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HEAVY-ION FUSION ACCELERATOR RESEARCH 1985

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Heavy-Ion Fusion Accelerator Research 1985

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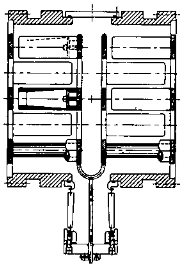
HEAVY-ION FUSION ACCELERATOR RESEARCH



THE CONCEPT OF GENERATING USEFUL POWER by means of inertial-confinement fusion (ICF) centers around various schemes for compressing and heating small pellets of deuterium or tritium to the point that net energy is released in a thermonuclear reaction. Many approaches have been proposed for focusing the necessary energy on the fuel pellets; among those under active study are lasers and heavy- and light-ion accelerators. Heavy ions—the thrust of our effort at LBL—are particularly attractive, since high-current heavy-ion accelerators can be made to operate efficiently and at high repetition rates.

Two types of heavy-ion accelerators are now under active study: the rf linac, used in conjunction with storage rings (being studied principally in West Germany), and the induction linac, the approached favored here. In its simplest terms, the induction linac consists of a series of ferromagnetic cores powered by carefully timed pulses of high voltage. Each disklike core then acts like the core of a transformer, with the ion beam (passing through a hole in the disk) behaving like the secondary. Proper timing of the pulses to the cores then establishes a gradient for accelerating bunches of particles. The attractions of this design over the rf linac are (a) its conceptual simplicity (see Fig. 23), (b) the considerable experience accrued in its application to high-current electron-beam acceleration, (c) its single-pass nature (which avoids the need for beam accumulation in a storage ring), and (d) the ease with which it can be scaled up from smaller test accelerators. This last point suggests that the most important technical issues can be resolved at relatively low cost.

In line with this argument, the plan for exploring the physics and technology of induction linac development involves a series of increasingly sophisticated experiments. The first, which has yielded significant experimental results during the past two years, is the single-beam transport experiment (SBTE). In it we have explored the physics of a single space-charge-dominated beam. Second is the multiple-beam experiment (MBE),

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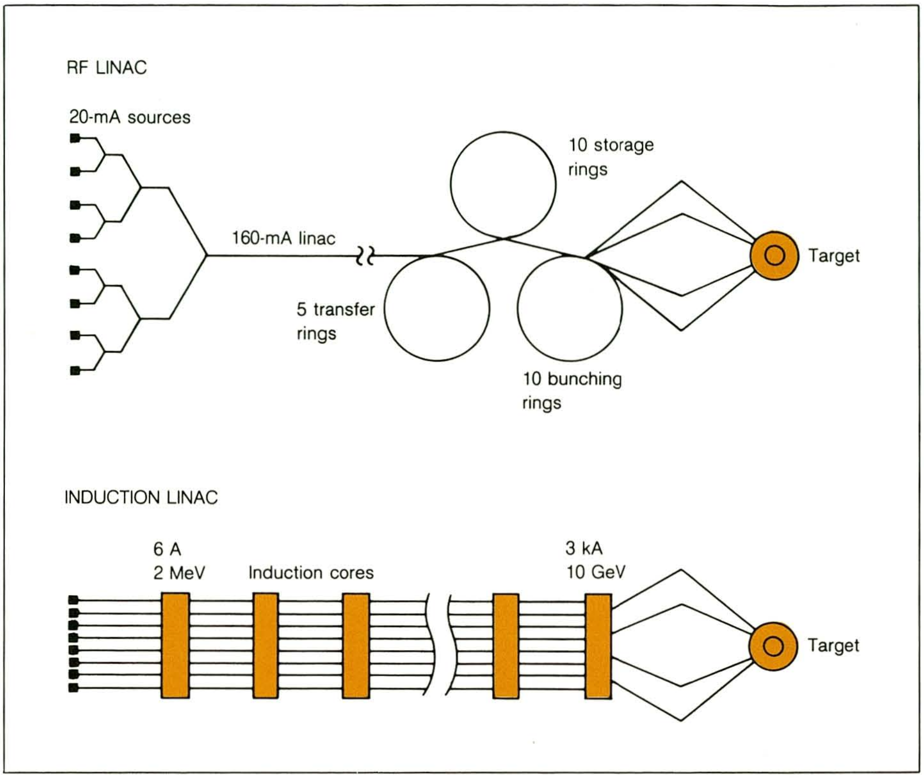
Fig. 23. Simplified conceptual designs for inertial-fusion drivers based on rf and induction linear accelerators. In contrast to the multiple transfer, storage, and bunching rings of the rf linac, the induction linac might require several thousand induction modules.



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in which four independent beams will be transported and accelerated through a multigap accelerating structure. This four-beam MBE may then be followed by a 16-beam design that will ultimately be expanded to serve as the final step in the research program, the High-Temperature Experiment (HTE). Our aim in this final step will be to provide the data necessary to allow a quantitative evaluation of the prospects of heavy-ion accelerators as ICF drivers.

Single-Beam Transport Experiment

In the SBTE, a high-current cesium beam is transported through 41 focusing-defocusing pairs of electrostatic quadrupole lenses. The principal goal over the past two years has been to understand how the effect of mutual electrostatic repulsion—space charge—could limit the stability of such a beam. In the first half of fiscal 1985, this effort culminated in a detailed "map" of stability limits for a range of transport conditions. For certain focusing conditions, no such limit could be identified. During the past year, we also successfully implemented a longitudinal bunch-control system on the SBTE, and we installed a 90° electrostatic beam-energy analyzer.

Stability Studies

The apparatus for the SBTE consists of a thermionic cesium-ion source, an injector, a matching section comprising 5 quadrupoles, a periodic transport section of 82 quadrupoles, and a diagnostics chamber. Its purpose has been to explore stability limits for a space-charge-dominated heavy-ion beam in an alternating-gradient lattice—threshold information that will serve as a foundation for the design of the proposed HTE. The independent variable in our studies of stability has been the so-called phase advance, which can be understood in terms of the typical sinusoidal motion of an idealized single particle in the SBTE lattice. The phase advance σ_0 expresses, in units of degrees, the fraction of a full (360°) oscillation executed by the particle per lattice period. A second parameter, the depressed phase advance σ, reflects the defocusing force imposed by the mutual electrostatic repulsion of the particles in a high-current beam. Owing to this defocusing force, the period of oscillation increases, hence the numerical value of σ is smaller than that of σ_0. In fact, the larger the beam current, the smaller the value of σ.

Since our aim is ultimately to carry as much current as possible, we have sought with the SBTE to identify the lowest permissible value of σ as a function of σ_0. The result has been the plot of σ versus σ_0 shown in Fig. 24. The figure shows that in the region we have been able to explore no instability thresholds have been detected for values of $\sigma_0 < 90°$. These results are especially encouraging in light of early theoretical expectations that, for $\sigma_0 = 60°$, instabilities might appear at $\sigma = 24°$, or even 40°.

Instrumentation and Other Studies

Until the past year, we had no apparatus for accurately measuring beam energies. Instead, we relied on the measured voltages on pulsers and on time-of-flight measurements for determining energies. To provide this needed diagnostic, we installed and tested a 90° electrostatic energy analyzer at the end of the SBTE. The spectrometer for this analyzer, shown in Fig. 25, consists of a pair of flat electrodes bent into concentric arcs, with a gap of 1 inch between the electrodes. The detector, downstream of the spectrometer, is a harplike array of thirty 0.002-inch wires that intercept the beam. Tests have indicated that pulses a few microseconds long do not cause breakdown problems in the spectrometer (as initially feared), hence the analyzer appears suitable for eventual use on the full multiple-beam experiment. It is now in use for beam studies on MBE-4 (see pages 50–51).

In a long ion linac, we expect that it will often be necessary to use pulsed voltage waveforms with "ears" on the leading and trailing edges to prevent the spreading of the beam pulses due to longitudinal space-charge forces. Accordingly, we installed and successfully operated a longitudinal bunch-control system on the SBTE during 1985. The system comprises seven independent pulsers, which apply

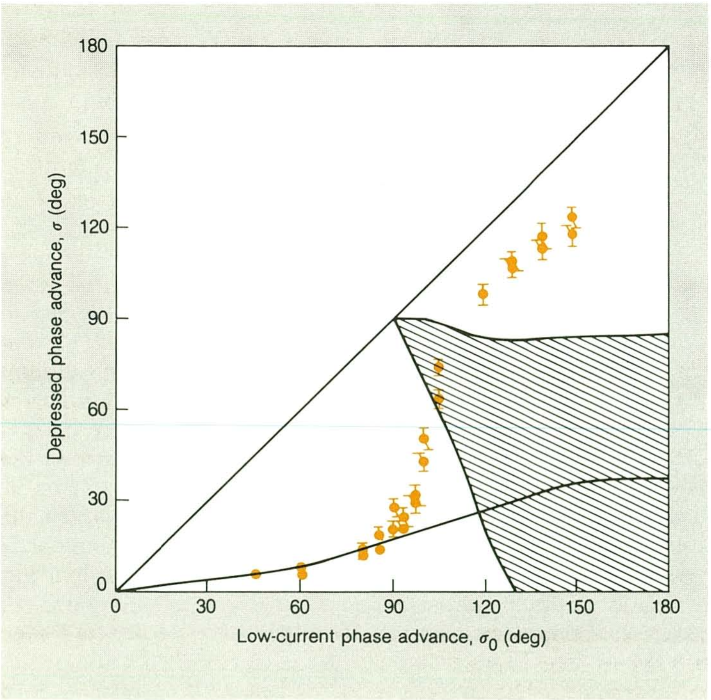

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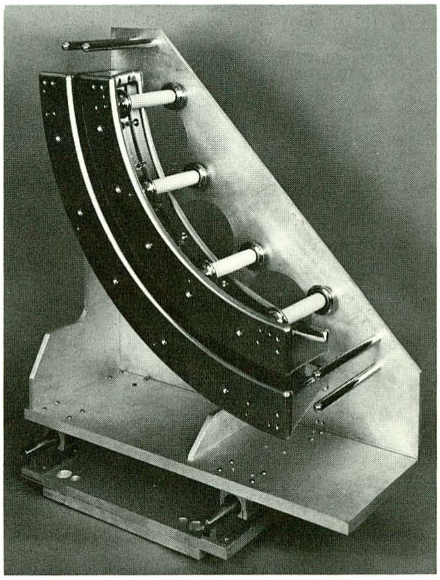
Fig. 24. **Plot of the high-current depressed phase advance σ as a function of the low-current phase advance σ_0, showing the stability limits determined by the SBTE. The various symbols indicate experiments in which beam was stably propagated and above which the beam was always stable; no instabilities could be detected for $\sigma_0 < 90°$. The solid line near the bottom of the plot indicates the lower limits of σ attainable with our experimental setup. The cross-hatched area marks a region of instability as calculated from the beam envelope equations. The region above the diagonal line is inaccessible, since σ cannot be larger than σ_0.**

shaped accelerating voltages to quadrupole pairs in the transport section of the accelerator. During early 1985, we also developed a nondestructive method of monitoring the charge per unit length of the SBTE beam. The method relies on measurements of the charge induced in the quadrupole electrodes by the space charge of the passing cesium beam. This passive diagnostic yields the beam current if the velocity is known.

Fig. 25. The curved electrodes of the electrostatic energy analyzer. The beam path is approximately 30 inches long.



Multiple-Beam Experiment

The first step beyond the SBTE is an experiment designed to serve as a "proof of principle" for the HTE. This four-beam experiment—called MBE-4—will be only 12 meters long, but when measured in terms of initial bunch length, its length corresponds to two-thirds the length of the HTE accelerator. It is therefore seen as a good test of accelerator physics principles, whereas technology development on the scale of the HTE must await a larger experiment. During 1985 MBE-4 was designed, the first four induction accelerating units were installed, and beam-current amplification was observed in our first round of experiments. Concurrent theoretical work produced a variety of acceleration schedules, together with the sets of associated voltage waveforms needed to implement them.

MBE-4 Design and Fabrication

Two elements of the philosophy behind the design of MBE-4 are worth special note. First, though on a much smaller scale, this experiment is being conducted to model much of the accelerator physics that we expect to encounter in the HTE (see Table 4). It will therefore demonstrate both energy amplification (×4) and current amplification (×4), hence significant power amplification (×16). In addition, as shown by the last entry in Table 4, it will address the same space-charge-dominated regime as the much larger experiment. Of particular importance is the opportunity that MBE-4 will afford us to assess electrical and mechanical tolerances demanded by high-current multiple-beam accelerators. The second element of the design philosophy is illustrated in Fig. 26. Though we do not expect the complete apparatus to be operational until early in 1987, the accelerator has been designed in sections, so that experiments can be conducted during the construction period. At the end of fiscal 1985, for example, only 4 of the 24 accelerator modules had been installed, but important experimental results had already been obtained.

At the end of September 1985, construction of the MBE-4 experimental

Table 4. A comparison of the principal parameters for MBE-4 and the High-Temperature Experiment (HTE).

	MBE-4	HTE
Number of beams	4	16
Injection energy, MeV	0.2	2
Ion	Cs	Na
Injection current, mA/beam	10	300
Final current, mA/beam	40	6000
Lattice half-period, m	0.23	$\gtrsim 0.3$ (varies)
Peak gap voltage, kV	30	250
No. of accelerating gaps	24	~500
Cores/gap	2 or 3	?
Total length, m	17	450
Length/injected pulse length	12	18
Final energy (variable), MeV	1	125
Minimum value of $\omega_p^2/2\omega_0^2 = [1 - (\sigma/\sigma_0)^2]$	0.96	0.98

apparatus had progressed to the point illustrated in Fig. 27. In place were the ion source, ten electrostatic quadrupole doublet arrays, four induction accelerating gaps, and five diagnostics boxes. The four-beam diode injector (shown in Fig. 27a) has operated consistently at and above its design voltage of 200 kV, producing beams well-matched in current and emittance. The injector comprises four aluminosilicate cesium emitters, each 1.5 inches in diameter. At 200 kV these surfaces emit 2 mA/cm^2 of Cs$^+$. A shaped graphite electrode then focuses the four beams through holes in a ground plate. The current of each beam is typically 10 mA, and the normalized emittance is 1.2×10^{-7} π m-rad. A beam-conditioning unit, consisting of four periods of quadrupole transport, allows each beam to be steered independently as it leaves the source, then collimates the beams at they enter the linac. The maximum current transmitted through the conditioning unit has been 13 mA.

The design of the quadrupole doublet assemblies for both the conditioning section and the first accelerator section is shown in Fig. 27b. The outside diameter of the housing is 12.7 inches. To achieve the alignment tolerances required for each of the 18 electrodes within an assembly, fabrication procedures and fixtures have been developed for each part. Measurements have confirmed that electrodes can be positioned with an accuracy of 0.002 inch.

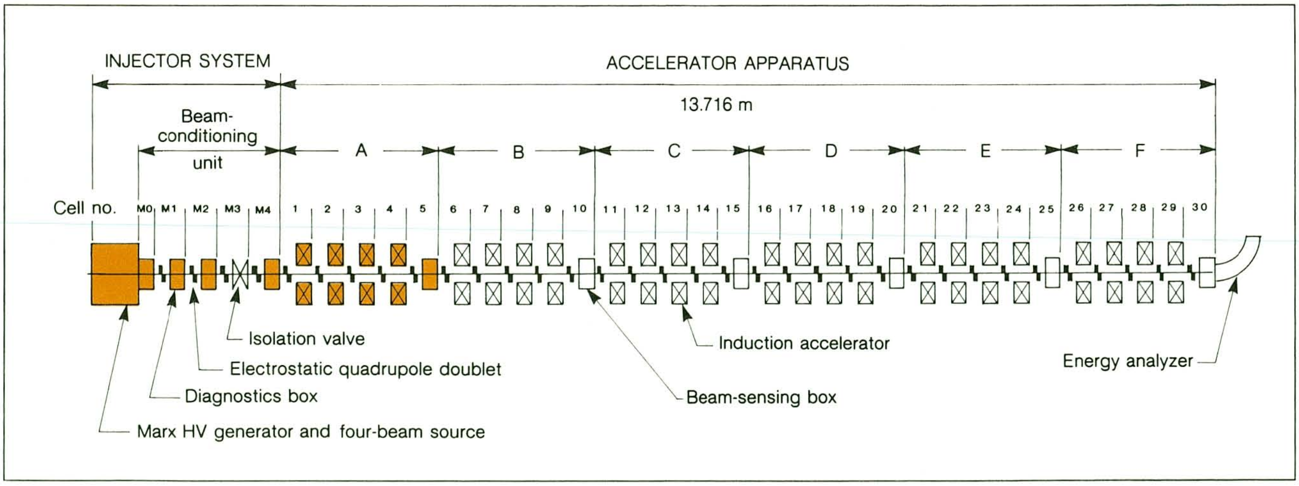


Fig. 26. Schematic of the complete MBE-4 design. The apparatus was designed so that experiments could be run as assembly proceeded. The injector section and accelerator section A were complete at the end of fiscal 1985; therefore, for the first phase of experimentation, the energy analyzer was placed immediately downstream of cell 5.

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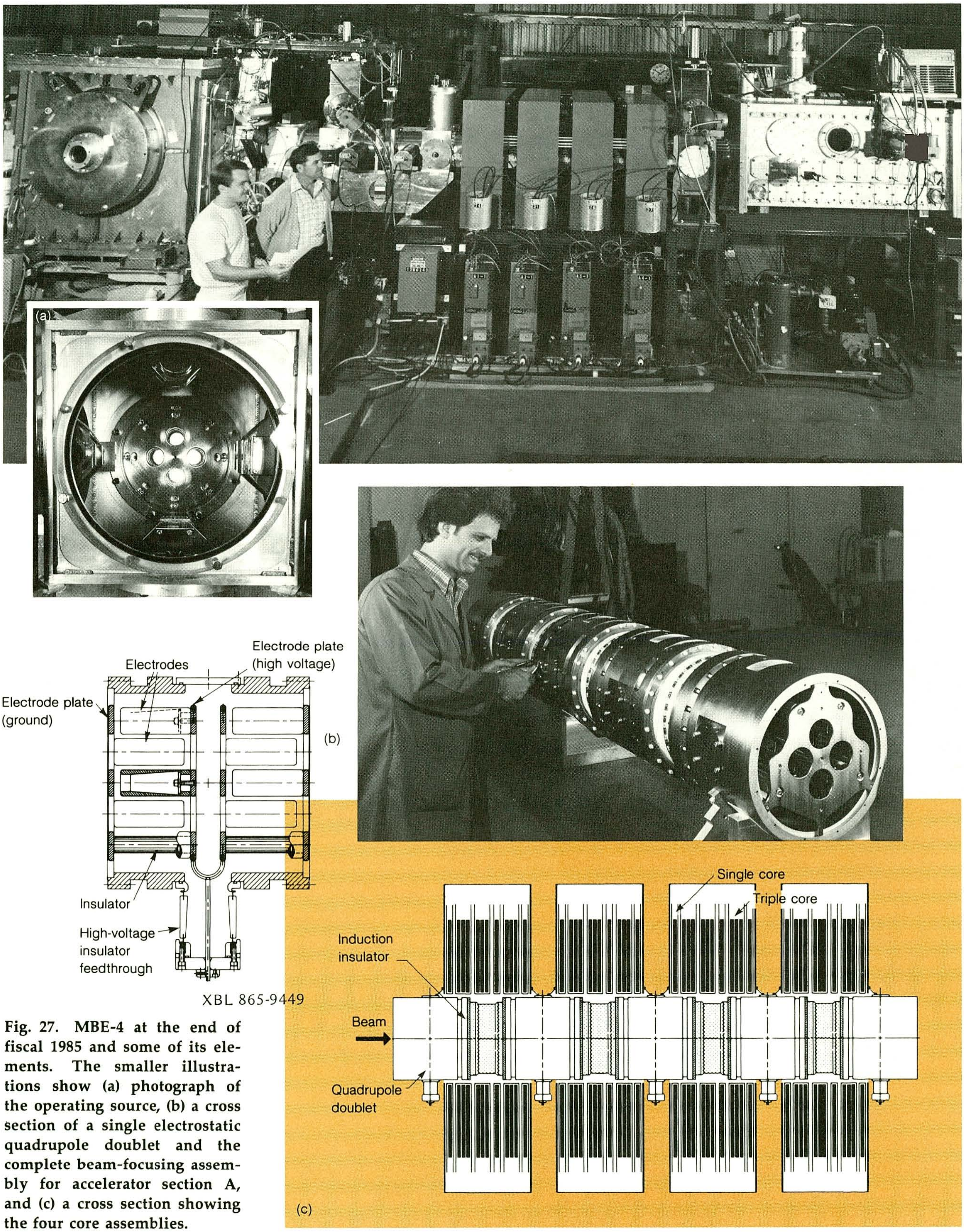

Fig. 27. **MBE-4 at the end of fiscal 1985 and some of its elements. The smaller illustrations show (a) photograph of the operating source, (b) a cross section of a single electrostatic quadrupole doublet and the complete beam-focusing assembly for accelerator section A, and (c) a cross section showing the four core assemblies.**

Each of the core assemblies for the four accelerating gaps now in operation comprises 12 Astron cores, arranged as shown in Fig. 27c. Each core assembly represents about 81 mV-sec of accelerating capability, substantially more than the 54 mV-sec needed for planned experiments. The core assemblies are driven by eight pulsers supplying roughly triangular accelerating voltage pulses.

Experimental Results

Following the successful operation of the eight core pulsers, four cesium beams were injected and accelerated in MBE-4 during the final weeks of fiscal 1985. No attempt was made at detailed optimization of the accelerating waveforms at this stage; in fact, the nominal schedule was designed assuming uniform current and kinetic energy as initial conditions—conditions not exactly realized in the accelerator. The accelerating voltage waveforms rise from zero at the beginning of the pulse, thus the head retains its original velocity, whereas the rest of the bunch is accelerated in a programmed fashion, with the tail receiving the most energy. In this way, the current is amplified as the bunch proceeds down the accelerator.

Figure 28 shows the current and kinetic energy for a 13-mA beam, measured as a function of time. The current was measured with a Faraday cup array one

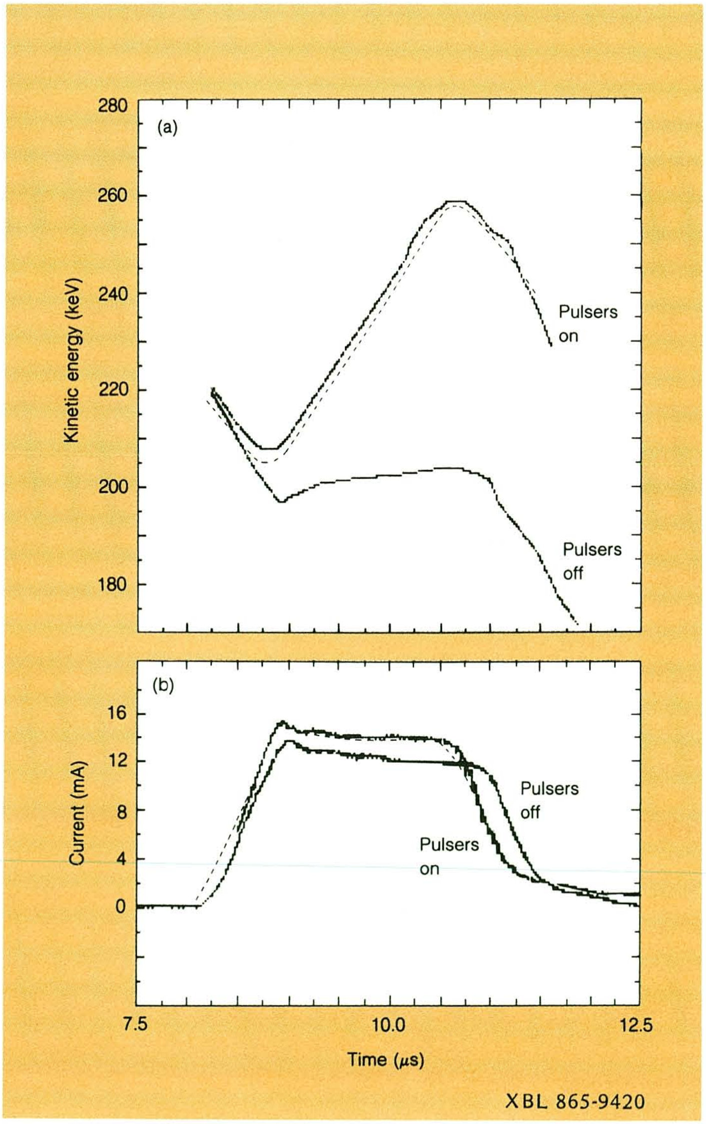

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Fig. 28. Experimental waveforms for (a) kinetic energy and (b) current for a 13-mA cesium beam with and without pulsers activated, measured downstream of the fourth accelerating gap of MBE-4. The dashed lines depict the results of theoretical calculations based on measured initial beam conditions. The lower plot clearly shows the effect of current amplification.

Fig. 29. (a) An illustration of current amplification, effected by shaped voltage waveforms, applied at the discete accelerating gaps of an induction linac. In this simple example, a ramped voltage is applied at gaps 1 and 2, its duration matched to the length of the pulse, and a simple step pulse is applied thereafter. The kinetic energy along the pulse length is shown at the right. The bunch length is held constant as the bunch velocity increases, hence the current is amplified. (b) A set of waveforms for the complete MBE-4, which would effect threefold current amplification. The waveforms are applied to gaps 1 through 24 as indicated in the figure.

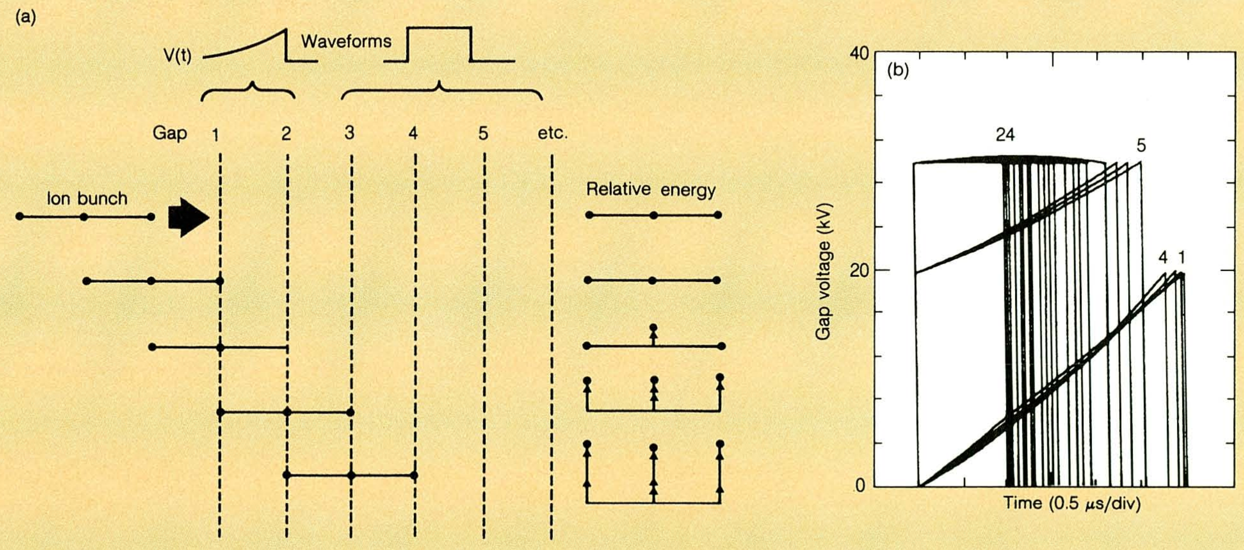
period downstream of the fourth accelerating gap, and the energy was measured with our electrostatic energy analyzer and averaged over many pulses. The lower value of current is observed without acceleration; with the pulsers operating, the tail of the beam arrives about 250 nsec sooner and the current is increased by approximately 13%. Total charge is conserved. The energy rises through the body of the bunch, with the tail gaining some 55 keV over the energy of the head.

The injector operates so as to yield particles with high energy in the leading edge of the bunch and particles with low energy in the trailing edge. The accelerating waveforms used in these initial experiments make no attempt to correct for this, and at the diagnostic station, the ends of each bunch have begun to drift apart. Additional pulsers will be deployed in the future to hold the bunch ends together. Given the actual accelerating waveforms and the measured initial conditions, we have computed the longitudinal behavior of the bunch. As shown by the dashed lines in Fig. 28, agreement with the data is excellent.

Pulse Waveforms and Accelerating Schedules

To realize current amplification in a linear induction accelerator—a requirement imposed by any envisioned application to inertial-confinement fusion—the initial set of accelerating modules must accelerate the tail of each bunch more than the head in some programmed fashion. (Thereafter, the pulse shapes can be more or less flat-topped.) This "program" is called an accelerating schedule, and a simple one is illustrated in Fig. 29a. These schedules, in turn, are implemented by the application of shaped voltage waveforms to the induction cores by a series of pulse-power supplies. During the past year, we have mounted an intensive three-pronged attack on the problem of designing these pulsers. First, we have developed and applied the computer code SLID to predict the ideal waveforms required for a particular acceleration schedule (it can also predict how beam behavior will deviate from ideal when nonideal waveforms are applied). Second, pulser experiments in the laboratory have enabled us to categorize the nonlinear impedance behavior of the core packages. And third, circuit analyses have led to specifications for some classes of realizable pulse shapes that can be superposed to provide good approximations to the ideal waveforms.

The reference acceleration schedule arrived at for the full 24-gap MBE-4, comprising 24 shaped waveforms, is shown in Fig. 29b. Operating under simple



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physical and technological constraints, our computer code produced these waveforms by a current self-replicating scheme. In this scheme, current increases in proportion to energy. Other schedules have also been developed in which current increases as $E^{1/2}$ or $E^{3/2}$. For the front end of a large linac, such as the HTE accelerator, where the quadrupoles will be operating at close to their breakdown limit, the $E^{1/2}$ schedule is likely to be the most practical. For MBE-4 even the most aggressive $E^{3/2}$ schedule may be workable. To synthesize the waveforms that constitute these schedules, simpler waveforms of three types will be superposed. The three types chosen are a constant-voltage form; a parabolic form $[V = V_0(2t - t^2)]$, possibly clamped; and a "one-minus-cosine" form $[V = V_0(1 - \cos \omega t)]$, possibly truncated. Pulser circuits have now been designed to generate these (and modified versions of these) waveforms, and models have been developed to simulate the response of the Astron cores to different voltages.

Other Experimental and Theoretical Activities

In concert with our work on the SBTE and MBE-4, we are continuing experimental and theoretical work that looks forward to an eventual High-Temperature Experiment (HTE). Among these activities in 1985 have been the conclusion of our work on collective-focusing effects, further measurements at the Bevalac aimed at elucidating the process of energy loss from energetic low-charge-state ions in matter, theoretical investigations of transverse beam dynamics, and calculations of beam dynamics for the HTE.

Neutralized-Beam Focusing Experiment

The goal of the so-called Robertson lens experiment has been to demonstrate focusing of a charge- and current-neutralized Cs$^+$ beam by a solenoid magnet. Theory argues that a beam of positive ions and electrons, strongly coupled through space-charge forces, should come to a common focus, rather than the two components being focused independently in accord with their different charge-to-mass ratios.

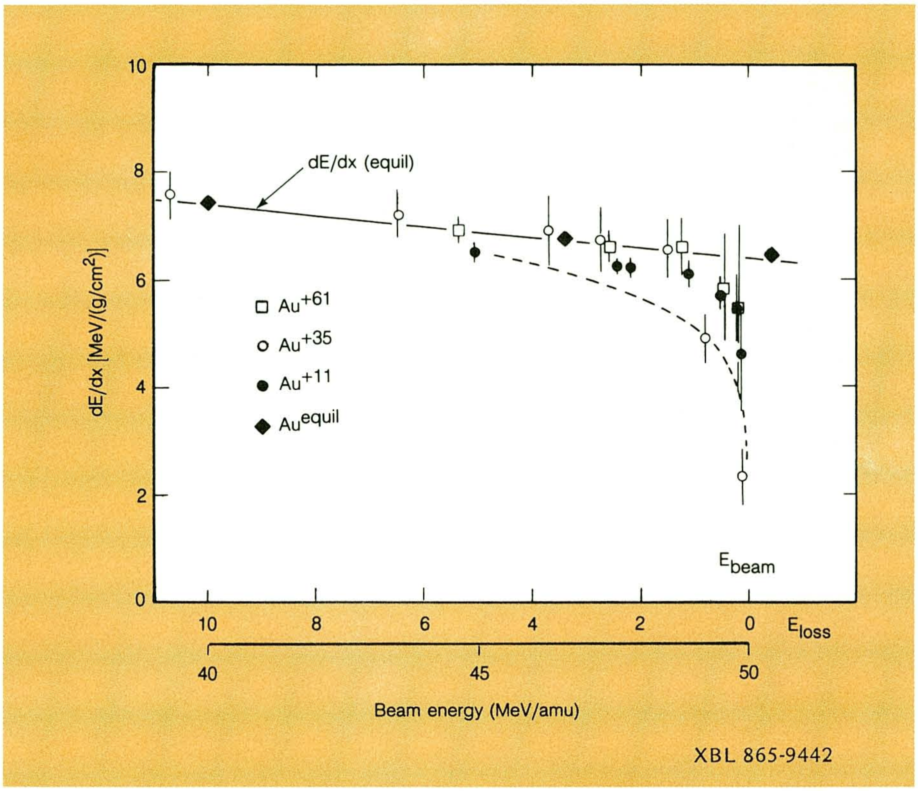
In 1984 we were able for the first time to demonstrate this collective-field focusing effect, and in 1985 we concluded our efforts on this problem with a series of computer simulations that accounted for the inevitable electron thermal effect ignored in the simple theory. We found that for a given longitudinal velocity and ion density there is an allowed upper limit on the electron temperature. If this temperature is exceeded, nonlinearities in the electric field can destroy the focusing effect. Simulations of an HTE final focus lens give quite favorable results: If the electron temperature is below 100 eV, designs with magnetic fields of about 400 gauss are possible. Simulation work at the Los Alamos National Laboratory has indicated that beam neutralization with a biased grid arrangement yields suitably low electron temperatures.

Range-Energy Measurements

A series of experiments continued at the Bevalac with the aim of understanding the process of charge equilibration when low-charge-state ions impinge on solid material. These experiments address a question of fundamental importance for future heavy-ion fusion reactors, where linac-accelerated ion beams will have charge states far below the equilibrium values characteristic of their velocity and the target material. As a result, the rate of energy loss from the ions will be low initially, but will increase rapidly as valence and outer-shell electrons are stripped from the ions until they reach charge-state equilibrium. The low initial rates of energy loss tend to increase the range of the ions in the target.

The results of work from the past year are shown in Fig. 30, where the rate of energy loss, dE/dx, in a hydrocarbon absorber is shown for beams with different initial charge states. The asymptote, labeled dE/dx(equil), represents the rate of energy loss from a charge-equilibrated beam at 50 MeV/amu. Beams of lower

Fig. 30. Energy loss rates for gold ions in a hydrocarbon target, for an initial beam energy of 50 MeV/amu. The asymptote at the top indicates the rate of energy loss for a charge-equilibrated beam. The dashed line is derived from a theory for energy loss from neutral gold ions at 46 MeV/amu.



charge states show lower initial values of dE/dx, but the values converge to the equilibrium values more quickly than theory would predict (dashed line).

Theory

For the design of MBE-4, the HTE, and any future fusion driver, it is necessary to determine the so-called beam envelope functions for various plausible design parameters. These functions establish the relationship among mean and maximum beam radius, phase advance, and depressed phase advance, given a set of fundamental design parameters, including emittance, quadrupole strength, line charge density, etc. During the past year, an improved matrix method yielded rather simple envelope equations that are accurate to ±1% for phase advances less than 90°. One way of applying the results of this method is to display a plot of transportable charge as a function of energy for different phase advances. The result is a set of rays (each of constant phase advance) emanating from the origin. Along each ray, a fourth parameter, the quadrupole pole-tip potential, increases in a regular way. Thus, a given energy and phase advance dictates a quadrupole strength and establishes the beam current.

Simulations of the behavior of high-current, low-emittance beams in the presence of real-life effects such as image forces and lens misalignments continue to turn up new puzzles to be unraveled. For off-axis beams, for example, image forces produce an oscillating, and slowing increasing, emittance. However, this effect can be essentially canceled by introducing a (usually undesirable) dodecapole component of the right sign in the guide field. As a result of this surprising finding, we are now studying the feasibility of separating the dodecapole and quadrupole functions into different focusing units. This would permit separate tuning of the two fields, and might make construction simpler for the magnetic focusing section of the accelerator. To be economically feasible, the number of dodecapole magnets required must be much smaller than the number of quadrupoles. A computer study to determine the number of required dodecapoles has begun.

We have also looked at effects due to alternating-sign octopoles (caused by end effects at the quadrupoles). This "interdigital nonlinearity" was found to cause no emittance growth under the conditions present in MBE-4, but where nonlinearities are twice as great (as they will be in the HTE), we expect emittance oscillations with an accompanying emittance growth for misaligned high-current beams.

Finally, we have studied the evolution of a beam with a nonuniform density profile. Work still in progress concerns the changes in the beam emittance and distribution function during the beam's passage through the injector diode and during transport through the accelerator, due to an initially nonuniform spatial distribution. Simulation results show that emittance growth occurs predominantly in the first plasma period, but oscillation of the emittance can persist under some conditions.

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