Progress on Tracking Simulations for the Laser-hybrid Accelerator for Radiobiological Applications (LhARA)

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Radiotherapy: Motivation

- Cancer is the second leading cause of death globally as given by the WHO.
- Radiotherapy is a well established method of treatment.
  - Most treatments use beams of X-rays.
  - Recent years make use of beams of protons which have the advantage of the Bragg peak.

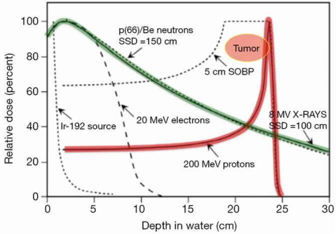

Figure: Schematic of dose distribution for various radiations. Figure taken from Giap et al. [1].

- The future will see a rise in the number of new cancer cases requiring:
  - Development of novel techniques (such as ”FLASH”).
  - Cost-effective system.
  - Improvement in the understanding of radiobiology.

Radiobiology

- Treatment planning is based on the ‘Relative Biological Effectiveness’ (RBE).
    - Ratio of dose to produce the same biological response as with photons.
    - Dependent on many factors including: energy, ion species, dose, dose rate, tissue type, and biological endpoint.
    - Proton treatments are planned with an assumption that RBE = 1.1

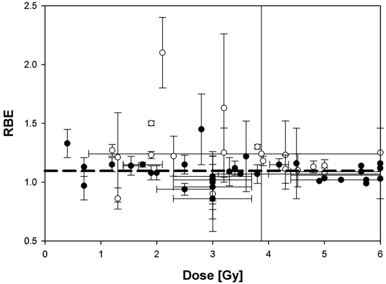

Figure: Paganetti et al. [2] experimental proton RBE values as a function of dose. Measurements *in vitro* are open circles and *in vivo* are closed circles.

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.

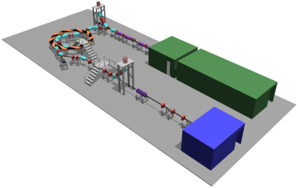

Figure: Schematic design of the LhARA facility. [3].

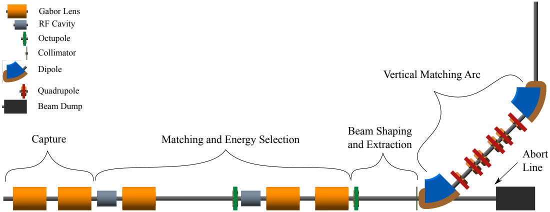

Figure: Schematic diagram of the stage 1 beam line.

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. ⇒ 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.

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.

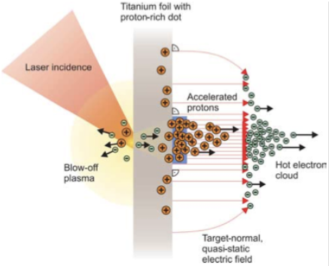

Figure: Graphic of TNSA process taken from Schwoerer [4].

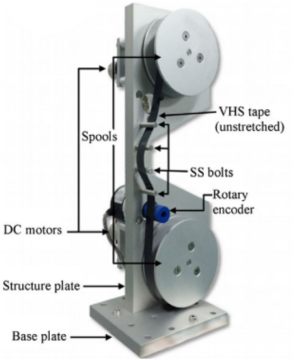

Figure: Tape drive system developed by Noaman-ul-Haq et al. [5].

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

Stage 1: Gabor Lenses

- Focusing a charged particle beam with an electron cloud was first proposed by Gabor in 1947 [6].
- 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.

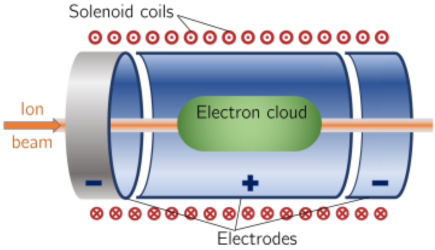

Figure: Schematic diagram of a Penning-Malmberg trap proposed for use in the Gabor lens for LhARA.

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

- 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.

Ideal Beam Tracking

- An ideal Gaussian beam was assumed for the design of the beam line.
- Plot in red and blue represents the beam tracked in MAD-X and BDSIM respectively without space charge [7].
- Plot in green represents the beam tracked in GPT [8] with the inclusion of space charge.

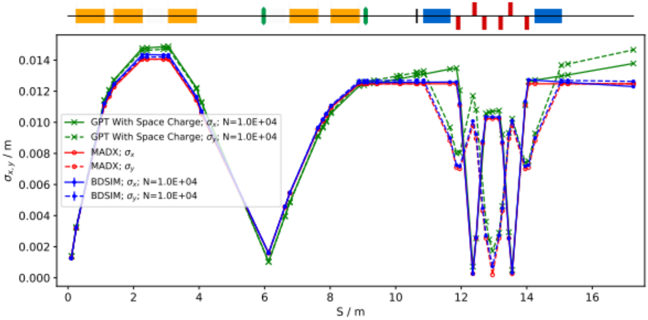

Figure: Simulation of an ideal beam evolution. Beam size plotted comparing BDSIM, MAD-X, and GPT for 10^4 macroparticles representing a full bunch charge of 10^9 protons.

Smilei Simulations

- PIC code Smilei [9] used to track particles in 2D from laser interaction.
  - Laser incident on plastic thin foil at 45°.
  - Particles coming out rear of foil tracked.
  - Convergence testing to avoid numerical simulation effects.

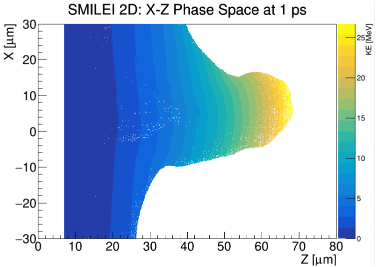

Figure: Position coordinates of protons coming out back of foil after 1 ps, colour corresponds to kinetic energy.

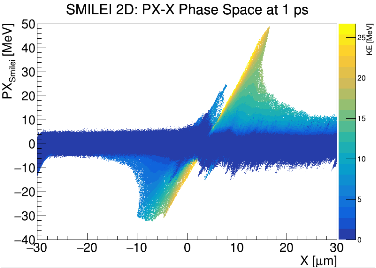

Figure: Transverse phase space of protons coming out back of foil after 1 ps, colour corresponds to kinetic energy.

- 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.

Smearing Third Dimension and Beam Line Tracking

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

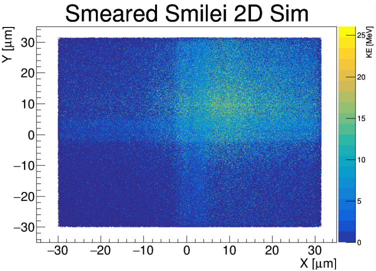

Figure: Position space of smeared distribution.

- 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 [7].
  - Output is input to GPT [8] to include the effects of space charge.
  - Beam then tracked through the rest of the beam line in BDSIM.

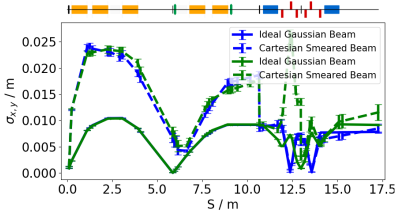

Figure: Preliminary comparison of particle tracking through stage 1 beam line.

Gabor Lens Prototype and Simulation

- A prototype Gabor lens was tested with 1 MeV protons at Surrey Ion Beam Centre
  - Unexpected ring-like patterns were observed

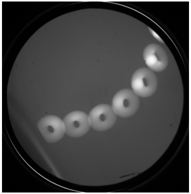

Figure: Camera image of six beam spots captured at a phosphor screen 67 cm downstream of the prototype Gabor lens.

- Simulations with VSim [10] show instabilities appear in the lens due to the initial electron cloud distribution.
  - Ring spots produced by instabilities:
    - Rotation of a plasma column around central axis of lens
    - Electron density with negative radial gradient
    - Offset between plasma centroid and beam axis

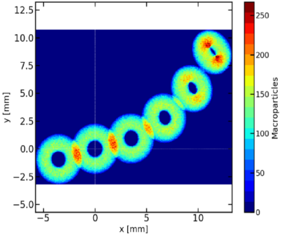

Figure: Plot of proton macroparticles hitting screen for a rotating electron plasma.

Published Papers

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The Laser-hybrid Accelerator for Radiobiological Applications

The LhARA collaboration

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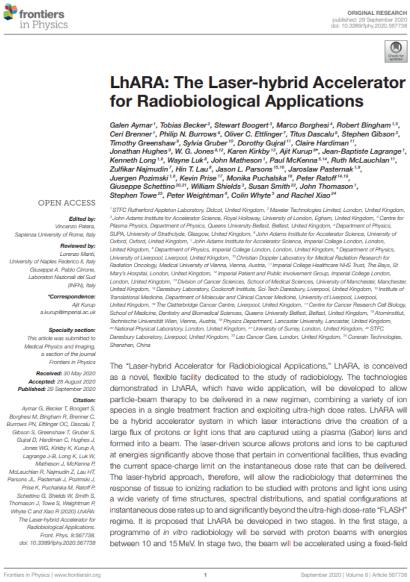

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LhARA: The Laser-hybrid Accelerator for Radiobiological Applications

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The "Laser-hybrid Accelerator for Radiobiological Applications," LhARA, is conceived as a novel, flexible facility dedicated to the study of radiobiology. The technologies demonstrated in LhARA, which have wide application, will be developed to allow particle-beam therapy to be delivered in a new regimen, combining a variety of ion species in a single treatment fraction and exploiting ultra-high dose rates. LhARA will be a hybrid accelerator system in which laser interactions drive the creation of a large flux of protons or light ions that are captured using a plasma (Gabor) lens and formed into a beam. The laser-driven source allows protons and ions to be captured at energies significantly above those that pertain in conventional facilities, thus evading the current space-charge limit on the instantaneous dose rate that can be delivered. The laser-hybrid approach, therefore, will allow the radiobiology that determines the response of tissue to ionizing radiation to be studied with protons and light ions using a wide variety of time structures, spectral distributions, and spatial configurations at instantaneous dose rates up to and significantly beyond the ultra-high dose-rate "FLASH" regime. It is proposed that LhARA be developed in two stages. In the first stage, a programme of *in vitro* radiobiology will be served with proton beams with energies between 10 and 15 MeV. In stage two, the beam will be accelerated using a fixed-field

Conclusion

- LhARA provides opportunity to both develop and prove novel systems and technologies.
- R&D effort ongoing which includes:
  - End-to-end simulation of a beam from laser target to end station.
  - Evaluation of the stability of the Gabor lens with PIC code.

The LhARA consortium

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