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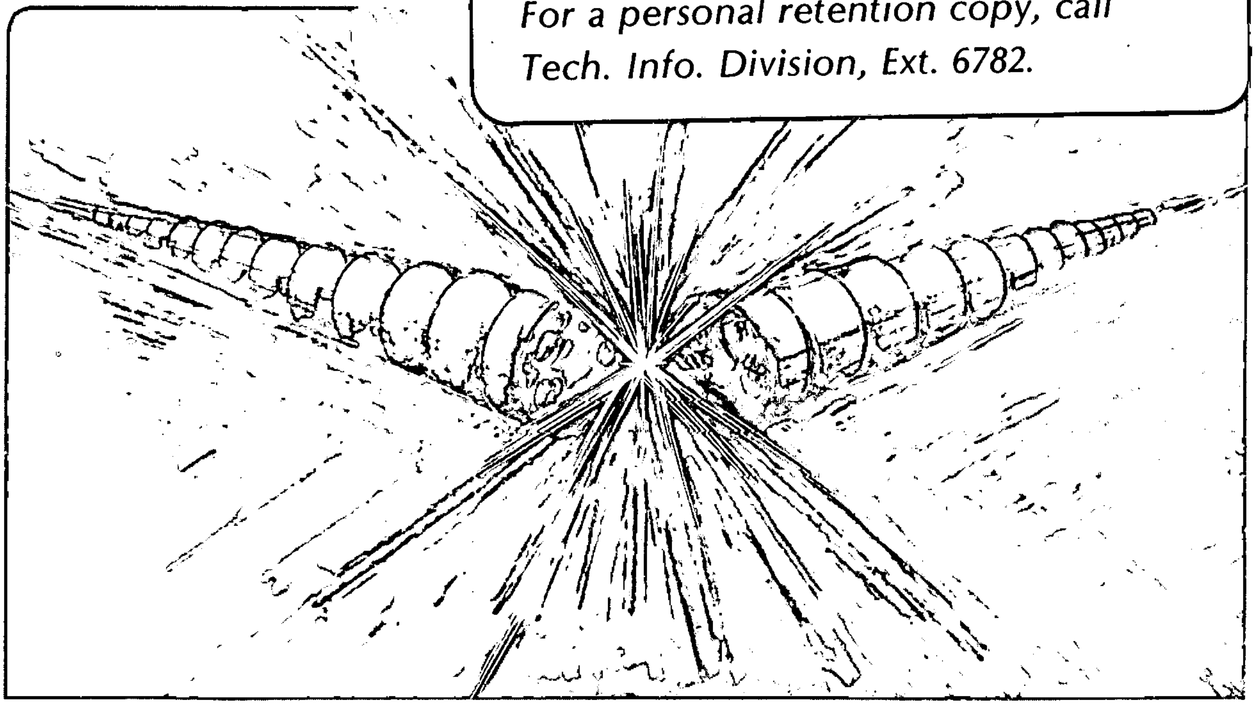

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Summary

A long-pulse induction acceleration unit has been installed in the high-current Cs^+ beam line at LBL and has accelerated heavy ions. A maximum energy gain of 250 keV for 1.5 μs is possible. The unit comprises 12 independent modules which may be used to synthesize a variety of waveforms by varying the triggering times of the low voltage trigger generators.

Introduction

The Heavy Ion Fusion group at LBL has developed conceptual designs of induction linacs which accelerate a few hundred microcoulombs of charge to megajoule energies for Inertial Confinement Fusion.[1] In these machines a single bunch of ions is accelerated from typically 1 MeV to 10 GeV with an accompanying decrease in pulse duration from about 10 μs at the entrance of the accelerator to 100 ns at the exit (followed by further bunching down to 20 ns in a drift distance between the accelerator and the fusion reactor). Because the ions are nonrelativistic throughout the process and can move with respect to each other, it is necessary to apply longitudinal control to the bunch, in the form of shaped waveforms, in addition to the usual flat voltage pulses (corrected for beam loading) which are required for a monoenergetic output. The required corrections which are new to acceleration of intense beams of heavy ions are, at any instant of time, a linear electric field in space for bunch-length control, plus the negative of the gradient of the space charge potential of the beam for counteracting space charge longitudinal defocusing. These requirements translate into specified desirable applied waveforms at any location. The largest deviations from flat waveforms occur in the low energy portion of the accelerator.

There exists a large technological data-base developed for acceleration of electron beams in the 1-10 kA range[2] which is directly applicable to the greater part of a heavy-ion induction linac. Most of the experience is for pulse durations well under 1 μs, corresponding to the high energy end of the ion accelerator. The large flat-pulse module built at NBS to provide a 2 μs, 400 kV pulse for acceleration of a 1 kA electron beam represents the culmination of an R&D program for economical long pulse modules and provides the only experience base for the low energy end of the ion machine[3]. Here we report on an early stage in an analogous process for heavy ions.

To provide the desired waveforms we are proposing to use a few types of standardized modules, containing core and pulser combinations which can be independently triggered, and to approximate the waveforms in staircase fashion by varying the firing times of a large number of them. The step amplitude chosen in the low energy end of the accelerator is nominally 25 kV, consequently several thousand steps are required with pulse durations longer than 1 μs. While the staircase approximations might appear coarse over a short distance such as 1 meter, they are probably satisfactory when averaged over distances of a few tens of meters (comparable to the bunch length) over which some appreciable intrabunch motion should just start to occur. This distance would contain about 100 modules, a module being defined as a single pulser driving a number of cores (two, in our case).

Description

The first such induction unit has just been completed and installed at the exit of the LBL high-current Cs^+ injector facility,[4] as shown in Figure 1, where it may be used for additional acceleration and correction of the energy profile of the ion beam. The main function of the device, however, is as an engineering prototype of one of the kinds of units that may be required in the future. There are 12 independently driven core pairs, i.e. 12 modules, within a common container, which would increase the particle energy by 250 keV if triggered simultaneously. The typical module consists of a high-power pulse generator which drives two large induction cores in parallel, a reset pulser which restores the magnetic core to negative saturation before the beginning of the acceleration pulse, and a correction network which is used to modify the accelerating pulse. Each core drives two resistively graded sections of the centrally located accelerating column, at a low enough voltage such that each of the two sections can support the full voltage. A simplified sketch of one module and its drive circuitry is shown in Figure 2.

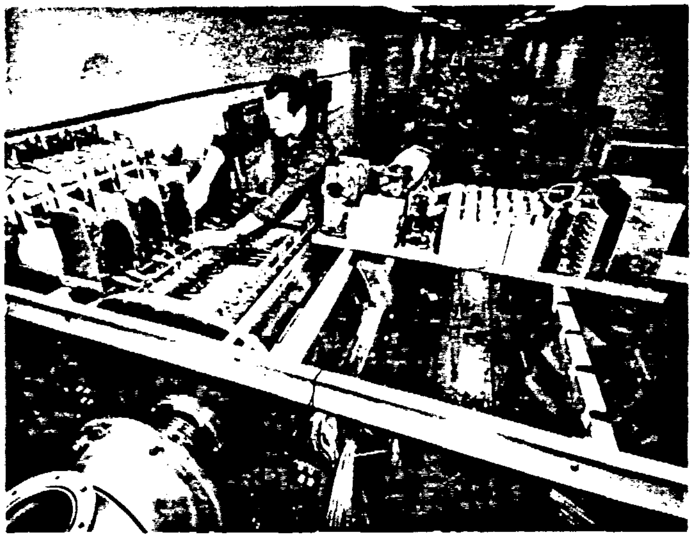

Fig. 1. The induction module being installed in the high-current Cs^+ beam line

The induction core is wound with 2 mil thick 3.25 percent silicon steel tape which is insulated with an inorganic phosphate coating with a ceramic filler, resulting in a radial packing fraction of 92 percent. The cores are insulated axially from the drive conductors with Mylar sheets, and the entire unit is

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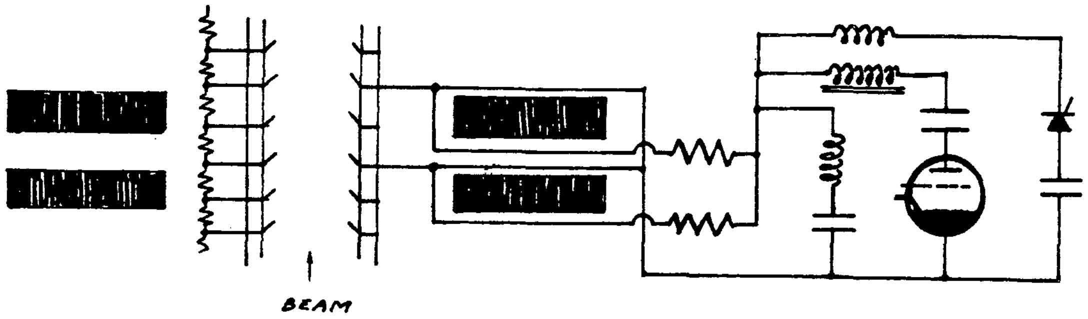

Fig. 2. Simplified sketch of the mechanical arrangement and electrical circuitry for one of the modules of the twelve-section accelerator unit

filled under vacuum with Freon TF, resulting in an axial packing fraction of 75 percent. While the average accelerating field along the column is only 2.5 kV/cm, the fields within the modules occasionally reach 100 kV/cm as a consequence of the dense packing of components within it. The drive conductors are made of copper sheets for the purpose of carrying the heat generated by the core losses to the outer radius with only a few tens of degrees temperature rise at the nominal rep rate of 1 pulse per second. A pulse duration of 1.5 μs was chosen for design purposes although the unit may be used for longer as well as for somewhat shorter pulses.

Results

In the period preceding delivery of the major component parts of the modules, various pulse generator options were tried. Initially, a line type PFN with a total capacity of 1.5 μF was used on a load simulating one core. The final version of this first exercise pulsed more than 2 x 10^6 times with no signs of degradation. The circuit was then modified to drive a load simulating two parallel cores. With this load the ignitron switching tubes darkened rapidly and failed at 10^5 pulses. Several iterations of the circuit were tried, and the manufacturer of the tube made several modifications to overcome the problems. The present version of the pulse generator uses a saturated inductor in series with the ignitron and a diode across the PFN, which is now essentially a capacitor, to protect the tube from reverse current. With these improvements, a test-module has pulsed in excess of 10^6 times. The gridded ignitron switch which evolved from this work also reduced firing jitter from ± 100 ns to ± 25 ns. A future report will describe the development and performance of the tube.

The completed 12-module unit has recently been placed into service. The oscilloscope traces in Figure 3 show its effect on the transit time of a Cs ion beam through a short drift section after the module. The beam energy at the entrance has been kept low to accentuate the effect. In a larger machine the beam energy would be measured with a spectrometer and the desired voltages applied as here, but the effect of any one unit would be very small. In the near future we will explore the range of available waveforms with the present module, and in the longer term construct a few more prototypes geared more specifically to the requirements of the anticipated High Temperature Experiment.[5, 6]

Design Considerations and Outlook

The choice of an of induction module design depends on the pulse duration and the (usually related) applied voltage. The present design is suitable for pulses of 1 μs and longer. As the pulse duration is increased the core losses and the electric stresses decrease, while at the same time there is only a small economic incentive to change the design. Going in the other, more difficult direction, however, requires several changes. For shorter pulses, the electric stresses between laminations eventually become excessive, and to reduce them the choices are, first, to decrease lamination width (to a practical minimum of about 1 cm) and second, to decrease lamination thickness (to about 1 mil). For still further reductions in pulse duration, it is necessary to interleave a thin sheet of insulation such as Mylar between the laminations, and, because this form of insulation is much better than the minimum required, it is permissible to increase the tape width. The change to the more positive type of insulation is accompanied by a drop in the radial packing fraction and an increase in winding cost, and it usually precludes annealing the finished core.

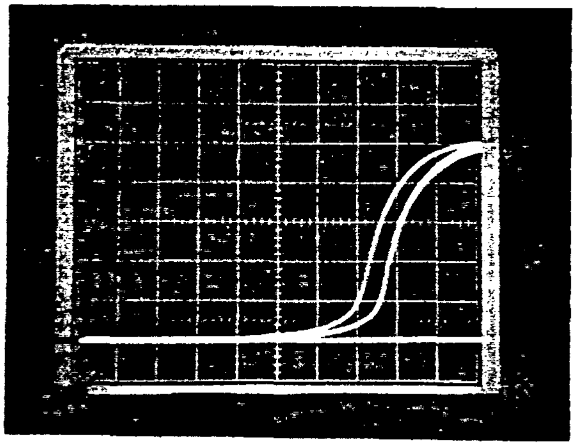

Fig. 3. Difference in times of flight of Cs beam through a 2.5 meter distance after the accelerator unit, for system on and off. Sweep speed 500 ns/div. Four beam pulses at each setting show that the system jitter is less than 50 ns.

A similar change of character occurs in the design of the pulse generating circuitry as the pulse duration is decreased. For pulses greater than 1 μs a lumped element network is satisfactory while for pulses below 100 ns a distributed line is usually preferred for the high-voltage pulses of interest. The present design uses 6 small capacitors to reduce lead inductance and problems with capacitor internal resonances, and the desired waveform is largely achieved with a correction network across the core. If a core is driven from a capacitor, large enough to behave as a voltage source, then the largest use

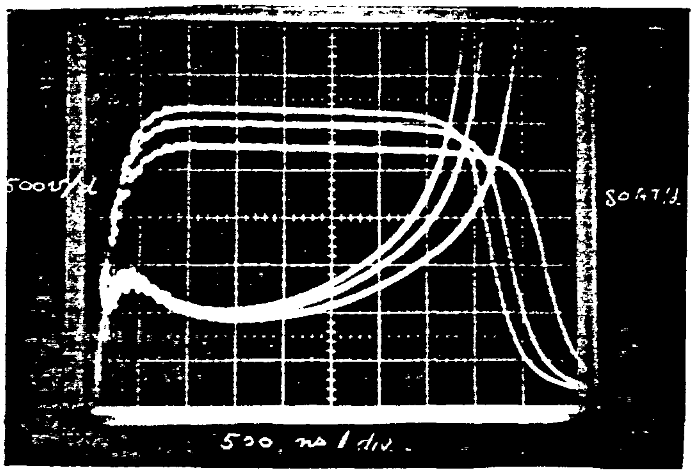

Fig. 4. Metglas core driven to saturation from a large capacitor. Top trace voltage, bottom trace current.

useful flux change can be obtained from the core, but the post-saturation drive current rises to large values, as shown in Figure 4, and efficiency suffers. Ideally, one would like the exciting current to go to zero as the core saturates. While this desirable behavior can be obtained with a controllable switch such as a hard tube, it is too expensive an option. Instead, a simple closing switch, a core with reasonably square-loop behavior, and a pulse-forming network were selected which decrease the post-pulse current at the expense of wasting some of the available flux during the voltage fall time, as shown in Figure 5. The correcting network is essentially an LC across the core which takes energy from the PFN at the start of the pulse, when the drive current is small, and returns it at the end of the pulse when the drive current is large.

The core losses, which are a function of eddy currents and hysteresis, may be reduced by several means, the main one being the use of thinner laminations in the regime of interest for induction linacs. Cost considerations, of course influence the designs. At the time the module was designed, the 2 mil steel was chosen because the pulser cost increased more than the material savings when going to 4 mil steel, and because the material cost increased substantially more than the pulser cost decreased when going to 1 mil material. The recently developed Metglas material, an amorphous magnetic metallic glass tape, has been decreasing in price and might become the material of choice in the future.

While we have been measuring sample cores of Metglas for four years, until recently we have not been able to obtain cores of the size of interest for induction linacs. Now we have two cores of Metglas 2605SC which may be compared, with some adjustment of numbers to take into account dimensional differences, with the silicon steel cores used in the module. Table I below gives the results for the finished cores.

Both types of cores should be considered developmental at this stage, and the costs given are for relatively small quantities of material. The induction change and impedance numbers are approximations for the way in which the cores are used in the present module, and could be improved with both circuit and core developments.

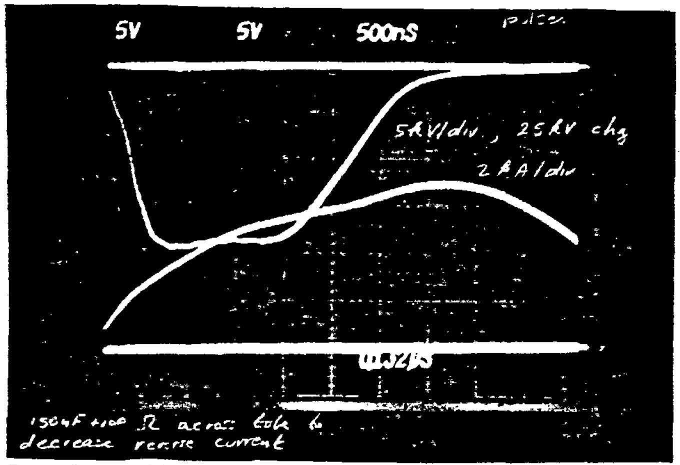

Fig. 5. Silicon steel core driven to saturation from a small capacitor, with a correction network at the output to modify waveform. This is the output voltage from the prototype of one module. Top trace voltage, bottom trace current.

Table I. Comparison of Core Materials

		2 mil silicon steel	Metglas
Saturation Induction,	kG	13.8	10.7
Remanent Induction,	kG	11.4	9.9
Coercive Force	Oe	1	0.1
Available Induction Change at High Impedance,	kG	20	17
Average Apparent Impedance During 1.5μs Pulse	Ω	5	20
Radial Packing Fraction	%	92	75
Cost	$/lb	6	24

Acknowledgment

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