PIC SIMULATIONS OF AN ACHROMATIC SOLENOIDAL FOCUSING SYSTEM FOR LMF*

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Abstract

The nominal 1000 MJ yield of a Laboratory Microfusion Facility (LMF) pellet requires at least a 1.5-meter radius target chamber to contain the blast. A geometry has been identified that uses an annular ion beam with a center plug, has a total transport length of 4 meters, and allows no direct line-of-sight from the target blast to the ion diode. An analytic model for an achromatic, 2-lens system that is capable of transporting a 30 MV, 1 MA Li ion beam over this distance has been developed. The system uses both self-B_θ and solenoidal magnetic lenses. The beam microdivergence requirement is minimized by locating the final solenoidal lens at the target chamber wall. We have verified the analytic model by PIC transport calculations. A realistic coil system has been designed to supply the required 2 Tesla solenoidal fields. Simulations show that a lithium beam can be transported over the 4 meter distance with better than 70% energy and power efficiency, delivering roughly 1 MJ/beam to the target if a 6 mrad microdivergence is achieved at the diode.

Introduction

The Laboratory Microfusion Facility (LMF) has been proposed for developing high gain, high yield inertial confinement fusion (ICF) targets. Sandia is studying a multimodule LMF approach based on the Hermes-III accelerator technology. As presently envisioned, each 40-TW module would produce a voltage pulse ramping from 27 to 32 MV with a peak current of 1.2 MA. Singly ionized lithium ions are accelerated in the ion diode and propagated to the target. A target chamber radius of at least 1.5 meters appears necessary to contain the 1000 MJ design yield. Using a center plug and an annular ion beam, a geometry with a 4 meter total transport distance has been identified that protects the ion diode from direct line-of-sight with the target blast. The voltage ramp allows time-of-flight (TOF) bunching of the ions over this distance. The output of several such modules would be combined to produce the desired intensity profile and total energy on target.

Achromatic Solenoidal Focusing

As discussed in a companion article[1], analysis has identified a solenoidal magnetic lens system as a possible light-ion LMF transport scheme. As part of the LMF design effort, it was deemed desirable to verify the feasibility of the solenoidal magnetic lens scheme using a particle-in-cell (PIC) transport code. The transport simulations could not only verify the analytic model, but could also ascertain the viability of the scheme for physically realizable coil designs, with beam divergence, and using time-dependent voltage and current waveforms. To accomplish these tasks we modified the existing ion transport code PICRAY[2] to perform calculations in the extraction geometry to be used in the LMF.

In Fig. 1 we show the initial transport geometry used to verify the analytic focusing model. Shown are the perfectly straight B_r and B_z contours of the finite difference approximation to the analytic magnetic field. Note that the calculation is cylindrically symmetric about the z-axis, thus the anode source is annular as are the magnetic field coils. The static simulation represented by Fig. 1 shows the expected focusing of the test ions, and thereby confirms both the parameters from the analytic theory and PICRAY's ability to properly simulate solenoidal focusing in extraction geometry.

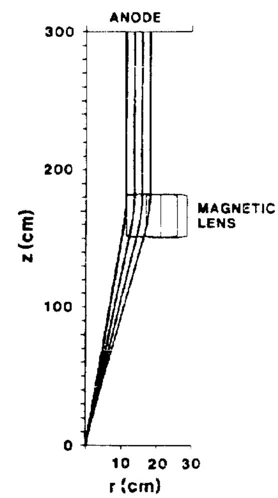

Figure 1. Sample ion trajectories for 30 MeV Li^{+3} ions (zero divergence) over a 3 meter distance using an idealized solenoidal magnetic lens. Nominal lens B_z = 19.7 kG, lens length is 30 cm. Annular ion beam: inner radius 9 cm, outer radius 18 cm. Perfect charge and current neutralization assumed over entire distance.

Realistic Magnetic Lens

The magnetic coil design code ATHETA[3], was used to produce a realistic magnetic field as shown in Fig. 2. Note that a vertical conductor has been placed half-a-coil length from either end of the coil to try to more closely approximate the field structure of an ideal lens.

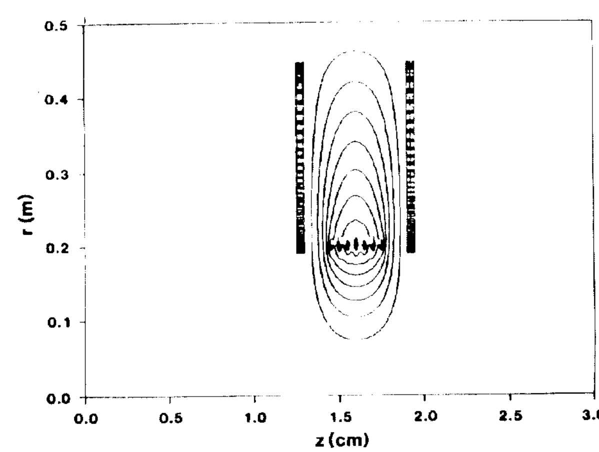

Figure 2. Contours of magnetic stream function for the real coil system as calculated using ATHETA. Note the presence of the vertical conductors to "square-off" the field and more closely approximate an ideal lens.

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Fig. 3 shows 30 MeV Li^{+3} ion trajectories using this magnetic field configuration in a more sophisticated simulation. The ion beam is uniformly injected along the top boundary of the figure between radii of 7.5 to 15 cm. The top boundary is assumed to be the location of the gas cell foil. The total propagation length from the foil to the center of the target is 3 meters. The solenoidal magnetic lens is 30 cm in length and 1.5 m from the target (to be within the first wall).

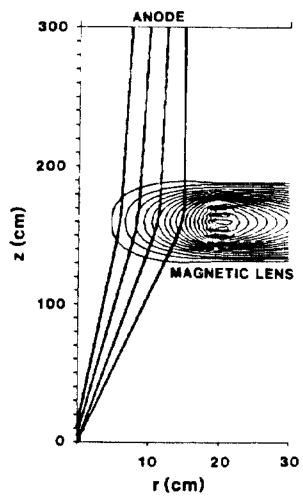

Figure 3. Sample ion trajectories for 30 MeV Li^{+3} ions over a 3 meter distance using a real magnetic lens ($<B_z>$ ~20 kG). Ion injection angles are calculated to compensate for self-B_θ bending in the diode and for the non-constant focusing strength of the lens as a function of radius.

The lithium ion beam is injected with a +3 charge state, commensurate with foil stripping equilibrium, but with an energy commensurate with acceleration in a +1 state. The initial ion injection angle is calculated to compensate for self-field magnetic bending in the diode (high current beam) as given by the analytic theory[1]. Additionally, a geometric angle is superimposed on the self-field term to help focus the inner edges of the beam where the solenoidal magnetic lens is weakest. In an actual diode these injection angles would be obtained by shaping the anode emitting surface.

Results

We have used the magnetic lens along with the self-field bending and geometric compensations discussed in the previous section to study the transport of Li^{+3} ion beams with time-dependent voltage and current waveforms appropriate for an LMF driver module. The voltage and current waveforms used in these simulations (Fig. 4.) were calculated using a circuit modeling code[4].

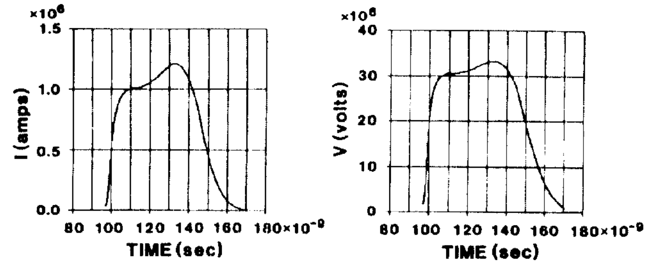

Figure 4. Voltage and current waveforms used as input to the transport calculations.

Using these waveforms, and assuming that the ion beam has zero divergence, we find that the transport scheme is capable of focusing 1.45 out of 1.57 MJ of lithium ion energy with a peak power of about 50 TW (28 ns FWHM) onto a 1 cm radius spherical target. Thus the energy transport efficiency is approximately 92%. We have also studied the effect of source divergence on the transport efficiency. We use simulations of ideal ballistic transport (a perfectly focusing diode with no self-field bending) as a standard for comparison. Table I tallies the total energy and peak power transported to a 1 cm radius spherical target as a function of total ion beam divergence.

The parenthetical numbers are the ratio of the table entry to the zero divergence ballistic value. Note that TOF bunching raises the peak power on target to about 50 TW for a diode power of only 40 TW. Importantly, we see that the performance of the solenoidal magnetic lens degrades more slowly with divergence than normal ballistic transport.

The final case that we consider is increasing the total transport distance to 4 meters with the lens-to-target distance held at 1.5 meters. Using an annular beam (7.5-15 cm radius) and a central plug, geometrically we can insure that there is no open line-of-sight from the target blast to the diode for this transport distance. Table II compares the transport results for 3 and 4 meter distances.

We see that the total energy is only degraded by about 5% in going from 3 to 4 meter total transport, but that the peak power is decreased by almost 10%. The FWHM of the power pulse is smaller (~17 ns) for the 4 meter case. The 4 meter power pulse, shown in Fig. 5, looks like a credible target-driver.

Future Work

The main caveats to be emphasized in these calculations are that we have ignored the focal effects of the insulating magnetic field in the actual ion diode by beginning these calculations at the transport cell, and we have assumed 100% current neutrality throughout the transport length.

Table I. Variation in energy and power on a 1 cm target with total ion divergence for ballistic and magnetic lens systems.

Total Divergence (mrad)	Energy on Target (MJ)		Peak Power (TW)	
	Ballistic	Lens	Ballistic	Lens
0	1.57 (1.0)	1.45 (.92)	50.8 (1.0)	51.7 (1.02)
6	0.87 (.55)	1.16 (.74)	29.3 (.58)	41.7 (.82)
8.5	0.62 (.39)	0.89 (.57)	22.2 (.44)	32.4 (.63)
12	0.46 (.29)	0.70 (.45)	18.3 (.36)	26.2 (.52)

Table II. Variation in energy and power on a 1 cm target with total divergence for 3 and 4 meter total transport distance.

Total Divergence A (TW)	Energy on Target (mrad)				Peak Power (MJ)			
	3 meter		4 meter		3 meter		4 meter	
0	1.46	(1.0)	1.46	(1.0)	51.7	(1.0)	51.2	(.99)
6	1.16	(.80)	1.09	(.75)	41.7	(.81)	37.8	(.73)

In particular, the assumption of current neutrality might break down within the strong B_r region of the solenoidal lens. In both cases we require the new capability to calculate the self-B_θ of an ion beam in extraction geometry to relax these assumptions. We will be adding this capability to PICRAY in the near future. Finally, we need to more carefully document the source divergence algorithm in PICRAY to insure that we are faithfully producing a Gaussian beam profile.

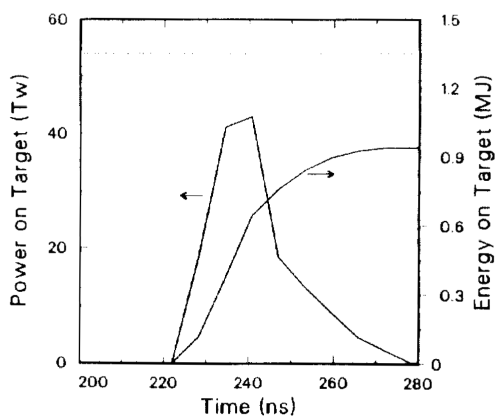

Figure 5. Power and energy as a function of time on a 2 cm diameter spherical target for a 4 meter transport distance and a 6 milliradian beam divergence. The dotted line indicates the total beam energy injected at the diode.

References

1. C. L. Olson, "Achromatic Magnetic Lens System for High Current Ion Beams," Proceedings, 1988 Linear Accelerator Conference, CEBAF, Oct. 3-7 1988, to be published.
2. J. P. Quintenz, R. S. Coats, T. A. Mehlhorn, J. E. Maenchen, and P. A. Miller, Bull. Am. Phys. Soc., 30, 1603, (1985).
3. J. P. Quintenz and D. B. Seidel, "ATHETA - A Quick Magnetic-field Solver for General Boundary Conditions," Particle Beam Fusion Progress Report, Jan-Jun 1984, SAND84-1336.
4. D. L. Johnson, "A Conceptual Design for an LMF Accelerator Module," Proceedings, 1989 Particle Accelerator Conference, March 20-23, 1989.

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