SECOND BEAM TEST AND NUMERICAL INVESTIGATION OF THE IMPERIAL COLLEGE PLASMA (GABOR) LENS PROTOTYPE

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Abstract

The design of the ‘Laser-hybrid Accelerator for Radiobiological Applications’ (LhARA) is based on a series of plasma lenses to capture, focus, and select the energy of the ions produced in the laser-target interaction. A second beam test of the first plasma lens prototype, built at the Imperial College London, took place in October 2017 at the Ion Beam Centre of the University of Surrey. 1.4 MeV proton pencil beams were imaged 0.67 m downstream of the lens on a scintillator screen over a wide range of settings. On top of the focussing effect, the electron plasma converted pencil beams into rings. The intensity of each ring shows a different degree of modulation along its circumference. Analysis of the results indicates non-uniformity and an off-axis rotation of the electron plasma.

The effect on the beam is presented and compared to results of a simulation of the plasma dynamics and proton beam transport through the lens. A particle-tracking code was used to study the impact of plasma instabilities on the focusing forces produced by the lens. The $m = 1$ diocotron instability was associated with the formation of rings from the pencil beams.

INTRODUCTION

Recent developments in laser-drive proton and ion sources offer a unique possibility to provide beams for radiobiology research. By capturing the laser-driven ions at energies two orders of magnitude greater than those pertaining to conventional sources, it will be possible to evade the current space-charge limit on the instantaneous proton and ion flux that can be delivered.

An attractive approach to providing the strong-focusing element required to capture the low-energy (~15 MeV) ion flux produced in the laser-target interaction is to exploit the strong focusing forces that can be provided by a cloud of electrons. Such an space-charge lens was initially proposed by Gabor in 1947 [1]. The lens is based on a configuration of high-voltage electrodes to confine the electron plasma longitudinally and a uniform axial magnetic field to confine the electrons radially. The resulting focal length is inversely proportional to the magnetic field strength squared [1].

In addition to the compact footprint and low cost, a space-charge lens has the potential to decrease the magnetic field required in the first focusing element near the source by a factor of more than 40 compared with that required for a conventional beam-capture solenoid of the same focusing strength [2]. Furthermore, it has been shown in simulation that a Gabor-lens-based system is capable of capturing laser-generated proton beams at energies as high as 250 MeV, the energy required to serve a proton-beam therapy facility [3].

The lens prototype constructed at Imperial College London (ICL) is part of the R&D work of LhARA collaboration [4]. The conceptual design for LhARA calls for five Gabor lenses to capture and focus the beam, and to provide an energy-selection system. A schematic of the prototype lens is shown in Fig. 1. The principal parameters are given in Table 1.

![Figure 1: Internal structure of the ICL Gabor lens (longitudinal cross-section). The main components are: 1-central anode, 2-end electrodes, 3-end flanges, 4-vacuum tube, 5-pancake coils, 6-outer tube, 7-high-voltage feed-through.](image)

Table 1: ICL Gabor Lens Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Anode length</td>
<td>444 mm</td>
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<tr>
<td>Anode inner diameter</td>
<td>85 mm</td>
</tr>
<tr>
<td>End electrode diameter</td>
<td>67 mm</td>
</tr>
<tr>
<td>Anode voltage</td>
<td>8–20 kV</td>
</tr>
<tr>
<td>Max. magnetic field strength</td>
<td>55 mT</td>
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EXPERIMENTAL SET-UP

The prototype lens was exposed to 1.4 MeV protons at the Surrey Ion Beam Centre in October 2017. Figure 2 shows a schematic diagram of one of the two setups used in the beam test. Upstream of the lens, narrow “beamlets” were created using an aperture plate with 30 holes of 1 mm radius drilled in a symmetrical pattern around the central axis. The “beamlets” were imaged downstream of the lens on a...
scintillator screen made out of a P43 phosphor surface on an aluminised pyrex substrate with an effective area of diameter 44.9 mm and a thickness of 10–15 µm. Photographs of the phosphor screen were acquired with a DSLR camera using an exposure long compared to the beam spill.

Figure 2: Schematic of the day 2 beam test setup. A different setup with a beam pipe of only 380 mm upstream of the lens was used in day 1 of the beam test.

Plasma was established in the lens by increasing the high voltage applied to the anode and the current in the magnetic coils. A significant increase in pressure from \( \sim 3 \times 10^{-7} \) mbar to \( \sim 3 \times 10^{-5} \) mbar was observed when a stable plasma was first established in the lens. Simulation of the plasma discharge within the lens indicated that a high electron density, \( \sim 5 \times 10^{-7} \) C m\(^{-3}\), was produced.

To identify the regime for which a stable plasma could be produced, a detector was used to measure the current of ions and electrons discharged by the lens [5]. The presence of a stable plasma in the lens was indicated by a steady voltage read from the detector. Plasma instability was observed at high voltages characterised by sparking and extreme variation in the reading of the detector as shown in Fig. 3.

Figure 4: Camera image of the 6 beam spots beyond the aperture with a lens voltage of 20 kV and a current through the coils of 0 A, 28 A, and 33 A. The dashed lines indicate the beam axis.

Figure 5 shows that the focusing strength is a function of the magnetic field strength and is independent of the current through the coil, as expected. Comparison with results of particle transport calculations shows good agreement in direction as well as in magnitude.

Figure 6 shows that, in addition to the circular motion of the plasma in the lens, there is a focusing force that increases with the external magnetic field. A possible cause for this effect is a misalignment between the beam axis and the axis.
of rotation of the plasma. The focusing strength varied non-linearly with the magnetic field showing a variable plasma-trapping efficiency. The diameters and the eccentricity of the rings were seen to depend on their position with respect to the central beam axis, as a result of the different \( x \) and \( y \) focusing forces experienced by each pencil beam.

![Figure 6: The \( x \) and \( y \) position of the centroids of the beam spots imaged with the Setup 1 (blue) and Setup 2 (red) with increasing magnetic field strength.](image)

**ELECTRON CLOUD DYNAMICS**

In a non-neutral plasma trap, a long electron cloud which is displaced from the central axis will undergo an off-axis rotation with constant frequency. The radial field of the image charge induced in the wall of the anode causes an \( \mathbf{E} \times \mathbf{B} \) rotation of the plasma. This collective normal mode of oscillation is also known as the \( m = 1 \) diocotron mode [7].

To better understand the anomalous focusing observed in the beam test, a particle-tracking code [8] was used to simulate the focusing effect of a long, uniform plasma column that was excited in a coherent off-axis rotation as outlined in Fig. 7. Six proton pencil beams were tracked through a time-dependent electromagnetic field map generated from the plasma distribution inside the lens [5].

The numerical results presented in Fig. 8 reproduced the main features of the images of the beams taken during the experiment. The modulation of intensity in each ring was linked to the rotation frequency of the plasma column. The changes in the relative separation and eccentricity of the rings were associated with changes in the electron density.

![Figure 7: Schematic representation of the \( m = 1 \) plasma diocotron mode [7] viewed along the axis of the lens.](image)

**CONCLUSION**

Anomalous beam focusing was observed with a prototype of a Gabor lens that converted thin pencil beams into rings. Particle transport simulations confirmed the formation of an electron cloud inside the lens and indicate that the plasma was excited in 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.

**ACKNOWLEDGEMENTS**

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**REFERENCES**


