Charged Particle Accelerators for Inertial Fusion Energy

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The long history of successful commercial applications of charged-particle accelerators is largely a result of initiatives by private industry. The Department of Energy views accelerators mainly as support equipment for particle physicists rather than components of an energy generation program. In FY 91, the DOE spent over 850 M$ on building and supporting accelerators for physics research versus 5 M$ on induction accelerators for fusion energy[1]. I believe this emphasis is skewed. We must address problems of long-term energy sources to preserve the possibility of basic research by future generations. In this paper, I shall review the rationale for accelerators as inertial fusion drivers, emphasizing that these devices provide a viable path to fusion energy from viewpoints of both physics and engineering.

In the conference talk, I covered the full range of accelerator fusion applications. Because of space limitations, this paper concentrates on induction linacs for ICF, an approach singled out in recent reports by the National Academy of Sciences[2] and the Fusion Policy Advisory Committee[3] as a promising path to long-term fusion power production. Review papers by Cook, Leung, Franzke, Hofmann and Reiser in these proceedings give details on light ion fusion and RF accelerator studies.

Fig. 1*a* illustrates the recently declassified concept of indirect-drive ICF targets. The idea is to convert the energy of a beam into an intense flux of soft X-rays inside a hohlraum, a closed chamber of high-Z material. With proper design of the low-density foam that fills the chamber, the beam can generate a symmetric X-ray flux with optimal time variation to provide strong compression of a high-gain target. In the ion beam target of Fig. 1*a*, two beams pass through the thin chamber shell and heat the foam to about 300 eV. Ideally, the ions should have a normalized range of about 20-30 mg/cm^2 to penetrate the shell and to deposit high energy density in the foam. Longer range ions can be used at the expense of a more complex target with reduced gain (Fig. 1*b*). It is necessary to extend the conversion region and decrease the focal spot size to achieve the required energy density.

Many physics issues of indirect-drive targets have already been resolved. Quoting from Ref. 2, "Experiments (Centurion/Halide) using a tiny fraction of the energy from a fission bomb underground have allowed demonstration of excellent performance, putting to rest fundamental questions about basic feasibility of attaining high

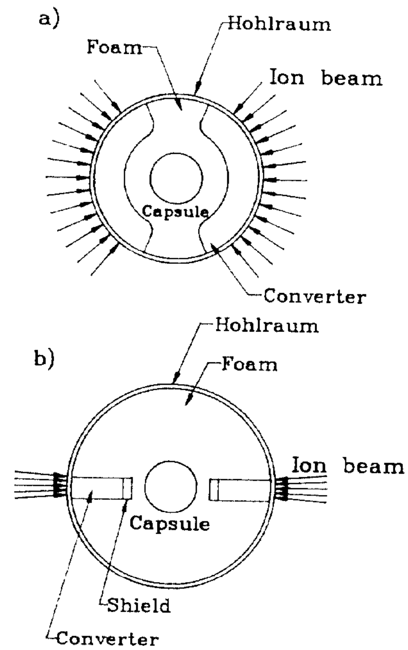

Fig 1. Principle of indirect-drive inertial fusion targets. a) Simple target design with optimum-range ions (20 mg/cm^2). b) Modified target for long-range ions (100 mg/cm^2).

gain." The drawback is that indirect targets require extra drive energy to compensate for the inefficiency of the X-ray conversion process. The estimated energy[4] for ion-driven targets is about 5 MJ for gain in the range 40-100. Although the net energy is modest, the physics challenge is to deliver the energy to small areas in short times (10 ns) at high power levels (5 x 10^{14} W). The focal spot radius requirement varies from 2 mm for high-energy ions to 1 cm for short-range ions. The beams must propagate a long distance to the focal point. With a target yield in the range 1 GJ, the reactor chamber has a radius of 5-10 m to prevent wall damage.

The power density at the converter must exceed 10^{14} W/cm^2. This precludes the direct application of conventional electromagnetic energy. The Poynting flux in an EM wave with E = 20 MV/m is only 10^8 W/cm^2. Electrodes cannot sustain higher fields in a repetitively-operated system. ICF demands an intermediate stage of power conditioning such as a charged particle accelerator. Accelerators convert electrical energy to stored beam energy that can transform to thermal energy in a material

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in a small area and short time. For example, focusing a low-emittance beam gives power compression in the transverse direction. High-compression is also possible in the axial direction. In an accelerator, the conversion of electrical to beam energy occurs over an extended distance. Non-relativistic ions can be axially bunched by a velocity tilt during or after acceleration. Finally, charged particles striking a solid material yield their energy in a short range.

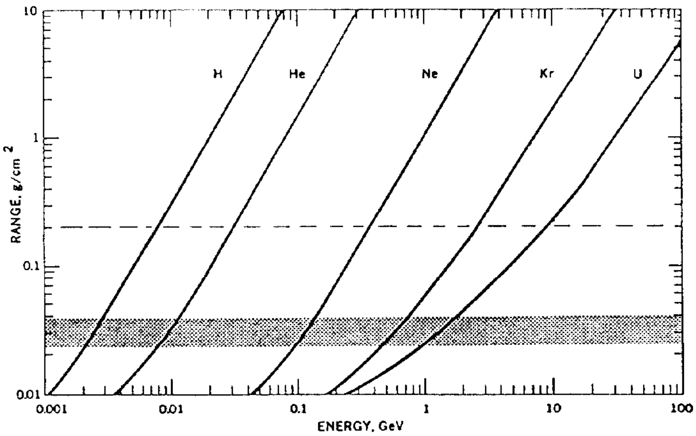

Fig. 2. Normalized ranges for ions in inertial fusion targets. Shaded area: optimum range. Dashed line: range for existing Heavy Ion Fusion studies.

Ions are more attractive than electrons for ICF because of their high stopping power. The variation of range with ion species gives several options for ion accelerator technology. Figure 2 shows that variation of normalized range with kinetic energy and ion species - the range corresponds to 10 MeV He, 100 MeV Ne, or 1500 MeV U. Higher energies are possible with advanced target designs (Fig. 1*b*). The corresponding beam currents to carry 500 TW are 50 MA for 10 MeV He, 5 MA for 100 MeV Ne, and 50 kA for 10 GeV U. Although these currents are beyond present capability, the dramatic advances in beam physics and accelerator technology in the past decade give cause for optimism.

ICF reactors with ion beam drivers have compelling advantages. In contrast to magnetic fusion devices like the Tokomak, the ICF reactor chamber is physically separate from the power source (driver) that creates the thermonuclear plasma. As a result, the engineering of the reactor is simplified. Ion accelerators have several desirable features compared with lasers. Accelerators are reliable, achieve good energy efficiency, and operate at adequate repetition rates (1-10 Hz). Ion beams can be compressed in space and time and focused into the reactor by magnetic lenses with no exposed physical surfaces. Most important, the energy deposition process of ions in matter is predictable. Ref. 3 recognizes these features: "We strongly urge augmenting the [inertial fusion] program for developing a driver of suitable efficiency and reliability to be useful for energy production, with emphasis on heavy ions...."

We can represent the ICF process with an ion beam driver by three stages of power compression (Fig. 3). In the first, electrical energy is stored over an extended period and then converted to beam energy by the accelerator in a time ranging from 20 ns to several ms. Beam manipulations amplify the power. The final stage involves conversion to soft X-rays. We can classify present approaches by their emphasis on electrical versus kinetic energy compression and the power levels for the transfer operations. Fig. 3 shows four current programs. The Kurchatov Institute is the leading laboratory for the study of imploding Z-pinches for fusion[5]. In this process, a large pulsed power generator drives current through an annular foil creating an imploding plasma. The system

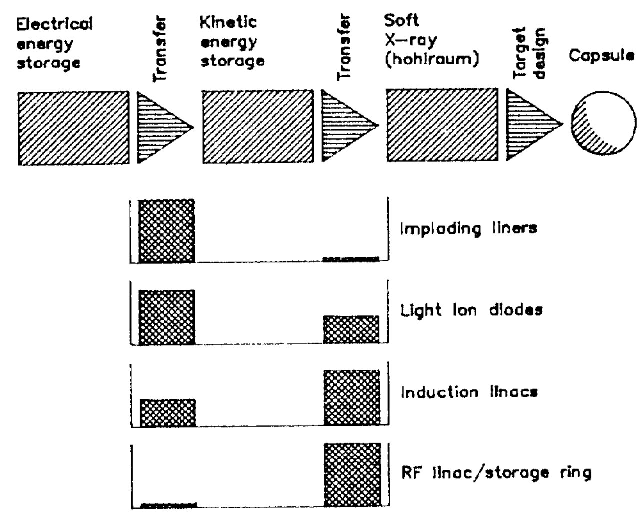

Fig. 3. Schematic view of power compression sequence for ion beam drivers and indirect-drive targets. Four present approaches to ion beam fusion with relative emphasis on electrical versus kinetic energy compression.

produces an intense burst of soft X-rays when the pinch stagnates on axis. In a sense, the plasma is a high-emittance, neutralized ion beam that gives modest power compression in space and time. This method places almost total reliance on electric power amplification. The other three approaches use higher quality beams. The main centers for light-ion fusion are Sandia National Laboratories[6] and the Kernforschungszentrum Karlsruhe[7]. These programs emphasize electrical energy compression, seeking only a factor of about 100 power amplification from beam manipulations. The accelerator electrodes must sustain fields exceeding 200 MV/m to create the necessary high ion current densities. This limits the technology to single shots. Nonetheless, LIF programs can make valuable contributions to energy applications in the areas of beam-target interactions at high intensity, target diagnostics and advanced methods for beam transport.

The other two accelerator options use multi-stage devices to generate lower current beams of heavy ions at higher kinetic energy (heavy ion fusion). High-energy accelerators extend the time and distance for conversion from electrical to kinetic energy; as a result, they can operate reliably at high-repetition-rate. The program at the GSI Darmstadt[8] is based on a conventional RF linac feeding a series of storage rings for beam compression. This approach uses kinetic energy storage and compression exclusively - the electric energy transfer occurs at low power density. The main physical problem of the RF accelerator option is the confinement of intense ion beams in storage rings at a low enough energy to be of interest for ICF. Even with the application of laser induced beam stacking[9] for phase space compression in rings, the ability to meet the focal spot requirement is marginal. Furthermore, there is no latitude to reduce the beam energy below 10 GeV. The main engineering problem is the cost and complexity of kinetic energy storage. Containment of 1 kJ heavy ion beam in a ring costs roughly 10^5 times as much as storing the same electrical energy in a low-inductance capacitor. Clearly, the imperative is to minimize kinetic energy storage in a practical system. Although there is no definitive answer, studies of the storage ring approach to date imply costly and complex systems.

The main center for the induction linac approach is the Lawrence Berkeley Laboratory[10] with assistance from Lawrence Livermore Laboratory. Induction linacs seek a balance between electric and kinetic energy storage for high average power at relatively low cost. The accelerators incorporate acceleration gaps with ferromagnetic isolation cores[11]. Each stage consists of an electrostatic acceleration gap driven directly by a pulsed power generator. The isolation chokes allow series gap stacking to achieve high beam kinetic energy. An advantage of the induction linac is that it can drive pulsed currents in the multi-kA range. The drawback is that the ferromagnetic core cost is high in the low gradient machines.

The induction linac HIF driver is a straight-through device to generate a single beam pulse at moderate repetition rate (<10 Hz). Shaped gap voltage pulses induce a velocity tilt in the non-relativistic ions to compress the beam as it moves through the system. The pulselength varies from several microseconds to about 100 ns. Final bunching to 10 ns occurs in drift transport lines near the reactor. To pass the maximum current, beams propagate near the space-charge limit in a parallel array of quadrupole lens channels. Experiments at LBL have demonstrated the transport of low emittance beams at high flux levels in a quadrupole array with almost a perfect balance between space-charge and focusing forces[12]. The main physics problem is longitudinal control of beam pulses in a heavily loaded accelerator[13] - the papers by Fessenden and Smith in these proceedings discuss this topic. Reference 14 summarizes system studies of power plant drivers carried out by LBL and other groups. Design studies to date use high-vacuum ballistic transport in the reactor as a baseline, limiting the beam kinetic energy to high values. Because induction linacs have low average gradient (<1 MV/m), the cost of cores and other equipment in a 10 GeV exceeds 1 B$.

The main engineering challenge for induction linac drivers is reduction of the driver cost. Two possible solutions are 1) to modify the accelerator technology and 2) to relax the beam requirements. Regarding accelerator technology, papers by Hewett, Yu and Newton in these proceedings report studies of recirculating geometries. A recirculating induction accelerator makes more effective use of isolation cores at expense of a complex acceleration process. In this paper, I will concentrate on second option, lowering requirements on beam quality and kinetic energy through alternative transport techniques in the reactor. Propagation of heavy ion beams through a plasma environment aroused considerable interest a decade ago[15], but lack of funds and a prevailing conservatism in driver design impeded further work. The parameters of conceptual heavy ion drivers to date are set largely by the limitations of ballistic beam propagation in high-vacuum. It is important to note that attractive plasma transport modes exist that can lead to dramatic reductions in the cost of accelerators.

Ballistic transport of a beam to a fusion target in high-vacuum has several drawbacks. The process demands low beam emittance and small energy spread. For example, to focus a 10 GeV U beam over a 10 m span with a compression from 10 cm to 2 mm implies a normalized emittance $\epsilon_n < 6 \times 10^{-6} \pi$-m-r. In vacuum, space-charge expansion limits beams to high kinetic energy and low current. Design studies[14] postulate a large number (20) of parallel beams to circumvent current limitations. Each beam must have its own transport line, final focusing lens array, and reactor entrance port. Transverse space-charge forces and electrostatic target charging preclude reduced beam energy or the acceleration of multiply-charged ions. Finally, it is doubtful that a high-vacuum environment is consistent with a practical reactor design.

One alternative is to improve ballistic focusing with electron neutralization to reduce space charge forces. Although a low emittance is still necessary, there is considerably more latitude to choose beam energy, ion charge state, and the number of reactor entrance ports. In this case, constraints derive mainly from beam transport in the accelerator rather than space-charge forces in the reactor. It may be possible to reduce the beam kinetic energy - although the emittance will be higher, the required focal spot is larger. Also, the use of multiply-charged ions reduces the accelerator length for a given kinetic energy.

An attractive neutralization option is to direct the beam through a preformed plasma cloud at the reactor entrance and then to allow it to propagate through a diffuse reactor plasma generated by the ionization of a low-density background gas. Acceleration of electrons from the plasma cloud by the beam space-charge potential gives effective neutralization. Electron conduction in the diffuse reactor plasma avoids electron heating as the focused ion beam compresses. With this process, it may be possible to transport the full energy beam current from an HIF driver with as few as two beams. Early studies[17] suggested that stable plasma propagation may be limited to a "1 torr window" in analogy with pinched electron beam experiments. Here, the upper limit on background gas pressure is set by beam stripping and the filamentation instability, while the plasma electron-ion two-stream instability sets a lower limit on pressure. The present belief[18] is that the consequences of the two-stream instability are small and that there is no lower limit on background gas pressure. The instability induces negligible beam energy loss through plasma heating and may allow a small fractional imbalance of beam and background electron currents.

An alternative plasma transport mode, self-pinched propagation[19], could dramatically impact the cost of an induction linac ICF driver. The idea is to focus a high-current beam to small spot outside the reactor shield with a short focal length lens. When the beam enters the chamber, a plasma provides complete cancellation of electric fields. In some circumstances, the plasma return current may occupy a larger area than the beam current, leaving enough beam-generated magnetic field to contain the ions in a constant radius pinch. This process does not violate conservation of emittance - it involves only a translation of a preexisting focus. The success of experiments at the Naval Research Laboratory on pinched electron beams in gas[20] and intense ion beam propagation in preformed plasma channels[21] demonstrate the successful control of hose and filamentation instabilities.

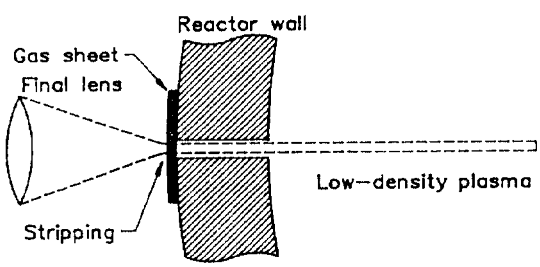

Fig. 4. Injection of a self-pinched beam into a plasma-filled inertial fusion reactor.

Previous work on heavy-ion beam self-pinches concentrated on a homogeneous high-density plasma with beam stripping extended along the propagation path[19]. Because of high predicted plasma conductivity, the residual magnetic field was low. In these studies, self-pinching was marginal. Figure 4 illustrates a better approach. Ion stripping occurs in a dense gas sheet at the external focal point. The highly-charged ions pass into a low-density plasma in the reactor. Simple scaling calculations show that conditions for a pinched beam equilibrium are easy to attain. Ion beams of proper range for ICF optimally have velocities of about 0.2c. This figure corresponds to a beam pulse length of 0.6 m, much shorter than the propagation distance. To avoid charge buildup, the plasma electrons in any cross section of the isolated beam slug must carry a negative current exactly equal to ion current. Suppose the ion current is given by $Z^* I_o$, where I_o is the particle current and Z^* is the ion charge state. A focusing magnetic field exists within the beam volume if the electron current occupies a larger area than the ion current. Inductance in the plasma column is minimized if the areas of the ion beam (A_b) and electron beam (A_e) are equal - the column resistance is lowest when the electrons occupy the maximum area. If A_e is slightly larger than A_b, then the net current inside beam volume is $I_{net} = Z^* I_o f_m$, where $f_m = (A_e - A_b)/A_e$. The paraxial envelope equation implies the following condition for a beam equilibrium,

$$\epsilon_n \cong Z^* r_o \left[\frac{e I_o f_m \beta\gamma}{2\pi\epsilon_o m_i c^3} \right]^{1/2}, \qquad [1]$$

where ϵ_n is the normalized emittance. For a 4 GeV uranium beam ($\beta = 0.2$), vacuum ballistic focusing to a 5 mm radius target requires a value $\epsilon_n = 10^{-5}\pi$-m-r. To see the implications of Eq. 1, consider a value 5 times higher. Two pinched beams with $I_o = 50$ kA irradiate the target - the uranium ions entering the reactor have charge state $Z^* = 40$ entering the reactor. For $r_o = 5$ mm, Eq. 1 implies that $f_m = 0.023$. Because of the high value of Z^*, a pinched equilibrium requires a net current of only 47 kA. Fig. 5 shows the approximate radial variation of field in the beam. The corresponding field energy per meter is

$$U_m = \left[\frac{\mu_o}{16\pi} \right] (I_o Z^* f_m)^2. \qquad [2]$$

For the example discussed, the energy is only 55 J/m. Alternatively, any resistive process that transfers more than 55 J/m from the beam to the plasma electrons will give sufficient magnetic field for a pinched equilibrium. Three resistive process that can account for the energy transfer are ionization of the background gas to create the plasma, heating of drifting electrons by the electron-ion two-stream instability, and acceleration of electrons to achieve approximate current neutralization of the beam. In fact, it is unlikely that a high intensity ion beam could propagate through a plasma without loosing at least 50 J/m. Higher energy loss would create stronger magnetic fields and a more tightly-pinched beam. I feel that a self-pinched equilibrium is a high-probability state for any stripped low-emittance ion beam. Similar optimistic predictions can be made for beams of light ions at reduced energy.

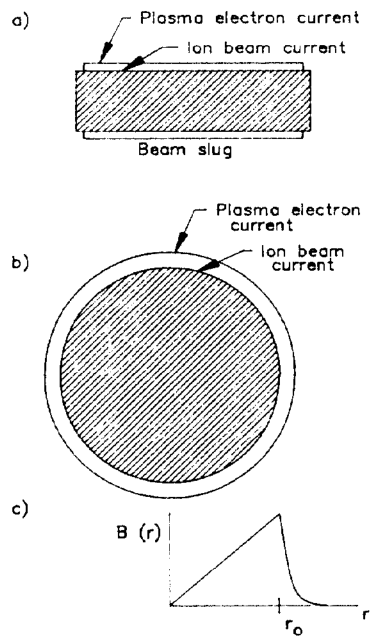

Fig. 5. Physics of the self-pinched heavy ion beam. a) Longitudinal section. b) Radial section. c) Radial variation of azimuthal magnetic field.

The self-pinched mode can alter the baseline parameters of HIF induction linacs for reduced size and cost. Relaxation of reactor transport limits would allow the use of lower beam kinetic energy and multiply charged ions, reducing the accelerator length. The corresponding smaller ion range would allow simple target designs and larger focal spots. The combination of the large focal spot and focusing external to the reactor would relax requirements on beam emittance and energy spread. In turn, a higher beam emittance would permit the use of existing ion sources and shortened quadrupole lenses. Because the limiting current in the accelerator scales inversely as the square of the quadrupole length, the machine can accommodate the higher currents associated with reduced beam energy. The self-pinched transport mode also widens the range of possibilities for reactor design. The problem of beam stripping in the reactor is no longer important and only a few small diameter apertures are necessary for beam injection. In summary, the already attractive option of induction linacs for ICF reactors can be enhanced through application of plasma transport methods.

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