FIRST TEST OF THE IMPERIAL COLLEGE GABOR (PLASMA) LENS PROTOTYPE AT THE SURREY ION BEAM CENTRE

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Abstract

The first plasma (Gabor) lens prototype operating at high electron density was built by the Imperial College London in 2015. In November 2015 the lens was tested at the Ion Beam Centre of the University of Surrey with a 1 MeV proton beam. Over 500 snapshots of the beam hitting a scintillator screen installed 0.5 m downstream of the lens were taken for a wide range of settings. Unexpectedly, instead of over- or underfocusing the incoming particles, the lens converted pencil beams into rings. In addition to the dependence of their radius on the lens settings, periodic features appeared along the circumference, suggesting that the electron plasma was exited into a coherent off-axis rotation. The cause of this phenomenon is under investigation.

INTRODUCTION

The Gabor lens, also referred to as plasma lens or space-charge lens, is an axially symmetric beam optics device based on a non-neutral plasma confined by a high voltage drop at its ends and by a uniform longitudinal magnetic field generated by some transverse coils (see Figure 1). The resulting focal length is inversely proportional to the plasma density, which in turn is proportional to the voltage or magnetic field squared (Brillouin flow equation) [1].

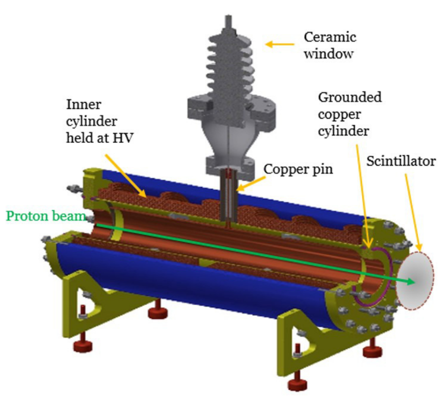

Figure 1: 3D rendering of the IC Gabor Lens. The distance between the lens exit and the scintillator screen is 0.5 m (not to scale in the diagram). The operational range for this model is 0–60 kV, 0–45 A if cooling is present.

The Imperial College (IC) Gabor lens project, which has been funded via the Imperial Confidence in Concept scheme, involves the construction of a high electron density (10^{-3} C/m^3) Gabor lens, its test with a proton beam at at the Ion Beam Centre of the University of Surrey (IBC) and, subsequently, its test with a laser-accelerated proton beam at the IC Cerberus laser facility. The Gabor lens is the ideal partner of laser-accelerated beams due its ability to reach high focusing with a low magnetic field compared to conventional solutions. For example, for a 25 MeV proton beam, in order to achieve a focal length of 1 m the required field is 0.06 T for a Gabor lens of 0.3 m vs. 2.6 T for a solenoid with the same effective length [2]. This is especially important when beams are produced with a 10÷20 deg divergence angle [3]. Moreover, its compactness and relatively low price are key if it is installed in particle beam therapy facilities [4, 5].

EXPERIMENTAL SET-UP

In November 2015 the lens was transported to the IBC and tested with a 1 MeV proton beam. The beam parameters at the entrance of the lens were changed by a magnetic triplet (placed about 0.3 m upstream of the lens) and a 4 jaw slit collimator. The beam shape was recorded on a YAG:Ce scintillator screen placed about 0.5 m downstream the lens. Over 500 pictures were taken for a range of voltages of the inner cylinder (10–24 kV) and currents through the wires of the coils (14–23 A) by a Nikon D700 12.1-megapixel CMOS camera with a Nikon 55mm f/2.8 AI-s macro objective. The operating vacuum pressure was in the order of 10^{-6} mbar.

To our surprise, when operational, the lens converted the incoming pencil beam into rings, whose radius increased with the coils current (see Figure 2). Although similar phenomena were observed by Neuner in 2000 [6], they were the result of a high-current electron discharge on the axis of the lens (pinch or skin mode), which caused either an over- or under-focusing of the beam thanks to the $1/r$ dependence of the generated azimuthal B field. In our experiment no discharge was present and therefore the recorded rings must have had a different origin.

15 kV - 13.5 A 15 kV - 17 A 15 kV - 22 A

Figure 2: 1 MeV proton pencil beam on the scintillator screen for three different coil currents.

DATA ANALYSIS

The rings can be characterised by 3 parameters: Gaussian peak intensity A along the circumference, Gaussian half-width Σ and radius R. Upon closer look we discovered that the rings did not have a uniform azimuthal intensity nor constant radius. Therefore, the analysis of the rings produced for different voltages and currents was carried out using the Radon transform method (Matlab), where projections of the ring (with the noise subtracted uniformly) were generated on a line passing through the approximate centre of each ring for angles between 0 and 179 deg. The sinograms obtained in this way were then centred and analysed for each angle in order to obtain the projections parameters a, σ, and r as function of φ, as shown in Figure 3. In order to reconstruct $A(\varphi)$, $\Sigma(\varphi)$ and $R(\varphi)$ from $a(\varphi)$, $\sigma(\varphi)$ and $r(\varphi)$ different ring shapes were created for different parameters and a LUT (a, σ, $r \rightarrow A$, Σ, R) defined.

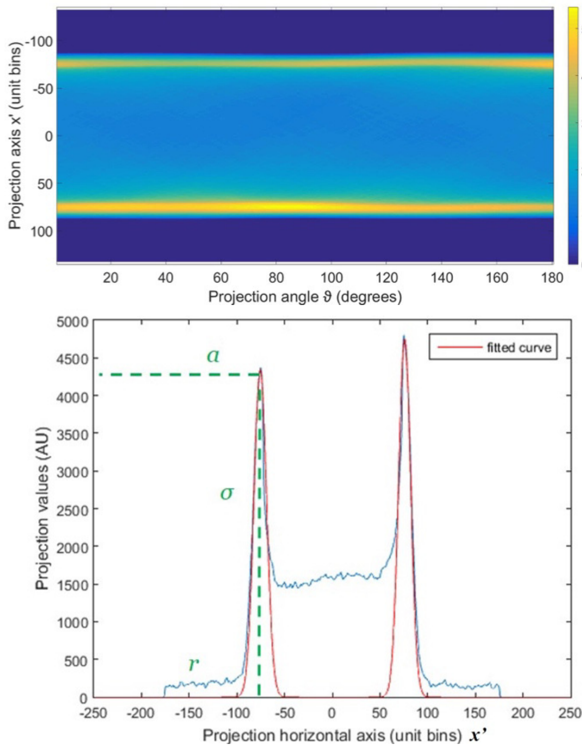

Figure 3: On top the sinogram for 15 kV - 22.0 A and below the projection slice at $\varphi = 0$ degree with a two-term Gaussian fit superimposed.

DISCUSSION

Figure 5(a)(c)(e) show the Gaussian peak intensity A, Gaussian half width Σ and radius R of the rings for different voltages and currents. The error bars represent the maxima and minima of the relevant parameter along φ. For a given voltage, the value of the current acts on R in a linear fashion once a plasma of enough density is created. Moreover, higher voltages enable larger rings and higher voltages require higher currents to obtain the same R. These two effects are what we would expect as a focusing of Σ instead if the lens worked as predicted by the theory. For larger rings the average peak intensity A gets fainter to maintain the overall intensity. Σ is constant and equal to the lens-off value for low currents, whereas it jumps to a different, higher value (irrespectively of the high-voltage level) when the right plasma is established.

In order to understand these trends better, we attempted to plot A, Σ and R vs. the average background noise registered on the scintillator (see Figure 5(b)(d)(f)), which we assumed proportional to the plasma density, and that would eliminate the degree of freedom represented by the vacuum pressure. Figure 5(b) shows clearly that the lens has an effect on the beam only when a certain level of background noise is reached, independently from the current applied to the coils, and that different voltages define different trends, which is consistent with the previous discussion.

CONCLUSION

Figure 4 is an example of the dependence of A vs. φ. It is possible to find periodic features along the rings, whose shape and period change depending on the voltage and current setting. This could imply that there is an ongoing plasma resonance effect which steers the beam away from its incoming direction. Given the geometry of the lens and how the electron cloud acts on the beam, the only possible explanation is that the electron cloud is exited into a coherent off-axis rotation.

A measurement campaign focused on finding the reason behind the resonance has started.

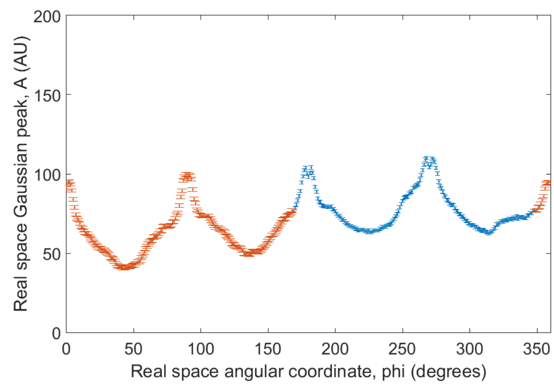

Figure 4: A vs. φ for 20 kV - 19.5 A. The minimum and maximum are used for the error bars in Fig. 5. The graph for Σ is similar, with the dips and peaks in quadrature.

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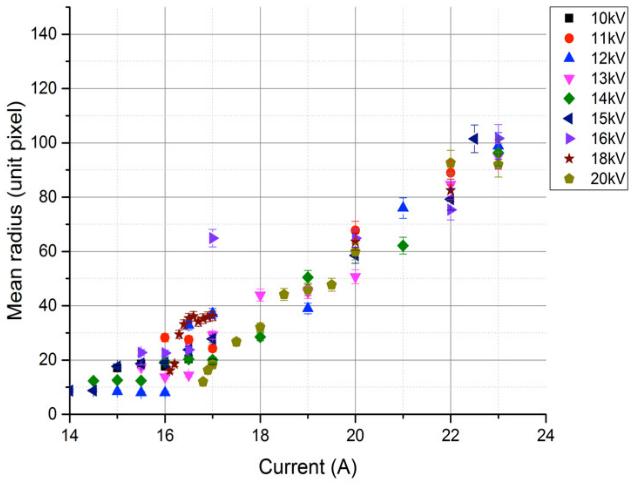
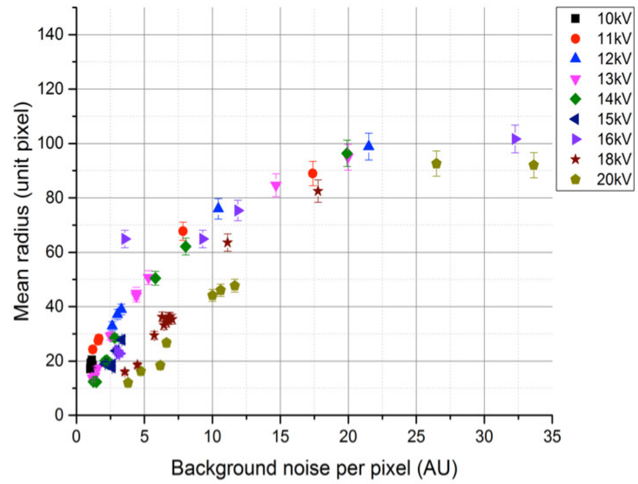
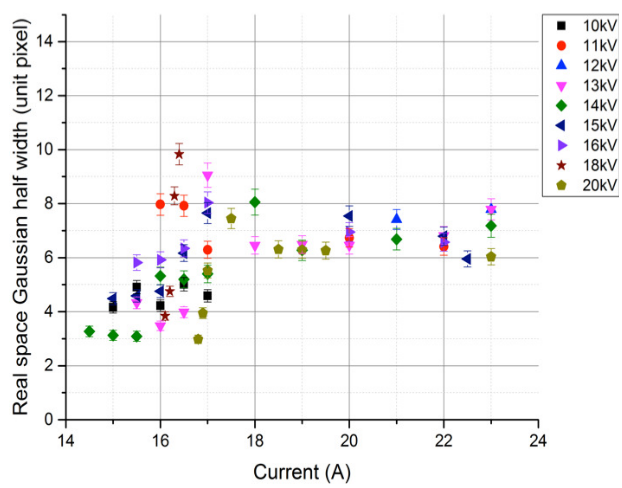


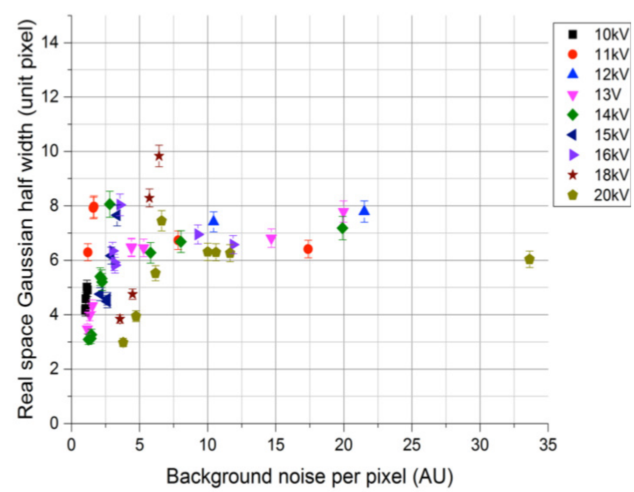
(a) R vs. current.



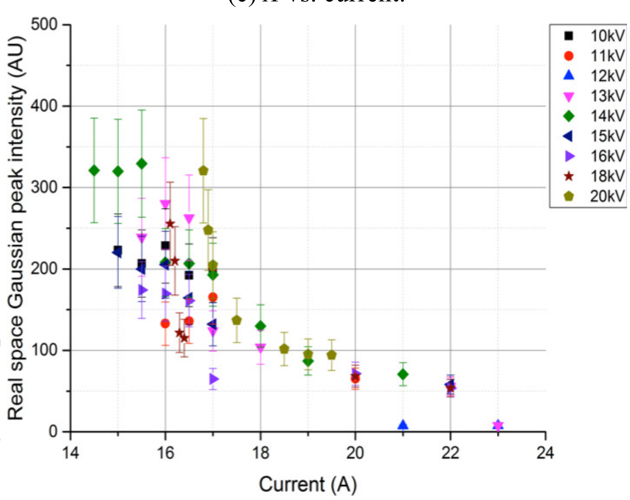
(b) R vs. mean background noise.



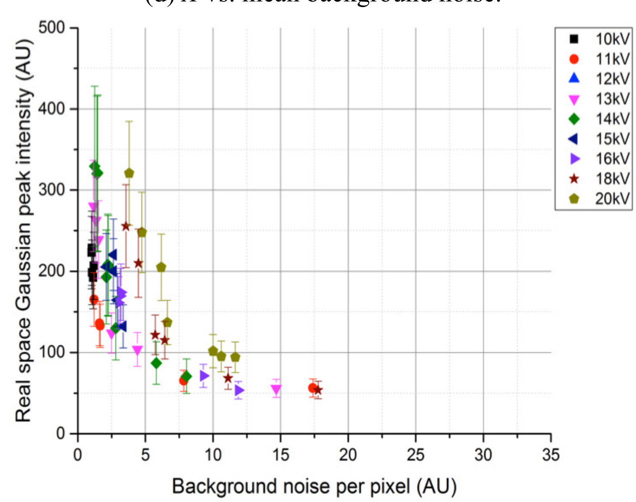
(c) A vs. current.



(d) A vs. mean background noise.



(e) Σ vs. current.



(f) Σ vs. mean background noise.

Figure 5: Gaussian peak intensity A, Gaussian half width Σ and radius R of the rings for different voltages and currents. The error bars represent the maxima and minima of the relevant parameter along φ (see Figure 4). In order to eliminate the degree of freedom represented by the vacuum pressure which fluctuated above 10^{-6} mbar, we plotted A, Σ and R vs. the average background noise registered on the scintillator, which we assumed proportional to the plasma density.