CURRENT STATUS OF THE RECIRCULATOR PROJECT AT LLNL*

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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 designed to transport space charge dominated beams. Currently, the machine extends to 90 degrees, or 10 half-lattice periods(HLP) with induction cores for acceleration placed on every other HLP. Full current transport with acceptable emittance growth without acceleration has been achieved [1]. Recently, a time stability measurement revealed a 2% energy change with time due to a source heating effect. Correcting for this and conducting steering experiments has ascertained the energy to an accuracy of 0.2%. In addition, the charge centroid is maintained to within 0.6-mm throughout the bend section. Initial studies of matches dependencies on beam quality indicate significant effects.

1 WHY THE RECIRCULATOR

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 [2]. 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 [3,4]. Usually the conceptual design of such a machine is linear, but an alternative concept, which may provide significant cost savings [5], 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.

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 and beam brightness must be demonstrated [6]. 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, an induction core, for acceleration and longitudinal compression, and a capacitive beam probe, or C-probe, for position monitoring. The dipole plates are designed to bend the beam by 9 degrees while the modulators are designed to accelerate the beam by 500-eV. The C-probes provide position measurements to within 100-μm.

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 μs	1 μs
Beam Current	2 mA	8 mA
Undepressed Phase Advance	78°	45°
Depressed Phase Advance	16°	12°

Figure 1 shows the current layout of the machine. Initially, a 4-μs 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 magnetic induction cores exist on 5 of the 10 HLP's as shown.

As reported earlier [1], full current transport through the 90˚ bend section was achieved with no acceleration and DC voltages (+/- 6.575-kV) on the bending dipole plates. The RMS normalized emittance,

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

for 90% of the full beam current after 90˚ was found to be below the acceptable limit for emittance growth. In the bend plane (x), the measured value is 0.045π-mm-mR while the out-of-plane (y) emittance is 0.068π-mm-mR. This compares to 0.021π-mm-mR measured directly after the source aperture.

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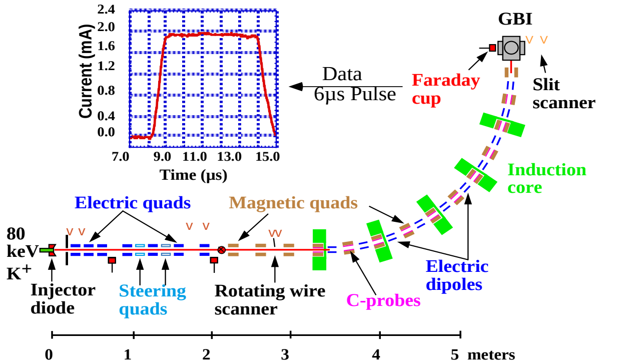

Figure 1: Current Recirculator Layout and Faraday cup data at 90 degrees.

3 TIME STABILITY

A time stability check of the C-probe signals was conducted. The accelerator was turned on and data taken at regularly time intervals. The measured y positions were stable to within the accuracy of the C-probes, but the x positions varied extensively, as much as 5 mm, before stabilizing after 6-7 hours of operation. This behavior was eventually determined to be caused by the heating of the alumino-silicate source, which operates at a temperature of 1000˚C. Even though the source is heat shielded, the temperature of capacitors around the source diode were found to increase by 40˚C, which lowers their capacitance. The lowering of this capacitance actually raises the voltage on the source diode, increasing the energy of the emerging beam. Thus, the x positions of the beam through the bend section change.

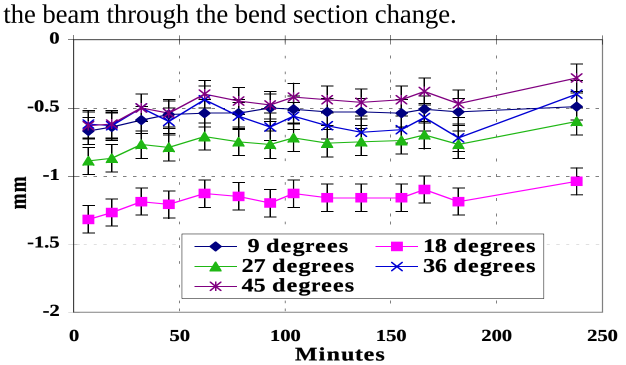

Figure 2: X Positions vs Time for different locations along the bend section (degrees of bend) after the temperature compensation amplifier was installed.

To solve this problem, a new control circuit was introduced for the source pulser power supply. A thermistor was added to the source tank to monitor the rise in temperature and put into the feedback loop of an approximately gain 1 amplifier. The amplifier modifies the DC control voltage for the power supply. As the temperature rises, the control voltage lowers, which lowers the output voltage of the power supply and compensates for the lower capacitance. Figure 2 shows the resulting x positions. With the compensation circuit, the x positions, as well as the y positions are constant in time to the accuracy of the C-probes.

4 STEERING

With the time dependence problem solved, the C-probe data clearly showed betatron motion in both x and y (see figure 3). This motion could be caused by misalignments of the source, matching section quads, straight section, or the bend section, or some combination of all four. To help ascertain the cause, steering experiments were performed using the steerers in the matching section. These steerers have the same mechanical structure as the quadrupoles, but the configuration of voltages provide dipole fields in x and y.

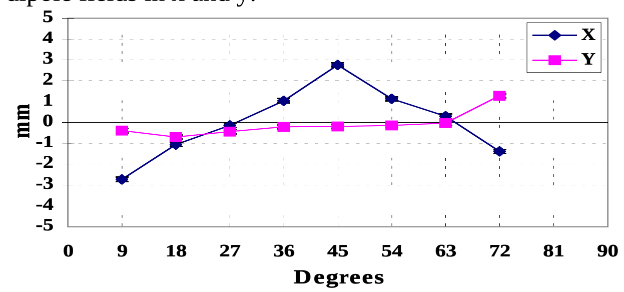

Figure 3: X and Y positions vs Bend Angle without steering.

In these experiments, it is assumed that most of the betatron amplitude arises from misalignments of the source and the quads before the first steerer, S1. First, the voltages on S1 were varied until the amplitude of the x betatron motion was minimized. This condition corresponds to the beam leaving S1 parallel to the beamline center. The amplitude of the betatron motion is the offset of the beam at S1. Then, by monitoring the C-probe approximately one betatron period, ~10 HLP's, away from the second steerer, S2, the field in S1 was increased until the beam centroid at S2 was near zero. Voltage were then applied to S2 and the strength varied until the betatron motion was minimized, which will occurs when the beam leaves S2 along the beamline center. This minimum occurs with the S1 field ~80V/cm and the S2 field ~60V/cm.

Figure 4 shows the measured x positions through the bend section with the above steering fields applied. The betatron motion is greatly reduced by applying steering voltages, which supports the assumption that most of the betatron motion is caused by misalignments of the source and of the first few quads. The betatron motion, however, does seem to grow as the beam passes through the bend section indicating the energy of the beam and the bending dipole fields are not exactly matched. The voltages on the dipole plates are know to an accuracy of 0.2% but the energy is less well known. Therefore, the energy of the beam was lowered by 0.5%, and the steering experiment was redone, with the steering fields becoming ~130V/cm in S1 and ~120V/cm in S2. The result is also plotted in figure 4. The x position of the beam now remains within 0.6-mm of the center all the way through the entire bend section.

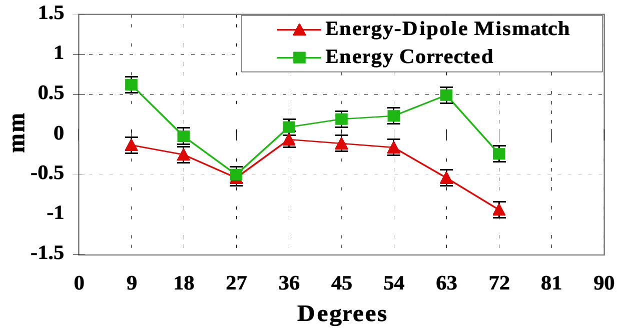

Figure 4: X positions vs Bend Angle with steering before and after energy-dipole mismatch correction.

5 MATCH SENSITIVITY

One important goal of the recirculator project is to study causes of emittance growth. One such possible cause is the matching section, which converts the uniformly diverging beam emitted from the source to the alternating focused-defocused beam needed for beam transport in the bend section. The requirement of a matched envelope in the bend section, puts four constraints on the quadrupoles strengths in the matching section. But there are seven quads in the matching section, or seven degrees of freedom. Thus, the problem of determining the matching section quadrupole strengths is an under constrained problem, with many possible solutions. But do all these solutions produce the same beam quality?

In order to answer that question, four different matches, or configurations of quadrupole strengths, were determined from solving the envelope equation numerically. The four matches are called the Unique, Best, Good, and Bad match. The Unique match, has the last three quads set to the same strength as the magnetic quadrupoles of the bend section. The Best and Good provide well matched envelopes in the bend section, but the behavior of the envelopes in the matching section is more erratic for the Good match. The Bad match does not provide a well matched envelope in the bend section and the behavior in the matching section is even more erratic than the Good match.

Table 2: Emittances (π-mm-mr) for Various Matches

Match	Q1Y defocus ε_y at matchbox	Q1Y focus ε_y at matchbox	Q1Y focus ε_x at 90˚
Unique	0.026	0.035	0.076
Best	0.025	0.039	0.065
Good	0.030	0.045	0.073
Bad	0.116	0.039	0.099

Table 2 lists the emittance for the four matches as measured by a slit scanner at the end of the matching section, right before the seventh quad. The measured emittance is in the out-of-bend plane dimension, y, and is measured for the two different polarity settings. Also shown is the in-bend plane emittance measured after the 90˚ bend section. The plot shows that only the Bad match has a significantly different emittance at the end of the matching section. However, there is some difference between the matches after the bend section. At this point the Best match has the lowest emittance value, being slightly less than the Unique and Good matches. The Bad match is still the match with the highest emittance value.

Even though the Good match has similar emittance values at the end of the matching section as the other matches, the phase space plot for the Q1Y negative polarity setting showed a unique behavior. The plot is shown in figure 5. One can clearly see a second spiral arm present in the phase space plot. As to the exact cause of this feature and why it only appears with the Good match is unclear at this time.

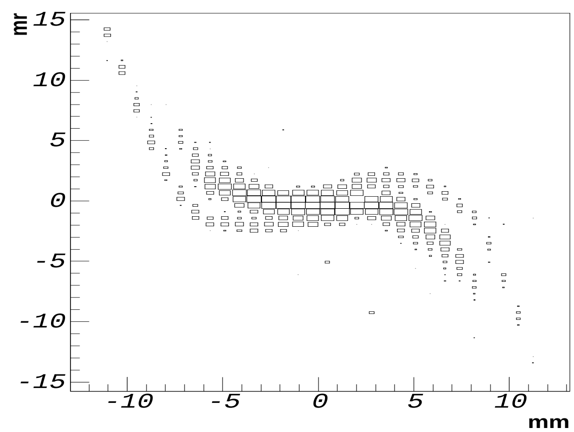

Figure 5: Phase space plot measure at end of matchbox with Q1Y defocusing and for the Good match.

6 SUMMARY

Experiments on the 90˚ bend section of the Recirculator are continuing. The beam position measurements are stable with time to the accuracy of the C-probes, beam steering experiments have made it possible to maintain the centroid position to within 0.6-mm throughout the bend section, and initial sensitivities studies of beam quality on the match has yielded significant differences. These results are all positive indications in the feasibility of recirculating space charge dominated heavy ion beams.

7 REFERENCES

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