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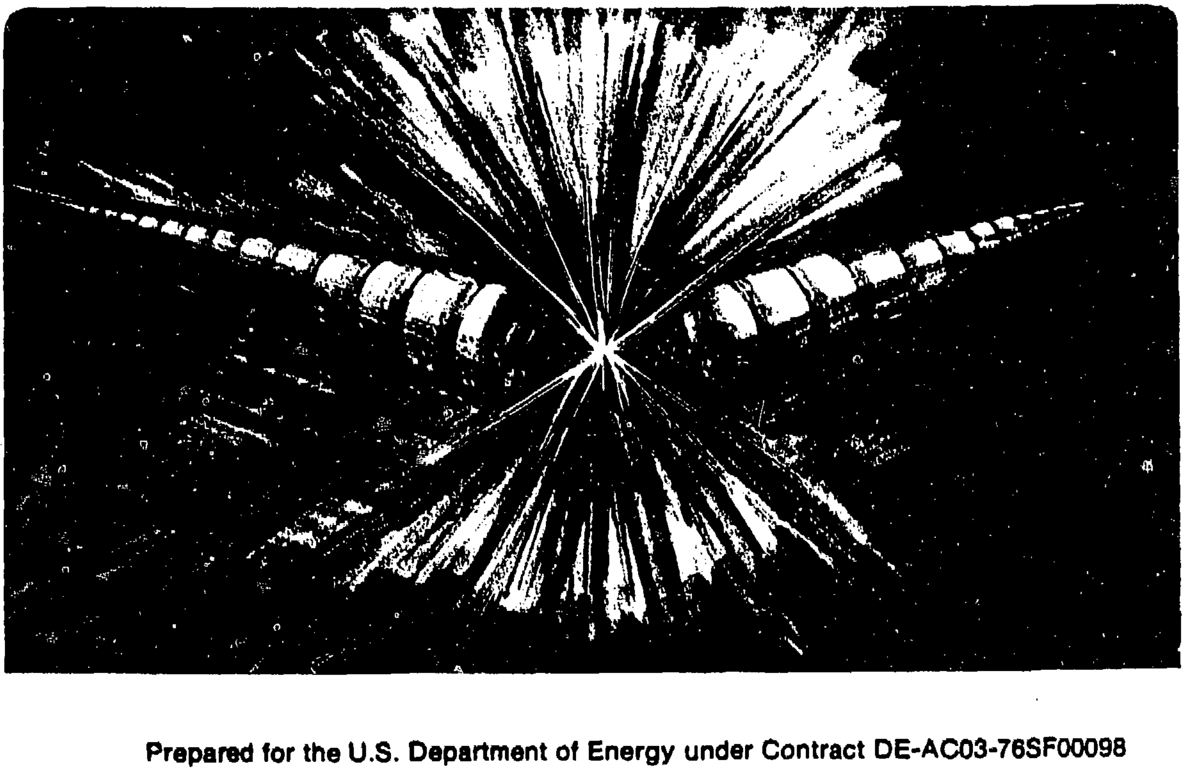

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RESEARCH IN THE U.S. ON HEAVY ION DRIVERS FOR INERTIAL CONFINEMENT FUSION

ABSTRACT

The U.S. study of high-energy multigap accelerators to produce large currents of heavy ions for inertial fusion is centered on the single-pass induction linac method. The large technology base associated with multi-gap accelerators for high-energy physics gives confidence that high efficiency, high repetition rate, and good availability can be achieved, and that the path from scientific demonstration to commercial realization can be a smooth one.

In an induction linac driver, multiple (parallel) ion beams are accelerated through a sequence of pulsed transformers. Crucial to the design is the manipulation of electric fields to amplify the beam current during acceleration.

A proof-of-principle induction linac experiment (MBE-4) is underway and has begun the first demonstration of current amplification, control of the bunch ends, and the acceleration of multiple beams.

A recently completed experiment, called the Single Beam Transport Experiment has shown that we can now count on more freedom to design an alternating-gradient quadrupole focussing channel to transport much higher ion-beam currents than formerly believed possible. This result, along with the recent development of efficient sources for multiply charged ions has rekindled interest in exploring drivers with heavy ions of charge state greater than unity. A recent Heavy Ion Fusion System Assessment (HIFSA) has shown that a substantial cost saving results from use of multiply-charged ions, and that a remarkably broad range of options exist for viable power-plant designs. The driver cost at 3-4 MJ could be 200$/joule or less, and the cost of electricity in the range of 50-55 mills/kWhr.

A next generation experiment is needed to address the questions of high-power beam transport by magnetic lenses, and of focusing the ions on a spot of order 1-2 mm radius in a stable, reproducible way.

THE INDUCTION LINAC APPROACH

Inertial confinement fusion (ICF) requires very high power irradiance, and energy deposited on the fusion target which are nearly independent of the driver type. For ions, the depth of deposition must be small (typically ~ 0.1 gm/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 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 now studied in W. Germany, USSR, and Japan, and the induction linac approach of 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 (≈ 10 GeV).

A typical set of final beam parameters suitable for a power reactor [1], is given in Table I. It must be emphasized that cost tradeoffs 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.

An induction linac driver is now envisioned as a <u>multiple beamlet</u> 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 ~ 16 - 64) appears to be the least expensive option at low energies (below ~ 50 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 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 given volt-sec product since a larger core volume is required.

For a core of given cross section ($\propto$ 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 magnets for the bulk of the linac is mandated by the requirement of system efficiency; this must be at least ~10% in an ICF driver and ideally $\gtrsim$ 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 ~4 $/lb (insulated and wound) this is a major cost item for the first 2-4 GV of a typical linac. At higher voltage the cost of pulsers and fabrication of the high gradient column with insulators dominate.

THE MULTIPLE BEAM EXPERIMENT, MBE-4

MBE-4 is a four beam induction linac under construction and preliminary operation at LBL that models much of the accelerator physics of the electrostatically focused section of a considerably longer induction accelerator [3]. Four parallel Cs^+ beams extracted from thermionic alumino-silicate sources in a 2.5 μs pulse and injected into the linac at 200 keV. Acceleration to approximately one MeV will be achieved when the experiment is complete in the summer of 1987. The current in each of the four beams will increase from 10 to 40 mA during acceleration due to both increase in beam speed and shortening of the bunch length. As a percentage of beam energy, the acceleration voltages in MBE-4 are much larger than will be used in a driver. Therefore, the consequences of errors in acceleration voltages will be more apparent and more easily assessed. Four beams are used to investigate potential effects caused by beam-beam coupling and to get practical experience in difficulties associated with accelerating and transversely controlling parallel beams. In examining the scaling with injection energy and with quadrupole size, we have been careful to preserve space charge domination of the beams both transversely and longitudinally. Measured in terms of initial bunch lengths, MBE-4 is comparable in length to the electrostatically focused portion of a driver.

The voltage waveforms on the first accelerator gaps are nearly triangular so as to impart an axial velocity shear or tilt to the beam by accelerating the tail of the beam more than the head. After the tail of the beam has entered the accelerator, the head of the beam can be accelerated as well and the waveforms on the downstream gaps can be essentially flat [4].

To date MBE-4 has accelerated four parallel space-charge-dominated cesium ion beams from 0.2 MV to .54 MV with current amplification of approximately 2.7. The experiments are in excellent agreement with our theoretical acceleration model. The acceleration schedule is one in which the current waveforms grow in amplitude and decrease in pulse duration in a self-similar or self-replicating way with acceleration distance. Aside from small fluctuations, generated by 2-3% errors in the acceleration waveforms, the experimental current waveforms are self-replicating. The acceleration errors are mostly corrected by "trim" pulsers located at every fourth accelerating gap. These are also used to control space charge spreading of the bunch ends. At large currents rapid current fluctuations are damped by space charge repulsion.

Experiments have demonstrated only a very weak transverse electrostatic repulsive interaction among the beams in the source area, which is easily corrected.

SINGLE BEAM TRANSPORT EXPERIMENT

A recently completed experiment, called the Single Beam Transport Experiment (SBTE) [5], has shown that we now can have the freedom to design an alternating-gradient quadrupole focussing channel to transport ion-beam currents much higher than formerly believed possible. SBTE employs a 10 mA, 120 keV Cs^+ beam transported by 87 electrostatic quadrupoles. In the presence of space charge, the transverse betatron oscillation frequency of a particle, ω, is lower than the value for little or no space-charge, ω_0, and is given approximately by the expression

$$\omega^2 = \omega_0^2 - \omega_p^2/2 \ ,$$

where ω_p is the beam plasma frequency. Instabilities have previously been predicted in certain ranges in (ω, ω_0) space and could result in loss of beam current or damage to the optical quality. The SBTE has established that there is significantly more latitude to choose the focussing parameters, ω and ω_0, than was previously suspected; in particular, values of ω/ω_0 as low as 0.1 can give stable transport. A beam with this low a value is "space-charge dominated", and the Debye length is very much less than the beam radius. These results from SBTE have rekindled interest in exploring drivers with heavy ions of charge state, q, greater than unity which, in general, will require operation at lower values of ω/ω_0.

HEAVY ION FUSION SYSTEMS ASSESSMENT STUDY

The Heavy Ion Fusion Systems Assessment (HIFSA) study [6] 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 models 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 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 reexamining previously suggested cost-saving ideas.[7] These ideas, modified by newer experimental results, make it possible to envision very significant cost reductions by (especially) using higher charge-to-mass ratios. Most of the study was done for $q = +3$, $A = 130$.

Some important conclusions are:

(1) COE is insensitive to repetition rate in the optimum range 3-9 pps.

(2) Symmetric 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 only of 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 [8] gives confidence that streaming instabilities will not destroy the emittance during transport through the target chamber.

ILSE: A PROPOSED INDUCTION LINAC SYSTEMS EXPERIMENT

Experiments to date, outlined above, lend confidence that several of the conditions and manipulations required in a fusion driver can be accomplished. Nonetheless, several other manipulations remain to be studied experimentally and will require ions of higher velocity. Thus we are proposing an experiment to study the physics of acceleration, combining and focusing ion beams at a level of current and power considerably exceeding that of MBE-4. In the preliminary design, 16 parallel beams of ions (C^+, Al^+, or Al^{++}) produced from a 2 MV injector [9] 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 apparatus will then be used to study the problems associated with focusing ion beams to a small spot. 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 10 MV of acceleration and a relatively light ion, which simulate 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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TABLE I

Example Driver Parameters

Pulse Energy	5.0 MJ
Particle Energy	10 GeV
Particle Type	B_i^+ (A = 209)
Pulse Power	250 TW
Pulse Length	20 ns
Rep. Rate per Reactor	5 Hz
Number of Beams per Reactor	20
Net Pulse Charge	500 μC
Emittance (unnormalized)	3×10^{-5} m-r
Momentum Width	± 1%
Spot Radius	4 mm

LIST OF FIGURES

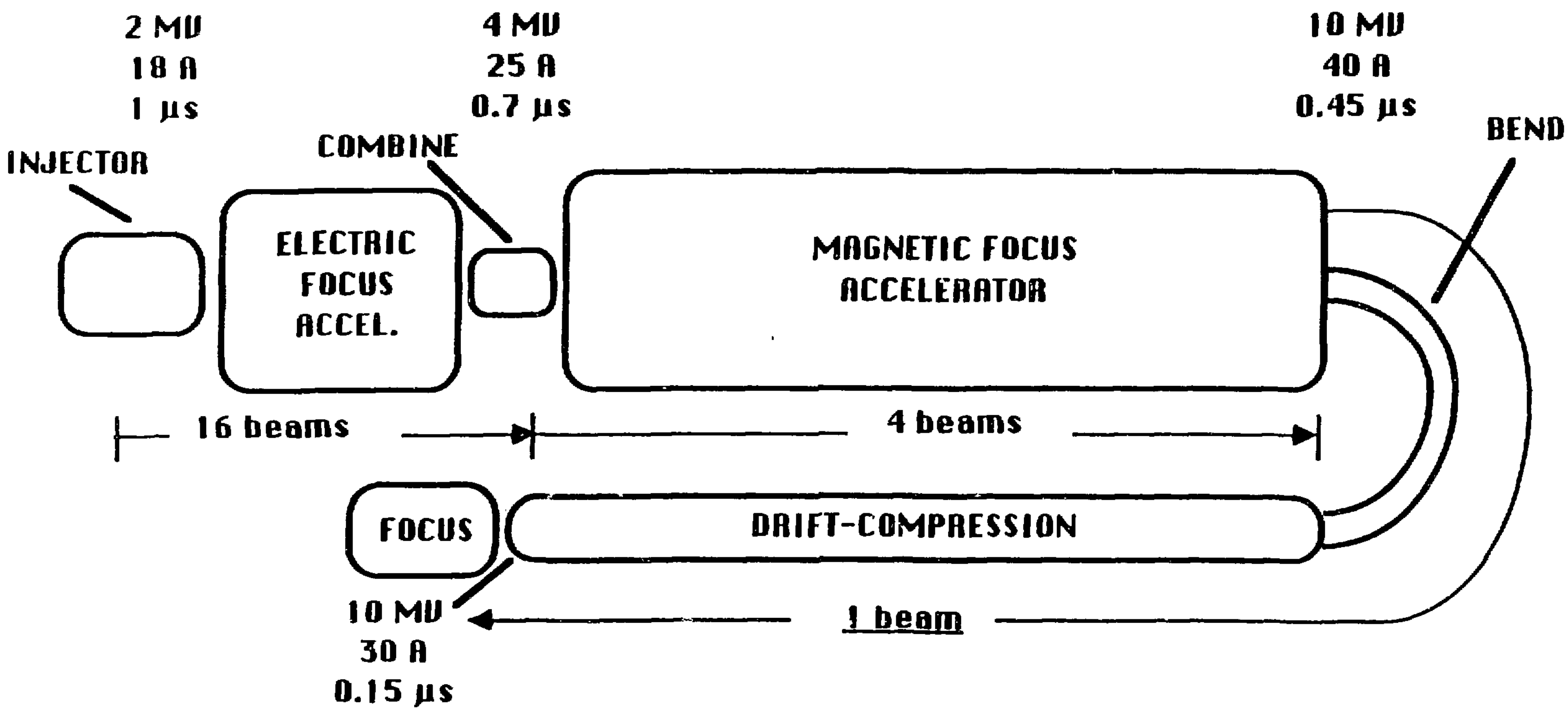

FIG. 1 Schematic of a future Induction Linac Systems Experiment