ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB140

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

T. S. Dascalu*, C. L. Cheung, H. T. Lau, K. Long[1], T. Nonnenmacher, J. Pozimski[1]
Imperial College London, London, UK
R. Bingham[1], C. Whyte, University of Strathclyde, Glasgow, UK
[1]also at STFC Rutherford Appleton Laboratory, Didcot, UK

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.

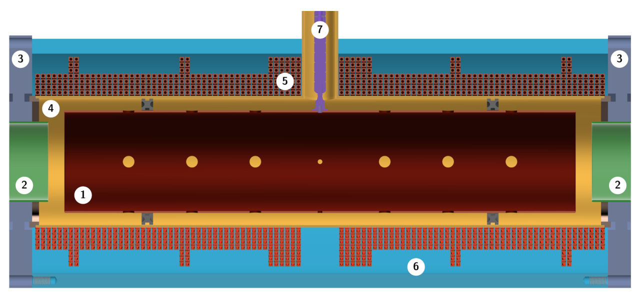

Figure 1: Internal structure of the ICL Gabor lens (longitudinal cross-section). The main components are: 1-central anode, 2-end electrodes, 3-end flanges, 4-vacuum tube, 5-pancake coils, 6-outer tube, 7-high-voltage feed-through.

Table 1: ICL Gabor Lens Specifications

Parameter	Value
Anode length	444 mm
Anode inner diameter	85 mm
End electrode diameter	67 mm
Anode voltage	8–20 kV
Max. magnetic field strength	55 mT

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

* t.dascalu19@imperial.ac.uk

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB140

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.

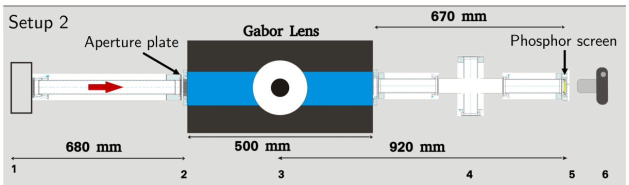

Figure 2: Schematic of the day 2 beam test setup. A different setup with a beam pipe of only 380 mm upstream of the lens was used in day 1 of the beam test.

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.

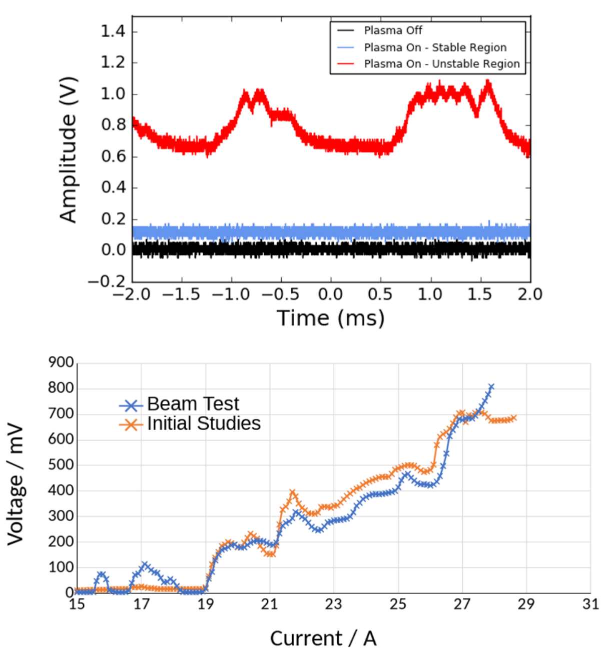

Figure 3: Top–Variation of discharge current from the lens in three regions: plasma off, plasma on, and plasma on in unstable region. Bottom–Voltage-current characteristic of the lens on the beam line (blue crosses) compared to measurements in the laboratory at ICL (orange crosses).

BEAM TRANSPORT RESULTS

Two main observations were made during the experiment when a plasma was established in the lens. Firstly, the focusing strength increased when the external magnetic field strength was increased. Secondly, the pencil beams were focused into rings with non-uniform intensity modulation (see Fig. 4). The latter observation indicates that the plasma was excited in a coherent off-axis rotation.

The rings were observed consistently throughout the two days of the beam test which suggests that the motion of the plasma was a characteristic of the geometry and operation of the lens. A similar conversion of a single proton beam into rings was reported in a previous measurement campaign [6].

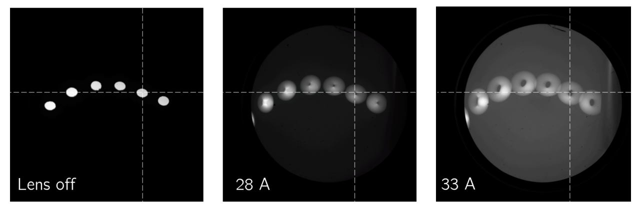

Figure 4: Camera image of the 6 beam spots beyond the aperture with a lens voltage of 20 kV and a current through the coils of 0 A, 28 A, and 33 A. The dashed lines indicate the beam axis.

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.

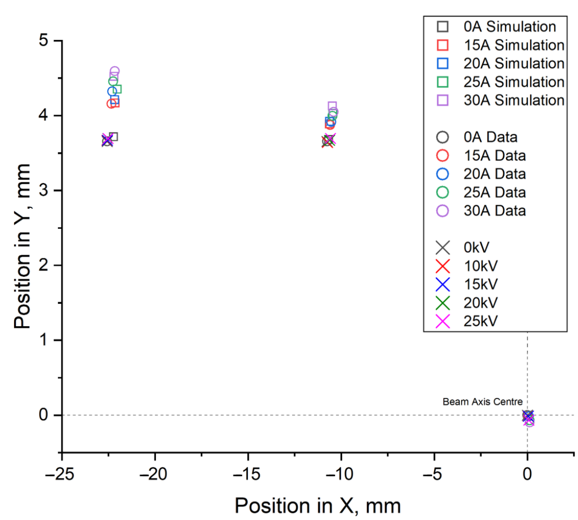

Figure 5: Position of the centroid of 3 beam spots. Squares and Circles represent variation in current through the coils only with no applied high voltage. Crosses represent variation in high voltage with no current through the coils.

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

12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB140

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.

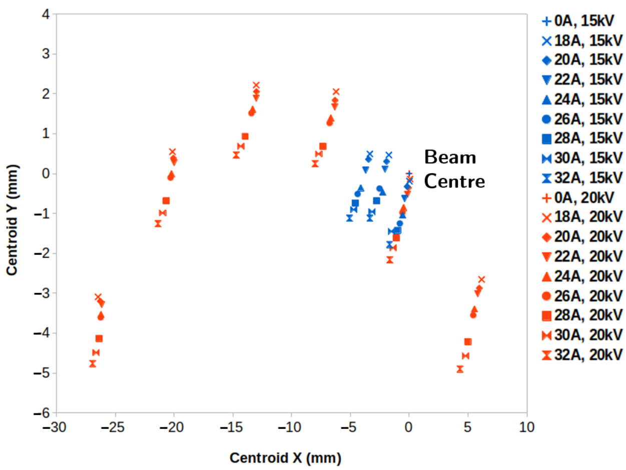

Figure 6: The x and y position of the centroids of the beam spots imaged with the Setup 1 (blue) and Setup 2 (red) with increasing magnetic field strength.

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.

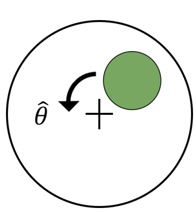

Figure 7: Schematic representation of the $m = 1$ plasma diocotron mode [7] viewed along the axis of the lens.

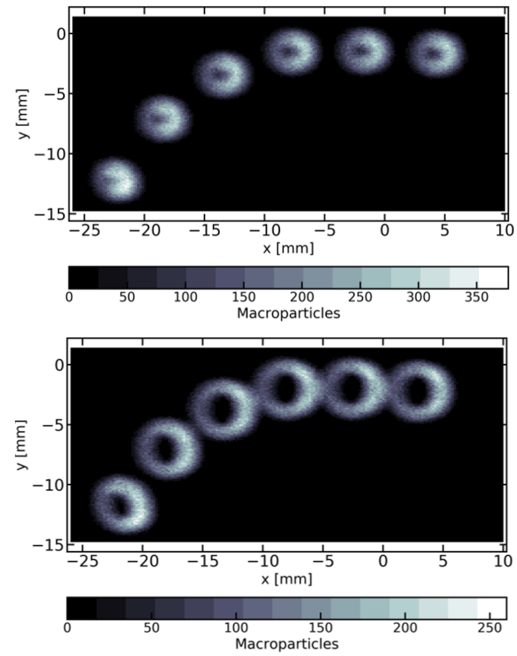

Figure 8: The effect of a plasma column rotating around the beam axis on six proton pencil beams as simulated with BDSIM [8] for electron densities of $0\,\mathrm{m}^{-3}$, $1.8\times10^{13}\,\mathrm{m}^{-3}$, and $2.8\times10^{14}\,\mathrm{m}^{-3}$. The uniform plasma column had a radius of 14 mm and it was displaced off-axis by 7 mm.

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

We would like to the thank the staff at the University of Surrey Ion Beam Centre, and in particular Vladimir Palitsin, for his support throughout the beam test. We would like to acknowledge the work of Piero Posocco at the 2017 beam test. Also, we gratefully acknowledge the Plasma Physics Group at Imperial College London for their scientific insight and technical support shared at various stages of the project.

REFERENCES

[1] D. Gabor, "A Space-Charge Lens for the Focusing of Ion Beams," *Nature*, vol. 160, no. 4055, pp. 89–90, 1947. doi:10.1038/160089b0

[2] J. Pozimski and O. Meusel, "Space charge lenses for particle beams," *Rev. Sci. Instrum.*, vol. 76, no. 6, pp. 0–6, 2005. doi:10.1063/1.1904203

[3] J. Pozimski and M. Aslaninejad, "Gabor lenses for capture and energy selection of laser driven ion beams in cancer treatment," *Laser Part. Beams*, vol. 31, no. 4, pp. 723–733, 2013. doi:10.1017/S0263034613000761

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB140

[4] G. Aymar *et al.*, "LhARA: The laser-hybrid accelerator for radiobiological applications," *Frontiers in Physics*, vol. 8, p. 432, 2020. doi:10.3389/fphy.2020.567738

[5] T. Nonnenmacher *et al.*, "Anomalous Beam Transport through Gabor (Plasma) Lens Prototype," *Applied Sciences*, vol. 11, no. 10, p. 4357, May 2021. doi:10.3390/app11104357

[6] P. A. Posocco, J. K. Pozimski, Y. Xia, and M. J. Merchant, "First Test of The Imperial College Gabor (Plasma) Lens prototype at the Surrey Ion Beam centre", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 1598–1600. doi:10.18429/JACoW-IPAC2016-TUPMY024

[7] K. S. Fine and C. F. Driscoll, "The finite length diocotron mode," *Phys. Plasmas*, vol. 5, no. 3, pp. 601–607, Mar. 1998. doi:10.1063/1.872752

[8] L. J. Nevay *et al.*, "BDSIM: An accelerator tracking code with particle–matter interactions," *Comput. Phys. Commun.*, vol. 252, p. 107200, Jul. 2020. doi:10.1016/j.cpc.2020.107200