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Author
Fessenden, T.J.

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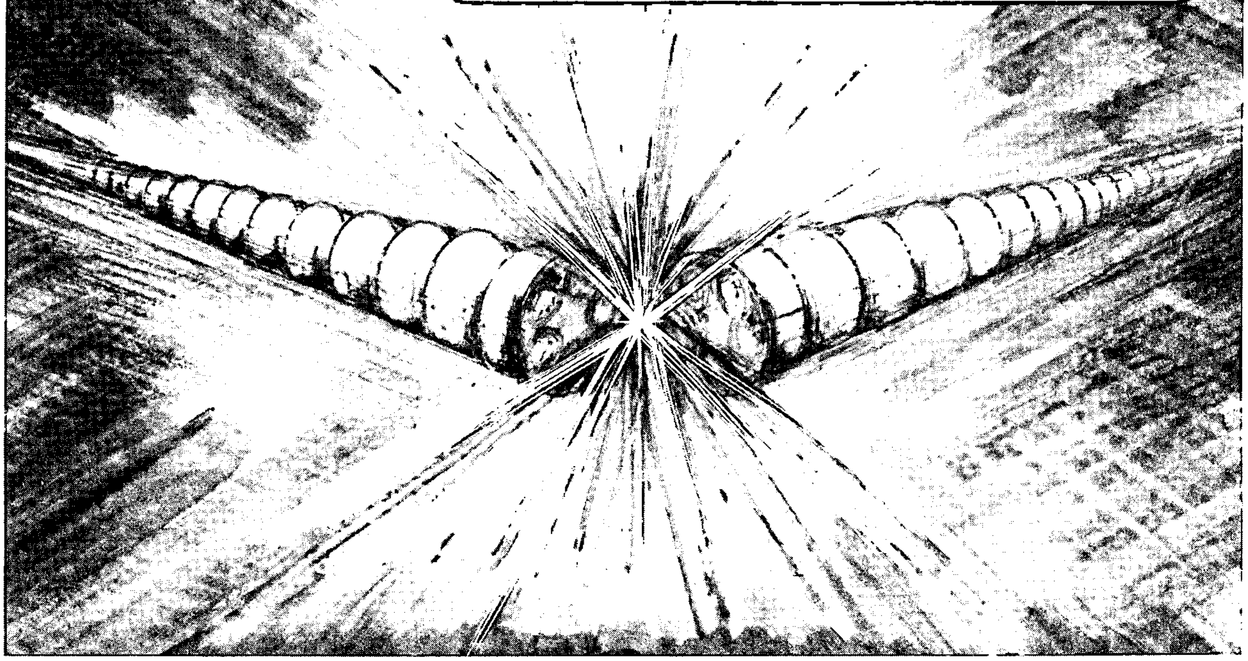

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Thomas J. Fessenden

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720

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Thomas J. Fessenden

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720, USA

Summary

Since October 1983, most of the research in the U.S. on heavy ion fusion (HIF) has been devoted to the physics and technology of the induction linac driver. The economic viability of the method was confirmed in the recent HIF Systems Assessment [1].

Research at Berkeley comprises three experimental activities: (a) The multiple-beam experiment, MBE-4, which accelerates four parallel, separately focused beams of cesium ions from 0.2 to 1 MeV; amplification of the beam power by a factor of nearly 40 is observed; (b) development of a 16-beam, pulsed, 2-MV injector; and (c) a single beam transport experiment (SBTE) for studying collective phenomena in ion beam transport.

In addition, a major activity has been the development of a physics and engineering design for a larger experiment to test (in a scaled way) almost all of the manipulations needed in a full-scale driver. A complicating feature in the design is the combining of beams (in sets of four to one); the penalty in collectively enhanced emittance growth must be balanced against the cost savings gained in a driver.

Introduction

At the Lawrence Berkeley Laboratory, the Heavy Ion Fusion Accelerator Research (HIFAR) group is studying the multiple beam induction linac as an accelerator-driver of heavy ions to achieve inertial fusion. This approach is intended to complement the RF Linac/storage ring approach being pursued in Germany, Japan, and the USSR.

Figure 1 shows a schematic of the HIFAR concept of an induction linac fusion driver. This concept emerged from the Heavy Ion Fusion Systems Assessment (HIFSA) study [1] that was conducted during 1984-86. This study concluded that at an electrical output power of 1 GWe, energy could be produced at costs equal to or somewhat less that projected by similar studies done for magnetic confinement and inertial fusion (STARFIRE [2], HIBALL [3]). The accelerator would comprise about 40% of the capital cost of the installation. Furthermore, no single component dominated the system economics. Variations in performance of different system components could be compensated by changes in the system configuration such that the net cost of energy remained remarkably constant.

There are many features that make induction linacs attractive as heavy ion fusion drivers. A relatively large technology base exists based on its use as an electron accelerator. No storage or accumulator rings are required to build up the required beam energy or to concentrate this energy to the necessary power levels. Current may be continuously amplified through the accelerator. The maximum electrical efficiency can approach 30 to 35% at total beam currents of several kiloamps. With "perfect" control of the accelerating waveforms there is, in principle, no longitudinal mixing of the particles in the beam bunch. A practical consideration is that many of the key accelerator issues occur at the lowest energy where the focusing system is least effective. Much of this physics can be examined with small scale experiments.

For the induction linac approach to an accelerator/driver to be successful, a number of issues must be satisfactorily resolved. The transport and acceleration physics of space-charge-dominated ion beam must be fully understood. The engineering complexity of accelerating many beams in parallel must be resolved. A consequence of continuous current amplification is that focus, steering, and bending systems must deal with time-changing beam speed and energy during the pulse. The growth in normalized transverse emittance must be limited to about a factor of 100. The longitudinal accelerating waveforms must adequately control the current pulse shape through the accelerator and, possibly, form the power pulse shape at the pellet. As the total beam current in the accelerator grows to large values, the beam loading must not lead to instability. And, finally, the economics of the entire system must be favorable.

The HIFAR group at LBL is attempting to answer these questions through a series of experiments of increasing scale. With these we intend to assess the physics, technology, and economics of the multiple ion beam induction linac as a fusion driver for commercial fusion.

At present experimental research at LBL is performed with three facilities:

1) SBTE--an ion beam transport experiment;
2) MBE-4--a multiple-beam ion induction linac; and
3) 2-MV injector--a 16 beam injector development.

In addition we are designing the Induction Linac System Experiment facility for addressing in a scaled way, many of the other physics issues that must be faced by an induction linac driver.

The Single Beam Transport Experiment (SBTE)

This is a facility for experimentally studying the transport of space-charge-dominated ion beams focused by electrostatic quadrupoles. Cesium$^+$ at an energy of $\approx$ 125 keV is transported over 13 m through 41 lattice periods at currents up to 20 mA. The focus electrodes were carefully designed to minimize contributions from unwanted higher order field components. The major results from this experiment, reported several years ago [4], showed that space-charge-dominated ion beams could be transported with little to no transverse emittance growth at higher currents and/or beam brightness than expected. These results have influenced HIFAR designs of induction linac drivers and led to reduced cost estimates. For the past year the facility has been used for the development of carbon sources for the 2-MV, 16-beam carbon injector to be described. We are presently in the process of completing a source test stand that will free the SBTE facility for additional propagation studies.

The Multiple Beam Experiment MBE-4

MBE-4 is an ion induction linac that accelerates four parallel cesium beams to energies greater than 0.9 MeV. The experiment models longitudinal beam dynamics and control in the electrostatic-focused section of an induction linac driver. At present MBE-4 is the principal experiment being conducted under the HIFAR program. This experiment is telling us just how "perfect" the accelerating waveforms must be as well as pointing out the consequences of inadequate waveform control. We are also studying the preservation of transverse emittance during the acceleration process.

The facility is approximately 17 m long which is about 15 times longer than the bunch lengths of the beams at injection. A schematic of the facility is presented in Fig. 2. Four cesium beams are obtained from four alumino-silicate sources at a temperature near 1000 °C. The beams are extracted by a 200-kV, 2.4-μsec pulse obtained from a Marx generator and are accelerated from 0.2 to more than 0.9 MeV by 24 induction units. The accelerator is 30 lattice periods long--each period is 0.46 m. The fabrication of the facility was begun in 1985 and completed in 1987. Experiments were performed at various stages of completion as the facility was fabricated [5].

Recent experiments have been concentrating on aggressive acceleration schedules in which the current amplifies from 4 x 10 mA to 4 x 90 mA with no loss of charge. Fig. 3 shows oscillograms of the current along MBE-4 at every fifth lattice period where diagnostic access is available. The current amplification results from both a velocity increase (factor of $\approx$ 2) and bunch length shortening (factor of $\approx$ 4) as the beams pass through the linac. For these experiments our control of the current pulse waveform was less than adequate. We are in the process of improving our control by adding more compensation waveforms to correct errors introduced by the injector and investigating less aggressive acceleration schedules which better model the accelerator physics of a driver. More details of recent MBE-4 experimental results along with a comparison with computations are contained in the invited paper [6] presented by H. Meuth at this conference. An analysis of the growth of current oscillations as a consequence of acceleration errors was recently presented by Warwick et al [7].

2-MV injector

The development of a 2-MV, 16-beam injector was begun at the Los Alamos National Laboratory in 1984 as a source of sodium beams for an induction linac experiment then being planned. In the summer of 1987 the injector development was moved to the Lawrence Berkeley Laboratory. It is our intention to use this injector for ILSE.

The design goals of the development are to produce 16 beams of C^+ at a current of 500 mA per beam at 2 MV. The beam energy and current should be flat to 0.1% for the 1 μsec pulse width; the normalized beam emittance should be less than 0.5 π mm-mrad (4 x rms). The development of metal vapor plasma sources of C^+ for the injector was begun by Humphries and Burkhart [8] at the University of New Mexico and at LANL. This development is being continued at LBL using the SBTE facility as a test bed. At present the source produces adequate current density at an emittance of 0.7 π mm-mrad for a beam of one-half the desired diameter. Tests of injector operation with one beam at full voltage are scheduled for November of this year. Details and the present status of this development are contained in the paper[9] of Rutkowski et al at this conference.

ILSE

We are also engaged in a conceptual engineering design of the Induction Linac Systems Experiment (ILSE) which is intended to address, at a reduced scale, the particle beam manipulations required of a heavy ion fusion driver. We expect to complete this design in September 1988. ILSE is a research program that, if approved by the U.S. Department of Energy, will require five or more years to complete. The experiments are intended to:

a) examine the physics of transversely combining space-charge dominated ion beams;
b) study acceleration in magnetic-focused ion linacs (this consideration prompted us to choose the relatively light ion C^+);
c) explore the bending of intense ion beams with time-changing energy;
d) study the physics of drift-compression current amplification:
e) examine the focusing of ion beams to a 2-3 mm spot; and
f) explore some of the plasma phenomena that will be present in the target chamber.

A block diagram of our concept of what the ILSE facility might look like is presented in Fig. 4. Sixteen beams of singly or doubly charged ions from the 2-MV injector are matched to an electrostatic transport system and accelerated to 4 MV by an electrostatic-focused induction linac. The initial current pulse duration is one microsecond. At this point the beams are combined to form four beams, which are matched to a magnetic-focused linac for further acceleration to 10 MV. One beam is then bent through 180 degrees and longitudinally compressed in a drift-compression section. This beam is used for a final focus experiment. Table 1 contains some of the parameters of the design.

An initial consideration of the design was the mechanical tolerances that could be allowed in the accelerator. The most stressing requirements are related to the beam combining section in which it is desirable to bring the beams as close together and moving as parallel as possible. For the purpose of this design, tolerances of 1 mm in position and 1 mrad in angle were accepted. From these the acceptable tolerances on the individual elements of the focusing structures were derived assuming a gaussian distribution of errors. This led to the specification of ± 0.1 mm on the position of the rods in the electrostatic focusing arrays. Details of this calculation as applied to a driver are contained in the paper of Smith and Hahn [10] presented at this conference.

Figure 5 shows a cross-section of an electrostatic-focused accelerating cell each of which is one-half lattice-period long. The clear aperture for each beamlet is 56 mm and the electrodes are 43 mm in diameter. Only the electrostatic quadrupole array is supported with precision. Each 16-beam array, consisting of 25 electrodes at polarities of typically ± 30 kV, is suspended by a total of 8 tension rods that are referenced to four alignment bars. The bars are aligned with a laser system possibly similar to that developed [11] for SLAC. Engineering indicates that this support system will achieve the positional tolerance of ± 0.1 mm on the focus electrodes. The circle within the support structure is approximately 1.5 m in diameter and represents the magnetic core material which is envisioned to be metallic glass.

The physics designs of the beam combining and bend sections are considered in the paper of Lee [12]. The conceptual engineering designs of these sections are not yet complete.

Figure 6 shows a longitudinal cross section of the cell design for the magnetic focus section of ILSE. The focusing elements are pulsed room-temperature quadrupole lenses, with the current windings placed in a configuration that could be adapted to a super-conducting D.C. design for a driver. The main windings in the design are longitudinally placed in two layers on the surface of a circular cylinder, in an approximately Cos 2θ pattern, and a sharp 90-degree transition to the end windings serves to economize on the overall length of the assembly. The detailed angular locations and lengths of the individual turns have been so computed as to suppress the dodecapole component of the field in the integral sense (i.e., when integrated over a quarter lattice period). The ideal accelerating waveforms are nearly square with a maximum amplitude of 180 kV. At the end of the the accelerator the current pulse duration has been reduced to 0.35 μsec.

Acknowledgment

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Figure Captions

Fig 1 Heavy Ion Induction Linac Driver Concept.

Fig. 2 Diagram of MBE-4.

Fig. 3 Faraday cup measurements of the cesium beam current along MBE-4. The vertical scale is 20 mA/div and the horizontal scale is 500 ns/div in all oscillograms.

Fig. 4 Schematic of the Induction Linac Systems Experiment (ILSE).

Fig. 5 Design of a 16-beam, electrostatic-focused accelerating cell.

Fig. 6 Design of a 4-beam magnetic-focused accelerating cell.

Table 1 Some ILSE Parameters

Beam energy at injection	2	MeV
Initial current in 16 beams	5.4	A
Pulse duration	1.0-0.35	μs
Final beam current in 4 beams	15	A
Final energy in 4 beams	55	J
Lattice lengths	0.9-1.2	m
Final beam energy	10	MeV
Total Accelerator length	37.5	m
Alignment tolerances	≤ 0.1	mm
Acceleration gradient	0.3	MV/m
Electrostatic Quad voltages to	± 35	kV
Magnetic Quad tip fields to	±1	T.
Bend Radius	8	m
Drift Compression length	50	m
Target current (1 beam)	≈10	A.

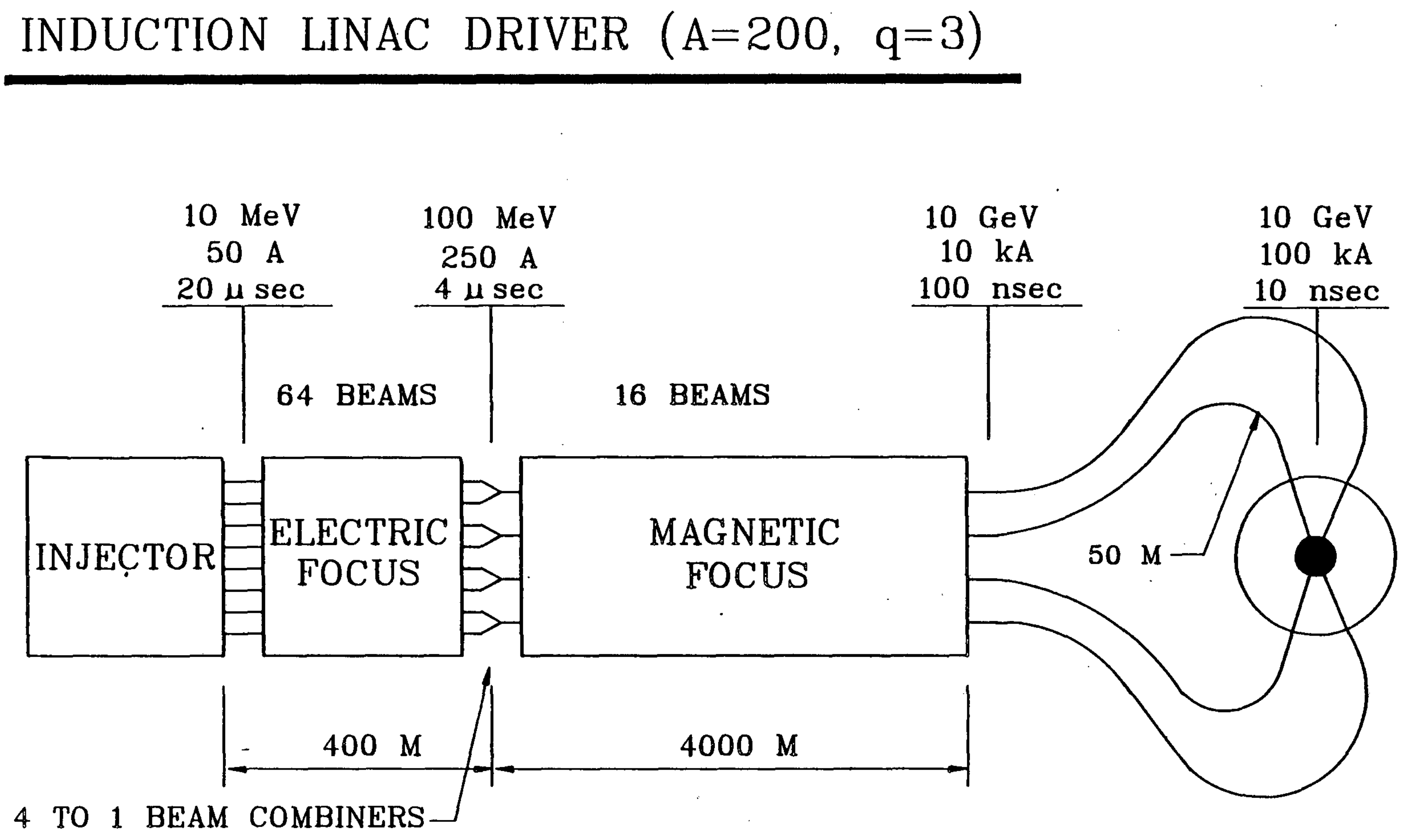

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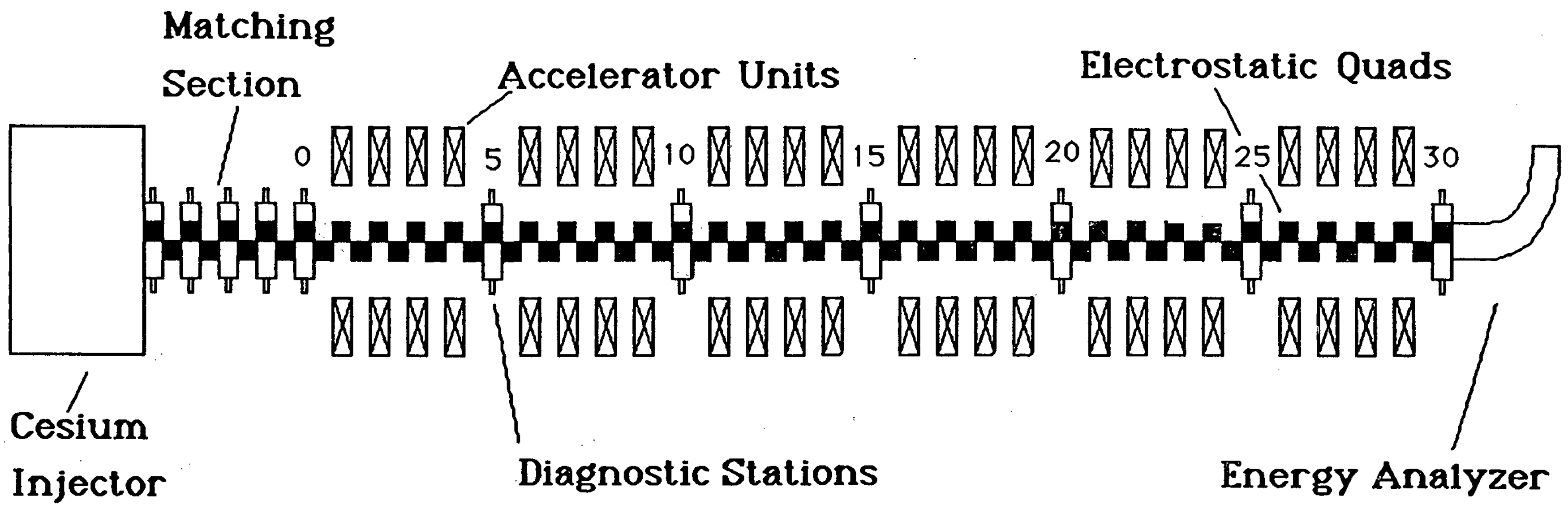
Fig. 1



Multiple Beam Experiment

MBE-4

Fig. 2

Current Amplification in MBE-4

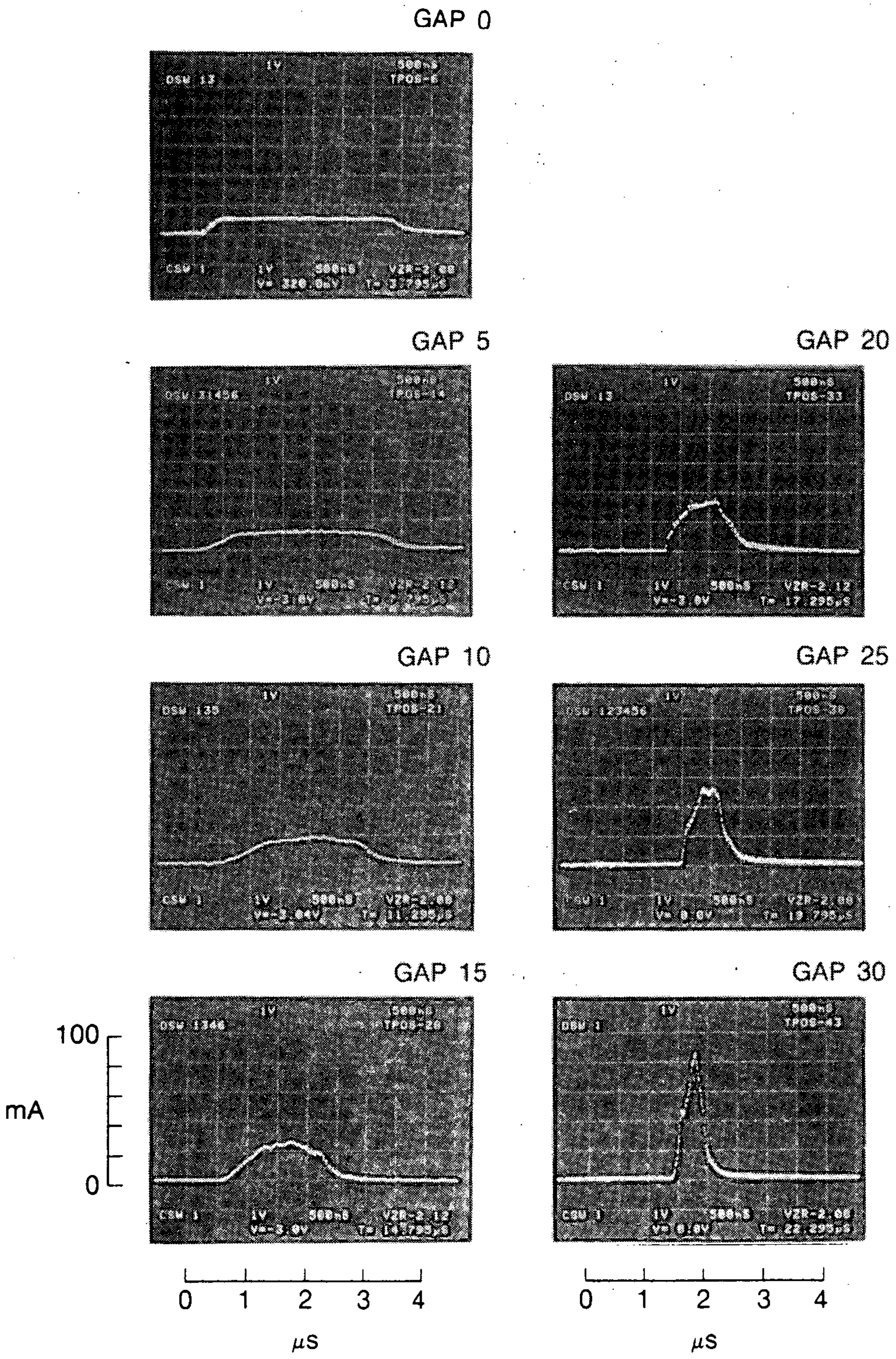


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Fig. 3

INDUCTION LINAC SYSTEMS EXPERIMENT

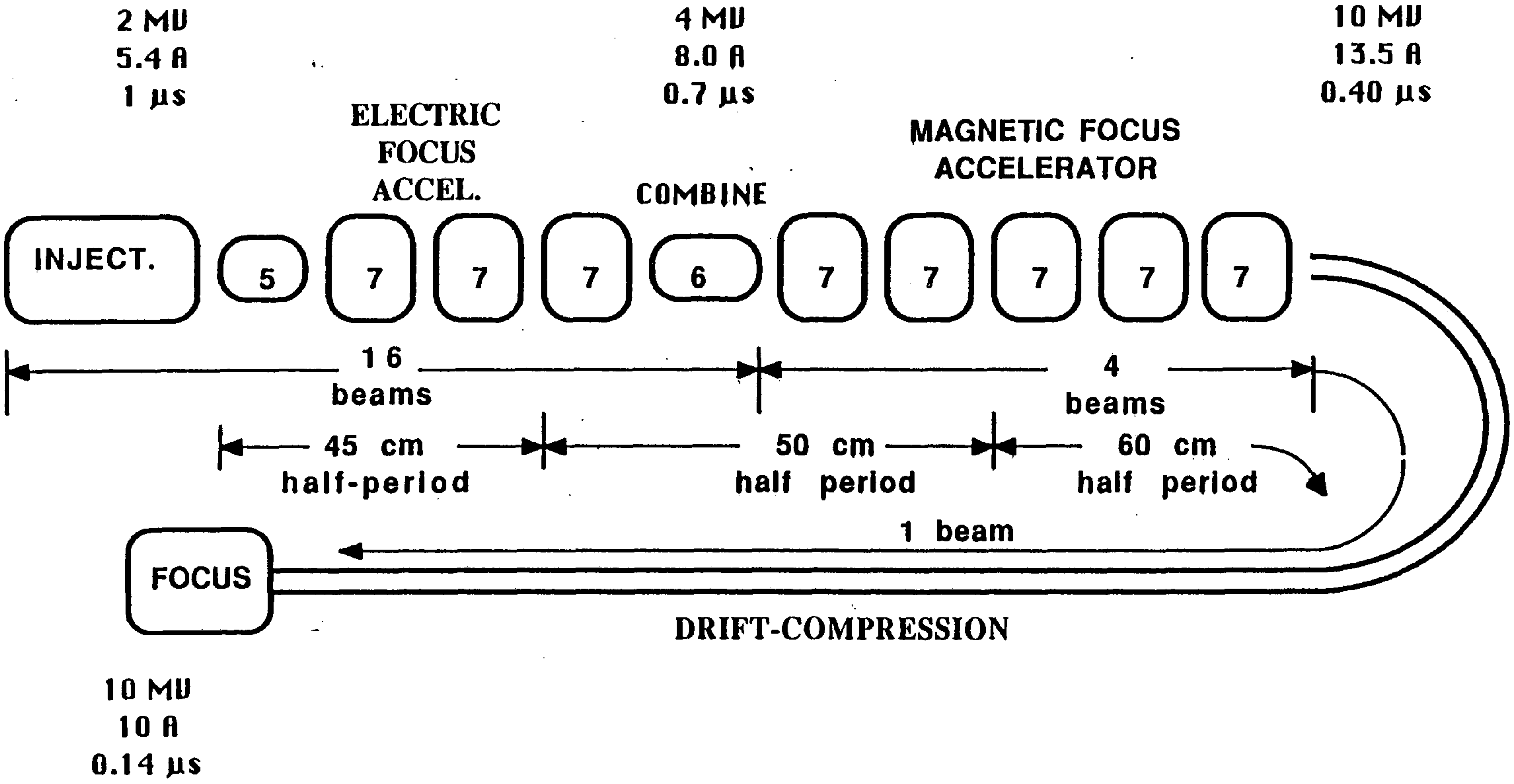

Fig. 4

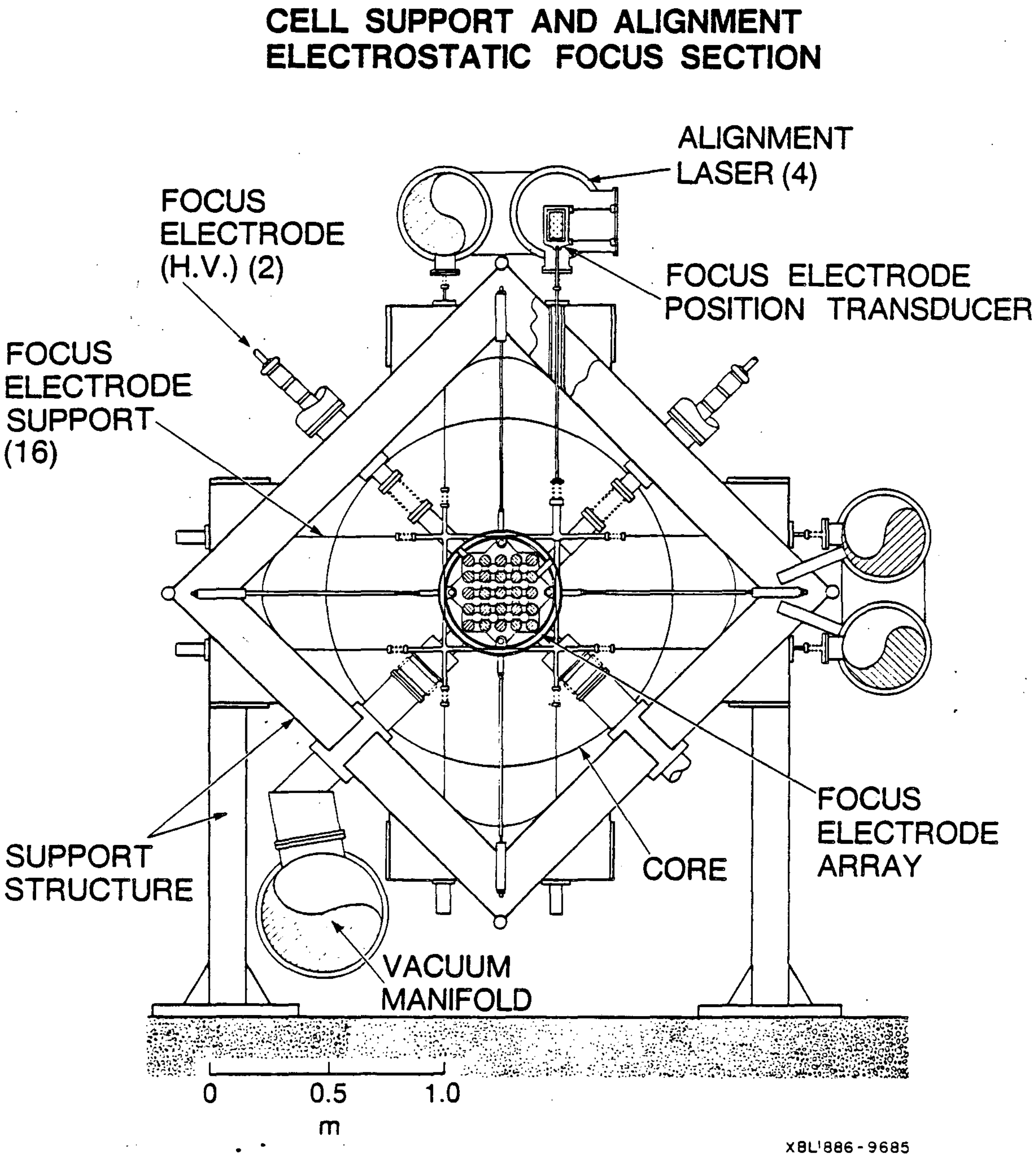
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Fig. 5

Cell Design Magnetic Focus Section

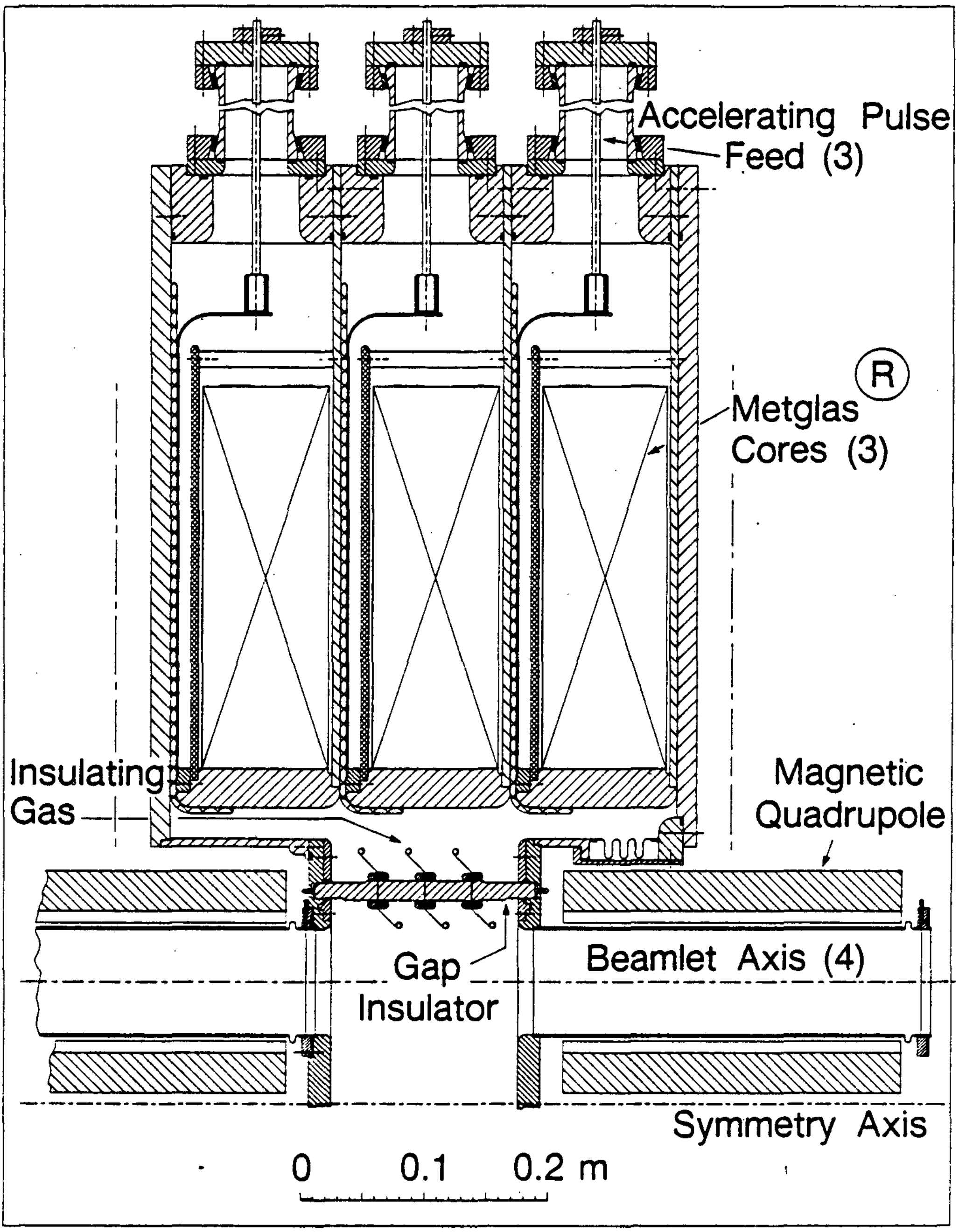

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Fig. 6

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
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