

Second Beam Test and Numerical Investigation of the Imperial College Plasma (Gabor) Lens Prototype

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1. Introduction – LhARA

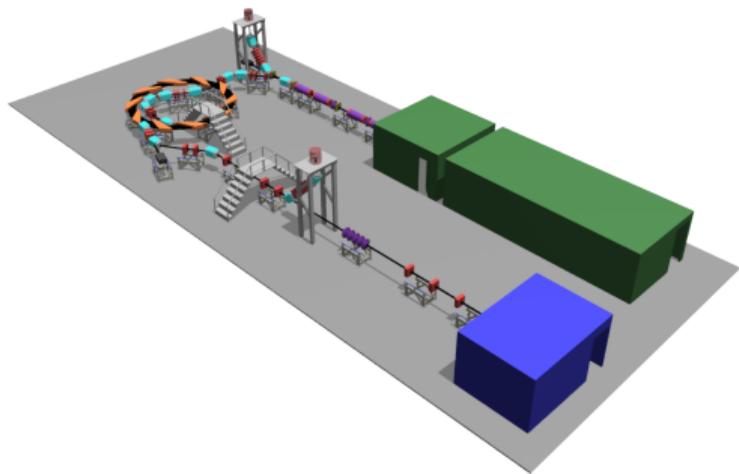


Fig. 1: The LhARA facility concept [1]

- ▶ Need for **systematic studies of the interaction** between ion beams and cancer cells
 - ▷ **develop better treatments**
- ▶ LhARA aims to deliver PBT in a new regimen:
 - ▷ **multiple ion species** in a single treatment fraction
 - ▷ **ultra-high dose rates**
 - ▷ a variety of time structures, spectral distributions, and spatial configurations

2. Gabor lens

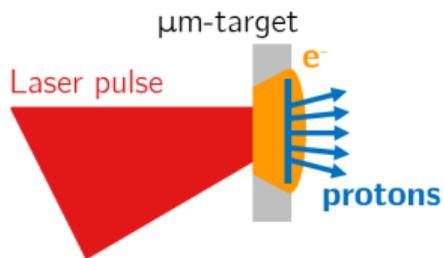


Fig. 2: A high-power pulsed laser drives the creation of a large flux of protons or light ions.

- ▶ **Strong-focusing** Gabor lenses **capture** the protons and ions by an electron cloud.
- ▶ Particles captured at energies significantly above those that pertain in conventional facilities.
- ▶ Evade the limits on the instantaneous dose rates.

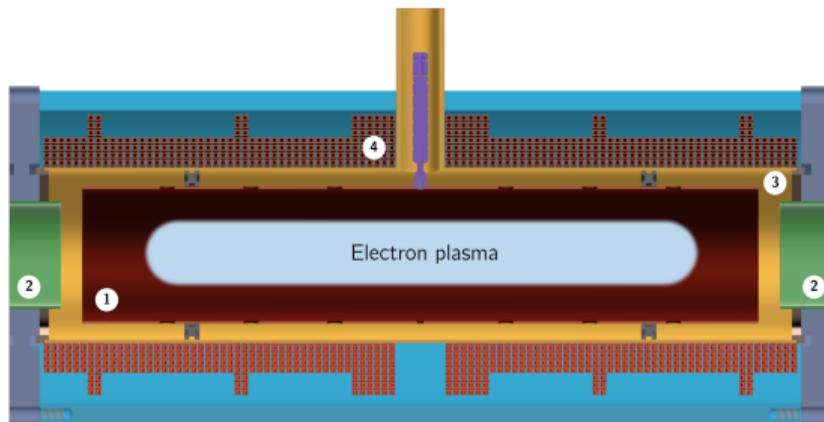


Fig. 3: The main components of the Gabor lens prototype built at Imperial (1–central anode, 2–end electrodes, 3–vacuum tube, 4–pancake coils) [4]

- ▶ Higher focusing strength for higher plasma density
- ▶ Greatly reduced magnetic field compared to a solenoid

$$\begin{array}{l} V_{\text{anode}} \quad 8\text{--}20 \text{ kV} \\ B_{\text{GL}} \quad \leq 55 \text{ mT} \\ n_e \sim 5 \times 10^{-7} \text{ Cm}^{-3} \end{array}$$

$$\frac{B_{\text{GL}}}{B_{\text{sol}}} = \sqrt{\frac{m_e}{m_{\text{ion}}}}$$

3. Beam test setup

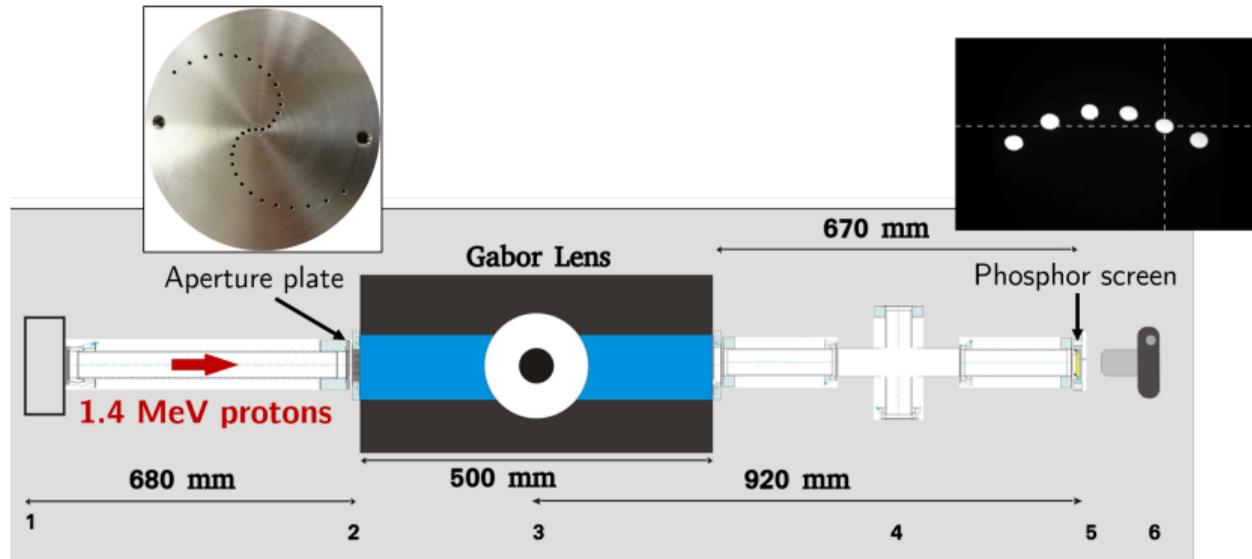


Fig. 4: Schematic of the beam test setup with the Gabor lens exposed to a proton beam at the Surrey Ion Beam Centre in 2017.

- ▶ High voltage and current settings that produced **stable plasma** identified previously at Imperial
- ▶ $r = 1 \text{ mm}$ **pencil beams** imaged downstream of the lens in 2 consecutive days

4. Beam test results

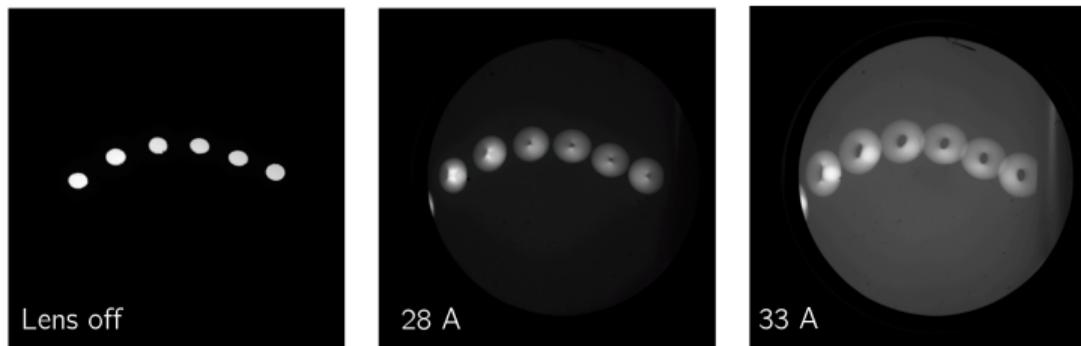


Fig. 5: Camera image of the six beam spots with the current through the coils of 0 A, 28 A, and 33 A.

- ▶ Pencil beam focused into **rings** with **non-uniform intensity**
- ▶ Ring diameter and eccentricity increases away from the beam axis
- ▶ **Focusing strength increases** for higher current through the coil
- ▶ Rings observed **consistently** throughout experiment
 - ▷ Plasma motion is a characteristic of the geometry and operation of the lens.
- ▶ Similar circular structure observed in experiment elsewhere [2]

**coherent
off-axis rotation
of the plasma**

5. Characterisation of lens performance

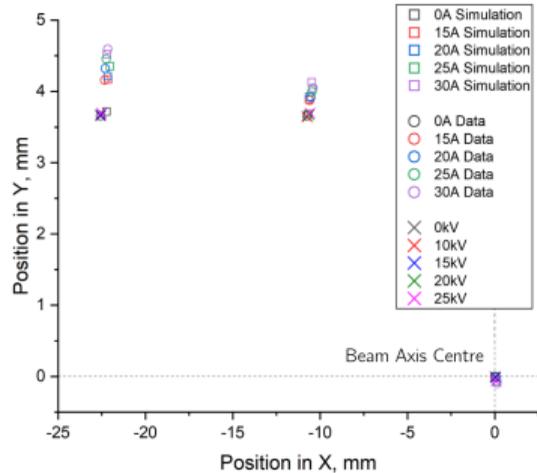


Fig. 6: Position of the centroid of 3 beam spots for varying magnetic field and anode voltages.

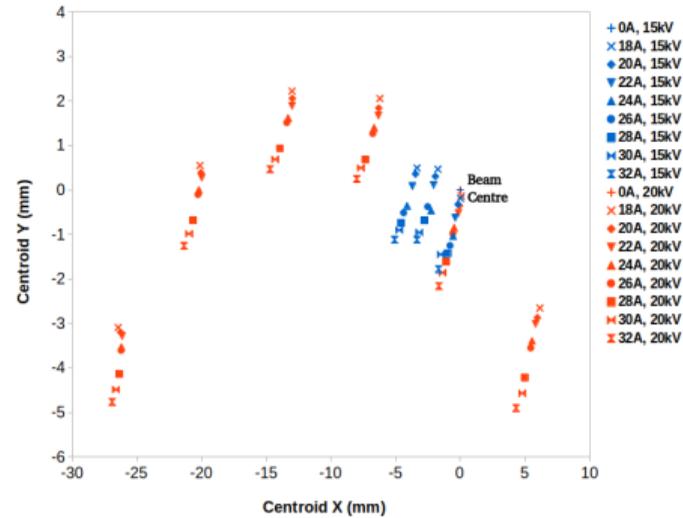
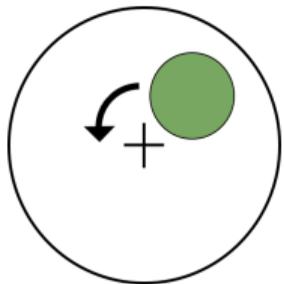


Fig. 7: Position of the centroid of two sets of beam spots with increasing magnetic field strength. The 3 spots (blue) and 6 spots (red) measurements were taken in consecutive days.

- ▶ Correlation between focusing strength, electron density, and magnetic field strength confirmed
 - ▷ Indicates the presence of a plasma.
- ▶ Additional focusing force observed separate from the plasma rotation

6. Particle-tracking simulation

Fig. 8: Schematic representation of the $m = 1$ plasma diocotron mode viewed along the axis of the lens.



- ▶ **Uniform** plasma column, radially displaced
- ▶ Radial image charge field causes an $E \times B$ drift of the plasma in the $\hat{\theta}$ direction
- ▶ Proton tracked through time-dependent electric field map in BDSIM [3]
 - ▷ Ring-like structure reproduced
- ▶ Separation and width of rings seen to vary with electron density
- ▶ Intensity modulation changes with the rotation frequency of the plasma column

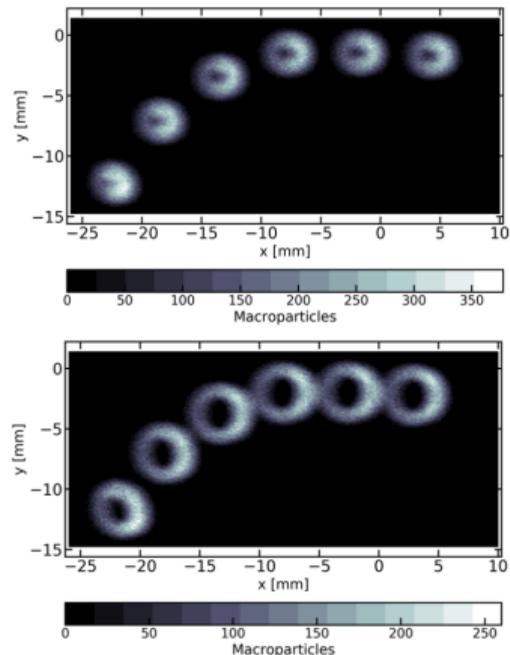


Fig. 9: Six pencil beams focused by a rotating uniform plasma column as simulated with BDSIM [3] for electron densities $n_e = 1.8 \times 10^{14} \text{ m}^{-3}$ (top) and $n_e = 2.8 \times 10^{14} \text{ m}^{-3}$ (bottom).

7. Conclusions

- ▶ A Gabor lens prototype was built at Imperial College and a regime where a plasma is present was identified.
- ▶ The lens was tested at the Surrey Ion Beam Centre with 1.4 MeV protons.
- ▶ The lens was observed to transform pencil beams into rings.
- ▶ Focusing strength varied non-linearly with the magnetic field strength – it shows a variable plasma trapping efficiency.
- ▶ Particle transport simulations
 - ▷ confirm the presence of a plasma
 - ▷ indicate the plasma was excited into a coherent off-axis rotation
- ▶ For the lens to be a reliable focusing device, the driving mechanism causing the rotation of the plasma needs to be identified and suppressed.

8. References

- [1] G. Aymar et al. LhARA: The Laser-hybrid Accelerator for Radiobiological Applications. *Frontiers in Physics*, 8:432, 2020.
- [2] U. Neuner, R. Bock, M. Roth, P. Spiller, C. Constantin, U. N. Funk, M. Geissel, S. Hakuli, D. H. H. Hoffmann, J. Jacoby, A. Kozyreva, N. A. Tahir, S. Udrea, D. Varentsov, and A. Tauschwitz. Shaping of intense ion beams into hollow cylindrical form. *Phys. Rev. Lett.*, 85:4518–4521, Nov 2000.
- [3] L. J. Nevay et al. Bdsim: An accelerator tracking code with particle-matter interactions. *Comput. Phys. Commun.*, page 107200, 2020.
- [4] T. Nonnenmacher, T. S. Dascalu, R. Bingham, C. L. Cheung, H. T. Lau, K. R. Long, J. Pozimski, and C. Whyte. Anomalous beam transport through Gabor (plasma) lens prototype. 4 2021.