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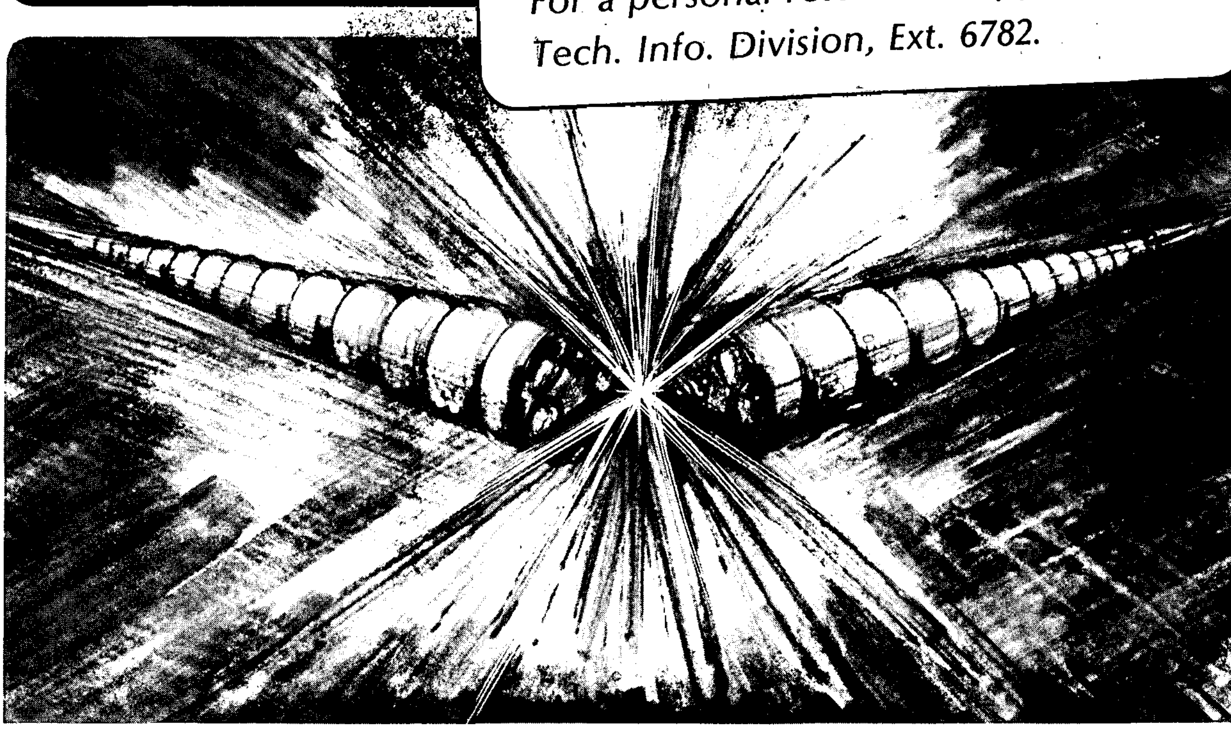

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1. INTRODUCTION

As described in an earlier talk by Dr. James E. Leiss of the U.S. Department of Energy, the major emphasis of the U.S. program in Heavy Ion Fusion Accelerator Research, in the next few years, will be on developing and understanding induction-linac systems that employ multiple beams of high-current heavy ions[1]. A large part of that effort is underway at Lawrence Berkeley Laboratory and Los Alamos National Laboratory, with additional activities at Stanford Linear Accelerator Center, Naval Research Laboratory, and Lawrence Livermore National Laboratory.

The culmination of the plan lies in building the High Temperature Experiment (HTE) which will involve, as we see it now, an ion induction linac to deliver multiple high current beams, that can be focussed and overlapped on a two-millimeter diameter spot. A suitable choice of parameters seems to be: 16 beams of Na^{+1} ions, 125 MeV and 3.75 kJ beam energy. If the accelerator system is a success, and no unpleasant surprises in the form of insurmountable problems of beam dynamics are encountered, the experiment will, in addition, verify that the energy deposition of ions in hot solid-density plasma is as straightforward as we believe at present.

We can identify a sequence of three major experimental activities as follows:

1. The Single-Beam Transport Experiment (SBTE): A quadrupole transport system consisting of 5 matching lenses and 41 identical F-D lens pairs to test the stability, or otherwise, of transport of a high-current Cs^{+1} beam over a long distance. First results from operation of a short section (6 F-D lens pairs) were reported at the IEEE Particle Accelerator Conference in Santa Fe[2].

2. The Multiple-Beam Experiment (MBE): An arrangement of long-pulse induction accelerating units between which are placed multiple-beam

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focussing arrays to transport 16 independent beams threading the same accelerating structure. The experiment is designed to simulate on a small scale as many as possible of the features to be encountered in the HTE.

3. The High Temperature Experiment (HTE): referred to above.

In addition, a number of parallel development activities are in progress: (a) testing of induction core samples with different formulations; (b) testing of insulator materials with the goal of arriving at a design in which a graded column complete with grading rings can be cast in a single unit, and have acceptable electrical and vacuum properties; (c) switch development, especially ignitrons and thyratrons for long-pulse operation; and (d) development (jointly LBL/LANL) of suitably intense, and bright, surface ionization ion sources. Many of the concerns about materials and components, and possible directions in which to seek solutions, will be addressed in the paper by Faltens[3)].

2. INDUCTION LINACS

The need for multi-kiloampere ion beams delivered in a short pulse (on the order of 50 nsec) first prompted examination of an accelerator driver based on induction linac technology, and its likely features have been described at previous HIF workshops and symposia. With regard to acceleration of the high current short-pulse ion beam, experience with multi-kiloampere short-pulse electron beams in a variety of induction linacs (FXR and ATA at Livermore being the most recent examples of large systems [4)5)]) provide a solid technological base, and broad operational experience. The difficulty of focussing intense slow-moving ion-beams, however, presents a sharp contrast to the relativistic electron-beam case where relatively simple solenoid lenses suffice. Given the technological limits on electric or magnetic forces in quadruple lenses, the desirable high-current short pulse operating condition cannot be properly reached until the heavy ion energy approaches 1 GeV (5 MeV/amu). The maximum ion current permitted by the transport system for the beam emerging from the source is far lower - in the range 1-10 amperes (see, for example, Fig. 1.).

The well-known strategy that is proposed is to accept the limitations of the transport system at each place along the driver, and to arrange for an acceleration schedule that allows the beam-current to grow (and the pulse duration to fall) at as rapid a rate as is reasonable and consistent with

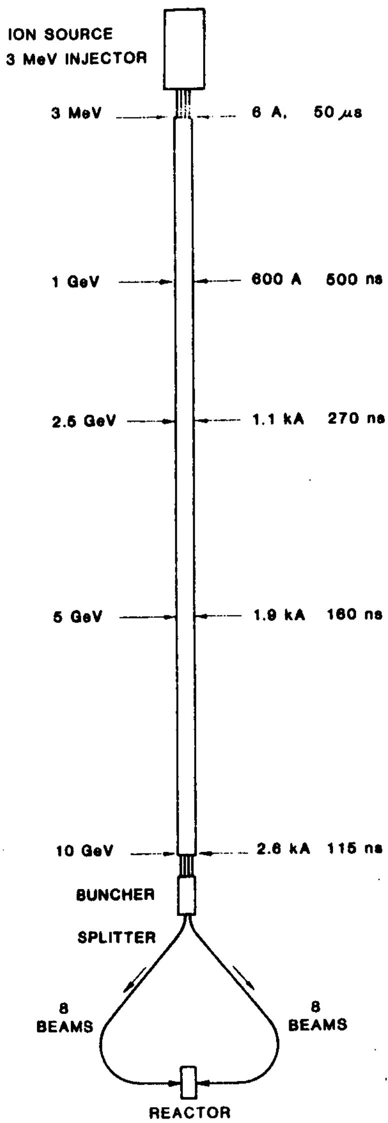

Figure 1. Example 3 MJ Driver[19].

staying below instability limits. This requires the application of time-dependent waveforms to the accelerating gaps, first, to halt the natural distension of the bunch and, second, to compress it slightly in length. In a driver, this manipulation of the bunch-length takes place in the first 10 percent of the length of the accelerator; from that point on the applied accelerating waveforms are essentially flat, as they are in an electron induction linac.

Thus, an ion induction linac, in which beam current amplification is to be accomplished, will differ in detail in its early stages from a conventional electron induction linac in two regards: The pulse-lengths will be longer, and the voltage waveforms must vary with time. Neither presents any essential difficulty. A longer pulse duration simply corresponds to adding a greater number of volt-seconds in the cores or to using a lower operating voltage in a core with a given number of volt-seconds. Fig. 2 shows how the desired volt-seconds per meter might vary along the length of an example design for HTE and how it relates to present experience. Note that the NBS accelerator units or the LBL long-pulse unit (Fig. 3) have adequate pulse length at their full design voltage[6,7]. Time dependent waveforms can be generated either by analogue pulse-shaping (as was done occasionally in the first Astron injector), or by choosing a fairly low operating voltage per module and arranging the firing delays to create a staircase approximation to the desired shape[3)7)]. Averaged over a large number of modules, disturbing effects due to the granularity of such an accelerating scheme on the longitudinal ion motion is believed to be negligible.

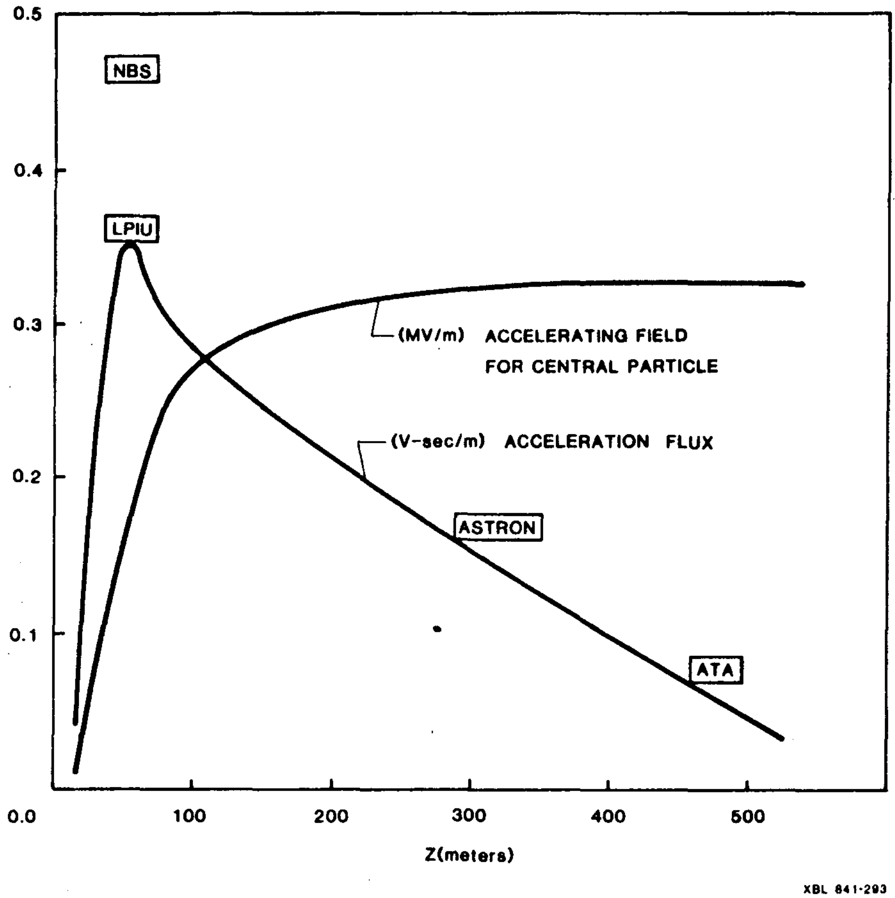

Figure 2. Desired volt-seconds/meter needed for example HTE.

While the basic features of the accelerating system do not differ in an essential way from past experience several improvements in the technical components are under study, mainly with a view to reducing cost:

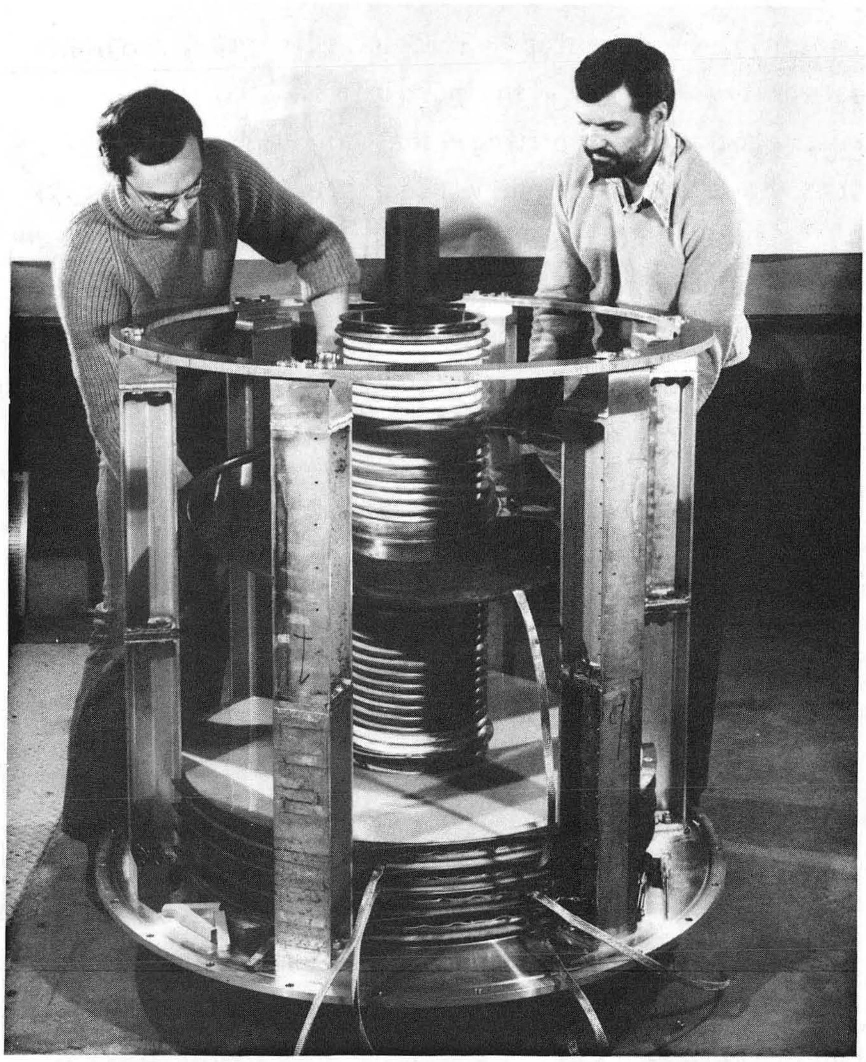

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Figure 3. LBL long pulse induction unit (LPIU)

- o <u>Cores</u>: Iron-alloy tape and ferrite have been common in the past; amorphous iron material ("metglas") may offer significant advantages. Because it is available in very thin ribbon form of relatively high resistivity, eddy-current losses are less than for other ferromagnetic tapes.
- o <u>Insulators</u>: Previous designs have used either lucite or graded columns made by brazing grading rings to successive rings of alumina or porcelain. Our present efforts lie in exploring graded columns made by casting the grading rings in place in long units. Because of the high ionization cross-section for heavy ions (compared, for example, with electrons) it is important that the outgassing of the

cast material be acceptably low; plastics may, perhaps, be suitable if loaded very heavily with inorganic material.

- Pulsers: Both pulse-forming lines and lumped-element pulse-forming networks have been commonly used previously; a heavy ion driver would use both kinds because of the differing pulse-lengths at the start and end.

Spark gaps and thyratrons have been commonly used as switches; recently, magnetic modulators incorporating amorphous iron ribbon have been successfully developed for short-pulse high repetition rate applications[8].

Somewhat more novelty, however, occurs when we consider the focussing structure. It now seems clear that electrostatic quadrupoles are preferred at the low energy end of an ion induction linac, with a transition to magnetic quadrupoles when the ion speed has reached a value $\beta \sim 0.05$. The use of multiple beams, each focussed by its own quadrupole transport channel, offers several advantages:

(1) If the number of multiple beams is made equal to the number of beams required for the final focus on the target (for example, sixteen), each beam can be conducted individually from source to target, and the complication - and emittance dilution - arising from septum-splitting at the end of the accelerator can be avoided.

(2) The capital cost of the linac is reduced by almost 30 percent if the number of beams is increased from one to a number in the range 4-16. This arises largely because the transportable total current at any point can thereby be increased by a factor of two, or so. An accelerating unit that supplies $q.\Delta V$ electron volts kinetic energy increment adds $\Delta W = (I.\tau\Delta V)$ joules to the beam, where I is the beam current, and τ the time of passage of the beam bunch through the unit. For the same increments, ΔV and ΔW, the size of the accelerating core, measured in terms of volt-seconds $\tau\Delta V$ is clearly less at higher beam current, I, with consequent cost reduction.

Increasing the number of beams very much beyond 16, however, causes the driver cost to rise. Although each beam could be smaller in cross-section, a fixed aperture allowance (we assume 1 cm) must be catered for in the individual transport channels to take care of equilibrium orbit errors arising from misalignments. Thus, increasing the number of beams beyond a certain point results in increased insulator size (and cost), and consequently a larger volume (and cost) of the core material lying outside the insulator.

(3) The increased beam current obtainable with multiple beams also helps in meeting the longitudinal stability criterion[9,10]

$$Z < gNZ_0/2\pi\beta L \ ,$$

where Z = Accelerator impedance (ohms/meter)

Z_0 = Free space impedance

βc = Particle speed

L = Bunch length

N = Tolerable number of e-foldings (~ a few)

g = Space-charge factor

For a 10 GeV, 3 MJ driver, the beam charge needed is $I\tau$ = 300 microcoulombs. The larger one can make the beam current, I, the smaller τ becomes, and hence $L = \beta c\tau$ – with consequent relaxation of the impedance requirement.

The usual problem of aligning focussing elements along the length of a linac to keep equilibrium orbit distortion acceptably small requires a new dimension of complexity when multiple beam lens arrays are used. Even with perfect longitudinal alignment of successive lens arrays, the inevitable inter-lens misalignments within each array will cause uncorrelated orbit deviations of each of the 16 beams. Such independent deviations cannot be removed by mechanical re-positioning of some number of lens-arrays but require more complicated diagnostics and control.

Finally, attention must be given to some additional transport questions which arise, not from the use of multiple beams but from the requirement of current amplification. In an rf linac, for example, the beam current is a constant; the pulse-train length expands in proportion to speed. Particles at the head of the pulse-train travel faster than those at the tail at any instant of time, but all particles passing a particular location (a given lens, for example) arrive there with the same speed. The situation is reversed for an induction linac in which the bunch length is kept constant (or nearly so); particles at the head and tail have almost the same speed at a given time but have different speeds as they pass through a given lens. As a consequence, in any section of the transport lattice the head and tail have a different phase advance per cell both for the coherent (σ_0) and incoherent (σ) tunes, making it difficult to maintain a perfectly matched beam over the whole length of the bunch. In particular, the response of the equilibrium orbit to misalignments depends on σ_0, and the spread in σ_0 will, therefore, add complications to any system for orbit corrections. Also, in the transition from the early stage of electrostatic quadrupole transport, where $\sigma_0 \propto 1/\beta^2$, to the later stage with magnetic quadrupoles, where $\sigma_0 \propto 1/\beta$, a further source of mismatching can occur. These effects are of concern only in the early stages of the accelerator and become quite negligible at higher energies where $[\Delta\beta/\beta]_z$ is very small. Calculations by Laslett for some specific examples indicate that only a small penalty need be paid in aperture to accommodate the envelope oscillations excited by such mismatches.[11)]

3. THE SINGLE BEAM TRANSPORT EXPERIMENT (SBTE)

The subject of high current beam transport in a quadrupole lattice has received a great deal of theoretical attention since Maschke first conjectured that an upper limit on current might be reached when the space-charge defocussing force equalled one-half of the mean restoring force due to the lenses (corresponding to $\sigma/\sigma_0 \sim 0.7$).[12)] Analytical work based on the Kapchinskij-Vladimirskij (KV) envelope equations, followed by particle-in-cell simulation studies have shed considerable light on the problem.[13)] Experimental results have begun to become available in the last year.[2,14,15,16)]

Results to date from SBTE will be presented in a poster session later in this Symposium.[17)] The experiment consists of 41 periods (82 lenses) of a quasi-FODO system of electrostatic quadrupoles (see Figure 4). Five

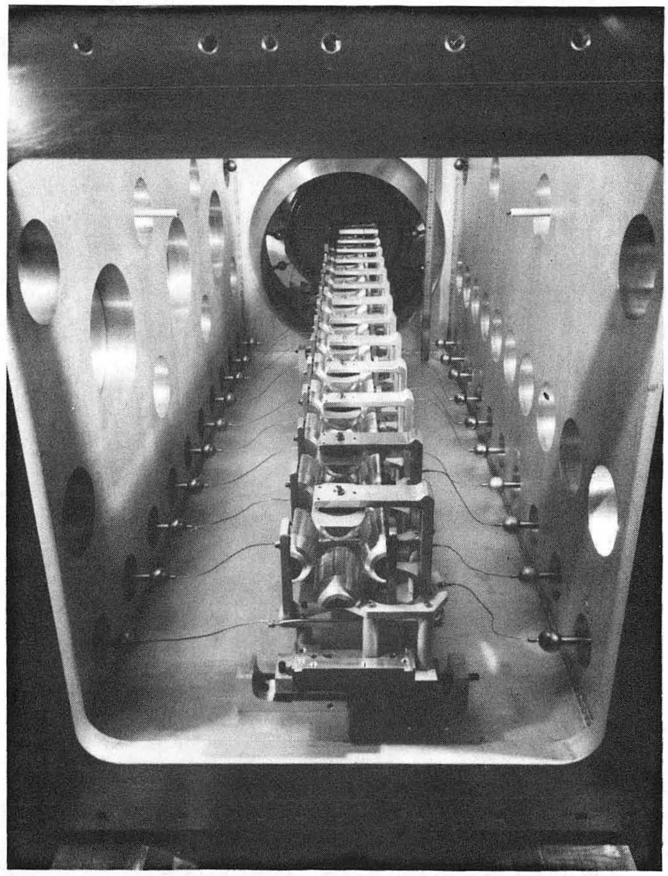

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Figure 4. Part of the SBTE

additional quadrupoles are used to match the 160 KeV cesium-ion beam from the injector to the transport lattice. With the voltages set to give a particular value of σ_0, both the injected current and beam emittance can be varied. The current and the emittance for a matched beam are measured at both the entry and exit of the 41 periods. If they have both remained unchanged, beam stability is inferred and a value of σ, the depressed phase advance, can be derived from a measurement of ε_n and the current (or beam size) by means of the envelope equation.

Up to two years ago we feared that transport difficulties would show up for certain values of ($\sigma_0 \rightarrow \sigma$) such as ($120^\circ \rightarrow 90^\circ$) and ($60^\circ \rightarrow 24^\circ$). The experiment has shown that, indeed, strong instability occurs when the phase advance is depressed from 120° down to 90°, but that with $\sigma_0 = 60^\circ$ (or somewhat higher or lower) no damaging effects occur even when σ is depressed down to 12°. Simulation results had already suggested that $\sigma = 24^\circ$ might not be limiting.[18)]

An important consequence is that earlier studies of induction linac designs for drivers, which assumed that 60° → 24° was limiting, are now believed to be based on assumptions that are too conservative.[19)]

4. MULTIPLE BEAM EXPERIMENT (MBE):

The conceptual design of this experiment is expected to occupy the next three months. Since it is intended to simulate, insofar as can be done on a small scale, as many of the novel features of the HTE as possible, it should incorporate: (a) multiple ion beams and (b) multiple induction modules to allow synthesis of accelerating waveforms to accomplish current amplification. It can serve as a test-bed into which new technical component solutions can be incorporated for field-testing as soon as they have been developed.

At present, we are thinking in terms of a 16-beam system. Essential ingredients include

1) Multiple-beam high-brightness source for a medium-mass ion (sodium preferably, potassium as an alternative). A surface-ionization source offers special advantages for high brightness - provided the emission is high enough. Source tests are in progress at LBL and LANL.

2) A 2-MeV injector to deliver a beam pulse a few microseconds in duration. The high-voltage source may be a Marx generator, or possibly a pulse transformer. The design and fabrication is at LANL.

3) A sequence of 5 multiple-beam focussing lens arrays, with ample diagnostics, to enable matching between the injector output and the accelerator input.

(Particular attention will be paid to pushing the performance level of these three items as close as reasonable to that appropriate to the HTE.)

4) An interleaved sequence of 16-beam electrostatic focussing arrays, and accelerating units (see Fig. 5). Preliminary designs are being developed by Laslett and Judd[20]. The half-period, L, of the transport lattice should increase slowly with beam voltage (approximately as $V^{1/3}$) for optimum current transmission. It seems convenient, instead, to pay some penalty in peak current and adopt a uniform choice of L = 32 cm, - an average of the optimum values. Since a FODO lattice requires one lens per half period, not much room is left for interpolation of the accelerator gaps between lenses - two to five modules,

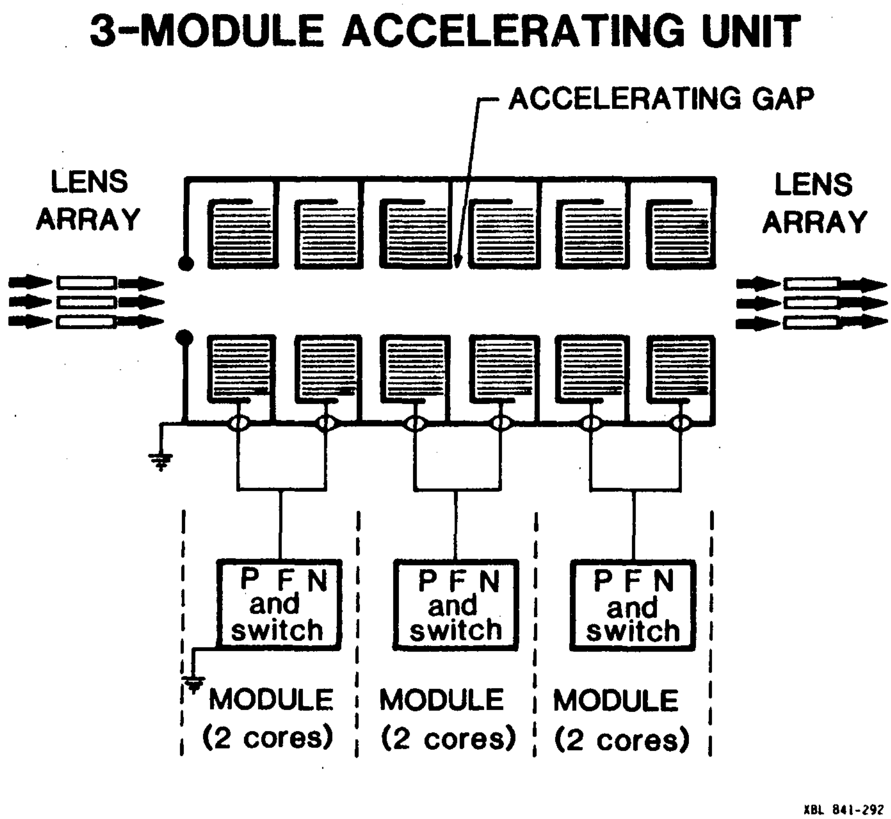

Figure 5. Schematic of accelerating structure for MBE showing definitions.

perhaps, can be incorporated between successive lenses. The entire experiment may comprise up to 300 modules and 90 focussing arrays.

It is intended to demonstrate current amplification of a factor of 2-3 in accelerating the beam from 2 MeV to 10 MeV. In addition the longitudinal modulations of particle motion, arising from the staircase-approximation to the ideal waveforms - combined with timing errors - can be examined. Experiments that can be accommodated at the end of MBE include final bunching over a drift length, final focussing (including neutralization), and transition to a magnetically-focussed multiple beam array.

5. HIGH TEMPERATURE EXPERIMENT (HTE)

Studies of the cost of induction linac drivers have revealed that in the megajoule range the cost is dominated by the number of megajoules per pulse and is relatively insensitive to the variation of other parameters.[19] In an experiment scaled down to provide temperatures in the 50–100 eV region, the beam energy needed is a few kilojoules - a thousand times less than a driver; the cost in this region seems to be related in lowest order to the ion-beam voltage (kinetic energy/qe). In seeking a solution at relatively low voltage, a light ion (A~15-30) is preferred. A tentative list of parameters is shown in Table I.

Table I - Tentative Parameters for HTE

Ion	:	Na^+ (A = 23)
Kinetic Energy	:	125 MeV
Beam Charge	:	30 μC
Number of Beams	:	16
Beam Energy	:	3.75 kJ
Final Pulse Direction	:	30 nsec

To obtain a temperature of 75 eV in a low-Z slab, two conditions are necessary: a) the specific energy, w, should be 10 MJ/gm; b) The beam irradiance, S, should, at least, match the radiative cooling rate (5 TW/cm^2). Writing the radius of the focal spot as $r = \epsilon_n/\beta\theta_0$; where θ_0 is the maximum angle of final convergence set by aberration limits ($\theta_0 \sim 15$ milliradians), we can write the following scaling relations (assuming the charge state is one)

$$w = \frac{\text{beam energy}}{\pi r^2 R} \propto \frac{I\tau V^2}{A\epsilon_n{}^2 R} , \qquad R = \text{Range, gm/cm}^2$$

$$S = \frac{\text{beam power}}{\pi r^2} \propto \frac{IV^2}{A\epsilon_n{}^2} .$$

Two cost-related factors appear in the denominator - the beam voltage, V, as remarked before and the pulse duration, τ, which is related to the total volt-seconds in the linac. Hence, to minimize the cost one desires low values for A, ϵ_n, and R, and a high value for the total current, I. A light ion clearly helps in the first of these factors. The full mass dependence is not shown explicitly here, however, since I, R and ϵ_n also depend on mass. If we use Maschke's functional form of limiting current - although the coefficient is uncertain - then $I \propto 1/A^{1/2}$, again arguing for choice of a light ion. At first glance, the scaling of R with ion mass would seem to be very unfavorable. While true at high beam voltages it is not so at low energies where a very heavy ion (for given V) is moving so slowly that only a small number of its electrons are stripped off and the effective charge contributing to the slowing-down process is not too different for a heavy or light ion. For ideal sources in which the emittance is controlled only by temperature the scaling of ϵ_n would also go in the wrong direction; in practice our experience with bright thermionic ion sources has shown that the emittance is dominated by non-thermal effects, for example, optical aberrations and imperfections.

While the choice of a light ion is important the use of multiple beams is even more so, mainly because the total current, I, can be increased, but also because the emittance, ϵ_n, of the individual multiple beams can be smaller than that for a single beam with current, I.

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