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INDUCTION LINACS FOR HEAVY ION FUSION

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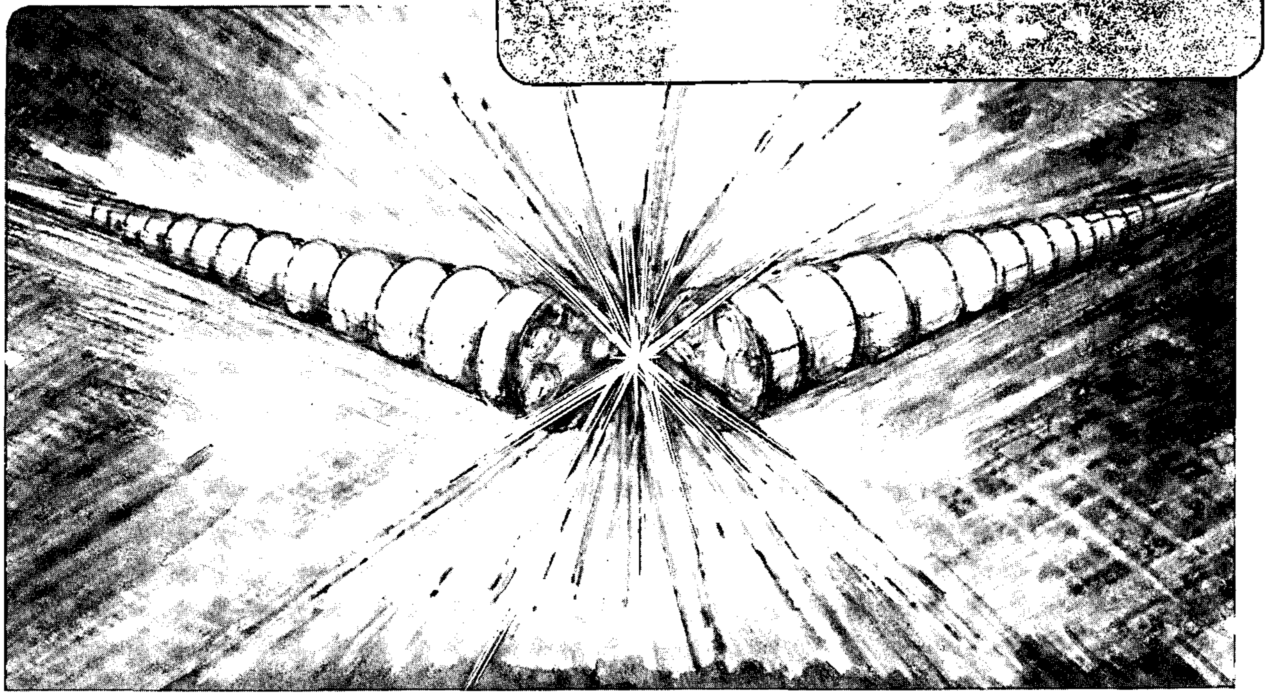

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## 1. INTRODUCTION

Inertial Confinement Fusion (ICF) is an alternative approach to magnetic Confinement Fusion for a future source of fusion electrical energy based on virtually inexhaustible fuel sources. The ICF method relies on supplying a large beam energy (3 MJ) in a short time (10 nsec) to ignite and burn a spherical capsule containing a few milligrams of deuterium and tritium; ablation of the surface--as a plasma--drives an implosion of the fuel, and leads to ignition at the center when the compression has reached an appropriate value (about 1000 times normal liquid density). The energy can be supplied directly; in that case a large number of beams must be brought in to illuminate the capsule in a spherically symmetric manner, which complicates the final focussing. Alternatively, the beam energy can be used to produce high temperature radiation which can be contained within a hohlraum to implode a separately placed capsule.

A multigap accelerator for heavy ions, relying on the physics and engineering base of research accelerators, combines several advantages as a driver for fusion energy over the other two driver candidates, laser and light ion beams, in the following regards:

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

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A discussion of target needs, reactor systems and the choice among driver systems is given by Keefe (1982).

The enormous current (20 particle-kiloamperes) that must be delivered in the final short pulse, and the preservation of a low beam emittance, are the two features that lie well beyond the experience of today's research accelerator experience.

The ion range must lie in the neighborhood of 0.1-0.2 gm $cm^{-2}$; thus the kinetic energy of a heavy ion is about 10 GeV (i.e., 50 MeV/amu) and the ion speed about 0.3 c. The focal spot at the target is about 2 mm radius at a stand-off distance of 10 m, and the normalized emittance should not exceed 20 mm-mrad. For details of the progress in studies of Heavy Ion Fusion (HIF) see the proceedings of the recent Heavy Ion Fusion Symposium in Washington, D.C., May 1986 [Bangerter et al. (1986)].

## 2. DRIVER CONFIGURATIONS

Two heavy-ion accelerator driver systems to deliver high current beams of heavy ions (A = 200) with kinetic energy about 10 GeV are shown schematically in Fig. 1.

The rf/storage ring method starts with eight low-ß 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)]. 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 finally delivered to the target in some ten to twenty separate beams.

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), Faltens et al. (1981)]. Sixteen multiple beams can be accelerated in the same structure with independent transport systems from source to target; this approach would represent the simplest single-pass system.

A knowledge of the space-charge limit for beam current is crucial in the design of just the low-ß parts of the rf/storage ring system, but is clearly central to the design of the induction linac at every point along its length.

## 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 (many 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 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 length further shortened correspondingly to about 10 nanoseconds, in the drift section between the accelerator exit and the final focussing lenses. Transverse space-charge forces are large enough that some sixteen parallel beams are needed to handle the beam in the drift-compression and focus sections. In the drift section one is relying on the longitudinal space-charge self-force in the beam to remove the velocity shear so that chromatic aberration does not spoil the final focussing conditions.

A proof-of-principle experiment, called MBE-4, is being assembled at Berkeley. The aim is to prove the principle of current amplification while keeping the longitudinal and transverse beam dynamics under control 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. When completed, the apparatus will have 24 accelerating gaps; at present, experiments are proceeding with the eight now installed.

The transverse dynamics in MBE-4 is strongly space-charge dominated in that the betatron phase-advance per focussing-lattice period for each beam is strongly depressed--from $\sigma_0 = 60°$ down to about $\sigma \sim 12°$. (See Fig. 2.) For a mono-energetic beam without acceleration the Berkeley Single Beam Transport Experiment (SBTE) (see below) has shown stable beam behavior to lower values of $\sigma$ (7° - 8°). New issues in transverse dynamics, however, 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 $\sigma_0$ and $\sigma$ that vary long 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.

Figure 3 shows an example of current amplification results obtained to date (June 1986), where it can be seen that the pulse duration has been shortened by nearly a factor of two and the current correspondingly increased [Fessenden et al. (1986)]. Because MBE-4 operates at relatively low energy (accelerating from 200 keV to 1 MeV), we can try rather aggressive schedules for current amplification, which correspond to setting up a large velocity shear, $\Delta\beta/\beta$. We do not have a firm argument for exactly how high a velocity-shear may be and still be considered tolerable. An experiment with $\Delta\beta/\beta = 0.4$ has been completed; this is more than will be needed in a driver.

## 4. HIGH CURRENT BEAM BEHAVIOR AND EMITTANCE GROWTH

### 4.1 The Single Beam Transport Experiment (SBTE)

Since the IEEE Particle Accelerator Conference in Vancouver in May 1985, the results on high-current beam transport limits [Tiefenback and Keefe (1985)] in the 87-quadrupole SBTE have been refined and more careful calibrations made. The results, shown in Fig. 4, are substantially unaltered; at the highest currents and lowest emittance values obtainable from the 120-200 kV cesium injector no detectable growth in emittance was observed in the 41-period transport section provided $\sigma_0$ did not exceed 88°. A threshold value of current above which emittance growth occurs could, however, be measured for values of $\sigma_0$ in excess of 88°. Since the transportable current is greatest for $\sigma_0 < 88°$, the design of drivers will be restricted to $\sigma_0$ values in this range. (Tiefenback (1986) has found that beyond $\sigma_0 = 88°$ the threshold corresponds rather well to the empirical condition that the beam plasma period equals the beam transit time through three lattice periods.)

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 $\sigma_o$ greater than 60°, and that $\sigma$ could probably be depressed from that value down to 24°, 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 $\sigma_o$, $\sigma$.

| $\sigma_0$ | 60° | 78° | 83° |
|---|---|---|---|
| $\sigma$ | < 7° | < 11° | < 15° |

## 4.2 Is There a Lower Limit on $\sigma_o$?

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

$$I_p = K(\eta B)^{2/3}(\varepsilon)_N{}^{2/3}V^{5/6}\Big/q^{1/2}A^{1/2}, \tag{1}$$

with B the limiting pole-tip field, $\eta$ the fraction of length occupied by magnetic lenses, qV the ion kinetic energy, and A,q, the ion mass and charge state respectively. (Two other equations, involving lattice-period and radius, must be simultaneously obeyed for Eq. (1) to hold). The coefficient, K, originally selected by Maschke was for an implicit assumption that $\sigma/\sigma_0$ could not be less than 0.7. In light of the improved knowledge from experiment and simulation it is useful to use the "smooth approximation" [Reiser (1978)] to write the explicit dependence of K on $\sigma_o$ and $\sigma$, viz:

$$K \propto \sigma_0{}^{2/3}\Big/(\sigma/\sigma_0)^{2/3} \tag{2}$$

Thus, in fact, if there were no lower bound on $\sigma/\sigma_0$ the transportable current could grow very large (the required aperture, however, would do likewise).

Just as the SBTE measurements were beginning, Hofmann and Haber, each using simulation codes for well-centered beams without images, reported that for $\sigma_0 = 60°$, $\sigma$ could be allowed to go lower than 24° without emittance growth occurring. During the course of SBTE measurements further simulations showed that values of $\sigma$ down to 1° or 2° might be alright.

Our view of the situation changed, however, with the simulation studies by Celata et al. (1985) of an off-axis beam--which corresponds to the real-world situation. For a beam with $\sigma/\sigma_0 = 6°/60°$, no growth was detected. If <u>either</u> a dodecapole component in the field <u>or</u> the effect of images in the electrodes was introduced, however, steady growth in the rms emittance accompanied by oscillations showed up clearly. When <u>both</u> images and the right amount of dodecapole component were included, however, the surprising result emerged that the emittance did not grow.

## 5. RE-DISTRIBUTION IN FIELD ENERGY IN HIGH-CURRENT LOW-EMITTANCE BEAMS

The growth in emittance due to a change in the beam distribution in configuration space alone has been a topic of much discussion in the past few years. An intense beam with a non-uniform spatial distribution will usually readjust itself in a fraction of a plasma period to an almost exactly uniform distribution. The change in electrostatic field energy is always such that energy is fed into the thermal motion of the beam particles thus causing emittance growth. For given initial and final distributions, Wangler has given a prescription for determining the amount of growth, which we can re-write in the form

$$\frac{\varepsilon_f}{\varepsilon_i} = \left(1 + \frac{1}{4} \frac{\langle x^2 \rangle}{\lambda_D^2} \frac{\Delta E}{E}\right)^{1/2}$$

where $\langle x^2 \rangle$ is the mean square radius of the beam, $\lambda_D$ is the Debye length (proportional to $\varepsilon/\sqrt{I}$), and $\Delta E/E$ is the fractional increase in electrostatic field energy as the beam relaxes from a non-uniform to a uniform shape. $\Delta E/E$ is of the order of 0.1 or less. Equation (3) is simply a statement of conservation of energy, i.e., the excess field energy shows up as increased thermal motion of the beam particles. In contrast to the case of a beam in a synchrotron, for instance, where

$\langle x^2 \rangle \ll \Delta_D^2$ and the effect is negligible, we are concerned with space-charge dominated beams with $\langle x^2 \rangle \gg \Delta_D^2$, and the effect can be quite serious.

This mechanism for emittance growth clearly can occur just after an ion source which is emitting a non-uniform beam. But it is also of importance in combining (or splitting) beams that are round or elliptical by means of a septum. Simulation results on emittance growth in the case where four beams are stacked side by side by septa to form a single larger beam were given by Celata (1986).

## 6. NEW CONSIDERATIONS FOR DRIVER DESIGN

Much of the early design work for induction linac drivers was restricted to considering that ions with charge state $q = 1$ were most suitable and, also, that $\sigma/\sigma_0 = 24°/60° = 0.4$ was an optimum 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, namely:

i) Reduced current at any point (V) in the driver (see Eq. 1)
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, consider the reference case given in 1981 for V = 10 GV, $q = 1$. (See Fig. 1). We could build only the first 5 GV part and use charge state $q = 2$ to give the same final kinetic energy, 10 GeV. We could still maintain the same particle current at each voltage point provided the product $q^{1/2}(\sigma/\sigma_0)^{2/3}$ is kept constant, i.e., $\sigma/\sigma_0 \propto q^{-3/4}$. (This can be seen from Eqs. (1) and (2)). Since we know that very low values are permitted for $\sigma/\sigma_0$, we can in principle continue this argument to higher charge states, dropping $\sigma/\sigma_0$ in value and shortening the accelerator at each step. A limitation occurs, however, beyond $q = 3$ (for $A = 200$) because the increased perveance (i.e., space-charge) in the final drift lines rises as $q^2$ and the increased cost of the very large number of final beam lines that will be needed 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 and Galvin with the MEVVA source [Brown and Galvin (1986)]. Using a similar source, Humphries (1986) 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 (1986)].

Since the SBTE has shown that $\sigma_0$ can exceed 60° safely (but not 88°), present driver designs have benefitted by using $\sigma_0 = 80°$, resulting in a somewhat greater beam current limit (see Eq. (2)).

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 $q = 3$ 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. If electrostatic lenses are used in the low velocity end, the mapping argument given earlier (for magnetic transport), from equal voltage points in a $q = 1$ to a $q > 1$ case, no longer holds unless the number of beams is increased. With higher charge-state, therefore, we visualize a driver starting with as many as 64 beamlets that undergo the bulk of the acceleration (See Fig. 5). Before this strategy can be established as a viable one, however, the emittance growth in combining high-current beams must be understood better.

## 7. THE HEAVY ION FUSION SYSTEMS STUDY (HIFSA)

The first systems assessment for a power plant based on an induction linac driver has been in progress for a year and a half under the auspices of EPRI and the DOE Office of Program Analysis and Office of Basic Energy Sciences. 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).

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 and a beam energy from 1 MJ to 10 MJ. 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.

## 8. SUMMARY

Experimental progress to date has strengthened our belief in the soundness and attractiveness of the heavy ion method for fusion. What surprises that have shown up in the laboratory (e.g., in SBTE) have all been of the pleasant kind so far.

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 the research and development activities.

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# Figure Captions

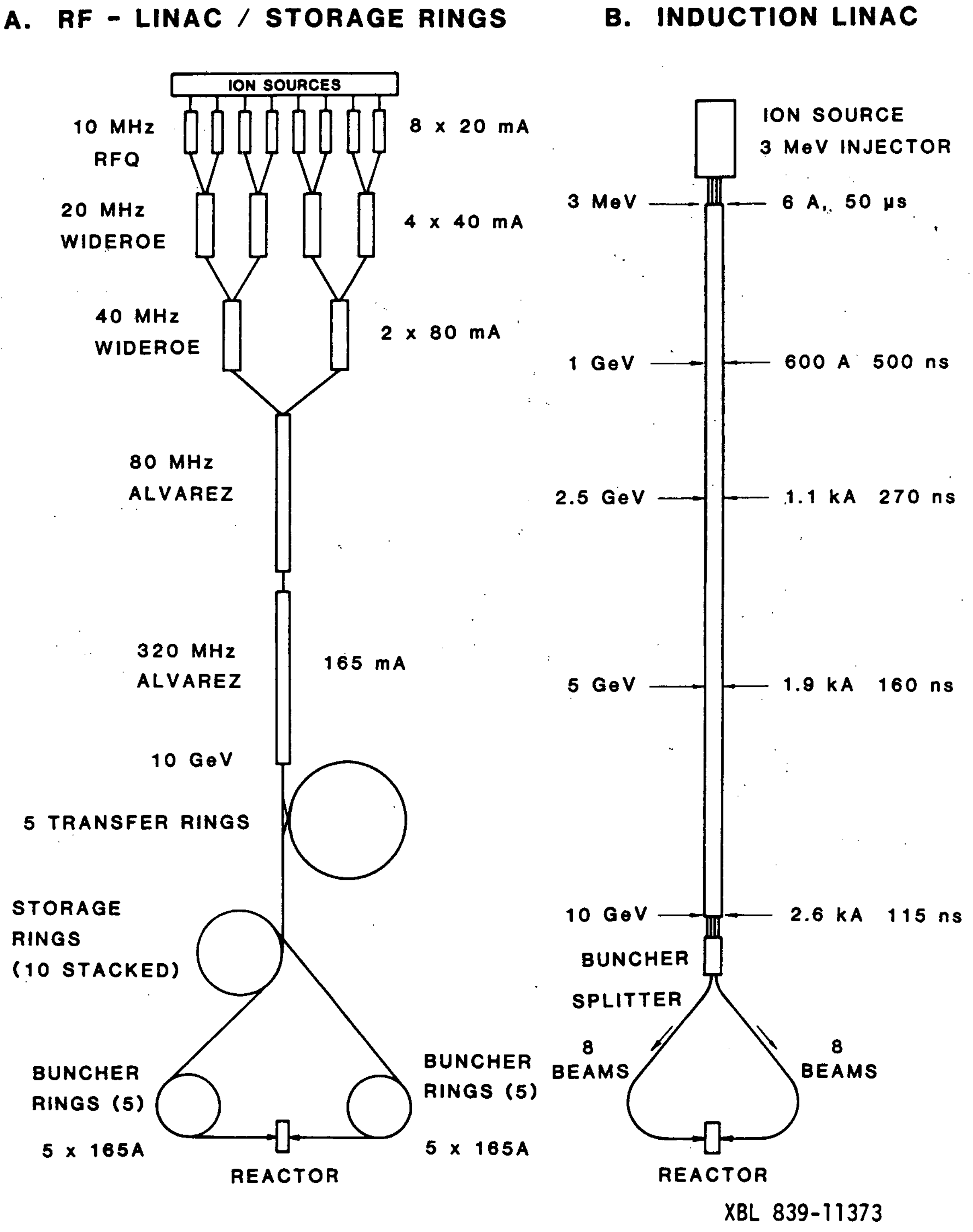
Fig. 1. Two designs for heavy-ion accelerator drivers at present under study. (a) In the rf linac scenario the current is amplified by a factor of $10^5$ in a sequence of multiple storage rings. (b) The induction linac uses current amplification during acceleration and final bunching in a transport-drift section to raise the current by a factor of 3,000.

Fig. 2. In a strong-focussing lattice (alternating focussing and defocussing quadrupoles) a single particle executes quasi-sinsusoidal betatron oscillations (upper). Its motion is characterized by the phase advance of the sinusoid per repeat length of the structure, $\sigma_0$. With space-charge present—a defocussing force—(lower) the phase advance, $\sigma$, (or oscillation frequency) is decreased.

Fig. 3. Oscillograms for all four beams in MBE-4 show the injected current traces (lower amplitude, longer duration) and the amplified current traces after eight accelerating units.

Fig. 4. Results from the Single Beam Transport Experiment. The solid data points are for cases where no emittance growth nor current loss could be detected. The dashed curve indicates the lower limit on $\sigma/\sigma_0$ that could be reached because of ion-source limitations. Above $\sigma_0 = 88°$, emittance growth and current loss can be avoided only for values of $\sigma/\sigma_0$ lying above the open data points.

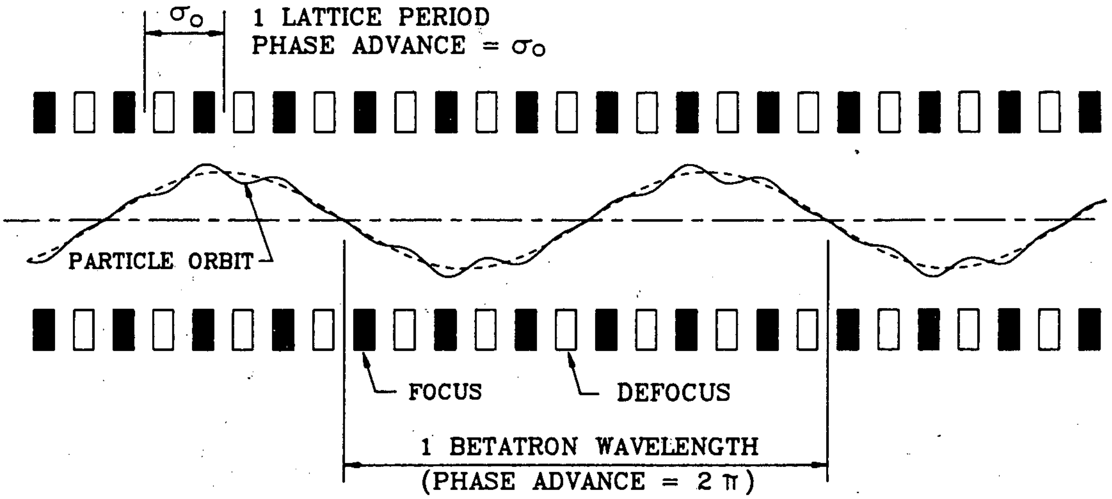
Fig. 5. Schematic of present concept for a driver using ions with charge state 3. The total beam current shown is in electrical (not particle) amperes.


A. RF - LINAC / STORAGE RINGS

B. INDUCTION LINAC

Figure 1

WITHOUT SPACE CHARGE



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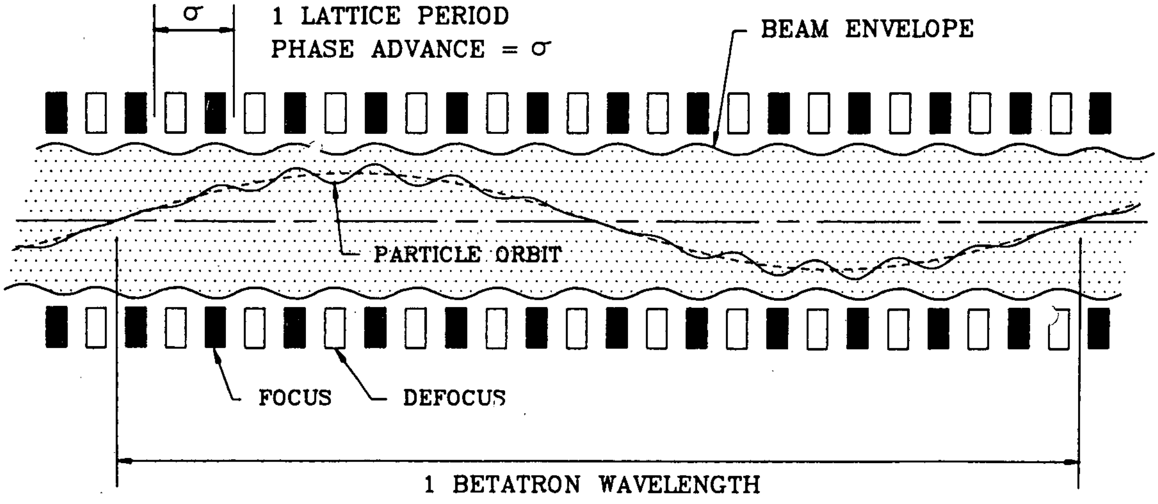

Figure 2

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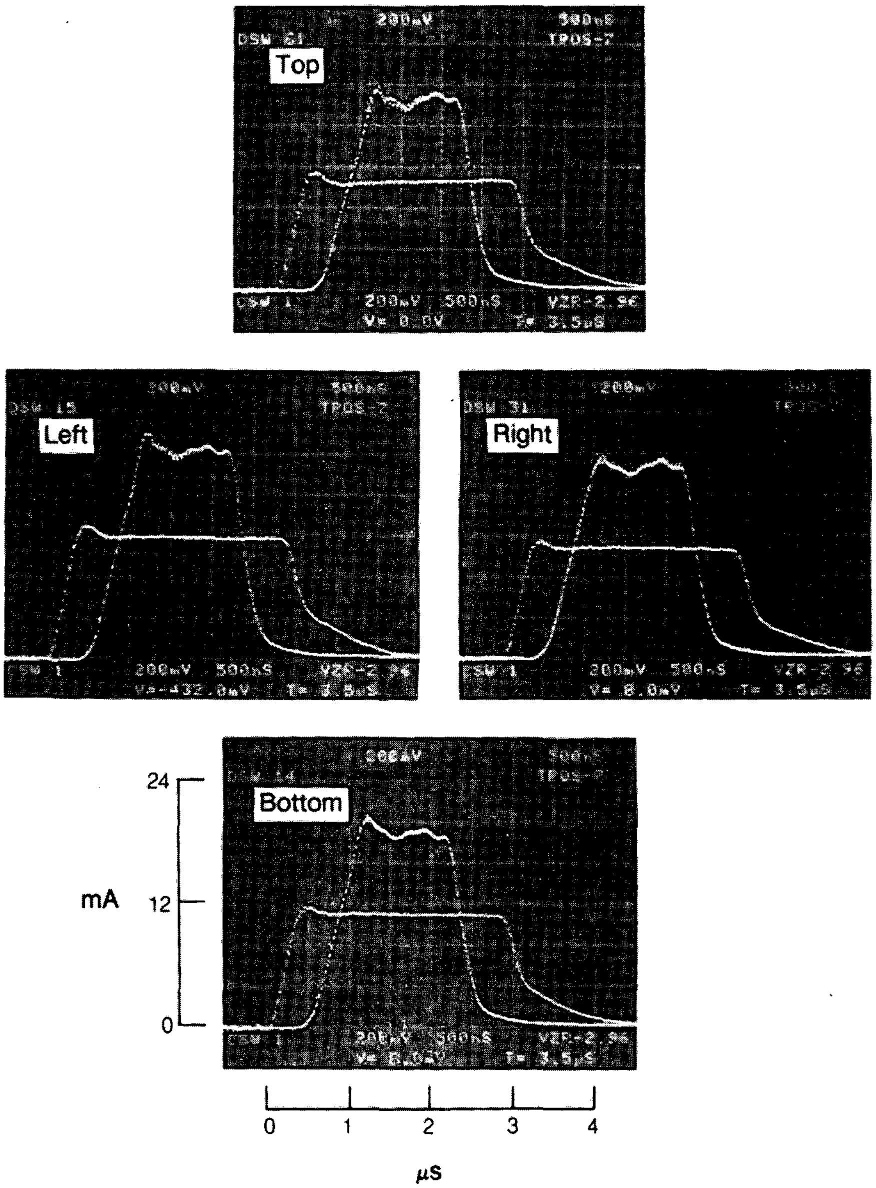

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Figure 3

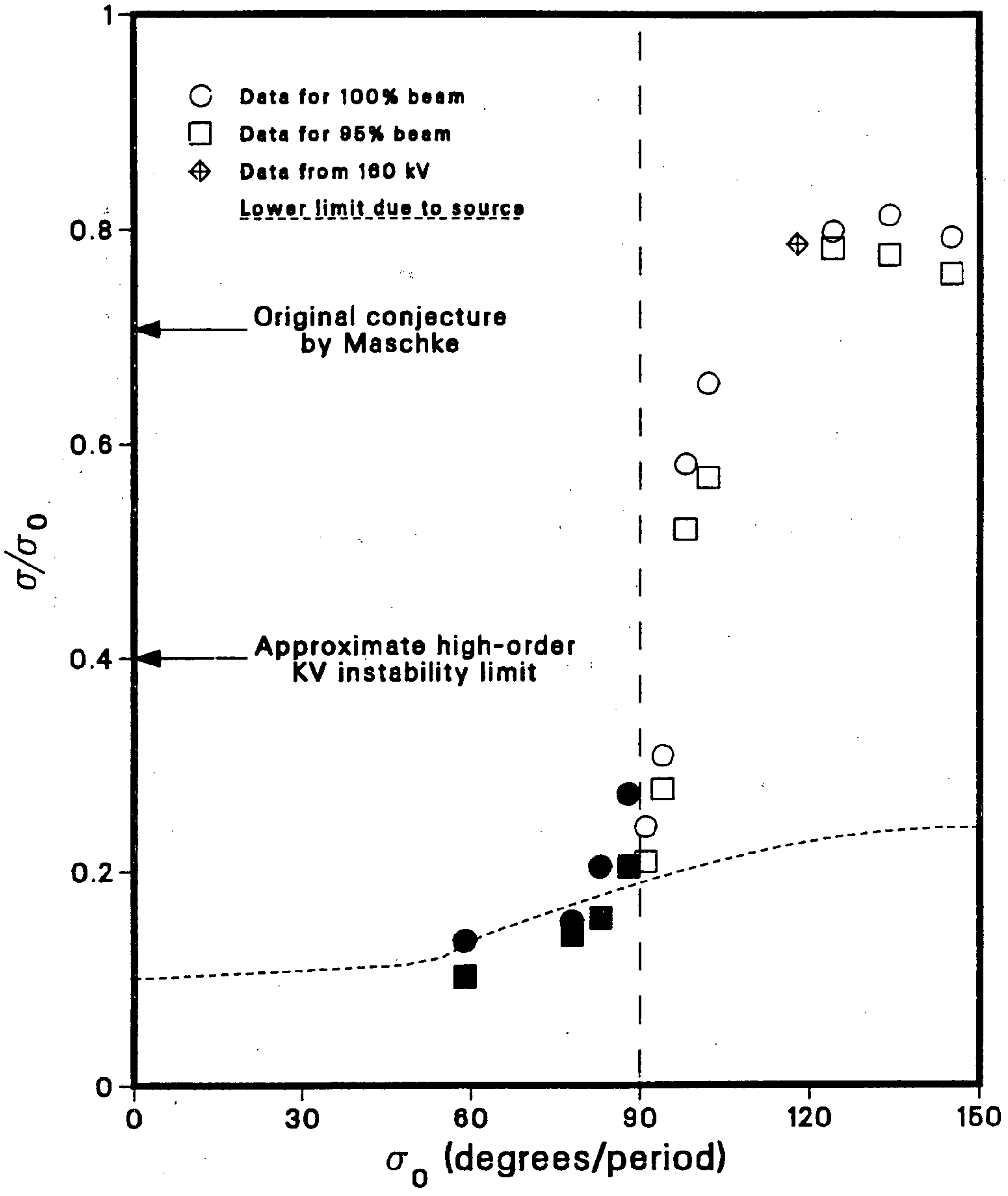

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Figure 4

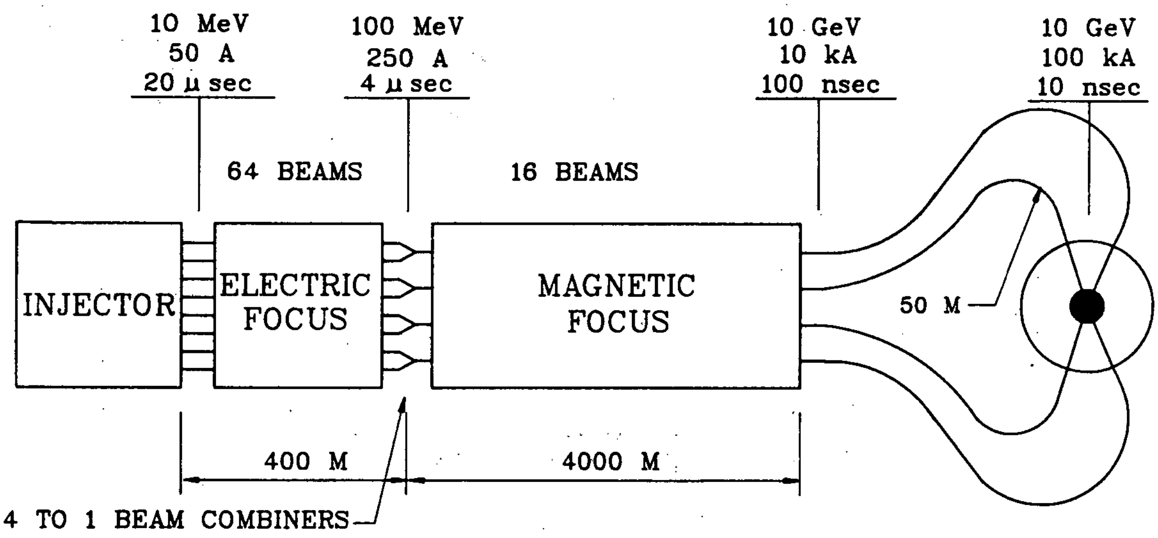

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Figure 5