

RECENT PROGRESS IN THE DEVELOPMENT OF A CIRCULAR ION INDUCTION ACCELERATOR FOR SPACE CHARGE DOMINATED BEAMS AT LLNL*

L. Ahle, T. C. Sangster, D. Autrey, J. Barnard, G. Craig, A. Friedman, D. P. Grote, E. Halaxa, R. L. Hanks, M. Hernandez, H. C. Kirbie, B. G. Logan, S. M. Lund, G. Mant, A. W. Molvik, W. M. Sharp
Lawrence Livermore National Laboratory, Livermore, CA 94551 USA
D. Berners**, S. Eylon, D. L. Judd, L. Reginato
Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA
A. Debeling, W. Fritz
Bechtel Nevada Corporation, Las Vegas, NV 89193 USA

Abstract

The Heavy Ion Fusion Group at Lawrence Livermore National Laboratory has for several years been developing the world's first circular ion induction accelerator. This machine has recently been extended to 90 degrees, or 10 half-lattice periods(HLP) with full beam transport. In addition, induction cores have been installed on five of the HLP's, each with an independent arbitrary waveform pulser. An arbitrary waveform pulser for the bending electrostatic dipoles has also been enabled. Together, they have allowed the first attempts at coordinated bending and acceleration of the beam. The results of these first attempts will be reported on in the paper by examining the output of various diagnostic devices, such as the capacitive Beam Probes(C-probes), slit scanners, and the Gated Beam Imager(GBI).

1 INTRODUCTION

Currently, heavy ion beams are being pursued as a candidate for a driver of an Inertial Fusion(IFE) power plant. In such a power plant, ion beams would provide the input energy necessary to ignite small D-T capsules [1]. The accelerator for such a driver would need to accelerate space charge dominated ion beams to a total kinetic energy of a few GeV while providing pulse compression and be able to operate at a rate of ~5-Hz [2,3]. Usually the conceptual design of such a machine is linear, but an alternative concept, which may provide significant cost savings [4], is a circular machine, or recirculator. However, a space charge dominated, ion induction, circular machine has never been built before. Thus, the HIF Group at LLNL has been developing a small recirculator in order to investigate the validity of such a concept.

* This work has been performed under the auspices of the US DOE by LLNL under contract W-7505-ENG-48.

** Present Address: Stanford University, Palo Alto, CA 94305, USA

2 THE RECIRCULATOR

In order to validate the recirculator for an IFE power plant driver, coordinating bending and acceleration of the beam while maintaining transverse and longitudinal control beam brightness must be demonstrated [5]. Table 1 lists some important characteristics of the recirculator. In designing this machine, all of the important dimensionless beam parameters, such as perveance, were kept the same as a full scale driver machine. Each half lattice period(HLP) of the recirculator consists of a permanent magnetic quadrupole for focusing, an electrostatic dipole for bending the beam, and an induction core, or modulator, for acceleration and longitudinal compression. The dipole plates are designed to provide a 9 degree bend to the beam while the modulators are designed to provide 500-eV of acceleration.

Table 1: Recirculator Specifications

Circumference	14.4m	
Beam Species	K ⁺	
# of laps	15	
Max. Beam Radius	1.5 cm	
Beam Statistic	Lap 1	Lap 15
Beam Energy	80 keV	320 keV
Pulse Duration	4 μ s	1 μ s
Beam Current	2 mA	8 mA
Undepressed Phase Advance	78°	45°
Depressed Phase Advance	16°	12°

In the fall of 1997, the machine was extended from a 45 degree bend [6] to a 90 degree bend section. Figure 1 shows the current layout of the machine. Initially, a 4- μ s beam pulse is injected by a source diode with an energy of 80-keV through a 1-cm diameter aperture which provides an initial beam current of 2-mA. Upon injection the beam enters an electrostatic matching section used to convert the uniformly expanding beam to an AG focused

beam. A short magnetic transport section follows which then leads to the 90 degree bend section. Following the bend section is the End Tank which houses several diagnostics (a Faraday cup, parallel slit scanner, and a gated beam imager) to measure beam quality. Also as part of the upgrade, magnetic induction cores were added to 5 of the 10 HLP's as shown.

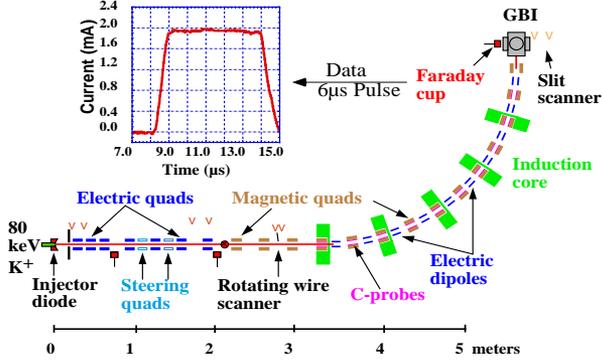


Figure 1: Current Recirculator Layout and Faraday cup data at 90 degrees.

The first attempts at beam transport through the 90 degree section were done with no acceleration and DC voltages (+/- 6.575-kV) on the bending dipole plates. Full current transport was achieved with less than 1% loss as measured by Faraday Cups. The RMS normalized emittance,

$$\epsilon_{rms}^2 = 4\gamma\beta(\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2)$$

for 90% of full beam current was also measured after 90 degrees. In the bend plane (x), the measured value is 0.045 π -mm-mR while the out-of-plane (y) emittance is 0.068 π -mm-mR. This compares to 0.021 π -mm-mR measured directly after the source aperture. The growth seen is within the design specifications.

3 CAPACITIVE BEAM PROBES

In order to monitor the beam as it travels through the accelerator, a capacitive beam probe (C-probe), which measures the transverse beam position as a function of time, was also installed in each HLP as part of the upgrade. The C-probe [7] is a ceramic cylindrical shell whose inside is coated by copper. The copper coating is divided into four equal areas by divisions parallel to the cylinder axis. The C-probe is placed inside the beam pipe and as the beam passes through it, a charge is induced on each pad. The induced charge is a function of the charge centroid and the total current of the beam. Each signal is amplified and digitized through the computer control system and analyzed to obtain the charge centroid. Bench tests of the system, using a conducting rod to simulate the beam, have yielded a resolution of 70 μm [6].

Figures 2 and 3 show the x position and y position as a function of HLP number. HLP 0 corresponds to a C-probe in the straight section while HLP n refers to the C-

probe immediately after the nth dipole plate. The different curves represent different applied voltages on the dipole plates. From the y position plot, the shot to shot repeatability of the measurement is clearly seen, while the x position shot demonstrates the sensitivity of the system to small perturbations. From tests characterizing the digitizing electronics, a systematic error of $\sim 700\text{-}\mu\text{m}$ is estimated for each point. That systematic error should decrease upon adding some refinements to the algorithm that calculates the position.

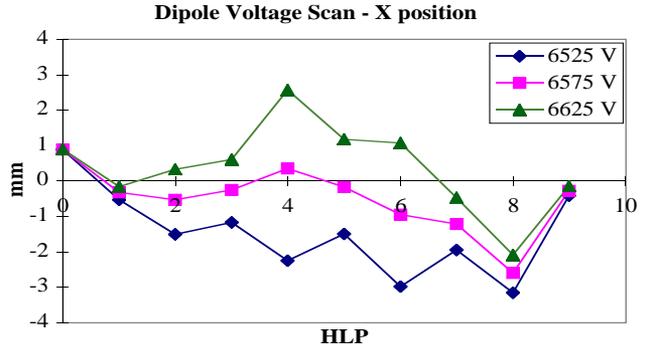


Figure 2: X positions as measured by C-probes for various dipole voltages.

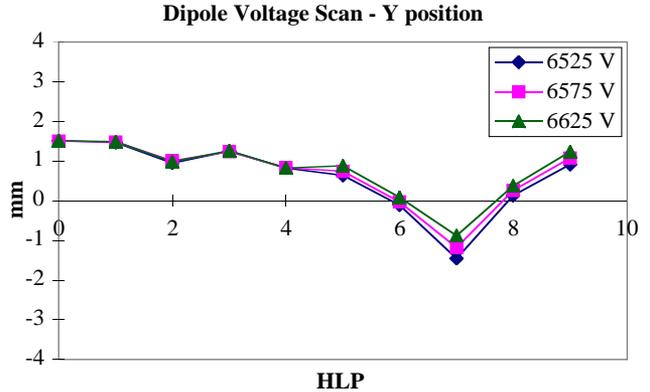


Figure 3: Y positions as measured by C-probes for various dipole voltages.

4 GATED BEAM IMAGER

In addition to beam position, the emittance growth of the beam as it travels through the bend section is of critical importance. In a full scale driver, the final beam pulse must be compressed to ~ 10 ns and a final spot size of a few mm. If the emittance is growth is too large, this final focus on the target will not be possible. Traditionally, a parallel slit scan has been used to measure the emittance of space charge dominated beams, but LLNL has developed a new device to measure the emittance, the Gated Beam Imager [8].

The GBI uses a pepperpot design in which the beam is incident on a hole with 100 μm diameter holes creating many beamlets. Each beamlet is emittance dominated and is allowed to drift to a micro channel plate(MCP). The MCP is coated with a thin layer of stainless steel, ~ 150

nm, which stops the ions and produces several few eV electrons per ion. After passing through the MCP, the electrons are proximity focused on to a phosphor screen. The light generated is focused and captured by a CCD camera that sits outside of vacuum. The image can then be analyzed to determine the emittance in both transverse directions. The MCP also allows time gating of the GBI to measure emittance as a function of time.

As of fall of 1997, the functionality of the GBI had been achieved, but there was still some slight discrepancy in direct comparisons between slit scanner data and GBI data [6]. After the analysis of the GBI images was changed to more closely mimic the slit scan, agreement between the two devices was achieved. At 90 degrees, the slit scan measurement yielded $\epsilon_x=0.045$ and $\epsilon_y=0.068$ π -mm-mR while the GBI yielded $\epsilon_x=0.043$ and $\epsilon_y=0.065$ π -mm-mR. Both of these comparison are well within the estimated 15% systematic error associated with each measurement.

5 ACCELERATION

In order for the acceleration of the beam to be controlled throughout the bend section, the voltage on the dipole plates need to be ramped up. For the full ring, the dipoles need to be ramped from approximately 7-kV to 28-kV in ~ 240 - μ s. To meet this challenge, LBNL has developed a prototype dipole pulser [9]. This pulser delivers only the positive polarity, but the design can be used with only slight modifications to build a pulser for the negative polarity. Bench tests of the pulser system indicate that it delivers the necessary voltage ramp.

Currently, we are in the process of enabling the pulser on the 90 degree bend section. When connected the pulser provide voltages for the positive plates in HLP 6-10. The rest of the plates are operated with DC voltages. The initial test of the system has shown that it does not yet have the desired shot to shot repeatability at the low voltage level necessary on the initial lap. Figure 4 shows C-probe data from three successive pulses taken within a minute of each other. This clearly shows the variance from pulse to pulse. From the DC voltage data presented in figure 2, the pulse to pulse variance is less than 2%. Currently, we are exploring ways to modify the feedback loop of the pulser to obtain the necessary repeatability.

Presently the electronics for the modulator are just going through their initial implementation on the bend section. While the bench tests are very encouraging, there is no data to show at this time.

6 CONCLUSION

Lawrence Livermore National Laboratory is currently developing the world's first circular ion induction accelerator, the recirculator. This machine has been extended to 90 degrees with full current transport. The emittance growth in this bend section is well within the design requirements. The C-probe system has been

enabled and has allowed for accurate beam position monitoring throughout the bend section and, the GBI has been fully reconciled with the more standard slit scanner. Initial test for the pulser to do the necessary ramping of the dipole voltage during acceleration have been performed. Currently we are performing the initial test of the electronics for the modulators. In the next month, we expect to make the first attempts at coordinating bending and acceleration.

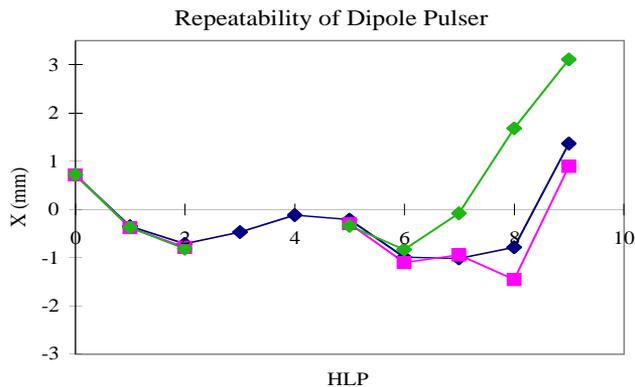


Figure 4: C-probe X positions for three consecutive pulses with dipole plates in HLP 6 through 10 connected to pulser.

7 REFERENCES

- [1] R. O. Bangerter, *Nuovo Cimento* **106A** (11), 1445-1456 (1993).
- [2] M. Tabak et al., *Nuclear Fusion* **38** (4), 509 (1998).
- [3] R. Moir, "Inertial Fusion Energy Power Plants Based on Laser or Ion Beams," Proc. of ICENES 98, Tel-Aviv, Israel, June 28 -July 2, 1998, to be published.
- [4] W. R. Meier et al., "An Integrated Systems Model for Heavy Ion Drivers," Proc. of Inter. Symp. on Heavy Ion Inertial Fusion, Heidelberg, Germany, Sept. 24-27, 1997, to be published in *Nucl. Inst. and Meth. A*.
- [5] A. Friedman et al., *Fusion Engineering and Design* **32-33**, 235-246 (1996).
- [6] T. C. Sangster et al., "Status of Experiments Leading to a Small Recirculator," Proc. of Inter. Symp. on Heavy Ion Inertial Fusion, Heidelberg, Germany, Sept. 24-27, 1997, to be published in *Nucl. Inst. and Meth. A*.
- [7] F. J. Deadrick et al., "Development of Beam Position Monitors for Heavy Ion Recirculators," Proc. of Particle Accelerator Conference, Dallas, TX, May 1995, 2557 (1995).
- [8] L. Ahle and H. S. Hopkins, "Gated Beam Imager for Heavy Ion Beams", Proc. of Beam Instrumentation Workshop, SLAC, May 4-7, 1998, to be published.
- [9] D. P. Berners and L. L. Reginato, "Arbitrary Waveform Generator for Electrostatic Dipoles in a Heavy Ion Recirculator," Proc. of Particle Accelerator Conference, Vancouver, B.C., Canada, May 12-16, 1997, (1997).