Imperial College London

Update on the study and design of the Gabor lens

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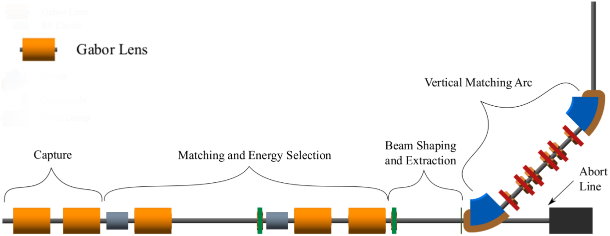
Gabor lens studies - motivation

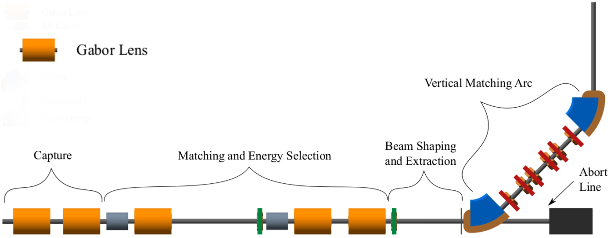
- Key element for LhARA
  - cost-effective alternative to solenoids
  - ensures energy selection

Stage 1 beamline



Gabor lens studies - motivation

Stage 1 beamline



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

Outline

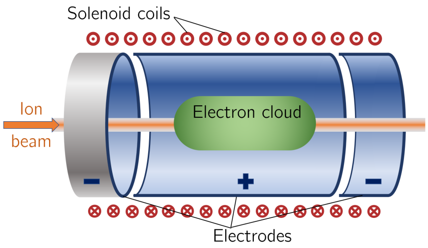
- Gabor lens - advantages
- The 'Imperial' lens prototype
  - Simulation of the stable regime
  - Beam test
  - Simulation of most common instabilities
- Numerical model of 'dipole' instability
- Comparison between simulations and experiment
- Impact on the new design of the lens

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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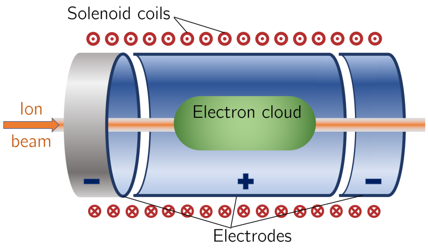


Penning-Malmberg trap

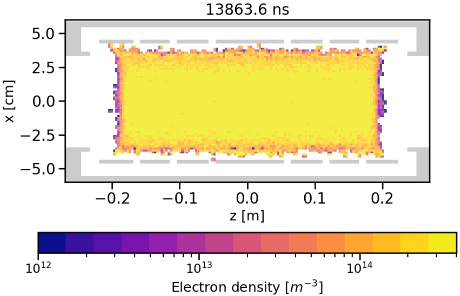
Challenges

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

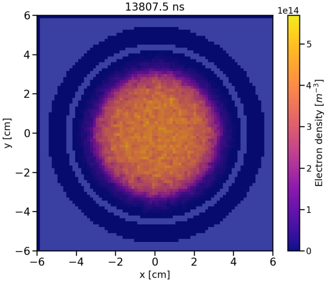
n_e	$\lesssim 5 \times 10^{15}\ \mathrm{m}^{-3}$
V_{anode}	$\lesssim 30$ kV
B_{GL}	$\lesssim 33$ mT

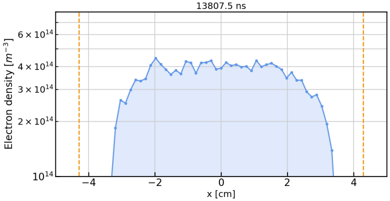
Lens parameters required for LhARA

Stable operation of the lens



Longitudinal cross-section





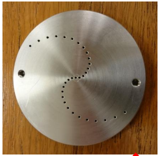
Transverse cross-section

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

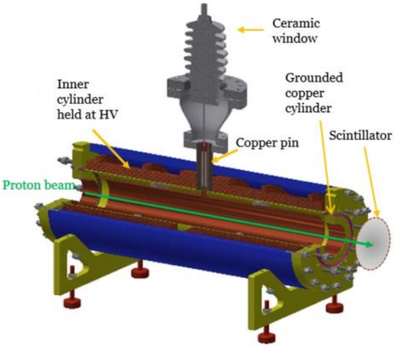
- Electron densities of $10^{14} - 10^{15}\,\mathrm{m}^{-3}$ can be achieved
- Plasma is stable for $t \leq 20\,\mu\mathrm{s}$ and rotates around beam axis
- The lens is partially filled

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

Surrey beam test of the 'Imperial lens'

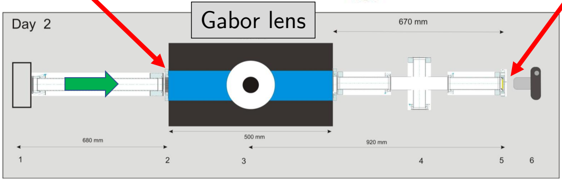


Aperture



Phosphor Screen

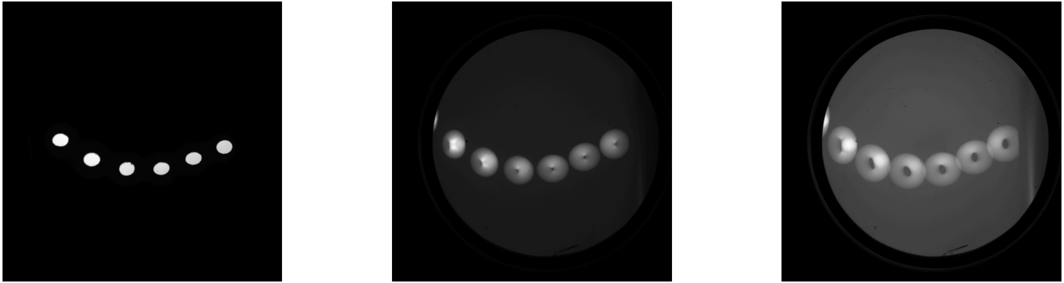
1.4 MeV protons



Experimental arrangement

Beam test results

Lens off | 28 A | 35 A



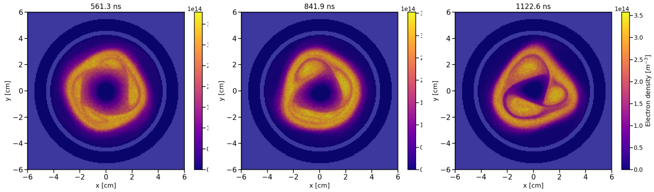
⟶ Increasing the current in the coil ⟶

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

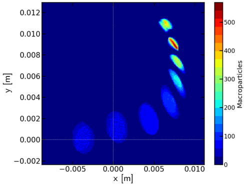
Indication of: Non-uniform, rotating plasma column

Investigate the most typical instabilities

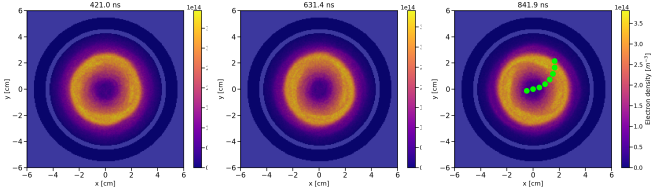
Diocotron instability



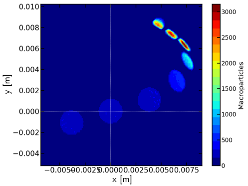
beam tracking →



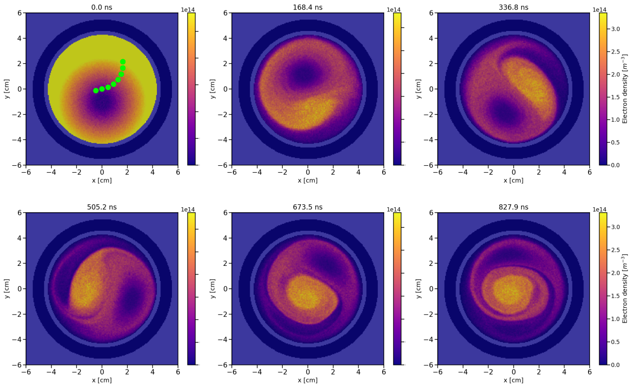
Electron ring

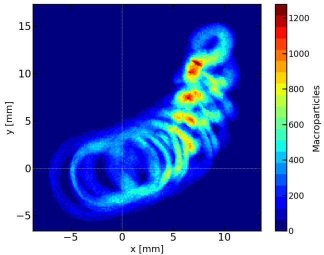


beam tracking →



Instability with dipole structure leads to rings





Pencil beams are focused into ring shapes

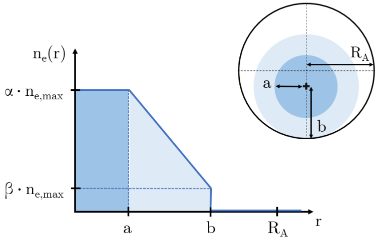
- Two regions of low and high electron density
- Instability lasts for 1 μs
- Possible driving mechanism: stream of electrons

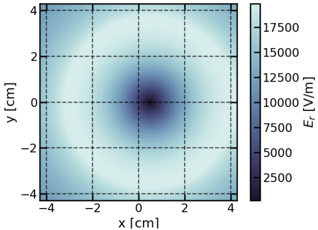
- Ring formation linked to asymmetry and rotation of the plasma

Alternative model of the electron cloud

- Full simulation of plasma and proton beam using the PIC code is computationally expensive
- **Aims:**
  - Investigate the parameter space for the plasma
  - Understand the origin of the images taken during the beam test
  - Reproduce the main features
- **Model** the instability:
  - Idealised cylindrical electron cloud which rotates
  - Generate 4D electric field map for the plasma
  - Track the pencil beams using BDSIM[5]

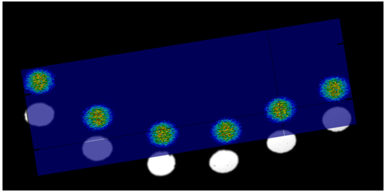
Idealised density profile



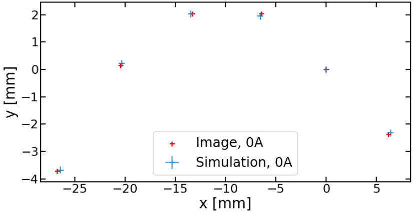


[5] https://doi.org/10.1016/j.cpc.2020.107200

Match the divergence and position of the pencil beams



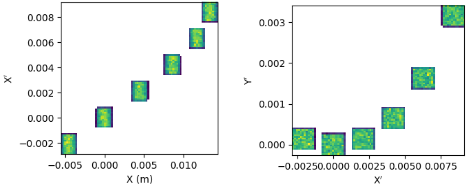
Simulation output overlaid on image



Centroids of the pencil beams

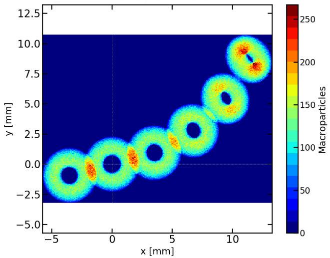
Phase-space of pencil beams at entry plane of the lens:

- Position determined by the aperture
- x-, y-divergence can be found from size and position of the beam spots on the screen (lens tuned off)



Phase-space at entry plane of the lens

Simulation vs. experiment



Macroparticles hitting the screen as simulated with BDSIM

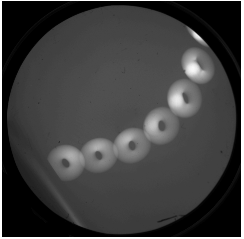


Image of the screen from the beam test

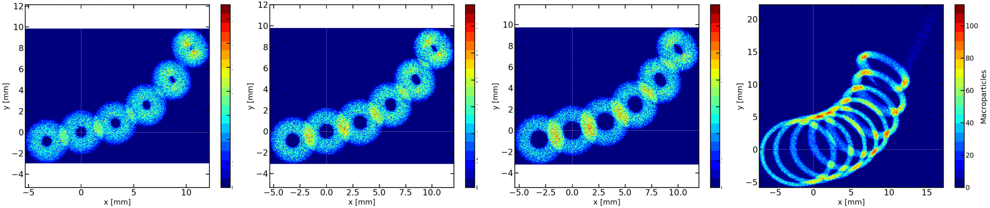
Qualitative agreement obtained when tuning the free parameters of the model:

- 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



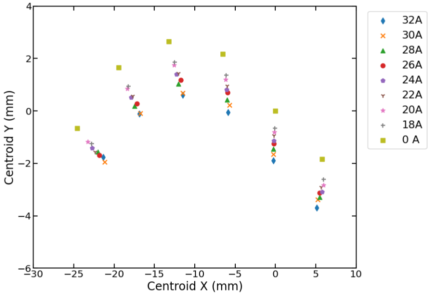
(a) $n_{\mathrm{e,max}} = 1.6$ (b) $n_{\mathrm{e,max}} = 1.8$ (c) $n_{\mathrm{e,max}} = 2$ (d) $n_{\mathrm{e,max}} = 4$

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

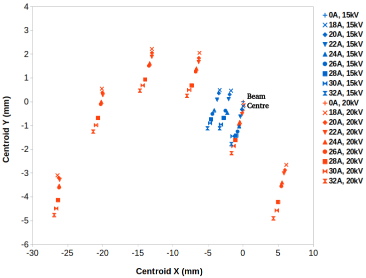
- It provides a method to estimate the density of the plasma during the beam test
- Current estimation: filling factor $< 5\%$ compared to the max. theoretical electron density

Variability between measurements

- Work in progress to obtain quantitative agreement
- Signs that the rotation of the plasma column changed when incrementing the current in the coil



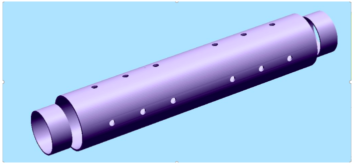
(Values from simulations)



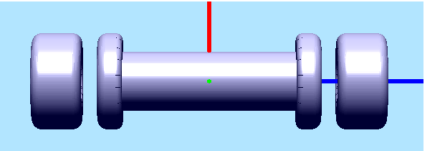
(Data from beam test)

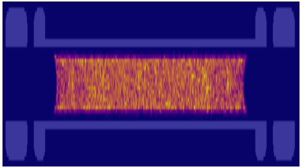
Impact on new design of the lens

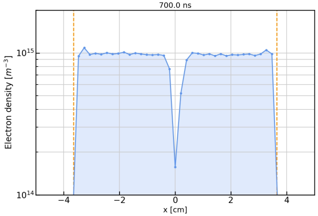
Old design



New design







Simulation of the new lens

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

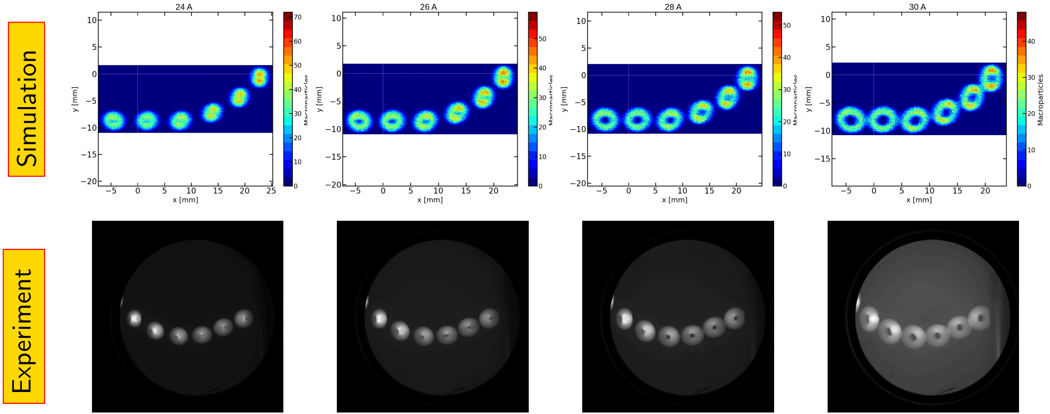
Next steps in the design

- 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



- Matching patterns when the current through the coil is increased