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ENGINEERING DEVELOPMENT FOR A SMALL-SCALE RECIRCULATOR EXPERIMENT*

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ABSTRACT

Lawrence Livermore National Laboratory (LLNL) is evaluating the physics and technology of recirculating induction accelerators for heavy-ion inertial-fusion drivers. As part of this evaluation, we are building a small-scale recirculator to demonstrate the concept and to use as a test bed for the development of recirculator technologies.

System designs have been completed and components are presently being designed and developed for the small-scale recirculator. The hardware being developed includes both mechanical and electrical components of the beamline. Our present development are focused efforts in two areas; 1) the design of the modular beamline component called a "half-lattice module" which must satisfy challenging space and vacuum requirements and 2) the development of an advanced solid-state modulator which will generate precisely tailored electrical pulses at repetition rates exceeding 100 kHz for acceleration.

This paper will discuss results of the design and development activities that are presently being conducted to implement the small-scale recirculator experiments. An overview of the system design will be presented along with a discussion of the implications of this design on the mechanical and electrical hardware. The paper will focus primarily on discussions of the development and design of the half-lattice period hardware and the advanced solid-state modulator.

I. INTRODUCTION

Recirculating induction accelerators are being investigated as potential low-cost drivers for inertial fusion energy. A recirculator is a circular induction accelerator where beams of heavy ions are accelerated and bent in a closed path as illustrated in figure 1.

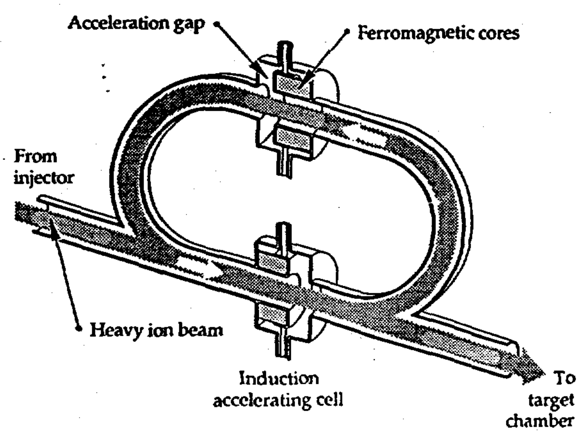

Figure 1. A recirculator utilizes the same accelerator components multiple times.

To use the recirculator as an inertial fusion driver, the ions are then extracted from this closed path and focused on an inertial fusion target. The recirculator appears to be an economically attractive driver option when compared to other induction accelerator technologies because the acceleration sequence reuses the most expensive components of the induction accelerator. However, the

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induction accelerator. However, the recirculator also presents new technical challenges.

The HIF project at LLNL is designing and building a small-scale recirculator to demonstrate feasibility of the recirculator concept.[1] This small-scale recirculator is a 4.5 meter diameter ring which will accelerate singly ionized potassium ions to 320 keV after 15 laps around the ring. This ring will be used to investigate the physics and demonstrate the technology associated with accelerating and transporting a space charge dominated beam in a circular induction accelerator. Beam dynamics issues such as centroid control, longitudinal control, insertion/extraction and emittance growth will be investigated.

The small-scale recirculator is being designed and built sequentially. Presently, the injector and matching sections have been built and tested. Some of hardware required for the ring is presently being designed or developed. This paper will discuss the ongoing recirculator technology and hardware development efforts that support the construction of the small recirculator. We will discuss the system and component designs of the small-recirculator including the design development of the half lattice module and the advanced modulator development necessary for accelerating the ion beam.

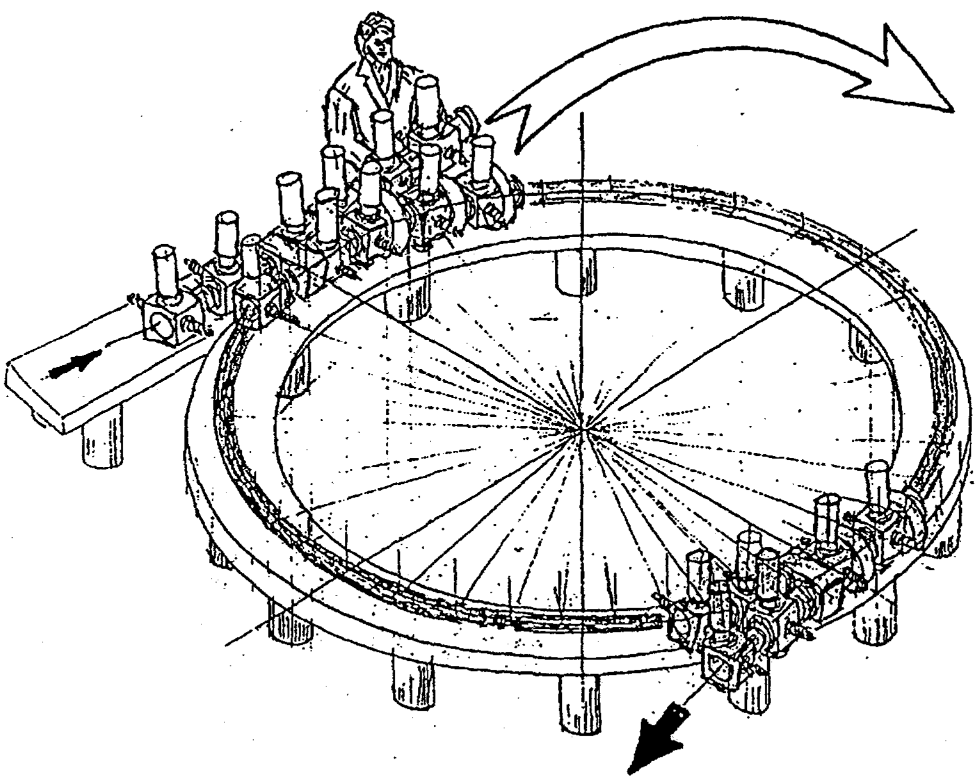

Figure 2. The small-scale recirculator will have all of the major components required for full scale driver.

II. DESCRIPTION OF THE SMALL RECIRCULATOR

A conceptual illustration of the small recirculator is shown in figure 2.

The small-scale recirculator consists of four main elements, 1) an injector for generating the ion beam 2) a matching section to transition the circular beam into the magnetic quadrupole focusing of the ring, 3) the insertion/extraction section for transporting the beam into and out of the ring and 4) the circular accelerator for accelerating the beam.

The beam is generated in a high voltage diode with a potassium xeolite source. Singly ionized potassium ions are extracted from the diode with an 80 kV pulse generated by a standard thyratron line-type pulser. An ion beam current of approximately 2 mA is accelerated into an electrostatic matching section where it is conditioned for insertion into the recirculator ring. The matching section is approximately 2 meters long and consists of 7 electrostatic quadrupoles.

The beam exits the matching section into the insertion region, where it is bent with a series of electric kickers to insert the ions into the ring. A large area quadrupole magnet is used to maintain the periodic quadrupole focusing field on the beam during insertion and extraction.

Once the beam is in the ring, the ions will get accelerated, focused and bent as they pass through the 40 half-lattice modules which make up the ring. The half-lattice modules are the basic building blocks of the recirculator. The half-lattice module has three primary components, an induction accelerating cell for accelerating the beam, an electric dipole for bending the beam and a magnetic quadrupole for focusing the beam as it traverses the ring. In addition, each half-lattice period provides access to the beam for diagnostics and ports for vacuum. A sectional view of the half-lattice module is shown in figure 3.

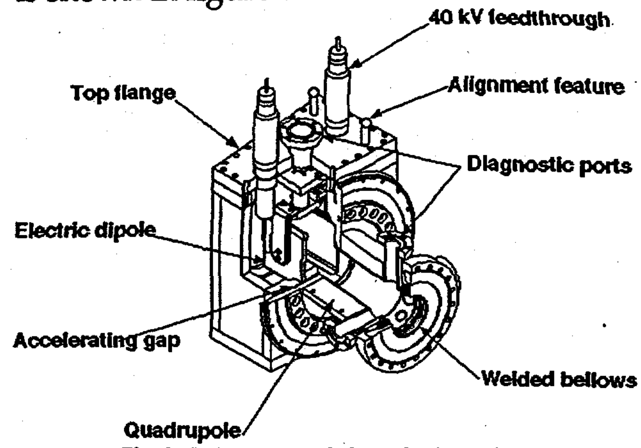

Figure 3. The half-lattice module is the basic building block for the recirculator.

In the ring, the ions will get accelerated in 470 V increments as they pass through 34 induction accelerating cells. There is one induction cell for every half-lattice period with the exception of the six half-lattice periods in the insertion/extraction region where there is no acceleration.

Electric dipoles provide a time varying electric field to bend the beam around the ring. The field on the dipoles must be precisely coordinated with the beam energy during an acceleration sequence to maintain a constant bend radius. The beam will gain nominally 16 keV per lap and after 15 laps will have an energy of approximately 320 keV. Electric kickers in the insertion/extraction stage will redirect the ion pulse out of the ring.

III. STATUS/DESCRIPTION OF HARDWARE DEVELOPMENT

There are a number of electrical and mechanical challenges that need to be addressed to build a recirculator. The challenges range from the packaging of acceleration, bending, focusing, diagnostic and vacuum elements into a single compact module or half-lattice period2 to developing the extremely agile modulator technology required to drive the induction cells.

The half-lattice module and the induction cell modulator are being developed in parallel by separate teams in the Heavy Ion Fusion project at LLNL. The design of this small-scale recirculating induction accelerator places a premium on performance and efficient space utilization. Close coordination between the two design teams is essential to insure the hardware meets the required performance specifications as well as fits within the stringent physical constraints of the system design. In addition, the design of the hardware must allow adequate access for testing, maintenance, assembly and disassembly. The following sections will describe the component requirements, the design and the status of development of the two critical components of the small recirculator, i.e. the half-lattice module and the induction cell modulator.

A. Half-lattice module

The fundamental building block of the recirculating induction accelerator is the half-lattice module shown in figure 3. The half-lattice module is the foundation for nearly every component that makes up the recirculator. Each module consists of a dipole housing and steering dipoles, a magnetic quadrupole focusing magnet, an accelerating gap, diagnostic ports and a beam tube. Each component of the half-lattice module has its own individual requirements and space constraints in addition to the overall space constraints placed on the entire module by the system design. Table 1 below shows the variety of requirements and constraints that must be satisfied by the module and its primary components, i.e., dipole, quadrupoles and accelerating gap.

Component/Module	Requirement
Dipole	
Operating voltage	70 kV b
Alignment of dipole plates	250 μm
Quadrupole focusing	
Alignment tolerances	250 μm
Quadrupole field	.3T
∫B'dz	.93T
Accelerating gap	
Accelerating voltage	470V
Half-lattice module	
Vacuum	10^{-8} torr
Overall length	36 cm
Beam tube diameter	6.8 cm
Bend angle	9°

Table 1. Half-lattice module requirements

As shown in figure 3 the electrostatic dipoles are simply two parallel plates that generate a transverse electric field to bend the ion beams when voltage is applied to the plates. The steering dipole plates are precisely contoured, spaced, and aligned to provide not only the basic 9 degree bend angle for the beam centerline but also compensate for in-plane steering errors. In order to provide the flexibility and opportunity to experiment with various dipole plate designs, the plates are mounted to the lid of the housing and connected to welded hi-voltage feed-throughs. The dipole plates themselves are mounted in precision adjustment mechanisms to allow precise alignment to fiducials on the housing lid. Dowel pins are used to maintain alignment between the lid and the dipole housing. Installation of new dipole plates requires that the lid and holding mechanisms be placed in a fixture and the new plates located to precise measurements using a coordinate measuring machine (CMM). Details of this alignment procedure may be found in reference 2.

The permanent magnet quadrupoles are purchased fully assembled and field mapped from a vendor. They are positioned on the outer diameter of the beam tube and clamped in place to maintain position and orientation during subsequent operations. The magnetic transport of the ion beam is being tested on the Magnetic Transport Experiment (MTE) currently being assembled at LLNL.

The half-lattice module must also provide the acceleration gap necessary to impart energy to the beam from the induction cell modulator. The induction voltage of 470 volts is developed across a gap formed and vacuumed sealed by a .005 inch kapton film. Mechanical connections crossing the gap maintain electrical isolation through the use of ceramic insulators. The mechanical connections must be sufficient to maintain the vacuum seal, the precision alignment, and to support the induction modulator.

Packaging of all of these components into a single half-lattice module is a very challenging task. The most stringent packaging requirements are placed on the induction cell modulator. It is physically constrained to a toroidal volume with approximately 25 centimeters inner diameter by approximately 60 centimeters outer diameter by 10 centimeters axial. This volume houses the induction cores, energy storage, and pulse shaping circuits required for agile control of the accelerating waveform. The inner diameter of the modulator is constrained by the need to allow access to the diagnostic ports and magnetic quadrupole without disturbing the quadrupole alignment. Radial growth of the induction modulator cell is limited by interference with the walls and columns in the laboratory. Along the beam axis, the induction modulator must fit between the dipole housing and the diagnostics ports. The axial length of the modulator and cell is constrained to approximately 10 centimeters. The estimated weight of the induction modulator cell is approximately 200 lbs.

Precision alignment of the dipole and quadrupole components of the half-lattice module is essential. In general, the procedure will be to establish the center line and orientation of the magnetic quadrupole on the half-lattice period cell utilizing a CMM. The CMM will be used to align the dipole plates to the magnetic axis of the quadrupole. The dipole housing lid will be pinned to the housing to allow removal and reinstallation during operations. After pinning, fiducials will be installed and measured, establishing the lid and half-lattice period local coordinate systems. Inserting the half-lattice period into the recirculator ring will be done by mapping the local coordinates of the cell into the global system for the ring and positioning the half-lattice period to those coordinates using precision optical measurements. Precision alignment of the half-lattice period cell and it's insertion into the recirculator ring are documented more thoroughly in reference 2.

The half-lattice period cell is fabricated from non-magnetic stainless steel which must be normalized after welding to eliminate residual magnetic fields which could distort the beam. Precision manufacturing and tight tolerances are required for certain critical surfaces such as those defining the acceleration gap, mating surfaces between the half-lattice periods, mounting flanges for diagnostics, and the beam tube. The inner diameter of the tube must be precisely controlled to maintain the alignment and centering of the capacitive probe, a non-intercepting diagnostic being developed for beam diagnosis and control. The outer diameter of the beam tube must be precisely maintained and held concentric with the inner diameter in order to keep the permanent magnet quadrupoles precisely aligned to the center line of the beam. Copper-sealed knife edge and metal O-ring seals are used to meet the high vacuum requirements of the half-lattice period module. The half-lattice module weight exclusive of the induction modulator is estimated to be approximately 280 lbs.

Two fabrication options for the dipole housing are under evaluation. In the first technique, the dipole housing box is fabricated as a weldment from stainless steel plates. This method requires considerable machining and vacuum-compatible welding as well as precision fixturing to establish the correct dimensions and angles. In addition, the housing must be normalized after welding. This method is well suited to high volume manufacturing. The second method of fabrication involves electrical discharge machining (EDM) the dipole housing box from a solid block of stainless steel. This has the disadvantages of longer fabrication time and less efficient use of the material. However, it saves on the costs associated with welding and fixturing. Machining costs are actually lower, because the EDM operation is unattended. The flexibility in the fabrication processes allow us to utilize the resources of various machine shops effectively.

B. Modulator development

One of the most difficult and critical challenges faced in building a recirculator is driving the induction accelerator cells that couple pulsed electrical energy into the ion beam. The modulator that drives the induction cells must perform three primary functions, each of which is critical to the operation of the recirculator. These primary functions include acceleration, longitudinal confinement and cell reset. For the small recirculator, acceleration of the beam requires a sequence of nominally 470 volt pulses that are 4 to 2 microseconds in duration. The acceleration pulses are nominally square pulses with slight "tilts" in the voltage to compress the beam longitudinally. These tilts also vary from pulse to pulse within a single acceleration sequence. Figure 4 illustrates the range of pulse shapes and pulse widths required for acceleration on the small recirculator.

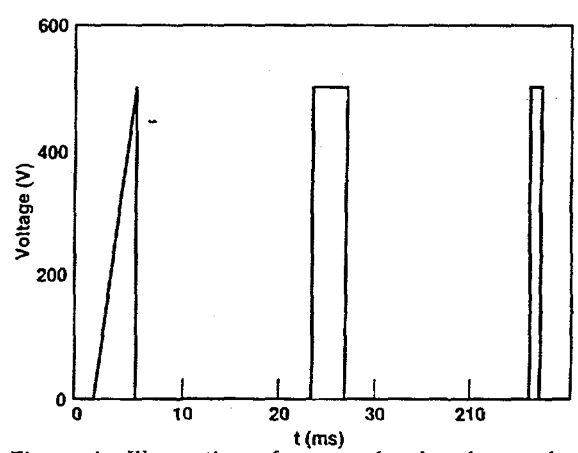

Figure 4. Illustration of range of pulse shapes that must be generated by induction cell modulators.

Longitudinal confinement of the ion beam is necessary to compensate for the space charge forces which are acting to expand the beam in the axial direction. Short "ear" pulses must be generated that accelerate the tail of the beam and decelerate the head of the beam just enough to balance the space charge forces. Similar to the acceleration pulses, the shape and amplitude of the ear pulses must also vary within a single acceleration sequence. Figure 5 shows an example of the bipolar ear pulses that will be required for the small recirculator.

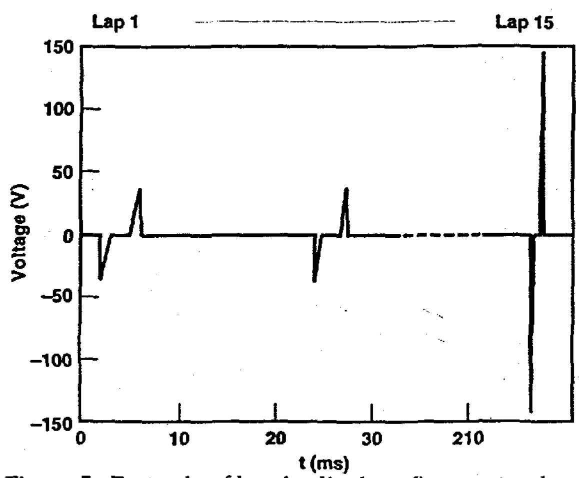

Figure 5. Example of longitudinal confinement pulses required for small recirculator.

Reset of the magnetic core material in each cell is required to return the magnetic material to its initial state in preparation for the next pulse. If the magnetic core material is not adequately reset after each pulse, the flux density in the core will gradually build up until the core saturates, shorting out the modulator. Aside from a potentially disastrous impact on the modulator, a saturated core will inhibit further acceleration of the ion beam .

In the recirculator, a sequence of pulses must be generated by each modulator to accelerate the beam. The time between each pulse in a sequence is determined by the time required for the beam to complete one lap around the ring. In our 4.5 meter diameter ring, this time varies from approximately 25 μs to 10 μs.

One of the objectives of this experiment is to demonstrate beam compression. As a result, not only will the velocity of the beam be increasing through each lap, but the duration of the beam will be decreasing. The modulator must be agile enough to generate a wide spectrum of pulses and have the ability to change their shape and duration from pulse to pulse. For this reason, a modulator is being developed that utilizes the latest MOSFET technology to achieve the required agility.

The modulator requirements for the small recirculator are challenging, but the basic requirements of repetition rate and reset have been demonstrated in previous development efforts.[3,4] However, those development efforts focused on using the MOSFETS as on/off switches. This mode of operation is inadequate for the small recirculator because of the radical changes in pulse shape that are required from lap 1 to lap 15 as seen in figure 4. Our present development efforts are focused on developing a high power MOSFET amplifier to generate the required waveforms.

There are a number of modulator/cell configurations that could be used to generate the appropriate waveforms for acceleration of the ion beam. The most flexible approach is to generate the acceleration and the bipolar ear pulses separately, however this would require a bipolar amplifier for the ears. Ultimately, the beam needs to see the waveform shown in figure 6 which is the summation of the acceleration and ear pulses.

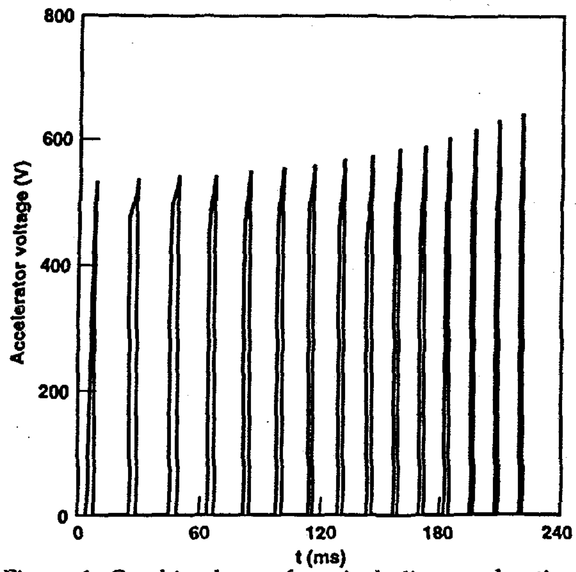

Figure 6. Combined waveform including acceleration and longitudinal confinement.

It is important to note that the resultant waveform is not bipolar. The approach being pursued on the small recirculator is to inductively sum the outputs of a 500V main acceleration amplifier and a 200V ear pulse amplifier so that the required waveform appears across a single accelerating gap.

MOSFET arrays are being used as amplifier elements to tailor the waveshape and regulate the voltage that appears across the gap. The amplifier configuration allows the generation of arbitrary waveshapes. Programmable waveform generators drive the parallel MOSFET arrays to generate the desired acceleration waveforms for the beam. A block diagram of the modulator is shown in figure 7.

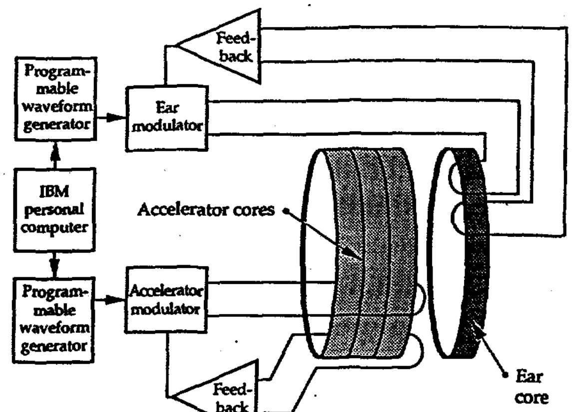

Figure 7. Block diagram induction cell modulator for small-scale recirculator.

The circuit analysis program, Micro-Cap IV is being used to model the electronic portion of the design including the cell and amplification circuits. Figure 8 is a typical simulation showing an input waveform compared with the output voltage at the accelerator cell including reset.

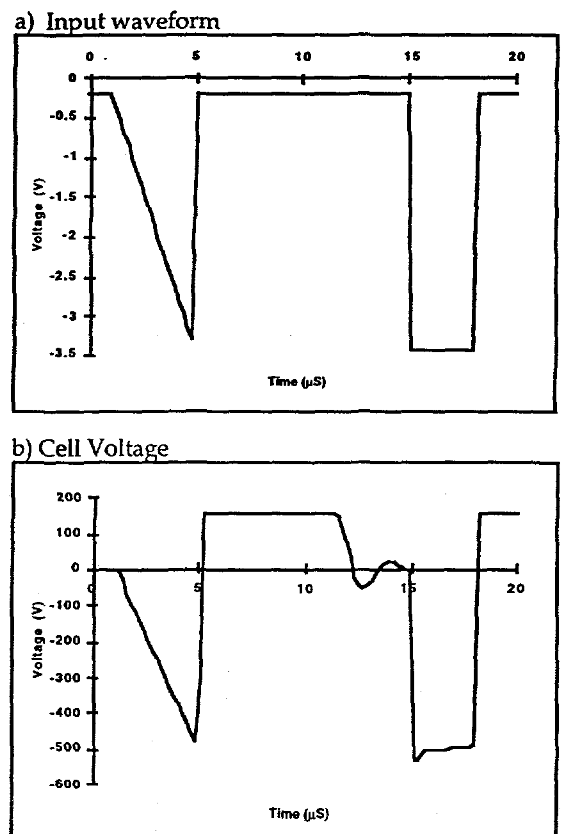

Figure 8. Micro-cap IV is emulation of small-scale recirculator modulator.

A drawing of how the cell modulator package is integrated onto the half-lattice period hardware is shown in figure 9.

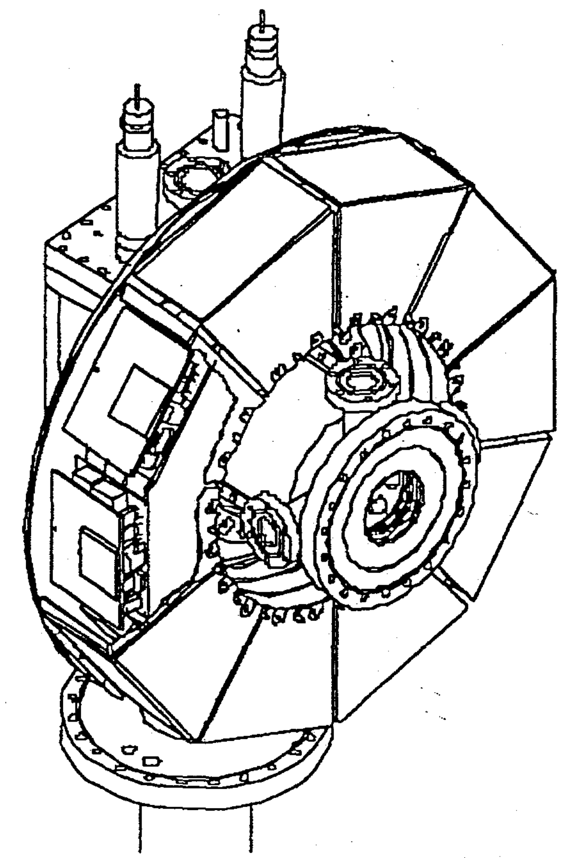

Figure 9. Half-lattice module with induction cell and modulator.

Unlike more conventional system designs for induction accelerators, the modulator is integral to the cell to eliminate the need for connecting cables to carry the pulses to the induction cell. This approach was taken to eliminate the possibility of unwanted reflections occurring because of impedance mismatches between the cable and the time varying load. The long pulse durations make it impractical to rely on time isolation of the load and the modulator to insure that reflections don't disturb the desired pulsed fidelity.

VI. SUMMARY

A full sequence of development and test activities is planned to validate the mechanical and electronics design features of the half-lattice module and induction cell modulator. Two prototype half-lattice modules are being fabricated using the techniques outlined above. Construction of two prototypes will allow us to further develop our assembly, installation, and alignment procedures. In addition, we will be able to evaluate the first fully integrated half module and induction cell for a recirculator.

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2 V. Karpenko, et. al, "Mechanical Design of Recirculating Accelerator Experiments for Heavy-Ion Fusion", Proceedings of the 1995 Particle Accelerator Conference, Dallas Texas, May 1995 (UCRL-JC119583)

3 H. Kirbie, et. al, "A FET-Switched Induction Accelerator Cell", Proceedings of the 9th IEEE Pulsed Power Conference, Albuquerque, NM, 1993, p. 415.

4 H. Kirbie, et. al, "Development of Solid State Induction Modulators for High PRF Accelerators", Proceedings of the 10th IEEE Pulsed Power Conference, Albuquerque, NM, July 10, 1995

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