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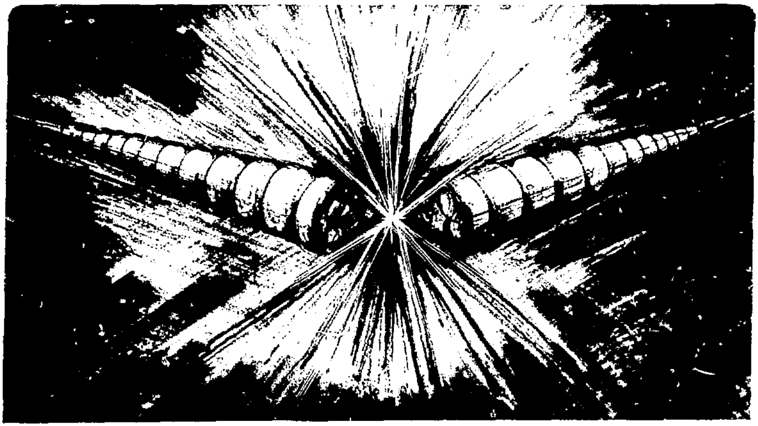

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HEAVY ION INDUCTION LINACS FOR ICF

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Inertial Confinement Fusion may be initiated by several possible driver systems able to deliver a few megajoules of energy to a target pellet a few millimeters in radius in a time of about 10 nsec. The expected target gain as a function of input energy is shown in Figure 1. Since 1976 intensive study and experimentation have been devoted to the use of beams of heavy ions as the driver for a pellet implosion, and the progress in this field is summarized in the proceedings of annual workshops held by the principal National Laboratories involved in this research: Argonne, Berkeley, Brookhaven, and Livermore.[1,2,3,4] Some of the principal advantages of the choice of heavy ions are the ability to transmit terawatts of power in the beams and to focus them onto the target at 10 meter distances with final focusing magnets which may be shielded from the explosion. The possible accelerator choices have been generally narrowed down to an r.f. linac operated in conjunction with a number of storage rings, and a single-pass induction linac.

GAIN VERSUS DRIVING ENERGY FOR DOUBLE-SHELLED TARGETS

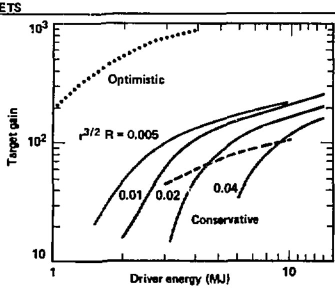


Figure 1

The technology of handling charged particle beams is well developed in the field of high-energy accelerators, but the range-energy relation, Fig. 2, and target requirements cause the parameter range of interest for HIF (Heavy Ion Fusion Drivers) to be one where the accelerated current is high and the single particle kinetic energy low compared to those of most other new accelerators. A maximum acceptable energy is in the vicinity of 20 GeV, which requires a corresponding current of 15 kA for a 3 MJ pulse. A heavy ion with a weight of ~200 amu is still non-relativistic at the final energy, therefore it is possible and advantageous to utilize a longitudinal compression of the bunch in the final transport lines to achieve a power amplification of an order of magnitude. The maximum current to be handled in the accelerator therefore is a few kiloamperes, a level which is well matched to the capabilities of an induction accelerator.

HEAVY IONS ALLOW EFFICIENT ENERGY DEPOSITION WITH HIGH VOLTAGE LOW CURRENT BEAMS

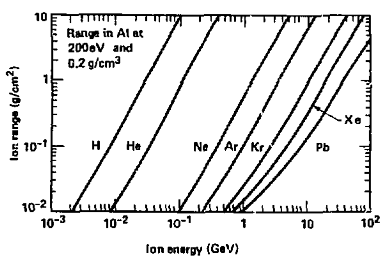


Figure 2

TABLE I

SOME ELECTRON INDUCTION LINACS

Accelerator	Astron Injector Livermore, 1963	ERA Injector Berkeley, 1971	NEP 2 Injector Dubna, 1971	ATA Livermore, 1978	NBS Proposed, 1971
Kinetic Energy, MeV	3.7	4.0	30	50	100
Beam Current on Target, Amps.	350	900	250	10,000	2,000
Pulse Duration, ns	300	2-45	500	50	2,000
Pulse Energy, kJ	0.4	0.1	3.8	25	400
Rep Rate, pps	0-60	0-5	50	5	1
Number of Switch Modules	300	17	750	200	250

Some of the main parameters of induction linacs which have been built, or are under construction, are listed in Table 1. All of the machines shown there are electron machines. A current of heavy ions is equivalent to a current of electrons, for the same pulse duration, as far as the individual induction acceleration modules are concerned; the major difference is that the required transverse focusing fields for the ions greatly exceed those for the same current of electrons. The electron machines basically consist of a number of identical modules, because electrons are usually very relativistic and therefore not subject to significant intrabunch longitudinal motion during their transit through an accelerator. The comparable ion machine, on the other hand, shows a gradual change throughout its length: at the low energy end a large fraction of the space is devoted to focusing quadrupoles, and the accelerating modules tend to be large and bulky; at the high energy end only about 10 percent of the length is devoted to focusing, and the modules are much smaller. The reasons for this gradual transformation are that magnetic focusing forces become stronger in direct proportion to particle velocity, thereby requiring fewer quadrupole magnets, and, for a fixed bunch length, the time of passage of the bunch through a module varies inversely with velocity, thereby requiring a smaller core cross-sectional area for the same acceleration rate. The heavy ion induction linac therefore is expected to resemble the NBS 2-μsec module at the low energy and, the Astron 300-ns modules midway, and the ERA 45-ns modules near the full energy points, with many focusing elements interspersed between them.

The radial cross-sectional area of an induction module core is determined by

$$A = \frac{Vt}{\Delta B} = \frac{VQ}{\Delta B I} , \qquad (1)$$

where V is the acceleration voltage, t is the pulse duration, Q is the total accelerated charge, I is the current at the location of the module, and ΔB is the available field change for the magnetic material used. The core losses are in part determined by the core volume, and therefore increase at least as quickly as the core area. Consequently, the acceleration efficiency increases with increasing beam current while the required core volume and cost decrease. The trade-offs between acceleration and focusing requirements are conflicting, and are being sorted out and optimized with the aid of the design program LIACEP.[5] Necessary inputs for the program are maximum focusing and acceleration field limits, transverse and longitudinal focusing requirements as a function of beam parameters, and cost data.

In all alternate HIF schemes near the target, and in the induction linac – because of the capability of adjusting current by longitudinal bunch control throughout the machine – it is desirable to transport the maximum amount of current stably in a given focusing structure. This topic has been pursued analytically and computationally with good agreement, but an experimental verification of the transport limits remains to be done. The envelope equation,[6] Eq. 2.

$$\frac{d^2 a_{x,y}}{ds^2} = -\frac{B'_{x,y}(s)}{[B\rho]} \; a_{x,y} \; + \; \frac{\varepsilon_N{}^2}{\beta^2\gamma^2 a^3_{x,y}} + \frac{4q^2}{A} + \frac{Nr_p}{\beta^2\gamma^3}\,\frac{1}{a_x + a_y}, \qquad (2)$$

where the first term on the right represents the external focusing, the second term the effect of the normalized emittance of the beam, and the third term the space charge defocusing – gives the highest stable transportable current for the analytically tractable K-V distribution of uniform density when the betatron phase advance per period of structure is depressed by the space charge of the beam from 60° at zero current to 24° at maximum current, as shown in Fig. 3. This result has

BEAM TRANSPORT in a QUADRUPOLE FOCUSING CHANNEL

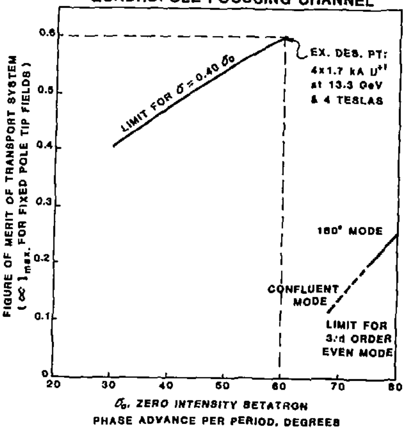
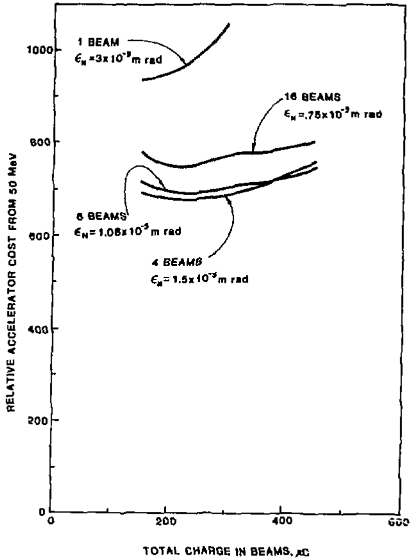


Figure 3 XBL 8010-12381

been scaled appropriately throughout the range of energies in the machine, and within the acceptable emittance limits, to specify the focusing requirements.



3 MJ DRIVER, U^{+1}, 1 HZ, $\Delta\sigma = 60° - 24°$

Figure 4 XBL 8010-12382

One of the possible options which has been explored, and which had previously been found essential for the final focusing system,[7] is the sub-division of the beam into a number of beamlets in order to decrease the transverse and longitudinal space charge forces. In an ideal system, subject to the total emittance being proportional to $\sqrt{I}$, the transportable current increases as $n^{2/3}$ for n beamlets in a transport system limited by peak pole tip fields, and somewhat less in a real system with dilution in the process of combining beams. Some of the LIACEP cost minimization results are shown in Fig. 4, where the cost minimum is seen to be, for an induction linac, when 4 or 8 beamlets are accelerated. At very low energies additional savings may be possible through the use of a larger number of beamlets which are electrostatically focussed, using either periodic einzel lenses[8] or quadrupoles.[9]

The multiple beamlet approach yields a higher acceleration efficiency as well as substantially lower costs than the single beam case. A significant benefit in matching the number of beamlets in the accelerator to the number required in the final focusing lines is the avoidance of the dilution due to the splitting of the beam at the end of the accelerator. Fig. 5 shows a 4-beamlet module and Fig. 6 shows the final transport and focusing system of a power producing design.

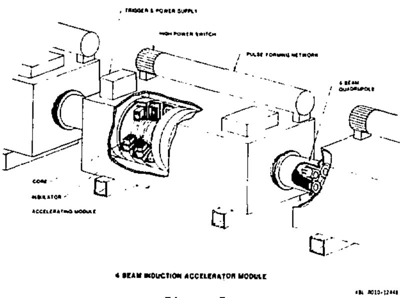


Figure 5

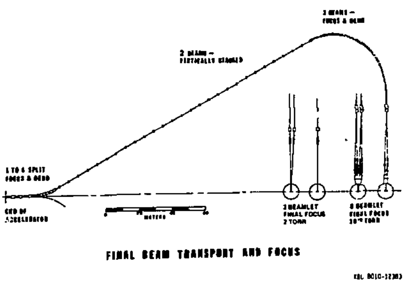


Figure 6

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