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

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1. Introduction – LhARA

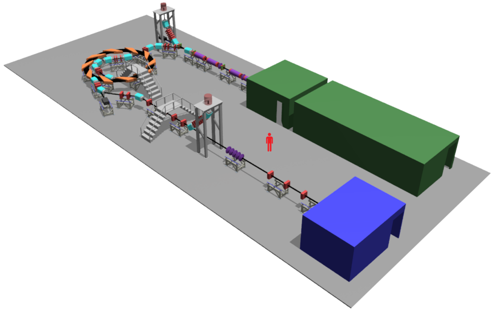


Fig. 1: The LhARA facility concept [1]

- Need for **systematic studies of the interaction** between ion beams and cancer cells
  - **develop better treatments**
- LhARA aims to deliver proton beam therapy in a **new regimen**:
  - variety of **different ion species**
  - at **high** and **ultra-high dose rates**
  - variety of time structures, spectral distributions, and spatial configurations

2. Gabor lens

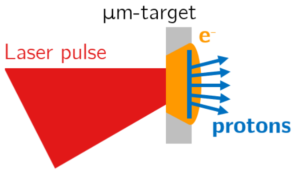


Fig. 2: A high-power pulsed laser drives the creation of a large flux of protons or light ions.

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

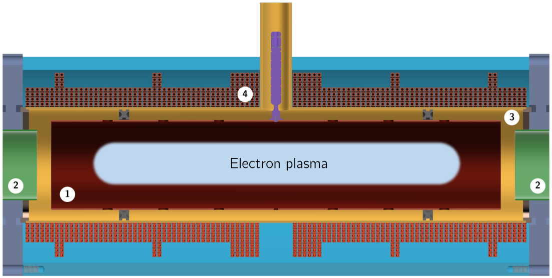


Fig. 3: The main components of the Gabor lens prototype built at Imperial (1–central anode, 2–end electrodes, 3–vacuum tube, 4–pancake coils) [5]

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

V_{anode}	8–20 kV
B_{GL}	$\leq$ 55 mT
n_e	$\sim 5 \times 10^{-7}\,\mathrm{Cm}^{-3}$

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

3. Beam test setup

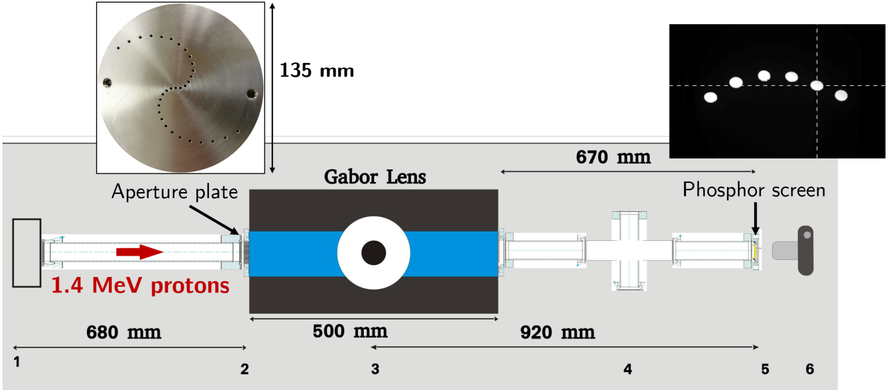


Fig. 4: Schematic of the beam test setup with the Gabor lens exposed to a proton beam at the Surrey Ion Beam Centre in 2017.

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

4. Beam test results

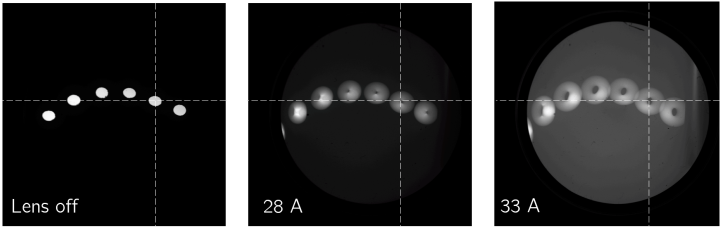


Fig. 5: Camera image of the six beam spots with the current through the coils of 0 A, 28 A, and 33 A.

- 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 [3]

coherent
off-axis rotation
of the plasma

5. Characterisation of lens performance

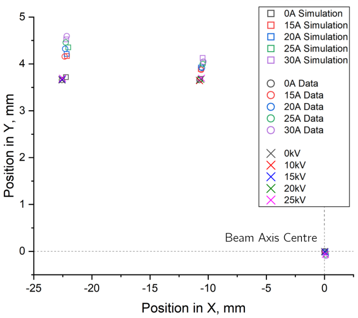


Fig. 6: Position of the centroid of 3 beam spots for varying magnetic field and anode voltages.

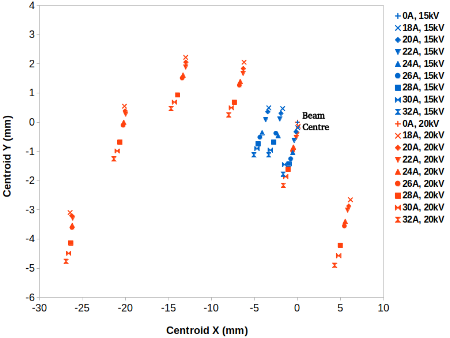
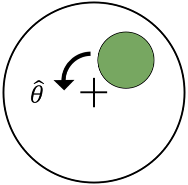


Fig. 7: Position of the centroid of two sets of beam spots with increasing magnetic field strength. The 3 spots (blue) and 6 spots (red) measurements were taken on consecutive days.

- 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**×**B** drift of the plasma in the $\hat{\theta}$ direction [2]
- Proton tracked through time-dependent electric field map in BDSIM [4]
  - 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

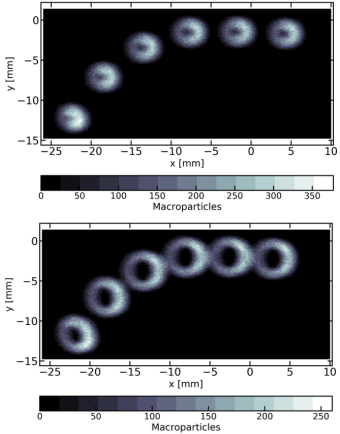


Fig. 9: Six pencil beams focused by a rotating uniform plasma column as simulated with BDSIM [4] for electron densities $n_e = 1.8 \times 10^{14}\ \mathrm{m}^{-3}$ (top) and $n_e = 2.8 \times 10^{14}\ \mathrm{m}^{-3}$ (bottom).

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 intro 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] K. S. Fine and C. F. Driscoll. The finite length diocotron mode. *Physics of Plasmas*, 5(3):601–607, 1998.

[3] U. Neuner et al. Shaping of intense ion beams into hollow cylindrical form. *Phys. Rev. Lett.*, 85:4518–4521, Nov 2000.

[4] L. J. Nevay et al. Bdsim: An accelerator tracking code with particle-matter interactions. *Comput. Phys. Commun.*, page 107200, 2020.

[5] T. Nonnenmacher, T.-S. Dascalu, R. Bingham, C. L. Cheung, H.-T. Lau, K. Long, J. Pozimski, and C. Whyte. Anomalous beam transport through Gabor (plasma) lens prototype. *Applied Sciences*, 11(10), 2021.