beam radius will be ~1.2 cm.

Because the heavy-ion beam in the small recirculator is nonrelativistic and accelerating, the waveforms required to accelerate (via pulses supplied to the induction cores) and bend the beam (via voltages applied to the electric dipole plates) will be technologically challenging. The induction waveforms will require the accurate synthesis of detailed voltage pulses with a repetition rate increasing from 40 to 90 KHz at the initial and final beam energies due to the increasing beam velocity. Furthermore, detailed "ear" pulse structures and lap-to-lap variation of the pulse duration must control the beam length. A prototype induction modulator has been developed which meets these requirements on repetition rate and pulse variability. The voltage waveform for the electric dipoles must also be correctly timed with respect to the pulses that power the induction cores for beam acceleration. A modulator which produces the precise, high voltage, temporally ramped dipole voltage pulse is under development at LBNL.

Until the rest of the ring is complete it will be possible to employ intercepting diagnostics, and to use these to calibrate the non-intercepting diagnostics that will be critical to operation of the full ring. The ring will incorporate two extraction sections, so the extracted beam can be diagnosed with detailed intercepting diagnostics twice each lap. As with earlier linac experiments at LBNL, excellent shot-to-shot repeatability is anticipated.

As of this writing, the source and injector diode are in operation, and a beam has been transported through a linear focusing channel consisting of an electrostatic-quadrupole matching section, which is a modified segment of LBNL's SBTE apparatus, and a magnetic transport section consisting of seven quadrupole magnets. The design of the HLP for the recirculator ring has been completed, aided substantially by simulations using the 3D PIC code WARP-3D. The simulations allowed the dipole plates to be shaped, minimizing the sextupole component and providing equal focusing in the two transverse directions. Two HLP's are undergoing final alignment; beam is expected through them in September, 1996. Capacitive, non-intercepting diagnostics for beam centroid monitoring have been developed, tested and calibrated. Additionally, the beam has been well-characterized using a number of intercepting diagnostics. For additional details on results of the linear transport experiments see ref. 7.

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REFERENCES:

* Current address: Bechtel Nevada Corporation.

[1] E.A. Abramyan, and V.A. Gapanov, Atomnaya Energiya 20, 385 (1966).

[2] O.A. Anderson, et.al., Proc. 1989 Part. Accel. Conf., Chicago, March (1989).

[3] A. Friedman et al., Phys. Fluids B4, 2203 (1992).

[4] C.M. Celata A. Faltens, D.L. Judd, L. Smith, and M.G. Tiefenback, Proc. of 1987 Part. Acc. Conf., Washington, D.C., 2 (1987), 1167.

[5] C. Celata et al., Proc. 1995 International HIF Symposium, Princeton. To appear in *Fusion and Engineering Design, V33-34 (in press).*

[6] J.J Barnard, et al., "Recirculating Induction Accelerators as Drivers for Heavy-Ion Fusion," *Phys. Fluids B: Plasma Physics* 5, 2698 (1993).

[7] T.J. Fessenden, et al., "Intense Heavy-Ion Beam Transport with Electric and Magnetic Quadrupoles," Proc. 1995 International HIF Symposium, Princeton. To appear in *Fusion and Engineering Design, V33-34 (in press).*