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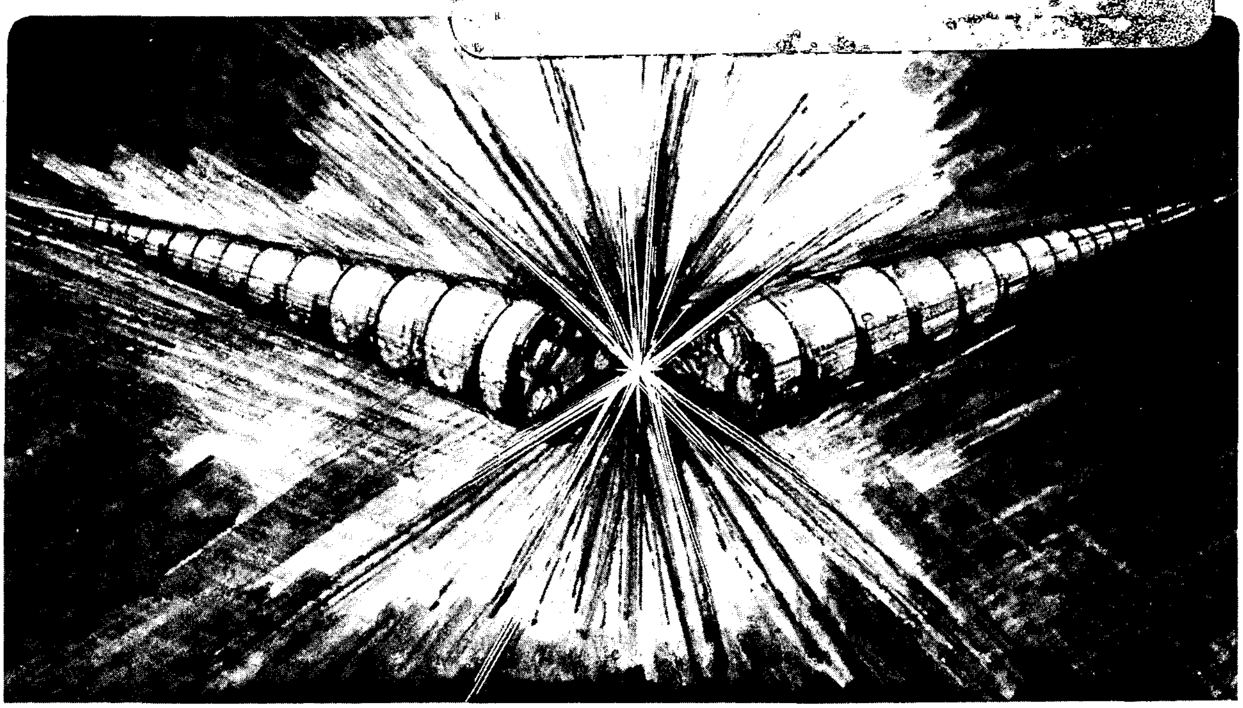

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HIGHLIGHTS OF THE HEAVY ION FUSION SYMPOSIUM*

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Abstract

The current status and prospects for inertial confinement fusion based on the use of intense beams of heavy ions will be described in the light of results presented at the International Symposium on Heavy Ion Fusion, (Washington, DC, May 27-29, 1986).

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 the surface of 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 when the compression has reached an appropriate value. The energy can be supplied directly (difficult because of symmetry) or indirectly, by generating high temperature radiation inside a hohlraum. A multigap accelerator for heavy ions, relying on the physics and engineering base of research accelerators, has distinct advantages as a driver for fusion energy over the other two driver candidates, lasers and light ions, in the following regards:

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

The enormous current (20 particle-kiloamperes) that must be delivered in the final short pulse with a beam of low emittance is the feature that lies well beyond the experience of today's research accelerator experience.

2. The Symposium Structure

Over a hundred people from a variety of countries attended the three-day Symposium last week in Washington. A printed Proceedings is being prepared.[1] In the early years of the Heavy Ion Fusion (HIF) program, beginning in 1976, interested workers gathered for Workshop meetings of one or two weeks but, as the subjects developed in sophistication, the Workshop format was superseded by the present sequence of Symposia.

The program structure for last week's meeting had these elements: a) Program Reports, b) Technical Reviews, c) Accelerator and Beam Physics, d) Final Focussing, e) Atomic Physics and Beam-Plasma Interaction, f) Target Design, g) Systems Studies. In my view, the highlights were mainly in categories (c), (e) and (g), and I shall spend most of the discussion on these. Many of the interesting items on Acceleration and Beam Physics are, however, being presented in papers at this meeting, and I shall not cover these but refer instead to the relevant reports which are available in the Proceedings of the present Conference.[2]

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3. Driver Configurations

Two heavy-ion accelerator driver systems to deliver high current beams of heavy ions (A = 200) with kinetic energy about 10 GeV (i.e. 50 MeV/amu and $\beta = 0.3$) are shown schematically in Fig. 1.

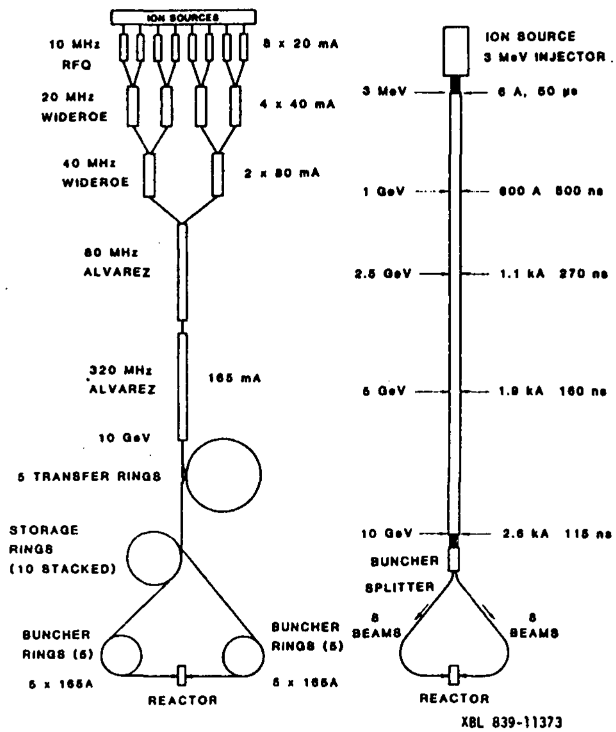

Fig. 1. Schematics of RF/Storage Ring Driver[3] and an Induction Linac Driver[8]. The latter design has been improved substantially in recent years (see Fig. 6).

The rf/storage ring method 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. 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 relies on amplifying the current simultaneously with acceleration to keep pace with the kinematic change in the space-charge limit. 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 is crucial in the design of the low-β parts of the rf/storage ring system, and is clearly central to the design of the induction linac at every point along its length.

4. Programs

In Japan the work at INS on the "LITL" and "TALL" RFQ injectors for TARN presented by Hirao are the most relevant to HIF; in addition, the systems work related to the HIBLIC point design for a power plant is continuing.[1]

West Germany has a strong program in high current low-β acceleration of ions, and I refer you to papers by Junior, by Schempp and by Muller at this meeting.[2] A major contribution of the German program has been the very valuable and detailed systems study, HIBALL.[3] A sequence of experiments to study ion interactions in plasmas has been defined. This study and, also, the elucidation of the beam physics in high current storage rings will be greatly enhanced when the Experimental Storage Ring, or ESR (part of the SIS-18 project) has been completed five years from now.

In France, two experiments are being prepared to study ion energy-loss in plasmas, one at Bruyeres-le-Chatel by Dei-Cas, the other by Deutsch at Orsay.[1] In each case the ions are produced from a tandem van de Graaff accelerator.

In Britain, effort countinues on high-current beam behavior (in collaboration with Maryland) as reported by Pryor.[1] Also, a very interesting experiment by Rees is just beginning at the unique ISIS facility at Rutherford-Appleton Laboratory to try to understand the longitudinal microwave instability limits for a bunched beam in a storage ring.

The U.S. program concentrates on the multiple-beam induction linac method, with the major activities at LBL and at LANL. Both LLNL and LANL participate in the design of targets suitable for HIF. The first major assessment study of the induction linac method for power production is nearing completion. Preliminary results which range over four reactor types, five target concepts, and countless induction linac designs were the subject of reports by Dudziak and Herrmannsfeldt, Waganer, Zuckerman, Driemeyer, Bangerter, and Pendergrass.[1]

5. Beam Plasma Experiments

The rate of energy loss of heavy ions in a hot dense plasma is greater than in cold matter because of contributions from the unbound electrons. Several experiments, all in Europe, intend to study this effect in the near future. (See Fig. 2.) The shortening of the range enhances the deposition of energy per gram for a fusion target -- and thus is favorable. The range shortening can be as big as 50% for low-energy ions but is much less for the ions of 50 MeV/amu needed for fusion.

At GSI the UNILAC beam will be collimated and passed through a z-pinch plasma ($n \approx 10^{19}cm^{-3}$) followed by an energy analyzer. In another experiment it is believed that the beam from the first five tanks of the MAXILAC injector (described by Muller[1,2]) can be focussed to a 1 mm x 2 mm spot to produce a low temperature plasma in a gas-jet target. Meyer-ter-Veyn described interesting plasma experiments that can be performed with a high-current beam of high charge-state ions from the Experimental Storage Ring when it is completed some years from now.[1]

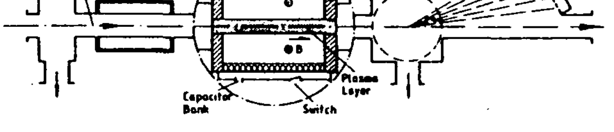

Fig. 2. Conceptual Set-Up of a Beam-Plasma Experiment

At Orsay, Deutsch and co-workers will imminently use a tandem Van de Graaff and a relatively cold (5 eV) linear discharge plasma in hydrogen to make similar measurements.[1]

A difficult and ambitious experiment is being prepared by Dei-Cas at Bruyeres-le-Chatel. Here the collimated beam of ions from a tandem Van de Graaff will be passed through a hot (200 eV), solid-density plasma created by focussing a high-power laser beam on a target. Both the spatial extent and time duration of the plasma are small and interpretation of the results will require accurate diagnosis of the plasma conditions with high resolution.

6. 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 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. (Some new calculations on the drift-compression stage were given by Ho.[1])

Because there is no other report at this Conference on the multiple beam linac experiment, MBE-4, in progress at Berkeley with cesium ions, I shall present here some of the details.

About 50% of the planned apparatus has now been assembled and results of measurements to date were given at the Symposium in two reports presented by Warwick and by Kim.[1] 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. 3) 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.

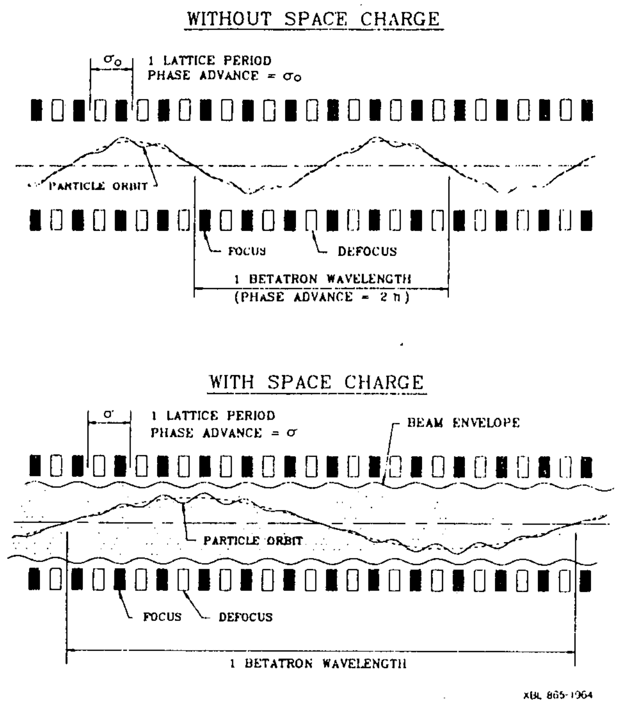

Fig. 3. Transverse motion of a particle in an alternating gradient focussing lattice. A lattice period corresponds to a focussing lens, a drift, a defocussing lens and another drift (FODO). The definition of phase advance per period of the quasi-sinusoidal motion is shown for cases in which space-charge effects are negligible (top, σ_0), and strong (bottom, σ).

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 the ends of the bunch to spread 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.

Figure 4 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 may be and still be considered tolerable. An experiment with $\Delta\beta/\beta = 0.4$ was described by Kim;[1] this is more than will be needed in a driver.

7. High-Current Beam Behavior and Emittance Growth

7.1 The Single Beam Transport Experiment (SBTE)

Since the IEEE Particle Accelerator Conference in Vancouver in May 1985[4] 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 Fig. 5, 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 88°. A threshold value of current above which emittance growth occurs could, however, be measured for values of σ_0 in excess of 88°. Since the transportable current is greatest for $\sigma_0 < 88°$, the design of drivers will be restricted to σ_0 values in this range. (Tiefenback 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).[5]

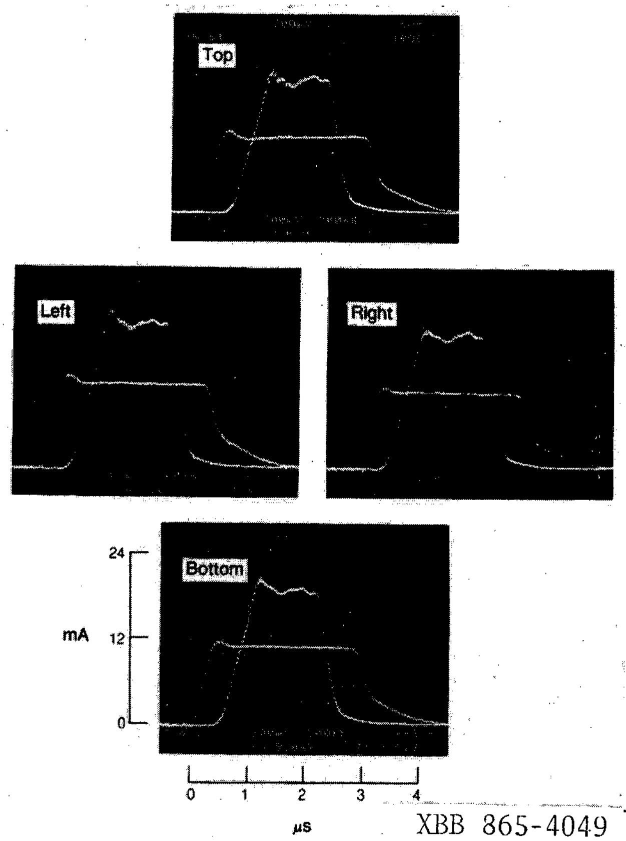

Fig. 4. Current profiles for the four beams in MBE-4 measured after the eighth accelerating gap, with the pulsers off (lower amplitude trace), and on (higher amplitude trace). The current amplification accompanying acceleration is clearly visible.

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.[6] 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°

7.2 Is There a Lower Limit on σ/σ_0?

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:

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

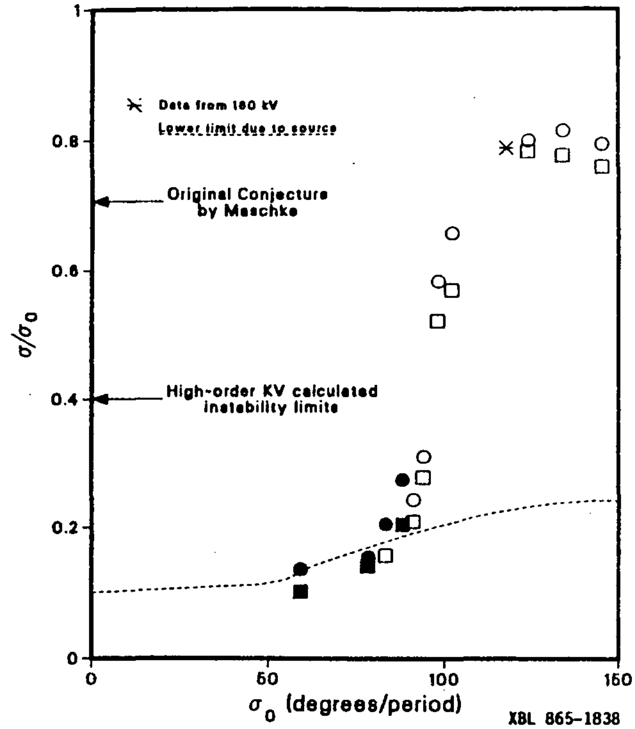

Fig. 5. Values of σ/σ_0 for various σ_0 reported by Tiefenback.[5] Calculated values of σ are based on the emittance for 95% (squares) and 100% (circles) of the beam. The line indicates the lower observable bound set by the source brightness. Emittance growth was observed only for $\sigma_0 \geq 88°$.

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 use the "smooth approximation"[7] to write the explicit dependence of K on σ, σ_0, viz.:

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

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 either a dodecapole component in the field or the effect of images in the electrodes was introduced, r.m.s. emittance oscillations and steady growth showed up clearly. When both images and the right amount of dodecapole component were included, however, the surprising result emerged that the emittance did not grow.[8]

8. 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[9] which we can re-write in the form:

$$\frac{\epsilon_f}{\epsilon_1} = \left(1 + \frac{1}{4}\,\frac{\langle x^2\rangle}{\lambda_D^2}\,\frac{\Delta E}{E}\right)^{1/2} \qquad (3)$$

where $\langle x^2\rangle$ is the mean square radius of the beam, λ_D is the Debye length (proportional to $\epsilon/\sqrt{I}$), and $\Delta E/E$ is the fractional increase in electrostatic field energy as the beam relaxes from a non-uniform to a uniform shape. 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 $\langle x^2\rangle \ll \lambda_D^2$ and the effect is negligible, we are concerned with space-charge dominated beams with $\langle x^2\rangle \gg \lambda_D^2$ and the effect can be quite serious. Results given at the Symposium are expanded on in reports at this Conference by Anderson, Guy, Hofmann, Klabunde, and Wangler.[2]

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 were given by Celata.[1]

9. 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.[10] The driver design program, LIACEP[11], did, however, indicate that capital 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 and simulations 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.[10] (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 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 was given in more detail in an invited paper by Lee.[1]

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.[1] 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.[12]

Since the SBTE has shown that σ_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.[10] 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. 6). Before this strategy can be established as a viable one, however, the emittance growth in combining high-current beams must be understood better.

10. 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[3] 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 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 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.

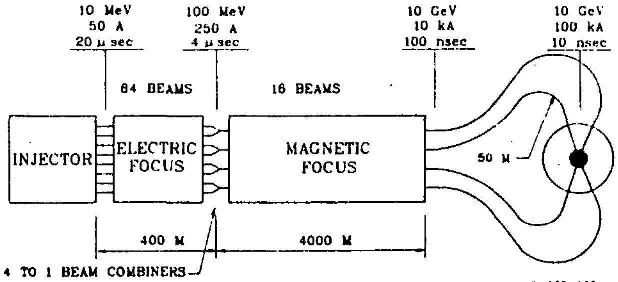

Fig. 6. Schematic of current concept for a 3.3 MJ driver that uses ions with $A = 200$, $q = 3$.

11. 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.

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