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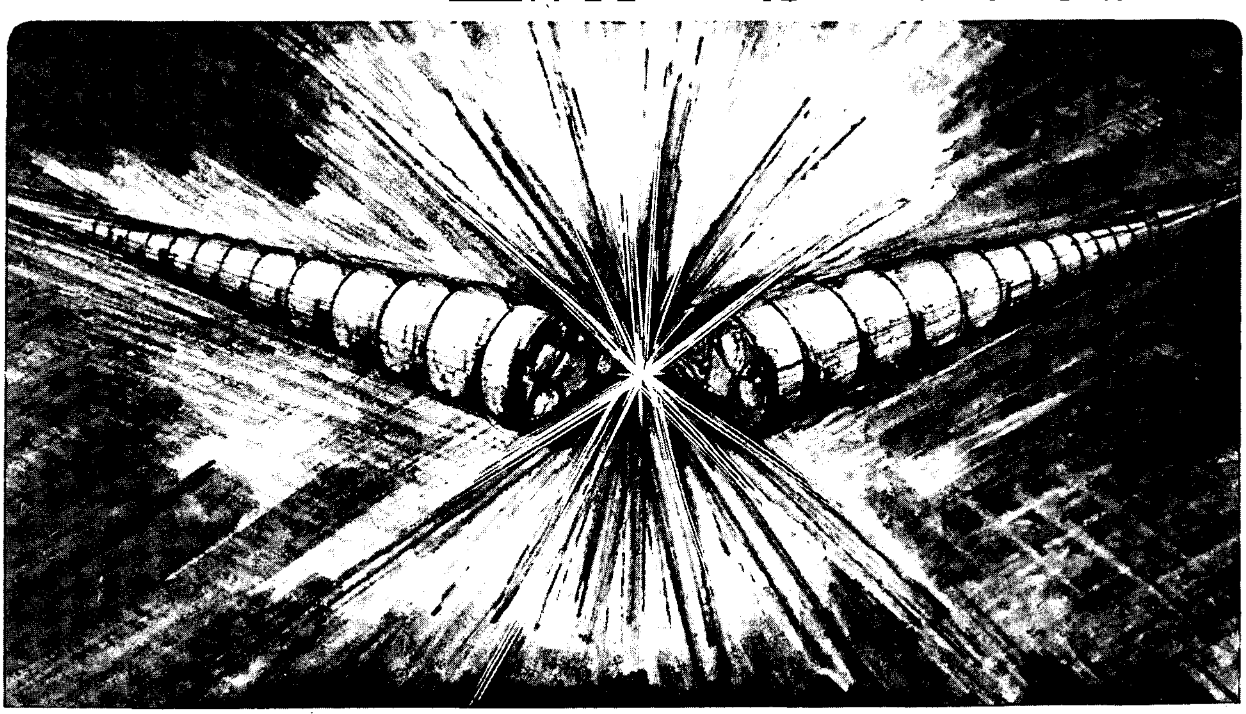

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ABSTRACT

In the last three years, the U.S. program in Heavy Ion Fusion has concentrated on understanding the induction linac approach to a power-plant driver. In this method it is important that the beam current be maximized throughout the accelerator. Consequently, it is crucial to understand the space-charge limit in the AG transport system in the linac and, also, to achieve current amplification during acceleration to keep pace with the kinematical increase of this limit with energy. Experimental results on both these matters and also on the use of multiple beams (inside the same accelerating structure) will be described.

A new examination of the most attractive properties of the induction linac for a fusion driver has clearly pointed to the advantage of using heavy ions with a charge-state greater than unity -- perhaps $q = 3$ may be an optimum. This development places even greater importance on understanding space-charge limits and mechanisms for emittance growth; also, it will require a new emphasis on the development of a suitable ion source.

INDUCTION LINAC DRIVER

The general concept of a heavy-ion induction linac using current amplification has been reported on often in this Symposium series (preceded by the "Workshop" series).[1] The basic idea 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 can be made to decrease and the current can be amplified from amperes at injection to kiloamperes at the end of the accelerator (~ 10 GeV). The current is further amplified by a factor of about 10, and the pulse length further shortened 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.[2]

With the passage of time, improvements in the design have taken place, and confidence has grown as a result of experimental and theoretical

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studies. A significant design improvement, made in 1981, was the incorporation of several independently-focussed beams inside the same accelerating structure.[3,4] Apart from the physics advantage that each beamlet could have a smaller emittance than that of an equivalent single large beam -- and so allow focussing to a smaller spot -- a design with multiple beams was also shown to be cost effective if the number was in the range of 8 to 16 beams. At any point in the accelerator the larger the number of beams the larger the current that can be transported and the shorter the acceleration pulse length. The economic optimum balances the decrease in the acceleration unit costs against the increase in cost of the transport lenses.

Experiments relevant to the Induction Linac method can be thought of in two broad categories (which are not completely independent):

(1) Proof-of-Principle Experiments, where the design is believe to be based on sound principles but where one wishes to be sure that there are no unmanageable surprises;

(2) Discovery Experiments, where there is no satisfactory theoretical understanding and answers have to be arrived at empirically.

Our present experiment (MBE-4) at LBL belongs in the first category, and others to be discussed below (SBTE, MEVVA) in the second. A proposed new experiment (ILSE) would have elements of both.

MULTIPLE BEAM EXPERIMENT (MBE-4)

About 50% of the planned apparatus[5] has now been assembled and results of measurements to date are given at this meeting in two reports presented by Warwick[6] and by Kim.[7] The experiment 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).

The transverse dynamics is strongly space-charge dominated in that the betatron phase-advance per focussing-lattice period is strongly depressed -- from $\sigma_0 = 60°$ down to about $\sigma \sim 12°$. (See Fig. 1) For a mono-energetic beam without acceleration the SBTE (see below) has shown stable beam behavior to lower values of σ (7° - 8°), but new issues in transverse dynamics 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_0 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 cause collective forces that are accelerating at the head and decelerating at the tail and, if not counteracted, will cause bunch spreading both in length and in momentum. A major part of the experimental effort is centered on designing and successfully employing the electrical pulsers to handle the correcting fields at the bunch ends.

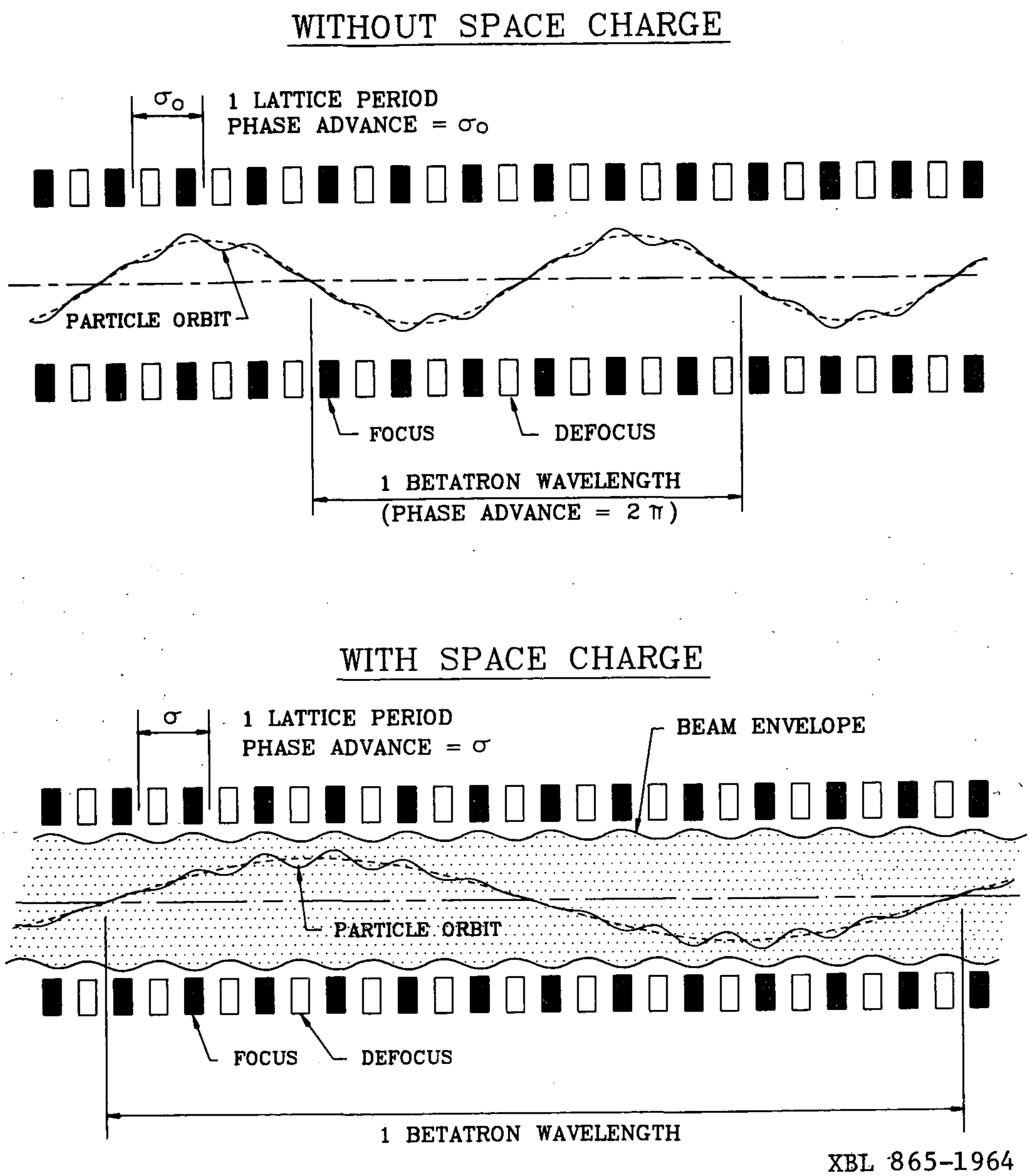

Fig. 1: Transverse motion of a particle in an alternating gradient focussing lattice. A lattice period corresponds to a focussing lens, a drift, a defocussing lens and another drift (FODO). The definition of phase advance per period of the quasi-sinusoidal motion is shown for cases in which space-charge effects are negligible (top, σ_0), and strong (bottom, σ).

Figure 2 shows an example of current amplification results obtained to date, where it can be seen that the pulse duration has been shortened by nearly a factor of two and the current correspondingly increased. 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 can be and still be considered tolerable. An experiment with $\Delta\beta/\beta = 0.4$ is described in the poster paper by Kim;[7] this is more than will be needed in a driver.

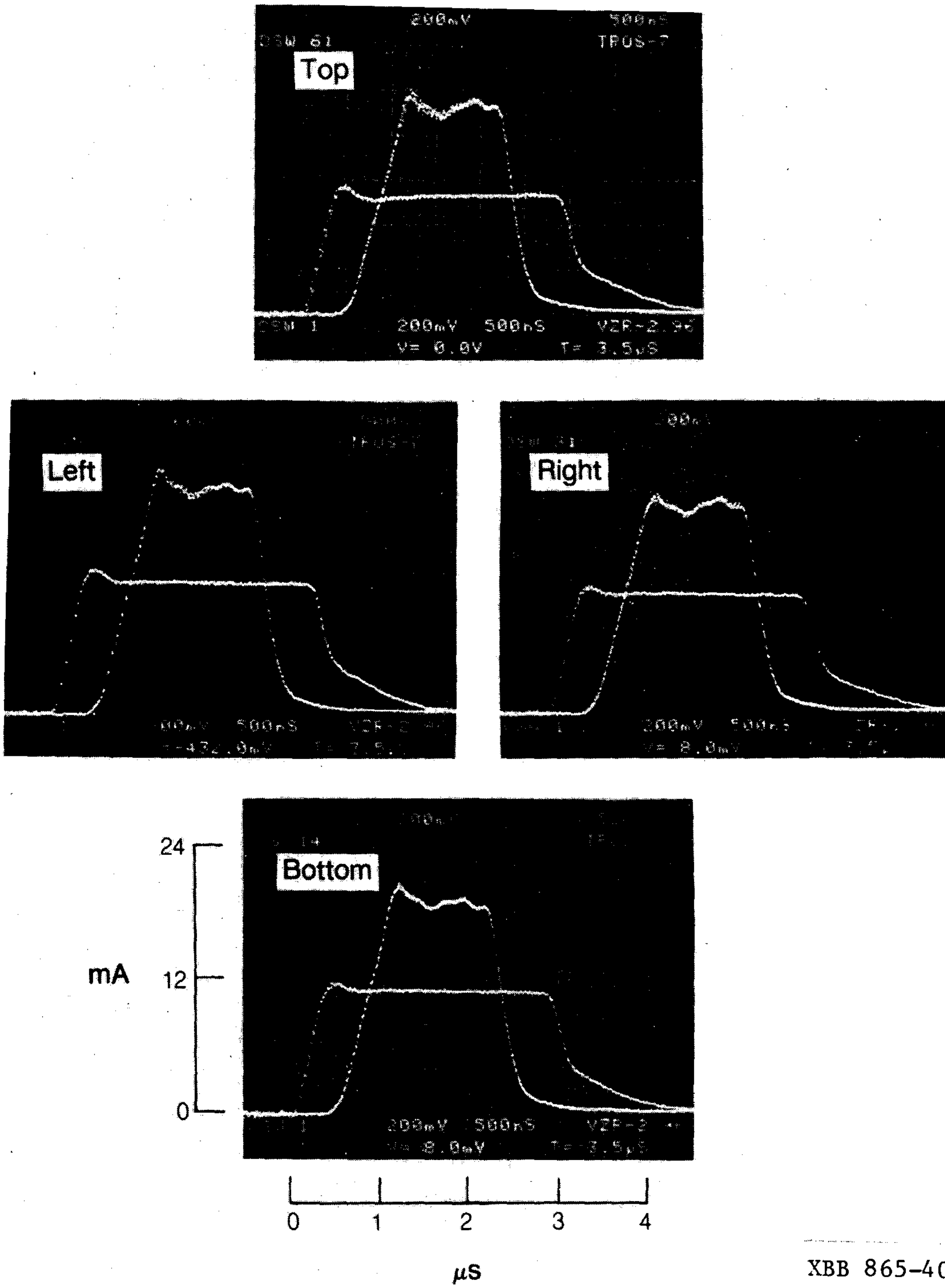

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Fig. 2: Current profiles for the four beams in MBE-4 measured after the eighth accelerating gap, with the pulsers off (lower amplitude trace), and on (higher amplitude trace). The current amplification accompanying acceleration is clearly visible.

SINGLE BEAM TRANSPORT EXPERIMENT (SBTE)

Since the IEEE Particle Accelerator Conference in Vancouver in May 1985 the results on high-current beam transport limits in the 87-quadrupole SBTE have been refined and more careful calibrations made. The results, shown in Figure 3, 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 σ_0 did not exceed 85°. A threshold value of current above which emittance growth occurred could, however, be measured for values of σ_0 in excess of 85°. Since the transportable current is greatest for $\sigma_0 < 85°$, the design of drivers will be restricted to σ_0 values in this range. (Tiefenback has found that beyond $\sigma_0 = 85°$ the threshold corresponds rather well to the empirical condition that the beam plasma period equals the beam transit time through three lattice periods).[8]

Earlier theoretical work on beam current limits in AG focussing systems utilizing an idealized distribution (K-V) indicated that it could be dangerous to use σ_0 greater than 60° and that σ could probably be depressed from that value down to 24°, but not below. The experimental limits from SBTE shown in Table I can be seen to be much more encouraging:

Table I - Experimental Limits on σ_0, σ

σ_0	60°	78°	83°
σ	< 7°	< 11°	< 15°

EMITTANCE GROWTH IN HIGH-CURRENT BEAMS

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

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

with B the limiting pole-tip field, η the fraction of length occupied by magnetic lenses, qV the ion kinetic energy, 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, first suggested by Maschke was given for an implicit assumption that σ/σ_0 could not be less than 0.7. In light of the improved knowledge from experiment and simulation it is useful to write the explicit dependence of K on σ, σ_0, viz.:

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

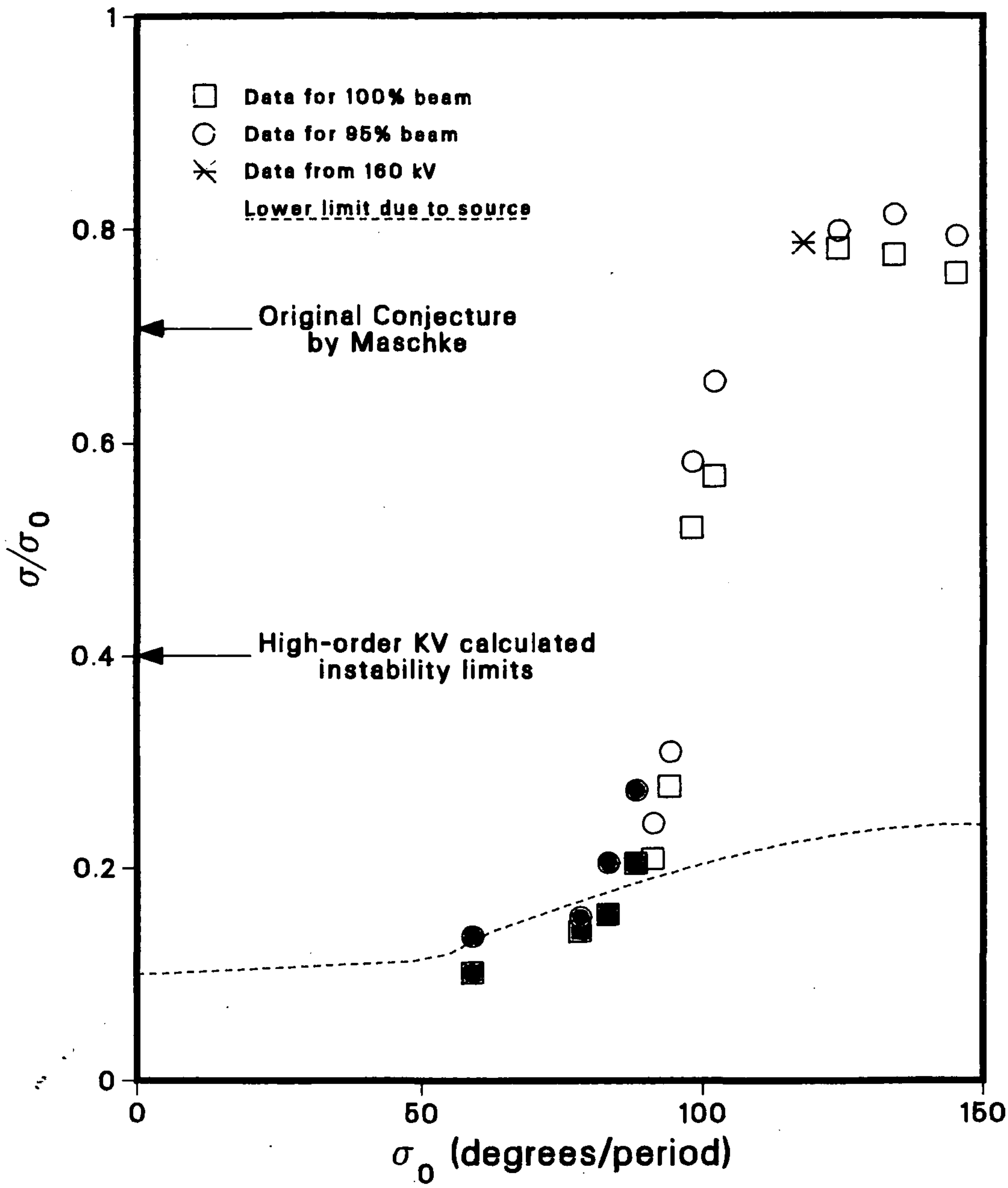

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Fig. 3: Values of σ/σ_0 for various σ_0 reported by Tiefanback.[8] Calculated values of σ are based on the emittance for 95% (squares) and 100% (circles) of the beam. The line indicates the lower observable bound set by the source brightness. Emittance growth was observed only for $\sigma_0 \geq 88°$.

If, in fact, there were no lower bound on σ/σ_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 $\sigma_0 = 60°$, σ could be allowed to go lower that 24° without emittance growth occurring. During the course of SBTE measurements further simulations showed that values of σ down to 1° or 2° might be alright.

The situation changed, however, with Celata's simulation studies 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, r.m.s. emittance oscillations and steady growth 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.[9]

A pessimist might thus argue that it is dangerous to consider designing a system with σ/σ_0 as low as 6°/60° because we have identified two mechanisms that can cause trouble. The optimist, on the other hand, could argue that self-cancelling effects such as described, even if they are not understood, can be used to carry us below this value. For the moment it is probably only prudent to consider that designs with σ lower than experimentally established may be on shaky ground, at least until we have a more thorough understanding of all the physics.

The growth in emittance due to 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[10] (This result is implicit in earlier work by Lee and Yu).[11] In a report at this meeting Anderson has made a significant advance in the theory by describing how the growth evolves without assuming what the final distribution will be.[12]

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 one are given by Celata.[13]

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.[3] The driver design program, LIACEP[14], did, however, indicate that cost savings could accrue 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 from a beam with $q = 1$ at some intermediate energy.

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

(iv) Neutralization after the final lenses to prevent focal-spot enlargement by space-charge.

The results from SBTE have altered 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, $q = 1$. 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 $q^{3/2} (\sigma/\sigma_0)^2$ 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 σ/σ_0, we can in principle continue this argument to higher charge-states, dropping σ/σ_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 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 in the invited paper by Lee.[15]

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.[16] 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.[17]

Since the SBTE has shown that σ_0 can exceed 60° safely (but not 85°) 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.[3] 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 and, hence, is now receiving much 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 from the injector, which are then combined, perhaps at 250 MeV, to create the 16 beamlets that undergo the bulk of the acceleration (See Fig. 4). Before this strategy can be established as a viable one, however, the emittance growth in combining high-current beams must be understood better.[12,13]

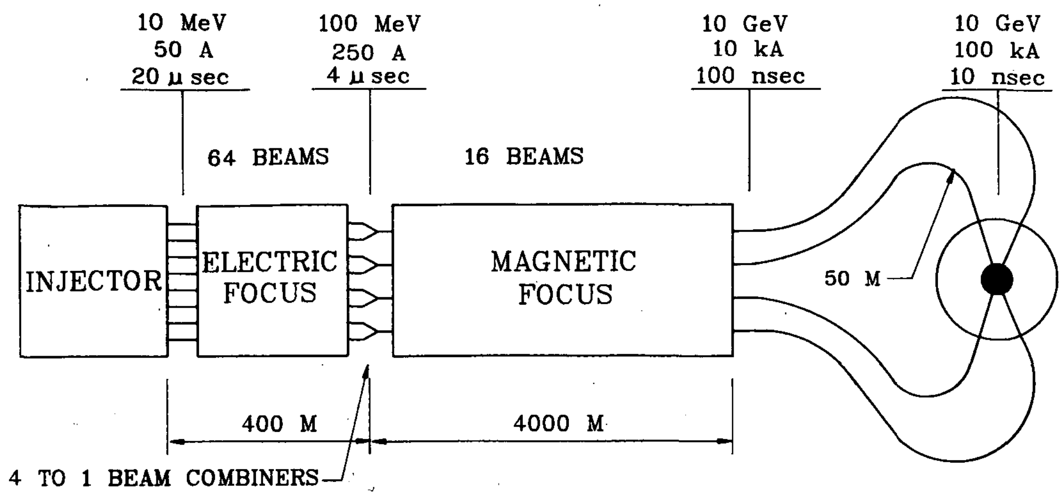

Fig. 4: Schematic of current concept for a 3.3 MJ driver that uses ions with A = 200, q = 3.

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[18] 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). The preliminary results to date are given in the paper by Dudziak and Herrmannsfeldt,[19] and further details appear in other reports at this meeting from the groups at MDAC, LANL, LLNL and LBL.[20]

Four different reactor types and five different target designs are included in the examination. The driver parameters range from 5 GeV to 20 GeV and 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 2000 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.

EXPERIMENTS THAT NEED TO BE DONE

An induction linac driver will rely on many concepts which are still untested in the laboratory. We need to move on in our laboratory studies of space-charge-dominated beams to address the following issues:

- Magnetic transport (including the transition from electric to magnetic focussing)
- Combining beams
- Bending beams
- Drift-compression (adjusted to remove velocity shear)
- Final focus with neutralization

These topics all involve beam physics that needs to be explored. Other physics can become involved when one deals with ion beams with high energy and high power, e.g. surface emission of gas, ions, or electrons, due to beam loss from a beam "halo", or unanticipated surprises analogous to the "brickwall" effect seen at the CERN ISR. Thus it is desirable to move up from the present laboratory level of ~ 1 joule, 1 MW, to maintain credibility that extrapolation to driver parameters is believable. We add therefore to the list:

- Handling ion beams with high energy and high power.

Most of the issues to be addressed require or benefit from use of magnetic elements and hence an ion with velocity, $\beta > 0.04$ (where $\underset{\sim}{v} \times \underset{\sim}{B} \geq \underset{\sim}{E}$). At low energies the cost of induction acceleration is relatively high, so that to explore features such as the above at affordable beam voltage (say 10 MV) and cost, will require the use of a light ion in the range from A =12 to 27.

At LBL we are in the process of designing and proposing to the U.S. DOE an experiment which would move forward to address the topics listed earlier. A central component of the 10 MV medium-weight ion experiment will be the unique 2 MV mutiple-beam injector being developed at LANL, which will be reported on at this meeting.[21]

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 quite 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.

Several more experiments related to driver physics need urgently to be done, and they can be addressed on a laboratory scale.

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