

Efficient Capture and Transport of Laser-Accelerated Carbon Ions Using Solenoid Magnets

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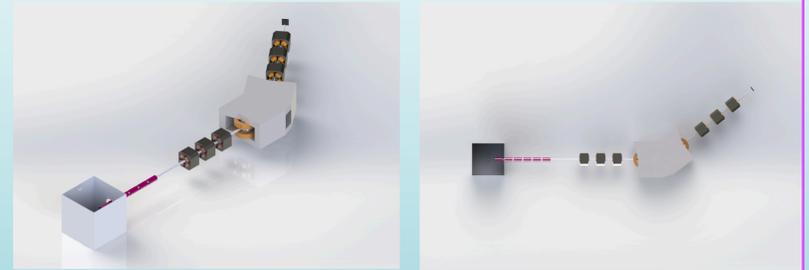
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Abstract

Hadron therapy with laser-accelerated particles is an emerging research area that introduces significant challenges for beam capture and transport due to the large divergence and broad phase space of the produced ions. Efficient collection of these particles is essential for the development of practical laser-driven therapy beamlines. In this work, the use of solenoid magnets for the capture and transport of laser-accelerated ions is investigated through particle tracking simulations. Fully stripped carbon ions with an energy of 100 MeV/u and an initial full divergence angle of 20° were modeled. A transport line consisting of six solenoids placed 200 mm downstream of the target and spaced by 50 mm was analyzed. Additional studies were performed to evaluate the influence of beam divergence and magnet geometry on the transport efficiency. Divergence angles between 10° and 40° (full angle) were considered, together with variations in the solenoid inner diameter. Simulations were also performed for a polyenergetic ion beam with energies ranging from 66 MeV/u to 100 MeV/u. The results show that the proposed configuration achieves a transmission efficiency of approximately 25% while simultaneously providing strong focusing of the beam. The resulting reduction in beam spread improves the suitability of the transported beam for downstream energy selection and beam conditioning systems. These findings indicate that compact solenoid arrays may provide an effective solution for the capture and transport of laser-accelerated ions in future laser-driven hadron therapy facilities.

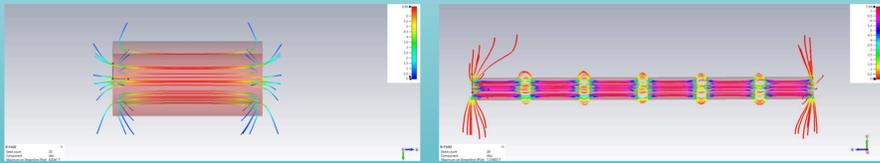
Preliminary Beamline Concept



Preliminary Beamline Design

Preliminary Beamline Design
Top View

Solenoid Design



Single Solenoid

Six Solenoid Assembly

For carbon ions at 100 MeV/u, the magnetic rigidity is $B\rho \approx 2.96$ T, indicating that strong focusing requires large integrated magnetic field strength. Each solenoid in the model was assigned 100 turns carrying 14 kA. Using the long-solenoid approximation with an effective length of 240 mm yields an on-axis field of approximately 7 T, consistent with the simulated peak field of 7.44 T when fringe-field overlap between neighboring solenoids is included.

The operating currents required for the proposed solenoid design are on the order of 14–15 kA. Such current levels are achievable using either pulsed water-cooled copper conductors or superconducting windings which require less current for the same performance.

The pulsed copper solenoid configuration is characterized by relatively low inductance per unit (613 μ H) and a moderate total inductance of 14.3 mH for the six-solenoid assembly. This allows the system to be energized rapidly, with a total charging time of approximately 1.4 s. This charging time however, makes it difficult to operate in practice requiring extremely precise synchronization with the laser pulse in order for the particles to experience the peak on axis magnetic field. The required supply current on the order of 20 kA is high but remains within the capabilities of modern pulsed-power systems. However, resistive losses in the copper windings lead to significant ohmic heating, which limits repetition rate and necessitates active cooling and careful thermal management. The increase in current requirements is due to the filling factor of the copper coils, requiring large amounts of insulation between each other as well as from the outside in order for them to be safely operated.

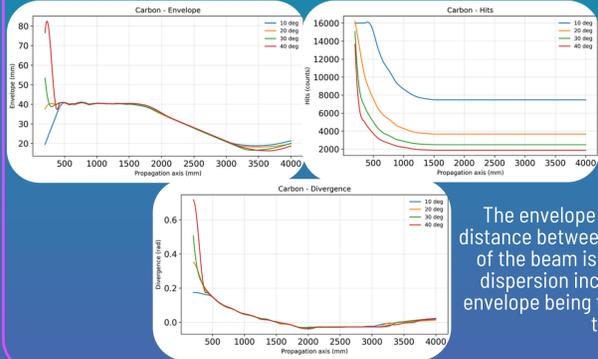
In contrast, the HTS solenoid option operates at a much lower supply current of approximately 400 A, made possible by the large number of turns and high filling factor of the superconducting coil modules. The substantially higher inductance of the HTS configuration (22.9 H total) implies slower current ramp-up and ramp-down, but this limitation is offset by the fact that they function in a continuous mode making operation in practice easier in contrast with the pulsed alternative.

From a beam dynamics perspective, both technologies provide the same focusing characteristics. This indicates that the choice between copper and HTS solenoids is primarily driven by operational considerations rather than optical constraints. Pulsed copper magnets offer simplicity, and relatively easier integration for proof-of-principle experiments, but higher upfront and operation cost, while HTS magnets provide a scalable path toward clinically relevant operation with higher duty cycles and improved long-term stability.

	Copper Pulsed Solenoid	High Temperature Superconducting Solenoid	
Inductance of 1 solenoid	613 μ H	Inductance of 1 solenoid	0.98 H
Total inductance	14.3 mH	Total inductance	22.9 H
Supply Current	20000	Supply Current	400
Total charging time	1.4 s	Continuous Operation	

Beam Simulation Results

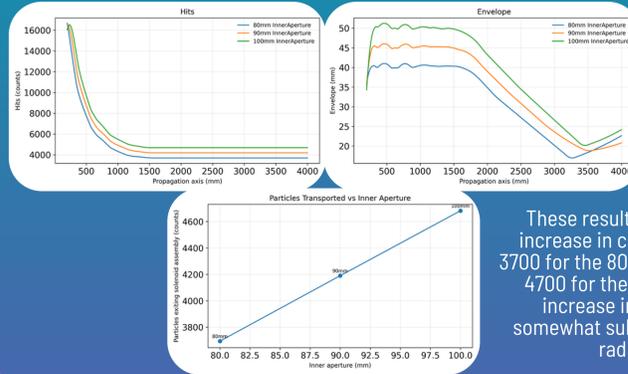
Divergence Comparison 100 MeV/u Carbon Ion Beam



In the Divergence Comparison study it can be seen that efficiency of transport drops significantly with each increase in step which is to be expected but given the region of interest, 20° full angle, the results show a 25% transmission rate using only the 6 solenoids. The best output is clearly the 10° angle which provides us with an almost 50% efficiency.

The envelope which is defined as the largest distance between an outer particle and the center of the beam is similar in results between each dispersion increment increase. With the best envelope being the one at 40° but with only ~12% transmission rate.

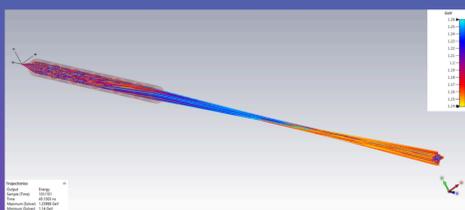
Solenoid Aperture Comparison 100 MeV/u Carbon Ion Beam



A comparison between different solenoid apertures, shows that in a similar fashion with the divergence angle, the transport efficiency grows with each increase in step (from 80 to 90 to 100 mm) while the envelope also increases with each increase in step.

These results show that while the increase in counts is minimal, from 3700 for the 80mm aperture solenoid to 4700 for the 100 mm solenoid, the increase in envelope radius is somewhat substantial, from 17.5 mm radius to 20mm.

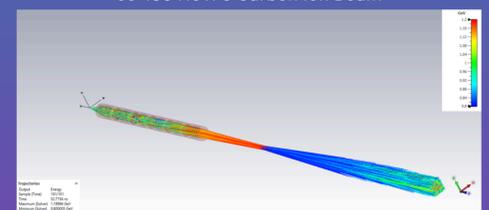
Trajectory Results 95-105 MeV/u Carbon Ion Beam



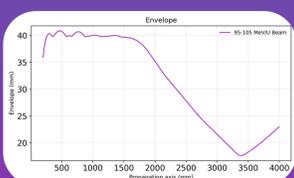
A trajectory comparison between two beams at 20° divergence but different energy ranges was also performed, with the results showing that the main envelope of the beam is larger for the 66-100 MeV/u beam. This shows that the solenoids exhibit a degree of chromaticity which is to be expected given their focusing capabilities. The transmission rate is similar in both cases, showing a 25% efficiency all around.

The spatial distribution was also plotted at the solenoid assembly entrance and at the focal spot shown by the envelope plot which is relevant information for the following magnetic components such as quadrupoles. It can be seen that the main bunch of the particles is concentrated in the middle which makes the region of interest for transport smaller than the envelope calculated.

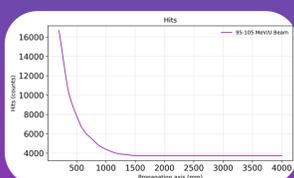
Trajectory Results 66-100 MeV/u Carbon Ion Beam



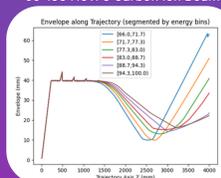
Envelope Evolution along Trajectory



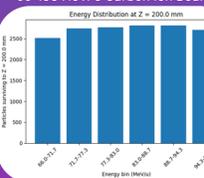
Transport Efficiency along Trajectory



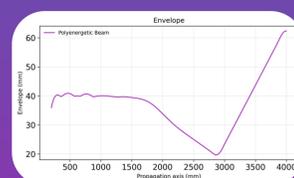
Envelope segmented by bins 66-100 MeV/u Carbon Ion Beam



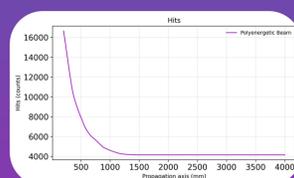
Initial Energy Distribution 66-100 MeV/u Carbon Ion Beam



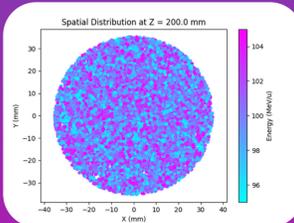
Envelope Evolution along Trajectory



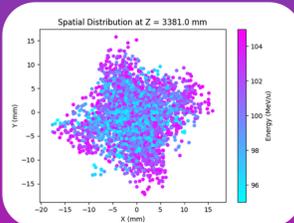
Transport Efficiency along Trajectory



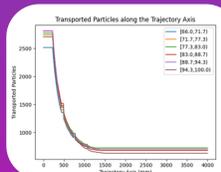
Spatial Particle Distribution at solenoid assembly entrance



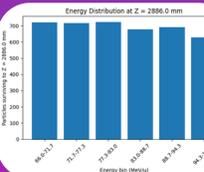
Spatial Particle Distribution at focal spot



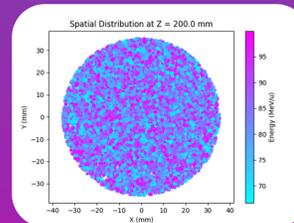
Transport segmented by bins 66-100 MeV/u Carbon Ion Beam



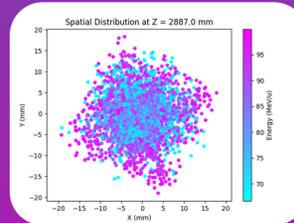
Energy Distribution at Focal Spot 66-100 MeV/u Carbon Ion Beam



Spatial Particle Distribution at solenoid assembly entrance



Spatial Particle Distribution at focal spot



Acknowledgements