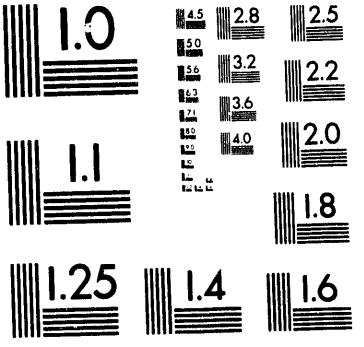
1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6

1 of 1

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Induction Accelerator Development for Heavy Ion Fusion

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Submitted to the International Symposium on Heavy Ion
Inertial Fusion, Frascati, Italy, May 25-28, 1993

*This work was supported by the Office of Energy Research, Office of Fusion Energy, U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Induction Accelerator Development for Heavy Ion Fusion[1]

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SUMMARY

For approximately a decade, the Heavy Ion Fusion Accelerator Research (HIFAR) group at LBL has been exploring the use of induction accelerators with multiple beams as the driver for inertial fusion targets. Scaled experiments have investigated the transport of space charge dominated beams (SBTE), and the current amplification and transverse emittance control in induction linacs (MBE-4) with very encouraging results. In order to study many of the beam manipulations required by a driver and to further develop economically competitive technology, a proposal has been made in partnership with LLNL to build a 10 MeV accelerator and to conduct a series of experiments collectively called the Induction Linac System Experiments (ILSE).The major components critical to the ILSE accelerator are currently under development. We have constructed a full scale induction module and we have tested a number of amorphous magnetic materials developed by Allied Signal to establish an overall optimal design. The electric and magnetic quadrupoles critical to the transport and focusing of heavy ion beams are also under development. The hardware is intended to be economically competitive for a driver without sacrificing any of the physics or performance requirements.This paper will concentrate on the recent developments and tests of the major components required by the ILSE accelerator.

materials such as the Metglas TCA and the conventional Ni-Fe is continuing, and a final decision on the most cost effective material will not be made until after the project is approved.

2.1. Induction Cell

The principle of linear acceleration by magnetic induction has been thoroughly covered in many publications. Heavy ion induction accelerators, however, are unique in their requirements. The acceleration waveforms are continuously variable throughout the ILSE acceleration cycle and the focusing half lattice periods (HLP) varies accordingly from an initial 33 cm for the first 16 modules to 41 cm for the next 16 and finally 50 cm for the remainder of the accelerator. A number of factors influenced our decision to choose the 2" wide Metglas for our induction cells. First of all, it gave us the flexibility to use identical cells for the different half lattice periods. For example, the 33 cm HLP uses three cells, the 41 cm four cells and the 50 cm five cells bolted together to form a module. Between each module there is axial space for high voltage feedthrough, magnet power, and most importantly, alignment and structural supports for the quadrupoles. A second reason for the 2" width was the fact that we wanted to avoid cumbersome liquid insulation (oil) in the acceleration gap. With the 2" width, the voltage per gap is 33 kV which can be held off reliably with gas insulation (SF_6 or $CO_2 + N_2$). Another argument for maintaining acceleration voltages of 33 kV is that the line modulators which drive the core can utilize reliable and inexpensive glass thyratrons rather than expensive high voltage ceramic units or unreliable spark gaps. Another advantage of using a narrower ribbon is that the voltage per layer is lower, thus allowing a thinner interlaminar insulation (2.5 μm) to hold off the voltage, and this results in a higher packing factor (0.8 to 0.9). The inside diameter of the induction cell is determined by the size of four beam electrostatic quadrupole and the voltage hold off requirements. The gradient and pulse duration now dictate the volt-seconds, hence the outside diameter. Allowing 50% more volt-seconds than the minimum dictated by the 1 μs pulse, the outside diameter is 1.5 m. The magnetic field H is related to magnetizing current I by $H = I/2\pi r$. Because the outside radius is about three times the inside radius, the inside portion of the core will saturate before the outer portion is fully magnetized. Saturation of the inner portion will cause nonlinear current flow which makes pulse shaping more difficult. In order to maximize utilization of the magnetic material, the core is segmented radially into three sections. The three cores are now driven in parallel and will approach saturation very nearly at the same time. The voltage will, of course, be one-third as high, while the drive current will be three times higher. An additional benefit of segmenting the core is that the thyratron switch will operate at a more conservative voltage level (22 kV charge), resulting in a more reliable system. A detailed cross-section of the segmented cell is shown in Figure 3.

Each induction core is supported by a mandrel and flanked by a thick plate on one side and a thin one on the other. The thick plate constitutes the ground return and the thin one terminates the high-voltage cable feed. On each side of the core are several layers of Mylar to insulate the high voltage from the ground. The high voltage will be fed through standard high-voltage connectors to the outer core and will be connected to the two inside cores by means of high-voltage wire embedded in the thick plate.

Three cells are bolted together to form a 33 cm HLP module, and eight modules are assembled together to form a section or cell-block with complete diagnostics capability. Figure 4 shows a complete cell block for the 33 cm HLP electrostatic focus section with quadrupoles inside. The space between three-cell modules is required for quadrupole support, high voltage feed-through, and articulation devices.

2.2. Waveform Generator

The acceleration schedule for ILSE will require careful tailoring of the voltage waveforms at each gap in order to provide energy gain, current multiplication, and longitudinal focusing. Figure 5 shows the acceleration waveforms dictated by heavy ion beam transport physics. Initially, the voltage is sawtooth with over 1 μs duration and then becomes rectangular with shorter and shorter duration. These waveforms should be replicated to within a percent of the ideal. To satisfy these requirements, we have chosen to build pulse-forming networks (PFN) switched by a thyratron. This technology can produce the desired waveforms to within a few percent and will have to be augmented by some active or fast correction devices to meet the specifications. This combination is the most cost-effective way to satisfy all the requirements. Active solid state devices or hard tube modulators to produce all the desired waveforms would be prohibitively expensive. To achieve the desired accuracy, each PFN will be designed with time varying impedance in order to complement the nonlinearity of the induction cell. As can be seen from the magnetizing current, the impedance of the induction cell decreases as the magnetic material approaches saturation; the PFN will likewise have an impedance which "decreases in time." Using this approach, we hope to be within a few percent of the ideal wave shape. The fast correction will then be required to handle a very small fraction of the total current. The voltage to the cell will be slightly higher than required, and the fast correction will basically act as a shunt regulator in a feedback system to lower the voltage to the desired level. The shunt regulator has not been designed yet, but it will consist of a stepdown transformer with FET to act as variable resistors.

The block diagram of the complete drive system is shown in Figure 6. The DC power supply charges the command resonant charger (CRC) which pulse charges the tapered impedance pulse-forming network (PFN) which powers the induction accelerator cores once the thyratron is triggered. During the charge cycle from the CRC to the PFN, the current flows through the cores and partially resets them. Because of their large diameter, however, this charging current is insufficient to fully reset them, and a separate reset pulse is required.

The desired sawtooth and rectangular pulses are generated by ladder-type PFNs. These networks use discrete components to build a series of harmonics that together approximate the desired wave shape. Each component or stage of the network is associated with a different portion of the pulse. Taking the load impedance as the instantaneous value of the voltage divided by the current for a particular cell, the impedance of each stage can be matched to that load at the time associated with that stage. The two types of networks for generating the sawtooth and rectangular pulses are simulated on the computer prior to building full-scale prototypes. Figure 7 shows a simplified circuit for a rectangular pulse generator with computer simulation and the actual waveform. Figure 8 is the computer simulation for a sawtooth generator.

2.3. Test Stand

During the past year we have constructed a full scale test stand to study the issues associated with a heavy ion induction accelerator. The test stand consists of three full-scale cells which simulate the 33 cm HLP module. This module is driven by PFNs which deliver rectangular pulses to the cells. Reset to the cells is provided by a SCR pulser which can drive the magnetic material below $-B_r$ to obtain a greater flux swing. The initial cores were all wound using the 2605 S3A material since approximately one tonne was left over from a previous project at a small cost to us. This materials is not the optimum for ILSE, but it did allow us to assemble the system and develop all the hardware associated with the drive system. We have since tested a variety of other alloys, chosen the optimal material for ILSE, and are currently in the process of replacing the S3A material with SC or other material which will be more suitable. This test stand will eventually house the electrostatic quadrupole and the magnetic quadrupole for in situ testing. The alignment and articulation systems for the quadrupoles will also be prototyped once the project is approved.

3. SUMMARY

The HIFAR group at LBL has undertaken the development of an induction accelerator for heavy ion fusion. This accelerator is somewhat unique when compared to the standard ones for electrons in that the waveforms are continually changing throughout the acceleration cycle. This accelerator will address many of the transport issues for driver scale beams and will help resolve many technology issues associated with magnetic materials, waveform generators, alignment, and electrostatic and magnetic quadrupoles. Most importantly, this accelerator will answer many questions associated with the economic viability and reliability of an eventual driver for inertial confinement fusion.

ACKNOWLEDGMENTS

The technology development for heavy ion induction accelerators presented in this paper reflects the efforts of many individuals in the HIFAR group from the EE and ME departments who support the scientific staff responsible for the physics design of this accelerator. Those individuals who participated in this effort are listed below alphabetically: W. Abraham, D. Berners, J. Broad, B. Dudak, A. Faltens, M. Fong, W. Ghiorso, W. Greenway, R. Hipple, C. Houston, T. Katayanagi, C. Lionberger, H. Meyer, J. Perez, C. Peters, C. Pike, T. Purtell, J. Pruyn, J. Rice, J. Stoker, W. Tiffany, D. Vanecek, and from LLNL, F. Deadrick and M. Newton. Their efforts are deeply appreciated.

FIGURE CAPTIONS

Figure 1. Top: Losses (J/m^3) at different rates of magnetization dB/dt (T/μs) measured by Allied for annealed 2605SC Metglas. Bottom: B-H loops, dB/dt (T/μs), at different rates of magnetization, measured by Allied, for annealed 2605SC Metglas. The dotted lines represent LBL data for the same material unannealed with 2.5 μm of Mylar wound between turns.

Figure 2. Dynamic magnetization curves taken at constant voltage and different saturation times for unannealed 2605 alloys.

Figure 3. Detailed cross section of radially segmented induction cells for the electrostatic focus section.

Figure 4. Eight modules of three cells each (33-cm HLP) form a "cell block" in the electrostatic focus section.

Figure 5. Ideal accelerating waveforms. This figure shows the ideal voltage waveforms for every second accelerating gap needed to achieve self-similar current amplification through the accelerator portion of ILSE.

Figure 6. Block diagram of a drive system that generates the acceleration voltage for the induction cells.

Figure 7. The schematic, computer-simulation results, and actual test results of the square-wave pulse generator.

Figure 8. Unipolar network design to generate a ramp, along with the resulting waveform in computer simulation.

FOOTNOTES

1. Work supported by the Director, Office of Energy Research, Office of Fusion Energy, U.S. Department of Energy under Contract no. DE-AC03-76SF00098.

2. A list of the contributors is listed under Acknowledgments

3. Metglas is a trademark of Allied Signal Corporation.

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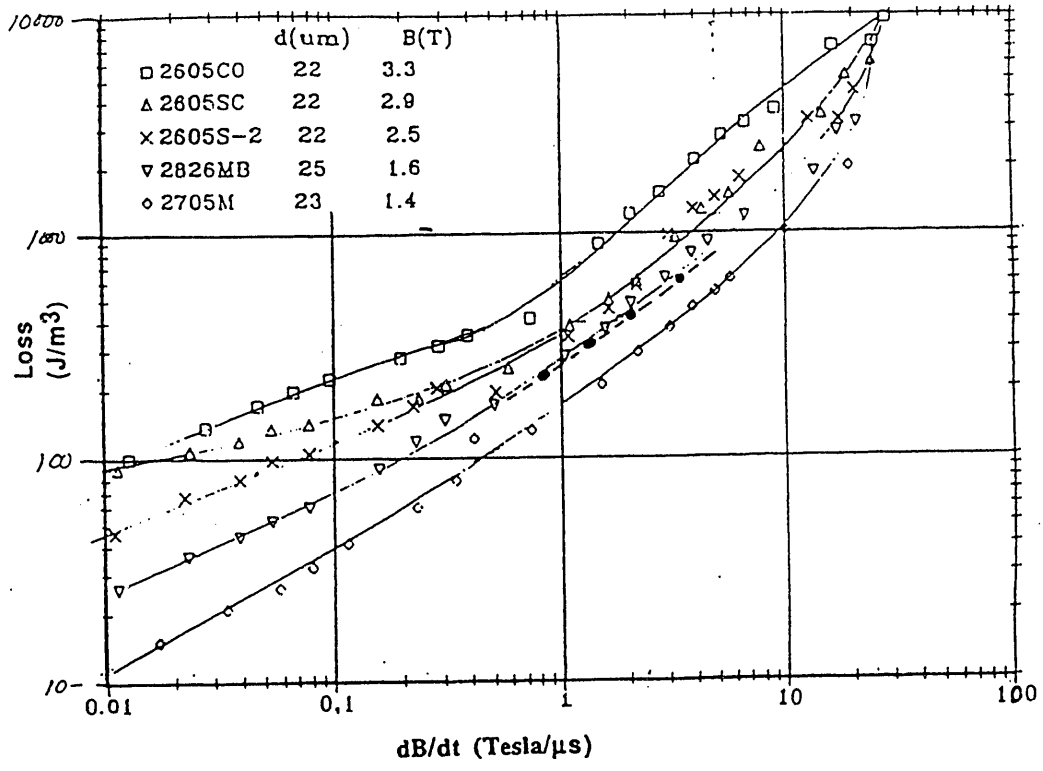
[1] T. Fessenden, R.O. Bangerter, D. Berners, J. Chew, S. Eylon, A. Faltens,W. Fawley, C. Fong, M. Fong, K. Hahn, E. Henestroza, D. Judd, E. Lee, C. Lionberger, S. Mukherjee, C. Peters, C. Pike, G. Raymond, L. Reginato, H. Rutkowski, P. Seidl, L. Smith, D. Vanecek, S. Yu, F. Deadrick, A. Friedman, L. Griffith, D. Hewett, M. Newton, H. Shay, Proc. 14th Intl. Conf. Plasma Physics and Controlled Nuclear Fusion Research, Germany, September 30 - October 7, 1992.

[2] A. Faltens and S. Rosenblum, *J. Appl. Phys.* **57**(1) April 15, 1985.

[3] C.H. Smith, *IEEE Trans. Magn.* MAG20, 1320 (1984).


d(um) B(T)
□ 2605CO 22 3.3
△ 2605SC 22 2.9
× 2605S-2 22 2.5
▽ 2826MB 25 1.6
◇ 2705M 23 1.4
Loss (J/m3)
0.01
0.1
1
10
100
dB/dt (Tesla/µs)

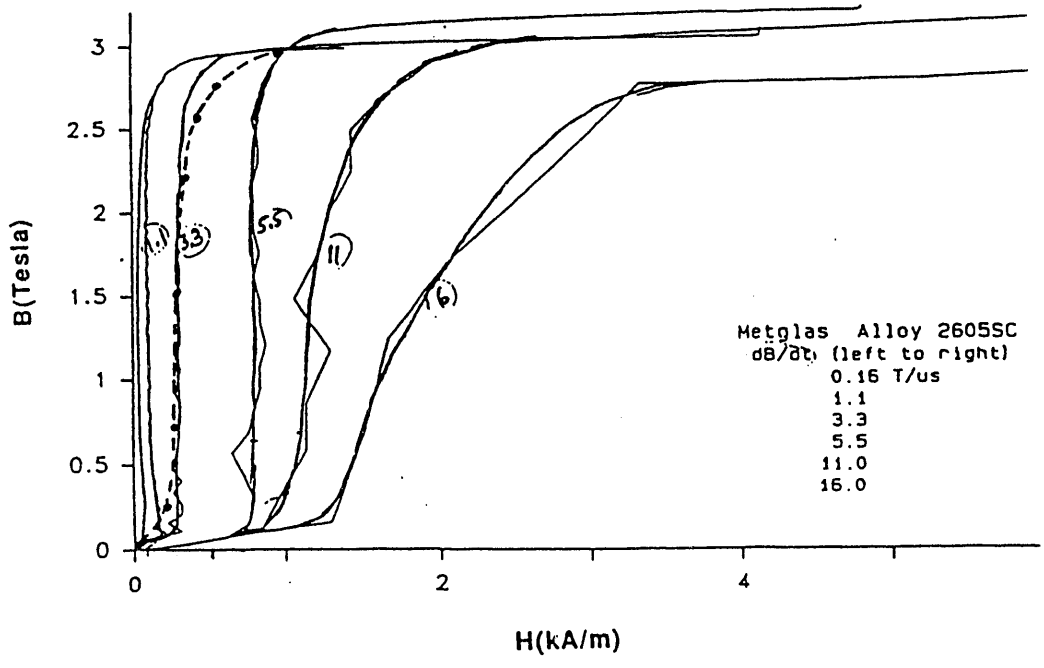

B(Tesla)
H(kA/m)
Metglas Alloy 2605SC
dB/dt (left to right)
0.16 T/us
1.1
3.3
5.5
11.0
16.0

Figure 1

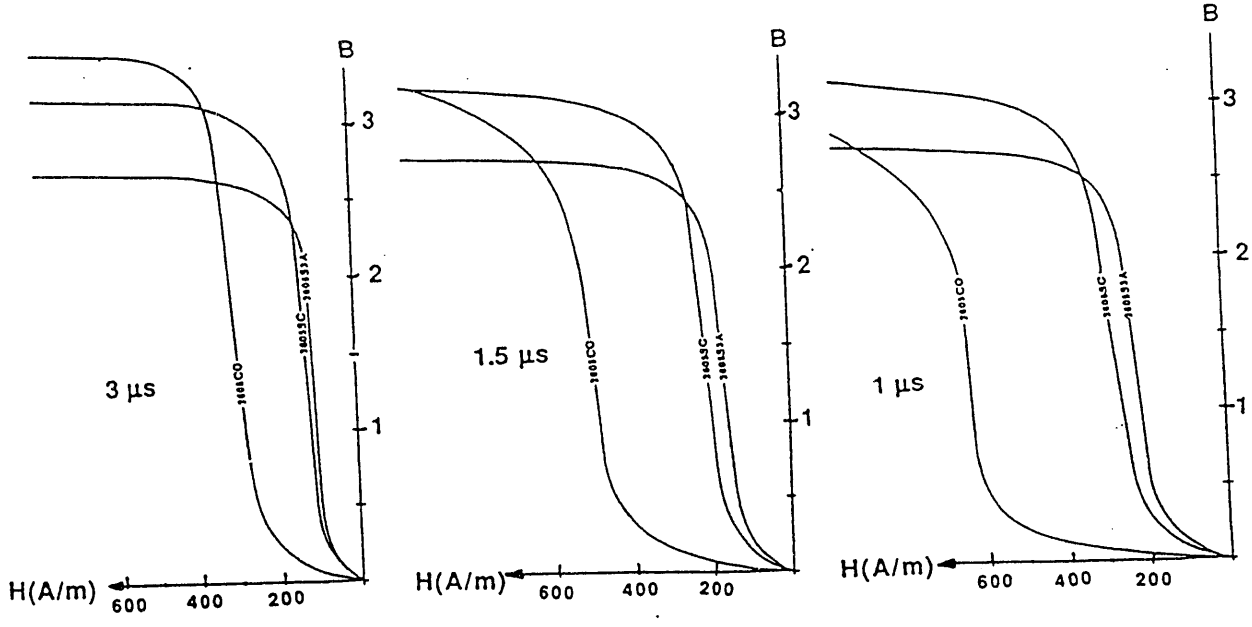

B
3
2
1
3 µs
H(A/m)
600
400
200
B
3
2
1
1.5 µs
H(A/m)
600
400
200
B
3
2
1
1 µs
H(A/m)
600
400
200

Figure 2

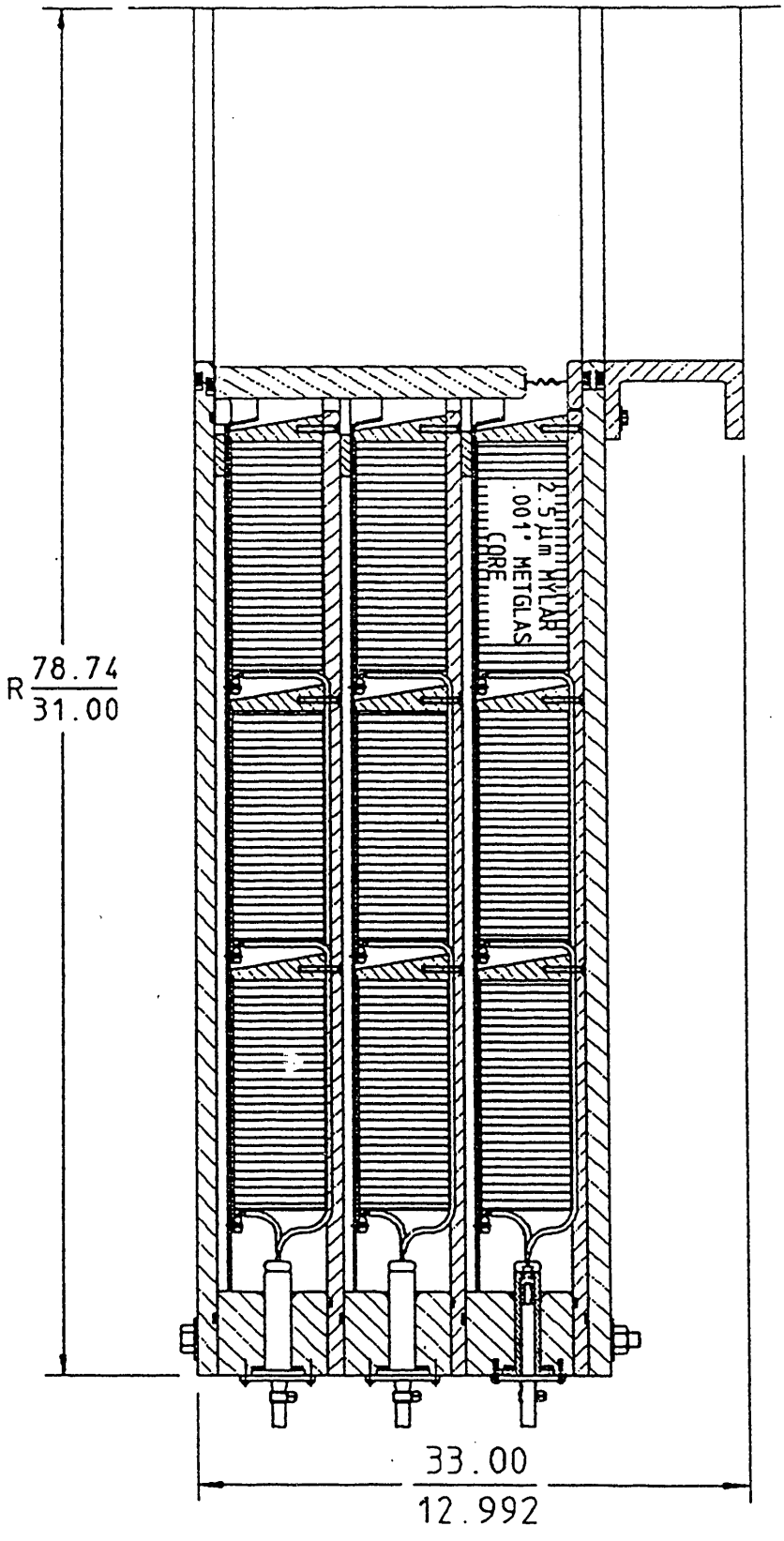


Figure 3

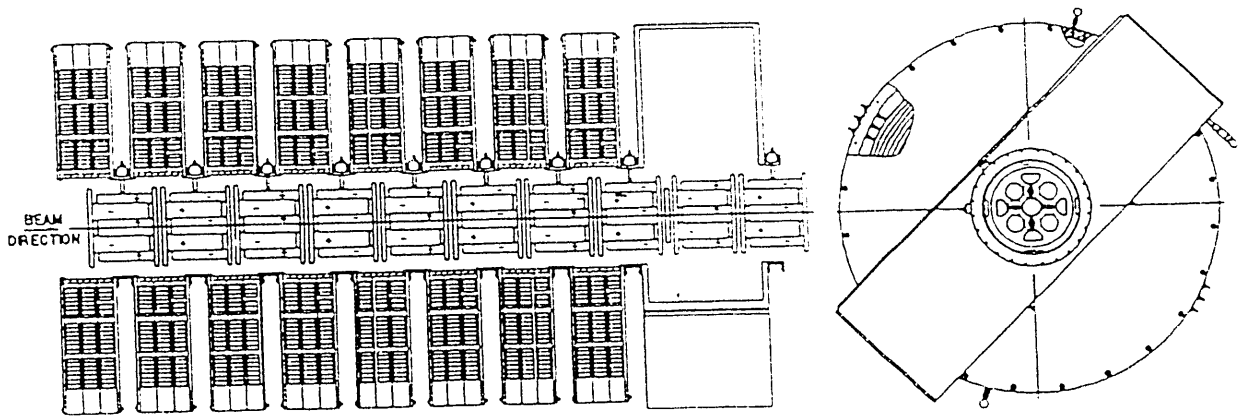


Figure 4

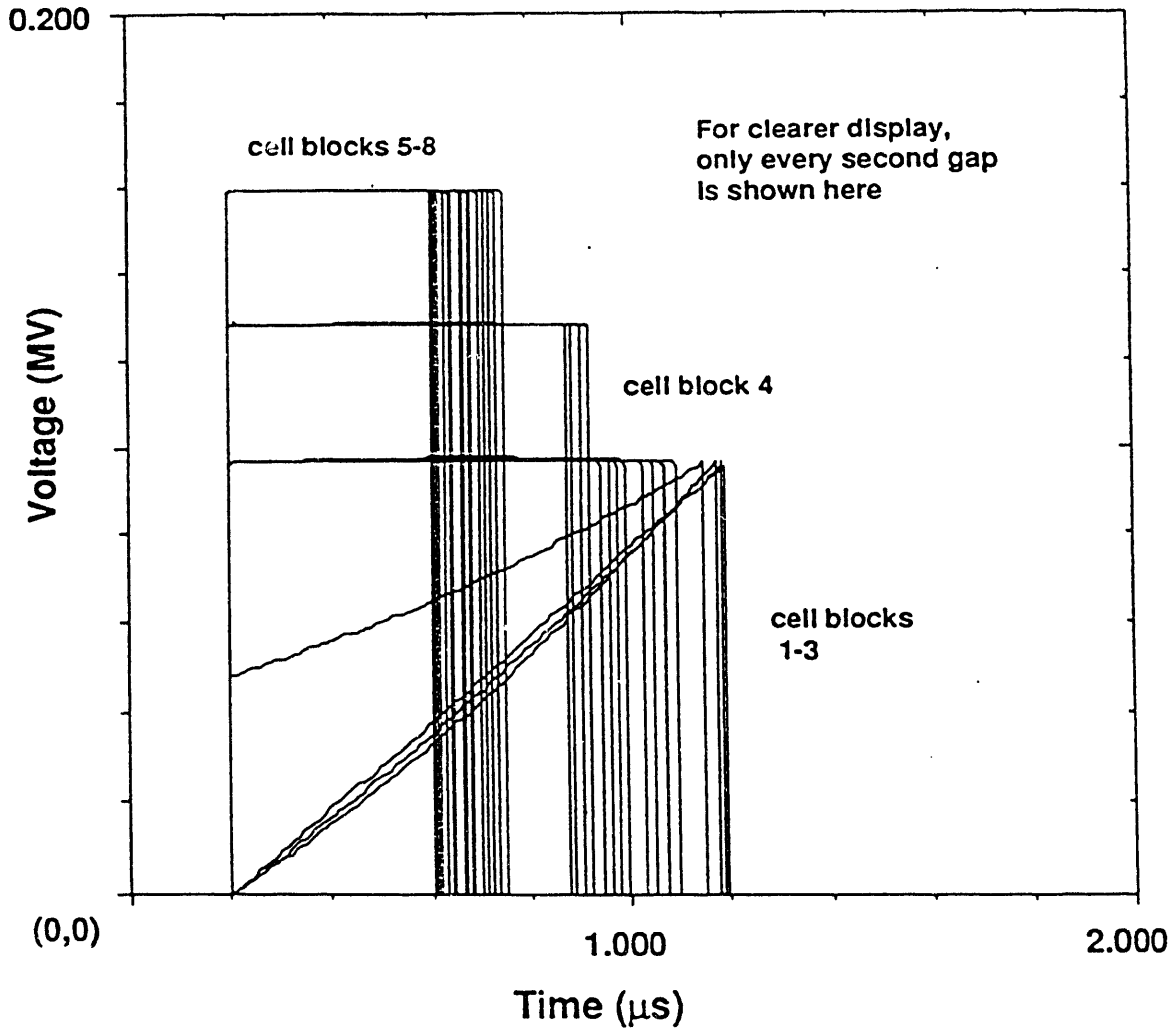

0.200
cell blocks 5-8
For clearer display,
only every second gap
is shown here
cell block 4
cell blocks
1-3
Voltage (MV)
(0,0)
1.000
2.000
Time (μs)

Figure 5

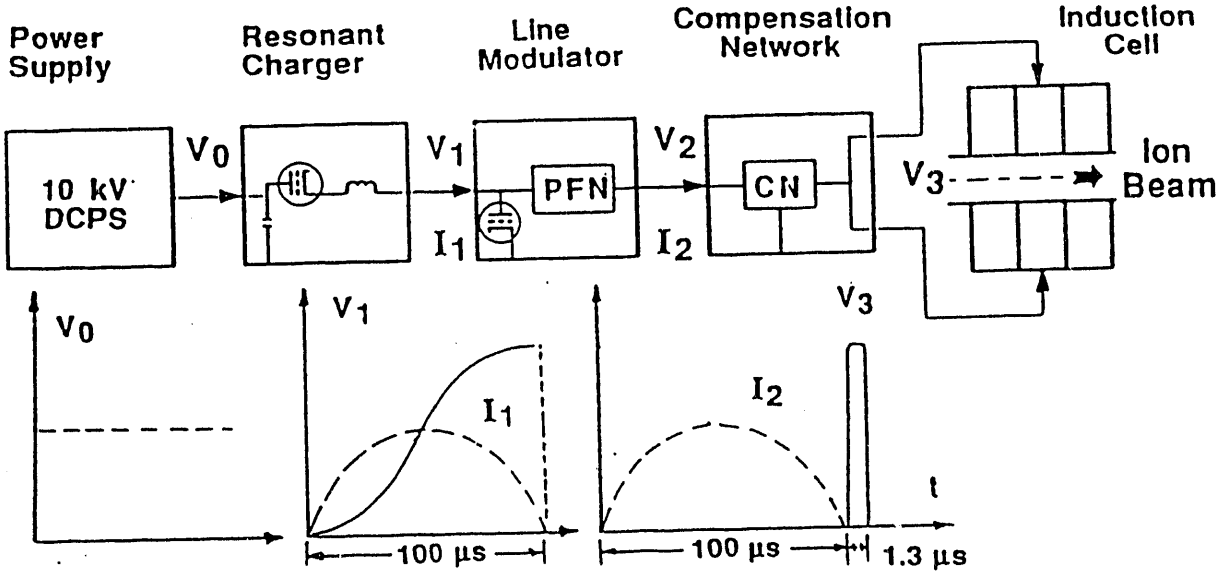
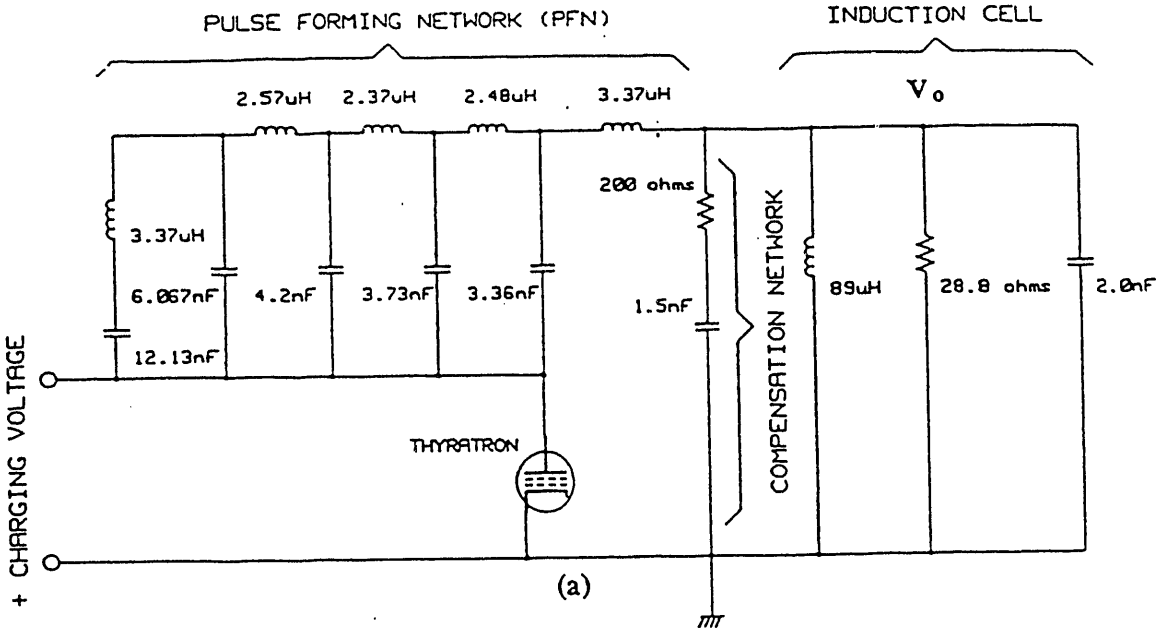
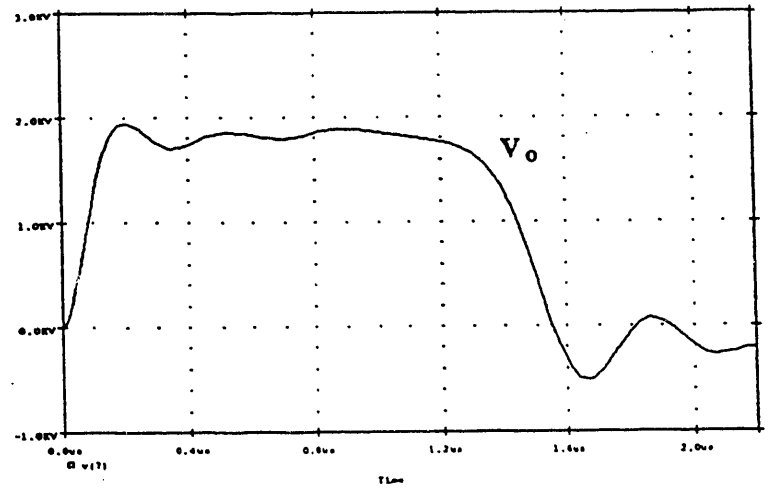

Power Supply
Resonant Charger
Line Modulator
Compensation Network
Induction Cell
10 kV DCPS
V0
V1
I1
PFN
V2
I2
CN
V3
Ion Beam
V0
V1
I1
V3
I2
t
100 µs
100 µs
1.3 µs

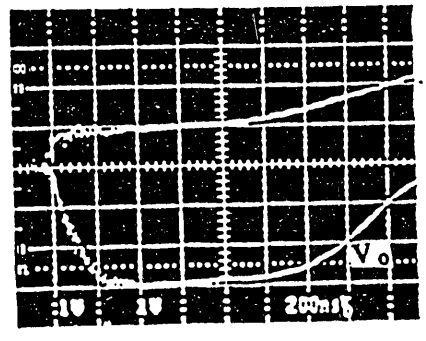
Figure 6


PULSE FORMING NETWORK (PFN)
INDUCTION CELL
2.57uH
2.37uH
2.48uH
3.37uH
Vo
200 ohms
3.37uH
6.067nF
4.2nF
3.73nF
3.36nF
1.5nF
COMPENSATION NETWORK
89uH
28.8 ohms
2.0nF
12.13nF
THYRATRON
+ CHARGING VOLTAGE

(a)

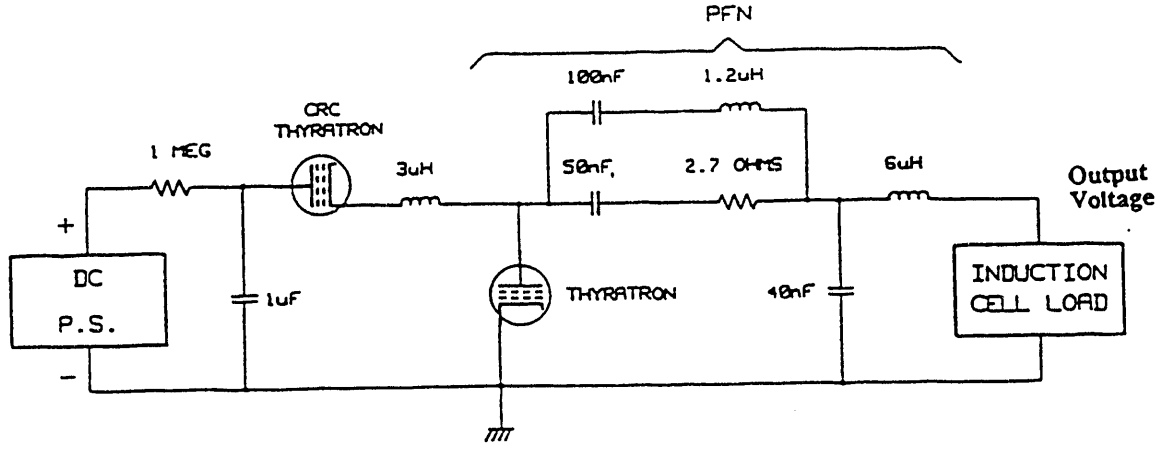

Vo

(b)


Vo

(c)

Figure 7


PFN
100nF
1.2uH
CRC
THYRATRON
1 MEG
3uH
50nF,
2.7 OHMS
6uH
Output
Voltage
+
DC
P.S.
-
1uF
THYRATRON
40nF
INDUCTION
CELL LOAD

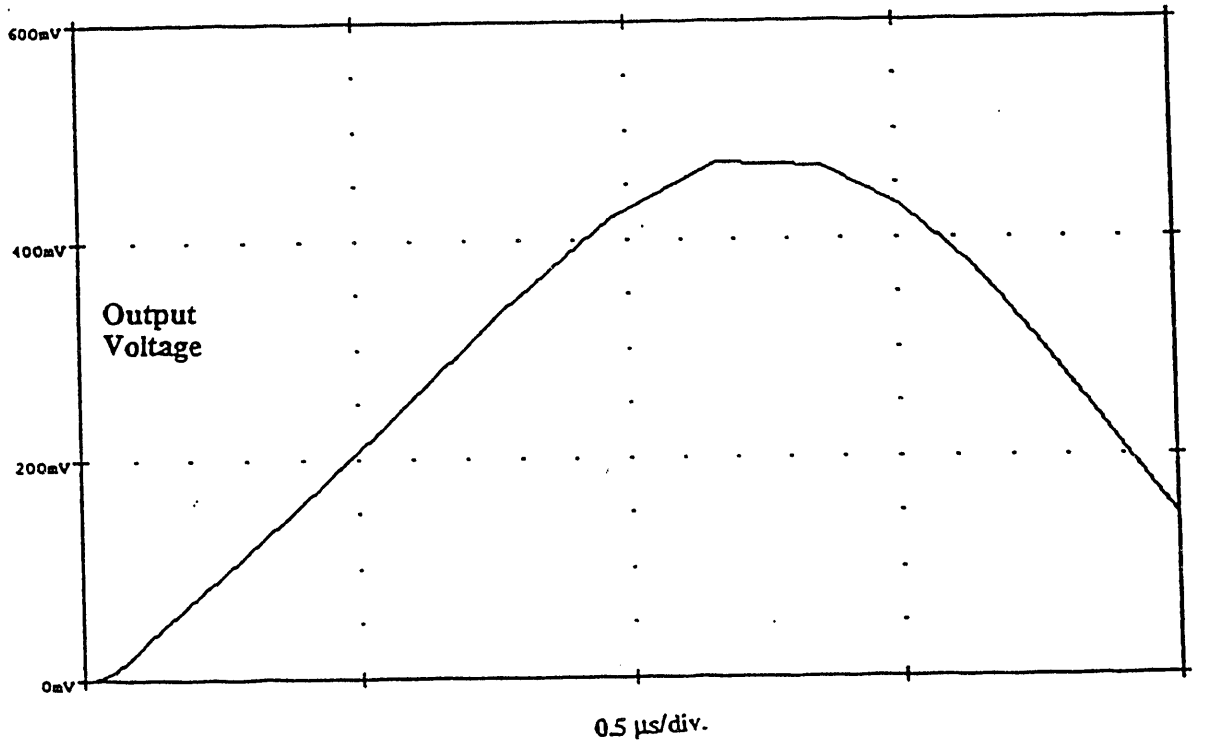

600mV
400mV
200mV
0mV
Output
Voltage
0.5 µs/div.

Figure 8

DATE
FILMED
10/19/93
END