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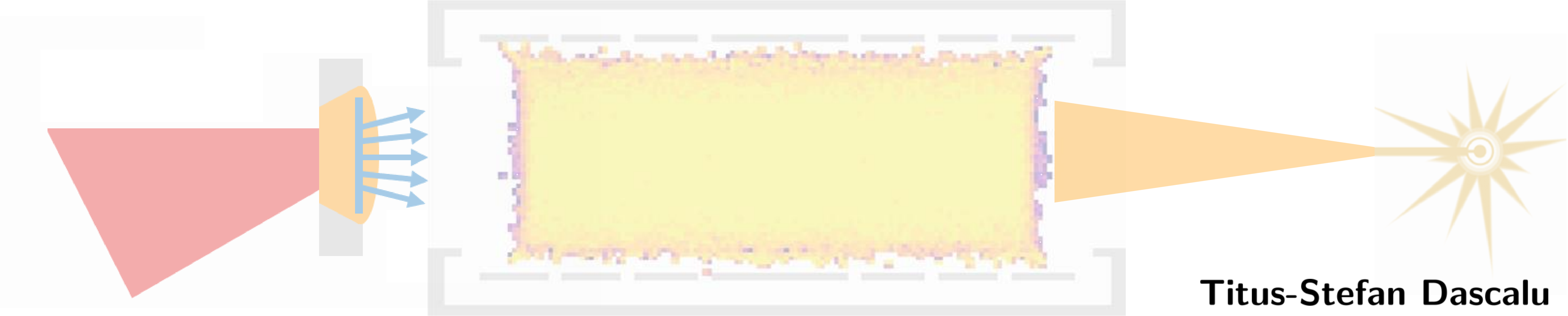
London

Investigation of plasma (Gabor) lenses for capture and focusing of laser-driven ions



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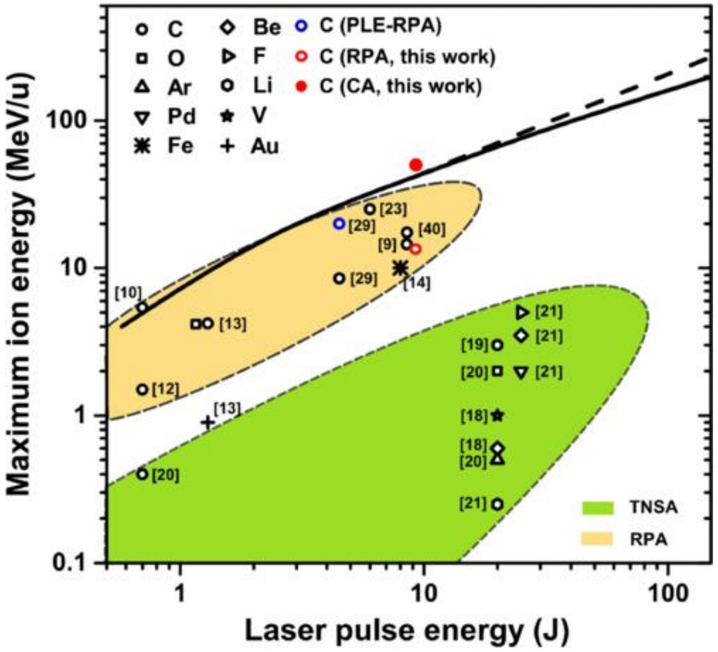
IOP HEPP & APP Annual Conference
6th April 2022

Laser-driven ion sources

Ma et al., Phys. Rev. Lett. 122, 014803 (2019)



High brightness

$10^{11} - 10^{13}$ particles/shot

High laminarity

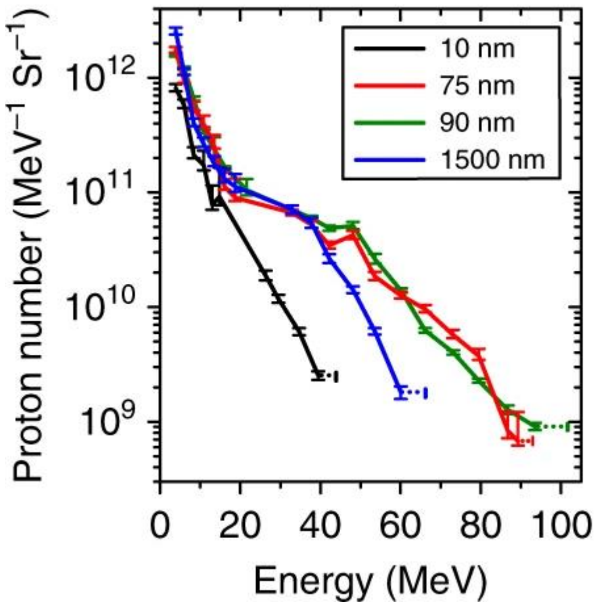
rms emittance $< 0.01\,\pi$ mm-mrad

High energy, short duration ($\sim$ps) at source

Triggarable

Broadband energy

quasi-thermal spectrum

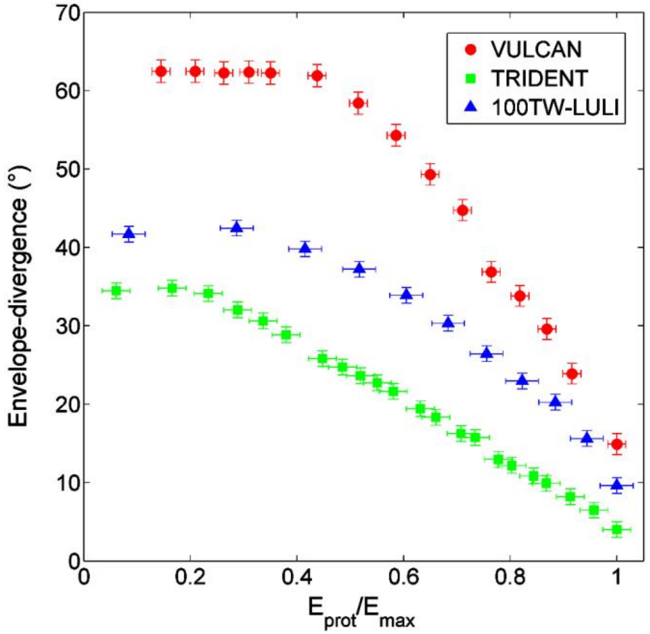


Higginson et al., Nat. Commun. 9, 724 (2018)

Generated beams are typically:

Highly divergent

$> 10^\circ$ emission cone

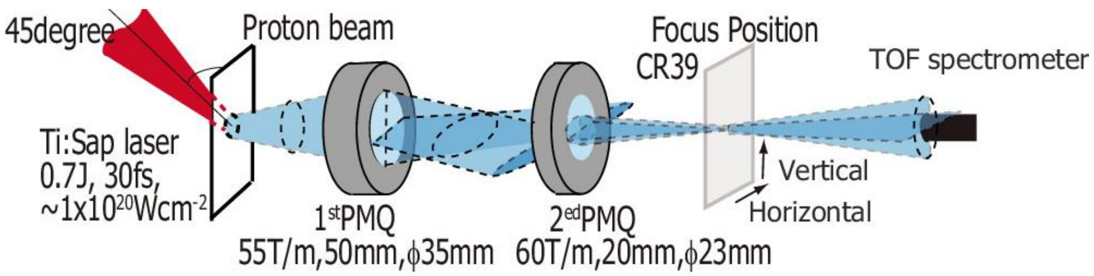


Nürnberg et al., Rev. Sci. Instrum. 80, 033301 (2009)

Solutions for ion capture and transport

Ahmed et al., Sci. Rep. 11, 699 (2021) Kar et al., Nat. Commun. 7, 10792 (2016)

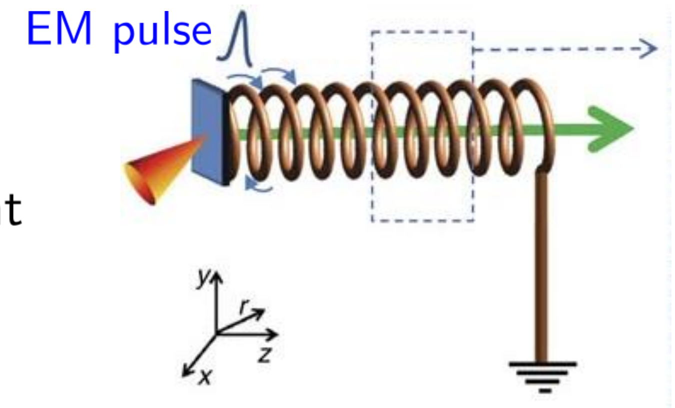
PMQ



transmission $\sim 30\%$ field gradients 50–500 T/m

Nishiuchi et al., Appl. Phys. Lett. 94, 061107 (2009)

Helical coil targetry



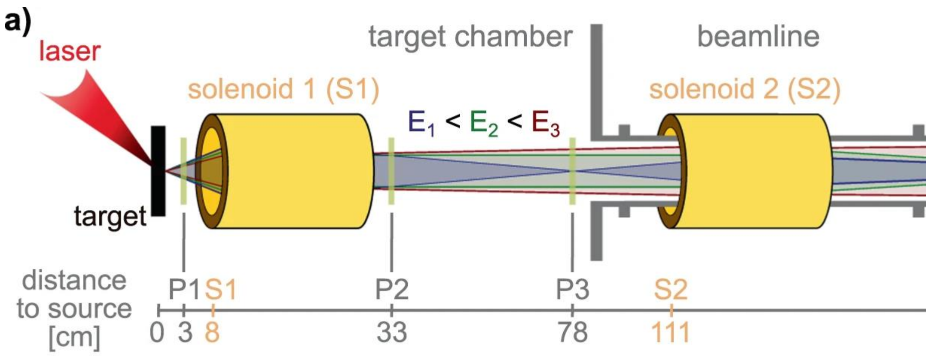
acceleration gradient ~ 2 GeV/m

divergence $< 1°$

repeatability, rep. rate

Brack et al., Sci. Rep. 10, 9118 (2020)

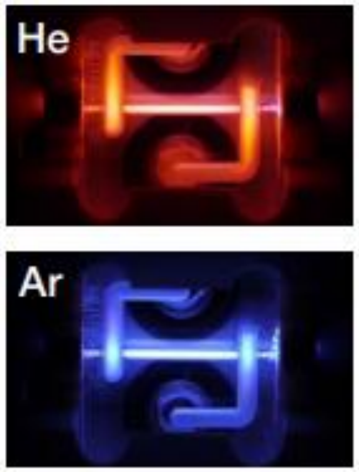
High-field pulsed solenoids



transmission $\leq 50\%$ rep. rate ≤ 3 pulses/min

Sjobak et al., Phys. Rev. Accel. Beams 24, 121306 (2021)
Lindstrøm et al., Phys. Rev. Lett. 121, 194801 (2018)

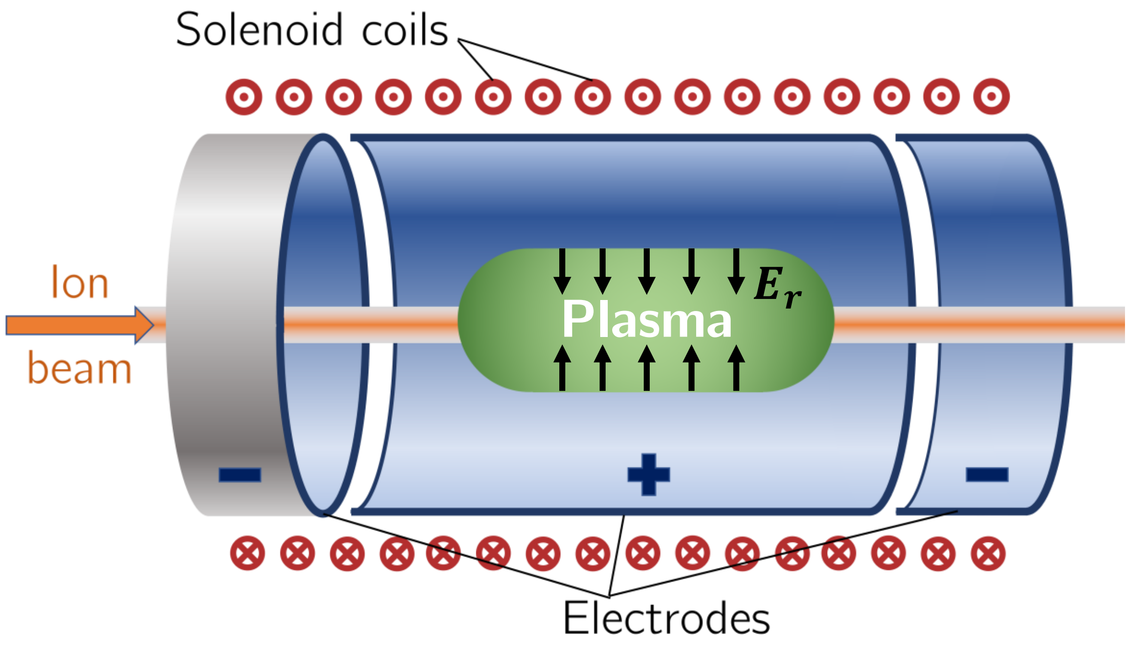
Active plasma lens

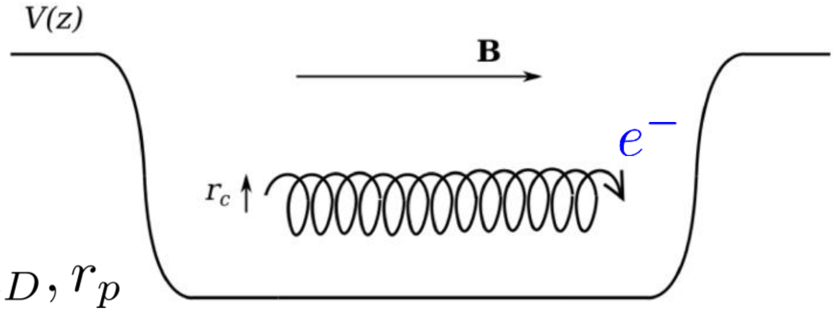


field gradient 3.6 kT/m

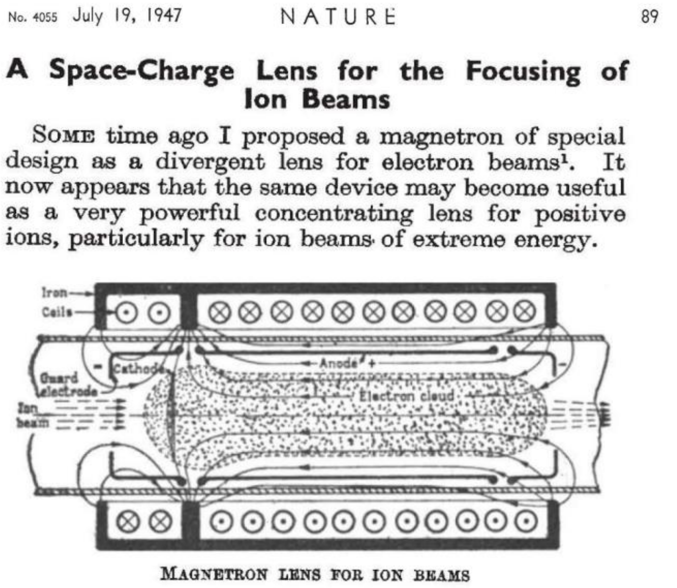
beam-driven plasma wakefields

Electron-plasma (Gabor) lens





$$r_c \ll \lambda_D, r_p$$



No. 4055 July 19, 1947 NATURE 89

A Space-Charge Lens for the Focusing of Ion Beams

Some time ago I proposed a magnetron of special design as a divergent lens for electron beams¹. It now appears that the same device may become useful as a very powerful concentrating lens for positive ions, particularly for ion beams of extreme energy.

MAGNETRON LENS FOR ION BEAMS

Gabor, Nature 160, 89-90 (1947)

$$\boxed{\frac{1}{f} = \frac{e^2 Z}{4\epsilon_0} \frac{n_e}{U} l}$$

U = ion K.E.

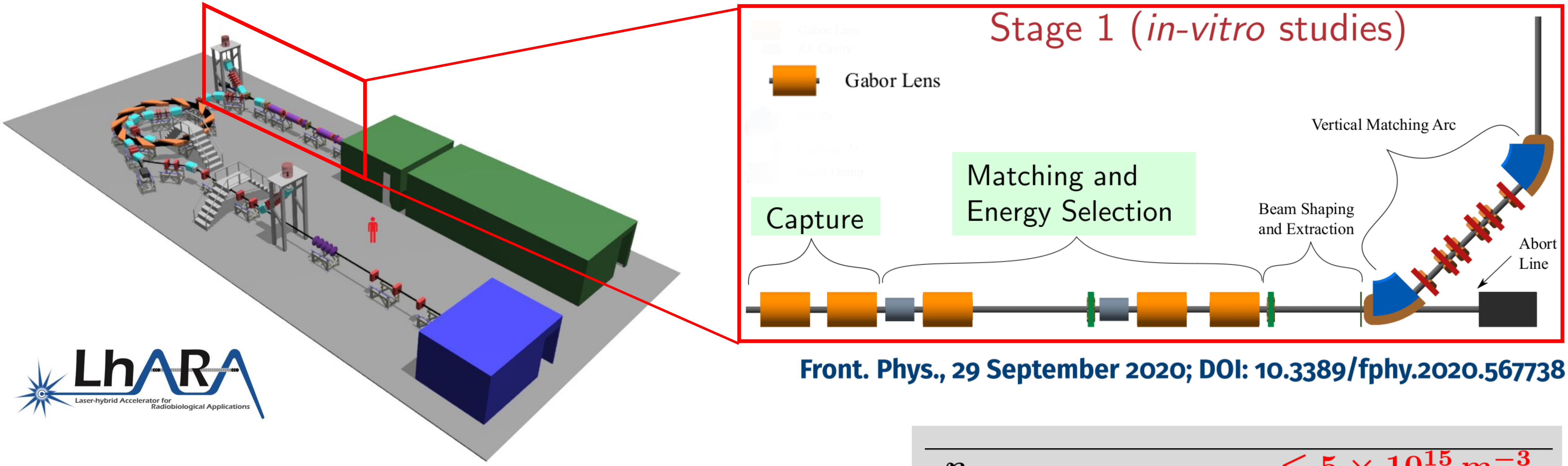
n_e = electron number density

conventional solenoid or quadrupole lenses: $f \propto \sqrt{U}$

Pozimski, Laser Part. Beams 31, 723-733 (2013)

$$B_{GPL} = B_{sol}\sqrt{\frac{m_e}{m_{ion}} Z}$$

Plasma lenses for LhARA



Front. Phys., 29 September 2020; DOI: 10.3389/fphy.2020.567738

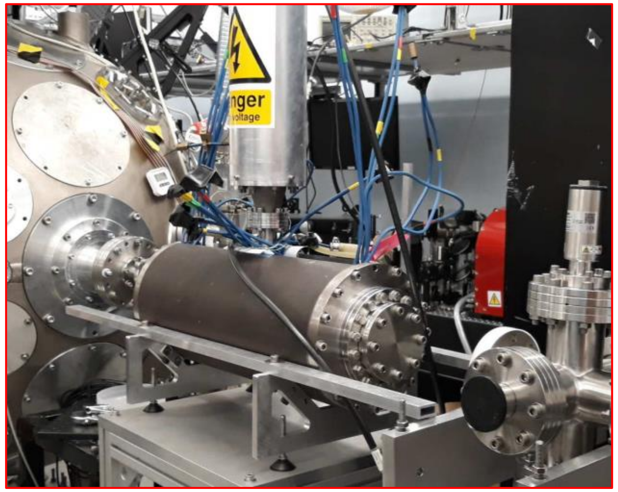
n_e	$\leq 5 \times 10^{15}\ \mathrm{m^{-3}}$
V_{anode}	≤ 30 kV
B_{GL}	≤ 33 mT
e-Cloud size (r, L)	~ 3 cm, 86 cm

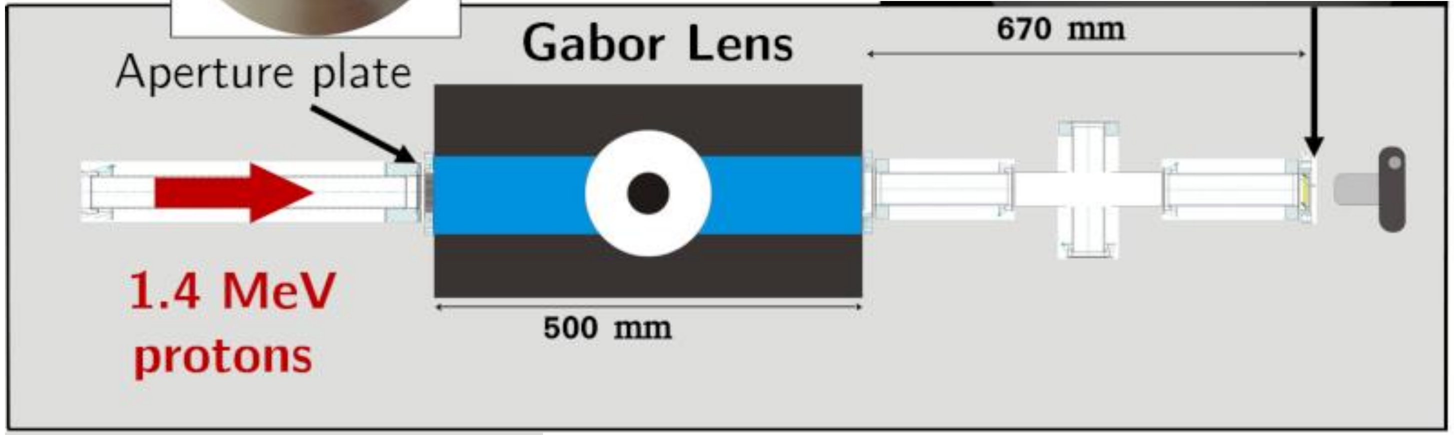
Lens parameters required for LhARA

- **Laser-driven, high-flux proton/ion source for systematic radiobiology programme**
  - ▷ Overcome instantaneous dose-rate limitations (capture at > 10 MeV)
  - ▷ Proton/ion bunches as short as 10–40 ns
  - ▷ Fast post-acceleration with an FFA

Lens prototype built and tested with proton beams

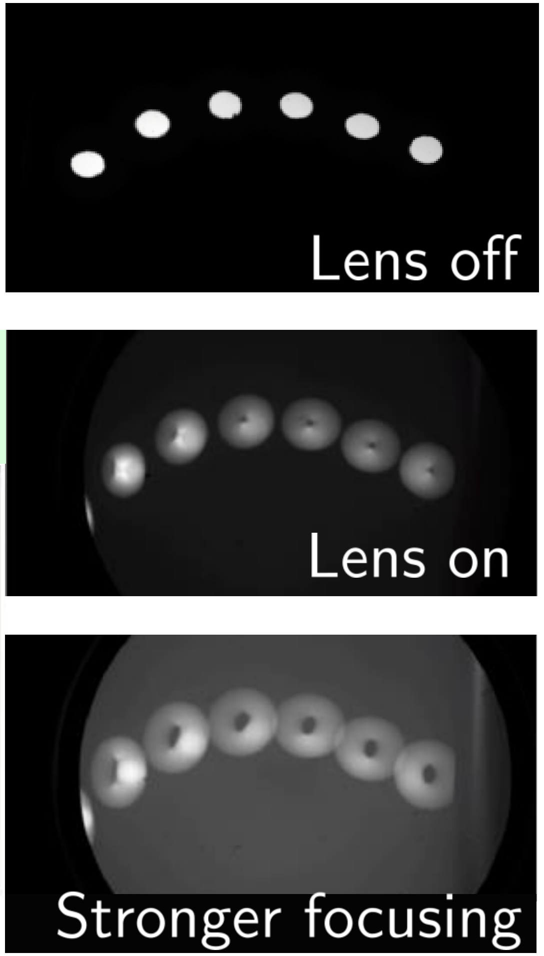
Nonnenmacher et al., Appl. Sci. 11(10), 4357 (2021)

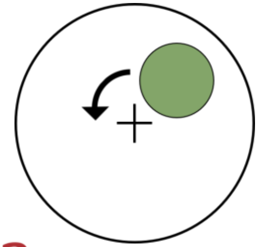




Beam test setup

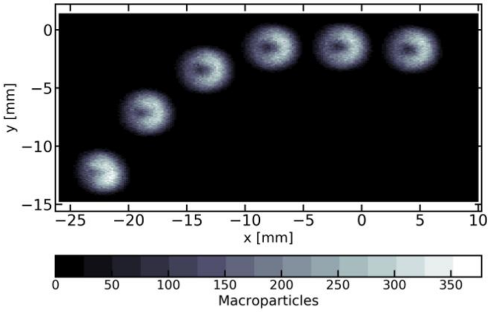
Phosphor screen



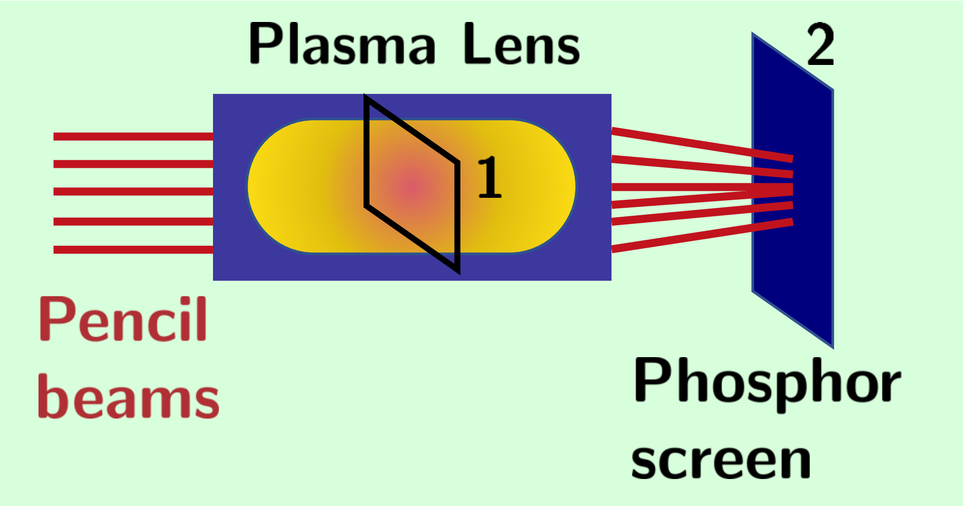


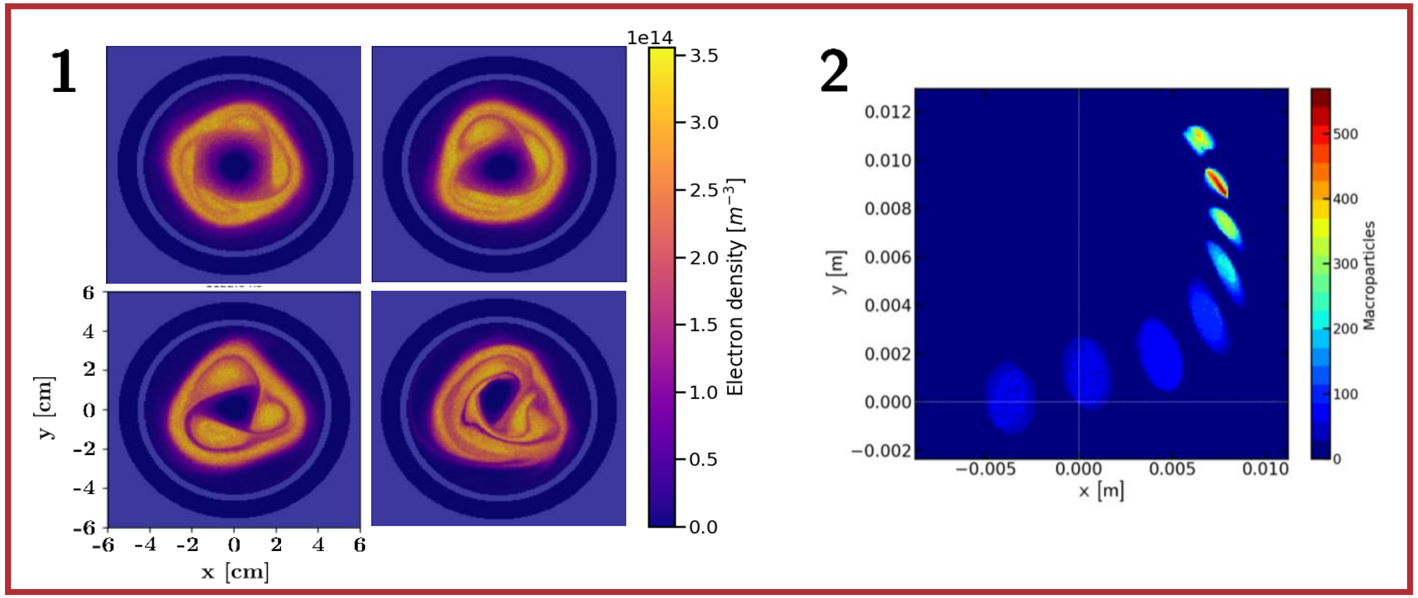
Plasma coherent rotation

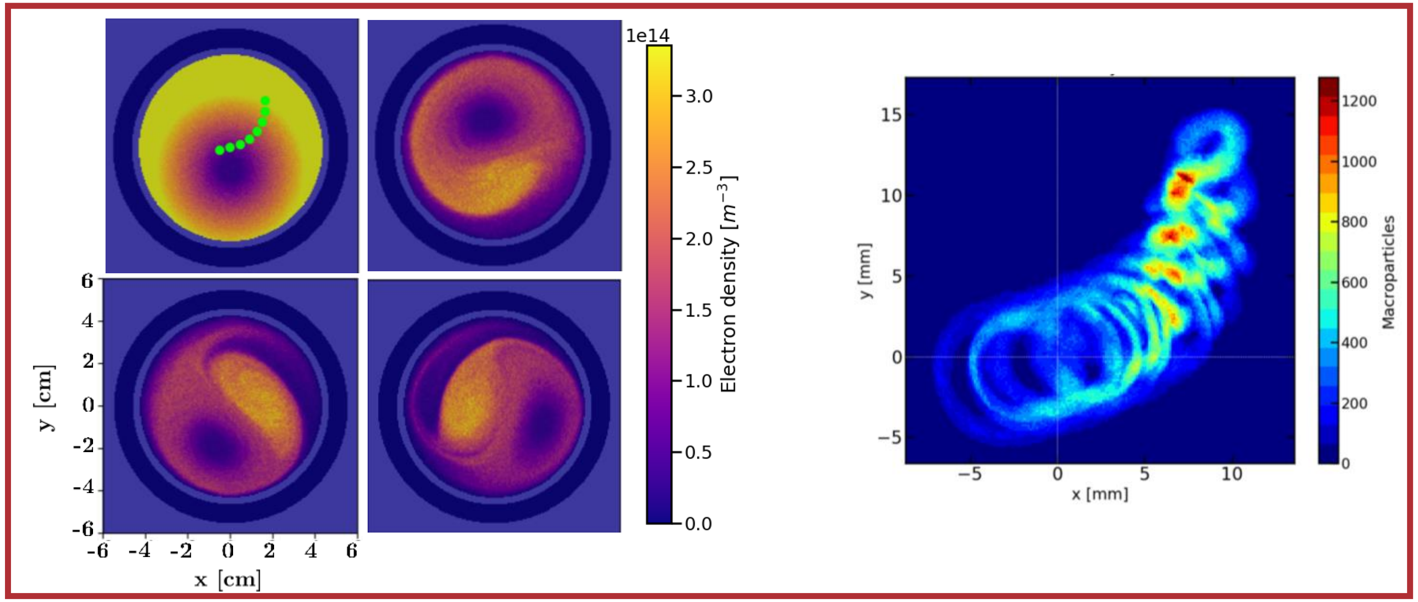
+ beam-tracking



Plasma instabilities impact on beam transport





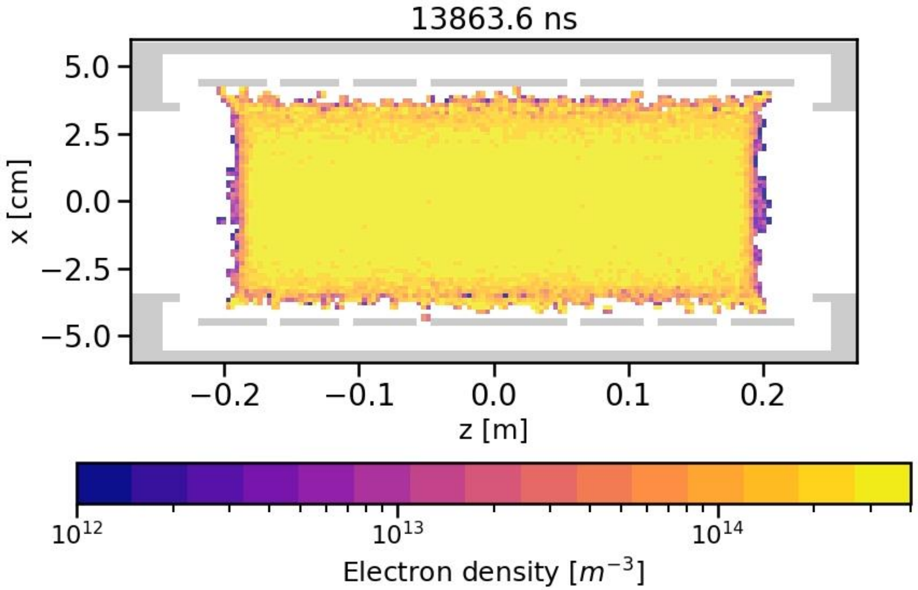


- Typical plasma instabilities observed in particle-in-cell **(PIC) simulations** with VSim
- Thin pencil-beams were tracked through the unstable plasmas

VSim, https://txcorp.com/vsim

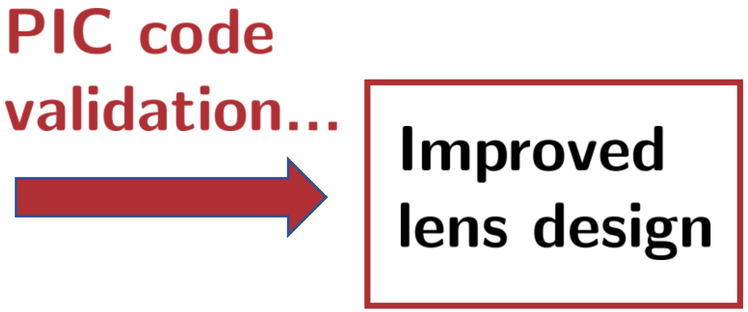
Nieter et al., J. Comput. Phys. 196, 448-473 (2004)

Model for the stable operation of the lens



PIC simulations of stable plasma:

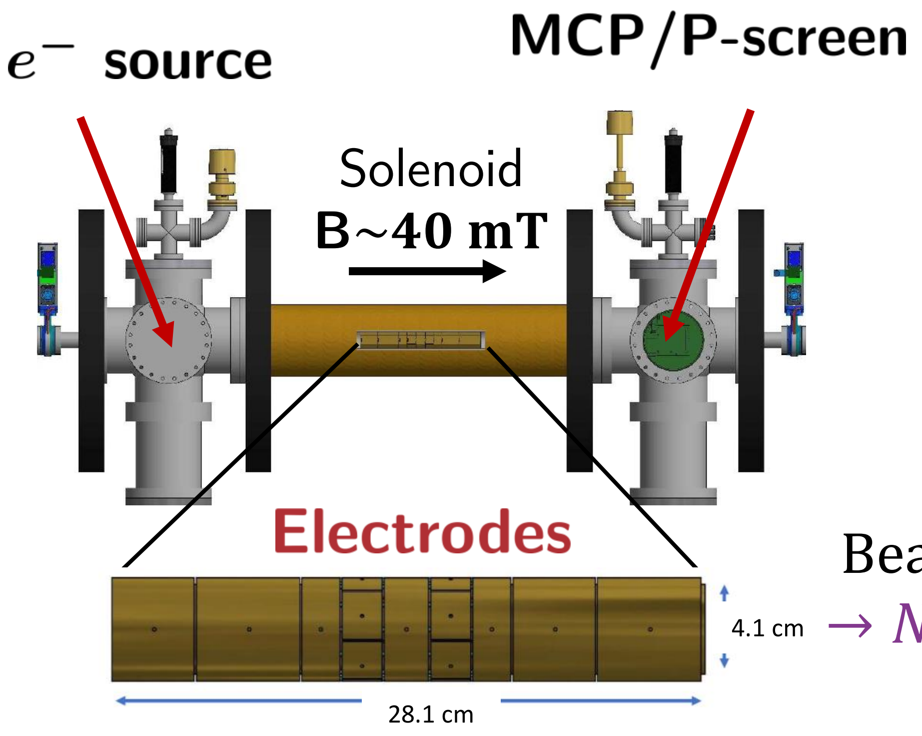
- Electron densities of 10^{14}–$10^{15}\,\mathrm{m}^{-3}$ remain confined
- Plasma is stable for $t \leq 20\,\mu\mathrm{s}$ and rotates around beam axis
- The lens is partially filled



PIC code validation...

Improved lens design

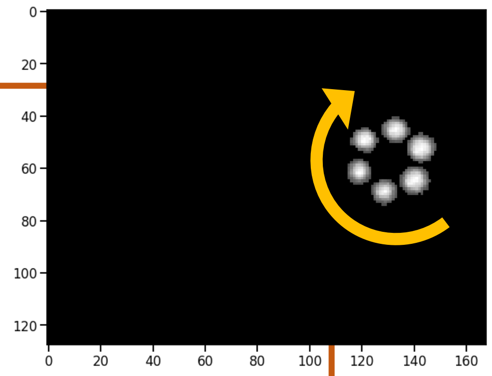
Measurements with trapped electrons–1

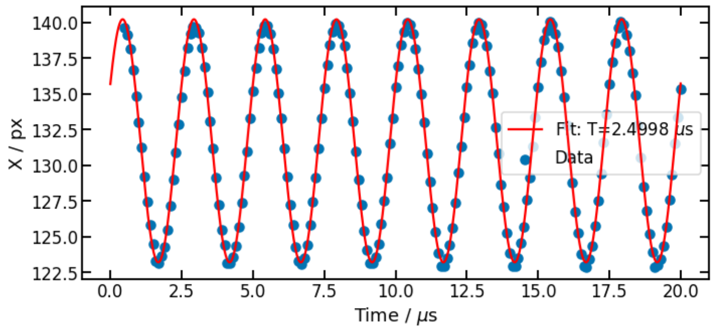


Beam catching
→ $N_e \sim 10^5 – 10^6$

6 m positron beamline:

- e^+/e^- plasma (cooling & compression)
- Destructive + non-destructive diagnostics
- Configurable trapping region



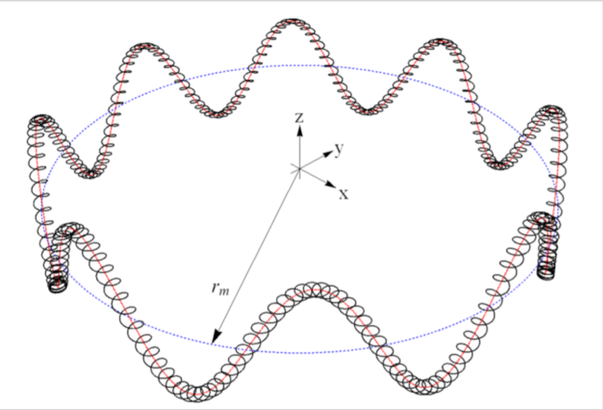


Single electron undergoes:

Axial motion (~5– 25 MHz)

Modified cyclotron motion (~1 GHz)

Magnetron rotation (~5– 500 kHz)

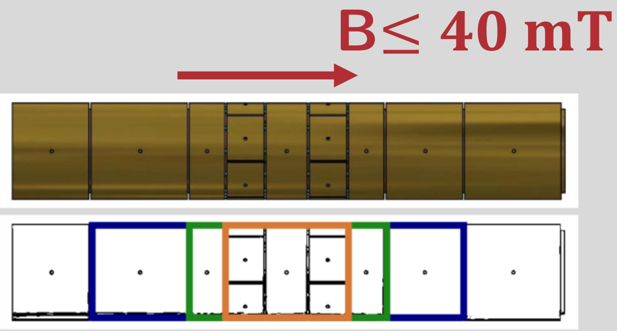


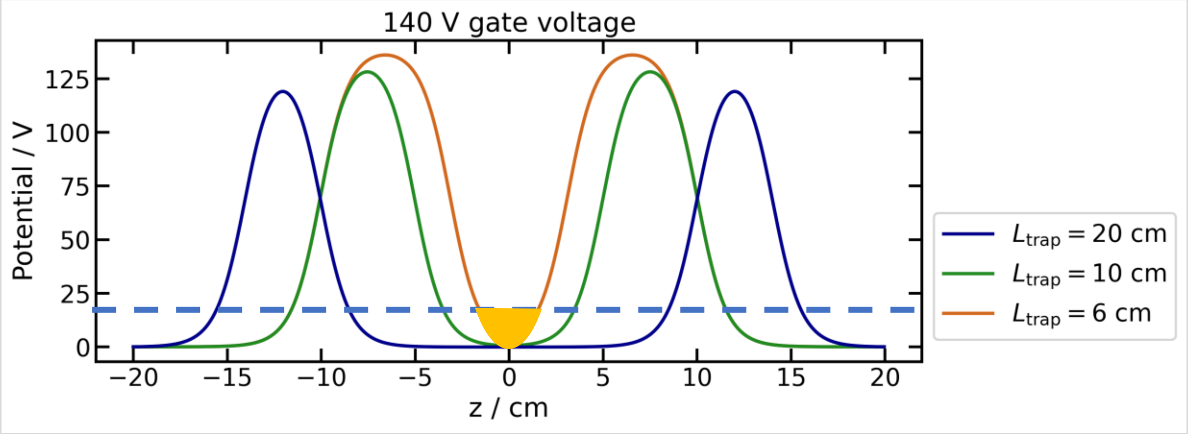
A.Deller, PhD Thesis, Swansea University (2013)

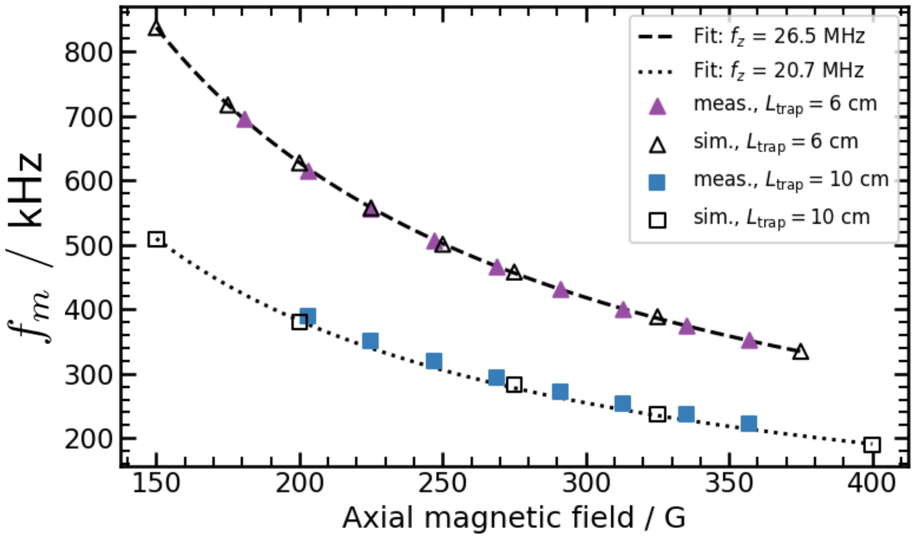
Measurements with trapped electrons–2

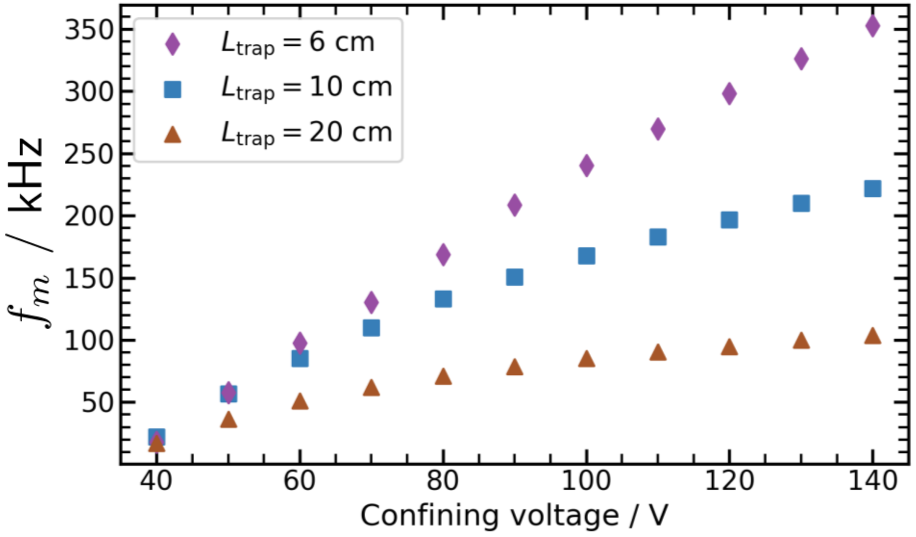
Magnetron frequency f_m measured for several configurations of the trap :

- **Catch-hold-dump sequences**
- **Destructive measurements on P-screen**









Summary

- Ongoing developments promise significant progress in performance of laser-ion accelerators (energy range, repetition rate, stability, feedback control). **New technologies are required for optimal capture, focusing, and beam-transport which must:**
  - be **compact and cost-effective** in line with the laser-driven sources,
  - maintain these features **at higher ion energies.**
- **First Gabor lens prototype built for LhARA was prone to plasma instabilities**
  - PIC code used for **simulations of both stable and unstable trapped plasma**
- **Ongoing work to validate the PIC code against measurements on existing plasma trap**
- **Towards practical Gabor lens**
  - Follow-up measurements at Swansea at higher plasma densities
  - LhARA work package milestone: **design & construction of a new Gabor lens test bench**

Thank you for listening!

Imperial College London

Department of Physics

Faculty of Medicine

ICR The Institute of Cancer Research

Medical Research Council

UKRI Oxford Institute for Radiation Oncology

University of Oxford

JAI John Adams Institute for Accelerator Science

CCAP Centre for the Clinical Application of Particles

Imperial College Academic Health Science Centre

Cancer Research UK | Imperial Centre

NHS Imperial College Healthcare NHS Trust

MANCHESTER 1824 The University of Manchester

University of Birmingham

Queen's University Belfast

University of Liverpool

Lancaster University

University of Strathclyde Glasgow Department of Physics

UCL Medical Physics & Biomedical Engineering

Royal Holloway University of London

University

Clinical

Partners

Accelerator

Industry

Laboratory

NHS University Hospitals Birmingham NHS Foundation Trust

NHS The Clatterbridge Cancer Centre NHS Foundation Trust

institut Curie

UKRI Science and Technology Facilities Council

INFN Catania

ASTeC

Particle Physics Department

ISIS Neutron and Muon Source

CLF central laser facility

Swansea University Prifysgol Abertawe

University of Birmingham | Positron Imaging Centre

University of Birmingham | Cyclotron Facility

The Cockcroft Institute of Accelerator Science and Technology

Corerain 鲲云科技

LEO Cancer Care

MAXELER Technologies Maximum Performance Computing

The Rosalind Franklin Institute

NPL National Physical Laboratory

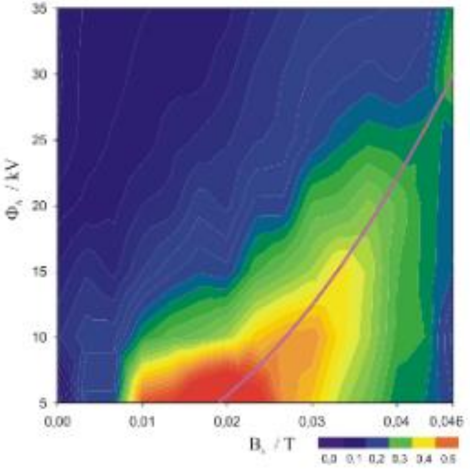
LhARA Laser-hybrid Accelerator for Radiobiological Applications

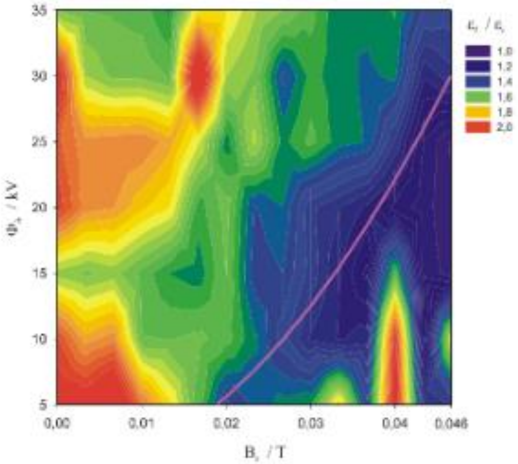
Back-up slides

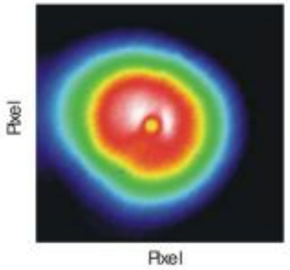
Previous studies of Gabor lenses

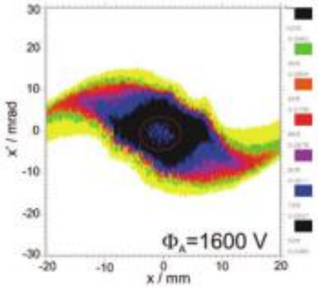
- Previous designs and experiments: performance lower than predicted
  - focusing strength (low filling factors)[1,4]
  - aberrations (focusing quality)[1]
  - emittance growth[2]

- Previous numerical simulations
  - state of the plasma strongly depends on the external field strengths
  - plasma instabilities[3,4]


filling factor


emittance growth





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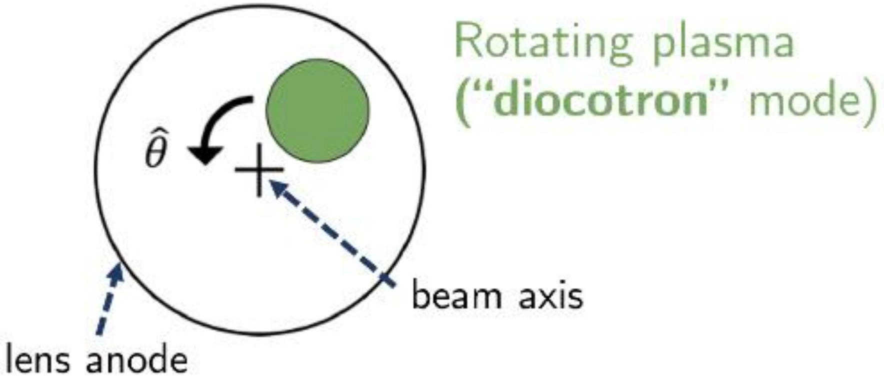
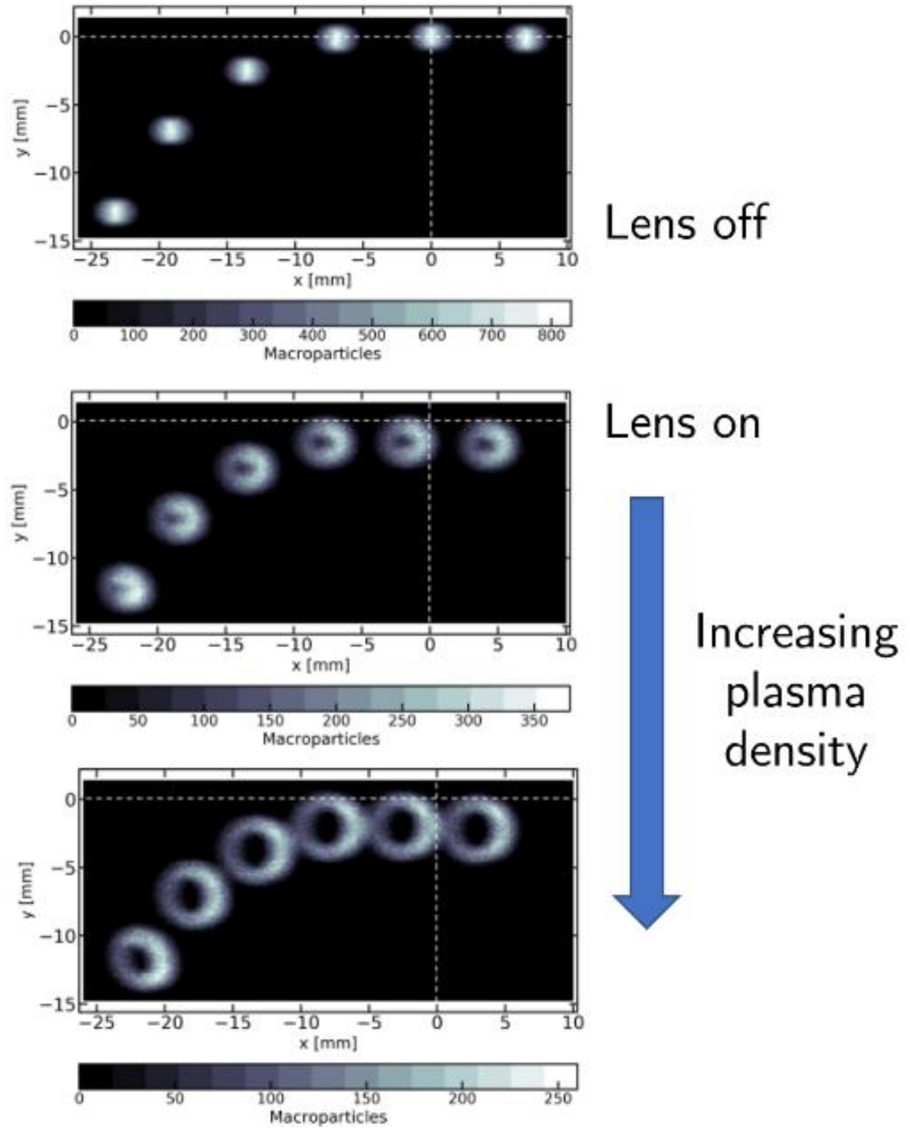
[1] O. Meusel, arXiv:1309.4654
[2] J.A. Palkovic, FERMILAB-CONF-88-177, 88-10-03
[3] M. Droba, IPAC 2013, TUPWO008
[4] K. Schulte, IPAC 2012, TUPPC007

Coherent plasma rotation

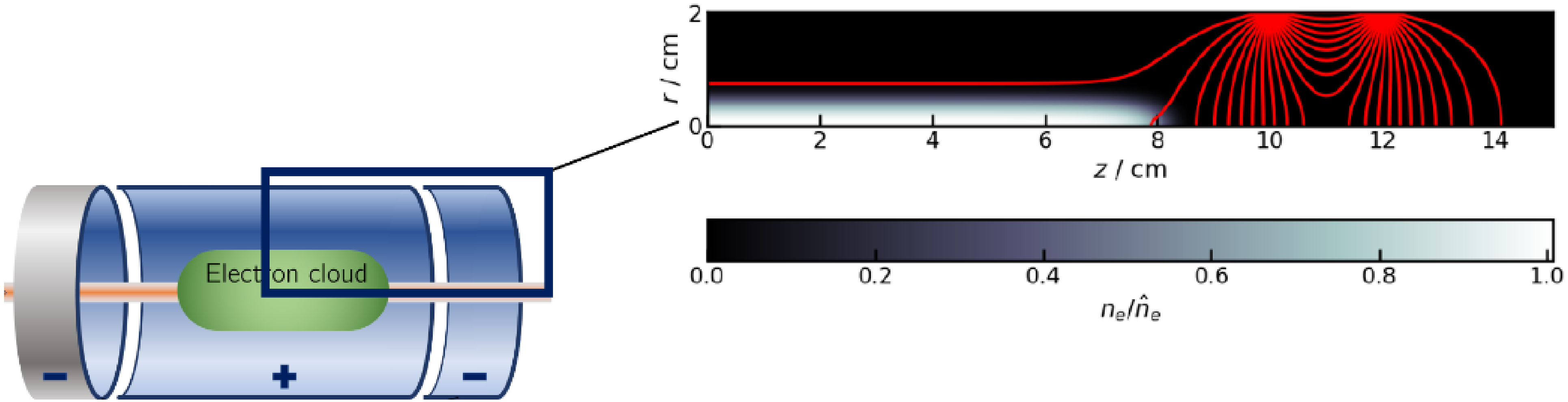


- ▶ **Uniform** plasma column, radially displaced
- ▶ Radial image charge field causes an **E**×**B** drift of the plasma in the $\hat{\theta}$ direction
- ▶ Proton tracked through time-dependent electric field map in BDSIM
  - ▷ Ring-like structure reproduced



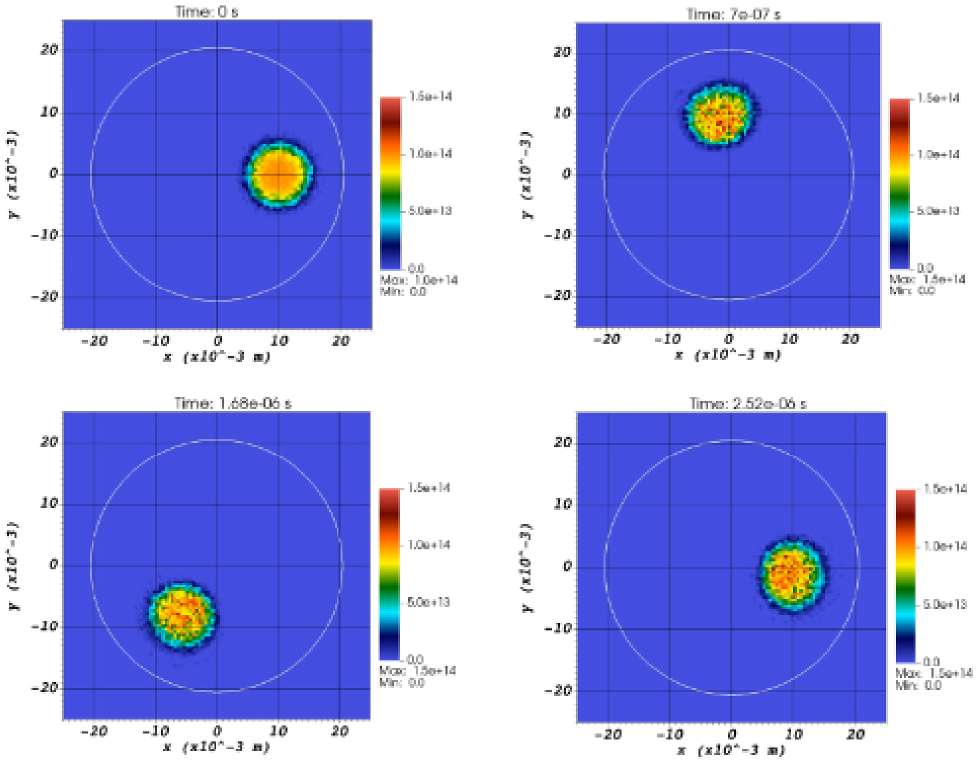
Modelling the stable state of the plasma

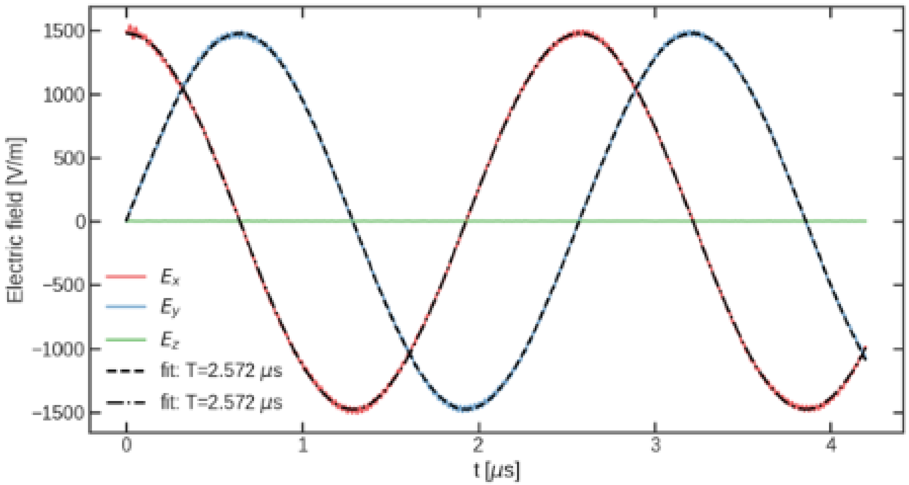
- PIC simulations are limited to short time scales $\sim 10\,\mu s$
  - Absence of collisions
- Alternative for fully thermalised plasma
  - Numerically solve a highly non-linear 2-D Poisson equation



- Both methods (1), (2) can provide more **realistic field maps** for beam-tracking

PIC simulation of dicotron mode





- Rotation of the plasma column observed in PIC simulations
  - both at low and high electron density
  - for a small number of periods limited by CPU time