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PROGRESS IN HEAVY-ION DRIVERS FOR INERTIAL FUSION

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Abstract

Heavy-ion induction accelerators are being developed as fusion drivers for ICF power production in the U.S. Inertial Fusion Energy (IFE) program, in the Office of Fusion Energy of the U.S. Department of Energy. In addition, they represent an attractive driver option for a high-yield microfusion facility for defense research. This paper describes recent progress in induction drivers for Heavy-Ion Fusion (HIF), and plans for future work. It presents research aimed at developing drivers having reduced cost and size, specifically advanced induction linacs and recirculating induction accelerators (recirculators). The goals and design of the Elise accelerator being built at Lawrence Berkeley Laboratory (LBL), as the first stage of the ILSE (Induction Linac Systems Experiments) program, are described. Elise will accelerate, for the first time, space-charge-dominated ion beams which are of full driver scale in line-charge density and diameter. Elise will be a platform on which the critical beam manipulations of the induction approach can be explored. An experimental program at Lawrence Livermore National Laboratory (LLNL) exploring the recirculator principle on a small scale is described in some detail; it is expected that these studies will result ultimately in an operational prototype recirculating induction accelerator. In addition, other elements of the U.S. HIF program are described.

1. INTRODUCTION

As discussed in detail at this Technical Committee Meeting, the Inertial Confinement Fusion (ICF) Program in the United States is currently employing and developing large glass lasers including Nova, Omega Upgrade, and the National Ignition Facility (NIF) as research tools with the goal of achieving ignition and gain in a fusion target, and is developing light-ion beam as well as gas and solid-state laser technology for a high-yield facility to follow the NIF. This program is run by the Defense Programs Office within the U. S. Department of Energy, and has a dual-purpose nature. It is motivated in the near term by the need for a physics research facility for defense-related studies, and in the longer term by its role in paving the way to a practical, economical, and environmentally attractive source of fusion electric power. Because the critical target physics issues, and other issues including response of materials in the fusion chamber to the target explosion, will be addressed by this sizable program, a research program in Inertial Fusion Energy is very cost-effective. However, the glass lasers in the NIF will not themselves have the pulse rate, efficiency, nor durability needed for power production.

Accelerators for high-energy physics research typically have long lifetimes and good availability; we believe that an accelerator designed as a fusion driver can share these attributes. Since the beams will be focused onto the target by magnetic fields, the final lens will not be subject to serious damage from the exploding targets. Induction accelerators in particular are efficient, low-impedance devices that naturally accelerate a high-current beam, can readily amplify the current of that beam, and can easily meet repetition rate requirements of a few pulses per second. For these reasons, the heavy-ion induction accelerator is the driver being

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pursued for an ICF power plant in the U.S. Inertial Fusion Energy (IFE) program, in the Office of Fusion Energy of the U.S. Department of Energy, and is an attractive driver option for a high-yield microfusion facility for defense research. However, significant technology development must be carried out before a Heavy-Ion Fusion (HIF) driver is realized. Because driver development is deemed the long lead-time item in the IFE development sequence, the programmatic emphasis is currently being placed on high-current ion accelerator research.

For a fusion power technology to be viable, it must offer an economically attractive power plant at a reasonable size (of order 1 GW electric output), and must have favorable properties with respect to environmental concerns. Recent studies indicate that the cost of electricity from an HIF power plant can compare favorably with those of tokamak fusion, future fission and coal, and suggest that the environmental attributes can be benign as well.[1-4]

Furthermore, the development program leading to a pilot power plant must be affordable. The HIF development cost will be minimal because the program builds upon a multi-billion dollar worldwide investment in particle accelerators, and upon a large and multi-faceted inertial fusion program based upon lasers and light-ion drivers. The NIF can test the most important heavy-ion target physics issues: soft x-ray transport and drive symmetry, hohlraum plasma dynamics, and capsule implosion hydrodynamics, and mixing of unwanted material into the central fuel. It will be possible to deploy experiments on the NIF which focus the laser beams into smaller hohlraums (filled with high-atomic-number doped gas at 1/10 the critical density) placed at each end of the larger hohlraum which contains the fusion capsule. These will emit their x-rays into the main hohlraum in the same way as do the converters at the ends of a two-sided heavy-ion fusion hohlraum. Experiments using light-ion drivers will also yield information which is important to heavy-ion scenarios, including ion energy deposition and conversion to x-rays in foams, radiation transport, capsule symmetry requirements, and beam propagation in the target chamber. Lawrence Livermore National Laboratory and Lawrence Berkeley Laboratory staff are working with staff from Sandia National Laboratory and elsewhere, to develop a better understanding of ion drivers in general. These "common ion driver" activities are described in some detail in another paper presented at this meeting [5].

The use of a non-solid first surface in the chamber (in the HYLIFE-II design [2] and others) obviates any need for a separate large-scale materials testing facility; experiments on the NIF and other lasers will provide much of the needed data. An Engineering Test Facility (ETF) accelerator built to explore target physics and target-chamber dynamics can be used in the subsequent demonstration power plant as well. In one scenario, such a program might be pursued as an international effort. In another scenario, the ETF driver might also serve as the driver for a high-yield microfusion capability for defense research.

These multiple-use attributes are made possible by the physical decoupling of the driver, the fusion chamber, and the target. A beam switchyard will enable one accelerator to drive several target chambers at the same time. The cost penalty associated with the requisite pulse repetition rate should be negligible. Reduced-yield targets can be used in scaled fusion chambers, enabling the resolution of nuclear engineering issues at minimal cost. Finally, an accelerator driver can be built in stages, thereby combining the accelerator development program with the construction of the eventual facility.

Research into HIF drivers outside the U.S. has emphasized radio-frequency (RF) linac technology in conjunction with storage rings, and this approach is described elsewhere at this meeting. The U.S. induction-based research program and the RF-based efforts are complementary. While the decision to pursue induction technology in the U.S. was made for well-defined reasons, not the least of which was a lower predicted driver cost, RF technology is more mature and may prove entirely adequate to the fusion-driver task. Discussions of the advantages of each of these approaches can be found in References [6,7].

In Section 2 below, we review the basic design of a radiatively-driven heavy-ion target using "two-sided" illumination (with beams in two clusters), and the requirements imposed by such a target upon the incoming beams.

In Section 3 we present a schematic of an induction linear accelerator designed around these requirements. The research program is working toward expansion of the usable design regime of a linear accelerator, toward a lower final particle energy. These considerations are also discussed in that section.

The recirculating induction accelerator promises cost reduction by re-using the same accelerating and focusing (confining) elements multiple times.[8] The recirculator concept is discussed in Section 4.

The goals and design of the Elise accelerator are briefly described in Section 5. Planned for construction at LBL, Elise is an outgrowth of the ILSE (Induction Linac Systems Experiments) concept, and represents the initial phase of that overall program.[9,10] Elise will be a 5 MeV, multi-beam induction linac accelerating potassium (K^+, ~39 AMU) ions produced by LBL's new electrostatic-quadrupole (ESQ) injector, which is also described briefly in Section 5. Elise will serve as a testbed upon which a variety of experiments using driver-scale (in diameter and line-charge density) beams will be carried out. These will ultimately include beam merging, drift-compression, and focusing onto a small spot. Elise is discussed in detail in another paper of this meeting.[10]

A recently-initiated experimental program in beam bending and recirculation at LLNL is described in Section 6. The small prototype recirculator resulting from this work will be the first accelerator of its type. The goal of these experiments is to explore virtually all of the critical recirculator beam manipulations that can be tested with beams smaller than full size. Because of the unique opportunity they will afford for the study of space-charge-dominated beam behavior on a long time scale, experiments on the small recirculator will be important to linear accelerators as well. This program is described in considerable detail since it has not been presented previously.

Finally, ongoing research is examining issues including beam propagation in the target chamber, long-time beam dynamics, and detailed beam optics in structures including injectors, beam combiners, plasma lenses, and magnetically confined transport of space-charge-dominated beams. A brief outline of these elements of the program is presented in Section 7.

2. REVIEW OF REQUIREMENTS IMPOSED BY THE TARGET

The U.S. Heavy Ion Fusion program has concentrated on targets which enclose the fusion capsule in a hohlraum, with a radiation converter of radius ~2-6 mm at each end. These converters are each illuminated by a cluster of beams with a narrow cone angle. This geometry is similar enough to that of an indirectly-driven laser fusion target that the design methods and tools used for the latter carry over directly. Furthermore, the illumination geometry is favorable for power-plant design, relative to concepts which require that the beams enter the fusion chamber from a wide multiplicity of directions. To achieve a gain of 10-100, such a target is projected to require a total incident beam energy of order 5 MJ in a suitably shaped pulse, with duration (for the main part of the pulse) of order 10 ns and a longer initial "foot" preceding. Other geometries are possible; these include spherical or nearly-spherical targets, single-sided targets with a single radiator, and "single-sided" targets with two radiators which are illuminated "sideways" (at 90° to the symmetry axis of the main hohlraum) by beam clusters coming from ports on the same side of the fusion chamber.

The energy-range relation of ions stopping in matter (Fig. 1) is an important factor in selecting the ion energy. It is necessary to stop the incident ions in a relatively small amount of matter (range R ~ 0.02-0.2 g/cm^2) if the amount of converter material heated by the incident beams is to be kept small enough for a specific energy deposition of order 10^8 J/g; the energy devoted to overcoming the specific heat of the converter material must be minimized if high conversion efficiency of ion energy to x-rays is to be obtained. For an ion of mass ~100-200 AMU, the required energy per ion is found to be of order 1-10 GeV. For a light ion of mass ~1-7 AMU, the corresponding energy is of order 3-100 MeV. The heavy-ion fusion program has emphasized drivers using singly-charged mass 100-200 ions because their relatively high allowed energy allows the requisite ~5 MJ to be achieved at a relatively low current (compared to that of a lighter ion scenario), which in turn allows non-neutralized ballistic focusing of the

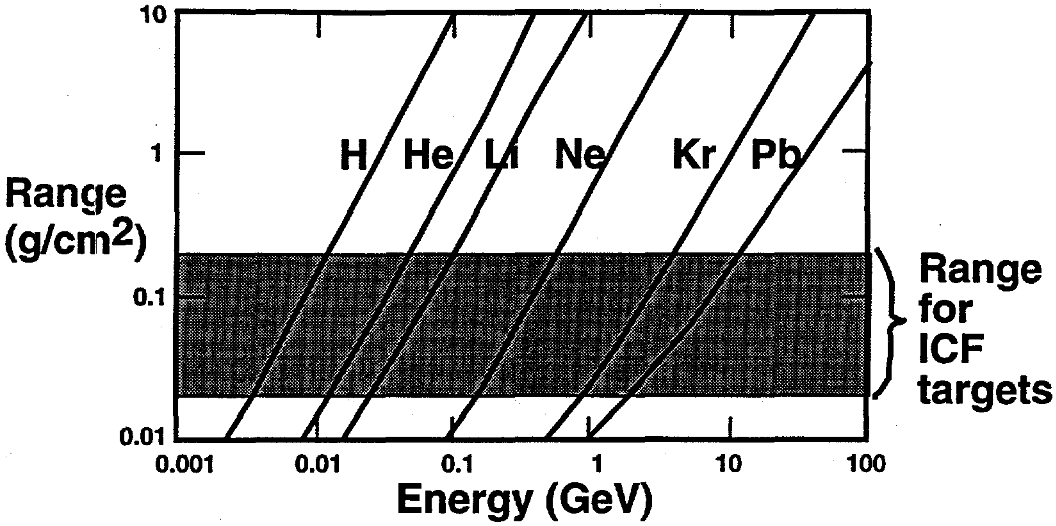

Fig. 1. Range-energy relation for various ions stopping in matter.

beam onto the target in near-vacuum. The achievable power on target is limited by several effects which add roughly in quadrature; these include beam space charge, beam emittance (thermal pressure), misalignments, and aberrations. The dependence of the focusable power upon ion energy as set by space charge is especially steep, varying as the 5/2 power.[7] Thus for non-neutralized focusing there is a strong incentive to operate at high ion energy and correspondingly large ion mass. However, as discussed in the next section, use of a lighter ion, or a higher charge state, may convey certain advantages, despite a likely requirement of at least partially neutralized transport to the target.

Most power plant concepts call for near-ballistic focus of the beams through a fusion chamber with radius 4-10 m. If one assumes a 10 m separation between the middle of the final magnetic optic and the target, and a 3 mm radius spot on target, the particles must be aimed with a "microdivergence" angle of $0.003/10 = 3\times10^{-4}$ radians. This same angle represents the ratio of transverse thermal velocity to directed beam velocity, and its square ($\sim10^{-7}$) represents the ratio of transverse thermal to directed energies. For a 10 GeV beam, the transverse temperature must remain below ~1 keV. The transverse emittance, or projected phase space area, is the product of beam transverse dimension and velocity spread, the latter normalized to the directed velocity and so measured as an angle. The final optic does not produce a perfect image; geometric and chromatic aberrations limit the achievable spot size. Uncorrected optics are limited to a focusing angle of about 15 mrad. For a beam with a focal spot radius of 3 mm focused through a 15 mrad angle from a maximum radius 15 cm, one obtains an emittance requirement of π(150 mm)(0.3 mrad) = π(3 mm)(15 mrad) = 45 π-mm-mrad (ignoring space charge).

Similarly, the ability of the optical system to focus ions with a range of energies onto a small spot is limited. Chromatic aberrations limit the relative momentum variation $\delta p_z/p_z$ to about 0.3%. Optically-corrected focusing designs are employed in other accelerator applications, and have been studied for HIF [11], but remain to be shown practical.

Alternative modes of transporting the beams to the target include neutralized or partially neutralized ballistic transport, as well as self-pinched propagation in a channel. Neutralization may be important if operation at higher chamber pressures associated with a greater shot-to-shot repetition rate (for some chamber designs) is to be practical. By easing the effects of space charge, these modes open up a larger region in parameter space at lower ion energy and mass. Pinch-mode propagation would offer a number of advantages, including smaller holes in the chamber wall, and acceptance of beams with a greater longitudinal velocity spread. At present, near-ballistic transport in near-vacuum remains the baseline model.

3. LINEAR ACCELERATOR CONCEPTS

Induction accelerators apply electromotive force to the beams by passing them through a series of efficient one-turn pulsed transformers (see Fig. 2). Pulsed power causes an azimuthal B_θ to build up in the toroidal ferromagnetic "cores." The changing flux in these cores induces the axial EMF; conducting surfaces are arranged so that this EMF appears across an "accelerating gap" in the beam pipe. Because of the large permeability of these cores, the magnetic field build-up is slowed, allowing almost-d.c., relatively flat pulses. Longitudinal confinement of the beams requires voltage "ears," or temporal ramps on the ends of the voltage waveform timed to coincide with the passage of the front and back tips of the beams through the accelerating gap (see Fig. 3). In contrast with RF accelerators, there is no requirement for constant frequency, so longitudinal compression and increasing velocity can produce an increasing current, up to the limits of the transverse confining fields.

A "conventional" linear induction accelerator designed using ions of mass ~200 to meet the requirements imposed by the "conventional" target is depicted schematically in Fig. 4. Such an accelerator achieves economy by passing multiple beams through each induction core. Power amplification to the required 10^{14}-10^{15} W is achieved by beam combining, acceleration, and longitudinal bunching. The accelerator lattice must transversely "focus" the beam (confine it against its own space charge, and to a much lesser degree its own thermal pressure); in modern accelerators this is effected with alternating-gradient quadrupole lenses, which may be either electrostatic or magnetic. Each lens focuses the beam in one plane while defocusing it in the other; however, because the beam is larger (and thus experiences stronger fields) as it passes through a focusing element, the net effect is a strong focusing.

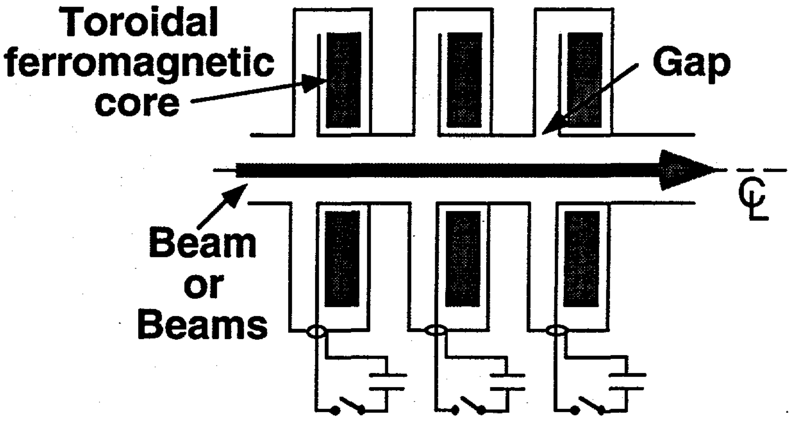

Fig. 2. Induction module geometry.

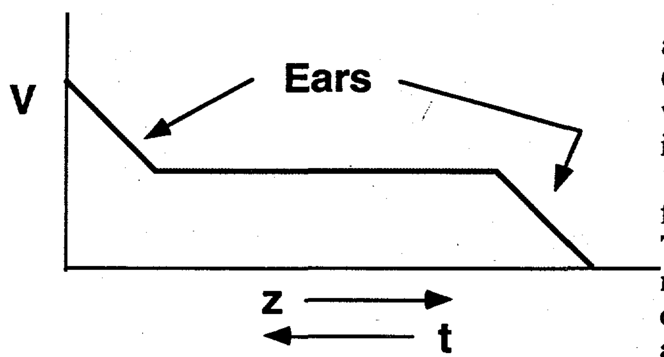

Fig. 3. Typical accelerating waveform.

In such a "conventional" HIF accelerator, multi-beam injection with 16-64 beamlets is followed by acceleration with electrostatic transverse focusing. Four-into-one beam merging is effected at 10-100 MeV, with a transition to magnetic focusing in roughly the same energy range. The linear approach, in comparison with the recirculating approach discussed below, enjoys relatively simple timing and control, acceleration and focusing tailored to the beam at each point, no need for bends except near the target, and reduced vacuum requirements because debris from the wall is readily pumped away between shots and does not accumulate. However, the length and need for a high gradient ~1 MV/m establish the cost.

In present designs the major part of the accelerator employs magnetic focusing. It may well be possible to accelerate beams in an induction linac with an average gradient exceeding 1 MV/m, by suitable grading of insulators. The cost penalty of the larger cores needed for a higher gradient would be more than offset by the reduced length.

Beam merging is likely to be an important cost-reduction technique because at low energy it is desirable to employ many beams, while at high energy economics drives the design toward fewer beams. Electrostatic quadrupoles are generally to be preferred at low energy

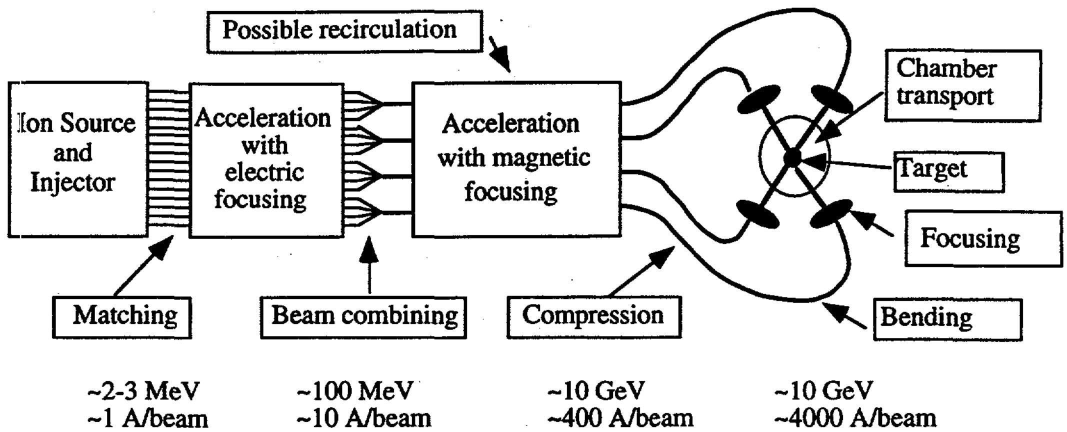

Fig. 4. Schematic of a "conventional" induction accelerator driver.

because their focusing power scales more favorably with velocity at low energy. Also at low energy the quadrupoles must be closely spaced along the axis to provide sufficient confinement, and it is difficult to fit electromagnets in. Finally, electrostatic elements are cheaper to fabricate. The limits imposed by voltage breakdown imply that a small aperture, and thus a relatively large number of beams, must be used. In contrast, at higher energy focusing should use magnetic quadrupoles. Longitudinal compression at constant radius is possible with magnets because the confinable line charge density rises with the beam energy. Also, if small-aperture magnets were used, most of the induction core's bore would be filled with superconducting magnet insulation and coils instead of beam. Thus, at high energy, efficient core use dictates a large aperture, and a smaller number of thicker beams.

However, beam merging inevitably leads to an emittance increase because empty phase space is entrained in the combining process. This can be minimized by bringing the beams together in a "Stonehenge" geometry, which gives good packing. Such a geometry is depicted in Fig. 5.

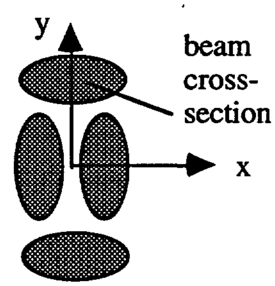

Fig. 5. "Stonehenge" geometry

As explained above, a high ion mass (of order 200) allows rigid beams with high energy, of order 10 GeV, and implies that relatively few ions are needed, reducing collective effects and easing focusing requirements. The baseline induction linac concept assumes a kinetic energy ~10 GeV. At lower masses, preservation of a small ion range in the target implies that the ion energy must be reduced. Use of a reduced ion energy would permit a shorter accelerator, and a smaller ion stopping range would enhance the target gain. However, the required current to produce ~5 MJ on target is considerably higher, and so a detailed optimization must be carried out. Smaller ion masses (as low as 39) are routinely used in present-day and near-term experiments. LBL, LLNL, and Sandia National Laboratories are working together to understand these tradeoffs as they apply to the various accelerator technologies being considered for ion-beam driven fusion.

Substantial improvements in cost and efficiency of induction linacs may well be possible through the use of lower-energy ions. The energy gain in a core is given by the product $IV\tau$, where I is the beam current, V the voltage gain, and τ the pulse duration. Because cost and losses increase with increasing $V\tau$, a large current and small voltage would be preferable. The minimum beam energy is set by the scaling of focusable current onto the target (assuming unneutralized focusing), with the beam energy varying as the inverse 2/5 power of the number of beams. It is also set by the "Maschke current limit." For magnetic focusing, $I_{max} \sim 4\times10^5 \, B \, \beta^2 \, a$ Amperes, where B is the quadrupole field at the pole tip (T), a the beam radius (cm), and β the ratio of beam velocity to the speed of light (the expression for electric focusing is similar). Note that I_{max} varies as the beam radius, not the beam area. One maximizes the current through a given core by using a large number of small beams. Thus, the ion energy can be lowered (while still delivering enough total energy to the target) by neutralizing the beam in the chamber and/or using a large number of small beams. The ultimate limits are set by alignment and fabrication precision; a general prejudice against using many beams must be overcome by experimental experience. [7]

Nonlinear image forces in an electrostatic-focusing accelerator are excessive if the beam radius is larger than ~80% of the aperture. Thus, such machines have been designed with a beam-pipe (and quadrupole bore) radius b = 1.25a + 1 cm. The additive 1 cm accounts for limitations on machining and alignment tolerances, and the buildup of beam mismatch oscillations. "Nominal" beam and pipe radii have generally been assumed to be a ~1.6 cm, b ~ 3 cm. Recent experiments [12] have refined our understanding of quadrupole breakdown voltage as a function of size, and at present a ~ 1 cm, b ~ 2.3 cm appears to be an optimal design point. (The calculated transportable current through a given pipe in a multi-beam array has not changed as a result of this new information, but the beams are smaller and there are more of them). In some applications the additive 1 cm can be relaxed as well, especially at the very front of the machine. Future improvements in technology may allow smaller apertures, with correspondingly larger multi-beam currents at the low-energy end.

4. RECIRCULATING INDUCTION ACCELERATORS

A recirculating induction accelerator 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. [8], and possibly less), and the accelerating cores are smaller and are not driven so close to saturation because there is no need to accelerate the beam at the maximum possible rate. The recirculator designs considered to date employ greater axial compression than is typically assumed for linac designs, with a smaller number of longer beams used initially, and do not employ beam merging.

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 in Section 6 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 high repetition frequencies of order 100 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; LLNL has already achieved 200 kHz bursts at 5 kV and 800 A, with pulse widths of 0.5-2 μs, but with a non-variable format.[13] Because of its long path length, a recirculator driver will require a high vacuum of $\sim 10^{-10}$ to 10^{-11} torr. Collisional interactions (intrabeam charge exchange, ionization of background gas, stripping of beam ions by gas collisions) can drive beam or gas ions into the walls of the beam pipe, and so cause the desorption of material off the walls. This material will interact with the beam on its next pass. Thus, a high vacuum 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.

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 50 to 100 laps. Relative to a "conventional" linac, the length is reduced by a factor of order 2-3, but the beam path length lengthened to perhaps ~200 km. Here too, the research program aims to develop the necessary physics and technology. Hybrid designs (with a recirculator at the low-energy end) are also possible.

5. THE ILSE PROGRAM AND THE ELISE PROJECT

Early experiments with intense space-charge dominated ion beams were very successful. These included source development tests using cesium, as well as experiments performed on the SBTE and MBE-4 facilities at LBL.[14] However, these experiments tested only a few driver elements: sources, injectors, beam matching, and acceleration with electric focusing. Moreover, the beams were small in comparison with those that will be employed in a driver.

To begin addressing the physics and technology issues associated with full-scale beams, LBL, in collaboration with LLNL, formulated an accelerator project and suite of experiments known as ILSE (Induction Linac Systems Experiments). The full ILSE accelerator concept consists of a four-beam electric-focusing accelerator bringing a potassium beam to 5 MeV, followed by a one-beam magnetic-focusing accelerator to 10 MeV. The beam will have the same line-charge density as that of a driver, and will be of the same diameter. However, to reduce cost it will use a shorter pulse and lower energy. The critical dimensionless parameters relating betatron wavelengths to the accelerator lattice period will be the same as in a driver. Experiments to be performed as part of the ILSE sequence include beam merging, drift-compression and pulse-shaping, beam bending, focusing onto a spot, and recirculation.

At the request of the Department of Energy, a proposal for construction at LBL of the four-beam electrostatic-focusing part of the ILSE accelerator (the elements up to about 5 MeV) was submitted this year. This electrostatic-focusing accelerator is known as "Elise." In December of 1994, the Elise proposal received "Key Decision 1" approval, allowing engineering design to begin. It is anticipated that the Elise accelerator will be completed before the end of this decade. Details of Elise were presented in another paper at this meeting [10].

In anticipation of the ILSE program of accelerator development and experiments, LBL, in collaboration with LLNL, has developed, over the past two years, a single-beam injector which produces a full-scale beam suitable for injection into one channel of the Elise accelerator. This injector is of a novel "ESQ" type, employing a sequence of electrostatic quadrupole lenses with a superposed voltage gradient along the axis. The net effect is to both confine and accelerate the beam. The entire system consists of a dished hot-plate source with an internal filament, an axisymmetric diode section taking the beam to 1 MeV, and the ESQ section. This section decouples the strict relationship between accelerating and focusing voltages inherent in earlier "electrostatic aperture column" designs, alleviates difficulties associated with breakdown limits, and produces a high-quality beam. This injector was described in detail in another paper at this meeting [15].

Ultimately, a recirculating accelerator using the ILSE linac as its front end is anticipated. Before such an ILSE-scale recirculator can be credibly proposed, it will be necessary to develop the technology and physics on a smaller scale. This development is underway at LLNL, as described in the next section, and the small recirculator will prepare the way for an ILSE-scale ring in much the same way that SBTE and MBE-4 laid the groundwork for the Elise linac.

6. PLANNED EXPERIMENTS IN BENDING AND RECIRCULATION

Lawrence Livermore National Laboratory, in collaboration with Lawrence Berkeley Laboratory, is currently developing a small prototype heavy-ion, intense beam, 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 for application to inertial fusion energy. The small recirculator will be assembled and operated as a series of experiments over several years' time. During the next year a linear experiment using permanent-magnet quadrupoles is planned at LLNL; this will afford the first measurement of space-charge-dominated beam quality after magnetic transport. The next experiment will be a study of beam transport around a ~90° bend (without acceleration, at first). In the later phases of the experimental sequence, the machine will be operated in a full recirculating mode with a variety of beam manipulations. Associated with these beam manipulations are technologically challenging problems in pulsed-power waveform synthesis. Fig. 6. illustrates the overall 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.

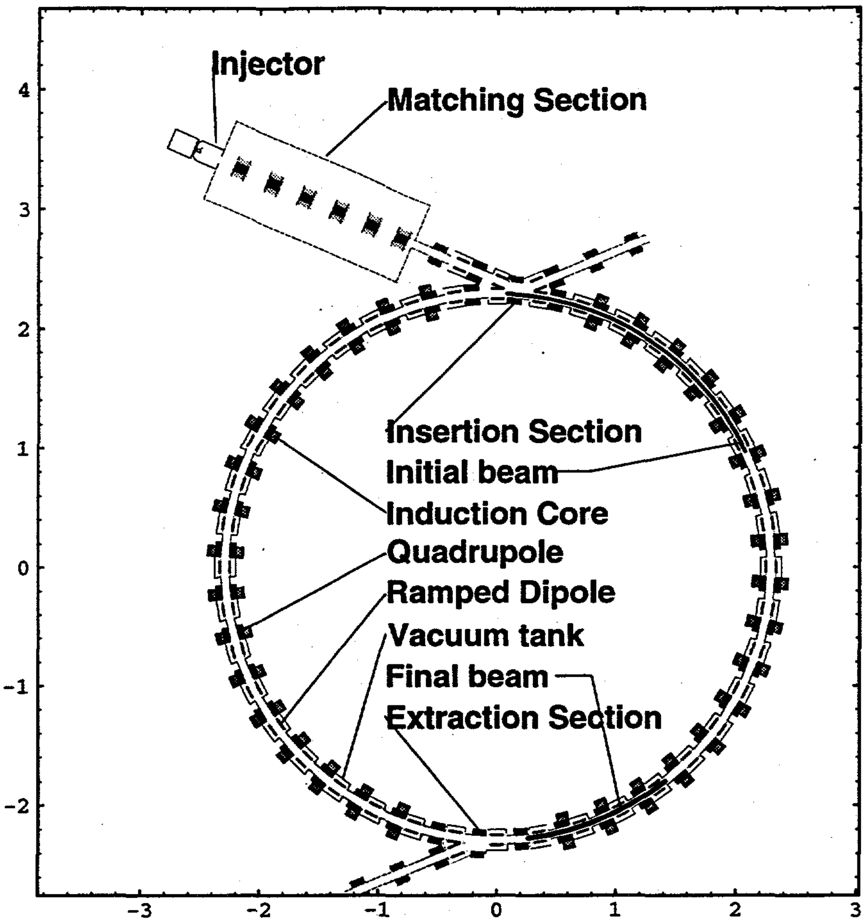

Fig. 6. Overview of final small recirculator configuration (scales in meters).

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 ~0.3 T at the pipe wall, and will be bent 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 several special large-aperture quadrupole magnets through which the beam will be inserted and extracted. The beam ion is singly charged potassium, 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. (No induction cores will be present in the lattice periods where the beam is inserted and extracted.) The initial current of the beam on insertion into the ring 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 of the betatron motion of the ions in the ring's "lattice" of quadrupoles and dipoles will be $\sigma_0 = 78°$ per lattice period in the absence of beam space charge, and $\sigma = 16°$ per lattice period in the presence of space charge; the depression is a result of diminished net focusing when space charge is accounted for. After the full 15 laps of acceleration, the beam will have a final current of 8 mA, with a corresponding line-charge density and average beam radius of 0.00721 μC/m and 1.3 cm, and the final pulse duration will be 1 μsec. Also, at the final beam energy, the phase advances will decrease to $\sigma_0 = 45°$ and $\sigma = 12°$ per lattice period.

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. They will require the accurate synthesis of detailed voltage pulses with a repetition rate ranging from approximately 40 to 90 KHz at the initial and final beam energies due to the beam recirculating through the accelerator lattice. The voltage pulses for the electric bending dipoles must be correctly timed with respect to the pulses that power the induction cores for beam acceleration, all while the longitudinal dynamics of the heavy-ion beam varies due to its nonrelativistic energy. Furthermore, detailed "ear" pulse structures and lap-to-lap variation of the pulse duration must be added to the accelerating waveforms to maintain or decrease the beam length.

The small recirculator will be constructed, and experiments carried out, in a build-and-test sequence. Until all 360° 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 the successful operation of the full ring. As currently planned, the ring will incorporate two extraction sections 180° apart, and the extracted beam can thereby be diagnosed with detailed intercepting diagnostics twice each lap. As with earlier linac experiments at LBL, excellent shot-to-shot repeatability is anticipated.

At this writing, the source and injector diode have been fabricated and are operating, and are injecting beam into the electrostatic-focusing matching section, which is a modified segment of LBL's SBTE apparatus. The matching section uses every second quadrupole of the original structure for focusing, with the quadrupole voltages individually tunable, and steering elements in some of the vacated quadrupole positions. Fifteen permanent-magnet quadrupoles have been procured, and the mechanical design of the "half-lattice period" is partially completed.

Initial experiments will study beam transport in a linear channel, using some of the quadrupole magnets destined for the recirculator. These experiments will afford the first phase-space measurements of the magnetic transport of such space-charge-dominated ion beams. They will characterize the beam prior to injection into the recirculator, provide a test-bed for diagnostic development (especially the capacitive pickup centroid position monitors), and afford a preliminary assessment of the role of electrons in magnetic beam transport. We now describe the main sequence of experiments planned.

a). Transport of space-charge-dominated beams around bends. After the first bend has been assembled (approximately 90°), the bending of space-charge-dominated beams will be studied. 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 the WARP3d code [16], it occurs at changes in the accelerator's curvature where the distribution of beam particles must relax toward a new equilibrium. Thus, a circular recirculator is to be preferred over one with a "racetrack" shape. The transition of the beam from a straight transport line into the ring will represent such a change of curvature, and will allow us to experimentally study this effect. Emittance growth can also result from imperfections in the applied focusing and bending fields.

Analytic theory, and detailed 3-D particle-in-cell computer simulations, indicate that bend-induced emittance growth in driver-scale recirculators will be minimal. The parameters of the small recirculator, with its sharp bends, are such that a measurable amount of emittance growth is expected to take place over the full fifteen laps, with most of this growth occurring in the first two laps. Even over a single 90° bend, detailed intercepting beam diagnostics (using a two-slit apparatus to measure both transverse position and momentum of the ions) will be able to detect relatively small changes in the distribution of beam particles as a result of the bend. An important goal of these initial experiments will be validation of the computer models and scaling laws used to predict both linear and recirculator driver behavior.

b). Insertion and extraction. In order to switch the beam into and out of the ring, it is necessary to apply dipole bending fields that vary in time. In a driver-scale recirculator, insertion and extraction are carried out over a number of half lattice periods. In the small recirculator it is possible to insert or extract the beam in a single half lattice period. However, even for the small ring, extraction will require real-time adjustment of the dipole immediately upstream of the extraction section as well as the dipole within that section. An additional requirement is that transverse confinement of the beam against its own defocusing space-charge forces must be carried out continuously, even during the insertion or extraction process, or else the beam would grow excessively in size. Furthermore, the optical quality of the magnetic quadrupole lenses which provide this transverse confinement must be high, or aberrations will distort the beam over multiple laps. To this end, a large-aperture quadrupole element must be employed; its inside dimension in the vertical plane need be no larger than that of a normal quadrupole, but its dimension in the plane of the ring must be larger by a factor of approximately 2.5. We have concentrated on magnetic quadrupoles for this application, and for the small ring plan to use a permanent-magnet quadrupole with an expanded aperture. For a driver, a set of special large-aperture electromagnets ("Panofsky quadrupoles") will be employed. Initially, the extraction process should be just a mirror-image of insertion; however, at higher energies extraction becomes more challenging because bending the beam becomes more difficult.

c. Acceleration. In a driver-scale recirculator ring, the beam current is increased (via a reduction of the pulse duration) by an order of magnitude over ~100 laps. Approximately half of this increase is due to the increase in the beam's velocity. The remainder is due to an imposed axial compression of the beam—it is made physically shorter— as it is accelerated. This compression process will be discussed in a later subsection. The small recirculator is designed to use both mechanisms, together or separately, to increase the beam current.

To better understand the control of an accelerated beam which is simultaneously being bent, and to confirm that the acceleration process does not adversely affect beam quality, acceleration experiments will be carried out using a partial ring. Detailed diagnostics will measure the distribution of beam ions both with and without acceleration. In order to keep the beam centered in the channel, it will be necessary to ramp the dipole fields in concert with the changing beam energy. The technology to do this will be developed, and the integrated functioning of the bending and accelerating systems will be confirmed.

d. Longitudinal confinement. The shape and timing of the "ear" pulses is critical if the beam tips are to be quiescently confined. These will most likely be provided using separate waveform generators, possibly triggered by the passage of the beam. Different beam-tip shapes (line-charge density falloffs) and techniques for generating the ear waveforms will be tested, and their effects on beam quality assessed. 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.

e. Steering. The pipe aperture of the small recirculator has been chosen for adequate beam clearances, even in the presence of a required head-to-tail energy difference if the pulse is to be compressed. However, in this case the transverse centroid at the beam tail travels around the machine at a larger radius than that at the beam head due to "dispersion" in the bend. It is possible to adjust the dipole field strength in a time-varying manner such that the centroid remains centered in the pipe at all times. This requires that additional time-varying "tweaker" voltages be applied to the dipoles. Some preliminary consideration has been given to the necessary circuitry, and this enhancement appears to be practical. In a driver-scale recirculator such tweaker control would allow a smaller pipe size, thereby reducing the cost. Since determination of the required tweaker fields does not require measurement of the beam, they do not represent true steering fields in the sense described in the balance of this section.

Steering of the beam requires adjustment, on the basis of measurements of the beam centroid motion, of the dipole bending fields, and of auxiliary fields which act in the vertical plane. Such steering is essential to multi-lap operation of the small recirculator, and of driver-scale recirculators as well. The principal method of beam steering will use beam centroid information obtained on the corresponding lap of the previous shot. Because of the expected good shot-to-shot repeatability of the system, this information should provide sufficiently reliable input to accomplish this task. This inter-shot (so-called "shot-to-shot") steering can most simply be carried out by setting the steering fields to a value which does not change as the beam passes by. Such "time-independent" steering should provide the bulk of the necessary correction.

In addition, it will be highly desirable to include a small amount of time-dependent steering at one or two stations around the ring. This will serve to remove the small amount of accumulated centroid position error which arises from the head-to-tail energy and current variation of the beam.

The ultimate method of steering will rely on information from the current shot. The beam centroid position will be measured, and steering corrections applied at a location downstream from the measuring station. This "feed-forward steering" will have the advantage of removing random, non-repeatable errors, as well as those which remain systematic from shot to shot.

f. Multi-lap operation. As described above, acceleration of a beam which is being simultaneously bent requires the careful synchronization of the rising dipole bending field with the increasing beam energy. "Ear" fields are required to prevent the beam from elongating due to its own space charge repulsion. In the absence of these ear fields, the beam would double in length after approximately three laps. In the absence of steering the beam will random-walk off-axis after about one lap. Thus, multiple-lap operation requires a technologically challenging coordination of acceleration, bending, ear, and steering fields. In addition, confirmation that the beam waveform and emittance evolve as predicted by numerical and analytical calculations will require the long path length afforded by multiple lap operation.

g. Bunch compression. Tweaker fields will not be required if the bunch length is kept constant. However, one goal is to decrease the bunch length by a factor of two. This requires that the tail of the beam have a larger velocity than the head, and so additional tweaker fields (as discussed in subsection e above) will be required to center the beam from head to tail. In addition, the accelerating waveforms for a beam undergoing compression are more complex than those for a beam which is not compressed. In general, they become tilted rather than flat. Finally, as the beam compresses axially its radial extent becomes larger. It thereby samples more of the non-linear fields from the accelerator lattice elements, creating more opportunity for emittance growth and possible beam loss. Preservation of a small emittance will again be the central beam physics question which will be addressed.

7. OTHER ELEMENTS OF THE U.S. HIF RESEARCH PROGRAM

The U.S. Heavy Ion Fusion program is also carrying out an intensive program of technology development and smaller-scale experiments. In addition to the injector and recirculator efforts described above, and the Elise technology development program now underway, three other experimental efforts are being pursued at LBL.

The first of these is an experimental study of beam merging, using the MBE-4 apparatus with new, angled sources feeding into one of the existing transport lines through a new combining section.[17] The final element through which the four beams pass must both bend and focus the beams. Because there is no room for conventional electrostatic quadrupole rods, the element is a "squirrel cage" made of individual wires, each held at the appropriate voltage. The beams are brought together in the "Stonehenge" configuration described above. The early stages of this experimental work have already had significant spin-off benefit in ion source improvements and understanding of beam current limits, which are proving larger than previously had been thought.

The second effort is a magnetic quadrupole development program. These "current-dominated" quadrupoles are being designed with a geometry that will be suitable to the superconducting elements planned for a driver. Tests to date have focused on the mechanical and heat-transfer properties of the magnets; near-term tests will begin to consider their optical properties (the detailed winding design is still being optimized as of this writing). Experiments exploring beam transport through a set of such magnets will be carried out if funding is available, initially using the beam from LBL's new ESQ injector.[18]

The third is a study of plasma lenses, building on recent work in Europe. This work is being carried out in collaboration with A. Tauschwitz, a visitor at LBL from GSI. Such lenses may be attractive as final optics, either with or without a channel through which the focused beam is transported to the target.[19]

A smaller experimental program at the University of Maryland [20] is studying longitudinal beam dynamics, including wave propagation, and most recently is using a channel with a resistive wall to explore the longitudinal microwave instability as it applies to HIF drivers, where it is driven by the impedance of the accelerating modules. Detailed theoretical [21] and computational [22] studies indicate that this instability will have a moderate growth rate, and that careful beam control (and possibly feed-forward stabilization techniques) will be necessary to preserve beam quality. The Maryland experiments will serve to validate and normalize these calculations.

Because the space-charge dominated beams in an induction accelerator are effectively non-neutral plasmas, theoretical and computational modeling of these beams is carried out using techniques related to those used in both the accelerator and plasma physics communities. Models employed range from simple zero-dimensional codes based upon analytically-derived scaling relations, through fluid- and moment-equation simulations, up to large and elaborate discrete-particle simulations. In addition to LBL and LLNL, theoretical and simulation efforts are underway at the Naval Research Laboratory [23], the Princeton Plasma Physics Laboratory [24], and MIT. [25]

The CIRCE code [26] is a multi-dimensional model which solves an envelope equation (evolving moments such as centroid position and transverse extent) for each of a number (typically a hundred or greater) of "slices" of the beam. The longitudinal dynamics of the beam is modeled by evolving the positions and velocities of the slices using fluid equations. CIRCE is used to assess alignment tolerances, accelerating schedules, and steering techniques in both linacs and recirculators. It is useful for any application in which the evolution of the detailed internal degrees of freedom of the beam need not be resolved (*e.g.*, emittance growth processes); at present, the beam emittance is assumed constant in CIRCE.

Because the beam resides in the accelerator for relatively few plasma oscillation periods, particle-in-cell simulation techniques are especially effective and have proved invaluable to the design and analysis of ongoing experiments, and to the prediction of the behavior of future machines. The WARP code includes both fully three-dimensional (WARP3d) [16] and axisymmetric (WARPrz) [22] particle-in-cell simulation models. The former is used for "near first-principles" studies of MBE-4, the ESQ injector, the small recirculator, the Elise accelerator, beam bending, beam combining, and other accelerator experiments and elements. The axisymmetric model is used for long-term beam dynamics studies including the effects of accelerating module impedance. WARP3d uses a number of novel techniques to render it both accurate and efficient. These include a capability for subgrid-scale placement of internal conductor boundaries, a capability of simulating "bent" accelerator structures, and a technique for rapidly following particles through a sequence of sharp-edged accelerator "lattice elements," using a relatively small number of time steps while preserving accuracy. On some problems (such as the ESQ injector), the code is run in a quasi-steady state mode, whereby a 3-D run can be completed in just a few minutes of computer time; this makes it suitable for iterative design calculations. The ultimate goal of this code development is effective simulations of both the ILSE experiments and a driver, from the source through the final focus, into the codes used to model propagation in the fusion chamber, and ultimately into the target design codes. A number of other particle-in-cell codes employ a "slice" description of the beam (assuming slow variation of quantities along the beam); much application, as well as detailed studies of the properties of such particle-in-cell models of beams and plasmas, has been carried out.[23]

In addition to these accelerator development efforts, the program is exploring all of the proposed modes of propagating the beams through the fusion chamber to the target. The BIC (Beam-in-Chamber) code [27] is an axisymmetric electromagnetic code which allows the computational grid to taper down to small radius, preserving resolution as the beam converges toward the target. It is used to examine the near-ballistic propagation modes, and such processes as beam neutralization and stripping. Higher-density pinched propagation modes are being