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The U.S. Inertial Fusion Energy (IFE) Program is developing induction accelerator technology toward the goal of electric power production using Heavy-Ion beam-driven inertial Fusion (HIF). The recirculating induction accelerator promises driver cost reduction by repeatedly passing the beam through the same set of accelerating and focusing elements.[1] We present plans for and progress toward a small (4.5-m diameter) prototype recirculator,[2] which will accelerate K^+ ions through 15 laps, from 80 to 320 keV and from 2 to 8 mA. Beam confinement is effected via permanent-magnet quadrupoles; bending is via electric dipoles. Scaling laws, and extensive particle and fluid simulations of the space-charge dominated beam behavior, have been used to arrive at the design. An injector and matching section are operational. Initial experiments are investigating intense-beam transport in a linear magnetic channel; near-term plans include studies of transport around a bend. Later experiments will study insertion/extraction and acceleration with centroid control.

I. RECIRCULATOR CONCEPT

A recirculating induction accelerator potentially offers cost reduction relative to a "conventional" ion induction linac. The overall accelerator length is reduced (by a factor of ~2-3, to about 3.6 km in the "C-design" recirculator of Ref. [1] and possibly shorter), and the accelerating cores are smaller because acceleration can be slower. Research on recirculator drivers has centered on four-beam multi-ring designs, with each ring augmenting the beam's energy by an order of magnitude over 50 to 100 laps. In contrast with most HIF induction linac concepts,[3] the recirculator designs considered to date do not employ beam merging. Hybrid designs (with a recirculator at the low-energy end) are also possible and may prove attractive.

The beam-dynamics issues which must be resolved before a recirculating driver can be built include centroid control, longitudinal control, 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 repetition frequencies ~50 kHz, 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. Present technology has achieved 200 kHz bursts at 5 kV and 800 A with pulse widths of 0.5-2 ms, but with a non-variable format.[4] Because of its long (~200 km) beam path length and the fact that the beam repeatedly visits each section of the beam line, a recirculator driver will require a vacuum of $\sim 10^{-10}$ to 10^{-11} torr.

II. DESIGN OF SMALL RECIRCULATOR

LLNL, in collaboration with LBL, Titan-Beta, and EG&G, is currently developing a small prototype ion recirculator. This "small recirculator" is intended to explore, in a scaled manner, the beam-dynamics issues in a recirculating driver for inertial fusion energy. The small recirculator will be assembled and operated as a series of experiments over several years' time. Fig. 1. illustrates the overall physics design of the final small recirculator, and lists some of the elements which must all work together, both in it and in a full-scale fusion driver.

The small recirculator will have a circumference of 14.4 meters, a 3.5 cm aperture radius (pipe radius) for the beam focusing and bending elements, and a half-lattice period of 36 cm. The beam will be transversely focused with alternating-gradient permanent magnet quadrupoles with a field of ~0.294 T at the pipe wall, and will be bent

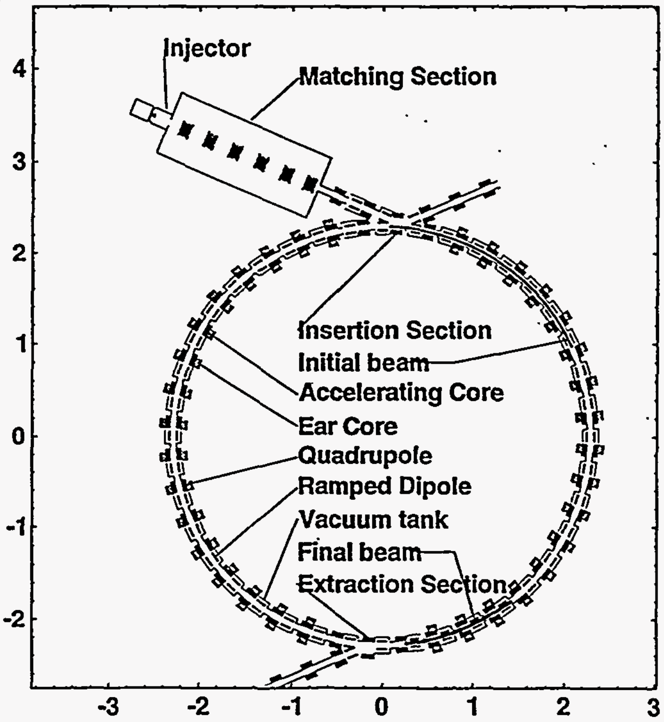

Fig. 1. Overview of final configuration (scales in meters).

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with electric dipole deflector plates. These quadrupoles and dipoles will each physically occupy about 30% of the axial lattice length, and the full recirculator ring will consist of 40 half-lattice periods, including two using special large-aperture quadrupole magnets through which the beam will be inserted and/or extracted. The beam ion is K^+ (mass 39 AMU), and the beam will be accelerated from an initial particle kinetic energy of 80 keV to 320 keV over 15 laps by 34 induction cores. The initial current of the beam will be 2 mA, corresponding to a line-charge density of 0.0036 μC/m and characteristic beam radius of 1.1 cm, and the initial pulse duration will be 4 μsec. Also, the initial phase advance per lattice period will be $\sigma_0 = 78°$, depressed to $\sigma = 16°$ by space charge. After 15 laps of acceleration, the beam current will have increased to 8 mA, with a corresponding line-charge density of 0.00721 μC/m, an average beam radius of 1.3 cm, and a final pulse duration of 1 μsec. Also, the phase advances will decrease to $\sigma_0 = 45°$ and $\sigma = 12°$.

Because the heavy-ion beam in the small recirculator is nonrelativistic and accelerating, the variable-format waveforms required to accelerate and bend the beam will require repetition rates ranging from approximately 40 to 90 kHz at the initial and final beam energies.[5] The voltage pulses for the electric dipoles must be correctly ramped in concert with the changing beam energy. Detailed "ear" pulses and lap-to-lap variation of the pulse duration and shape must be added to the accelerating waveforms to maintain or decrease the beam length. In order to switch the beam into or out of the ring, it is necessary to apply dipole fields that vary in time. Transverse confinement of the beam must be carried out during the insertion or extraction process. The design we are developing uses a permanent-magnet quadrupole with an expanded aperture.

III. EXPERIMENT PLANS

Linear experiments now getting underway will measure space-charge-dominated beam quality after transport through a permanent-magnet quadrupole lattice, will characterize the beam prior to injection into the recirculator, provide a test-bed for diagnostic development and afford a preliminary assessment of the role of electrons in magnetic beam transport (see Fig. 2).

The next experiments will study beam transport around a ~90° bend (without acceleration, at first). Emittance growth can result from the non-uniform distribution of beam space-charge resulting from the action of centrifugal forces. As revealed in particle simulations using WARP3d [6] and interpreted theoretically [7], it occurs at changes in the accelerator's curvature where the distribution of beam particles relaxes toward a new equilibrium. Also, the electric dipoles introduce field aberrations. Detailed 3-D simulations show that proper shaping of the dipole plates should render the beam distortion minimal. In the small recirculator, a measurable amount of emittance growth is expected to take place over the fifteen laps, mostly occurring in the first two laps.[8]

Later experiments will study insertion and extraction, acceleration (at first in a partial ring to facilitate measurement of the beam using intercepting diagnostics), beam steering, bunch compression, and full integrated operation of the recirculator.[2] Preservation of a small emittance will again be the central beam physics issue to be addressed.

The principal non-intercepting diagnostic is a segmented capacitive pickup located inside the quadrupoles.[9] Until the ring is complete it will be possible to employ intercepting diagnostics. As currently planned, the ring will incorporate two extraction sections 180° apart, and the extracted beam can be diagnosed with detailed intercepting diagnostics twice each lap. As with earlier linac experiments at LBL, excellent shot-to-shot repeatability is anticipated and, so far, observed.

The long beam residence in the machine, up to (and possibly exceeding) 300 full lattice periods, will provide a unique opportunity to observe and characterize the longitudinal propagation of space-charge waves along the beam. Such waves will be launched (deliberately or otherwise) by mismatching the applied ear fields. The small recirculator will afford the longest beam path length of any near-term facility, and so will be able to explore issues such as slow thermalization which are important to both recirculating and linear drivers.

IV. STATUS AND INITIAL RESULTS

The injector diode[10], matching section, and straight experiment have been fabricated and are now operating; the layout is depicted schematically in Fig. 2. Fifteen

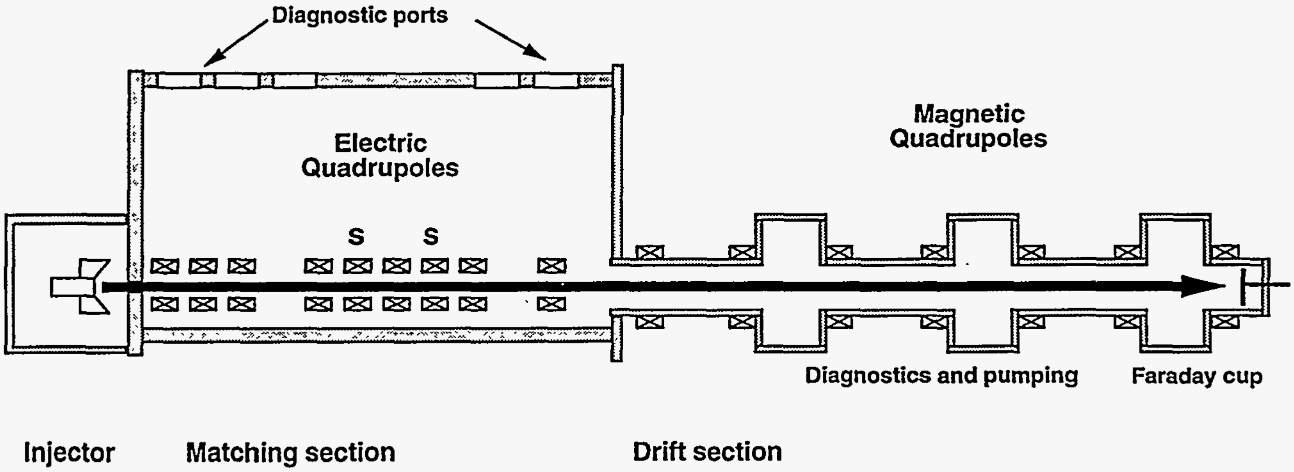

Fig. 2. Linear configuration (overall length 4.568 m from source plate to final Faraday cup).

permanent-magnet quadrupoles have been procured; seven will be used in the straight experiment (a shorter line will serve as the link from matching section to ring). The mechanical design of the "half-lattice period" is nearly complete.[11]

The electrostatic-quadrupole matching section gives the circular beam from the diode an elliptical cross-section, suitable for alternating-gradient transport in the transfer line and the recirculator. A section of the SBTE apparatus from LBL was adapted by EG&G to serve this function. The voltages applied to the various quadrupole elements in order to obtain a matched beam were derived using an envelope calculation and range from ± 1.8 to ± 4.0 kV. The fifth and seventh elements are intended for minor beam steering rather than for focusing. Insertable Faraday cups are located after the third and ninth elements.

Time-resolved measurements of beam properties have been obtained at various locations throughout the matching and magnetic transport sections. The current has been measured using Faraday cups at positions .67 and 1.9 m downstream of the diode source in the matching section, as well as at a position 3.16 m downstream in the magnetic transport section. An energy analyzer developed at LBL (consisting of curved electrostatic plates, across which various potential differences are placed) was located 1.75 m downstream of the source. A two-slit scanner was placed at positions .2 and 1.6 m downstream of the source, providing measurements of emittance, beam radius and beam centroid location.

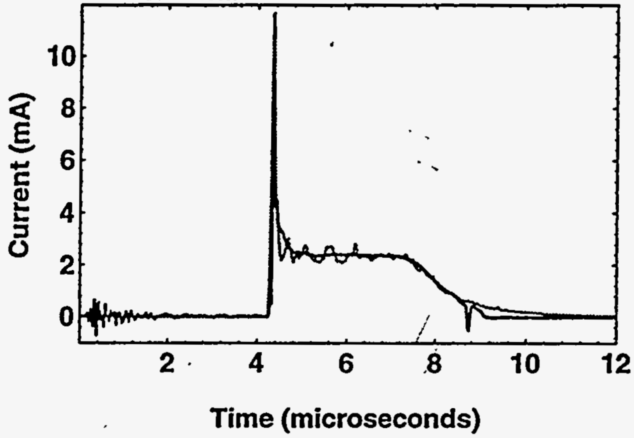

Fig. 3. Experimental (black) and simulated (gray) current.

Figure 3 shows an example of the current vs. time at the second Faraday cup location. Also plotted are results from the 1-D Code HINJ[12] showing close agreement between simulation and experiment. The plot shows a large current spike at the head of the pulse. The spike arises because the rise time of the diode voltage (about 1 μs) is longer than the ideal rise time of 0.48 μs.[13] With the slower rise time, particles emitted at the beginning of the pulse have significantly lower energy than particles emitted subsequently and so particle overtaking occurs. A modification of the pulser circuitry to halve the rise time is planned. The code results are slightly noisier than the experiment; this results from a numerical deconvolution of the voltage waveform (to account for time lags in the voltage monitor), which introduced noise into the voltage waveform used by the code. Shown in Fig. 4 is a measurement of the horizontal normalized edge emittance (4x rms) at the end of the matching section. The high initial value appears to be due to the instantaneously high line-charge density.

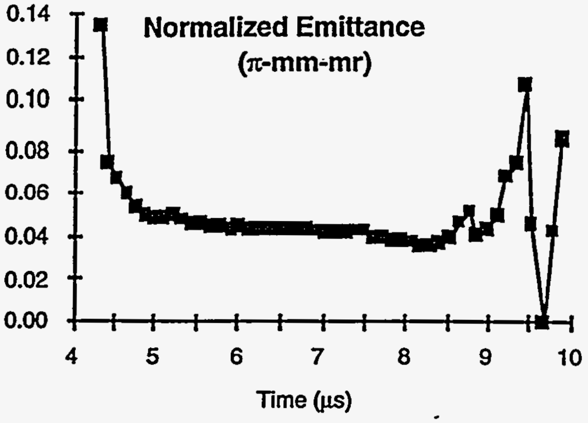

Fig. 4. Normalized emittance at end of matching section

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