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HEAVY ION FUSION HALF-YEAR REPORT APRIL 1, 1980 - SEPTEMBER 30, 1980

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Accelerator & Fusion Research Division

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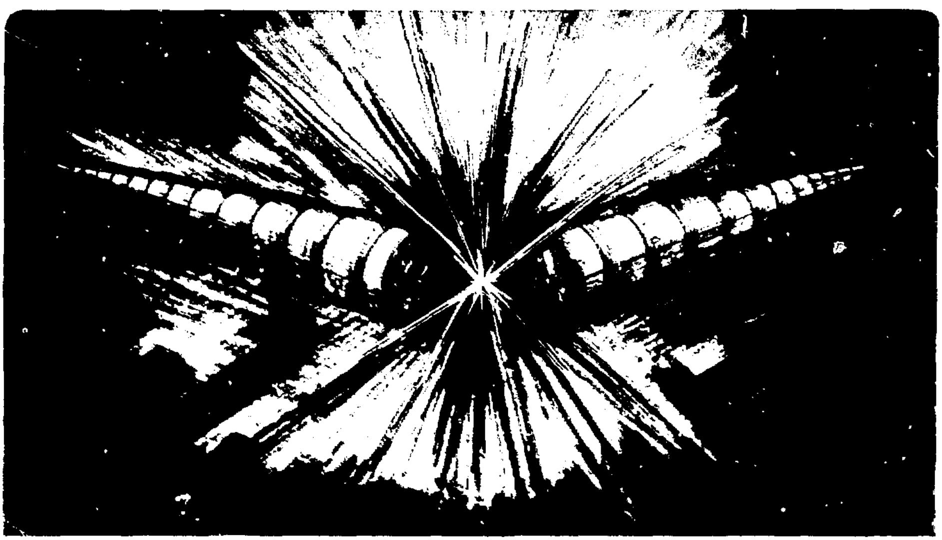

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HEAVY ION FUSION HALF-YEAR REPORT

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Heavy Ion Fusion Half-Year Report

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HIGHLIGHTS

Major accomplishments in the second half of Fiscal Year 1980 include:

The large aperture Cs^{+1} contact ionization source has been operational through most of this period. The full system comprised of source plus three drift tubes was brought into operation early in April 1980. Beam profiles and current measurements indicate that the system performs close to design specifications.

System studies have been expanded to include multiple beam systems, in addition to the single beam systems studied heretofore.

Work has continued on the development of beam diagnostic devices. Most of the effort has been directed toward the development of the electron beam probe and scintillator systems.

Zeolite source development is continuing, with major emphasis on source stability and lifetime.

A model for the longitudinal resistive wall instability has been developed which indicates the induction linac beam should be stable to first order in the resistance. Considerable theory effort has also been concentrated upon the transport of space charge dominated beams through periodic focussing structures.

A multiple electrostatic quadrupole array capable of handling forty nine parallel beamlets has been designed and constructed.

A. EXPERIMENTAL RESEARCH AND DEVELOPMENT ACTIVITIES

1. High Current Cesium Ion Beam Experiment

In April 1980 the Cs^{+1} injector, including all three drift tubes became operational. A diagnostic tank was mounted at the end of the last drift tube for the purpose of studying the accelerated beam in detail. The diagnostic tank contains a large Faraday cup for total current measurements and a small movable probe for beam profile measurements. In addition, different scintillator materials and cellulose nitrate films can be insertea through an airlock. Extensive studies of the beam at 1 MeV energy showed satisfactory profile and emittance measurements ($<2\ 10^{-6}$ mrad). This complete system is shown in Figure 1.

In an effort to increase the beam energy, it was necessary to replace the curved grid in the last drift tube with a new ribbon grid that can hold higher voltages. This change took place in June 1980, during which period we installed moveable radial probes at the entrance to all three drift tubes. The probes are inserted through holes in the drift tubes, perpendicular to the axis. Such probes enable us to follow the beam envelope through the accelerator. The new grid has solved the breakdown problem and the drift tube probes are operational.

A schematic of the injector is shown in Figure 2 along with a shaded area showing the calculated beam envelope. The expected beam envelope is independent of the total beam energy, as long as the voltages at each accelerator gap are equal. The envelope was measured at three locations and is indicated by vertical bars in Fig. 2. The density profile of the beam inside the diagnostic tank is shown in Fig. 3.

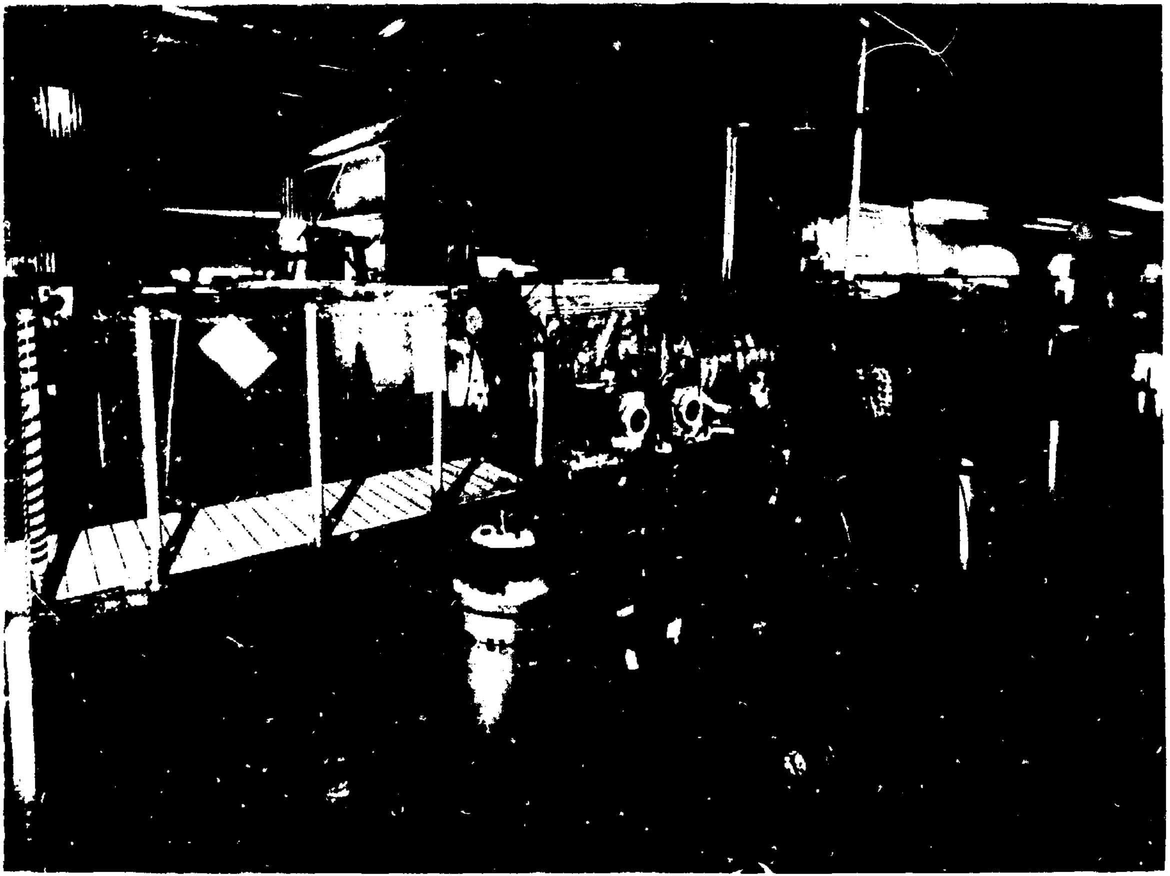

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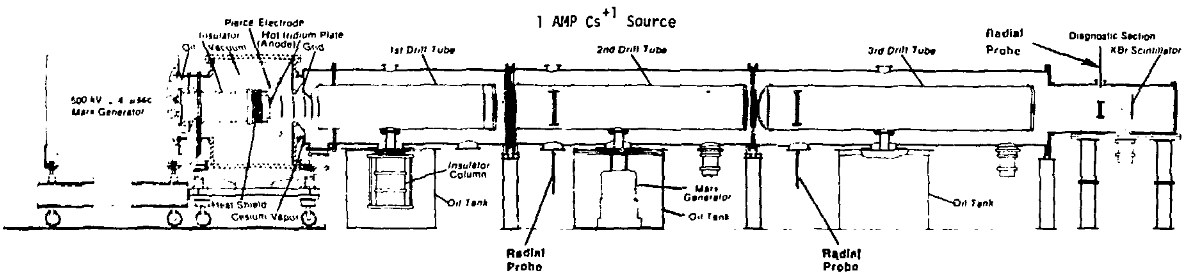
Figure 1: 2.0 MeV Cs^{+1} Contact Ionization Source.
Fuel System showing source plus three pulsed drift tubes.



COMPARISON OF CALCULATED AND MEASURED BEAM ENVELOPES

XBL 8010-12495

FIGURE 2

Figure 2: Schematic of System

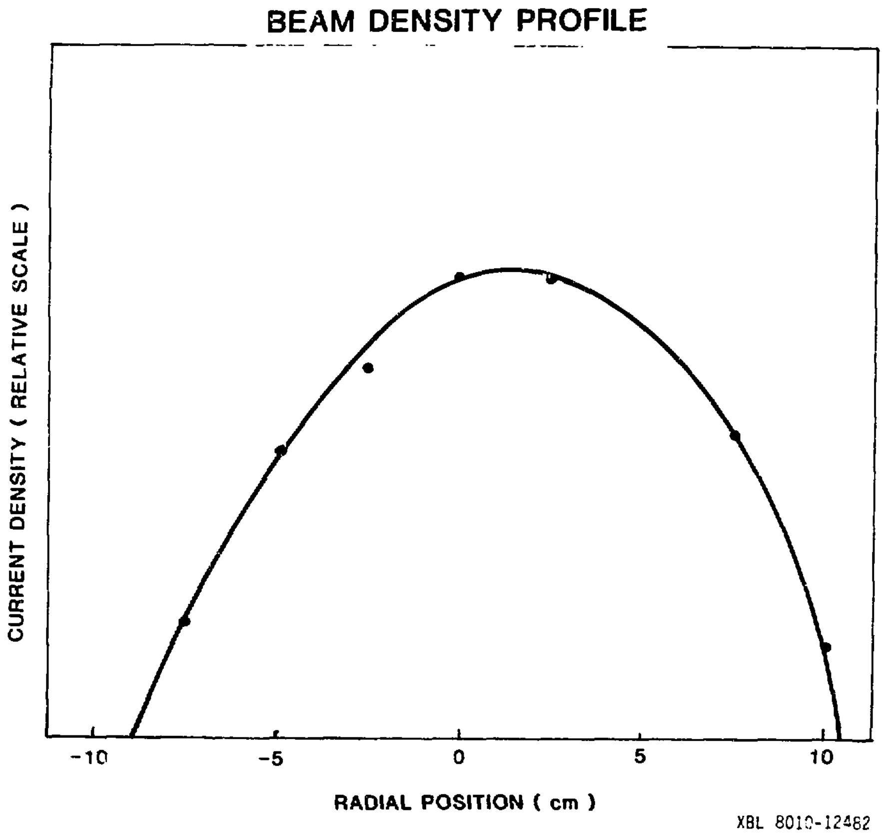


FIGURE 3

Figure 3: Beam density profile

The emittance measurements are done by inserting a slit or a series of slits (0.5 - 5mm wide) inside the diagnostic tank, and following the different beamlets with vertical scanning probes. For a slit size of 1mm the beamlet radial expansion is dominated by its emittance rather than space charge forces. In order to sample the beam at any position on its cross section in addition to following it in the z directions, a new probe was constructed. The new probe is designed to fit in the diagnostic tank and can scan in the radial, azimuthal and axial directions. Its axial motion will be the full extent of the diagnostic tank (1.5m) and its accuracy in the radial position will be ~ 125μm. The new probe is scheduled to be installed in October 1980.

2. Beam Diagnostic Technique Development.

a. The Electron Beam Probe

During the second half of FY 1980 we continued the development of the Electron Beam Probe (EBP) as a new diagnostic tool to measure the Cs^{+1} beam space charce profile. Following the earlier computer studies, which predicted the electron beam deflection as a function of the ion beam parameters a computer program was written for inverting the experimental data. The inversion program uses the measured deflections at different initial angles, as input, and calculates the best fit space charge profile assuming cylindrical symmetry. The program, along with a few examples, is described in HI-FAN-102.

An electron gun, suitable for the EBP, was designed and built. In order to avoid decceleration of the electron beam inside the tank, the gun is biased at 2-20 kV negative with respect to the tank and the accelerating grid. An electron beam has been obtained and detected on a P22 phosphor sheet. The beam is 1-2 mm in diameter and responds as expected to variations in the gun parameters, emitter temperature, anode, cathode and grid voltages. Preliminary tests of the EBP are scheduled for the beginning of FY 81.

b. Scintillator Diagnostics

Scintillator study has continued throughout this period. The (C31000M) photomultiplier has been commissioned and used to study several scintillators.

The materials that suffered rapid radiation damage (loss of scintillation after less than 50 pulses) were:

1. Pilot B
2. $Bi_4Ge_3O_{12}$

They have been eliminated from further consideration.

The materials still under consideration are

1. CaF_2(Eu) which works well except that the rise and fall times of the light output are somewhat slower than we would like ($T \approx$ 500ns).

2. NE 901 glass scintillator which was tested briefly and found to have a complex rise time over ~1μs and a rapid decay (~100ns). This will be studied further.

We are presently making a test scintillator out of pure CaF_2 to see if the slow rise time is associated with the europium dopant which shifts the UV emission of the CaF_2 into the visible region.

3. Zeolite Source Development

Zeolite ion sources may provide a suitable emitter for future induction linacs. An evaluation program of such sources is underway. Commercial sources as well as sources constructed at LBL are being examined. The emission limit of a zeolite is a function of its temperature. Above ~1200^{o}C the zeolite starts to evaporate and its life time is reduced. Presently we have achieved a current density of 100 mA/cm^2 of Cs^{+1} for 5 μs pulses at 0.5 Hz without noticeable decrease in current. Presently we are continuing lifetime measurements as well as measurements of the ionic conductivity inside the zeolite. Thallium and Barium ions have also been produced from zeolite prepared here.

B. INDUCTION MODULE DEVELOPMENT

Work has been continuing throughout on the design and construction of the prototype induction module for the Ion Induction Linac Test Bed, and its associated pulsers.

The pulsers will probably be based on ignitrons because of their low cost compared to thyratrons, but we have been making measurements on the jitter and firing delay of Type A ignitrons from English Electric Valve and from National, as functions of temperature and igniter voltage. At a tube temperature of 40^{0}C, jitter of less than 100ns is achievable. Further study of the required temperature stability is in progress as well as examination of tubes with dual igniters from both manufactures to see if they have less jitter than the single igniter version tested thus far.

We are presently constructing an ignitron pulser with a lumped element pulse-forming network which will drive a dummy load made up of two packages of silicon steel toroids made out of 2 mil thick ribbon. Each package will have 39×10^{-3} volt-sec and they will be driven in parallel. This will provide a good representation of the electrical behavior of a corelet and will be used to evaluate jitter, delay, and life, of the pulser under realistic operating conditions.

Core material tests have continued and have involved mostly examination of winding and insulation techniques as well as drive-strap geometry.

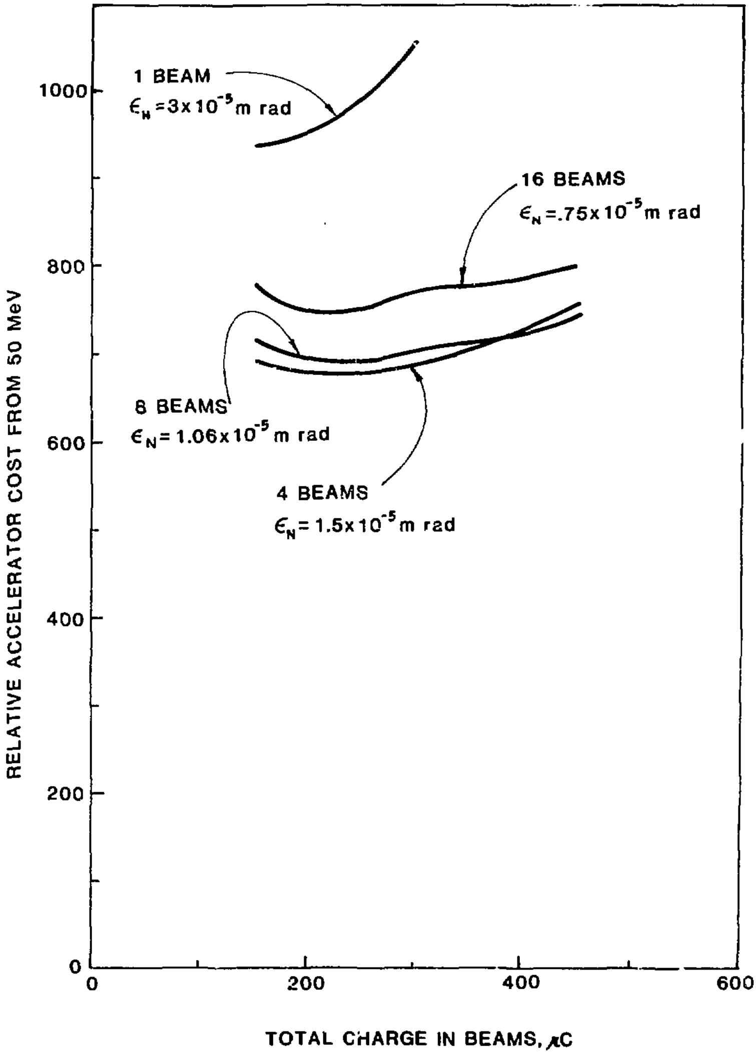
C. INDUCTION LINAC SYSTEM STUDIES

We have been looking at the accelerator sections of drivers to see if it might be economical to accelerate more than one beam in the accelerator.

To accomplish this the computer code LIACEP (Linear Induction Accelerator Cost Evaluation Program) was modified to include multiple beam magnetic focusing elements. Superconducting cosine coil quadrupoles are configured to provide transport of 4, 8, and 16 beams in addition to the single beam case.

Figure 4 shows the relative cost of the accelerator portion of a U^{+1}, 3 MJ driver at 1 Hz as a function of total charge in the accelerator beams. We find that at 225 μc charge, an accelerator with 4 beams, each with 1.5×10^{-5} m-rad normalized emittance and 56.2 μC of charge in each bore, is approximately 30 percent less costly than a single beam accelerator, with a normalized emittance of 3×10^{-5} m-rad and 225 μC of charge. Additional cost savings would show up in the final beam transport for a 4-beam accelerator because the 4-way beam splitting at the end of the accelerator is not required. Also, for this case the accelerator efficiency increases and accelerator length decreases with more than 1 beam.

It is planned to expand this effort to injector options and examine multiple beams with both electrostatic and magnetic focusing elements.



3 MJ DRIVER, U^{+1}, 1 HZ, $\Delta\sigma = 60^\circ - 24^\circ$

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Figure 4

D. INJECTOR STUDIES WITH MULTIPLE ELECTROSTATIC QUADRUPOLES

The injection system for the induction linac uses a system of pulsed drift tubes. The first such structure, which has been operating for some time, and is the subject of discussions elsewhere in this report, has a focusing system consisting only of shaped grids at the entrance aperture to each drift tube. There are at least two major objections to this system:

1. In practice: the grids themselves cause various problems such as beam interception, injection of secondary electrons which partially neutralize the ion beam, and are a source of electrons which may be accelerated backwards essentially shorting out the drift tube gap.
2. In theory: the lack of alternative transverse focusing systems limits the current and pulse length, and thereby limits the charge, I, to values below that needed for the LIA as a fusion driver unless the dimensions are scaled up substantially.

Clearly, a focusing system is required that can be extended indefinitely in length and which could carry substantially higher currents. Electrostatic quadrupoles have been looked at for this purpose for some time, but in order to transport adequate currents, it was found that rather high voltages and poor aspect ratios (i.e., high aperture/length) were needed. A preferable scheme is to subdivide the beam into several ribbon or annular beamlets and use einzel-lens type focussing. On the other hand, if it is possible to adopt the multiple electrostatic quadrupole concept developed by Maschke to this application, then the current per beamlet need not be very high and the voltages are quite modest.

A multiple quadrupole structure has been built which is suitable for insertion in the first drift tube. Some photographs taken during assembly show the simplicity of this device. (See Figure 5). It has 40 beamlets and approximately matches the design performance of the original structure, that is, 1.0 amperes at 1.0 MeV (current scales as $V^{3/2}$). The ratio of quadrupole length to usable aperture is about 30:1. The table below gives the expected performance of the structure when combined with a suitable matching system and multiple aperture gun. (These components have not yet been designed.)

Quadrupole Operation in Drift Tube No. 1

E(MeV)	β	I (mA) (Beamlet)	V Quad	Total Current (mA) (49 Beamlets)
0.4	0.00255	5.4	3360	265
0.5	0.00286	7.6	4200	372
0.6	0.00313	10.0	5040	519
0.7	0.00338	12.6	5880	617
0.8	0.00361	15.4	6720	755
0.9	0.00383	18.4	7560	902
1.0	0.00404	21.6	8400	1058

The currents listed in the table above represent space-charge limited transport with the phase shift for a K-V distribution of 60°-24°. The advantages of this structure include:

1. A simple design (it was designed and built in less than two months for less than $10,000).
2. The fact that the concept can be readily extended to more beamlets, higher currents, a longer structure permitting more charge, etc.
3. The presence of fields everywhere act as clearing electrodes to eliminate trapped electrons.

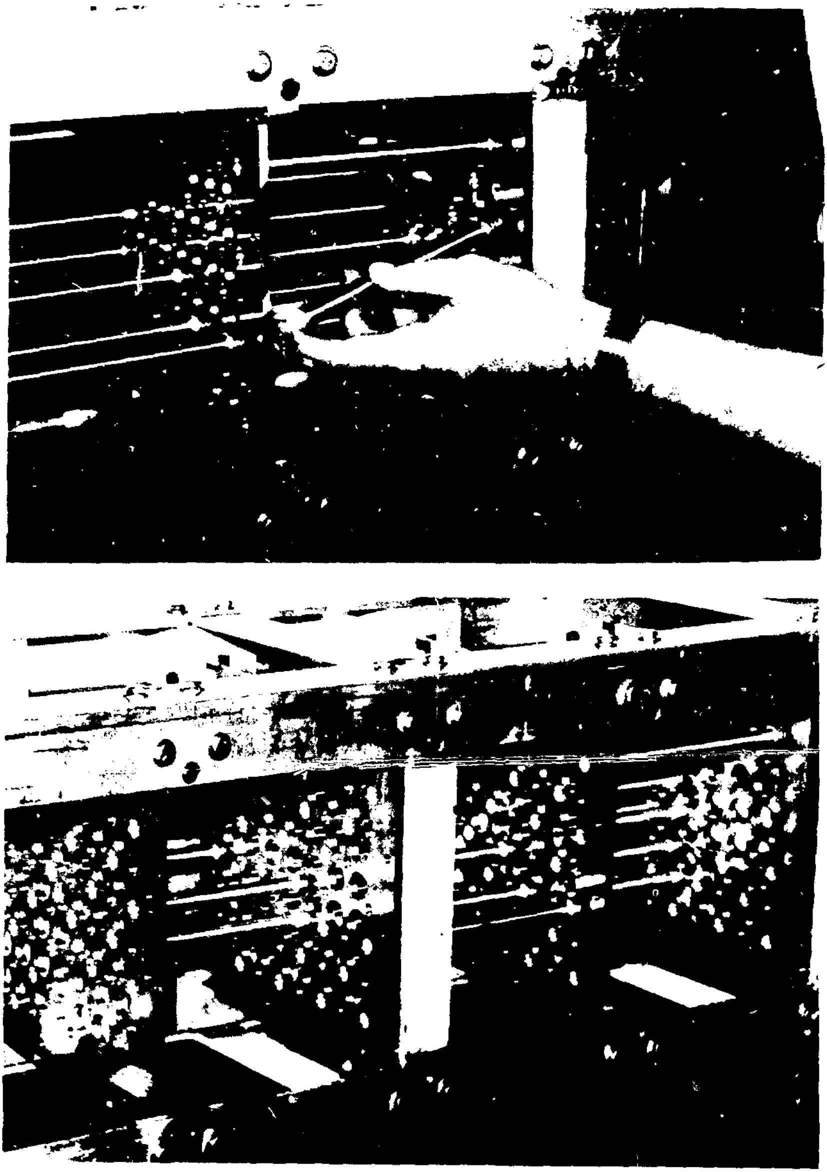

Figure 5: CBB 800 12014

Views of the 49 beam electrostatic quadrupole array during assembly. Alternate end plates are at the potentials of the quadrupole elements which are short pieces of 1/2" aluminum tubing. The tubes are insulated at one end by a ceramic ball and held in place at the other end by a spring.

4. After the first collimation of the beam (in which considerable effective area of the emitting surface is lost) there is no further interception of the beam.

It is expected that this structure will be tested in the next six months. If one assumes success for this approach, it would have important implications for the LIA driver. By greatly increasing the transportable current, by introducing multiple beams into the linac modules, it is possible to reduce significantly the pulse lengths required. This could make large differences in the cost of the LIA and reduces the severity of the beam handling problem in which it is required to compress longitudinally the pulse of charge.

E. THEORY

Final Focusing

After the last Claremont meeting (Nov. 1979), a final focusing array suggested by Karl Brown was designed. This design was then examined by Irving Haber, who was interested in investigating the transverse behavior of a non-KV beam in the final focusing process. His results were rather discouraging, but it was evident that the trouble occurred because the design required the beam to make large excursions in radius while passing through the system. Accordingly, a new array was developed, consisting finally of three triplets, which allowed the beam to expand gradually only once before converging on the target. The system was, moreover, optimized for minimum sensitivity to variation in intensity, mis-matches, and momentum errors. This new design has been used by Haber with excellent results. We conclude that the effect of non-linear space charge forces can be overcome if due care is taken in design of the focusing system. It does seem, however, that at least three triplets are required; for example, it was not possible to achieve the smooth beam profile using doublets.

Electrostatic Quadrupoles

In connection with the proposal to carry out a beam transport through about 90 periods of electrostatic quadrupoles, an effort is underway to examine the consequences of using real quadrupoles, which, unfortunately, are different from the idealized ones in that the fields are non-linear and that particle energy is not constant; i.e. kinetic plus potential energy is not conserved. In a transport line for beams of neglible intensity, these effects are not very significant. However, the point of the experiment is to address a new situation in which space charge fields are comparable to the focusing fields and beam emittances plays only a minor role in determining the matched beam size. In this regime of near cancellation of external and self forces, slight deviations can have a marked effect on betatron frequencies and beam emittance which could confuse a comparison of observed emittance growth with theoretical predictions based on a simple model.

Two approaches are being followed. First, Herrmannsfeldt's electron gun code has been modified to accommodate a quadrupole geometry and can, in principle, provide an entirely self-consistent solution of the problem, including image forces. The modification is operational, though it is not yet demonstrated that it can follow a beam for several periods with sufficient accuracy and at manageable expense in computer time. In the meantime a self-inconsistent approach is being pursued in which the space charge force is taken as linear, the beam is matched by using the non-linear external fields at the beam edge, and individual particle orbits are traced through the resulting total fields. At zero intensity, betatron frequencies depend only slightly on amplitude, but for the conventional "safe" tune depression of 60^0 to 24^0, the frequencies vary by about a factor of two between small and large amplitude. For greater tune depressions, which we would like to explore experimentally, a new effect appears--for large amplitude oscillation in one plane, small initial displacements in the other plane grow at first exponentially, then oscillate at large amplitude and finally vary between large and small amplitudes. If the variable kinetic energy feature is tuned off computationally, this effect disappears, indicating that it might not occur with magnetic quadrupoles. It remains to be seen what is implied in a measure of total emittance and, indeed, if the inconsistent model being used is describing a real effect.

Longitudinal Stability

A serious question has been raised as to the viability of the induction linac concept because of a possible resistive instability in the longitudinal degree of freedom. Energy efficient acceleration requires a high shunt impedance for the accelerating modules, which implies high induced fields by the beam, which are resistive in nature. A proper solution to the problem requires following a bunch through the accelerator, shock exciting sucessive modules in a manner analogous to the transverse beam breakup phenomenon in an electron linac. So far we have resorted to a much simpler model in which the impedance of the modules is represented by a pure, steady state resistance, resulting in a formalism identical with the familiar resistive wall effect. This model, applied to circular machines, has been proven correct for continuous beams but not for bunched beams, for which approximate solutions predict stability whereas in fact instability is observed. Channell, Sessler and Wurtele have developed a theory, starting from a bunch without velocity spread, which predicts stability for an induction linac bunch in lowest approximation and an acceptably small growth rate in higher approximation. The cold beam assumption should be good in this situation, because the intensity is so high that the velocity of space charge waves is much higher than the differential particles velocities; that is, a disturbance rattles back and forth along the bunch much faster than the beam particles themselves. Their result is being critically examined and the search for alternate tractable models continues.

Transverse-Longitudinal Coupling

For very intense beams, both transverse frequencies and the frequencies of longitudinal disturbances are characterized by the plasma frequency, in contrast to the more familiar case of high energy accelerators, in which space charge effects are a small perturbation on both longitudinal and transverse motion. In that case, most stability questions can be considered as longitudinal or transverse since the basic frequencies differ by orders of magnitude. We are studying the behavior of a continuous beam in order to discover the extent to which older concepts should be modified. Two approaches are being pursued -- a Vlasov treatment of a beam uniform longitudinally with a K-V transverse distribution and a fluid model based on a transverse distribution of approximately circular orbits with longitudinal and transverse temperatures. There are as yet no results to report from this work.

Beam Break-up Mode

A notorious instability in electron linacs is called the beam break-up mode. A slightly off-center beam excites a wave-guide mode which further deflects the beam. As a result, the tail end of the beam is lost because of the large induced transverse motion. This effect has been examined for the HIF induction linac case and seems to be unimportant, largely because the deflecting mode in the induction modules have a sufficiently low Q-value that the deflecting fields do not build up to a dangerous level.

F. PUBLICATIONS AND REPORTS

Number	Author	Title	Date
HI-FAN-110 (PUB-5039)	HIF Staff	Ion Induction Linac Test Bed	4/80
HI-FAN-111	L.J. Laslett	Concerning a Focusing Lattice for Parallel Multiple Beams	4/80
HI-FAN-112	L.J. Laslett	Lattice of ± Line Charges	5/80
HI-FAN-113	L.J. Laslett	The Fields of an Axi-Symmetric Beam of Constant Radius and with Density Constant Across the Cross-Section, but with a Longitudinal Variation of λ	6/80
HI-FAN-114 LBL-11429	D. Keefe	Heavy Ion Fusion Papers: Rapporteur Talk for IAEA Fusion Meeting, Brussels	7/80
HI-FAN-115	J. Shiloh	Electron Beam Probe	6/80
HI-FAN-116	HIF Staff	HIF Informal Quarterly Report April 1, 1980 - June 30, 1980	8/80
HI-FAN-117 LBID-244	L.J. Laslett	Image-Field Potential of a Uniformly-Charged Ellipse Situated Between a Set of Conducting Hyperbolic Surfaces	6/80
HI-FAN-118 SLAC-226	W. Herrmannsfeldt	Electron Trajectory Program	11/79
HI-FAN-119	L.J. Laslett	Individual-Particle Orbits in a Periodic FODO Electrostatic-Quadrupole Focusing System	8/80
HI-FAN-120 (LBL-11367)	P. Channell, A. Sessler, J. Wurtele	Longitudinal Resistive Stability of an Intense Charge Bunch in a Linear Accelerator	7/80
HI-FAN-121	L.J. Laslett	Moments of a K-V Distribution	9/80
HI-FAN-122	L.J. Laslett	The Figure of Merit for a Symmetrical Periodic FODO Transport Line as a Function of σ_0 — Numerical Results for an Occupancy Factor $\epsilon = 1/2$	9/80
LBL-11146	D. Keefe, A. Sessler	Heavy Ion Inertial Fusion Presented at the XIth International Conference on High Energy Accelerators, CERN	7/80

LBL 11120 (HI-FAN-123)	A. Faltens, E. Hoyer, D. Keefe L.J. Laslett, L. Smith, R. Bangerter,	Multi-Megajoule Heavy Ion Induction Linacs Presented at the 8th I.A.E.A. Conference on Plasma Physics and Controlled Nuclear Fusion Research, Brussels, Belgium	7/80
LBL 10301 SLAC PUB 2575 UC-28 Conf 7910 122	ed: W. Herrmannsfeldt	Proceedings of the Heavy Ion Fusion Workshop Claremont Hotel, Berkeley California, October 29 - November 1979	9/80

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