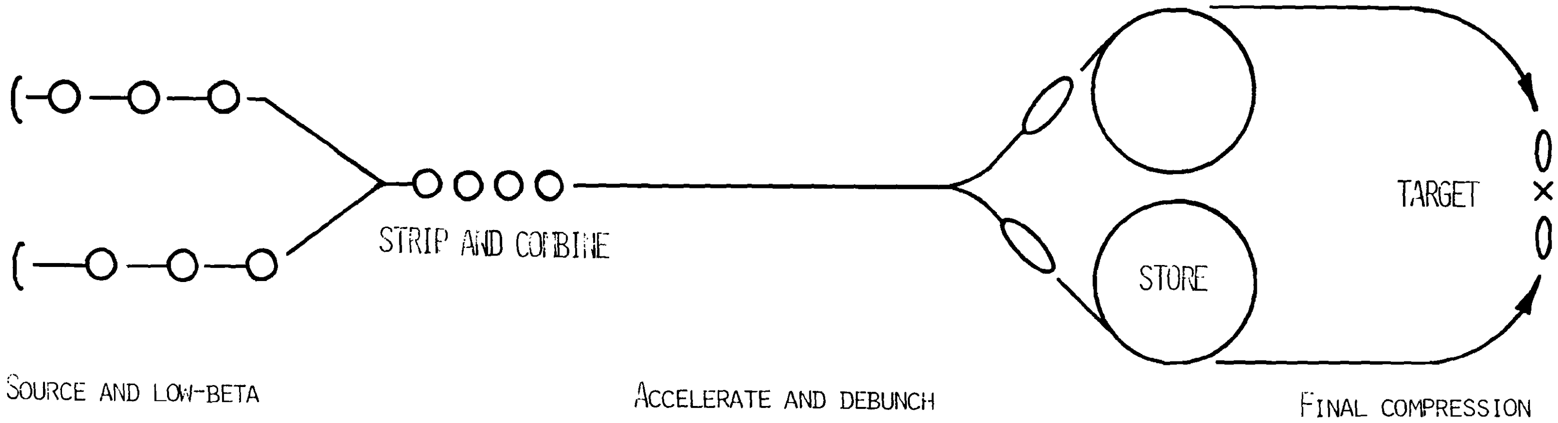
ION INDUCTION LINACS: REFERENCE DESIGN AND PROPOSED TEST-BED

Andy Faltens and Denis Keefe

Lawrence Berkeley Laboratory

I. INTRODUCTION

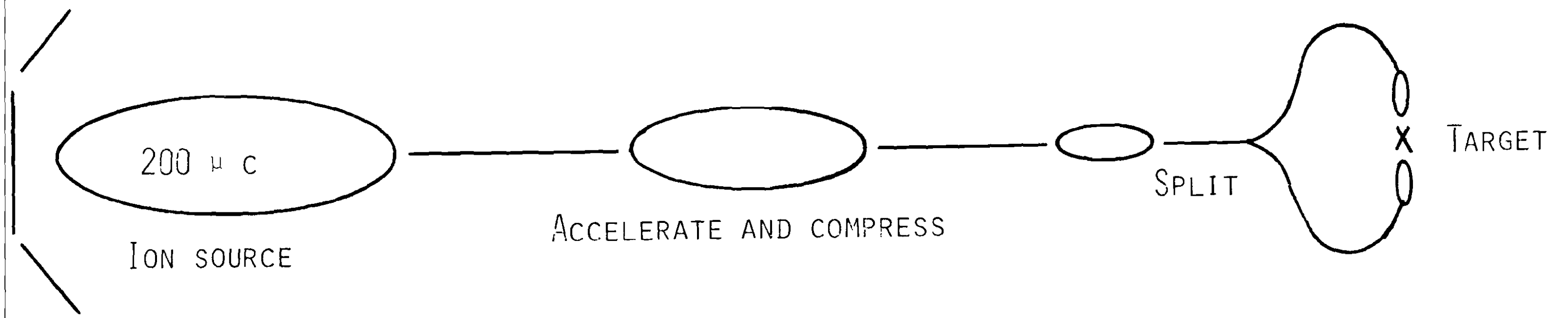
The LBL HIF program has concentrated on the induction linac approach because this type of machine is able to accelerate the entire charge required for fusion in a single, high current bunch, and because of our experience ten years ago using the Astron induction linac at LLL and subsequently building and operating our own machine at LBL. The operation of an r.f. linac with storage rings, Fig. 1, is based on an operating line where, excluding the tree of linacs at the lowest energies, acceleration is along a constant current trajectory to peak energy, and then along a constant energy trajectory as the current is compressed and multiplied to reach the required of beam power (> 100 TW). The operation of the linear induction accelerator, Fig. 2, is along a trajectory where the energy and current are increased simultaneously; at the end of acceleration the beam is split transversely into two groups of beams to provide for higher peak power and a left-right symmetrical pellet bombardment.



R&D NEEDED: ION SOURCE AND LOW-BETA ACCELERATOR
PHASE SPACE DILUTION AT EACH MANIPULATION
VACUUM AND CHARGE EXCHANGE CROSS SECTIONS
COST OPTIMIZATION

XBL 806-10083

Fig. 1 - RF Linac with Storage Ring Current Multipliers



R&D needed: Ion source and low-beta accelerator
Matching and phase space dilution
High-current beam transport
Cost optimization

XBL 806-10084

Fig. 2 - Linear Induction Accelerator "Single-Pass" System

2. REFERENCE DESIGN FOR 1 MEGAJOULE DRIVER

The parameters of our 1 MJ reference design are as follows:

Beam charge = 210 μC (electrical) of U^{+4}

$Q = 1$ MJ $P = 160$ TW

$T = 19$ GeV $R = 0.5$ gm/cm^2

$\epsilon_N = 3 \times 10^{-5}$ radian-meters Pellet radius = 1.25 mm

The major cost, about 80% , of the LIA conceptual design is in the induction accelerator itself, with the injector and source requiring about 10% and the final transport and focusing another 10%. The earliest concept (three years ago) for an induction linac driver was based on a large-aperture (radius ~ 50 cm) ion-emitter which could provide 5 amperes of beam current for injection into a drift tube accelerating structure, followed by iron core induction units at long pulse durations and ferrite core units at short durations. The 1979 version of the system looks very similar, although most components of the system have been examined and cost optimized. The major differences are: that the source current may be increased as required by using multiple beamlets with electrostatic focusing, as proposed by Herrmannsfeldt,[1)] thereby eliminating the need for unwieldy magnetic quadrupoles at low energies; that the induction acceleration may begin economically near the 10 MeV point instead of near 100 MeV; that the magnet occupancy factor (fraction of length occupied by magnets) may be decreased from 50% to about 10% as the energy is increased; that acceleration of bunches less than 100 ns in duration is not necessary; and that final focusing may be greatly improved by splitting the beam into many beamlets near the target chamber. A computer program, LIACEP, has been used for cost optimization of the accelerator portion of the system and has generated the desired operating parameters shown in Fig. 3. As the pulse duration is decreased with increasing beam voltage, the appearance of the accelerating modules changes gradually, from being similar to the modules designed and built at NBS for a 2 μsec., 400 kV pulse, Fig. 4, to being similar to the LLL Astron Injector 300 ns, 300 kV modules shown in Fig. 5, to finally being similar to the LBL ERA 250 kV 45 ns modules, Fig. 6. The applied voltage waveforms used in the electron induction machines shown were flat; for ion acceleration they need shaping as shown in Fig. 7, the details of which are being refined at this time as reported at this workshop by L. Jackson Laslett. Interspersed between the accelerating modules are superconducting quadrupoles whose pole tip field has been assumed to be 4 Teslas for design purposes.

There is still room for invention and improvement at both ends of the machine. At the front, the source parameters as used in the Reference Design were as follows:

Area ≈ 0.5 m^2	Current = 7.5 amps of U^{+1}
Voltage = 1 MV	Beam Charge = 150 μC of U^{+1}
Pulse Duration = 20 μsec	Current Density = 2 mA/cm^2

There is a wide variety of other choices that could be explored for future applications. At present, we are routinely using a large-aperture contact-ionization source for Cs^{+1} ions - this type of source can be used to produce U^{+1} ions. We have successfully tested a smaller alumina-silicate source for producing Cs^{+1} ions - such sources offer significant advantages

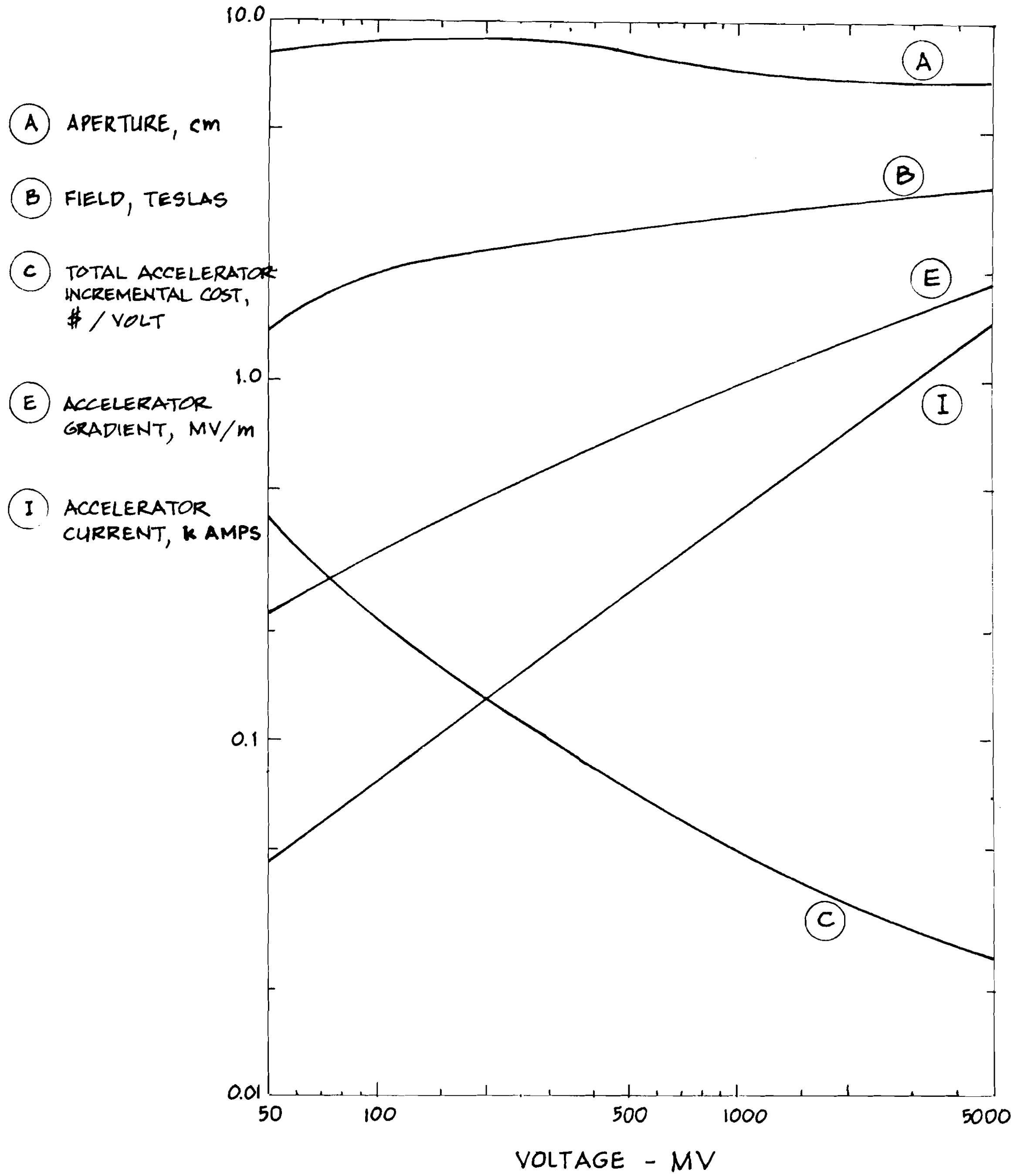


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Fig. 3 - 19 GeV U^{+4} 1 MJ Induction Linac Parameter

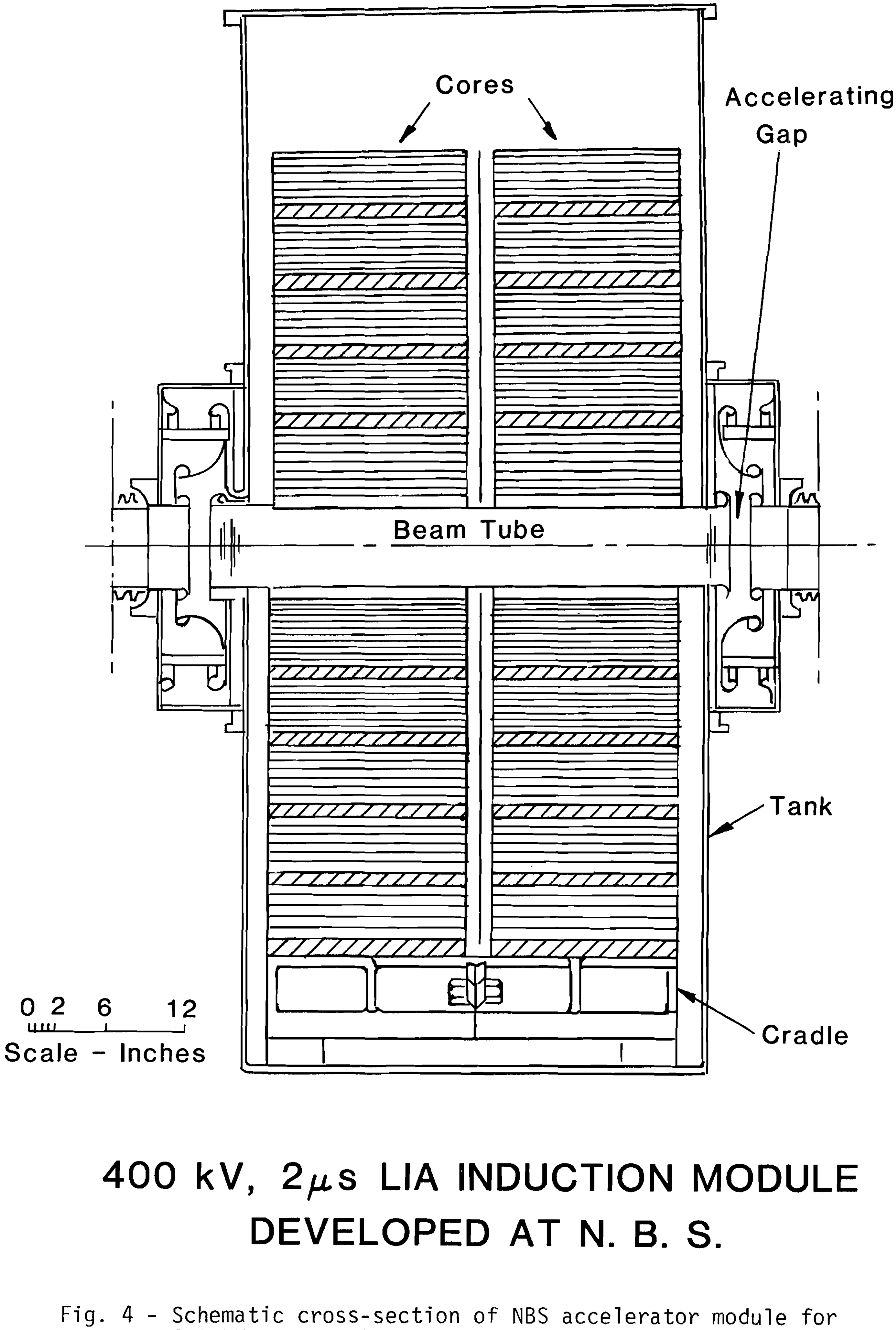


Fig. 4 - Schematic cross-section of NBS accelerator module for 400 kV, 2 μs pulses.

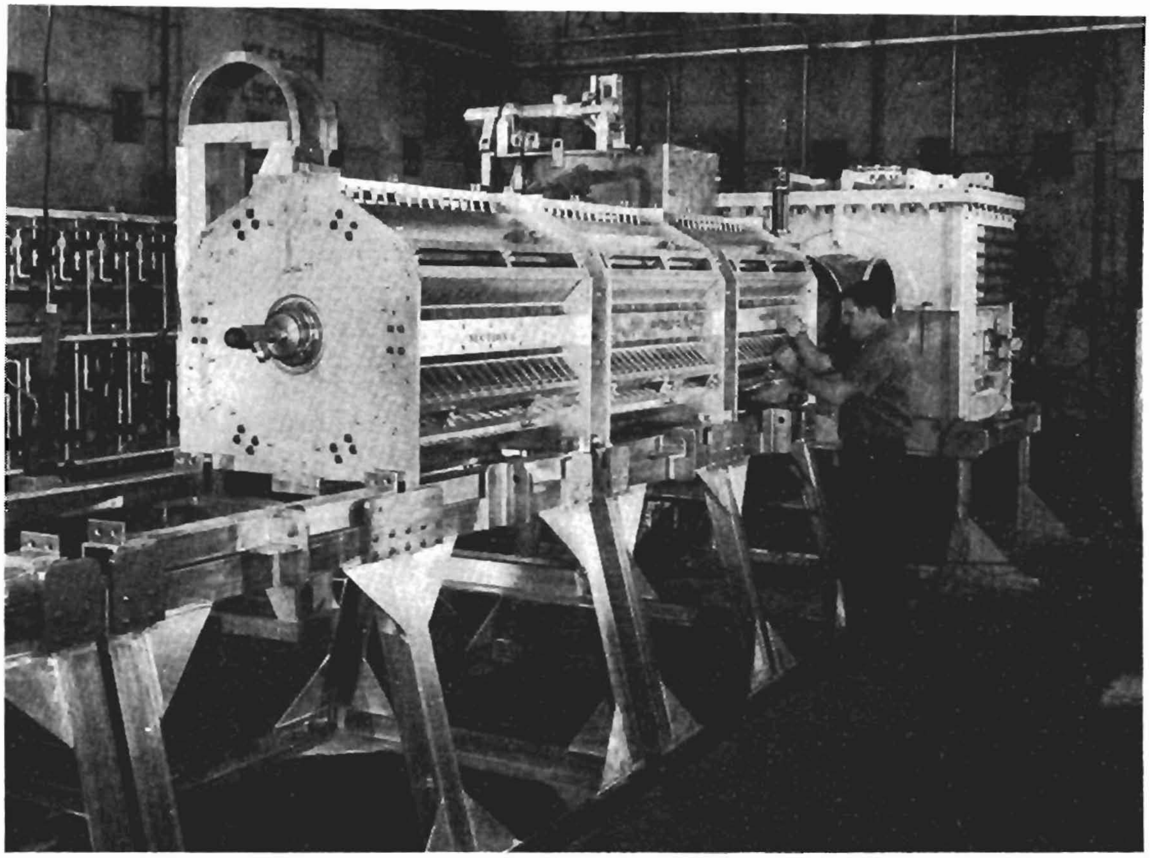


Fig. 5 - LLL Astron Injector accelerator modules for 300 kV, 300 ns pulses.

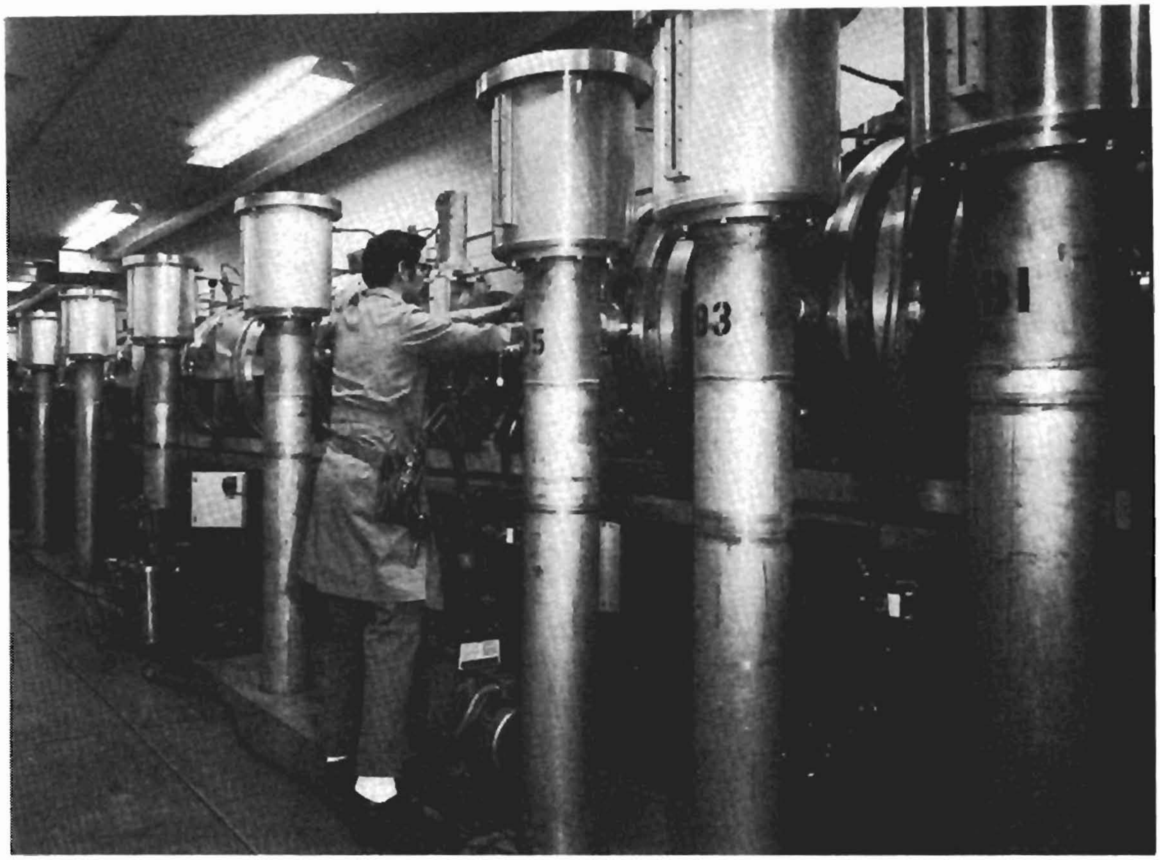


Fig. 6 - LBL ERA Injector Accelerator modules for 250 kV, 45 ns pulses.

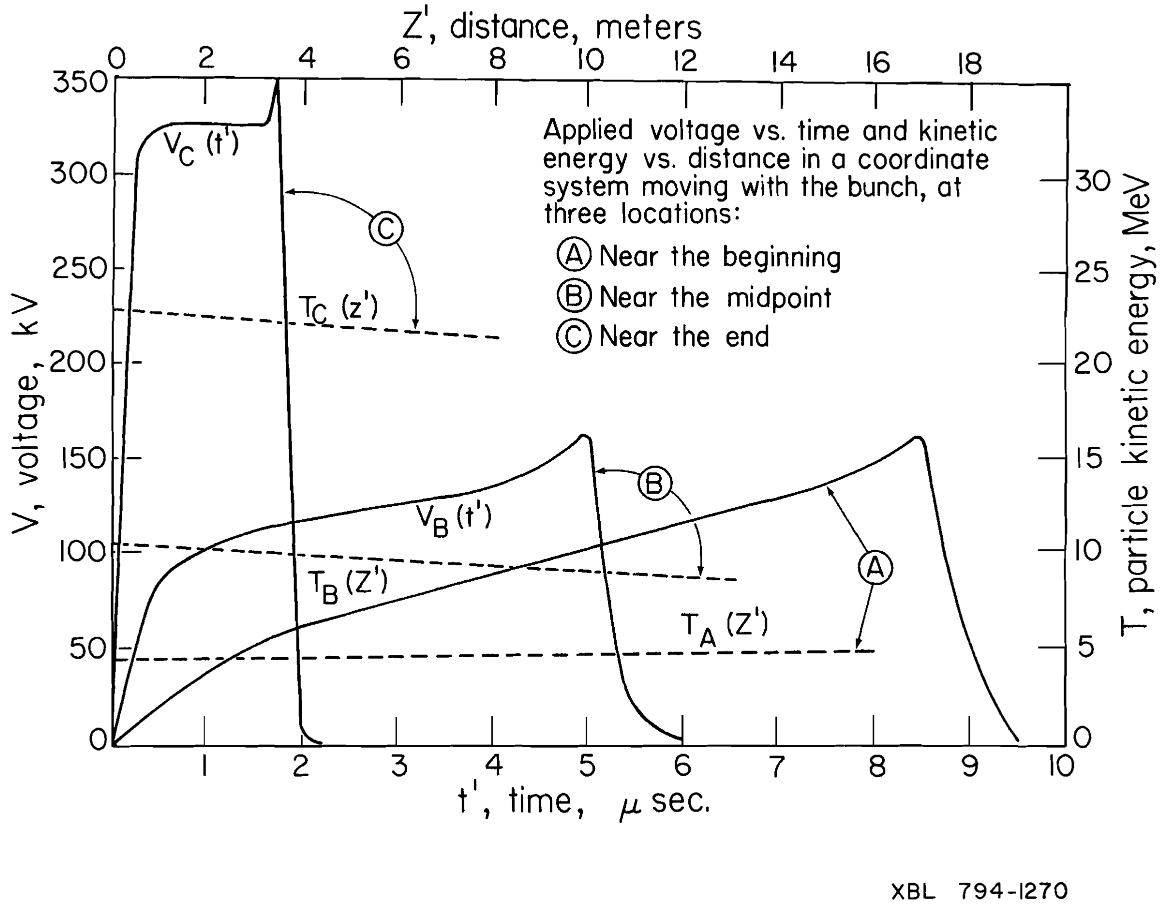


Fig. 7 - Ion Induction Accelerator Waveforms

for the production of thallium ions (mass number: 204). Finally, large-aperture sources, approaching the sizes needed, have been developed at LBL for plasma heating in Tokamaks and would allow production of a wide choice of ion species. One such Ehlers-type source has already produced amperes of xenon ions.

The total source current for some ions such as Cs^{+1} is limited by the downstream transport system rather than by the source itself; likewise, the large diameter sources and beams are dictated by the desire to decrease the transverse space charge fields, rather than by the current density emission limit. No major effort at LBL has been devoted to obtaining ions with masses higher than Xe and Cs, both of which have been generated in sufficient amounts, even though there has been a small advantage shown for heavier ions in some of the conceptual designs. The LBL contact ionization Cs source is shown in Fig. 8. Its emission density is adequate for a 1 MJ driver and would require scaling only in dimensions and voltage.

The injector for the reference design has three pulsed drift tubes. The first two are used to accelerate 150 μC of U^{+1} to an energy of 5 MeV, at which point a helium gas-jet stripper is introduced and an emergent beam with 210 μC (electrical) of U^{+4} ions is created and separated[2)]. This beam is accelerated by a further 8 MeV by passage through the third drift tube, and then enters the induction linac.

Other injector options need careful evaluation in the future. Solenoid focussing has been examined in some detail and while workable, is too cumbersome an approach. The limits of applicability of grid focussing needs

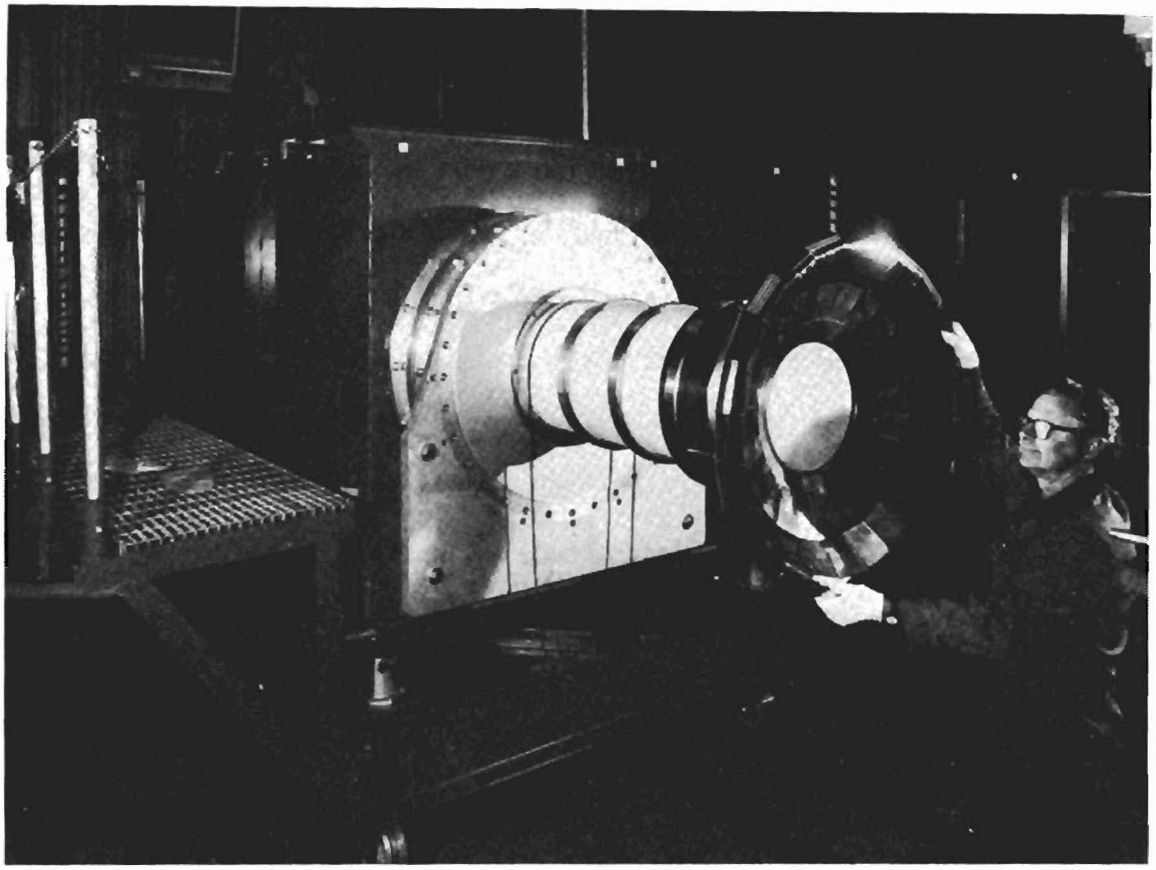


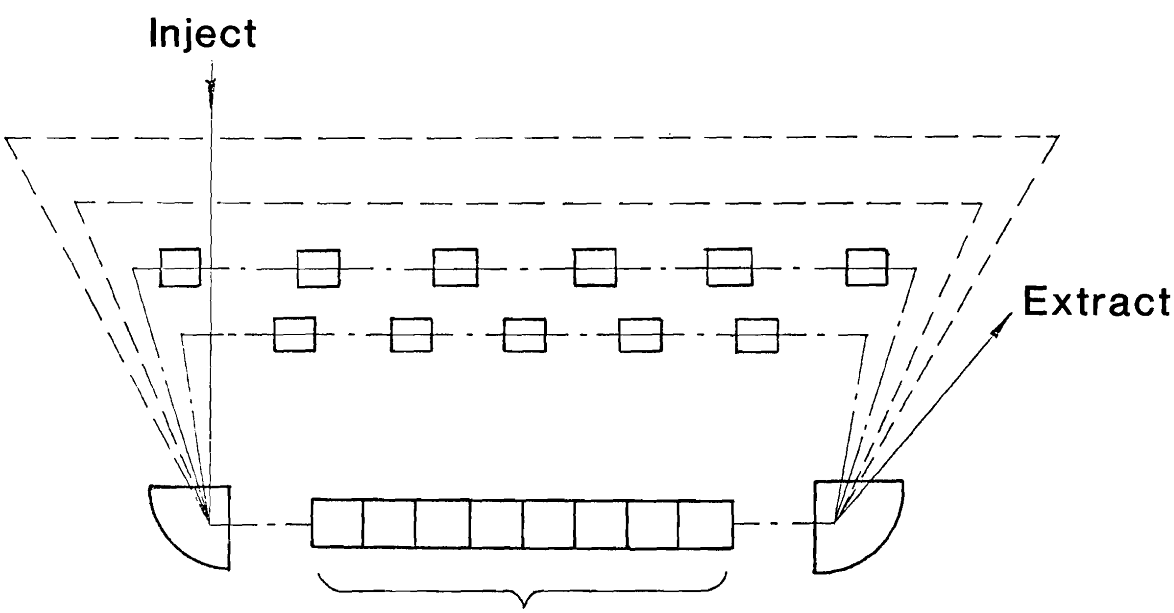
Fig. 8 - 1 Amp Cs^{+1} Contact Ionization Source.

more study and also the use of electrostatic quadrupoles within the drift-tubes (either large-aperture or stacked small-aperture arrays as suggested by Maschke at this meeting) remain to be evaluated. The multiple beam electrostatic focusing system designed by Herrmannsfeldt has been simulated computationally, including space charge, and Figures 2-7 of Reference 1, show the rectangular and annular ribbon configurations as well as particle trajectories through enough of the system to show that it is extendable indefinitely.

Another injector possiblity, the recirculator shown in Fig. 9, allows the acceleration structure to be used several times in one pulse. The magnetic focussing lenses are held at fixed field. The recirculator is limited to long intervals between bunch passage times by the recovery time limitations of existing switches. With any of the alternative concepts shown, and future ones yet to be discovered, the decision on their suitability for use is on the basis of economic comparison. In general the magnetic quadrupoles have proven to be preferable as the energy is increased and the optimum energy for changing from electrostatic to magnetic lenses remains to be determined. At the present stage of conceptual designs, it is significant that at least one source and one injector concept exist, and that their costs are not dominant for the entire system.

A similar mix of technical and economic considerations applies to the final focusing problem. It is clear that the peak power delivered to the pellet may be greatly increased by proliferating the number of incident beams and final focusing elements. An apparently more stringent requirement for the subdivision into several beams is set by the need to keep the emittance of

RECIRCULATOR CONCEPT



Induction Accelerator (5 MV)

Burst Mode: 5-10 pulses with 20 μsec cycle

Current = Constant

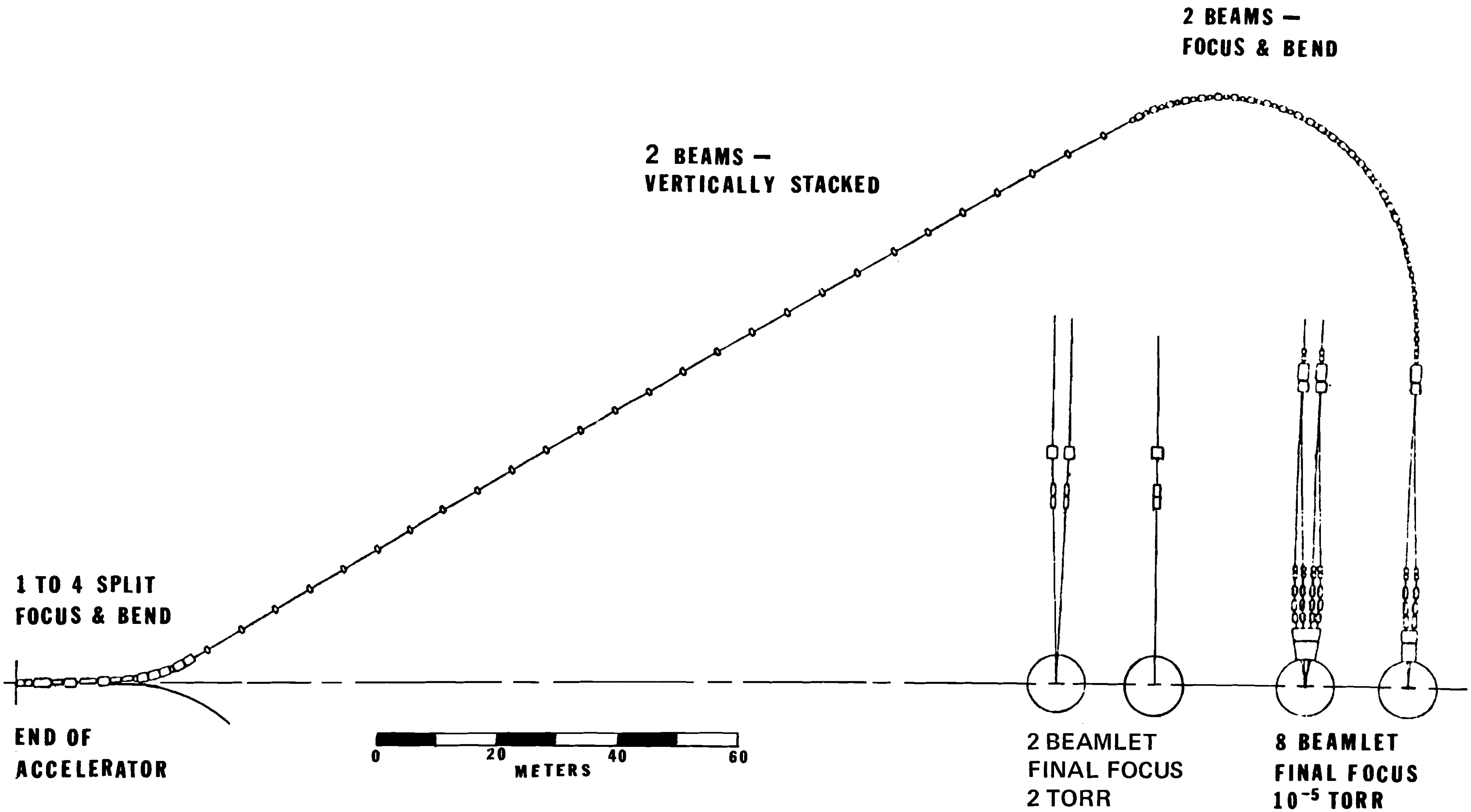
Pulse Duration = Constant

Fig. 9.

each beamlet small enough to avoid third-order aberrations in the final focussing lenses[3,4]. To accomplish such splitting the beam has to be enlarged greatly in transverse dimensions before passage through vertical and horizontal splitting magnets (see Fig. 5 of Reference 4); a necessary condition is that the energy density deposited in the septum edge be less than about 1 kJ/gm to avoid spalling. The gases liberated from the surfaces move too slowly to affect the beam during the passage time of the bunch. Just before the septum splitters that create the major subdivision into two pairs of beams an energy tilt is introduced into the bunch by strongly ramping the voltages in the final 280 meters of induction cores. This will cause the bunch length to collapse from 175 nsec, at the end of acceleration, to 10 nsec at the target, after it has traversed the full length of the transport line. A drawing of part of the final transport system is shown in Fig. 10. All of the estimates for the conceptual design are based on final focusing in a vacuum environment, with perhaps charge neutralization near the pellet. A completely different alternative is for a charge and current neutralized final transport in a low pressure gas, or a co-streaming electron beam. If such a scheme were viable, it would greatly reduce the complexity of the final focusing array of magnets and reduce some of the stringent requirements during the acceleration process.

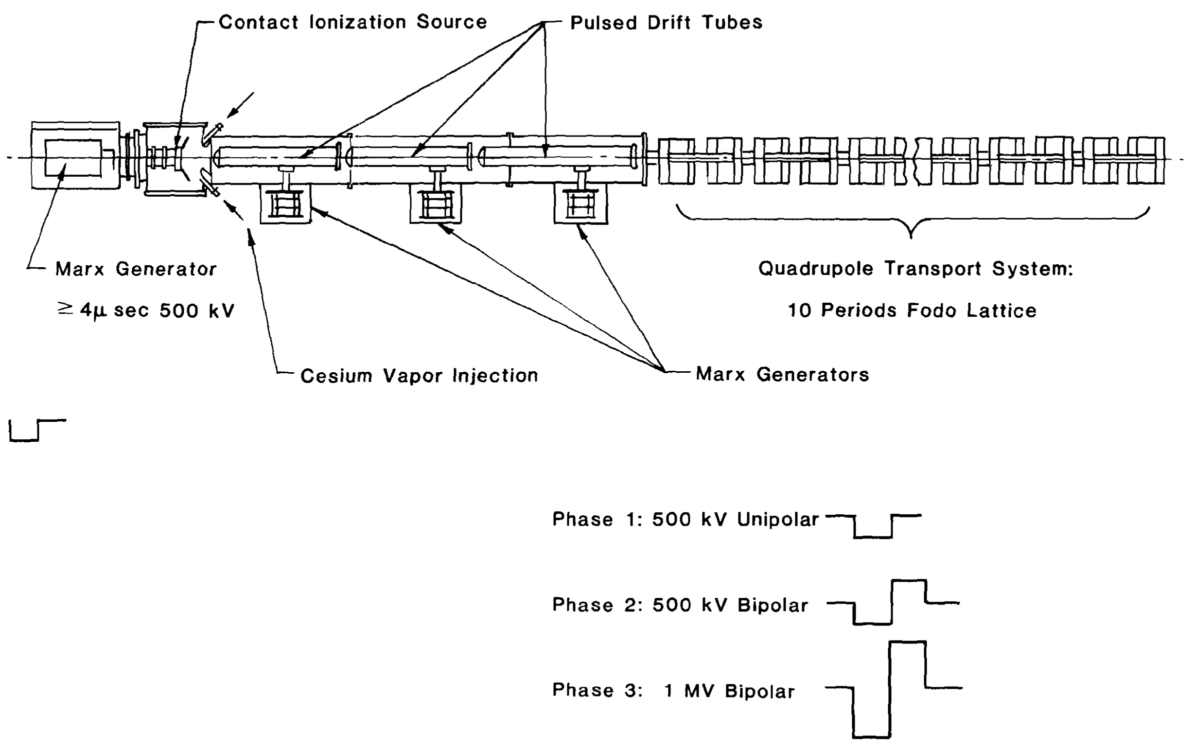
3. CURRENT AND PROPOSED LBL PROGRAM

The ongoing experimental program at LBL and the proposed one for the accelerator development facility (ADF) are aimed at verifying the design criteria experimentally and developing machine specifications. Basic to all HIF drivers is the question of the transverse stability limit in a focusing



FINAL BEAM TRANSPORT AND FOCUS

channel, which has been investigated analytically and computationally, but not yet experimentally. The 1 Amp 2 MeV Cs^{+1} beam propagation experiment, Fig. 11, is a first step towards an experimental verification of the transport theory. It would investigate matching into a quadrupole lattice with intense space charge and a finite bunch, and could roughly check regions of stability and instability. A substantially longer transport system is required for investigating the region near the threshold of instability.



1 AMP, 2 MeV, Cs^{+1} BEAM PROPAGATION EXPERIMENT

Fig. 11.

Figure 12 shows where the present and proposed experiments are in relation to the end goals, and where the research machines for heavy ion collisions are on the same scale; Table I tabulates some of the desirable values. These figures do not include the latest desire of the target designers to move toward lower particle energies.

TABLE I

BEAM VOLTAGE AND CHARGE FOR SINGLY-CHARGED CESIUM*

Example	Charge (μC)	Kinetic Energy (MeV)
1. 4 J (Current experiment)	2	2
2. 500 J	20	25
3. 100 kJ	$\geq$ 45	$\leq$ 2,200
4. 1 MJ	$\geq$ 80	$\leq$ 12,000

* For Uranium the beam charge needed is, typically, one-half that for Cesium.

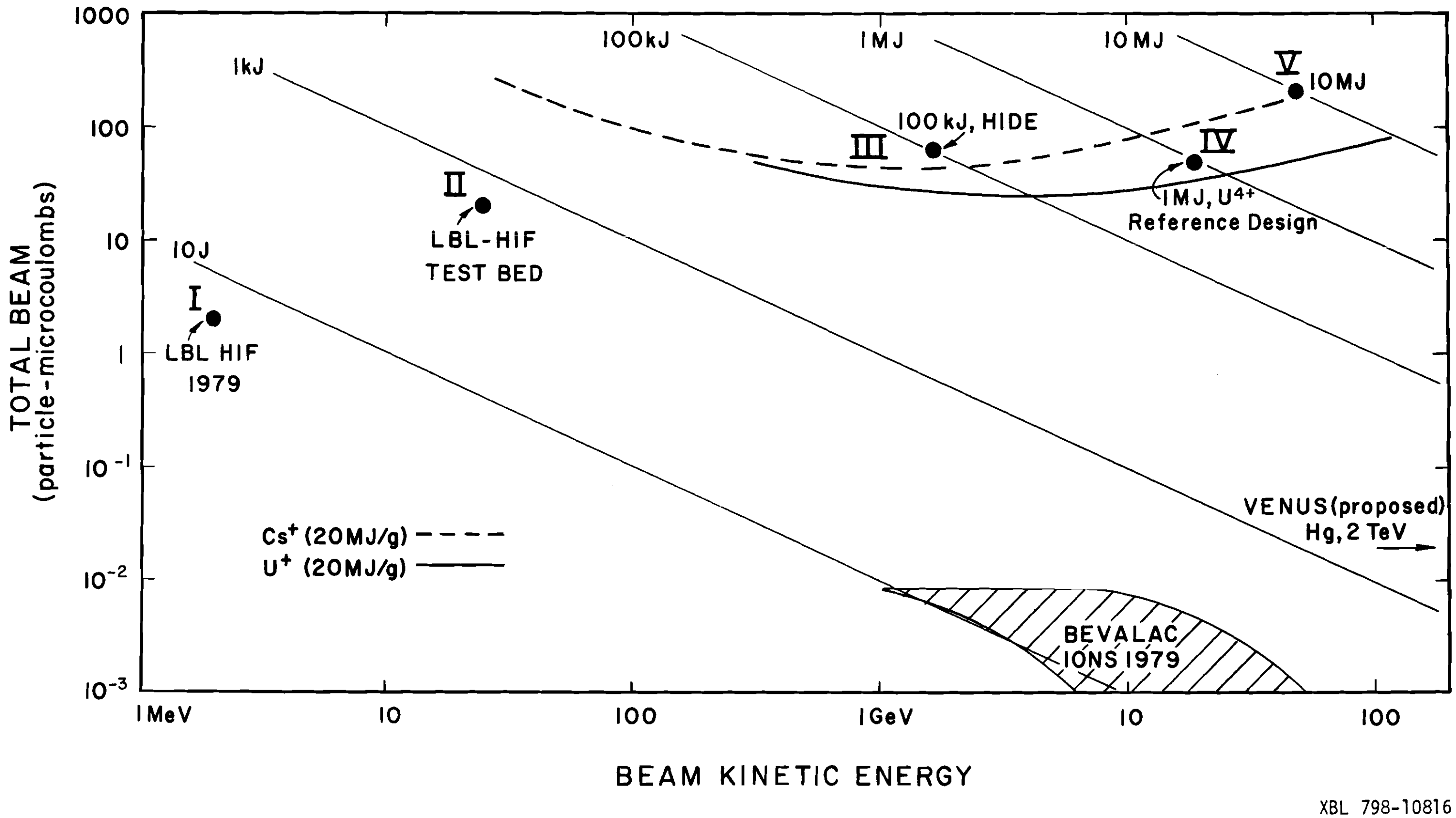


Fig. 12 - Present and proposed Heavy Ion Accelerators

The logical next step in increasing knowledge and experience in the acceleration of a large charge of heavy ions is the building of an ADF to answer some of the following physics questions:

-Beam Quality:

- Prepare and launch beam of significant current and charge into an induction linac structure.
- Show bunching by pulse compression (x1/5) in this structure.
- External bunching by further factor (x1/3).
- Demonstrate satisfactory 6-D phase volume.
- Explore instability limits.
- Realistically evaluate effects of imperfect operation of multi-element system.

-Beam Experiments:

- Focus (<1 cm)
- Bunch.
- Gains from neutralization
- "Damage" in slab geometry
- Beam Splitting

-Accelerate other ions (e.g. Potassium 39)

In parallel it is vital to develop engineering experience that will be needed for the design of HIDE and subsequent machines. Among the engineering goals are:

-Component Development:

- Induction Modules
- Superconducting Quadrupoles
- Periodic Internal Focusing Structure
- Beam Splitter
- Gas Stripper and Analyzer

-A Working Induction Linac to provide a Viable Framework for Higher Energy Designs

-Operating Experience with Emphasis on:

Component Performance

Sensitivity of Timing, Synchronization, Wave Form Errors

Some of the desiderata for ADF are listed in Table III

TABLE II.

One Would Like:	LBL Proposal:
Energy ~ 1 kJ	500 J
$L_{Accelerator} >> L_{Bunch}$ (20 m)	100 m
No. of Betatron Periods > 1	2
$\sqrt{\text{No. of Modules}} >> 1$	$\sqrt{81 \text{ modules}}$
$\sqrt{\text{No. of Switches}} >> 1$	$\sqrt{1000 \text{ switches}}$
Particle Interchange Between Front and Back of Bunch	some

While there are no firm values for the minimum number of elements required and for the other parameters, the values shown are about an order of magnitude above existing capabilities for most parameters, and furthermore, they occur in the most sensitive and interesting part of an ion induction linac. At the low energy end the beam is subjected to the most violent manipulations transversely and longitudinally, excluding its encounter with a pellet, in the entire system. Subsequent acceleration approaches a steady state condition, with a small fractional energy change per accelerating gap and only a modest bunching field required.

The appearance of the ADF is sketched in Fig. 13, and its operating parameters are shown in Fig. 14. The focusing quadrupoles are placed within the accelerating modules because of the low energy transport limits. Within the short length of the ADF, the bunch experiences many of the same maneuvers required in HIDE - specifically, a several-fold increase in the beam current, a physical shortening of the bunch length, and acceleration by a large number of independent pulsed devices which will have practical imperfections. Specifications for desirable waveforms are being developed, as described in the talk at the workshop by Jackson Laslett, and have the trend shown in Fig. 7. Further details are given in Reference 5.

REFERENCES

1. W. B. Herrmannsfeldt, Proc. H.I.F. Workshop, ANL, Sept. (1978), p. 273, ANL Report Number, 79-41.

2. W. B. Herrmannsfeldt, ibid., p. 267.

3. D. Neuffer, ibid., p. 333.

4. A. Faltens, E. Hoyer, D. Keefe, L. J. Laslett, ibid., p. 31.

5. Ion Induction Linac Test Bed, LBL Report PUB-5031 (Sept. 1979).

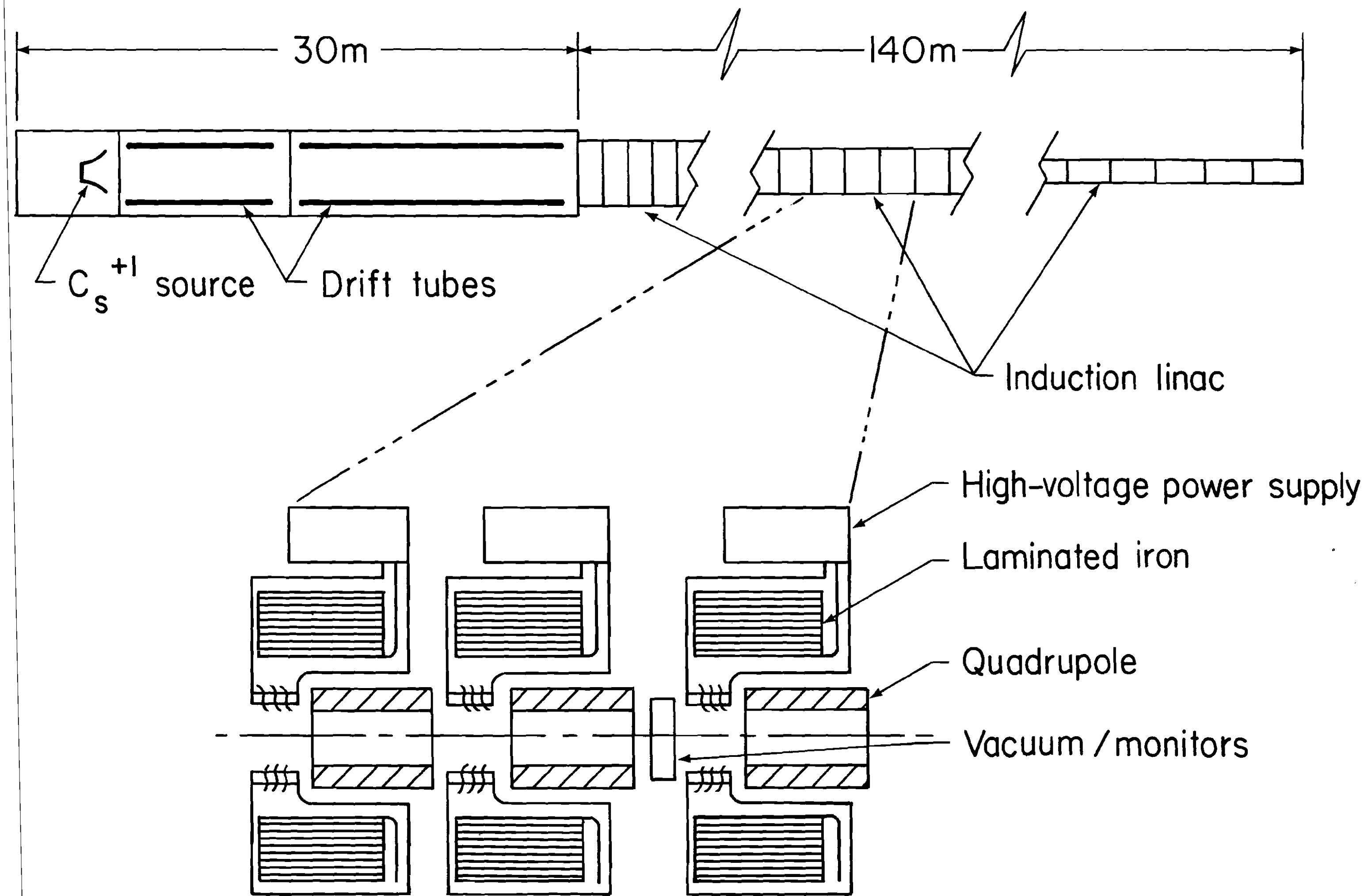


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Fig. 13 - 25 MeV Cs^{+1} 500 Joule Induction Linac Test Bed

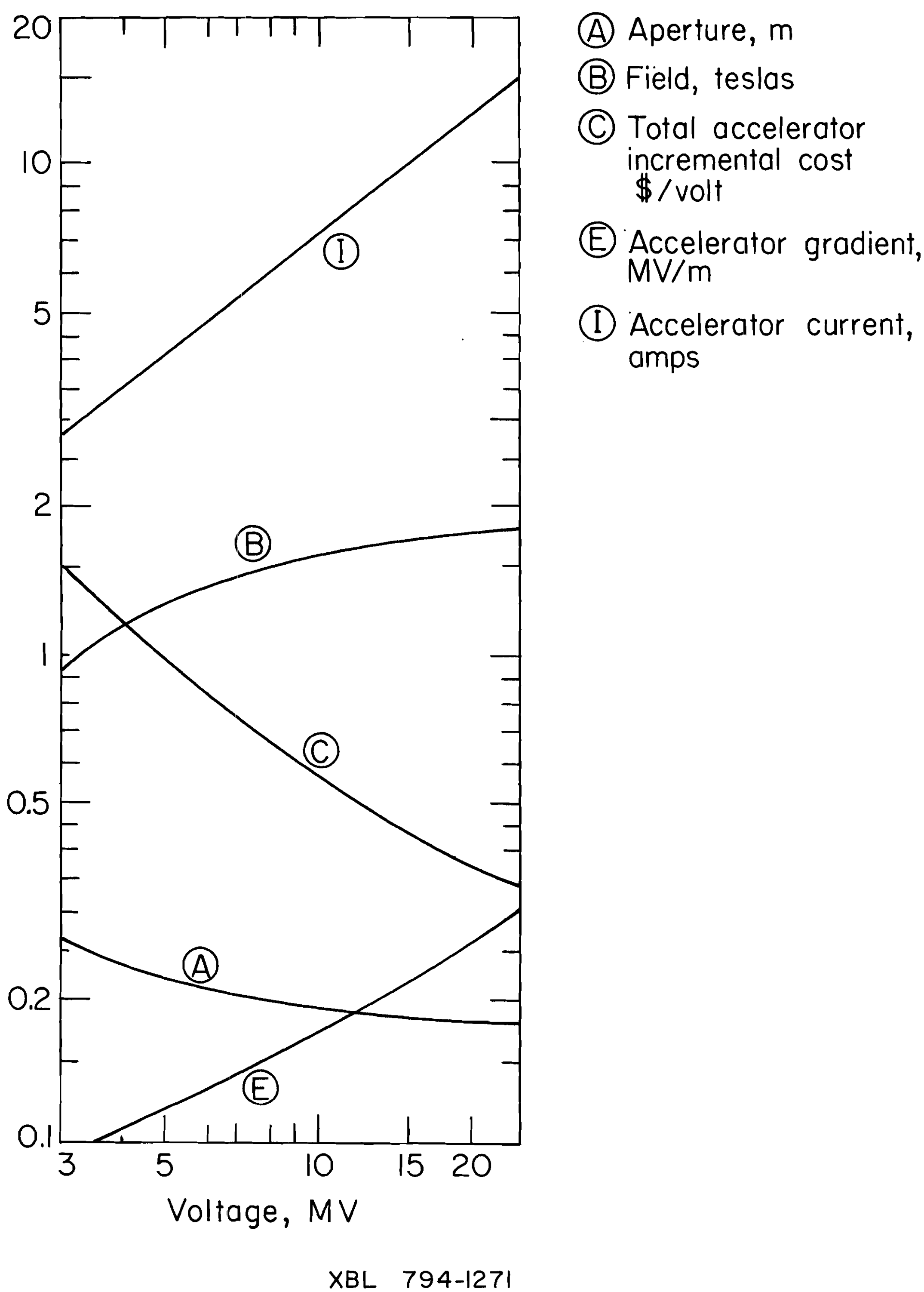

Fig. 14 - 25 MeV Cs^{+1} 500 Joule Induction Linac Parameters