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HEAVY ION FUSION HALF-YEAR REPORT. OCTOBER 1, 1979 - MARCH 31, 1980

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HEAVY ION FUSION HALF-YEAR REPORT
OCTOBER 1, 1979 - MARCH 31, 1980
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA

HIF STAFF

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HIGHLIGHTS

Major elements of the program in the first half of Fiscal Year 1980 included:

Characterization of the 1 amp, 1 MV, 2 μs beam after acceleration through one pulsed drift tube. The emittance seems to be more than satisfactory ($\epsilon_N < 10^{-5}$ rad-m).

Observation of current and energy spikes at the onset of the beam pulse occasioned by the unusually long transit-time (~ 1 μsec) of the mass 133 ions across the diode gap. A computer simulation and, later, an analytic treatment gave insight into the transients to be expected before the steady-state Child-Langmuir condition can be established. Additionally, they led to a prescription for a voltage profile that could "fool" the diode into behaving as if space-charge-limited conditions existed even during the early transient stage. When tried experimentally, it worked.

Completion of the full system, comprising of source and three drift-tubes, in February, 1980. Beam acceleration was not tried because we quickly discovered that insulator breakdown on Drift-tube No. 3 indicated that we had exceeded our license in trying to get by with a design that used elements to hand with minimum modification. Because, largely, of the effect on the cost of the Test Bed facility under design, Drift tube No. 3 was converted to a high-voltage test-stand to settle the breakdown question. These tests continued almost to the end of the half-year period.

Development of new beam diagnostic probes for high-intensity ion beams. Some small separate experimental systems have been prepared to test the feasibility of laser-scattering and electron-beam-probe techniques. If promising, these will be transferred to the 1 amp system and, later, incorporated in the Test-Bed. These smaller systems will also allow more suitable studies of benefits from neutralization and of ion source development.

A major re-direction of the design effort on the Induction Linac Test Bed to bring costs, based on R/D funds that include overhead, down from the M$ 40 system (described in LBL PUB-5031) to the canonical M$25. This exercise had its rewards in that the physics and engineering goals, essential to the extrapolation to a HIDE scenario, were preserved. Full documentation of the design is in final draft form.

PART A: EXPERIMENTAL RESEARCH AND DEVELOPMENT ACTIVITIES

I. High Current Cesium Ion Beam Experiment

Experimental studies with the large aperture Cs^{+1} contact ionization source are continuing. During the first quarter of this fiscal year the source together with the first pulsed drift tube were operated extensively. The properties of the accelerated beam (~ 1 amp, ~ 1 MeV) were studied by means of a "diagnostic" tank which contains a Faraday cup, beam profile probe and a KBr scintillation plate to provide an optical measure of beam quality. These experiments indicate that the source and acceleration system behave as designed. That is to say, the Child-Langmuir $V^{3/2}$ behavior is obeyed over a wide range of voltages up to the design maximum and the envelope follows the EGUN calculations by W.B. Herrmannsfeldt for a space-charge dominated beam.

It was observed that the presence of a 1/4" deep "honeycomb" grid in the drift tube nose produced enough ion collisions to give rise to slow secondary electrons which could neutralize the beam space charge. Under these conditions, the beam envelope decreases considerably in cross-section. By applying, variously, axial and crossed magnetic fields at different locations we were able to establish conclusively that the rather heavy grid was indeed the origin of the neutralizing electrons. Thus at the expense of scattering a small fraction of the beam it appears possible to transport considerably more beam through a given structure than in the unneutralised case. A system of this type would require similar neutralizing grids in the subsequent drift tubes but the accompanying deterioration of beam quality would still be within acceptable limits. This will be explored further as additional drift tubes are added. In the meantime, the heavy grid has been replaced with a fine-wire, highly transparent grid and electron neutralization has been eliminated.

The present current pulse is about 6 μsec in duration of which the first and last 1.5 μsec are not represented by the Child-Langmuir steady state current flow condition. In order to understand further the transient behavior a one dimensional computer code was developed. The first use of the code was to calculate the beam current and energy as a function of time at the emitter and collector with one accelerating gap and one drift space in between. Two

results were obtained: 1) transients in beam energy and current died out in a time of the order of the transit time of a particle in the Chile-Langmuir limit (for the actual system with a gap of .5 m and 1 MV potential this time is ~ 1 μs); and 2) the calculated beam pulse and the observed beam pulse are nearly identical indicating that longitudinal forces, especially space charge, are what really determine the profile of the beam. The second use of the code was to calculate what the applied electric field (as a function of time) should be to produce a completely square current pulse. At the same time, in fact, an analytic solution was developed as well. A first order approximation (adjusting the applied electric field risetime to ~ 1 μs from ~ 200 ns) in the real system produced an immediate improvement in the beam pulse shape.

Immediately following these experiments, the "diagnostic" tank was removed and preparations for the installation of the second and third pulsed drift tubes were begun. During the course of this work, one drift tube housing and drift tube insulation support assembly was set up and instrumented to determine the maximum voltage holding capability of the drift tube insulator column. This information is particularly needed at this time to guide the "Induction Linac Test Bed" design (See Part C).

Initial test results indicated a need to provide insulator shields on the vacuum side of the column (See Fig. A-1). Once this was done spark damage to the insulator surface was greatly reduced. The insulator was next voltage-conditioned by raising the voltage in increments to the point of breakdown. At any given voltage below a maximum voltage limit the sparking rate diminished to a very low rate and the voltage holding-time increased. The voltage was then raised and the process repeated until a voltage maximum was reached where sparking always occurred.

The early conditioning tests proceeded quite slowly. Many high voltage breakdowns accompanied by energetic x-ray bursts were observed. In the early stages of conditioning these breakdowns were usually fast but, as conditioning continued longer, slower bursts of x-rays lasting some tens of microseconds were observed. In addition pressure bursts were also observed to accompany these slow breakdowns. We suspect that this was due to adsorbed gas on the insulator surface. We also observed that any conditioning achieved was not permanent. If pulsing was interrupted for some hours, re-conditioning was necessary.

The next step taken was to de-gas the insulator column assembly. It was not practical to use direct heating techniques and we decided instead to use the glow discharge techniques of de-gassing The system was subjected to an argon gas glow discharge at ~ 0.1 torr of approximately 300 volts and 1.5A with a continuous flow through of Argon gas. Monitoring partial pressures with a residual gas analyzer, we were able to effect an order of magnitude reduction overnight in the H_2O peak in the mass spectrum.

Upon subsequent pumpdown and voltage-conditioning tests, we observed a much more rapid voltage conditioning process and a remarkable reduction in the full-gap first breakdown rate as evidenced by a great reduction in fast x-ray bursts. In addition, the long slow x-ray bursts disappeared quite rapidly as well as the accompanying pressure bursts. We have accordingly incorporated this technique as a standard procedure. As a final result, we have determined these insulator columns capable of holding 600 kV for > 20 μs. The original and modified insulator column designs are shown in Fig. A-1 (right-hand drawing).

At the present time the full system consisting of the large aperture Cs^{+1} ionization source plus three pulsed drift tubes is being installed and will be in operation in April 1980.

II. Beam Diagnostic Technique Development

We have devoted considerable effort to the development of new beam diagnostic techniques which will be beneficial to the understanding of beam transport problems and beam quality determinations for beams that are dominated by self space-charge fields. Non-destructive diagnostic techniques are of particular importance throughout the accelerator system and thus are felt to deserve special emphasis.

We describe below a development applicable to the present Cs^{+1} beam experiments in which Ba^{+1} is utilized, for convenience, as a surrogate in the optical analysis. A second technique utilizing an electron beam probe, which has a more general applicability, is also described. A third technique -- destructive but powerful -- involves the use of scintillators with a photo-multiplier array read-out to provide space and time resolution.

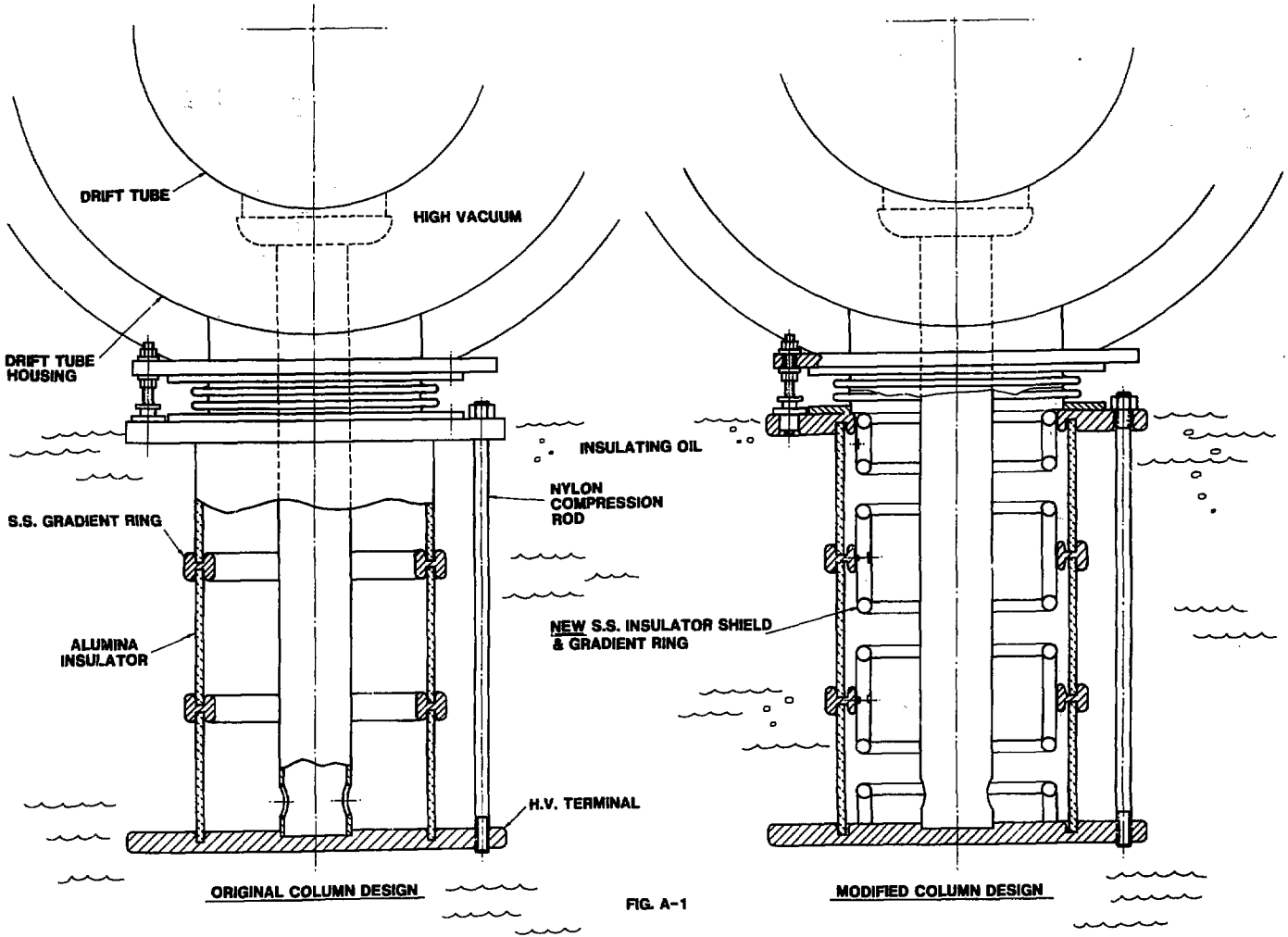

FIG. A-1

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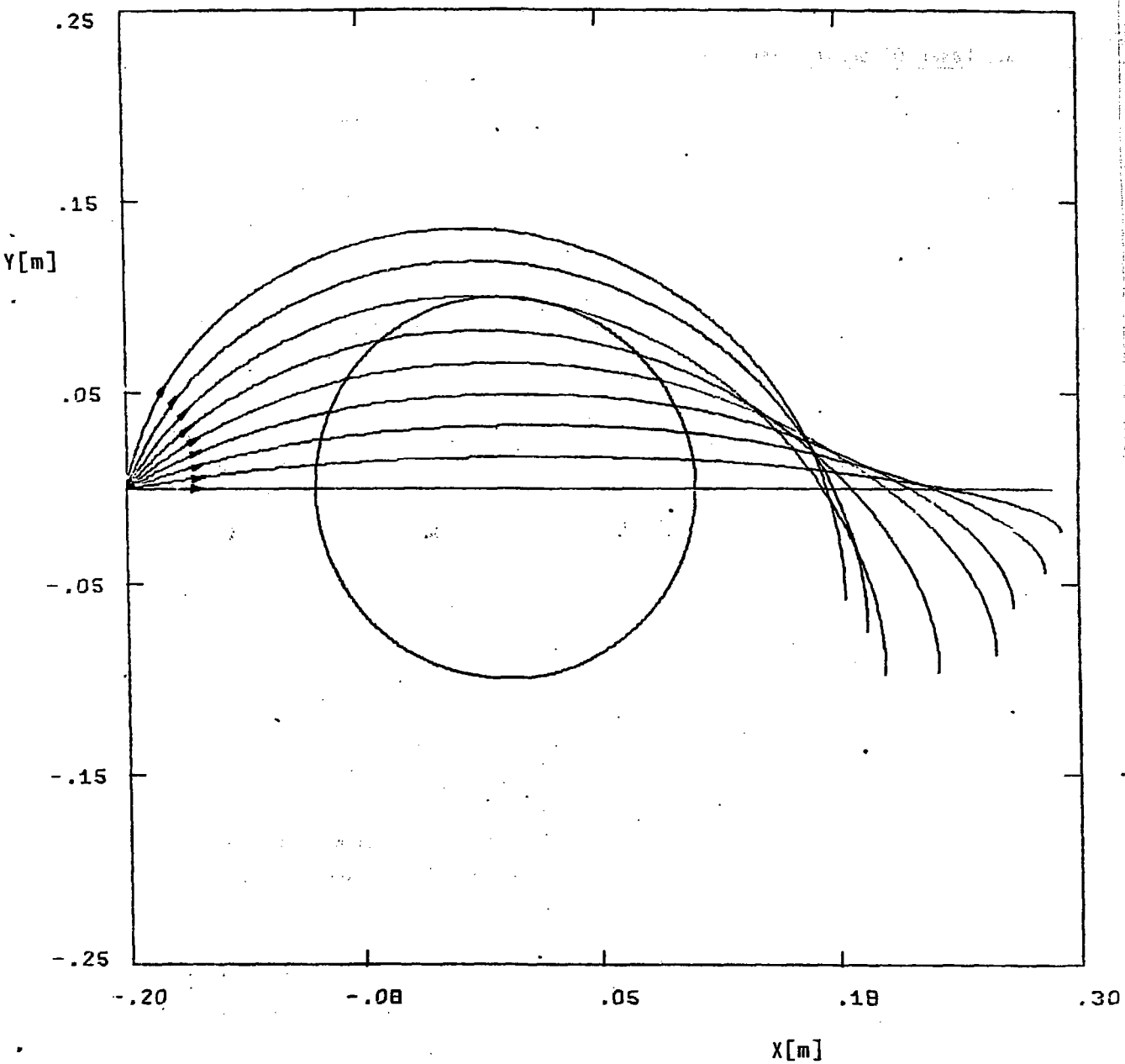


Figure A-2

Trajectories of 9 electron beams passing through the ion beam.

Ion beam parameters: Q = 1 μC/m

R = 0.1 m

Electron beam parameters: E = 6 KeV

ϕ = 0 - 80 deg.

a. Laser Diagnostic Techniques

Resonant laser scattering provides a way of measuring the ion velocity distribution in an ion beam in a given direction. By shining the laser light transversely to the ion beam and observing the Doppler broadening (~ 0.5 A) of the spontaneous emission at 90 deg. the transverse velocities can be measured. Corresponding measurements with the laser shining along or against the beam will give the longitudinal energy spread. Thus the 6-D emittance might be measured. These are desirable measurements for the proposed induction linac test bed and and subsequent accelerators.

Although it is not a trivial task to identify a suitable heavy ion with a first excited level within the wavelength range of available lasers, Ba^{1+} appears to be a reasonable choice with the first excited level at 4554 A (6^2S 1/2 → 6^2P 1/2). A disadvantage of Ba^{1+} ion is that the contact ionization requires a hotter surface temperature (1800 deg. K) than for Cs^{+1} (1200 deg. K). (Another way of generating Ba^{1+} from Zeolite may alleviate this problem.)

The laser diagnostic test facility consists of a vacuum tank 6" in dia. and 24" long, evacuated with a turbo-molecular pump, an ion source (contact ionization or Zeolite) which generates a heavy ion beam of variable energy up to 20kV, and a 100kW tunable dye laser (Phase-R DL 1100) of 300 nsec duration which illuminates the ion beam and excites the valence electron to the first excited level. The line shape of the resulting spontaneous emission is measured with a Fabry-Perot interferometer.

Currently we are investigating ways of generating an uncontaminated Ba^{1+} ion beam from a hot Zeolite surface. The laser is operational. We are in the process of installing an intra cavity dispersive element, a triple prism, which will enable us to tune the laser frequency with $\Delta\lambda$ = 0.5 A.

b. The Electron Beam Probe

The strong space charge associated with the Cs^{+1} ion beam and its possible neutralization by electrons, greatly affect the beam dynamics. Our past experience calls for better diagnostics of the beam space-charge distribution as a function of time.

During this first quarter of 1980 we have been studying a new and non-destructive space charge diagnostic employing an electron beam as a probe. In this scheme, a beam of electrons (1 mm diameter, 1-10 μA, 1-10 keV) is injected perpendicular to the ion beam at an angle with respect to the center of the beam. While passing through the ion beam, the electrons are subjected to the space charge forces and are deflected accordingly. For a given space-charge distribution, the electron-beam trajectory is a function of its initial position, angle and energy; and the measured deflection can be used to determine the beam space-charge distribution as a function of time. Our preliminary studies include a computer program to determine the trajectories, given the ion-beam and electron-beam parameters. A typical example of the computer output is shown in Fig. A-2. In this case the ion beam is taken to be infinitely long, 20 cm in diameter and with uniform space charge distribution of 1μC/m (these parameters correspond to a beam space charge potential of 10 kV between the edge of the beam and the center, and another 10 kV between the edge and the wall. The electron beam is injected with 6 keV and its angle is varied from 0-80 deg. in steps of 10 deg.

The electron beam will be chopped in time and, after passing through the ion beam, can be detected on a standard phosphor from which both spatial and time information can then be inferred. Currently we are adapting an existing inversion program for the measured data; in addition, we are constructing a proof-of-principle experiment.

c. Beam Scintillator Techniques

One way of imaging a charged particle beam is by means of a scintillating material on a screen, but data for scintillations caused by very slow ions is limited. Provided that the scintillator has a sufficiently fast flourescence lifetime and the viewing system is sufficiently sensitive, the advantages are:

1. viewing of the beam as a function of both time and position simultaneously;
2. using a lens for readout allows the scintillator screen to be placed in high voltage areas, e.g. inside the drift tubes, so that the beam profile can be observed at any point in the accelerator system.

At present we have been using KBr as a scintillator. Although this material works moderately well, it has a rather long fluorescence decay time (several hundred ns) and a low photon yield. Next, we will test $CaF_2(Eu)$ and $Bi_4Ge_3O_{12}$ in 1 μm thick layers. Later we will test 1 μm thick layers of Pilot B scintillator, and we will also investigate glass scintillators. The scintillator samples will be inserted through an air lock in the diagnostic tank and examined with an RCA 8575 photomultiplier coupled to a Jarrell-Ash 0.5 m monochromator to look at the scintillator rise time as a function of frequency. We will also install an RCA C3100M photomultiplier which has good sensitivity down to a wavelength of 180 nm. This will allow us to study scintillators in the UV region.

B. CORE MATERIALS TESTS

In this reporting period we have carried out tests on toroids made of amorphous magnetic glass materials produced by Allied Chemical Corporation and TDK Industries. The toroid from Allied Chemical was made of their Metglas 2605 SC in a 1" wide ribbon and had a net weight of Metglas of 290 grams. At a packing fraction f = 0.77 it gave a magnetization swing $\Delta B = 1.44T$ (i.e. 1.86T in the Metglas itself) and a core loss of 400 J/m^3 at a pulse width,

t_p = 2 μs. In terms of its behavior as a core material it is already competitive with $Ni_{50}Fe_{50}$ alloys at a much lower price in mass production.

The material from TDK was in the form of tiny test toroids, 31 mm OD and 6 mm high. This core also gave good performance having ΔB = 1.5T at f = 0.9 and losses of ~ 400 J/m^3 at t_p = 2 μs. We are presently negotiating with TDK to purchase a larger toroid of this material.

Our main aim at this point is to help stimulate the commercialization of a meterial of this type which would be useful for induction linac cores and good working relationships with the manufacturers have been developed, and Allied Chemical have recently indicated interest in the possibility of supplying material for the Test Bed. We are encouraged that the common interests of LLL, LBL, and SLA in this type of material is increasingly catching the attention of the suppliers.

C. ION INDUCTION LINAC STUDIES

During the past 6 months effort on the Test Bed has been primarily directed toward rescoping the test bed and accelerator-component design.

Early in the fiscal year budget considerations necessitated modifications to the Ion Induction Linac Test Bed, previously described in PUB-5031. We have examined options where the total cost of the project meets prescribed reduced budget guidelines. The objective was to meet most of the initial test bed goals with reduced funding. Considerable computation, preliminary design, and costing for this new objective was carried out.

The logical sequence of this process has been to lower the beam current from 2.75 amperes to 1 ampere; the reduced current results in smaller required beam apertures along the machine, leading to smaller quadrupoles and cores. The reduced beam diameter also allows a physically shorter sausage of charge,

while still maintaining a satisfactory aspect ratio, enabling the injected pulse duration to be decreased, from 7.3 μsec to 5.0 μsec.

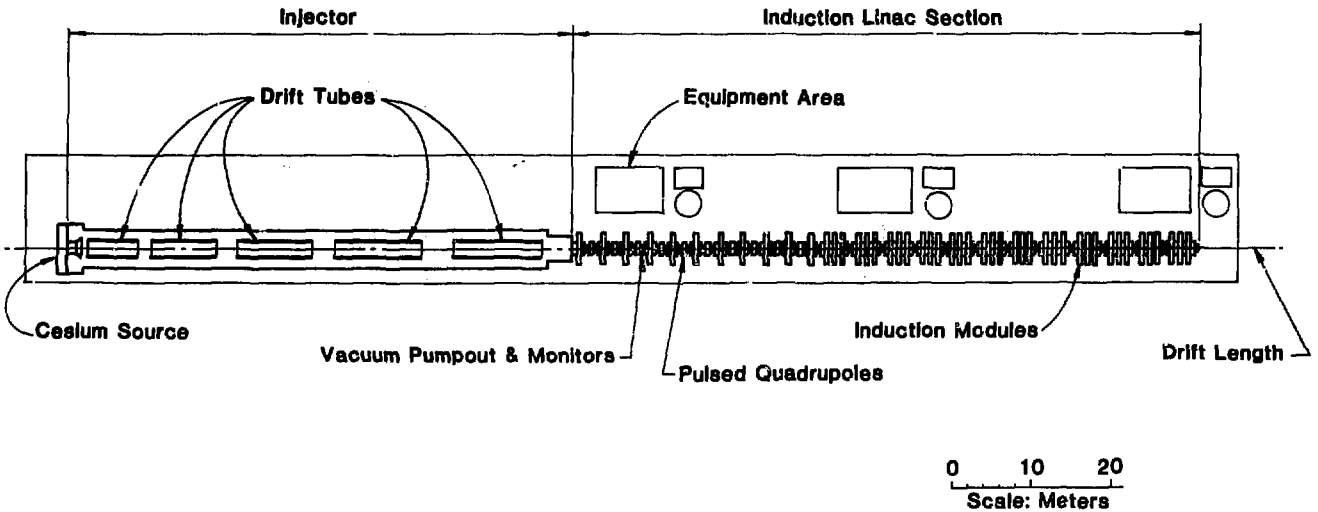
Computational work devoted to the accelerator design showed that the acceleration of the bunch at the beginning of the induction linac should proceed at less than the maximum technically feasible rate in order to keep the entire bunch within the stable transport passband. (This is the type of information that the test bed effort is intended to generate.)

As presently envisioned, the Ion Induction Linac, is shown schematically in Figure C-1. The Injector consists of the existing 1 Amp Cs^{+1} source 4 Joule system with 5 pulsed drift tubes. The Induction Linac Section is made up of 80 pulsed magnets, and 47 induction modules.

A list of the main accelerator parameters for the Test Bed are given in Table 1. From the initial test bed design, redesign has essentially maintained the length and number of quadrupoles in the induction linac section and slightly reduced the number of modules.

Figure C-2 shows an artist's rendition of the Ion Induction Linac showing the major accelerator components. The module detail shows the pulsed quadrupole internal to the induction core along with core pulsers.

A publication describing the redesigned Ion Induction Linac is in preparation.



10 MeV Cs^{+1} 50 JOULE ION INDUCTION LINAC LAYOUT

XBL 804-9315

FIGURE 1

TABLE 1

TEST BED ACCELERATOR PARAMETERS

Ion	Cs^{+1}
Accelerator Charge	5 μC
Normalized Beam Emittance	$9 \times 10^{-6}\pi$ m-rad
Injector	
Source:	500 kV, 1.0 amp contact ionization emitter with Pierce Gun Geometry
Structure:	5-500 kV pulsed drift tubes with electrostatic quad focusing
Energy:	3 MeV
Current:	1 ampere
Pulse Duration	5 μsec
Output bunch length:	10.5 meter
Injector length:	64 meter
Induction Linac Section (ILS)	
Acceleration:	47 induction modules, 320 kV Max module voltage
Focusing:	80 pulsed magnetic quadrupoles
Energy range:	3-10 MeV
Current range:	1-3.1 ampere
Beam energy:	50 joules
Half period:	1.0 meters
ILS length:	80 meters

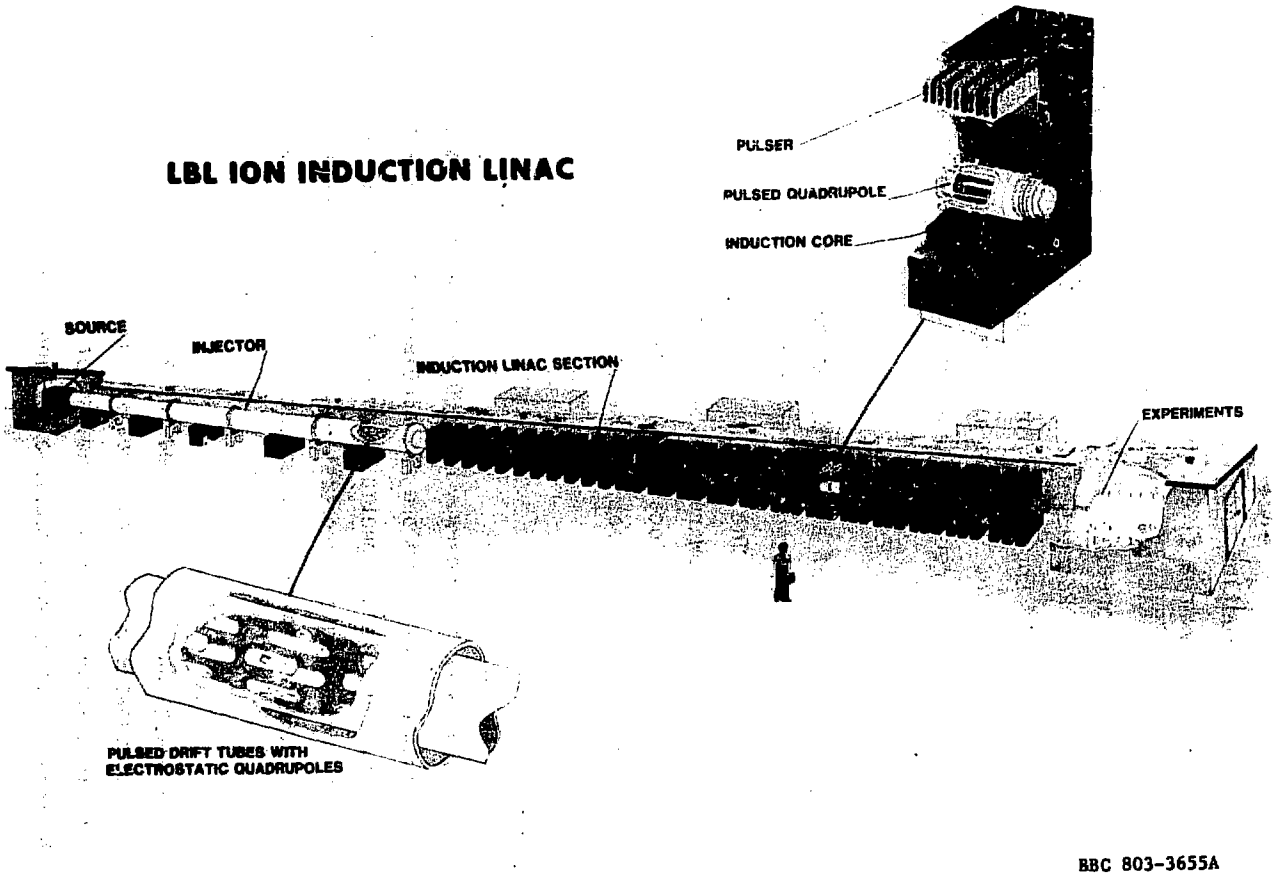


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FIGURE 2

Accelerator-Component Design:

In addition to the major accelerator redesign, effort continued with accelerator-component design.

Site Selection:

An important consideration of the project has been to find a suitable site (flexibility) for the construction and operation of the Test Bed. We have looked at three possible Bay Area sites, including LBL, and have decided that the University of California Richmond Field Station is the best location. The Richmond Field Station is an area of over 100 acres located off Highway 17 in Richmond. It is owned by the Regents of the University of California, administered by the College of Engineering of the Berkeley Campus, and operated for University research. We have had preliminary discussion with the College of Engineering and have received tentative approval to locate the Test Bed at the Field Station

Figure 3 shows the location of the Field Station with respect to LBL and cities in the Bay Area. The proposed Test Bed site, Fig 4 is located on the N-W corner of the Field Station. The area to be occupied by the Test Bed is relatively flat, sloping gently towards the San Francisco Bay which is about one-half mile to the south. This location provides a straight, unobstructed site of more than fifteen hundred feet for the accelerator and beam transport experiments.

Accelerating Module and Core Design:

Preliminary layout work is underway on module packaging. Among the parameters which must be considered are the acceleration voltage profile, the core and its pulser, the pulsed magnetic quadrupole and the vacuum system. A parallel effort is proceeding on core testing and pulser development. The combined effort is directed toward development of a prototype induction module.

Core Winder:

A preliminary design has been completed for an induction core winder. This winder will be capable of winding cores of thin electrical steel interleaved with insulation to a nominal weight of 10,000 lbs and a maximum diameter of 80 inches. It is very feasible for induction cores to be

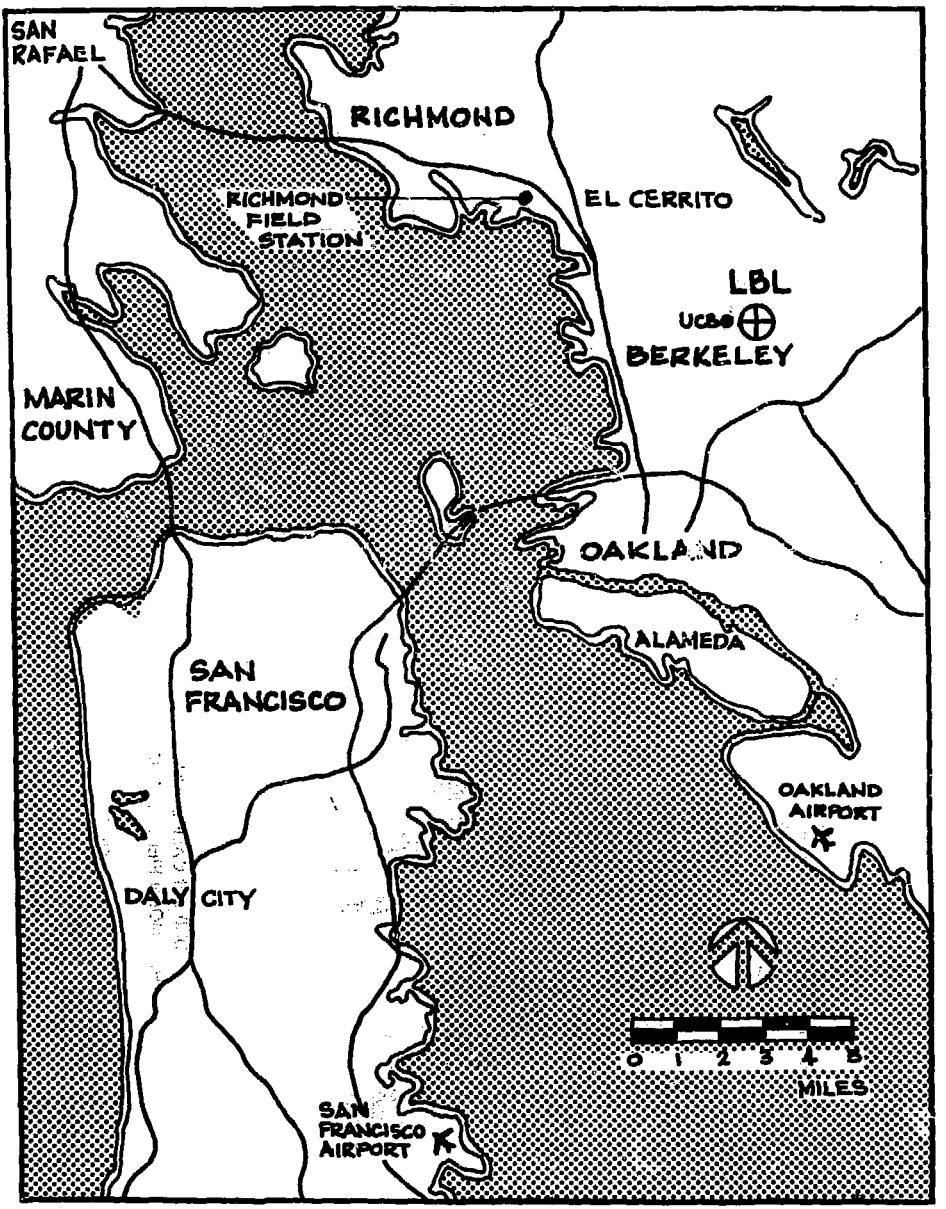

FIGURE 3

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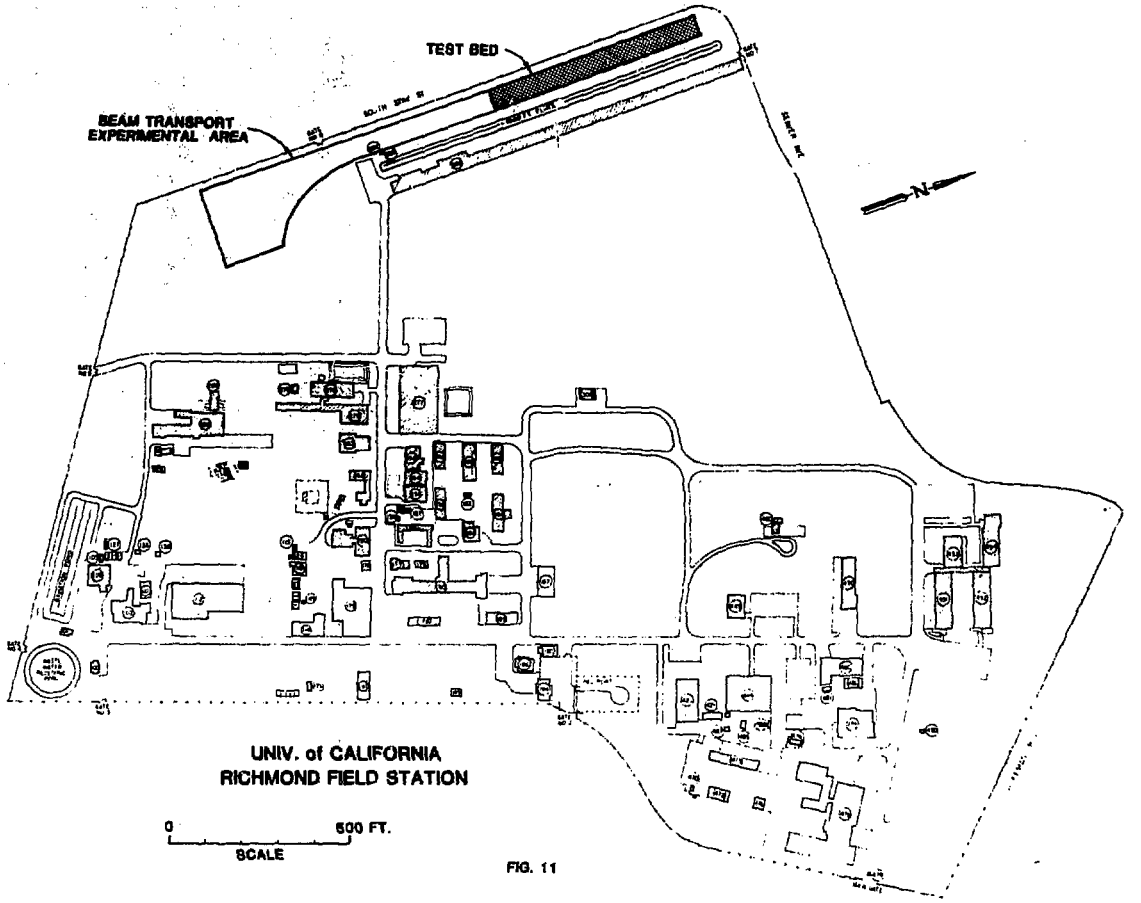

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FIGURE 4

manufactured at LBL if it is unattractive for them to be fabricated by industry. Detailed design and fabrication can commence when additional funding is available.

Core Pulsers:

A small developmental effort has been in progress on the ignitron PFN switch and its triggering circuit. Each accelerator module will be a box with a subdivided core, a pulsed quadrupole, and the core pulsers contained within it. The core subdivisions, or corelets, will be driven with lumped element pulse forming networks switched by ignitrons. The goal of this phase of the work is a compact triggering circuit which will be mounted adjacent to the ignitron and which will contain the bleeder and metering resistor string for the PFN, the trigger pulse generator, and a time delay circuit for timing adjustments. Part of the heat developed in the bleeder is used to heat the anode of the ignitron, and the entire package is temperature regulated from an external source.

Sample lots of several tube types have been obtained for life testing at the nominal 25kV operating voltage. Experimentally, some tubes have met 100 ns total jitter vaules and some have exceeded it by a small factor; the present work is striving to reduce jitter. For design purposes, a time jitter of ±50 ns has been assumed for the individual pulses, and the beam dynamical consequences of the resulting accelerating waveforms are being investigated computationally.

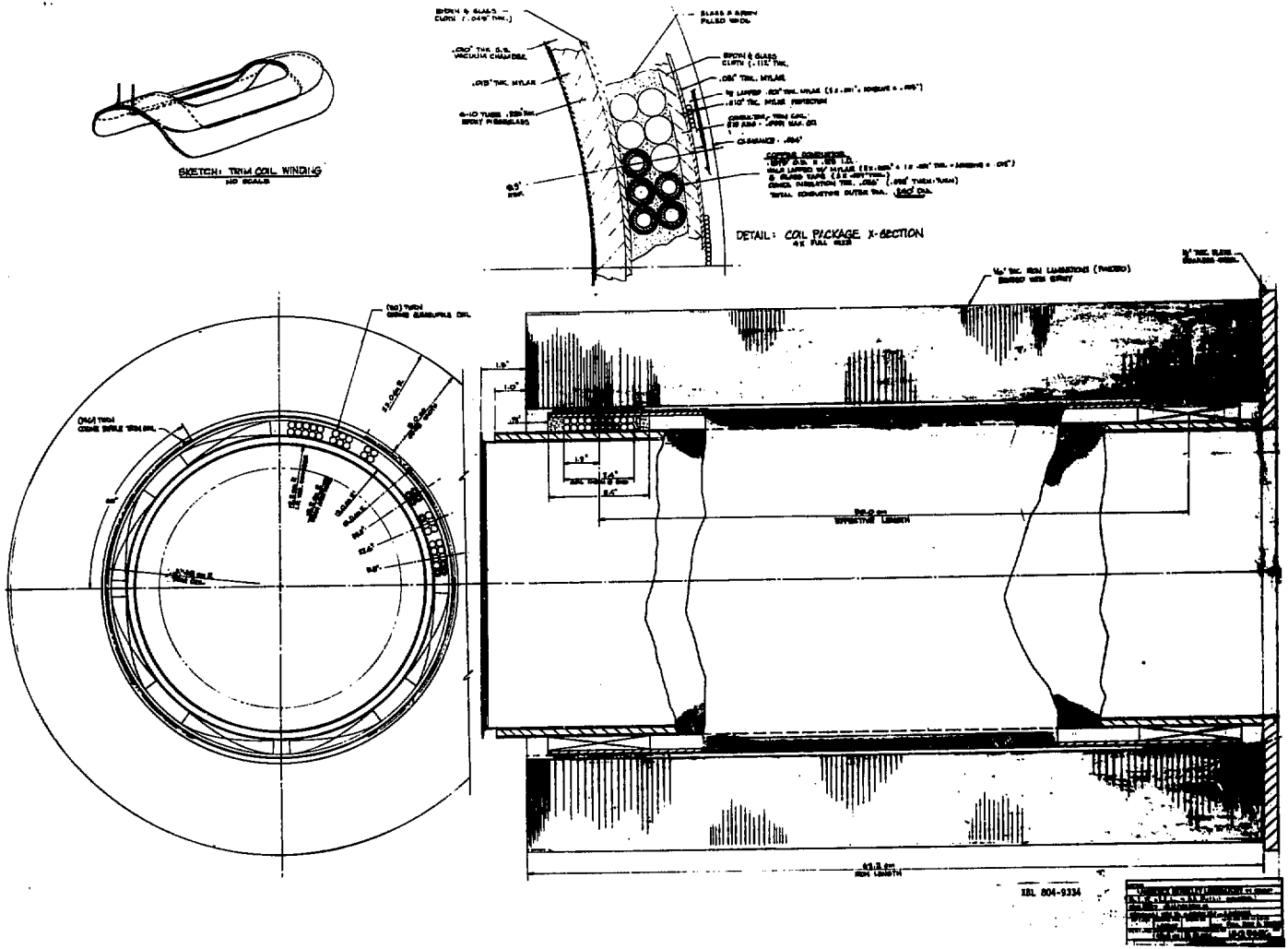
Pulsed Quadrupole

Design of the pulsed quadrupole is proceeding as shown in Figure 5. The quadrupole uses insulated 3/16" OD copper refrigeration tubing as conductor for the quadrupole cosine coils which are designed to operate to 25kV. Each magnet contains a dipole cosine coil for beam steering.

Magnet computations for the pulsed quadrupoles are underway. Within the 10.2 cm bore radius an error of less than 1 percent in the field integral is the design goal.

Vacuum System:

A tentative design for a cryo-pumping system for the Ion Induction Linac has been worked out and is shown in Figure 6. Initial system roughing will be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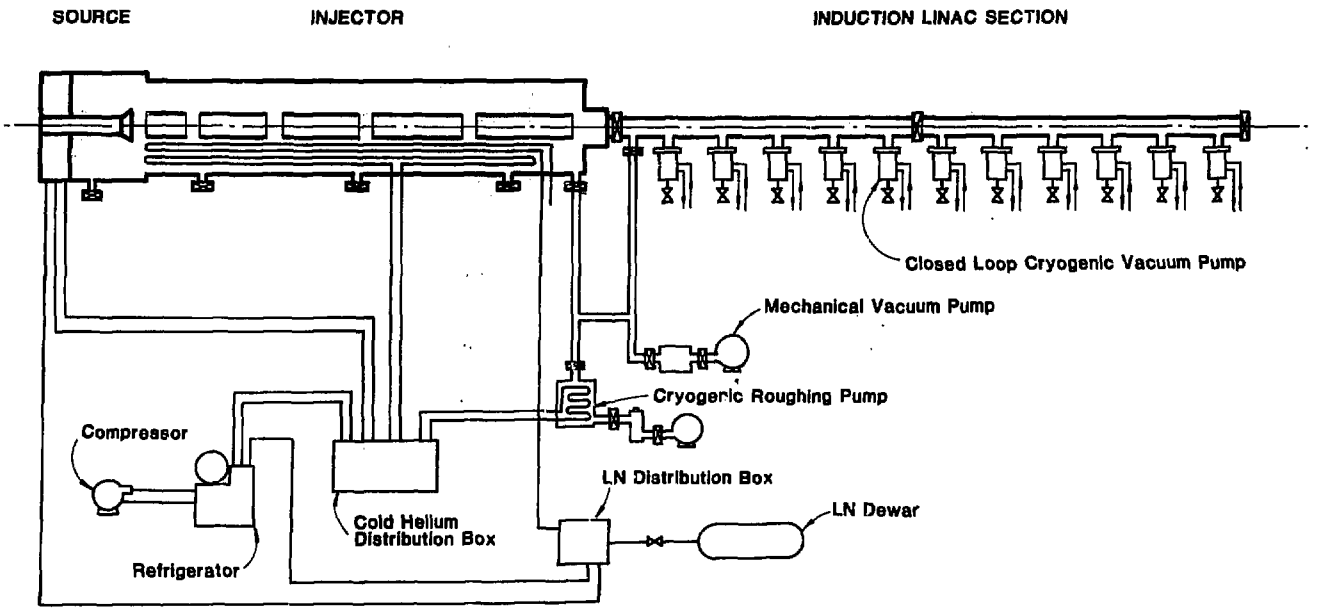
NO SCALE
DETAIL: COIL PACKAGE X-SECTION
4X FULL SIZE
IBL 804-9334

FIGURE 5



ION INDUCTION LINAC - VACUUM SCHEMATIC

XBL 804-9317

FIGURE 6

accomplished with a non-back-streaming mechanical pump to 1 Torr. Further roughing to 10^{-4} Torr will be done with a cryogenic roughing pump. To achieve the 10^{-7} 10^{-8} Torr vacuum in the accelerator, cryogenic panels operating near 20 K will be used in the source and drift tube sections and closed loop cryogenic pumps used along the induction linac section.

D. THEORY

Final Transport and Focusing

During and after the Claremont Workshop in November, attention was directed for the first time to the effect of space charge forces on the design of final transport lines intended to correct chromatic and geometric aberrations. In addition to changing the transverse oscillation frequencies, the self-forces also affect the dispersion of orbits for different momenta in bending magnets. Since dispersion is the key to chromatic corrections by separating orbits in space to allow a differential focusing strength with sextupoles, it is important that the influence of space charge be understood. A quasi-linear system of coupled equation for beam envelopes and dispersive forces has been formulated and their implications are being studied.

A lens system based on suggestions by Karl Brown for the part of the chain immediately preceding the final focusing elements was supplied to Irving Haber for a computer simulation of final focusing. Haber's results were not very encouraging; it was then realized that the configuration was unduly sensitive to non-linear self-forces and a new arrangement is being prepared for further simulation studies. (A. Garren, G. Krafft)

Electrostatic Quadrupoles

Two effects have been recognized which might restrict the use of electrostatic, as opposed to magnetic, focusing. The first is the fact that the kinetic energy of the ions is changed by some fraction of the lens potential as they enter and leave, which upsets the linearity of the focusing action. The second is the nature of the image forces induced by an elliptical beam in a hyperbolic electrode configuration; and analytic solution of the two

dimensional electrostatic image problem shows that the four-fold symmetry of the electrodes leads to a much larger octupole component in the image force than for a circular pipe such as would be used to conduct the beam through magnetic quadrupoles. In order to evaluate the importance of these effects, Herrmannsfeldt's electron gun design program is being modified to deal with a quadrupolar geometry. (Laslett, Close)

Test Bed Design

Theoretical help has been provided on numerous detailed questions - beam matching sections, tolerances, diagnostics, beam steering, etc. The greatest amount of attention has been devoted to the determination of the required voltage wave forms on the accelerating modules and the consequences of deviations from ideal conditions, both through practical limitations on realizable wave shapes and errors in amplitude or timing.

The goals adopted for the study of wave shapes were to maintain a beam current profile uniform in the longitudinal direction in order to minimize space charge forces and to bunch the beam as much as possible, consistent with maintaining transverse stability. The "ideal" shapes were determined by assuming a polynomial form for voltage vs. time in each module, subject only to the constraints of not exceeding the volt-seconds or maximum voltage available from each module; and then following various parts of the beam in time and distance through the machine, adjusting the wave shapes to achieve good performance. A major conclusion which emerged early in this process was that the entire bunch must enter the accelerator before any voltages are applied and that acceleration and bunching must begin gently. Thus the early modules are under-utilized and can be spaced farther apart than toward the end of the machine, where maximum acceleration is acceptable.

The next stage in design was to approximate the ideal voltage profiles by real ones. The differences are sufficiently great that it was found expedient to match, not by individual modules, but by averaging over pairs or triplets of adjacent modules. This work is about complete and a study of the effects of errors has been started. (Laslett, Chattopadhyay, Brady)

Beam-Stability

Work continues on the longer range and more general question of the stability of intense beams, with particular attention to the range of parameters appropriate to final transport and induction linacs. The investigation of transverse stability of a continuous beam is as complete as is warranted, pending the acquisition of experimental results, and the major effort now is directed toward longitudinal stability of a beam bunch and the possibility of adverse transverse-longitudinal coupling effects.

A model for longitudinal motion has been pursued in which the ions are confined in a square well, which is more appropriate to the induction linac than a quadratic well representing the linear r.f. restoring forces in a storage ring for low intensity or the self-consistent high intensity case analyzed previously by Neuffer. Individual particle motion is highly non-linear, but in a special way which permits the application of the usual linearized perturbation treatment. In the presence of a resistive wall, the model indicates instability for a range of parameters such that the characteristic oscillation time of particles in the well is of the order of the decay time of the surrounding wall currents, but also suggests stability for the anticipated induction linac parameters. (K. Kim, G. Krafft)

Using the computer program developed by V.K. Neil and R. Cooper to solve the one-dimensional (longitudinal) Vlasov equation, Neuffer has shown unstable behavior for an induction linac in the presence of a resistive wall and parabolic confining well but its reliability remains suspect. A one-dimensional simulation program initiated by Haber is close to being operational, and we should soon be able to compare the predictions of the two codes. In reality, the representation of the beam-accelerating cavity interaction as a simple resistive term is probably a gross oversimplification - as the bunch progresses along the machine it stimulates a succession of electrical circuits which then react on later portions of the beam; we are attempting to formulate the problem in a manner analogous to the treatment of the beam break-up mode in electron linacs. (Wang, Sternlieb)

In studying the stability of continuous beam in high energy accelerators, longitudinal and transverse effects are considered separately because the

characteristic frequencies are quite different. At very high intensities, however, both tend to be of the order of the plasma frequency and a separate treatment becomes questionable. A model for the beam in which the transverse motion consists of particles moving in counter-rotating circular orbits in mathematically tractable, though even less realistic than the K.V. distribution; for example, it leads to numerous instabilities due to the counter-streaming motion which surely will not occur in a real beam. However, the model can be extended to non-circular orbits, which would eliminate the two-stream instabilities and give some picture of more significant effects. This approach is being pursued, first in fluid approximation and then, hopefully, in linearized-Vlasov approximation. It should be pointed out that this issue is not the same as the longitudinal-transverse coupling due to non-linear fields at the end of a bunch; that problem is conceptually simpler but probably more difficult to treat analytically. (Mark (LLL), Smith)

E. PUBLICATIONS

Number	Author	Title	Date
HI-FAN-94 (LBL-9601)	J. Shiloh, W. Chupp A. Faltens, E. Keefe C. Kim, S. Rosenblum M. Tiefenback	A Pulsed Vapor Source for Use in Ion Sources for Heavy Ion Accelerators (published in App. Phys. Letters, April 1980)	10/79
HI-FAN-95	A. Garren	Beam Transport and Matching for Experiments with a 2 MeV Cesium Beam	10/79
HI-FAN-96	D. Keefe	Notes on Focussed Intensity, Beam Energy, Target Size for a Variable Kinetic-Energy U^{+1} Driver.	5/7/79
HI-FAN-97	HIF Staff	Ion Induction Linac 500 Joule Test Bed	9/79
HI-FAN-98	W. Herrmannsfeldt	Heavy Ion Accelerator Study Session	11/22/79
HI-FAN-99	D. Neuffer	Stability of a Self-Consistent Phase-Space Distribution Under Space Charge Perturbations (Submitted to Particle Accelerators)	8/7979
HI-FAN-100	L.J. Laslett	The Periodic Symmetrical FODO Quadrupole Lattice with $p = 2$ ($\eta = 1/2$)	1/80
HI-FAN-101 (LBL-10291)	HIF Staff	Year End Report: Heavy Ion Fusion Program Oct. 1978 - Sept. 1979	1/80
HI-FAN-102	HIF Staff	Informal Quarterly Report on HIF Program Oct. 1 - Dec. 31, 1979	1/80
HI-FAN-103	L.J. Laslett	Results of Computations Pertaining to Tune Depressions from $\sigma = 60$ deg. for $p = 1/2$	1/17/80
HI-FAN-104	A. Faltens, E. Hoyer, D. Keefe, C. Kim, L.J. Laslett, S. Rosenblum, L. Smith	Ion Induction Linac Test Bed (published as extended Abstract in CLEOS/ICP Conf. Report)	2/14/80
HI-FAN-105	L.J. Laslett	Perturbed Envelope Equations	3/18/80

APPENDIX

SUMMARY: HEAVY ION ACCELERATOR STUDY SESSION
Claremont Hotel, Oakland, California
October 29 - November 9, 1979

W. B. Herrmannsfeldt

HEAVY ION ACCELERATOR STUDY SESSION

Objective

To study the physics of high-intensity heavy-ion accelerators to assess their promise as ignitor systems for inertially confined fusion.

Participation

Approximately one hundred accelerator scientists participated in the study session held at the Claremont Hotel, Oakland, California, for two weeks during the period October 29 to November 9, 1979.

Organization

The study session was jointly sponsored by the Office of Inertial Fusion, (OIF) U.S. Department of Energy and the Lawrence Berkeley Laboratory, (LBL). THe chairman of the conference was Professor Burton Richter, Stanford Linear Accelerator Center (SLAC). The organizing committee was chaired by W. B. Herrmannsfeldt, SLAC/LBL, and T. Godlove, OIF. Other members of the organizing committee were: A. Maschke and E. Courant, BNL, R. Martin and T. Khoe, AN., and D. Keefe and L. Smith, LBL.

The study was divided into five working groups with attendees participating in one or more of these according to their specific interests and areas of specialization. Chairmen for these groups were chosen from among the attendees who were not part of one of the funded OIF heavy-ion fusion (HIF) programs. (More than half of the attendees were from programs other than HIF, including universities, foreign countries, high-energy physics, etc.) The working groups and their co-chairman were:

Low-beta Accelerators: R. Jameson, LASL and P. Lapostolle, France.
(Beta refers to the velocity in units of the velocity of light, v/c.)

Linear Accelerators: S. Penner and M. Wilson, both NBS.

Storage Rings: L. Teng, FNAL, E. Courant, BNL, and N.M. King, Great Britain.

Final Transport in Vacuum: A. Garren, LBL and I. Hofmann, West Germany.

Final Transport in Gas: C. Olson, SLA.

Background

This was the fourth in the series of annual workshops held to study the subject of heavy ion accelerator drivers for inertial fusion. Since the status of the field has changed rapidly during this period, the purpose and style of each of these sessions has also changed.

The first Claremont meeting, held in the same hotel in 1976, actually preceded formal funding for accelerator laboratories for HIF. This study was held to test the validity of early claims by proponents that HIF was in fact feasible, and to identify the most promising techniques and most critical questions.

The second workshop, held at BNL in 1977, saw a multitude of proposed systems and subsystems being sorted out to enable the community to better concentrate on comparable approaches. Some of the theoretical studies, such as the space charge limits for beam transport, began to show some progress.

The third workshop, held at ANL in 1978, resulted in over 400 pages of technical proceedings complete with a comparative evalution of the complete driver systems proposed by each of the three major centers; ANL, BNL and LBL. During this workshop, one of the systems, that using synchrotrons as the principal element for increasing the total energy in the beam, was more or lessdropped leaving two main line approaches: 1) a conventional rf accelerator with a system of storage rings for current multiplication, and 2) a single-pass linear induction accelerator propelling a single high intensity bunch of ions using waveform shaping to compress the bunch and increase the current. Both approaches require the use of a system of pulsed induction modules followed by a system of transport magnets extending over a distance sufficient to allow the beam to ballistically compress longitudinally to achieve the peak pulse power needed to ignite a fusion pellet.

It should be noted that the synchrotron approach, which was dropped at least partially because of the limited funding and manpower available to study it, has continued to be studied by two Japanese laboratories which were represented by three attendees at this year's workshop.

Finally, the 1979 study was convened with the express purpose of looking carefully at the physics questions (as opposed to questions of systems, pellets, economics, etc.) posed by the two main-line approaches. These questions were to be formulated and examined particularly in the light of recent experiences with other new accelerator systems such as storage rings for high-energy physics and induction accelerators for weapons-related activities. The majority attendees, and all of the chairmen of the working groups, were from such outside groups, and many had not attended any of the previous workshops. A brief discussion of target parameters and the results of recent theoretical work in pellet design was presented by way of an introduction for new workers. A significant change in beam requirements was identified by R. Bangerter, LLL, who presented the following table of target beam parameters:

Case	A	B	C
Beam energy	1 MJ	3 MJ	10 MJ
Peak power	100 TW	150 TW	300 TW
Kinetic energy	5 GeV	10 GeV	10 GeV
Spot radius	1 mm	2.5 mm	3 mm
Pulse length (total)	20 ns	20 ns	70 ns
Pulse length (peak)	6 ns	16 ns	20 ns

Ions at or above A = 200 atomic mass are assumed. Comparison with data given to previous workshops shows that, while the multimegajoule cases continue to be favored as higher confidence for achieving useful gain, the kinetic energy allowed for the ion beams has decreased. This requires a corresponding increase in beam intensity, although some growth (about a factor or two) has occured in spot radius and peak pulse length. Qualititatively, of course, increased intensity adds to the difficulty of achieving the necessary beam parameters while increasing the spot size and the peak pulse length increases the permitted six-dimensional beam emittance, thus easing the requirements. Paradoxically, increases in beam energy and kinetic energy tend to make the accelerator paramaters somewhat less stringent. This is because it is easier to contain and transport a higher energy beam in which overcoming collective

(space charge) forces requires a relatively smaller fraction of the total force needed for confinement.

Technical questions

A representative list of specific technical questions was defined by the organizing committee:

(1) Preservation of emittance during combining of beamlets,
   a) For low-beta and rf linacs:
   b) Coherent instabilities in the main accelerator.

(2) For induction linacs:
   a) High current injector systems.
   b) Coherent instabilities, both transverse and longitudinal.
   c) Waveform tolerances and jitter.

(3) For storage rings:

   a) Injection requiring debunching and stacking.
   b) Rebunching in the ring.
   c) Coherent effects, both transverse and longitudinal.
   d) Vacuum requirements.
   e) Charge exchange.
   f) Extraction.
   g) Cooling techniques, if useful.

(4) Final Transport, vacuum:

   a) Longitudinal pulse compression.
   b) Geometric aberrations.
   c) Chromatic aberrations.
   d) Beam splitting
   e) Coherent effects.

(5) Final transport, gas (may be required in a power reactor):
   a) Charge and current neutralization.

b) Two-stream instability.

c) Availability of "windows" for beam transport, i.e., ranges of pressure in which beam transport and reactor first-wall protection are compatible.

Test Beds

The two largest DOE laboratory programs in HIF, ANL and LBL, have each developed proposals to design and construct accelerator systems, called Test Beds, to demonstrate the principal parameters and components needed to construct a full-scale prototype driver. The test beds would be far too small and too low in energy to be useful as pellet drivers, but should serve to provide for the testing of components and verification of theoretical stability calculations. The study session did not have time to access adequately the degree to which the proposed test beds would fulfill these requirements, but did establish some specific questions which the test beds should be designed to answer.

Working Group Summaries

At the end of the study session the meeting site was shifted to the LBL auditorium to allow unlimited attendance by interested scientists who had not been able to participate in the workshop. The reports began with a summary of the target parameters described above. Then the working groups reported their findings starting with the final transport groups and working backwards.

(1) Final transport in gas: The group considered possible reactor scenarios to test the compatibility of the reactor environment (diameter and kind and pressure of gas) with the problem of transporting the beam to the target. The presently favored design concept, using either a lithium fall or a lithium wetted wall operating at about 375 deg. C, would have a pressure in the range 10^{-4} to 10^{-3} Torr. (This temperature is about the same as the operating temperature for light water reactors.) The group found that transport at pressures up to about 10^{-3} Torr for a reactor radius of five meters could encounter the two-stream instability but survive without too much damage. The 0.1 to 1.0 Torr "window" that had been defined earlier (assuming a noble gas to provide reactor front wall protection) appears to be closing

off with the lower kinetic energies called for (5 - 10 GeV). A practical problem with this scenario is the difficulty of pumping a noble gas well enough to avoid beam loss due to stripping in the last focusing magnet. The pinch mode, similar to that required for light ion beam fusion, still appears to be a possible transport mode. The most promising conclusion, however, is that the newly found window, coinciding with the parameters of the liquid lithium reactor scenario, provides a final beam transport scenario consistent with the favored reactor system.

(2) Final transport in vacuum: The transport line from the accelerator and/or storage ring to the reactor is evacuated. The problem of stable transport in this system is complicated by the fact that the beam is rapidly compressing longitudinally, thus causing the current to be continuously increasing. The approach used by the working group was to design the best possible system without space charge and then to modify the solution assuming uniform charge density in both the transverse and longitudinal directions. The designs resulting from this approach woudl then be tested using the numerical simulation methods developed for the space charge limited transport studies by Haber, Penner, Laslett, etc. These simulations, which were beyond the capabilities of the workshop during the limited time available, would account for the non-uniform space charge distribution. An example beam line was designed by K. Brown and J. Peterson during the study. It consists of three one-half wave modules and includes sextupole magnets for chromatic correction. Second order calculations yielded 85% transmission onto a 4 mm diameter target with 3% momentum spread. The relatively large momentum spread permits higher currents to be transported below instability thresholds, and is a significant parameter for all the preceding parts of an accelerator system. The principal effect of including space charge was to increase the maximum beam radius from 25 to 36 cm. In spite of the promising result given above, there was concern expressed in the summary that chromatic correction schemes may in practice do more harm than good, and that momentum spreads should be limited to ± 1%. The final transport group also issued a call for an intensified program of numerical calculation for the full simulation of these transport systems.

(3) Storage Rings: The working group on storage rings developed parameter sets for each of the three target cases. The special situations considered include:

a) Stacking at injection, with resulting emittance dilution,
b) Bunch compression in the ring prior to extraction,
c) Losses due to charge exchange collisions,
d) Current limitations imposed by coherent longitudinal effects.

Among the more significant conclusions was the finding that injection and ejection elements must be carefully protected against significant beam loss. The workshop resulted in a more intensified look at problems of coherent longitudinal instabilities. The thresholds for such instabilities were used to define the maximum currents to be stored. The limitations are acceptable if the coupling impedances can be limited to ~ 25 ohms per mode. Even if this should be difficult, the growth times for the instabilities may be longer that the necessary storage time. The spokesman for the working group called for intensified efforts to determine charge exchange cross sections of ions suitable for the HIF applications. One rather high cross section for cesium was reported from the Queen's University, Belfast, by the delegates from Great Britain. There was also a call for intensified studies of the coherent longitudinal effects and the structure impedances that can give longitudinal instabilities. The summary concluded that there are important and fascinating problems but "no insuperable obstacles" were found.

(4) Linacs: The linac working group considered both rf linacs and induction linacs.

RF linacs: The problem of merging beams by frequency multiplying, and the resultant emittance dilution, attracted the most attention. Numerical methods exist to treat these problems and need to be applied. Impedance effects and possible resulting instabilities need further study. The working group reported their consensus that transverse blowup is not to be expected and longitudinal blowup is unlikely but needs to be calculated.

The induction linac presents a very different, and in some ways, a simpler case than the rf linac. However, because there is so little relevant experience, there are more questions remaining than for the rf case. Most of these questions deal with longitudinal stability, the use of feedback control, waveform tolerances, behavior of the bunch ends, etc. Transverse dynamics, at least in the absence of transverse-longitudinal coupling, appears to be in good theoretical shape.

The recommendations of the linac working group include development of numerical methods of treating the problems described above and careful diagnostics to ensure useful measurements when beams are available from the proposed test bed systems. The conclusions were that "no fatal flaws were found and the consensus is that there probably aren't any."

(5) Low-beta accelerators: There are now several candidate systems for the low-beta accelerator for injection into the rf linac. These include, a) Conventional high voltage injection into a low frequency Wideroe linac. b) the rf quadrupole accelerators first developed in Russia and now being tested at LASL, and c) the arrays of small electrostatic quadrupoles, called MEQALAC by A. Maschke of BNL.

The low-beta working group considered many of the same problems faced by the linac group, and emerged with essentially the same conclusions described above. They ran some comparisons of the three systems defined above to check the scaling laws reported. They concluded that adequate safety margins exist for all parameters, although the necessary intensity could require some beam scraping. Scraping at low energy is quite tolerable and, in the worst case, simply requires more branches to the linac trees at slight overall increased cost.

European and Japanese Programs

The foreign delegates were asked to describe their HIF programs during the summary session. S. Kawasaki of Kanazawa University gave a brief discussion of the synchrotron program in Japan and discussed energy balance accounting in fusion. Since a fusion power plant of the same size is expected to be somewhat more expensive than a similar fission plant, it was not surprising that the energy balance payoff period is similarly longer. D. Bohne of GSI described the German effort. It is presently split between GSI, Frankfurt and Garching and is only just beginning to be funded. N. M. King described the program in Great Britain. Some funds that are available are earmarked for university programs. This permits starting such work as the charge exchange cross section work described earlier, but makes it difficult to begin serious work in a laboratory such as Rutherford which could act as a focus of the

university efforts. John Lawson discussed broader international collaborations, either among the European states or with independent alliances with the U.S. DOE programs. Since the classification programs do not directly affect the accelerator systems, the heavy ion drivers would be the ideal vehicle for such collaborations.

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