Update on the study and design of the Gabor lens

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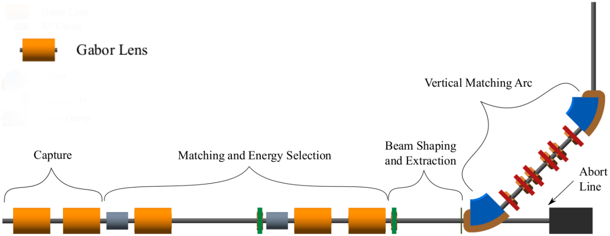
January 28, 2021

Gabor lens studies - motivation

- Key element for LhARA
  - cost-effective alternative to solenoids
  - ensures energy selection

Stage 1 beamline



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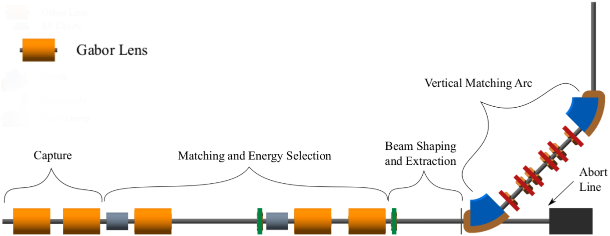


- Previous designs and experiments: performance lower than predicted
  - focusing strength (low filling factors)[1]
  - aberrations (focusing quality)[1]
  - emittance growth[2]
- Previous numerical simulations
  - state of the plasma strongly depends on the external field strengths
  - diocotron instability[3]

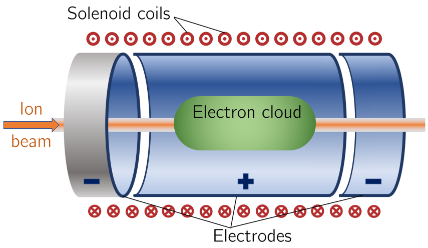
[1] O. Meusel, arXiv:1309.4654
[2] J.A. Palkovic, FERMILAB-CONF-88-177, 88-10-03
[3] M. Droba, IPAC 2013, TUPWO008

Space-charge lens

Advantages

- Focus in both planes simultaneously
- Energy dependent focusing strength
- Cost effective solution compared to solenoids

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



Penning-Malmberg trap

Space-charge lens

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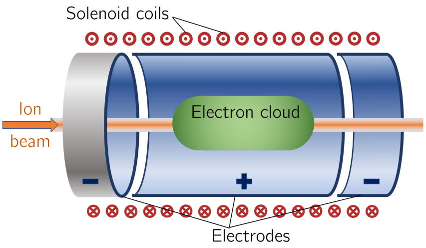


Penning-Malmberg trap

Challenges

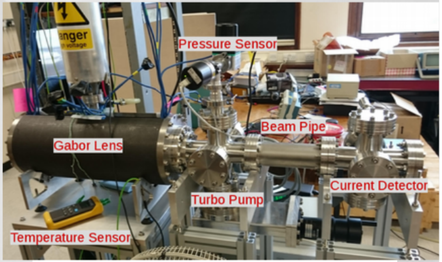
- High-vacuum, high-voltage operation
- Plasma instabilities
- Diagnostics

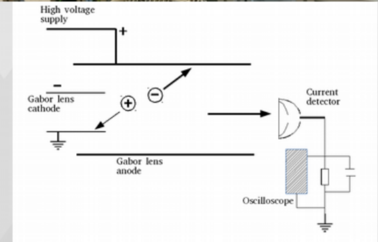
n_e	$\lesssim 5 \times 10^{15}\ \mathrm{m}^{-3}$
V_{anode}	$\lesssim 30$ kV
B_{GL}	$\lesssim 33$ mT

Lens parameters required for LhARA

Lab setup at Imperial

- High voltage and current through magnetic field applied to produce electric and magnetic fields, resepectively
- Measurements of the plasma made with a segmented current detector
- Cooling applied to lens to aid pressure reduction





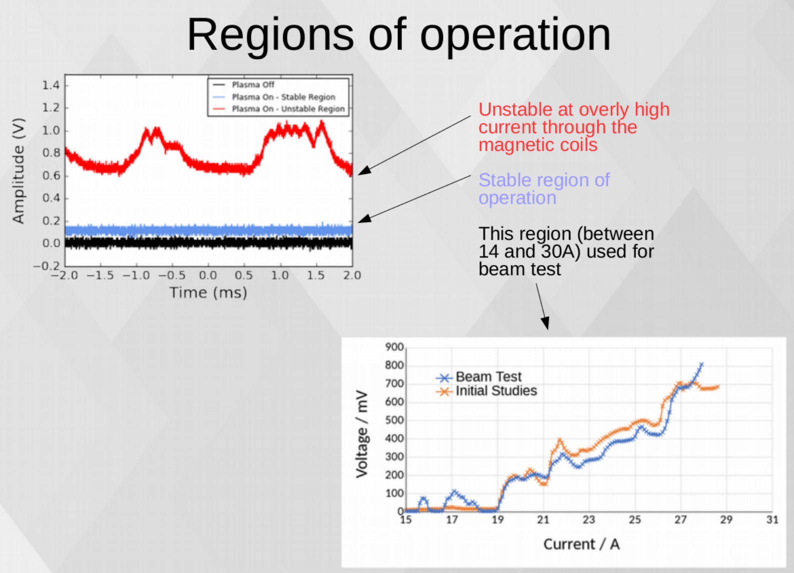
4

First prototype built at Imperial

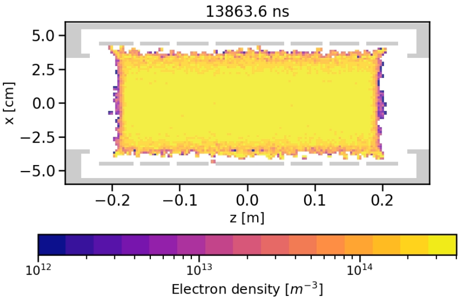
Imperial lens parameters

- Total length of 540 mm
- Central electrode: I.D. = 66 mm and O.D. 89 mm
- Magnetic Field: 55mT
- Electron Density: 5×10^{-7} C/m^3

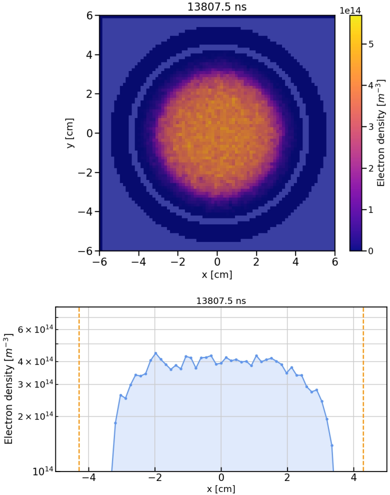
First prototype built at Imperial



Stable operation of the lens



Longitudinal cross-section



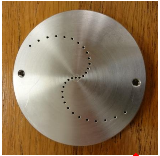
Transverse cross-section

The electron cloud was simulated with a PIC code[4]:

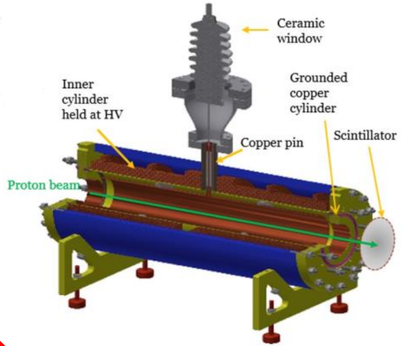
- Electron densities of $10^{14} - 10^{15}\,\mathrm{m}^{-3}$ can be achieved
- Plasma is stable for $t \leq 20\,\mu\mathrm{s}$ and rotates around beam axis
- The lens is partially filled

[4] VSim, https://txcorp.com/vsim

Surrey beam test of the 'Imperial lens'

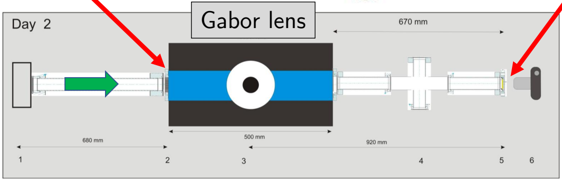


Aperture



Phosphor Screen

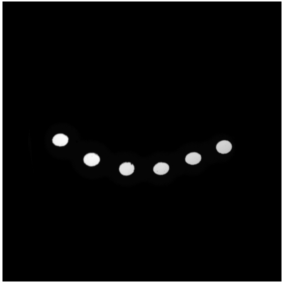
1.4 MeV protons



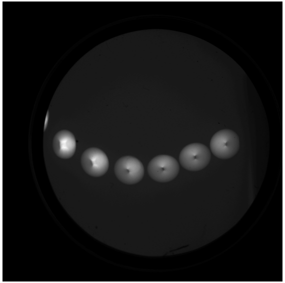
Experimental arrangement

Beam test results

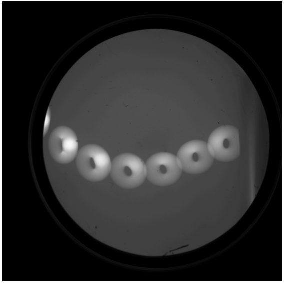
Lens off



28 A



35 A

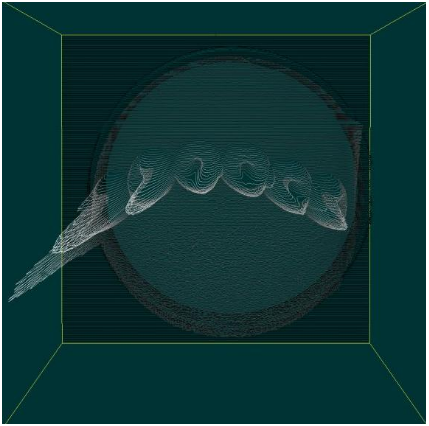


$\longrightarrow$ Increasing the current in the coil $\longrightarrow$

- Focusing occurs
- Pencil beams are focused into ring shapes
- The shape and intensity of each ring vary

Indication of: Non-uniform, rotating plasma column

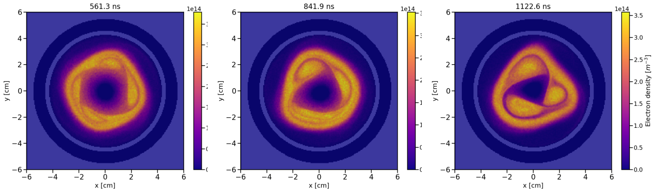
Beam test results



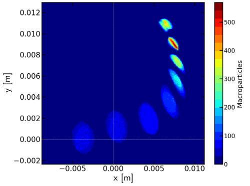
- Intensity profile of the six rings

Investigate the most typical instabilities

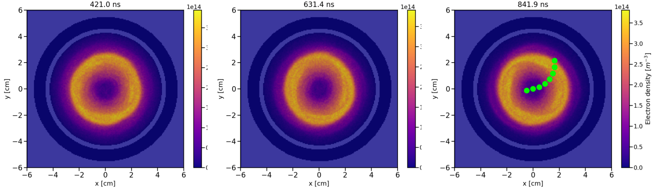
Diocotron instability



beam tracking →



Electron ring



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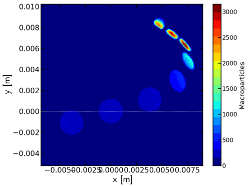
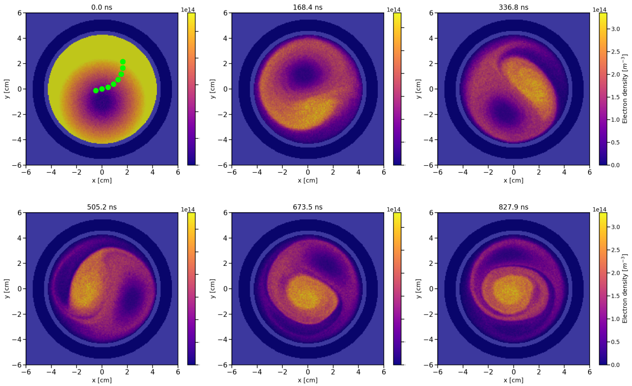
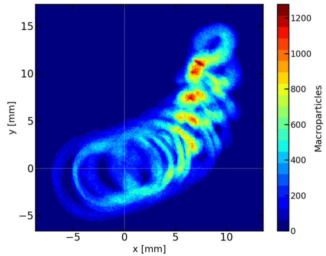


Instability with dipole structure leads to rings



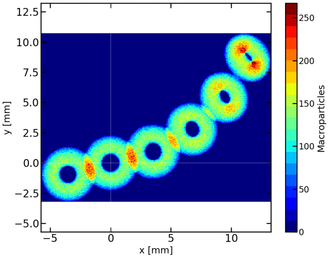
- Two regions of low and high electron density
- Instability lasts for 1 μs
- Possible driving mechanism: stream of electrons



Pencil beams are focused into ring shapes

- Ring formation linked to asymmetry and rotation of the plasma

Simulation vs. experiment



Macroparticles hitting the screen as simulated with BDSIM

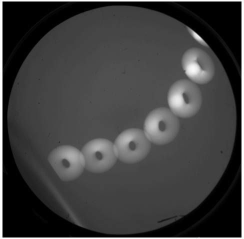


Image of the screen from the beam test

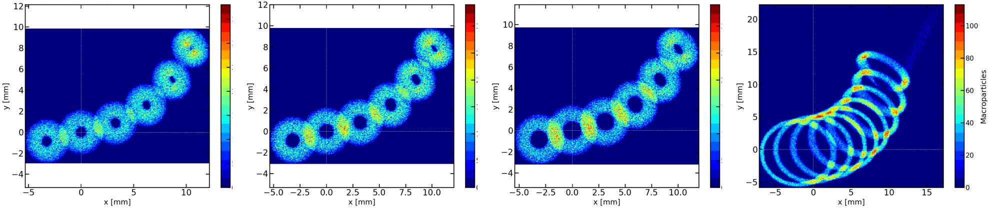
Qualitative agreement obtained when tuning the free parameters of the model:

- electron density
- radius and period of rotation of the plasma

Features not reproduced by simulation:

- intensity profile of each ring
- eccentricity of central pencil beam $\longrightarrow$ missalignement

Simulation output sensitive to density of plasma



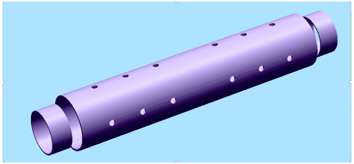
(a) $n_{\mathrm{e,max}} = 1.6$ (b) $n_{\mathrm{e,max}} = 1.8$ (c) $n_{\mathrm{e,max}} = 2$ (d) $n_{\mathrm{e,max}} = 4$

The effect of increasing the maximum electron density on the appearance of the ring spots (units of $10^{14}\,\mathrm{m}^{-3}$)

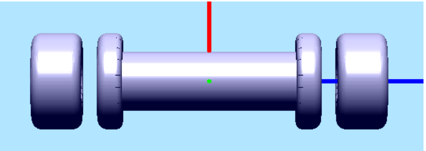
- It provides a method to estimate the density of the plasma during the beam test
- Current estimation: filling factor $< 5\%$ compared to the max. theoretical electron density

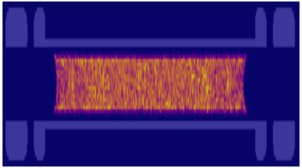
Impact on new design of the lens

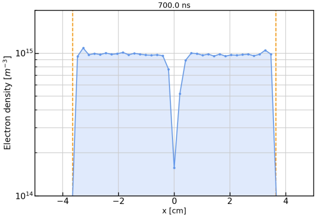
Old design



New design







Simulation of the new lens

- electron loss near the central axis
- no instability develops on timescale of 10 μs

Next steps in the design

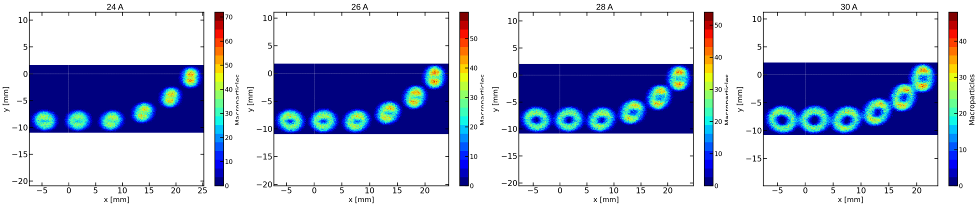
- active filling of the lens
- ensure $E \times B$ rotation of the plasma
- damping mechanism to ensure uniform filling

Summary

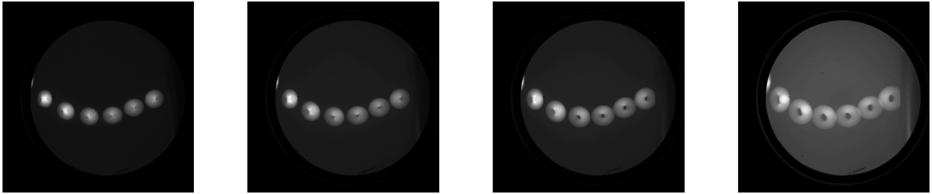
- Plasma under **stable regime of the lens simulated with PIC code**
  - establish the effect of the shape and configuration of electrodes on the uniformity of the electron cloud
- Most typical **instabilities observed in simulations**
- The **effect of these instabilities on pencil beams** was studied with both a PIC code and a particle tracking code
- Instability with dipole structure was associated to the **formation of ring spots** from the pencil beams
- An **idealised model** was created for the 'dipole' instability
  - **qualitative agreement** with experiment
  - offers an **estimation of the electron density** and a description of the **motion of the plasma**

Backup: Simulation vs. experiment

Simulation



Experiment



- Matching patterns when the current through the coil is increased