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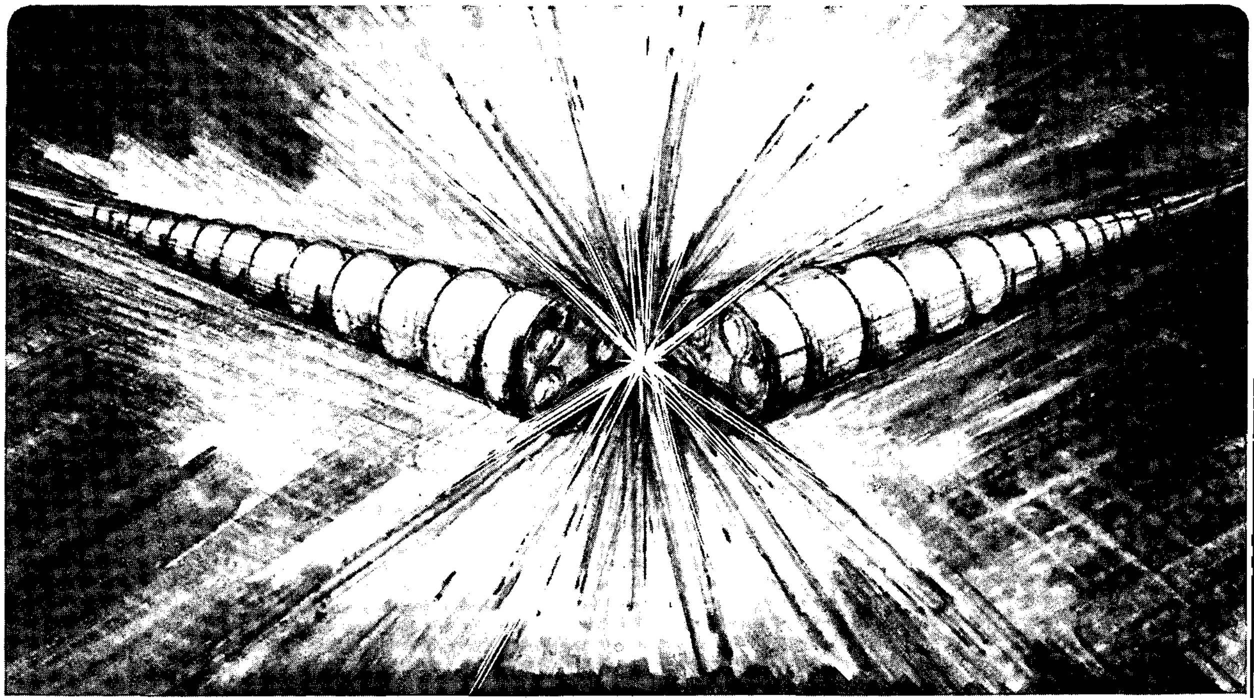

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INDUCTION LINACS FOR HEAVY ION FUSION*

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Abstract

Inertial fusion target physics imposes important constraints on the design of linacs for heavy-ion fusion. The most challenging constraint from a scientific standpoint is the requirement that the accelerator deliver more than 10^{14} W of beam power to a small quantity (less than 100 mg) of matter. The most challenging constraint from an engineering standpoint is accelerator cost. This paper explains the target physics requirements and shows how they lead to constraints on the usual accelerator parameters such as kinetic energy, current, and emittance. It will be shown that improvements in the final focusing system would have a beneficial effect on both scientific feasibility and cost.

The paper also discusses experiments that are presently underway in the United States, specifically, experiments on high-current injectors, recirculating induction accelerators, transverse beam combining, and a proposed accelerator called ILSE. Hardware development for ILSE is now in progress.

Introduction

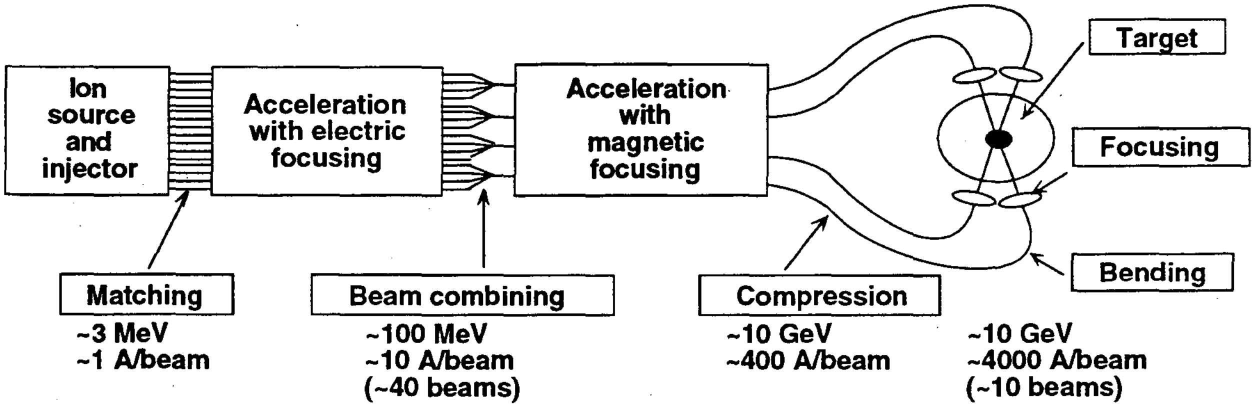
To produce energy economically in a heavy ion fusion power plant, the target gain must exceed about 30. The gain of an inertial fusion target is defined as the thermonuclear energy produced divided by the energy absorbed by the target. Detailed numerical simulations, normalized to an impressive body of experimental data, give the requirements that an accelerator must meet to produce the required target gain. These requirements are given in Table I. From a target standpoint, the ion range, R, given in terms of mass per unit area, is the important quantity. For a given value of R, the accelerator designer can choose ion mass, or equivalently ion kinetic energy, on the basis of accelerator considerations. Fig. 1 is a diagram of a typical induction accelerator designed to meet the requirements given in Table I.

It is noteworthy that large accelerators have already met many of the requirements. They store megajoules of beam energy. They can easily produce the required ion kinetic energy, and they routinely produce beams that can be focused to a small spot. The main new requirement for inertial fusion is obtaining high peak power (high peak ion current) while maintaining adequate beam quality to focus onto a small target a few meters away. Accelerating high current is not, by

TABLE I.

Requirements that an accelerator must meet to produce high gain. The accelerator must also be inexpensive, reliable, efficient, and have long life and a high repetition rate.

Beam energy	1 - 10 MJ
Focal radius	2-5 mm (at several meters standoff)
Ion Range	0.1 - 0.02 g/cm^2 (10 - 2 GeV heavy ions)
Pulse duration	~ 10 ns
Peak power	100 - 1000 TW (10-100 kA)



Power amplification to the required 10^{14}-10^{15} W is achieved by beam combining, acceleration and longitudinal bunching.

Figure 1. Diagram of a typical induction linac for heavy ion fusion. The voltage and current at each point are shown. Such a machine would have on the order of 10 beams in the magnetically focused section. The maximum beam current in the accelerator is about 4 kA. The tails of the beams are accelerated to a slightly higher velocity than the heads of the beams so that the beams compress by about a factor of 10 as they drift toward the target. This compression gives a final current of about 40 kA (~4 kA/beam).

itself, the issue for an induction linac. The ATA induction linac at Livermore accelerated about 10 kA of electrons, more than enough current for fusion (See Fig. 1). The main engineering challenge is accelerator cost.

Table I indicates that there is significant flexibility in choosing ion mass, kinetic energy, and focal spot radius. There are, however, important constraints among these parameters as will now be explained.

Target Considerations

This section gives a semi-quantitative description of important target considerations. The description is not intended to be accurate.

In an inertial fusion target, ignition occurs when the fuel gains energy faster than it loses energy. The important gain mechanisms are PdV work and thermonuclear burn. The important loss mechanisms are conduction and radiation. The rate of doing PdV work is directly related to the implosion velocity, v_{imp}. For ignition, v_{imp} is usually greater than 2×10^5 m/s. The ablation process that drives the implosion is most efficient when the ablation velocity, v_{abl}, is comparable to v_{imp}. A velocity of 2×10^5 m/s corresponds to a specific energy, $\varepsilon \sim v_{abl}^2/2$, of 2×10^{10} J/kg.

In directly driven targets, the ions produce the required value of ε by depositing their energy directly in the ablator as shown in Fig. 2a. For a spherical target, the mass of the heated material is $m = 4\pi r_t^2 R$, where r_t is the target radius. The focal spot radius, r, must be less than or equal to the target radius. The maximum target radius is determined by fluid instabilities and is approximately proportional to $E^{0.33}$ where E is the driver energy (total beam energy). The specific energy is given by $\mathcal{E} = E/m = E/(4\pi r_t^2 R)$. The implosion time is approximately given by r_t/v_{imp}. Thus, if E is specified, all other beam parameters such as pulse length, power, focal spot radius, and ion range are determined. (One can vary the values over some limited range by accepting reduced target gain.)

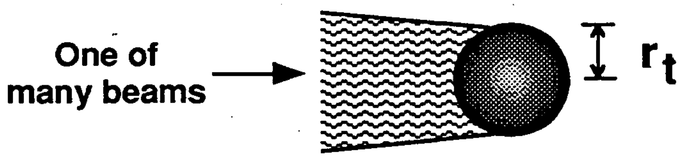


Figure 2(a). A directly driven target. The beam radius cannot be substantially larger than the target or some of the beam will miss the target. Only one of the many beams arrayed around the target is shown.

In an indirectly driven target (Fig. 2b), the ablator is heated by radiation produced in converters heated by the ion beams. The ion beams must deposit enough energy to heat the ablator, the cavity wall, and the radiators. The radiators must, of course, be hotter than the ablator. This requires a specific energy deposition $\mathcal{E} \geq 10^{11}$ J/kg. While $\mathcal{E}$ is larger for indirect drive, the mass can be smaller. For example, the mass of two cylindrical radiators is $2\pi r^2 R$, rather than $4\pi r^2 R$ in the directly driven, spherical case. More importantly, within limits, r and R are now related only through the relationship $E/(2\pi r^2 R) \geq 10^{11}$ J/kg. There is significant flexibility that can be exploited to minimize cost or optimize accelerator performance. Indirect drive also allows greater freedom in illumination geometry than direct drive, but it is less efficient.

Accelerator Considerations

If one considers simple quadrupole final focusing systems, aberrations become excessive if the ions converging onto the target make an angle θ larger than about 10 to 20 mr with respect to the beam axis. If θ = 10mr, r = 3mm, and $\beta\gamma = 0.33$ (10 GeV heavy ions), the normalized emittance is $\varepsilon_n = \pi\beta\gamma r\theta = 10\pi$ mm·mr. For heavy ions having kinetic energy, T, of 10 GeV, the ion range is approximately proportional to T. The reader can easily verify that ε_n is unchanged if θ remains fixed but T and r are allowed to vary in a way that leaves specific energy (target performance) constant. As noted above, the target description is not entirely accurate. While target performance primarily depends on T and r through the specific energy, there is a weak residual dependence on T and r for fixed specific energy. Chromatic aberrations limit the final momentum spread to a few tenths of one percent, which, together with the pulse length, lead to a longitudinal emittance requirement. The dependence of longitudinal emittance on kinetic energy is also weak.

For induction linacs, kinetic energy (voltage) is more expensive than beam current except at the very lowest energies. Since the emittance requirements do not depend strongly on kinetic energy, it is tempting to try to minimize cost by minimizing kinetic energy while increasing current to meet the power requirement. Of course, it may be difficult to get low emittance at high current. Calculations show that low kinetic energy does lead to low cost; but much below 10 GeV, it becomes difficult to focus the beams against their space charge. Beam neutralization is then needed. Development of neutralized focusing schemes that do not destroy beam quality would have a strong favorable impact on the economics of heavy ion fusion. The standard scenario shown in Fig. 1 does not use neutralization.

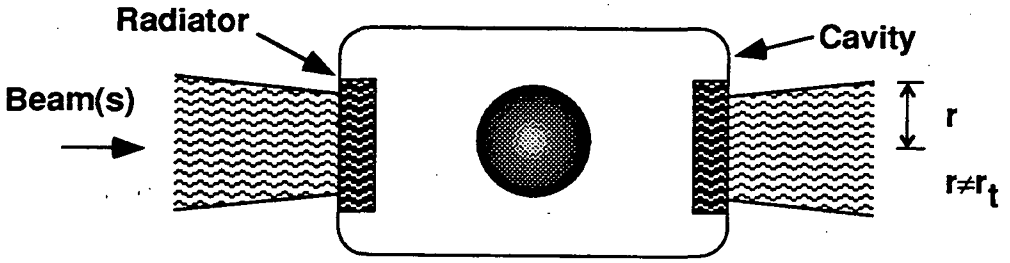


Figure 2(b). An indirectly driven target. Here, the cavity contains and symmetrizes the radiation which drives the implosion Note that the beam size is not directly related to the capsule size. The internal structure of the capsule (not shown) produces a spherically symmetrical implosion.

A second potential method to reduce accelerator cost is recirculation. A recirculator is essentially a linac bent into a circle. The currents needed for fusion clearly exceed the normal stability limits of circular machines, but it may be possible to recirculate 2 to 100 times.

Experimental Program

The considerations described above suggest the direction that the experimental program should take. The program should address the generation and acceleration of high-current beams having normalized emittance less than about 10π mm·mr. The program should study limits on beam current and methods of neutralized focusing. Finally, the program should study the recirculation of high-current beams.

Previous experiments [1] have addressed some of the important issues, but larger experiments are needed. In particular we have transported and accelerated intense ion beams with acceptable growth in emittance, but these beams carried only about 10 mA of current. We are now proposing a sequence of experiments called the Induction Linac System Experiments (ILSE) to address the issues described above at high current. Figure 3 is a diagram of the ILSE accelerator.

ILSE consists of a four-beam, 2 MeV injector, an accelerator section employing electrostatic focusing lenses, and an accelerator section employing magnetic focusing lenses. Each injector beam will carry about 1A. The electrostatic section accelerates four beams from 2 MeV to 5 MeV. At this point the four beams are combined transversely into a single beam that is then accelerated to 10 MeV in the magnetic section. Beam combining is a promising way to increase beam current and reduce cost; however, it leads to significant emittance growth due to the non-linear space-charge forces associated with the merging beams. Calculations indicate that the growth is acceptable because existing ion sources produce much lower emittance than required for final focus. ILSE will check the validity of the calculations. The ILSE beams will be driver-scale in diameter and charge per unit length. The main differences between ILSE and a driver are in number of beams, ion kinetic energy, and pulse length. To minimize ILSE cost these parameters are only large enough to address the important physics issues. As noted above, ILSE will have four beams in the electrostatic section and one beam in the magnetic section. Driver designs typically have 4 to 16 times as many beams as ILSE. Although ILSE will accelerate ions to only 10 MeV compared to 1-10 GeV for a driver, ILSE will have enough betatron periods to allow sensitive tests of emittance growth. The ILSE pulse length is about 1 μs. In a driver the pulse length will vary from tens of microseconds to about 100 ns. The ILSE experimental area is large enough to accommodate a large ring for recirculation studies. ILSE will enable us to study current limits, neutralization, and recirculation. According to present Department of Energy plans, the electrostatic section will be built before the magnetic section. The electrostatic section alone is referred to as Elise.

We have made substantial progress toward ILSE. A single beam, 2 MeV injector is currently in operation at Berkeley. The injector has achieved its design goals of 800 mA of potassium ions and a normalized emittance of 1π mm·mr. We have fabricated a number of components that will be needed for ILSE such as pulsers, induction cores, magnetic quadrupoles, and electrostatic quadrupoles. Further development is needed. We are currently assembling a small combining experiment to provide experience and data for the ILSE combining experiments.

Beam dynamics issues which must be resolved before the ILSE ring can be built include centroid control, longitudinal control, emittance preservation through bends,

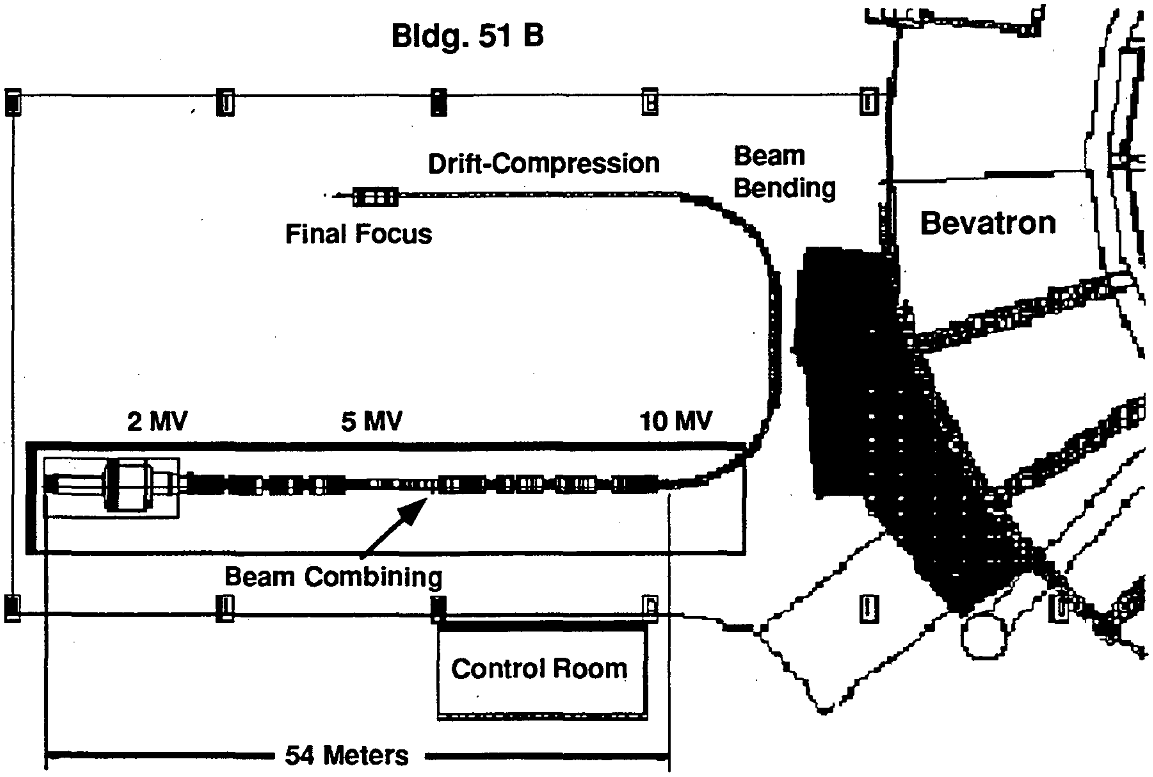
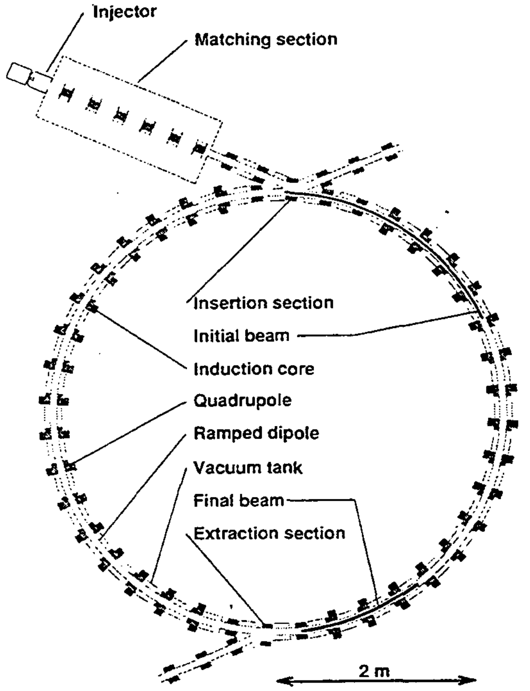


Figure 3. A schematic of the proposed ILSE accelerator. ILSE will be located in the old Bevatron complex at Lawrence Berkeley Laboratory.



Ion species: Potassium (mass 39)
Beam energy: 80-320 kV
Beam current: 2-8 mA
Pulse duration: 4-1 μs
Nominal number of laps: 15
Circumference: 14.4 m

Figure 4. Diagram of recirculator experiment.

and insertion/extraction of the beam into/out of the rings. These will be addressed at reduced scale in a sequence of experiments leading to a small "model" recirculator at Livermore. The waveform generators must supply variable accelerating pulses at high 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. Livermore has already achieved 200 kHz bursts at 5 kV and 800 A, but with a non-variable format. Figure 4 is a diagram of the recirculator experiment. This small experiment will not address issues of beam loss and activation. These issues are important for all heavy ion fusion accelerators that employ rings.

Readers wanting more information on the program should refer to a recent special issue of Il Nuovo Cimento [2].

Conclusions

Beam quality and cost are the two principal issues for heavy ion inertial fusion. Reducing ion kinetic energy below the usual value of 10 GeV and recirculation are two potential methods of cost reduction. Low kinetic energy requires the development of neutralized focusing methods. Recirculation requires the favorable resolution of a number of physics and technology issues. The ILSE Program, if approved by the U.S. Department of Energy, will resolve many of the outstanding issues for both approaches. Finally, the ILSE Program, in conjunction with the RF accelerator programs in other programs, will enable us to make a sound choice regarding the best technology for heavy ion fusion.

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