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Abstract

The multiple-beam induction linac approach to a heavy ion fusion driver features continuous current amplification along the accelerator and a minimum of transverse beam manipulation from source to pellet. Current amplification and bunch length control require careful shaping of the accelerating voltages. This driver approach exploits developments in electron induction linac technology that have occurred within the last 15 years at LBL, LLNL and NBS.

MBE-4 is a four beam induction linac that models much of the accelerator physics of the electrostatically focused section of a considerably longer induction accelerator. Four parallel Cs^+ beams are electrostatically focussed and will be accelerated from 200 keV to approximately one MeV when the experiment is complete in the spring of 1987. The current in each of the four beams will increase from 10 to 40 mA due to both increase in beam speed and shortening of the bunch length. Results of experiments with the injector and first eight accelerating gaps are presented.

Introduction

The heavy ion approach to controlled inertial fusion offers the advantages of: high repetition rate, good electrical efficiency, long stand-off distances from the target to the final focal lens, and good reliability based on the established technology of large high-energy particle accelerators. The implosion physics [1] of inertial fusion targets dictate that heavy ion accelerator systems must be capable of delivering 3-5 MJ of energy at power levels of several hundred terrawatts. The Heavy Ion Fusion Accelerator Research (HIFAR) program is addressing the accelerator physics and economic issues pertaining to a practical fusion driver employing high-energy (10 GeV) heavy ion beams produced by multigap accelerators. Since 1984 [2], the HIFAR program has concentrated on the multiple-beam linear induction accelerator because of its demonstrated ability to accelerate large electron currents and because of favorable preliminary cost estimates [3] of fusion power systems.

In an ion induction linac, precise control of the length of the multiple beam bunches must be maintained during acceleration and transport. In the accelerator this is accomplished by using a set of differently shaped acceleration voltages at each gap which bring about current amplification according to a prescribed "schedule". These voltages also compensate for the longitudinal space charge forces that tend to lengthen the bunch. A detailed theory of the development of acceleration schedules for induction linacs was recently published by Kim and Smith [4].

Because of the large beam currents, the accelerator physics are dominated by space charge effects and not emittance. However, both the transverse and longitudinal beam emittances must be carefully conserved to achieve the small focal spots that will be required at a target.

The Multiple Beam Experiment, MBE-4

In order to model the longitudinal dynamics of much longer accelerators, the length of the beam bunches in MBE-4 was kept short compared with the length of the accelerator. During acceleration, the current of each beam will increase from approximately 10 mA at injection to nearly 40 mA at the end of the experiment. The current magnification results from both an increase in particle speed and a shortening of the length of the beam bunches. As a percentage of beam energy, the acceleration voltages in MBE-4 are much larger than will be used in a driver. Therefore, the consequences of errors in acceleration voltages will be more apparent and more easily assessed. Four beams are used to investigate potential effects caused by beam-beam coupling and to get practical experience in difficulties associated with accelerating and transversely controlling parallel beams. In examining the scaling with injection energy and with quadrupole size, we have been careful to

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preserve space charge domination of the beams both transversely and longitudinally. Measured in terms of initial bunch lengths, MBE-4 is comparable in length to the electrostatically focused portion of a driver.

The experiment uses four beams of singly charged cesium obtained from four thermionic alumino-silicate sources. These are accelerated to 0.2 MV in a single gap injector [5]. The initial pulse duration is 2.5 μs which will be shortened to 0.6 μs at the end of the accelerator. The four beams are focused by arrays of electrostatic quadrupoles consisting of nine electrodes. A photograph of a quadrupole array is shown in Fig. 1. The beam-to-beam spacing is 6.67 cm and the clear aperture is 5.41 cm. The electrodes occupy one half the lattice length of 45.7 cm. These beams will be accelerated to nearly 1.0 MV by 24 linear induction modules in a total length of 17.2 m. A schematic diagram of the experiment is presented in Fig. 2. The experiment was completed through section B in March 1986 as shown in the photograph presented in Fig. 3. Further details of the design of MBE-4 can be found in ref [6].

The voltage waveforms on the first accelerator gaps are nearly triangular so as to impart an axial velocity shear or tilt to the beam by accelerating the tail of the beam more than the head. After the tail of the beam has entered the accelerator, the head of the beam can be accelerated as well and the waveforms on the downstream gaps are flatter. The Kim-Smith accelerator theory was incorporated into a computer code called SLID and used to generate [7] the ideal accelerator waveforms presented in Fig. 4 for the reference MBE-4 acceleration schedule. These waveforms were used as a initial guide for the synthesis of the waveforms delivered by the pulsers to the accelerating gaps. As the experiments proceeded, the

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Fig. 1. Photograph of a four-beam electrostatic quadrupole array

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Fig. 3. Photograph of MBE-4 taken in April 1986. The injector is on the left.

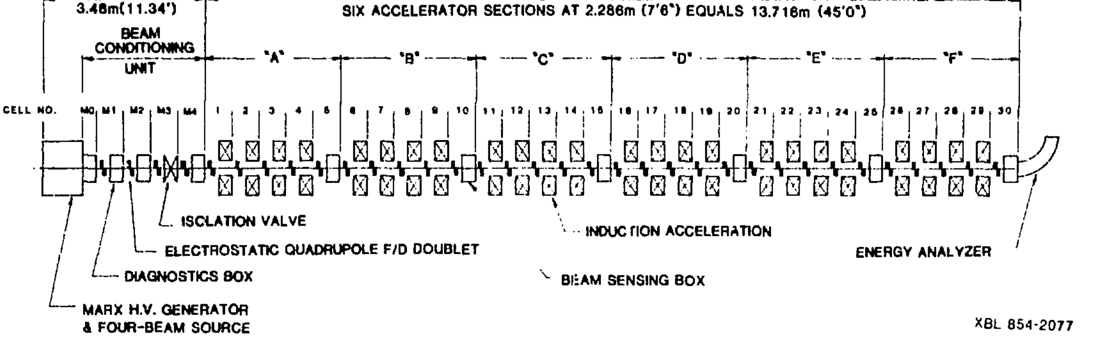

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Fig. 2. Schematic Diagram of MBE-4

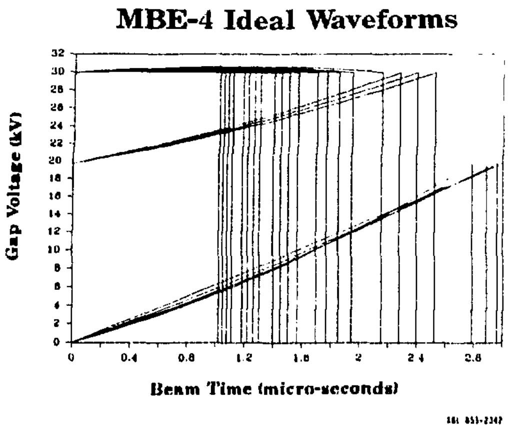

Fig. 4. Code Calculations of the Accelerating voltages for all 24 MBE-4 Gaps. No space charge effects are included here.

code was then used to develop specifications for the correction or "trim" pulsers which, along with the drive pulsers, apply voltage to accelerating gaps 4 and 9. In this way errors due to longitudinal space charge forces, errors traceable to the injector pulser, and errors in waveforms generated by previous accelerating gaps are simultaneously corrected.

Accelerator Pulsers

The drive voltages for each acceleration gap are generated by thyratron switched pulsers that have a maximum voltage capability of 30 kV. A typical circuit is presented in Fig. 5. By adjusting the values of C_1, C_2 and L_1 and using two (or occasionally more) pulsers per gap, we are able to synthesize the waveforms requested by the SLID code with errors of 2-3%. Thus far, two types of induction cores have been used--2 mil silicon steel cores containing 24 mV-sec of magnetic material, and 1 mil nickel-iron cores containing 6.8 mV-sec of magnetic material.

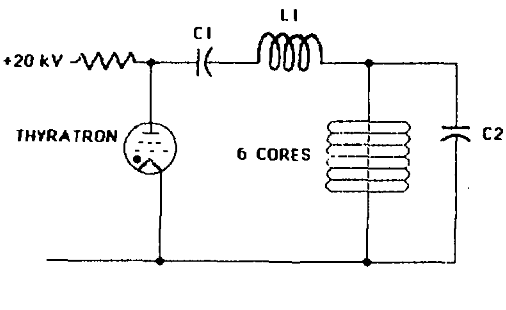

Fig. 5. Simplified MBE-4 Pulser Circuit Diagram

Diagnostics

As shown in Fig. 2, the induction accelerator units are placed in groups of four, followed by a box that allows pumping and diagnostic access to the beams. The accelerating voltages are monitored with a resistive divider placed across each accelerating gap. Our primary beam diagnostics are arrays of four biased Faraday cups for current measurements. These have rise times less than 0.1 μs and are remotely inserted into the beams as required. We also use arrays of four capacitive pickups which measure the line charge density of the beams and have the advantage of being non-intercepting. Emittance measurements are made using small Faraday cups placed behind parallel slits--each independently movable. Beam size measurements are made with parallel wire arrays called "Harps" that emit secondary electrons when struck by the Cesium beam. The wires are .25 mm wide and are located .5 mm apart. Finally, the beams are stopped at an electrostatic energy analyzer which examines the right hand beam and has an energy resolution of 0.5%. It can be seen on the right in the photograph of Fig. 3. As MBE-4 is constructed the analyzer is moved downstream.

Data is collected by a digitizing oscilloscope that is interfaced to a small computer. The computer is able to transfer data to and from the oscilloscope and run the SLID program for analysis, control, and interpretation of the experiments.

Experimental Progress

Experiments on MBE-4 are proceeding one section at a time as the apparatus is built. The beams produced by the injector are apertured to approximately 11 mA at the entrance to the conditioning section. Here the axis of each of the four beams is aligned with the axis of each of the electrostatic steering arrays, and the phase and amplitude of the envelope oscillations are adjusted to create matched beams in the accelerator.

Figure 6 shows oscillograms of the four beam currents at the entrance to the accelerator and at diagnostic station 10 -- the end of the present complement of the apparatus. With acceleration, the beamlet currents increase from 11 to 18 mA, the energy of the beam head increases from 0.2 to 0.29 MV, and the energy of the beam tail increases from 0.2 to 0.45 MV. The areas of the traces are

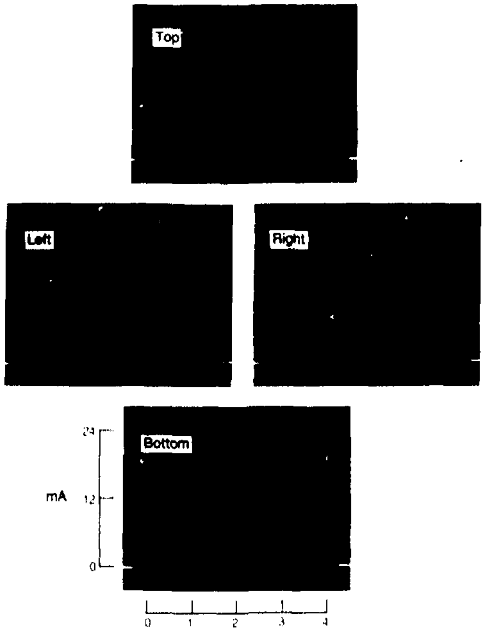

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Fig 6. Oscillograms of the four beam currents at the beginning and at the present end of MBE-4 (10-shot overlay at 0.2 Hz).

unchanged by acceleration indicating no loss of particles. Current fluctuations in the traces are due to small errors in the acceleration voltages of the first few gaps.

Beam space charge tends to reduce rapid current fluctuations as illustrated in Fig. 7. The upper trace shows fluctuations on a 0.6 mA pencil beam with weak longitudinal space charge forces that was accelerated to station 10. The lower trace is the full current beam accelerated by the same voltages.

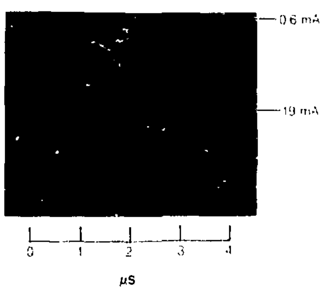

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Fig 7. Oscillograms of a 0.6 mA pencil beam and a 19 mA beam (different gains) at station 10 showing the effects of space charge.

Comments and Conclusions

The multiple beam accelerator experiment MBE-4 has accelerated four parallel-space-charge dominated cesium ion beams from 0.2 MV to nearly 0.5 MV with a current amplification of 1.6. The experiments are in excellent agreement with our theoretical acceleration model.

The acceleration schedule is one in which the current waveforms grow in amplitude and decrease in pulse duration in a self-similar or self-replicating way with acceleration distance. Aside from small fluctuations, generated by 2-3% errors in the acceleration waveforms, the experimental current waveforms are self-replicating. The acceleration errors are mostly corrected by "trim" pulsers located at every fourth accelerating gap. These are also used to control space charge spreading. At large currents rapid current fluctuations are damped by beam space charge.

Experiments have shown only a very weak electrostatic repulsive interaction among the beams in the source area which is easily corrected.

As MBE-4 grows longer, future experiments will give a clearer picture of the importance of current fluctuations in the operation of an ion induction linac and how effectively they may be controlled. We also will test techniques for steering beams with axial velocity shear.

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