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Abstract

There is a continuing study in the USA of the feasibility of an induction linac fusion driver, which would accelerate multiple heavy-ion beams through a sequence of pulsed transformers and amplify the beam current during acceleration. The driver cost could be \$200/oule or less and the cost of electricity in the range of .050-.055\$/kWhr. As a next stage of development to assess the feasibility of this approach we propose an "Induction Linac Systems Experiment". This will test some of the technology and multiple-beam manipulations necessary for a fusion driver.

The Induction Linac Approach

Inertial confinement fusion (ICF) requires that megajoules of energy at very high power be deposited on the fusion target, nearly independent of the driver type. The depth of deposition must be small (typically $\sim 0.1 \text{ g/cm}^2$ in a stopper material) to produce the high fusion yields required for an economically attractive power plant. The range condition can be met in principle by any ion species, accelerated sufficiently to match the range-energy relation, as well as by short wave-length ($< 300 \text{ nm}$) photons. For the heavy-ion driver approach to ICF two conventional but very high current accelerator technologies are being explored. These are the rf linac/storage ring system [1] now studied in W. Germany, USSR, and Japan, and the induction linac approach studied in the USA. For both accelerator types the combined considerations of space charge limits and range in dense matter lead to the use of heavy ions ($A = 200$) of high kinetic energy ($\sim 10 \text{ GeV}$).

A typical set of final beam parameters suitable for a power reactor [1], is given in Table 1. It must be emphasized that cost trade-offs among the many components of a complete power plant allow a broad range of system parameters (such as repetition rate) to be considered with minor effect on the final cost of electricity.

Table 1 Example Driver Parameters

Pulse Energy	5.0 MJ
Particle Energy	10 GeV
Ion	$\text{Bi}^+ (A=209)$
Pulse Power	250 TW
Rep. Rate per Reactor	5 Hz
Number of Beams per Reactor	20
Net Pulse Charge	500 μC
Final Emittance (un-normalized)	$3 \cdot 10^{-5} \text{ m rad}$
Momentum Width	$\pm 1\%$
Spot Radius	4 mm

An induction linac driver is now envisioned as a multiple beamlet transport lattice consisting of N closely packed parallel channels. Surrounding the lattice are massive induction cores of ferromagnetic material and associated pulser circuitry which apply a succession of long-duration, high-voltage pulses to the N parallel beamlets. A multiple beam source of heavy ions operates at 2-3 MV, producing the net charge per pulse required to achieve the desired pellet gain. Initial current (and therefore initial pulse length) are determined by transport limits in the lattice at low energy. The use of a large number of electrostatic quadrupole channels ($N = (6-64)$) appears to be the least expensive option at low energies (below $\sim 50 \text{ MV}$). This is followed by a lower number of superconducting magnetic channels ($N = 4-16$) for the rest of the accelerator. Combining of beams may therefore be required at this transition.

Furthermore, some splitting of beams may be required after acceleration to stay within transportable current limits in the final focus system.

The rationale for the use of multiple beams is that it increases the net charge which can be accelerated by a given cross section of core at a fixed accelerating gradient. Alternatively, a given amount of charge can be accelerated more rapidly with multiple beams since the pulse length is shortened and a core cross section of specified volt-seconds per meter flux swing can supply an increased gradient. However, an increase in the number of beamlets increases the cost and dimensions of the transport lattice and also increases the cost of the core for a given volt-second product since a larger core volume is required. For a core of given cross sectional area (volt-seconds/m), the volume of ferromagnetic material increases as its inside diameter is increased. Hence there is a tradeoff between transport and acceleration costs with an optimum at some finite number of beamlets. The determination of this optimum configuration is a complex problem depending on projected costs of magnets, cores, insulators, energy storage, pulsers and fabrication. The induction linac design code LIACEP [2] is used for this purpose.

The choice of superconducting focusing magnets for the bulk of the linac is mandated by the requirement of system efficiency; this must be at least $\sim 10\%$ in an ICF driver and ideally $> 20\%$ to avoid large circulating power fractions, which result in a high cost of electricity (COE). Induction cores are most likely to be constructed from thin laminations of amorphous iron, which is the preferred material due to its excellent electrical characteristics and flux swing. At a projected cost of $\sim \$4/\text{lb}$ (insulated and wound) this is a major cost item for the first 2-4 GeV of a typical linac. At higher voltage the price of pulsers and fabrication of the high gradient column with insulators dominate the cost.

Heavy Ion Fusion Systems Assessment Study

The Heavy Ion Fusion Systems Assessment (HIFSA) study [3] was conducted during 1984-86 with the specific objective of evaluating the prospects of using induction linac drivers to generate economical electrical power from inertial confinement fusion. Principal contributors were LBL, LLNL, LANL, McDonald-Douglas Astronautics Co., U. of Wisconsin, the U.S. Department of Energy and EPRI. The study used algorithmic methods of representative components of a fusion system to identify favored areas in the multidimensional parameter space. The resulting cost-of-electricity projections are comparable to those from other (magnetic) fusion scenarios, at a plant size of 1000 MWe. These results hold over a large area of parameter space, but depend especially on making large savings in the cost of the accelerator by using ions with charge-to-mass ratio about three times higher than has been usually assumed. The feasibility of actually realizing such savings has been shown: (1) by experiments showing better-than-previously-assumed transport stability for space charge dominated beams, and (2) by theoretical predictions that the final transport to the target pellet in the expected environment of a reactor chamber, may be sufficiently resistant to streaming instabilities. Neutralization in the chamber is required for the higher current pulses that result from the use of the higher charge-to-mass ratio beams.

The HIFSA study was organized to deal with the specific premise that fusion in general, and the HIF approach to ICF in particular, appears to be so costly and requires scaling to such large power plants that it has not been possible to design a program that would be attractive to the electric utility industry. The objective of the study was to perform an assessment of heavy ion inertial fusion systems based on induction accelerators, including representative reactor systems, beam focusing and final transport, target design, and system integration. Emphasis was given to systems for electric

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power production and to design innovations and parameter ranges which offer credible promise of reducing system size and cost. Effort concentrated on system and subsystem conceptual design and analysis, including cost/performance models for studying and exhibiting major system parameter variations. Identification of needed R&D was included.

Two important computational tools were developed for the study: The linac optimization program LIACEP was extensively rewritten, and the system program ICCOMO was written to permit examination of large areas of commercial plant parameter space to find local optima.

Probably the most important technical results of the study came from re-examining previously suggested cost-saving ideas.[4] These ideas, modified by newer experimental results, make it possible to envision very significant cost reductions by (especially) using higher charge-to-mass ratios.

Some important conclusions are:

- (1) COE is insensitive to repetition rate in the optimum range 3 - 9 Hz.
- (2) Symmetrically irradiated (direct drive) targets, which may use the beam energy more efficiently, do not result in lower COE because of the increased cost of the transport system.
- (3) High-gain targets ($G > 100$) are of only moderate utility since they increase the cost of the reactor vessel and their effect can be partly realized by higher rep-rate.
- (4) Major reductions in the cost of induction linacs result from using higher charge-to-mass ratios and multiple beams.
- (5) With the higher charge to mass ratios it is certainly necessary to invoke neutralization during final transport. Work by Stroud [5] gives confidence that streaming instabilities will not destroy the emittance during transport through the target chamber.

ILSE, a Proposed Induction Linac Systems Experiment

We are proposing an experiment [6] to study the physics of acceleration, combining and focusing of ion beams at a level of current and power considerably exceeding that of our last experiment. In the preliminary design, 16 parallel beams of ions (C^{+} , Al^{+} , or Al^{++}) produced from a 2MV injector [7] will be accelerated to several MV and combined transversely. The four resulting beams are then further accelerated to ≈ 10 MV and the growth in transverse and longitudinal emittance is determined for comparison with theory. The system will then be extended with a 180° bend, followed by a drift compression section and final focus.

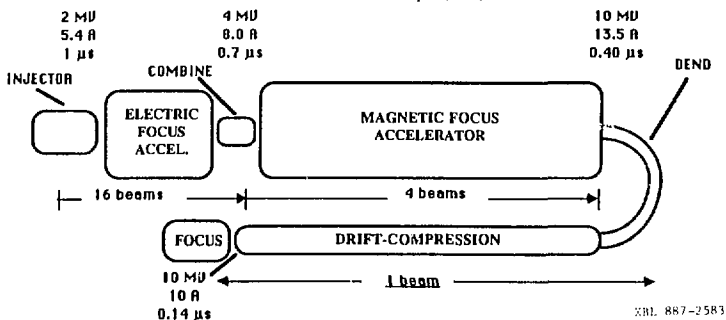
ILSE is designed to address the following physics and engineering objectives:

- (1) Examine the physics of transversely combining space-charge dominated ion beams.
- (2) Explore the transition from an electrostatic to a magnetic beam transport system.
- (3) Examine the physics of bending ion beams with intense space charge and with time dependent energy.
- (4) Study the physics of drift-compression current amplification.
- (5) Explore the focusing of intense ion beams to a 1-2 millimeter spot.

In addition, ILSE will advance the technology of heavy ion multiple-beam induction linacs much closer to that needed for a driver. Magnetic focusing elements are used after the point where beams are combined to the final focal spot. These desired features motivate the choice of 10MV of acceleration and a relatively light ion, which simulates a heavier ion at higher kinetic energy. A block diagram of a conceptual design for ILSE is presented in Fig. 1.

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Figure 1. Schematic Illustration of a future Induction Linac Systems Experiment