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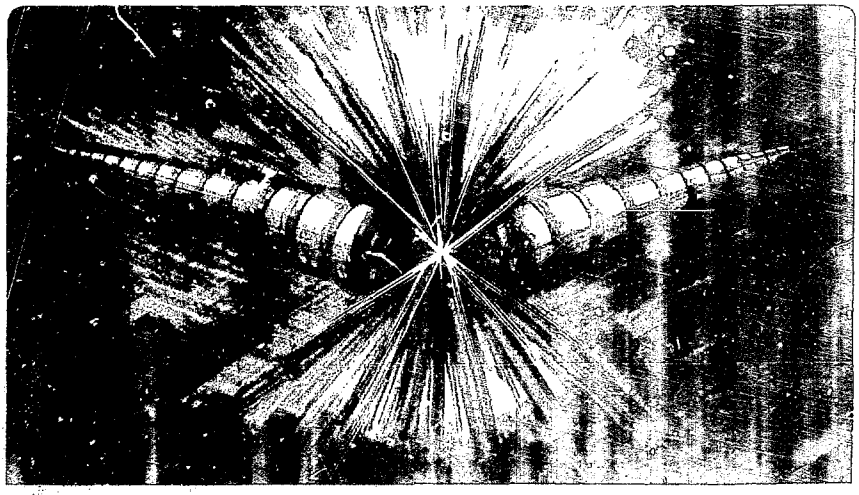
HEAVY ION FUSION YEAR-END REPORT
April 1, 1981 - September 30, 1981

Heavy Ion Fusion Staff

October 1981



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HEAVY ION FUSION YEAR-END REPORT*

April 1, 1981 - September 30, 1981

H.I.F. Staff

October 1981

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
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CONTENTS

HIGHLIGHTS 2

A. SINGLE BEAM TRANSPORT EXPERIMENT 3

B. DIAGNOSTIC DEVELOPMENT 8

C. THEORETICAL STUDIES 13

D. PUBLICATIONS AND REPORTS 19

E. STAFF 21

F. DISTRIBUTION LIST 22

HIGHLIGHTS

- A beam propagation experiment is being prepared to test theoretical predictions about transverse instabilities in a heavy ion beam with large space-charge effects in a long quadrupole transport system. The 200 keV injector which has the features of variable current density and variable emittance has been constructed.

- The Cs^+ pulsed drift tube injector model continues to operate for studies of beam optics, component testing in an intense ion-beam environment, and diagnostics development.

- The electron-beam probe has now yielded successful results on the time-resolved charge density of the Cs^+ ion-beam. It has revealed the existence of a significant number of electrons surrounding the ion-beam.

- The theory of longitudinal instabilities has been advanced. Improvements to the EGUN and other beam-dynamics codes continue and have yielded valuable results. Transport of high-intensity beams in an A.G. octupole system is under active study.

A. SINGLE BEAM TRANSPORT EXPERIMENT

1. Construction Progress

Fabrication and assembly continues on the equipment for the transport experiment described in the previous half-year report[1]. The purpose of the experiment is to study the dynamics and stability of a space charge dominated heavy ion beam in a long periodic focusing channel. The completed device will consist of the ion source with associated high voltage and focusing elements, the matching quadrupole section (for smoothly fitting the round beam from the source into the alternating gradient transport line), the transport channel consisting of 82 electrostatic quadrupole lenses in seven vacuum tank sections, and the associated control and diagnostic systems. A diagram of the first section is shown in Fig. 1.

The Marx generator for the source and all its power supplies, trigger, crowbar, and interlocks are installed and complete in their oil tank. The insulator on which the source is to be mounted has been leak tested and mounted on the tank, and the heater power supply for the source is in place.

The source and its extraction electrodes and emittance grids are undergoing final alignment before installation. Beam positioning is expected to be done within tolerance, so only one of the matching quadrupoles is being modified to allow beam steering near the source, to correct any divergence of the beam centerline from the machine axis of the transport channel.

All quadrupole faces, supports, and alignment fixtures are in hand.

The source vacuum housing (which also contains the first three of the five matching quadrupoles) is undergoing vacuum testing. The first of the

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1. Heavy Ion Fusion Half-Year Report, April 1981, LBL-12594

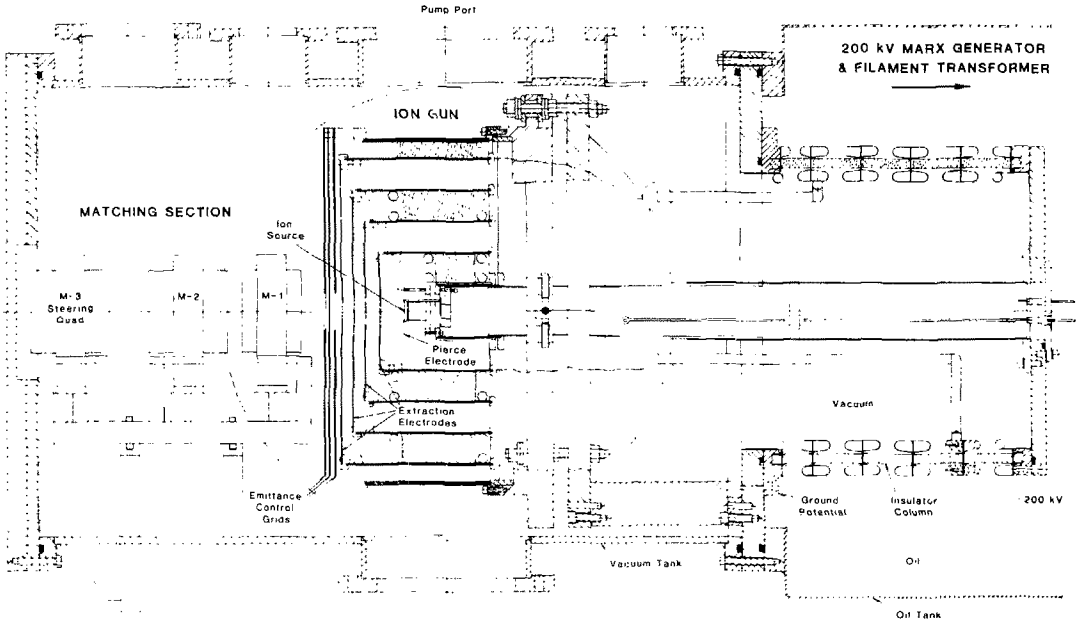

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Fig. 1 Single Beam Transport Experiment Gun & Matching Section

downstream vacuum chambers has been ordered, and delivery is expected by late November.

High voltage supplies for the first three quadrupoles are installed, and we have completed all RC networks for stiffening the quadrupoles against interception of beam or secondaries. All voltage monitors for the high voltage have also been completed. Other supplies will be ordered as the budget permits.

Four turbo-molecular pumps are required in the vacuum system, of which we have two in hand. The pump controls are designed and one set is completed. ready for use when the source and housing are installed, at which time the Marx generator and insulator will be high voltage tested. The three matching quadrupoles were successfully tested at voltage while being flooded with Cs^{+1} ions from the existing Cs^{+} injector, as described in the following section.

Diagnostic systems for the experiment have been planned. Detailed design of the Faraday cup and the emittance measurement slits is underway. Scintillator plates for envelope and emittance measurements are being fabricated. The hardware for the source diagnostics should be completed by mid-November.

The ion source and matching section should be ready for operation by the end of December. The first of the seven sections of the transport channel should be ready by the end of February 1982 and the complete channel is expected to be ready by the end of fiscal 1982.

2. Transport Matching Section Electrical Testing

As a test of the design of the electrostatic quadrupoles of the SBTE and to gain operating experience, the matching section quadrupoles of the SBTE were installed in the diagnostic tank of the 2 MV Cs^{+} injector. This allowed

electrical testing under very adverse conditions. The insulators and electrodes were bombarded by the ion beam. The matching section quadrupoles are shown in Fig. 2.

After some minor modifications to the insulator and electrodes the quadrupole array held 50kV D.C. in vacuum with no Cs^+ beam. With the beam on, however, there was a surface flash of the insulators holding the positive electrodes. The insulators did not go into a complete breakdown. Currents measured on the electrode cables were only a few amperes. The power supplies driving the electrodes were protected by megohm resistors so the electrodes were isolated by large capacitors and 50 ohm resistors both to damp the connecting cables and to insure that the electrode voltage did not collapse during the beam pulse of two microseconds. A complete electrode breakdown would have produced cable currents of several hundred amperes.

Electron beam probe measurements suggested that the Cs^+ beam had a "halo" of electrons. An aperture plate with a 6" diameter hole was installed one meter upstream. This plate passed the Cs^+ beam but stopped the electron halo. After the plate was in place the electrodes no longer flashed. The negative current on the positive electrode cable persisted, as well as positive current on the negative electrode cable. It seems clear that when Cs^+ ions strike the electrodes they knock out secondary electrons which are then mainly collected on the positive electrodes (+50 kV).

An aperture plate to limit the Cs^+ beam to a smaller diameter than the quadrupole electrode bore was then installed just in front of the electrodes, and the quadrupoles were connected to separate cables so that the currents to each quadrupole electrode could be measured. The 6" aperture plate was left in place. The positive current on the negative electrode cable was no longer present, but the negative current on the positive electrode cables was unchanged. Clearly, the Cs^+ beam was no longer producing secondary electrons

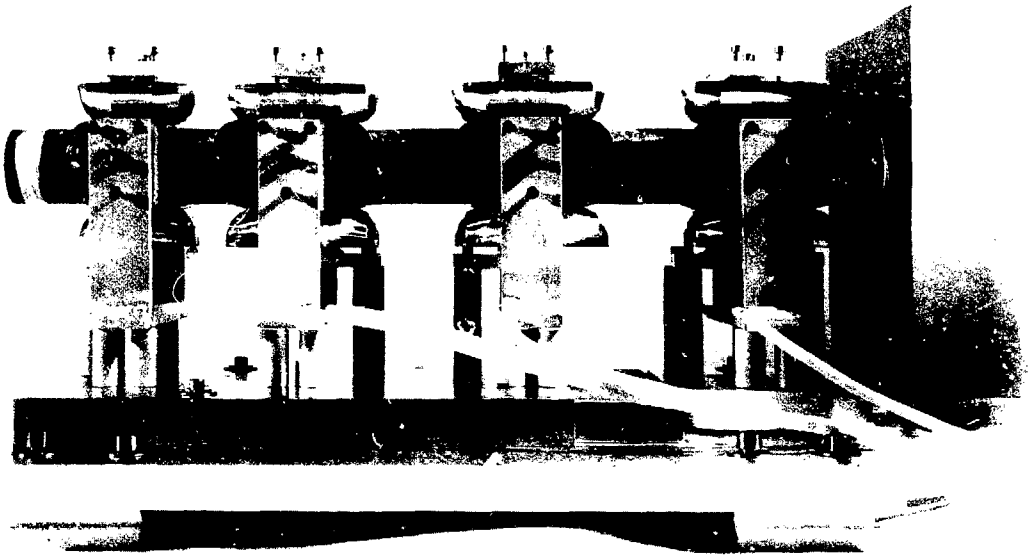

Fig. 2

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Matching Section Quadrupoles for the Single Beam Transport Experiment

from the negative electrode but rather from the small-halo aperture plate. This was verified by current measurements on the plate.

The insulators were able to withstand all such tests. Secondary electron currents of up to two amperes were measured with a Cs^+ current of only 0.25 amperes, which gives a lower limit to the secondary emission coefficient since not all of the Cs^+ beam was striking the aperture plate.

Since the electrode cables were isolated from the stabilizing capacitors with 50 ohms, the 2 amperes produced a 100 volt drop in the quadrupole voltage. This effect can be tolerated since the electron current was measured to decrease with successive quadrupoles along the beam path.

B. DIAGNOSTICS DEVELOPMENT

1. Heavy Ion Beam Scintillator Development

A continuing effort has been directed towards the development of a long lived, fast scintillator for heavy ion beam imaging at high current densities. As reported in the previous half-year report[1], europium doped calcium fluoride, $CaF_2(Eu)$, works quite well except that the light output diminishes exponentially with Cs ion dose with a mean lifetime of 900 pulses at a current density of 0.8 mA/cm^2. It would be especially desirable to develop a longer lived material for use on the Single Beam Transport Experiment because of its high current density and long pulse compared with the drift tube injector.

The sintered Al_2O_3 mentioned in the last report has proved to have a greater resistance to damage than the calcium flouride. Its light output decreases with a lifetime of 4000 pulses, an improvement of more than a factor of 4. During this reporting period efforts have been devoted to discovering how to make a successful transparent Al_2O_3 scintillator.

Sapphire (pure single crystal Al_2O_3) emits only ultraviolet light. We have carried out measurements of the pulsed light output of sapphire, sintered

alumina and CaF_2(Eu) using a scanning monochromator. The results are shown in Fig. 3 . The glass vacuum windows used cut off below 300 nm. We are planning to extend the measurements using quartz optics.

We have tried to plasma spray Al_2O_3 on glass but this appears to be too thick to be transparent. Finally, we have rf sputtered Al_2O_3 onto glass which appears to result in a good quality transparent surface; its performance, however, has not yet been tested in the ion beam. We are also examining the possibility of using wavelength shifters to convert the UV to visible light. If these attempts fail we may have to resort to the use of UV optics; this would present some technical difficulties which we are keen to avoid.

2. Electron Beam Probe

Information on the charge density distribution of the Cs^+ ion beam can be obtained by measuring deflections of a low current (5 - 50 μA) thin (< 3 mm diameter) electron beam passing through the ion beam. The realization of this is the Electron Beam Probe[2] consisting of an electron gun producing the specified beam at 5 to 10 kV and mounted so that it can be rotated transversely from 0° (electron beam aimed vertically down) to 50° inside the diagnostic tank, see Fig. 4. The E-beam strikes phosphor coated plates and the trace resulting from the deflection of the E-beam during passage of the ion-beam is photographed using 10,000 speed Polaroid film. An example trace is shown in Fig. 5. Both trial and error fitting and PIZZA[3], an inversion code for nonlinear problems, indicate a radial charge density in the ion beam which

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2. Heavy Ion Fusion Program Quarterly Report, April - June 1980. HI-FAN-116.
3. Computer Program PIZZA, Richard Sah, May 20, 1980. HI-FAN-107.

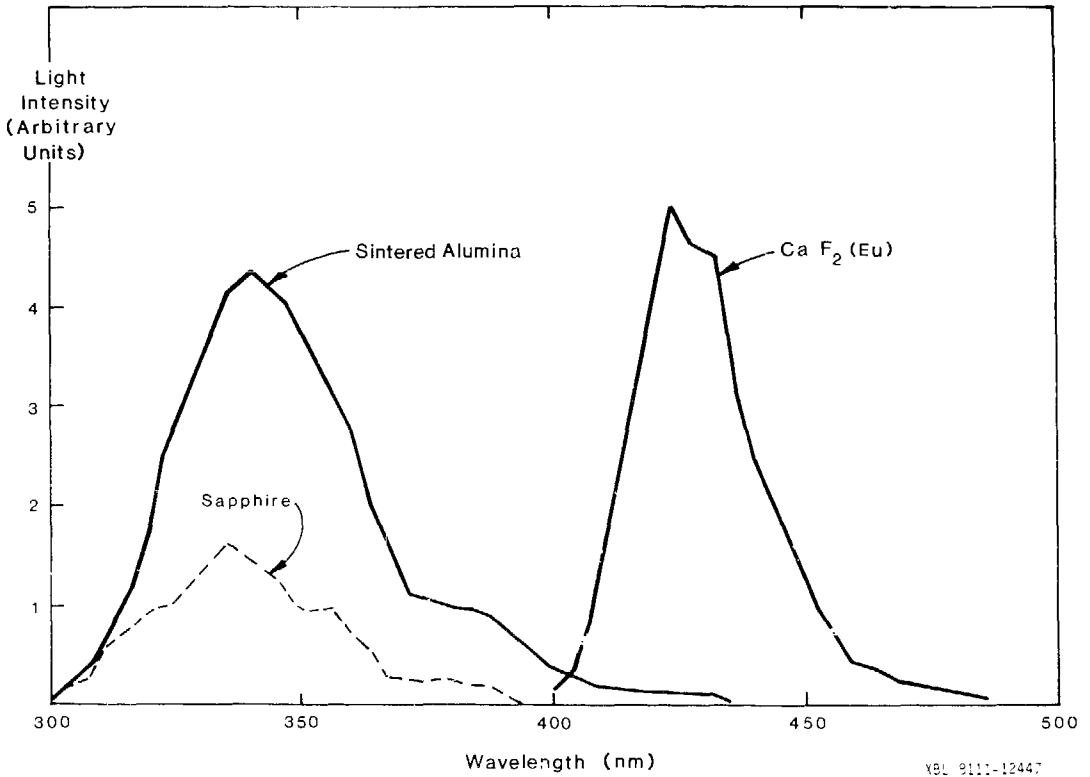

Fig. 3 Light Output of Selected Scintillators

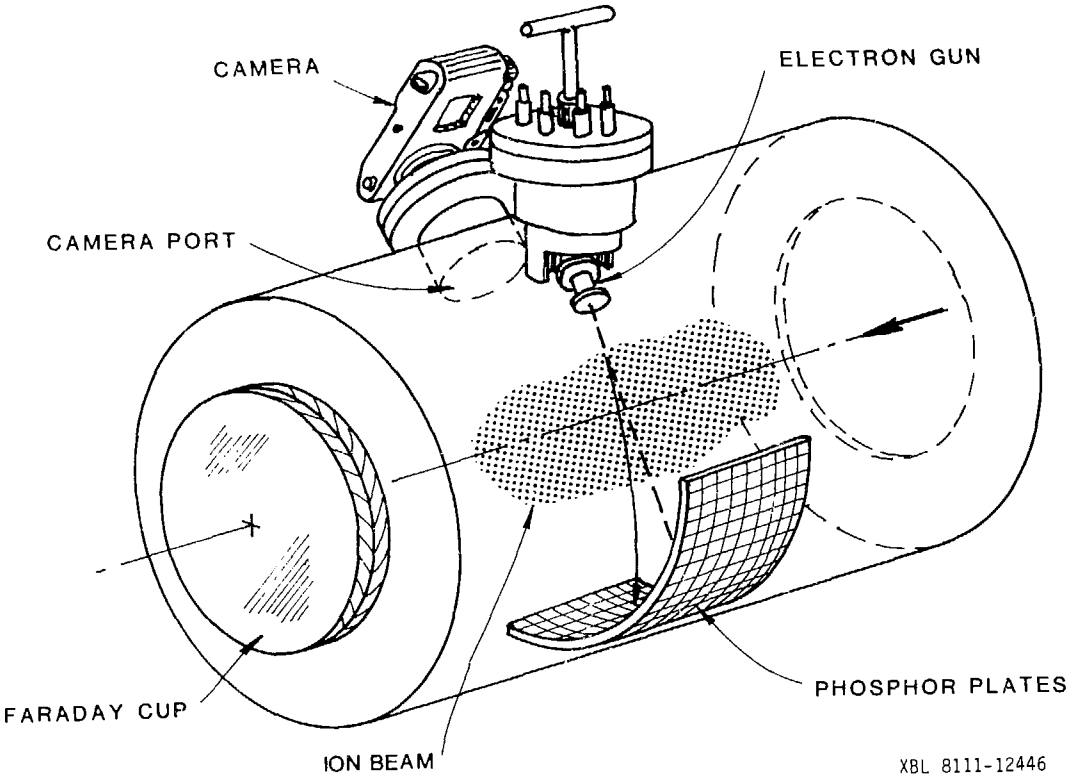

Fig. 4 Electron Beam Probe Mounted in the Diagnostic Tank

E=7kV

θ=17°

CONTINUOUS BEAM

Fig. 5a

CHOPPED BEAM

Fig. 5b

SCALE: 2.5 cm/div

GATING PULSE

10 V/d 50 ns/d

Fig. 5c

ION BEAM DIRECTION

XBB 807-10250

Fig. 5 Electron Beam Traces and Gating Pulse

includes large numbers of electrons forming a halo around the Cs^+ beam as shown in Figs. 6 and 7. There is some evidence for partial neutralization of the core of the ion beam as well. Longitudinal density distribution has not yet been examined. Neutralization of the ion beam from secondary electrons is also observed after the head of the ion beam strikes the end wall of the diagnostic tank and creates secondary electron emission.

The electron beam has been successfully chopped into short 50 ns pulses every 100 ns to give good time resolution of the deflection, see figures 5b and 5c. This is particularly important for unfolding the data for study of longitudinal charge density distribution and beam neutralization in time.

C. THEORETICAL STUDIES

1. Longitudinal Stability

A longitudinal simulation code[4] has been used to investigate the stability of bunched beams under the influence of the resistive impedance of the accelerating modules. Two analytic predictions regarding stability had been made earlier; one, using a square well model[5] for containment of the bunch, indicated stability while the other one[6], starting from a parabolic charge distribution with no velocity spread, also indicated stability to first order in the resistive component of the impedance. An analysis of the mathematical procedure used in the latter case suggested that the criterion for stability is that the e-folding distance for a space-charge perturbation running along the bunch should be long compared to the length of the bunch.

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4. J. Bisognano, I. Haber, L. Smith and A. Sternlieb, Proc. 1981 Particle Accelerator Conf., IEEE Trans. Nucl. Sci. NS-28, p. 2513.
5. K.J. Kim, Proc. HIF Workshop, Oct. 1979, LBL-10301/SLAC-PUB-2575, Sept. 1980, p. 187.
6. P.S. Channell, A.M. Sessler and J.S. Wurtele, LBL-12107, Feb. 1981.

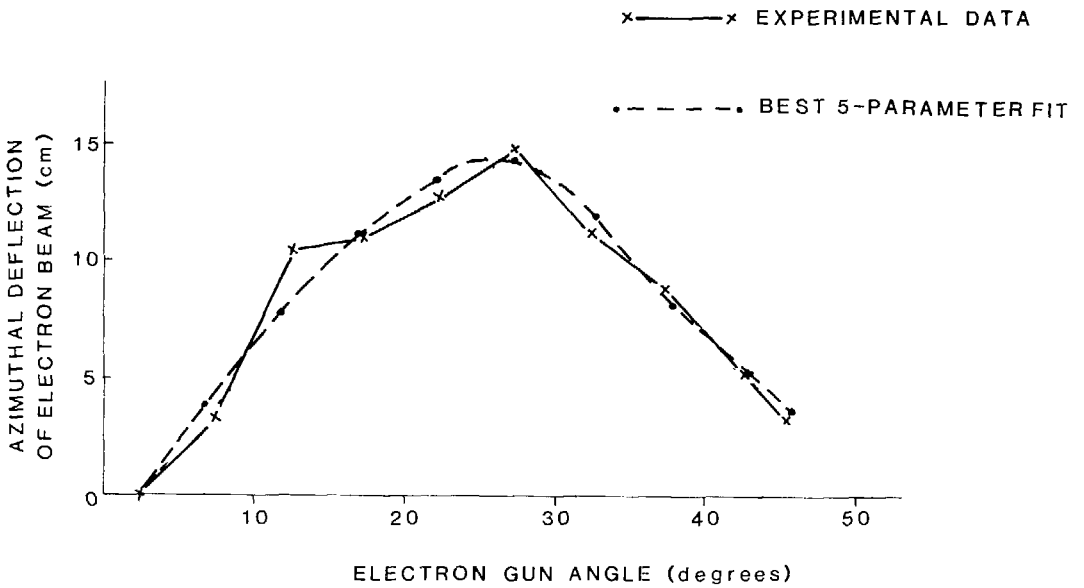

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Fig. 6 Azimuthal Deflection of Electron Beam vs. Electron Gun Angle

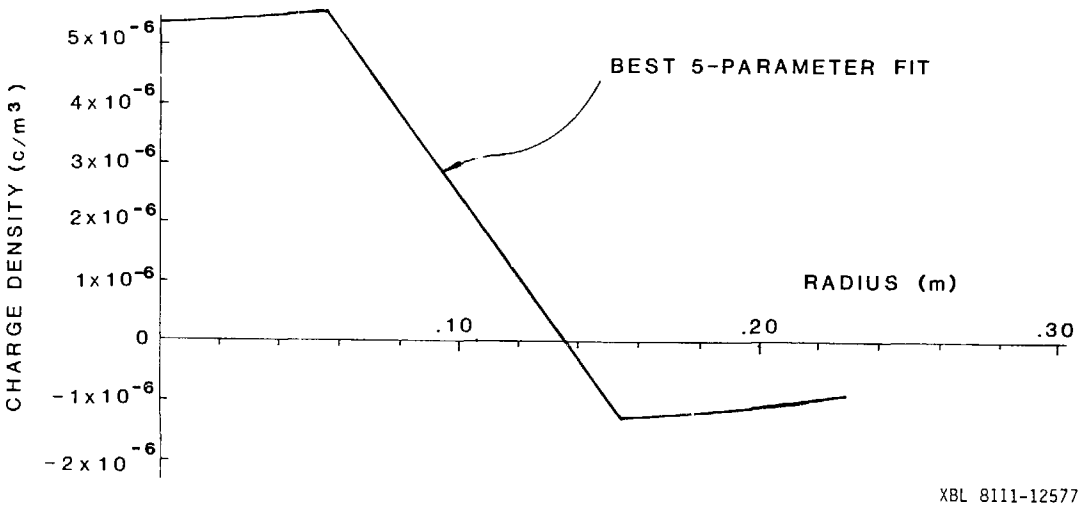

Fig. 7 Five Parameter Fit to Radial Charge Density

Although the square-well model represents more accurately a uniform current density bunch held together by auxiliary accelerating and decelerating voltages applied to tail and head, which is the anticipated mode of operation, it is unfortunately a more difficult case to study in simulation. For this reason, the simulation runs made thus far have been for the case of a parabolic charge distribution. By varying the resistance through the range suggested by theory, there does in fact appear to be a qualitative difference in bunch behavior above and below the suspected threshold; if the resistance is high, a perturbation does not reflect readily from the end of the bunch but rather chews the bunch apart starting from that end, whereas, with a low resistance, the end is perturbed but seems to recover as the wave reflects. There is much work yet to be done--for example, is it the e-folding distance that matters or the absolute magnitude of the disturbance We anticipate that a square distribution will be better behaved, as the square-well analysis predicts, but we have not yet tested the reliability of the code in handling abrupt discontinuities at the ends.

We have also modeled as realistically as possible two example cases of full scale drivers developed for cost and systems studies without regard to this phenomenon. An earlier version proved to be unacceptable, while a later example, involving multiple beams, was acceptable for the specified length of accelerator.

The simulation program was also applied to the parameters of the single beam transport experiment to see what might be learned from the deterioration of the front and back of the long pulses. It was determined that a slow rate of rise and fall of the current should be somewhat less disruptive of the ends than a rapid rise and fall.

2. Two and One-Half Dimensional Simulation

We feel that eventually a fully three-dimensional code will be needed for a satisfactory modeling of bunch behavior. As an intermediate step an r-z code is being developed and some results are expected shortly. An immediate application would be to the problem discussed in the previous section since the critical region appears to be the ends of the bunch, where the real fields are obviously described inadequately in a one-dimensional code.

3. Beam Transport Studies

The EGUN code now includes the external non-linear forces specific to the electrostatic electrode design adopted for the single beam transport experiment and a few runs have been made to compare with predictions of the semi-analytic work previously reported[7]. For modest betatron tune depressions, there is approximate agreement between the two approaches; more extreme cases are currently being studied. The code was also used to trace the beam through the matching section for a few sample cases of different emittances and currents and showed good agreement with the analytic results obtained by integrating the envelope equations. We therefore believe that the lens voltages specified by the analytic work are approximately correct and that the beam should pass through the matching section without significant disruption.

Since the advent of alternating gradient focusing there has been occasional speculation on the corresponding properties of non-linear lenses, but little motivation to pursue the matter because of the mathematical simplicity of

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7. E. Close and W.B. Herrmannsfeldt, Proc. 1981 Particle Accelerator Conf., op. cit., p. 2425.

linear systems. Since space charges forces can be highly non-linear, this simplicity loses much of its advantage for the transport of intense beams and it becomes interesting to inquire if there might be practical gains to be made by using alternating gradient octupoles, for example, rather than quadrupoles. This question is being pursued at LANL, LBL and SLAC. It appears that single particle motion is stable, provided that the amplitude is not too large; from analytic work and simulation runs with EGUN, an equilibrium current distribution appears to be hollow in the center. Further studies are in progress.

D. PUBLICATIONS AND REPORTS

Number	Author	Title	Date
HI-FAN-159 (LBL-12409) (Abstract)	A. Faltens, E. Hoyer, D. Keefe	A 3 megajoule Heavy Ion Fusion Driver (Abstract to be presented at the 4th Inter. Topical Conf. on High-Power Electron and Ion Beam Research and Tech., Palaiseau, France, 6/29 - 7/3/81)	5/20/81
HI-FAN-160	C. Kim	Single Beam Transport Experiment Ref. Parameters	5/20/81
HI-FAN-161	L.J. Laslett	Letters to Dr. I. Haber (NRL), Concerning Functions for Simulation Computations	5/28/81
HI-FAN-162	H.I.F. Staff	Heavy Ion Fusion Half-Year Report October 1, 1980, - March 31, 1981	6/4/81
HI-FAN-163	D. L. Judd R.O. Bangerter	Impact of New HIF Target Requirements On the Phase Space Constraint	6/18/81
HI-FAN-164	W. Herrmannsfeldt, T. Godlove, D. Keefe	Inertial Confinement Fusion System Using Heavy Ion Accelerators as Drivers (Atomkernenergie: Kerntechnik Bd. 36, 207, 1980)	6/21/81
HI-FAN-165 (LBL-12855)	D. Keefe, E. Hoyer	Proton Induction Linacs as High-Intensity Neutron Sources (Presented at the Vth ICANS meeting, Karlsruhe, Germany, June 1981)	7/7/81
HI-FAN-166 (LBL-12409)	A. Faltens, E. Hoyer, D. Keefe	A 3 Megajoule Heavy Ion Fusion Driver (Presented at the 4th Inter. Topical Conf. on High-Power Electron and Ion Beam Research and Technology, Palaiseau, France, June 29 - July 3, 1981)	7/10/81
HI-FAN-167 (LBL-12878)	A. Sternlieb	The Resistive Wall Instability in a Uniform Beam: Simulations vs. Analytical Results	7/15/81
HI-FAN-168 (LBL-12210)	D. Keefe	Research On High Beam-Current Accelerators (Published in Particle Accelerators II, 187 1981)	7/15/81
HI-FAN-169	L.J. Laslett	The Field Between and Within the Electrodes of a Periodic System Formed by Thin-Walled Co-Axial Circular Cylinders	7/17/81

Number	Author	Title	Date
HI-FAN-170	W. Herrmannsfeldt	Status of the US Heavy Ion Fusion Program	7/30/81
HI-FAN-171	L.J. Laslett	Tune, Matrix Elements, and Approximately Equivalent Hard-Edge Quadrupoles for Trapezoidal-Quadrupole Pairs	8/18/81
HI-FAN-172	A. Sessler	Collective Field Accelerators	9/9/81
HI-FAN-173	L.J. Laslett	"Equilibrium Distributions ..." -- Continued	9/29/81
HI-FAN-174 (LBL-13529)	H.I.F. Staff	HIF Year-End Report April 1981 - Sept. 1981	10/81
HI-FAN-175	L. Smith	Beam Dynamics in Heavy Ion Induction Linacs (Presented at the 1981 Linear Accel. Conf., Santa Fe, NM, Oct. 19 - Oct. 23, '81)	10/28/81
HI-FAN-175	A. Faltens, D. Keefe	Review of Induction Linacs (Presented at the 1981 Linear Accel. Conf., Santa Fe, NM, Oct. 19 - Oct. 23, '81)	10/28/81

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