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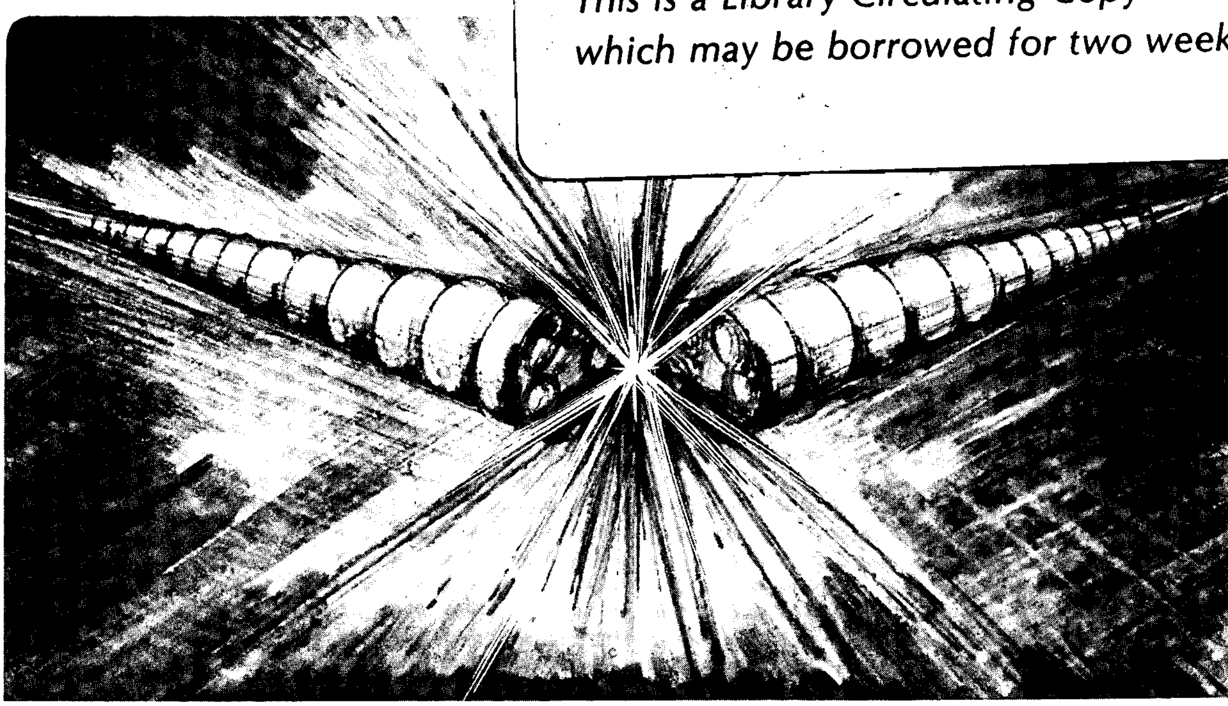

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HEAVY ION DRIVER TECHNOLOGY*

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ABSTRACT

The starting point for the examination of accelerator drivers using beams of heavy ions ($A \approx 200$) to drive the implosion of D-T pellets was the desire to develop a driver suitable for the production of electricity for civilian purposes by Inertial Confinement Fusion (ICF). The desired range of an ion beam in matter for ICF purposes is 0.1 gm/cm^2 (within a factor of two, either way), which requires an energy of 10 MeV for light ions or 10 GeV for heavy ions. Correspondingly, there is a factor of 1000 decrease in beam current on-target for heavy versus light ions.

Ion beams of 10 GeV can be produced in a multi-gap accelerator based on the accelerator technology that has been widely developed for research in high-energy and nuclear physics. Such an approach has the advantages of repetition rate, efficiency, reliability, and attainment of a long stand-off distance between the final lens and the pellet.

Major differences between fusion drivers and traditional accelerators include the following. The final beam current needed (~ 20 kA in a short pulse) is very much larger for a driver; such beams are dominated by repulsive space-charge effects since, even at 10 GeV, the ions are non-relativistic ($v/c = 0.3$). Also, the optical quality of the beams (called emittance by accelerator people) must be extremely good to ensure a suitably small focal spot at the pellet.

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Two schemes, one with a rf linac and storage rings, the other with a single-pass current-amplifying induction linac, are under study, the latter exclusively in the U.S. The induction linac approach lends itself to an examination in a sequence of scaled-down laboratory experiments since the most difficulties are expected to occur at the low energy end. Experiments and simulation have centered on a study of the transverse and longitudinal control of space-charge-dominated beams which are best described in terms of a non-neutral plasma rather than the traditional single-particle dynamics picture. An understanding of the high-current instability limits is required for arriving at a safe driver design.

The final on-target beam current is so high that it must be carried in 16 separate focussing channels leading into the combustion chamber. While the energy deposition of the ions is expected to be entirely classical, there is a wealth of plasma physics phenomena to be explored (by theory and simulation) in the final propagation of these beams through the low-density gas in the chamber and in the environment of the hot target; it is important that none of these could result in a significant portion of the beam missing the focal spot.

1. INTRODUCTION

The use of particle beams to supply the energy (~ 3-5 MJ) and irradiance (~ 1000 TW/cm^2) to the ICF capsule has taken two directions — light-ion drivers and heavy-ion drivers. Inspection of the range-energy curves (Fig. 1) shows that for the required range (0.1 - 0.2 gm/cm^2) a proton energy of 5-10 MeV is needed; generating huge currents of protons (50 mA) with single-gap pulse-power diodes was the approach taken by the Sandia (Albuquerque) laboratory in 1979. Improvements in pulse-power techniques that allow higher single-gap voltages (~ 30 MeV) have allowed that group to select lithium ions in recent years. The light-ion research with PBFA-2 is a major effort directed toward achieving the high-temperature conditions needed for fusion. In contrast, the research on heavy ion beams is a very much smaller effort and is directed almost entirely toward establishing the feasibility of a driver that would be most suitable for civilian power.

To achieve the same range in the fusion target a heavy ion ($A \approx 200$) must have a kinetic energy in the region of 10 GeV -- more than a thousand times that for a proton of the same range (see Fig. 1). For a given pulse length (10-20 nsec) the particle beam current can therefore be less by a corresponding factor. Also, damaging collective phenomena tend to scale with the ratio (Current/Mass) so that an additional factor of ~ 100 due to the mass also works in favor of heavy ions. Nonetheless, the particle beam current needed at the target is very large -- 20 kA for ions with charge-state, q, of unity --

compared with standard accelerator experience. The question of handling very high beam-currents and, at the same time, maintaining high-optical quality on the target -- have been, and remain, central to the heavy-ion fusion accelerator research (HIFAR) efforts. (In accelerator parlance, good optical quality corresponds to low beam emittance; emittance being measured by the product of the transverse size of the beam and the maximum transverse velocity components of the particles).

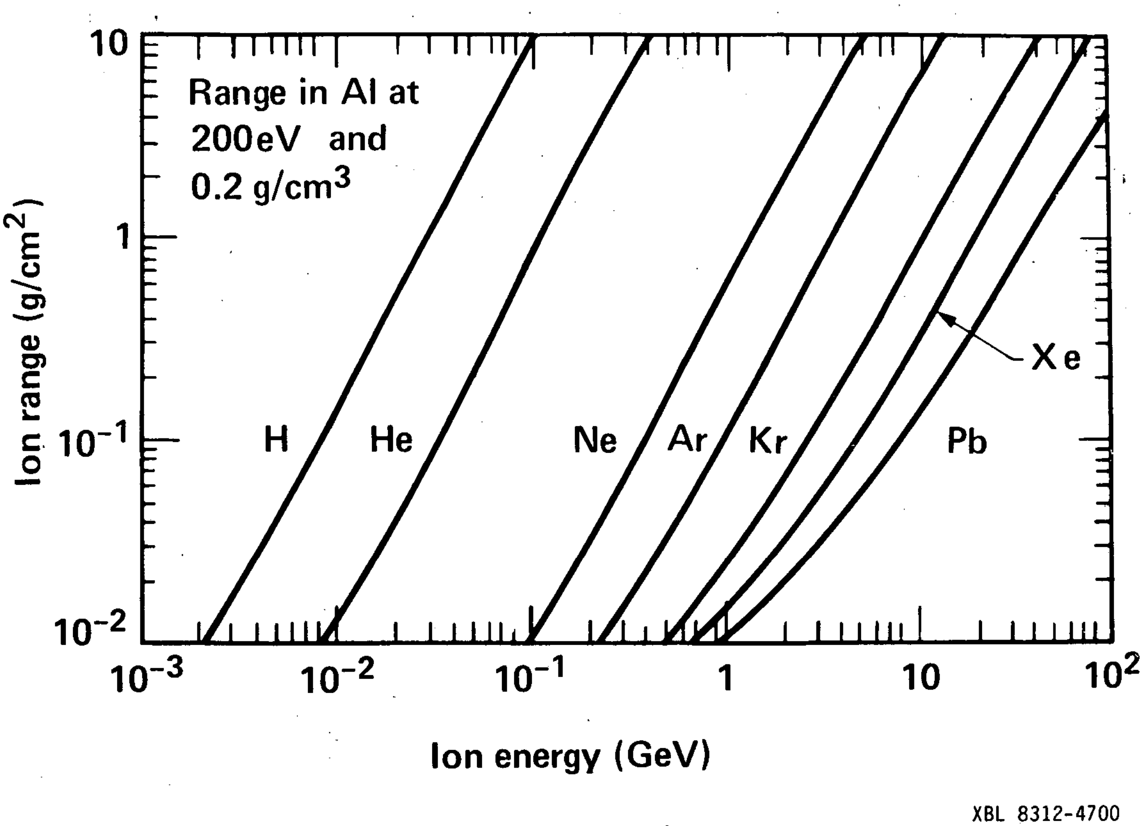

Figure 1: The range-energy relation for several ion species in hot matter (200 eV). The ion range of interest for inertial fusion is about 0.1-0.2 g cm^{-2}.

A multigap accelerator for heavy ions, relying on the physics and engineering base of research accelerators, offers a unique combination of several advantages as a driver for fusion energy in the following regards:

i) Efficiency
ii) Repetition rate
iii) Reliability/Lifetime
iv) Long stand-off distance for the final focus.

2. DRIVER CONFIGURATIONS

Two generically different heavy-ion accelerator driver systems to deliver high-current beams of heavy ions (A = 200) with kinetic energy about 10 GeV are under study at present.

One example of the rf/storage ring method (HIBALL) starts with eight low-β accelerators, the beams being sequentially combined in pairs--after some stages of acceleration--to deliver a high current beam (160 mA) to the main linac (Badger et al., 1984). See Figure 2a. In an r.f. linac, the current remains constant since the length of the bunch expands in direct proportion to the speed during acceleration. When acceleration to 10 GeV is complete, the current is amplified from 160 mA in a sequence of manipulations in storage rings, including multiturn injection and bunching, to 20 kA to be delivered finally to the target in some ten to twenty separate beams.

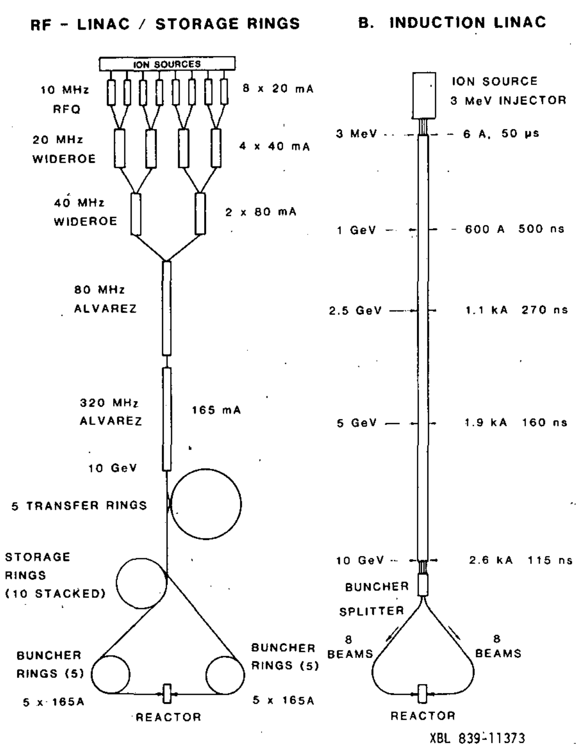

Figure 2: Schematic of two proposed accelerator driver systems: (a) The proposed 7-MJ driver for Hiball of the rf/storage-ring type. Current amplification occurs at full energy by multi-turn stacking in a cascade of rings. A final factor of ten comes from induction bunchers. (b) A single-pass four-beam induction linac (3 MJ) in which current amplification occurs continuously to keep pace with the space-charge limit.

The induction linac system, by contrast, relies on amplifying the current simultaneously with acceleration to keep pace with the kinematic change in the space-charge limit (Keefe, 1976). An induction linac consists of a sequence of ferromagnetic transformer cores each of which is driven by a small pulse-power circuit. Each is excited just as the beam pulse arrives and turned off as soon as the beam has passed by. Figure 2b shows an example for a singly-charged ion with A = 200 which employs four beams in the accelerator, each of which is split into four at the end to form the 16 beams delivered to the target (Faltens et al., 1981). It is sometimes convenient to think of sixteen beams accelerated from source to target in the same structure with independent transport systems; this approach would represent the simplest single-pass system.

While a knowledge of the space-charge limit for beam current (preserving good emittance) is crucial in the design of just the low-β parts of the rf/storage ring system, it is clearly central to the design of the induction linac at every point along its length. This subject has therefore been a major research topic, theoretically and experimentally, in the heavy ion fusion program for several years, and is addressed more extensively in Section 4.

The importance of obtaining high current can be illustrated as follows. The target requirements set, the kinetic energy (i.e. range) of the ion -- say, 10 GeV -- and also the total beam energy -- say, W = 3 MJ. Thus the amount of beam charge (for singly-charged ions) is determined as 3 MJ/10 GeV = 300 microcoulombs. In supplying the 3 MJ over the length of the accelerator it is advantageous to supply as much energy as one can at each gap in the multi-gap structure. If the voltage added per gap is ΔV, the energy added per gap is $\Delta W = I\tau\Delta V$. The product $\tau\Delta V$ is simply the volt-seconds product of the induction core supplying the voltage increment, and is related to the volume and hence the cost of the unit. Therefore, maximizing the current, I, at each accelerating station can result in lower core cost. In addition a large beam current can heavily load the driving circuitry and lead to high electrical efficiency.

3. THE CURRENT-AMPLIFYING INDUCTION LINAC

The basic idea of a heavy-ion induction linac using current amplification is to inject a long beam bunch (ten or more meters in length, several microseconds in duration) and to arrange for the inductive accelerating fields to supply a velocity shear so that, as the bunch passes any point along the accelerator, the bunch tail is moving faster than the head. As a consequence, the bunch duration (and usually, but not necessarily, the spatial length) will decrease, and the current will be amplified from amperes at injection to kiloamperes at the end of the driver (10 GeV). The current is further amplified by a factor of about 10, and the pulse duration shortened correspondingly to about 10 nanoseconds, by beam bunching in the drift section between the accelerator exit and the final focussing lenses. Disruptive transverse space-charge forces are large enough that some sixteen separate beams are needed to handle the ions in the drift-compression and focus sections. In the drift section, one is relying on the longitudinal space-charge self-force in the beam bunch to slow down the faster-moving tail and speed up the slower-moving head and, thereby, to remove the velocity shear so that chromatic aberration does not spoil the final focussing conditions.

Below, we discuss first, experiments addressing the key question of the limits set by space-charge on the current that can be transported without emittance degradation and second, experiments on current amplification.

4. HIGH CURRENT BEAM BEHAVIOR AND EMITTANCE GROWTH

4.1 The Single Beam Transport Experiment (SBTE)

The Single Beam Transport Experiment (SBTE) is the most extensive experiment of its kind on the propagation of space-charge-dominated ion beams in a long quadrupole-focussed transport channel (see Fig. 3). It consists of 87 alternating-gradient (AG)

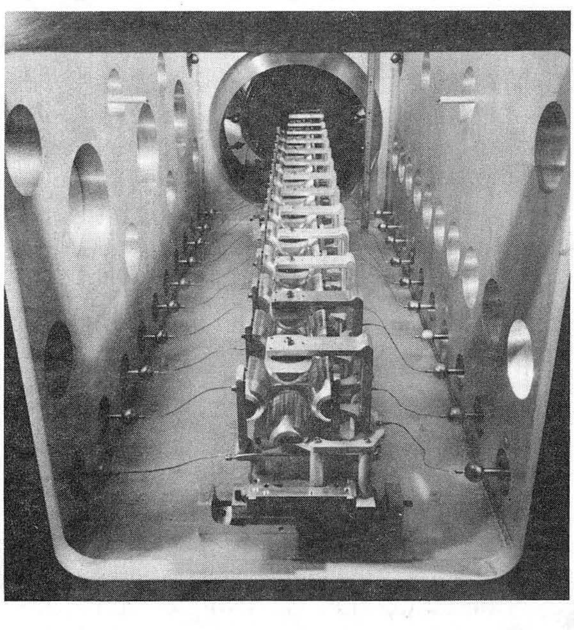

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Figure 3: Photograph of SBTE apparatus, showing 12 of the 87 quadrupole lenses.

electrostatic quadrupoles -- this is about one-tenth of the number of lenses needed in a driver. A beam of cesium ions is supplied from a hot zeolite emitter and injected into the channel from an injector which can be varied in voltage from 120 to 200 kV. Both the beam current and the beam emittance can be independently varied at the injector to study beam behavior for a variety of conditions. Empirically, the propagation is judged "stable" if both the beam current and the beam emittance are the same at the end of the channel as at the beginning.

Conditions are set up in a matching section (5 lenses) to ensure a "matched" beam, i.e., one in which the envelope pattern is identical in each lattice period.

A single-particle, alone or in a low-current beam, transported in an AG channel undergoes quasi-sinusoidal oscillations (betatron oscillations) with a phase-advance of σ_0 per repeat length of the lattice (see Fig. 4). In a high-current beam, however, the repulsive space charge self fields weaken the restoring force and the oscillations of a single particle are slowed, leading to a lower phase advance per lattice period, σ.

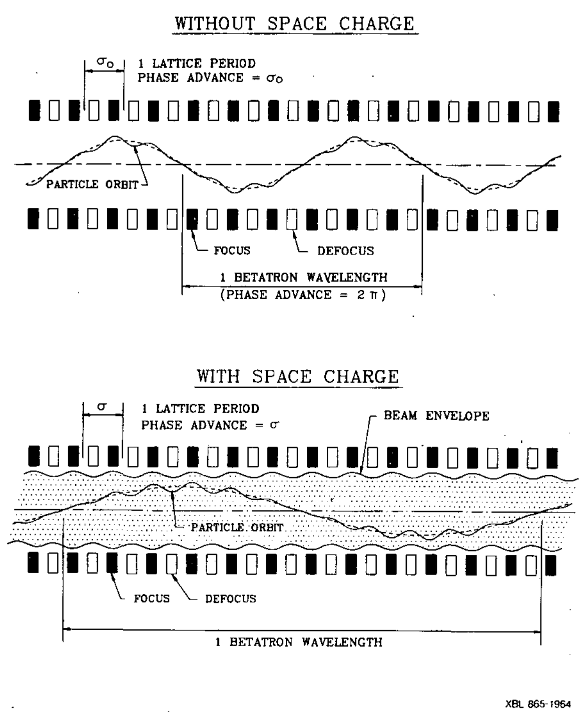

Figure 4: In a strong-focussing lattice (alternating focussing and defocussing quadrupoles) a single particle executes quasi-sinusoidal betatron oscillations (upper). Its motion is characterized by the phase advance of the sinusoid per repeat length of the structure, σ_0. With space-charge present -- a defocussing force -- the phase advance, σ, (or oscillation frequency) is decreased (lower).

The results are shown in Fig. 5; at the highest currents and lowest emittance values obtainable from the 120-200 kV cesium injector, no growth in emittance or loss in current were observed in the transport channel provided σ_0 did not exceed 88° (Tiefenback &

Keefe, 1985; Tiefenback, 1986). A threshold value of current above which emittance growth occurs could, however, be measured for values of σ_0 in excess of 88^o. Since the transportable current is greatest for $\sigma_0 < 88^o$, the design of drivers will be restricted to σ_0 values in this range.

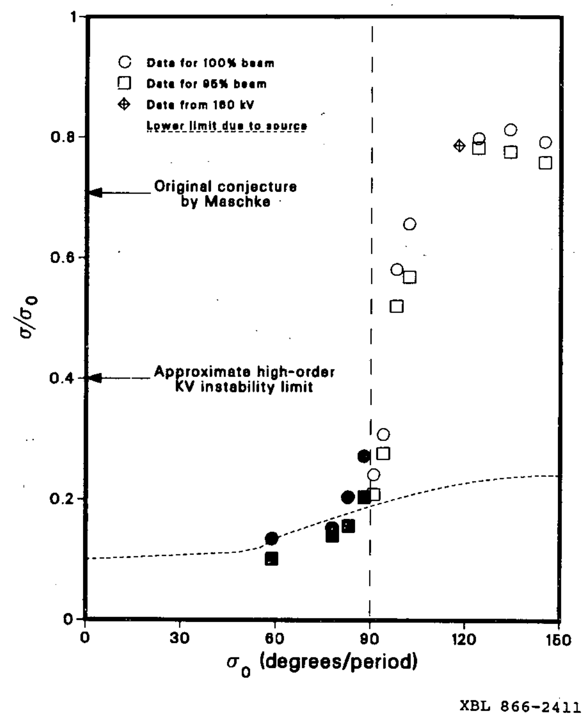

Figure 5: Results from the Single Beam Transport Experiment. The solid data points are for cases where no emittance growth or current loss could be detected. The dashed curve indicates the lower limit on σ/σ_0 that could be reached because of ion-source limitations. Above $\sigma_0 = 88^o$, emittance growth and current loss can be avoided only for values of σ/σ_0 lying above the open data points.

Earlier theoretical work on beam current limits in AG focussing systems utilizing an idealized distribution (the Kapchinskij-Vladimirskij or K-V) indicated that it could be dangerous to use σ_0 greater than 60^o, and that σ could probably be depressed from that value down to 24^o, but not below (Hofmann et al., 1983). The experimental limits from SBTE shown in Table 1 can be seen to be much more encouraging.

Table 1 - Experimental Limits on σ_0, σ.

	K-V prediction	Measured		
σ_0	$\leq 60^o$	60^o	78^o	83^o
σ	$\geq 24^o$	$< 7^o$	$< 11^o$	$< 15^o$

In his original consideration of high current limits in magnetic AG systems Maschke (1975) showed that the limiting particle current could be written (nonrelativistically) as:

$$I_p = K\,(\eta B)^{2/3}\,(\varepsilon_N)^{2/3} V^{5/6}/q^{1/2}A^{1/2}\ , \qquad (1)$$

with B the limiting pole-tip field, η the fraction of length occupied by magnetic lenses, qV the ion kinetic energy, ε_N the normalized emittance, and A,q, the ion mass and charge state respectively. It is useful to use the "smooth approximation" (Reiser, 1978) to write the explicit dependence of K on σ_o and σ (for small σ/σ_o), viz:

$$K \propto \sigma_o^{2/3}/(\sigma/\sigma_o)^{2/3} \qquad (2)$$

The coefficient, K, originally selected by Maschke was for an implicit conjecture that σ/σ_o could not be less than 0.7. The fact that we can use a somewhat higher value of σ_o and a very much lower value for (σ/σ_o) than thought possible a few years ago has led to reduced capital cost and increased electrical efficiency for heavy ion driver designs.

4.2 Multiple-beam Experiments

Assembly of a limited proof-of-principle experiment, called MBE-4, has been completed at Berkeley. (See Fig. 6). The aim is to prove the principle of current amplification while keeping the longitudinal and transverse beam dynamics under control (i.e. adequately small emittance) and, in addition, to face the additional complication of handling multiple beams (four in MBE-4). Four surface-ionization sources supply 20 mA apiece of cesium ions at 200 kV. The apparatus has 24 accelerating gaps and has achieved a peak current-amplification of a factor of nine. For comparison, in the few-thousand-meter length of a driver accelerator the current-amplification factor needed is about two hundred.

The transverse dynamics in MBE-4 is space-charge-dominated in that the betatron phase-advance per focussing-lattice period for each beam is strongly depressed -- from $\sigma_o = 60^o$ down to about $\sigma \sim 12^o$. New issues in transverse dynamics, other than those studied in SBTE, arise in MBE-4 because of (a) the difference in velocity along the bunch as it passes through a given lens, which results in values for σ_o and σ that vary along the bunch length, and (b) the discrete accelerating kicks which can cause envelope-mismatch oscillations.

For the longitudinal dynamics, two separate features arise in MBE-4. Space-charge effects throughout the body of each long bunch (about 100 cm long and 1 cm radius) are strong enough that the dynamical response to velocity kicks or acceleration errors is described in terms of space-charge (Langmuir) waves rather than in single-particle terms. Secondly, the tapered charge density that occurs at the ends of the bunch will result in collective forces that are accelerating at the head and decelerating at the tail and, if not counteracted, will make the ends of the bunch spread both in length and in momentum. A major part of the experimental effort is centered on designing and successfully deploying the electrical pulsers to handle the correcting fields at the bunch ends.

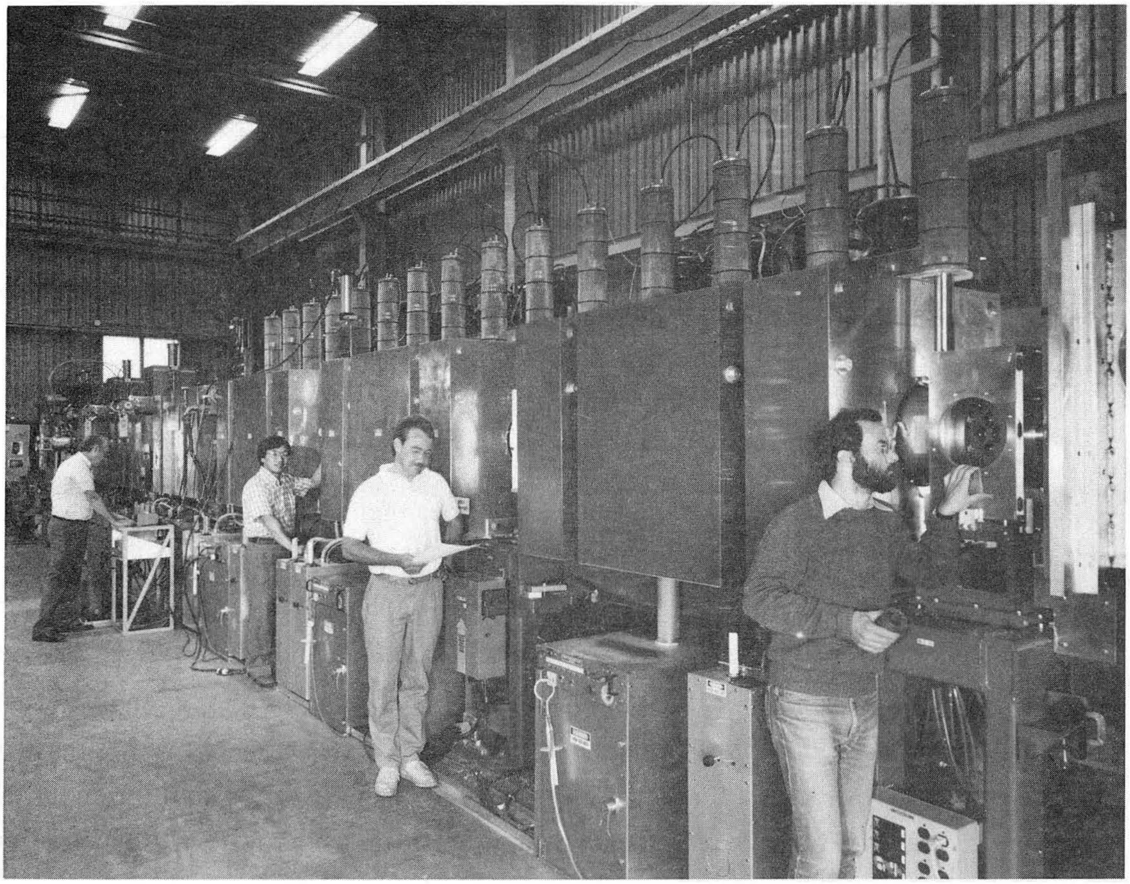

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Figure 6: The recently completed MBE-4 apparatus; the induction cores are housed in the square boxes.

Finally, the very complicated-question of coupling between the transverse and longitudinal dynamics may emerge as a key topic for study.

The oscillograms in Fig. 7 show an example of current amplification results. It can be seen that the pulse duration has been shortened by a factor of nine and the current correspondingly increased. Because MBE-4 operates at relatively low energy (accelerating from 200 keV to 1 MeV), we have been able to try rather aggressive schedules for current amplification, which correspond to setting up a large velocity shear, $\Delta\beta/\beta$. We do not have a precise argument for exactly how large a velocity-shear may be and still be considered tolerable. An experiment with $\Delta\beta/\beta = 0.4$ has been completed; this is much more than will be needed in a driver.

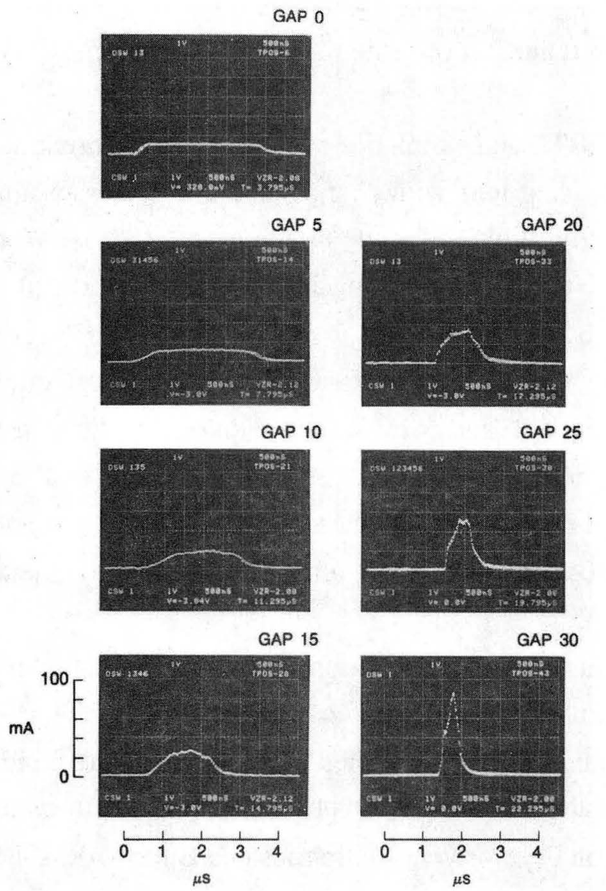

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Figure 7: Oscillograms for one of the beams in MBE-4 show the injected current trace (lowest amplitude, longest duration) and the amplified current traces after 4, 8, 12, 16, 20 and 24 accelerating units.

5. NEW CONSIDERATIONS FOR DRIVER DESIGN

Much of the early design work for induction linac drivers was restricted to considering that (a) ions with charge state q =1 were most suitable and (b) $\sigma/\sigma_0 = 24^o/60^o = 0.4$ was a limiting value. The driver design program, LIACEP (Faltens et al., 1979) did, however, indicate that capital savings could ensue if either condition could be relaxed, but at the cost of additional complications -- as perceived then -- namely:

i) Reduced particle beam current at any point (V) in the driver (see Eq. 1 for q-dependence)

ii) Generating ions with $q > 1$, which was visualized to be done by stripping a beam with $q = 1$ at some intermediate energy.

iii) An increased number of beam lines in the drift-compression section.

The results from SBTE and simulations have altered our thinking and encouraged us to re-open the matter of using ions with charge state $q > 1$. As an illustration, imagine that (σ/σ_0) has no lower limit; then, by going up in charge state, q, we can maintain the same particle current (Eqs. 1 and 2) by choosing a lower value for (σ/σ_0). Now the total voltage of the accelerator can be cut from 10 GV (for $q = 1$) to $(10/q)$ GV, resulting in a shorter and less expensive driver. This argument alone would suggest selecting the highest possible charge state to minimize size and cost. A limitation occurs, however, beyond $q = 3$ (for $A = 200$) because the increased space-charge problems in the final drift lines rise as q^2. A larger number of final beam lines will then be needed, and their added cost overrides the cost reduction in the accelerator. This argument is given in more detail by Lee (1986).

It now appears that the direct generation of adequately high currents of ions with $q > 1$ from a source is possible as a result of work by Brown with the MEVVA source (Brown, 1986). Using a similar source, Humphries has shown how to avoid plasma pre-fill of the extraction region, and thus has solved the problem of rapid turn-on of the source (< 1 μsec) needed for an induction linac driver (Humphries and Burkhardt, 1986).

With ions of $q = 1$, the low-velocity end of the linac (< 250 MeV) represented only 10% of the cost [Faltens et al. (1981)]. With ions of $q = 3$, however, the bulk of the accelerator has been shortened from 10 GV down to 3.3 GV, and the cost of the front-end represents a much more significant fraction of the overall cost; hence, it is now receiving more design attention. With higher charge-state, we visualize a driver starting with as many as 64 beamlets up to the 250 MeV point; whereupon they are combined in sets of four to provide 16 beams that undergo the bulk of the acceleration (See Fig. 8). Before this strategy can be established as a viable one, however, the emittance growth in combining high-current beams must be understood better.

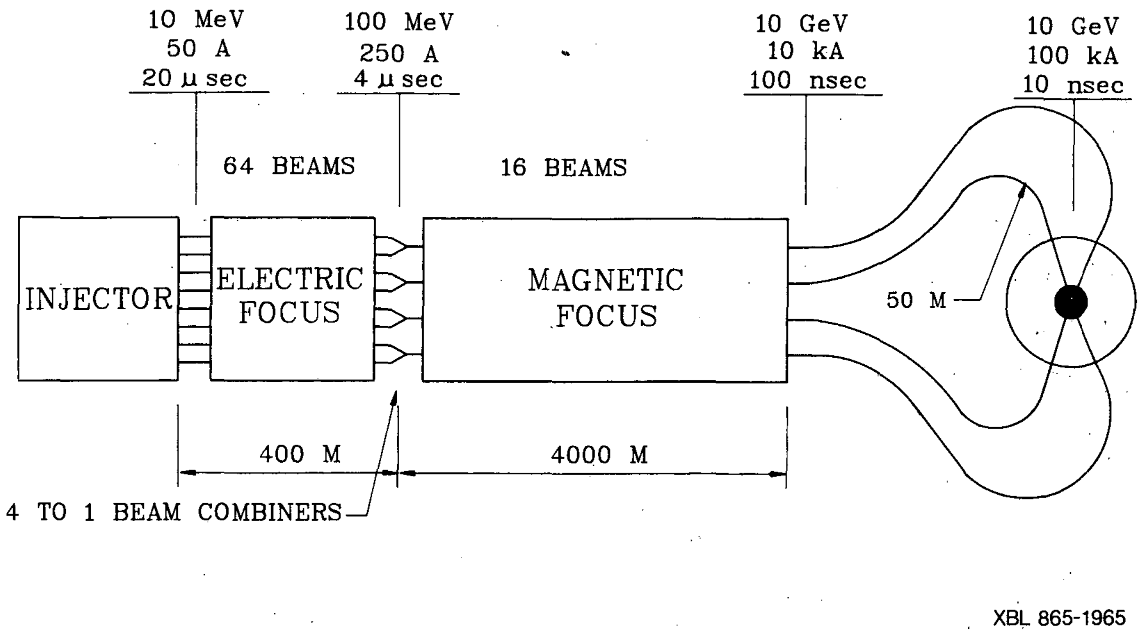

Figure 8: Schematic of present concept for a driver using ions with charge state 3. The total beam current shown is in approximate electrical (not particle) amperes.

6. THE HEAVY ION FUSION SYSTEMS STUDY (HIFSA)

The first systems assessment for a power plant based on an induction linac driver has been completed under the auspices of EPRI and the DOE Office of Program Analysis and Office of Basic Energy Sciences (Waganer et al., 1986). The major participants include McDonnell-Douglas (MDAC), LANL, LBL, and LLNL. The main emphasis as expressed in the term "Assessment" is not on developing a point-design such as HIBALL (Badger et al., 1984) but on exploring a broad range of parameters to establish general conclusions (A wide variety of point-designs can, of course, be generated from the results). An entire issue of "Fusion Technology" (February, 1988) is devoted to the results of the assessment.

Four different reactor types and five different target designs are included in the examination. The driver parameters range from a kinetic energy of 5 GeV to 20 GeV, a beam energy from 1 MJ to 10 MJ, a repetition rate of 2 Hz to 10 Hz, and result in an electrical efficiency in the range 20-40%. Results to date show that a cost of electricity of 5.5 cents kW-hr seems quite reasonable to expect for a 1000 MWe plant that uses ions with $A = 200$, $q = 3$. The familiar "economy-of-scale" effect is also apparent, with the cost of electricity being less (4.5 cents kW-hr) if a 1500 MWe plant is considered, or more (9.5 cents kW-hr) for a 500 MWe plant. One of the more interesting results is that such values of electric energy cost can be realized for a very broad range of driver parameters and for several choices of both reactor and target designs.

7. FUTURE STUDIES

Certain manipulations will be needed in a driver that have yet to be modelled in the laboratory, both to test the beam physics realistically and to establish the technology. We have proposed incorporating several relevant experiments in a sequential way in an apparatus called ILSE. (See Fig. 9). The purposes include:

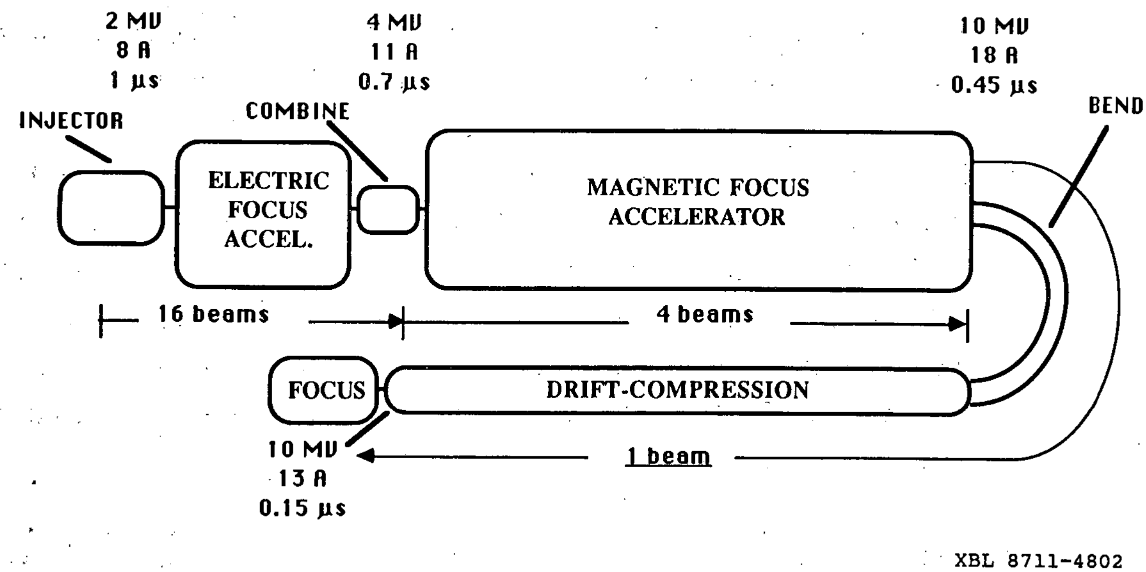

Figure 9: A schematic of ILSE. After acceleration, just one of the four beams is used for the bend, drift-compression, and focus experiments.

i) Scaling up the injector technology from the few-hundred kV level to 2 MV; also scaling up the number of multiple beams from 4 to 16. A 2 MV injector designed, and partially fabricated at LANL, is now being completed at LBL and could provide the ILSE injector.

ii) After acceleration from 2 MeV to 4 MeV, transverse stacking of the beams in sets of four to reduce the number of beams from 16 to 4. Such a manipulation is well-known to result in an increase in emittance by just over a factor of two for low-current beams. It has been recognized in the past three years that the increase can be much more for space-charge dominated beams. It is important to study the physics of this process in the laboratory to see if the actual emittance growth can be kept within tolerable limits for a driver.

iii) Magnetic focussing of the beam during acceleration from 4 MeV to 10 MeV. A light ion (carbon) has been selected for use in ILSE so that at the 4 MeV point the ion velocity is large enough that the ($\underset{\sim}{v} \times \underset{\sim}{B}$) force allows the use of reasonably-proportioned magnetic quadrupoles.

iv) Bending of one of the beams through a large angle (180^o) to model the bending that takes place between the end of a driver and the reaction chamber. Such achromatic bends are well tested and understood for low current beams but some new physics questions arise for space-charge-dominated beams.

v) Drift-compression physics. When it exits the accelerator the beam has a velocity-shear from head to tail which causes the tail to catch up with the head and bunching to occur. Because of longitudinal space-charge the head is collectively accelerated and the tail decelerated and the velocity-tilt virtually removed by the time the final focus lens is reached. While the process has been simulated with 2-1/2 D PIC codes, the physics is complicated enough that it needs exploration in the laboratory.

vi) Final beam focus to a target a few millimeters in size. The ILSE parameters should result in heating of the target to a few eV and production of plasma. There is a wide range of experiments related to propagation and focussing in a reactor that can be performed in the final focus section.

While the scale of ILSE is too small to produce a high-temperature target plasma, it can test the physics and technology of certain key driver parameters at a scale of one-tenth (or greater in some cases).

8. SUMMARY

Experimental progress to date has strengthened our belief in the soundness and attractiveness of the heavy ion method for fusion. The systems assessment has supported the view that the heavy ion approach can lead to economically attractive electric power and that a wide variety of options exists in all parameters. The systems work has also been of great help in pointing the way for future research and development activities.

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