LhARA Update: Source, Capture, and Stage 1 Transport

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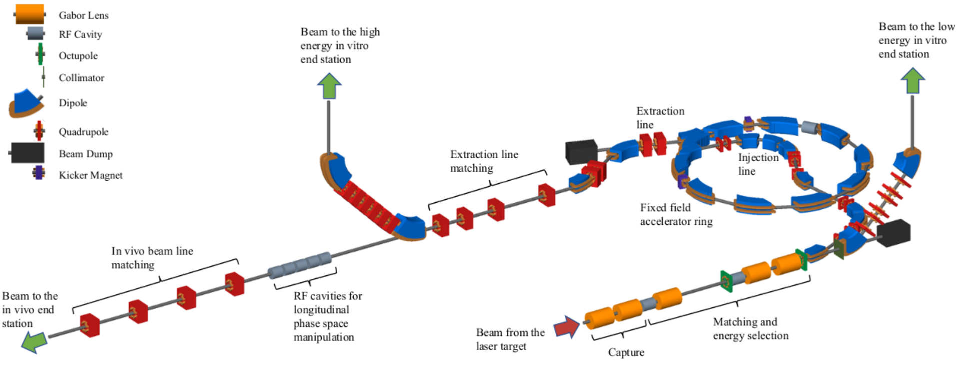
December 16, 2020

Laser-hybrid Accelerator for Radiobiological Applications (LhARA)

LhARA will be a unique facility dedicated to radiobiological research.

- Principle components:
  - Laser-driven proton and ion source.
  - Capture section with Gabor lenses.
  - Fixed field alternating gradient accelerator (FFA).
  - Two *in vitro* and one *in vivo* end station.
- Staged implementation:
  - **Stage 1: *In vitro* studies with protons up to 15 MeV.**
  - Stage 2: *In vitro* and *in vivo* studies with protons up to 127 MeV and ions up to 33 MeV/u.



Stage 1: Target Normal Sheath Acceleration (TNSA)

TNSA ion acceleration mechanism:

- Intense laser pulse ($\gg 10^{18}$ W/cm^2)
- Interaction with a solid thin foil creates a cloud of hot electrons.
- Cloud penetrates foil to the rear.
- The induced electric fields ionize and accelerate ions on the surface.

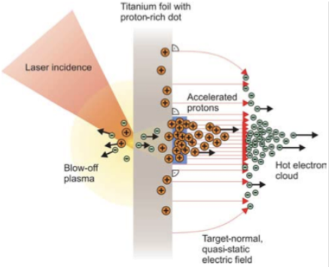


Figure: Graphic of TNSA process taken from Schwoerer [1].

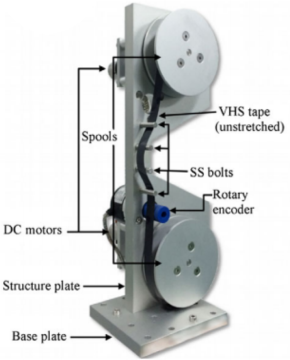


Figure: Tape drive system developed by Noaman-ul-Haq et al. [2].

- Tape drive is proposed to allow reproducible ion-flux.
- R&D to optimise design of target.

Stage 1: Gabor Lenses

- An electron cloud can be confined within a lens using a cylindrical anode within a uniform solenoid field.
- Focusing effect in both planes with a magnetic field reduced compared to a solenoid.

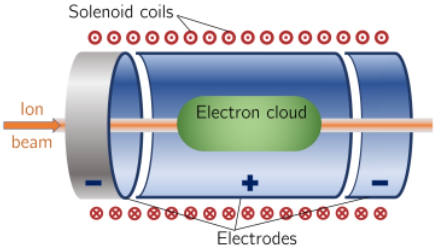


Figure: Schematic diagram of a Penning-Malmberg trap proposed for use in the Gabor lens for LhARA.

$$B_{\text{GPL}} = B_{\text{sol}} \sqrt{Z \frac{m_e}{m_{\text{ion}}}};$$

- where B_{GPL} and B_{sol} are magnetic fields in Gabor lens and solenoid,
- m_e and m_{ion} are mass of the electron and ion being focused,
- Z is charge state of ions.

LhARA Hybrid Approach

- Laser Source
  - High instantaneous flux ($> 10^9$) in a short pulse (10 ns – 40 ns).
  - Laser pulse triggered at a repetition rate of up to 10 Hz. $\Rightarrow$ Varied time structure.
  - Evade instantaneous flux limit due to space charge.
- Gabor Lens
  - Strong focusing in both planes.
  - Reduced magnetic fields compared to high-field solenoids.
- Fixed Field Alternating Gradient Accelerator (FFA)
  - Rapid cycling with repetition rates of 10 Hz – 100 Hz.
  - Compactness in size due to combined function magnets.
  - Various beam energies delivered without energy degraders.
  - Compactness with multiple ion species acceleration.

Simulation Codes for Stage 1 Tracking

Smilei

- Particle-In-Cell (PIC) code for plasma simulation.
- Generate distribution of particles.

BDSIM
Beam Delivery Simulation

- Uses Geant4 toolkit to simulate transport and particle-matter interactions.
- Propagates beam from Smilei through beam line.

GPT
General Particle Tracer

- 3D particle tracking with various 2D and 3D space charge models.
- Include space charge effects in distribution.

Ideal Beam Tracking

- An ideal Gaussian beam was tracked through the beamline.
- Plot in red and blue represents the beam tracked in MAD-X and BDSIM respectively without space charge [3].
- Plot in green represents the beam tracked in GPT [4] with the inclusion of space charge.

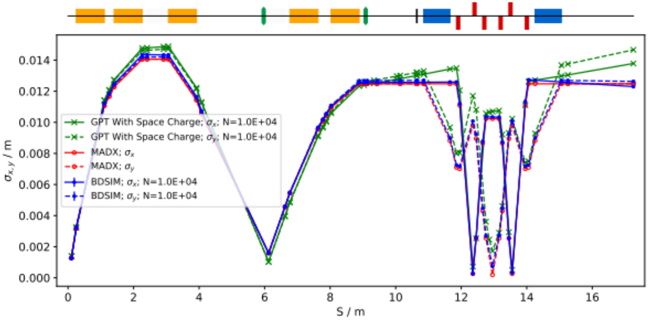
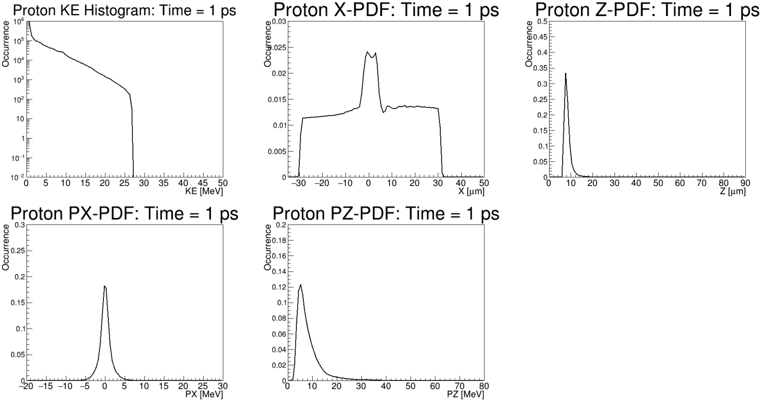


Figure: Simulation of an ideal beam evolution. Beam size plotted comparing BDSIM, MAD-X, and GPT for 10^4 macroparticles representing a full bunch charge of 10^9 protons.

Smilei Simulations

- PIC code Smilei [5] used to track particles in 2D from laser interaction.
  - Laser incident on plastic thin foil (2 micron assumed for simulation) at 45°.
  - Particles coming out rear of foil tracked.
  - Convergence testing to avoid numerical simulation effects.



Smilei Simulations

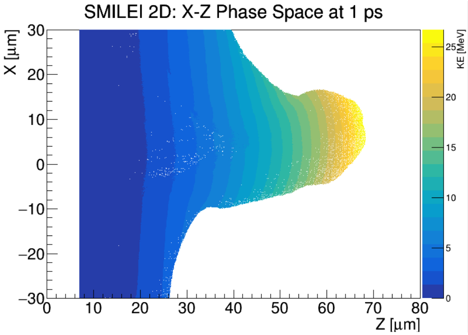


Figure: Position coordinates of protons coming out back of foil after 1 ps, colour corresponds to kinetic energy.

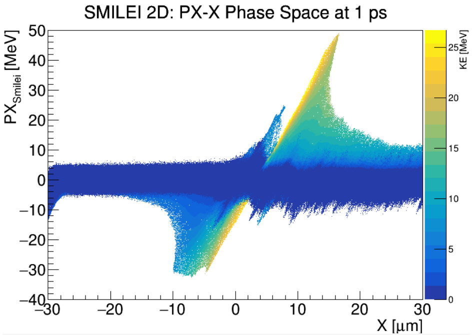
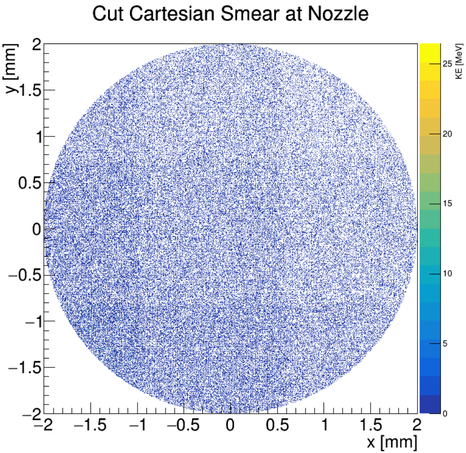


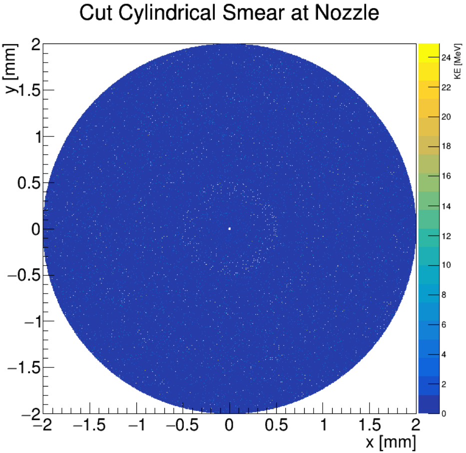
Figure: Transverse phase space of protons coming out back of foil after 1 ps, colour corresponds to kinetic energy.

- Highest energy protons correspond to travelling furthest longitudinally.
  - Higher energies than expected are observed in simulation.
- Higher energy protons come off at an angle due to incident angle of laser.
  - Transverse momentum similarly not centred at zero, which will lead to losses if uncorrected.

Smearing Third Dimension

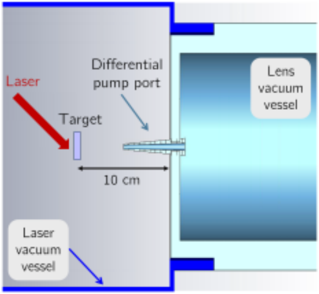
- Extend 2D simulations to 3D particle tracking.
  - One method is to assume the same shaped distribution. (Cartesian Smear)
  - Another method is assuming a cylindrical geometry and rotate distribution. (Cylindrical Smear)

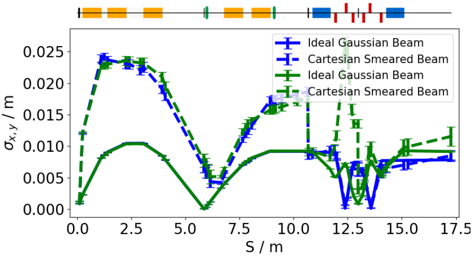




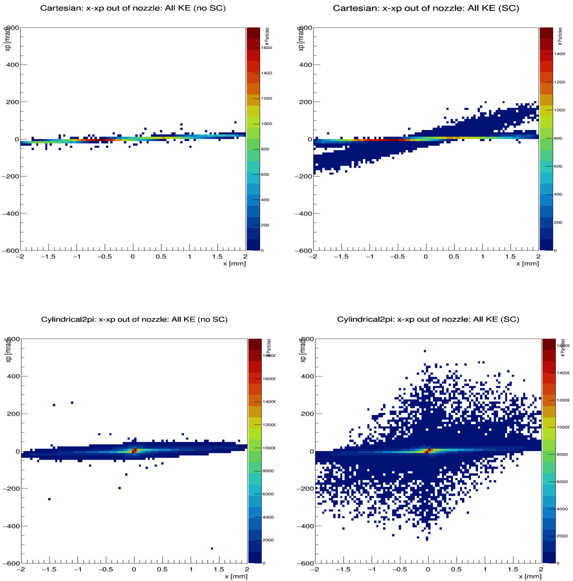
Beamline tracking

- The resulting distribution will then be used as an input for further beam line simulations:
  - Beam tracked for 5 cm in vacuum to a nozzle which collimates beam with BDSIM [3].
  - Output is input to GPT [4] to include the effects of space charge.
  - Beam then tracked through the rest of the beam line in BDSIM.



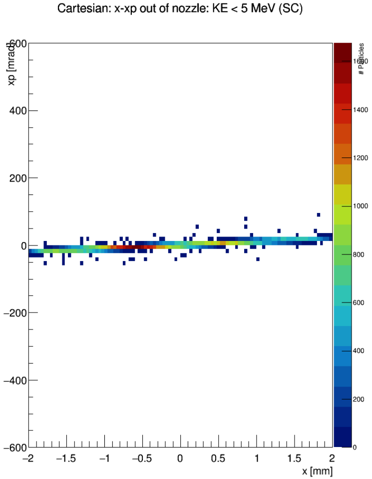


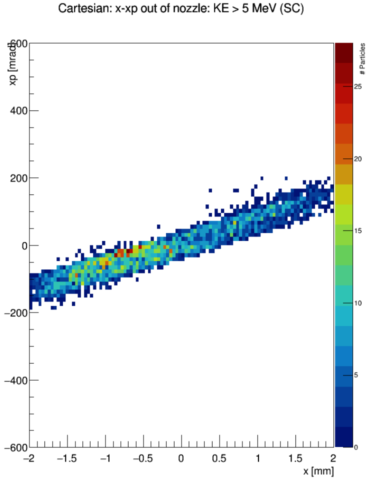
Effect of Space Charge (Transverse Phase Space)



- Preliminary result.
- Separate bands in the transverse phase space when space charge included.

Cartesian smeared beam (similarly can be seen in Cylindrical beam):

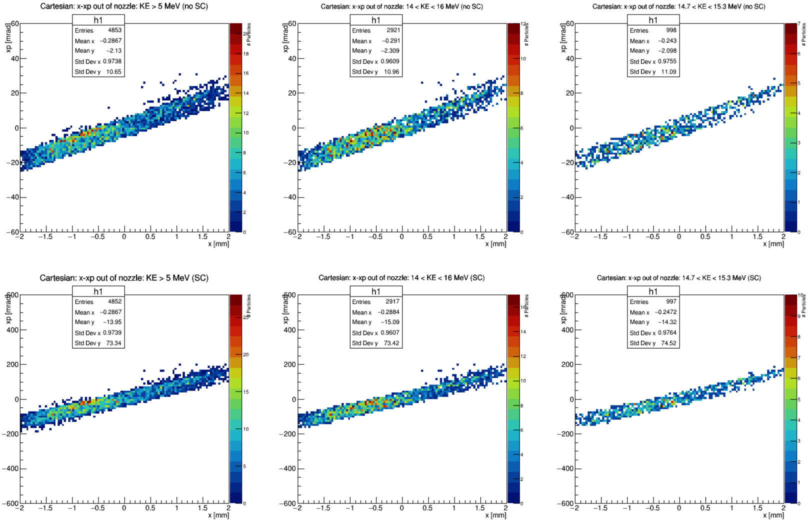




Effect of Space Charge (Transverse Phase Space)

High energy protons are spread out within this band.

- To be looked into.



Conclusion

- Preliminary end-to-end tracking of proton beam from laser target to end station.
  - Realistic beam appears quite different to the idealised beam.
- Future work:
  - Refine the smearing/sampling method.
  - Reoptimise the magnet strengths for capture and transport.
  - Analysis of other particles (i.e. electrons).

Thank you!

References

[1] H. Schwoerer *et al.*, “Laser-plasma acceleration of quasi-monoenergetic protons from microstructured targets.,” *Nature*, vol. 439, pp. 445 – 448, 2006.

[2] M. Noaman-ul Haq, H. Ahmed, T. Sokollik, L. Yu, Z. Liu, X. Yuan, F. Yuan, M. Mirzaie, X. Ge, L. Chen, and J. Zhang, “Statistical analysis of laser driven protons using a high-repetition-rate tape drive target system,” *Phys. Rev. Accel. Beams*, vol. 20, p. 041301, Apr 2017.

[3] L. J. Nevay *et al.*, “Bdsim: An accelerator tracking code with particle-matter interactions,” *Computer Physics Communications*, p. 107200, 2020.

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