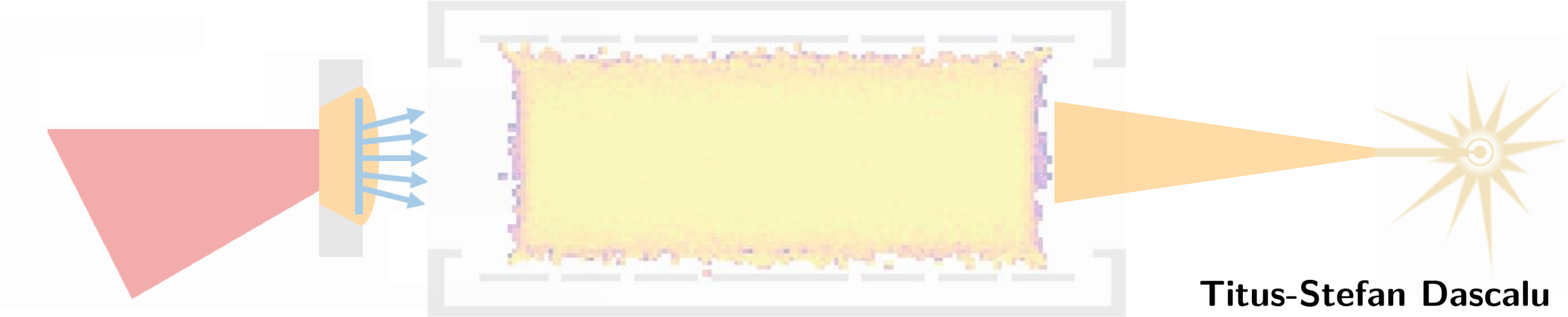
Investigation of plasma (Gabor) lenses for capture and focusing of laser-driven ions



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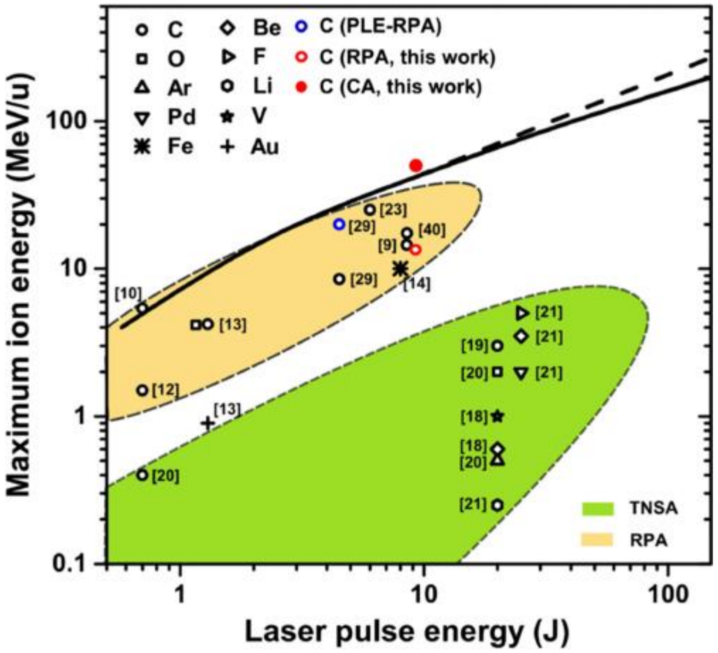
IOP HEPP & APP Annual Conference
6th April 2022

Laser-driven ion sources

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



High brightness

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

High laminarity

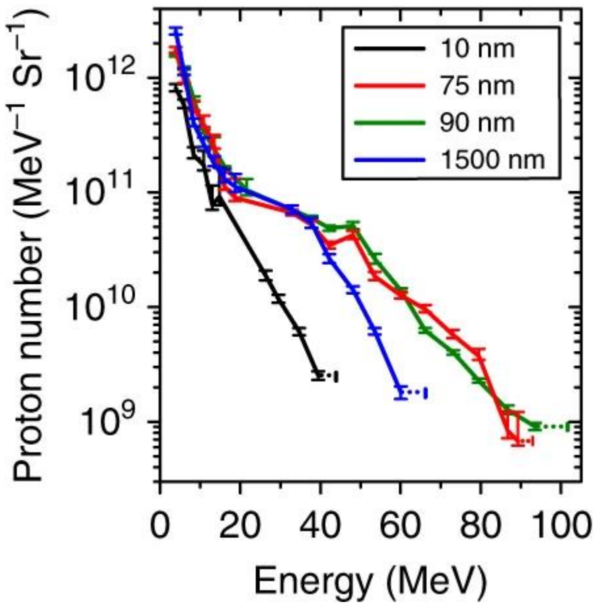
rms emittance $< 0.01\,\pi$ mm-mrad

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

Triggarable

Broadband energy

quasi-thermal spectrum

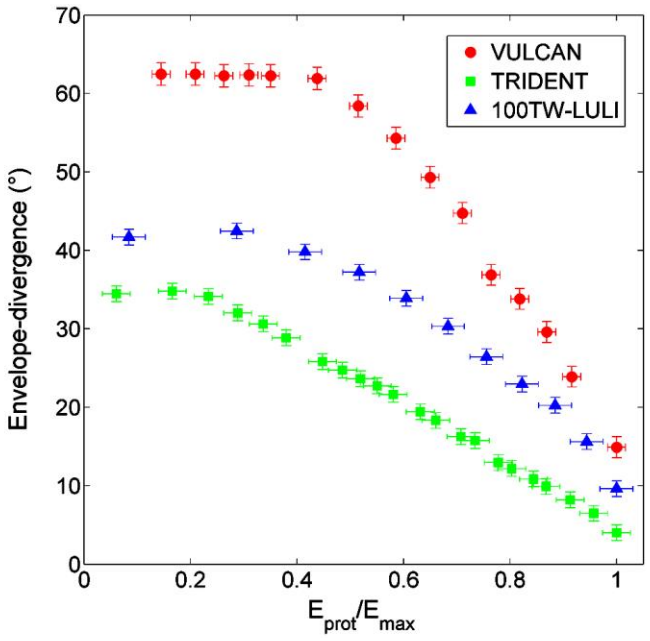


Higginson et al., Nat. Commun. 9, 724 (2018)

Generated beams are typically:

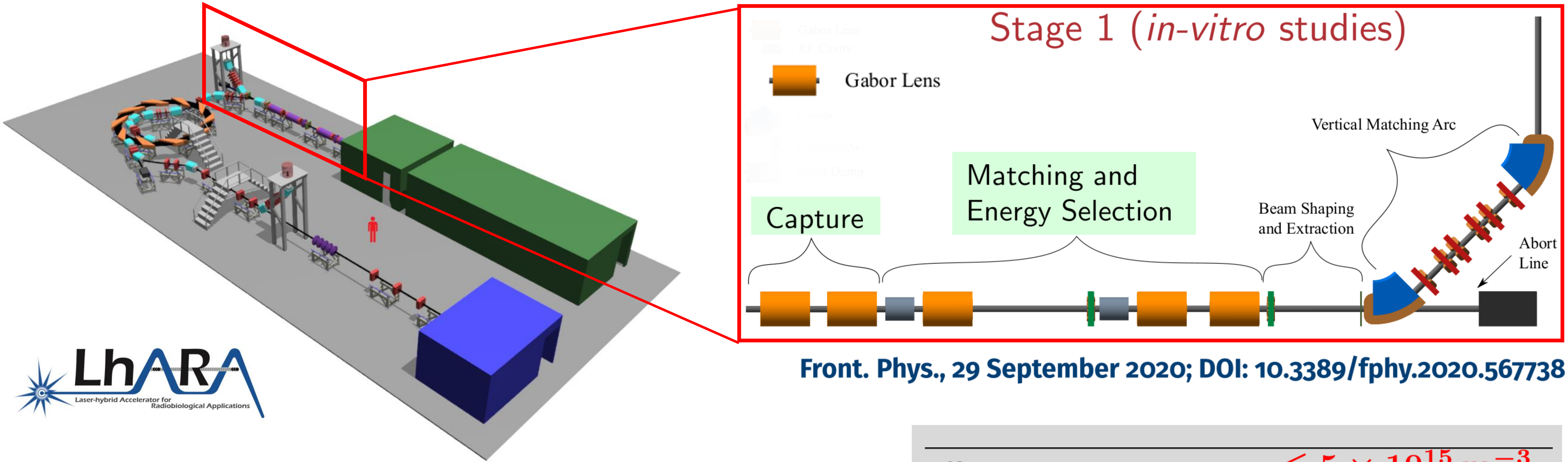
Highly divergent

$> 10^\circ$ emission cone



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

Plasma lenses for LhARA



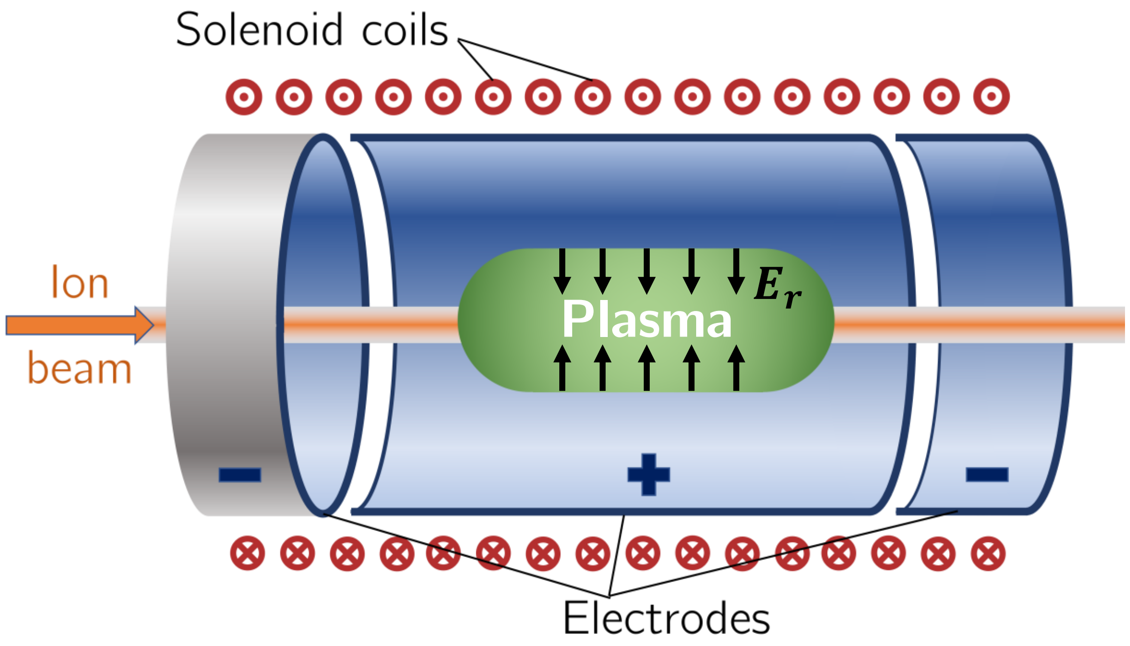
Front. Phys., 29 September 2020; DOI: 10.3389/fphy.2020.567738

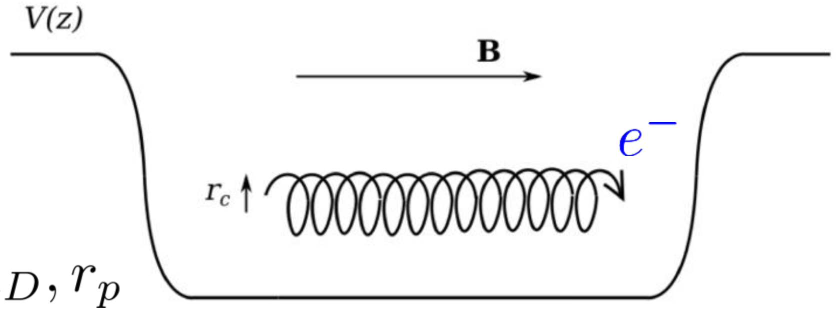
- **Laser-driven, high-flux proton/ion source for systematic radiobiology programme**
  - ▷ Overcome instantaneous dose-rate limitations (capture at > 10 MeV)
  - ▷ Proton/ion bunches as short as 10–40 ns
  - ▷ Fast post-acceleration with an FFA

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

Electron-plasma (Gabor) lens



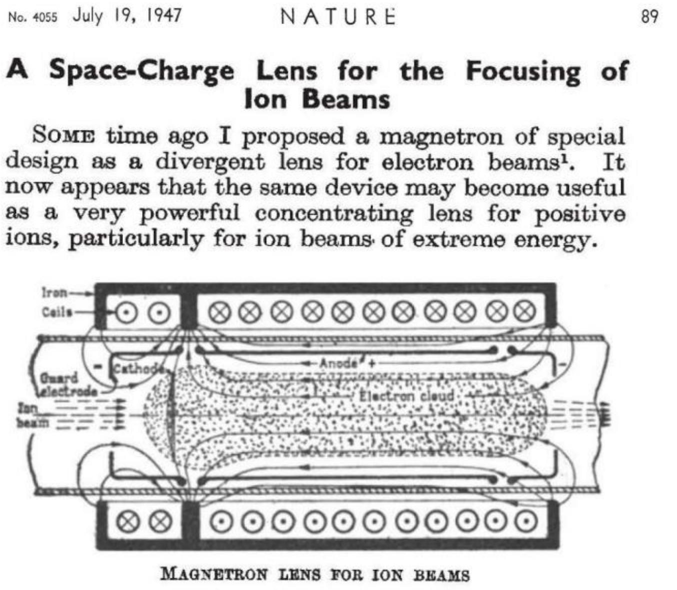


$r_c \ll \lambda_D, r_p$

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

U = ion K.E.

n_e = electron number density



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 beams[1]. 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

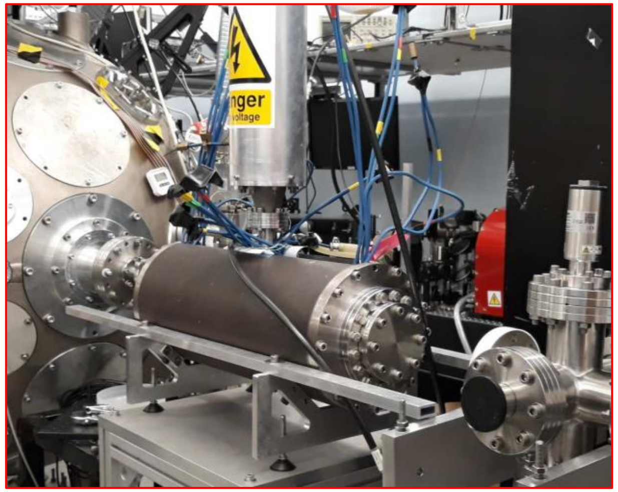
Gabor, Nature 160, 89-90 (1947)

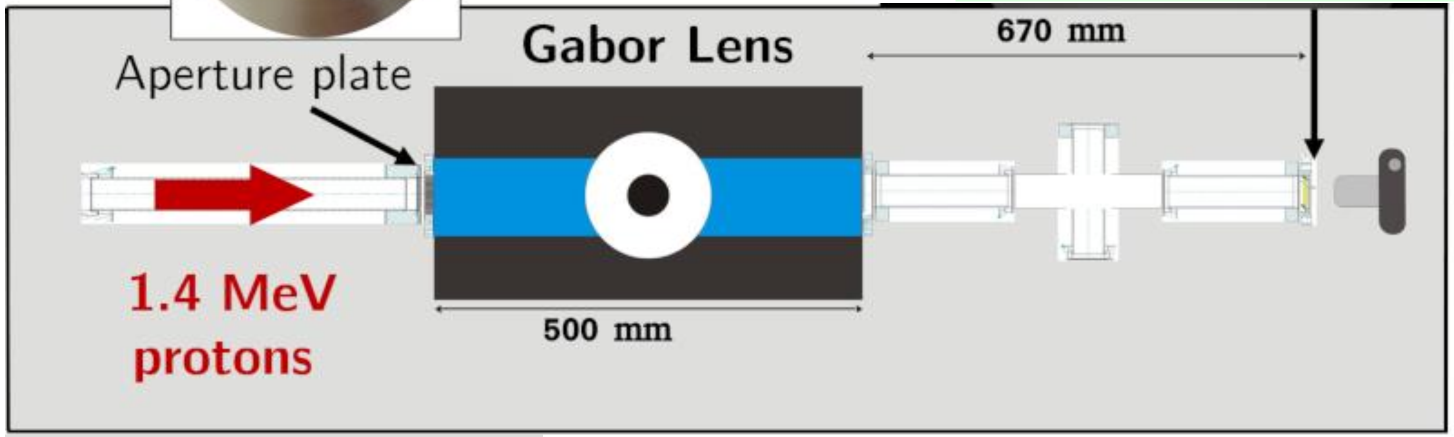
$$B_{GPL} = B_{sol}\sqrt{\frac{m_e}{m_{ion}}Z}$$

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

Lens prototype built and tested with proton beams

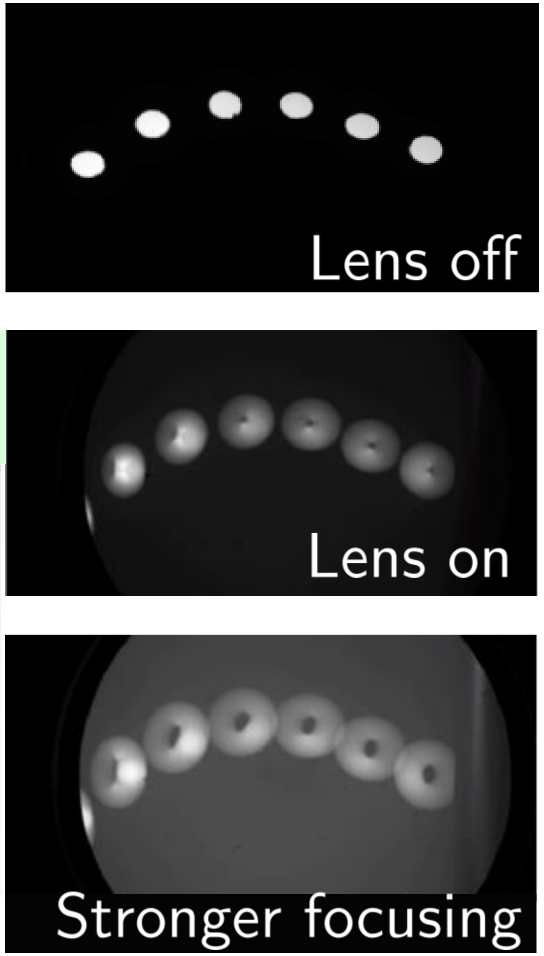
Nonnenmacher et al., Appl. Sci. 11(10), 4357 (2021)

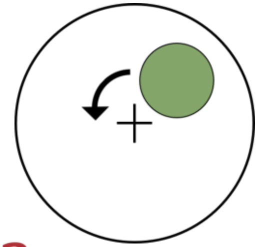




Beam test setup

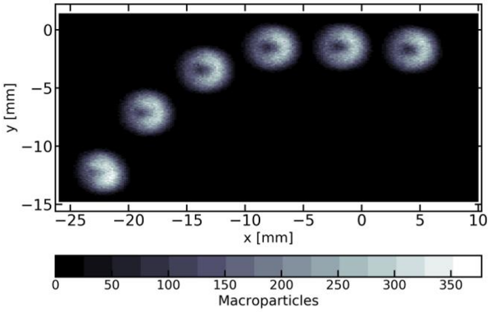
Phosphor screen



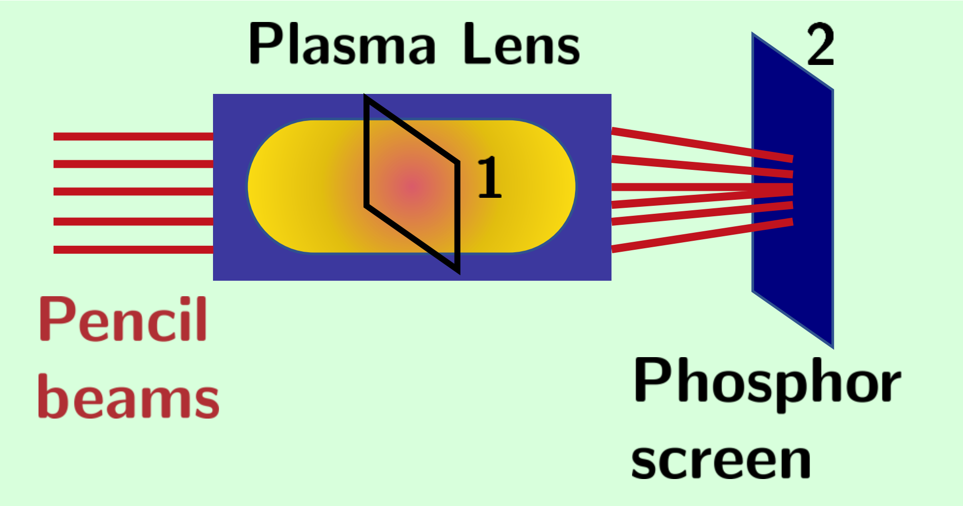


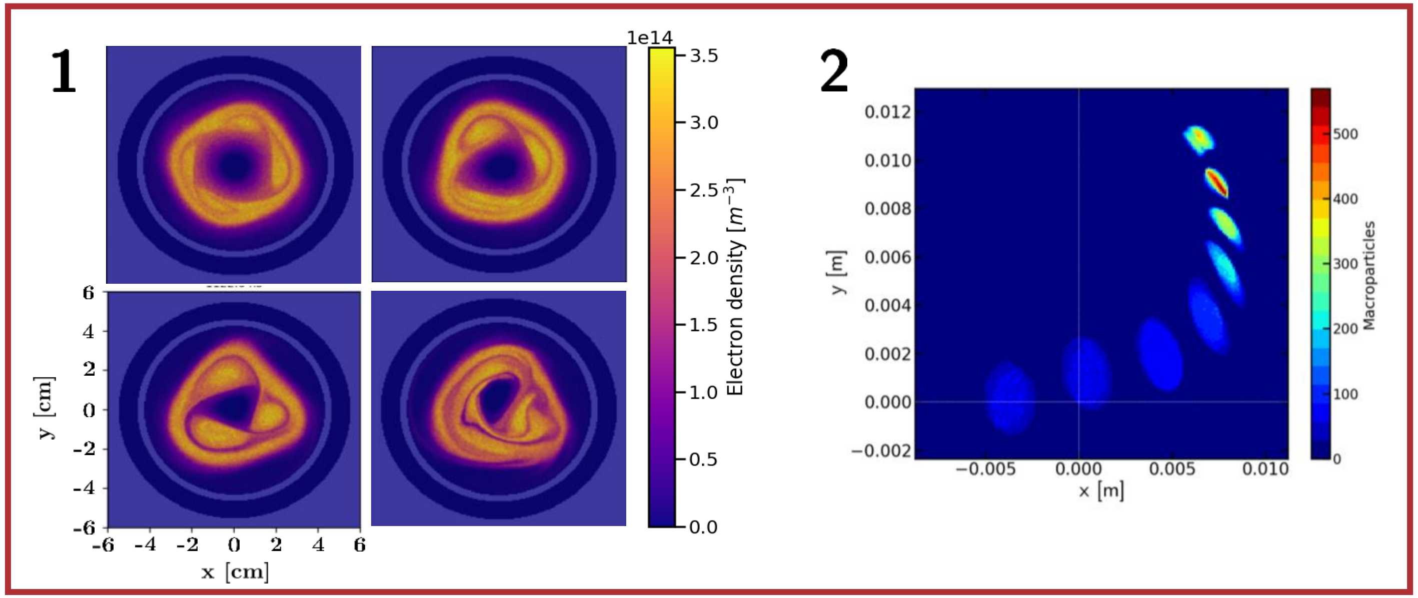
Plasma coherent rotation

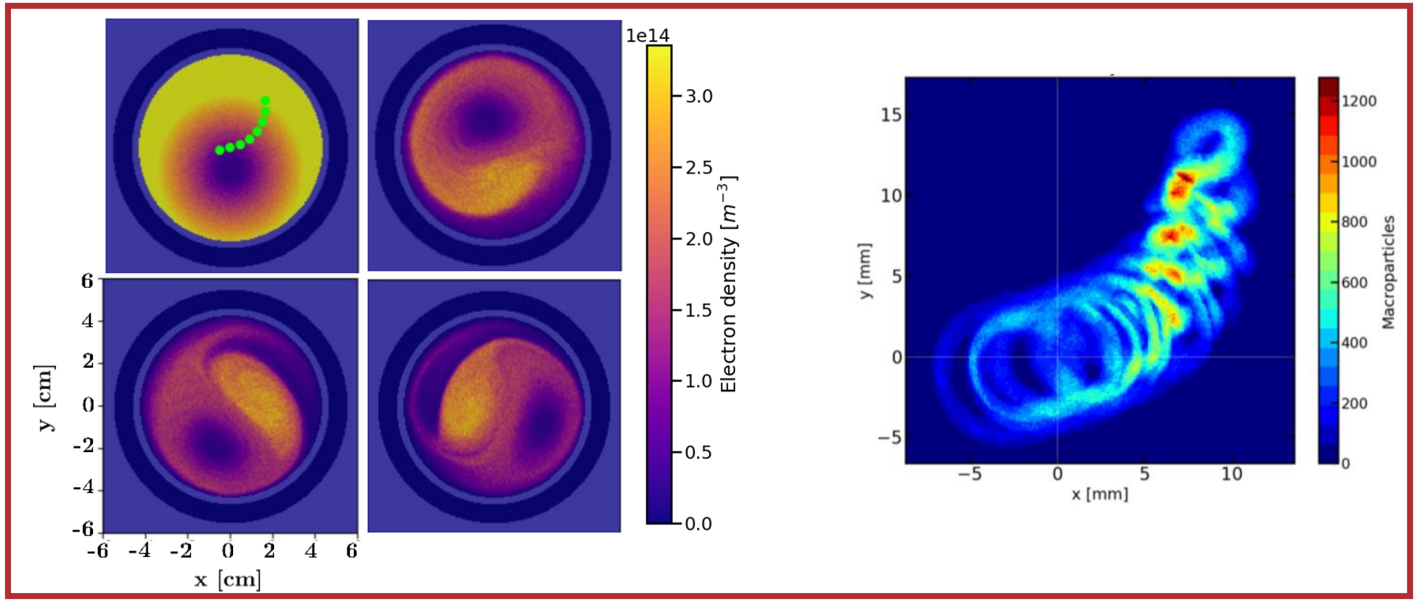
+ beam-tracking



Plasma instabilities impact on beam transport





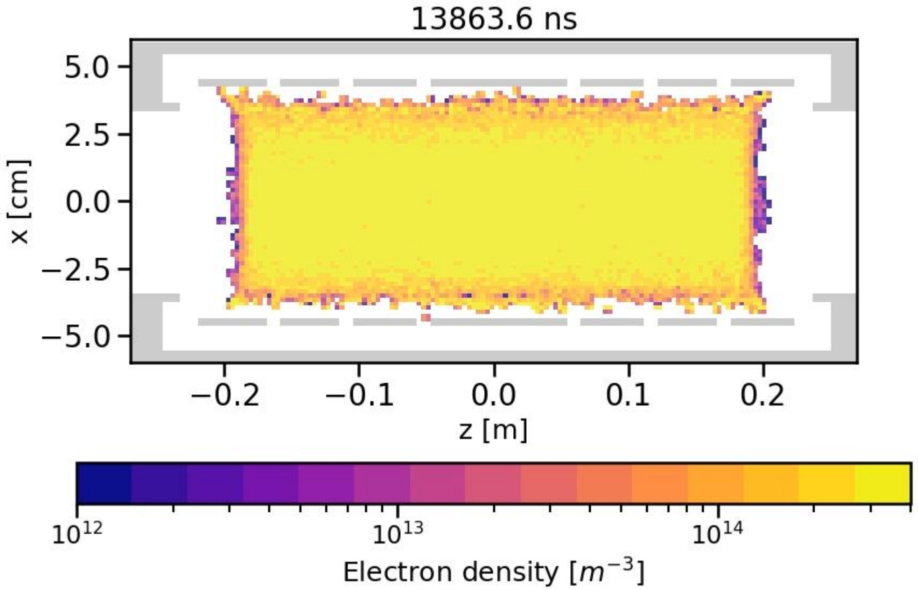


- Typical plasma instabilities observed in particle-in-cell **(PIC) simulations** with VSim
- Thin pencil-beams were tracked through the unstable plasmas

VSim, https://txcorp.com/vsim

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

Model for the stable operation of the lens



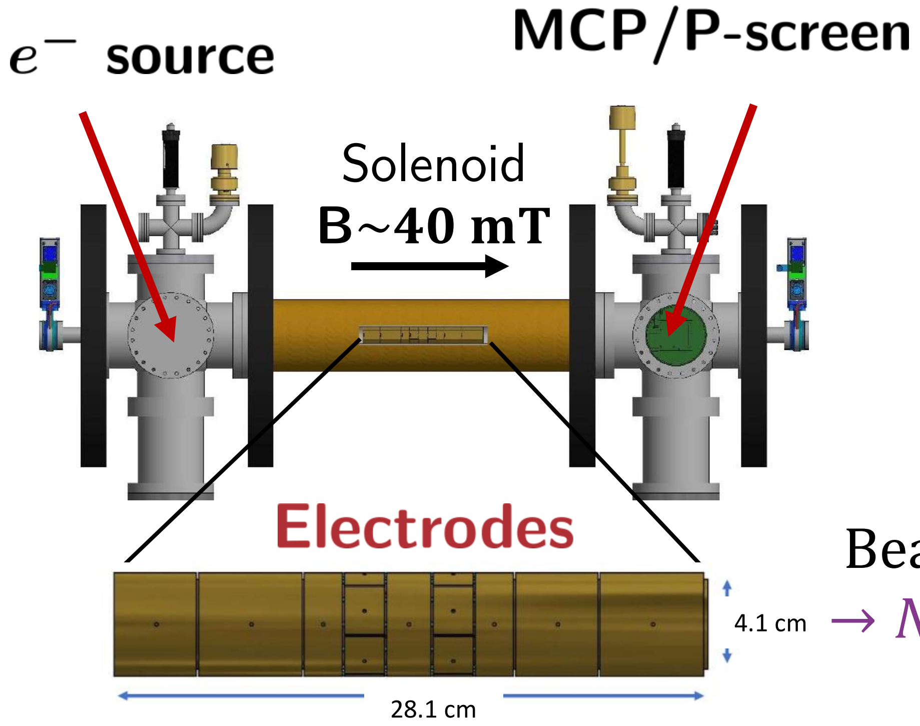
PIC simulations of stable plasma:

- 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


e^- source

MCP/P-screen

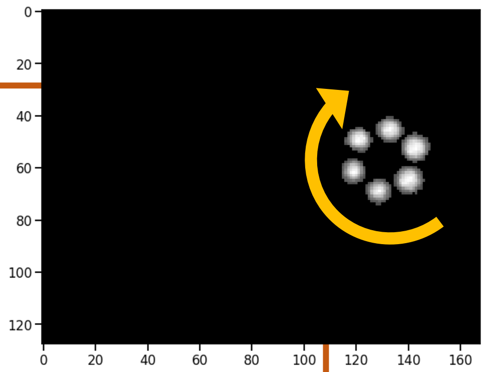
Solenoid
B~40 mT

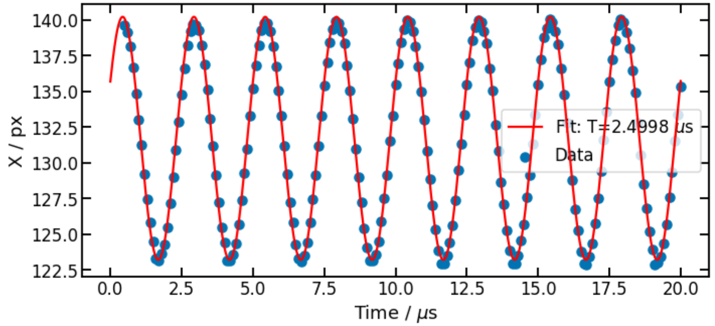
Electrodes

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

6 m positron beamline:

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



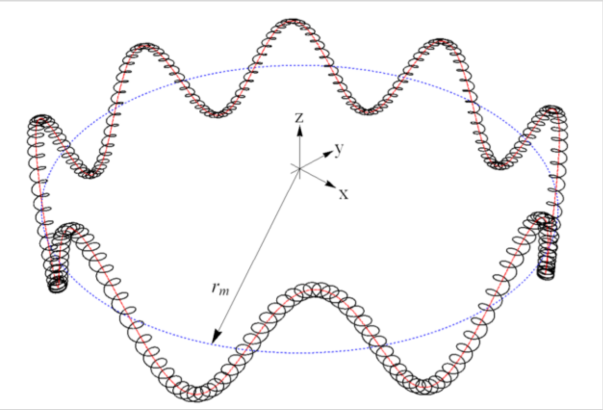


Single electron undergoes:

Axial motion (~5–25 MHz)

Modified cyclotron motion (~1 GHz)

Magnetron rotation (~5–500 kHz)

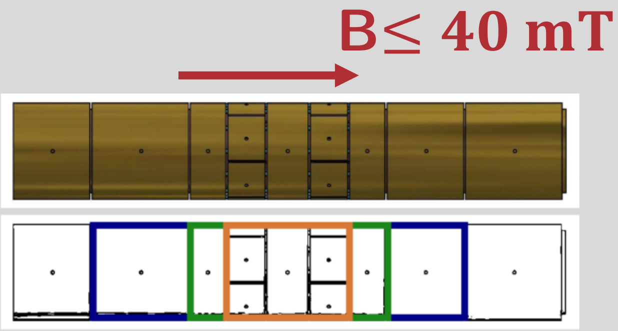


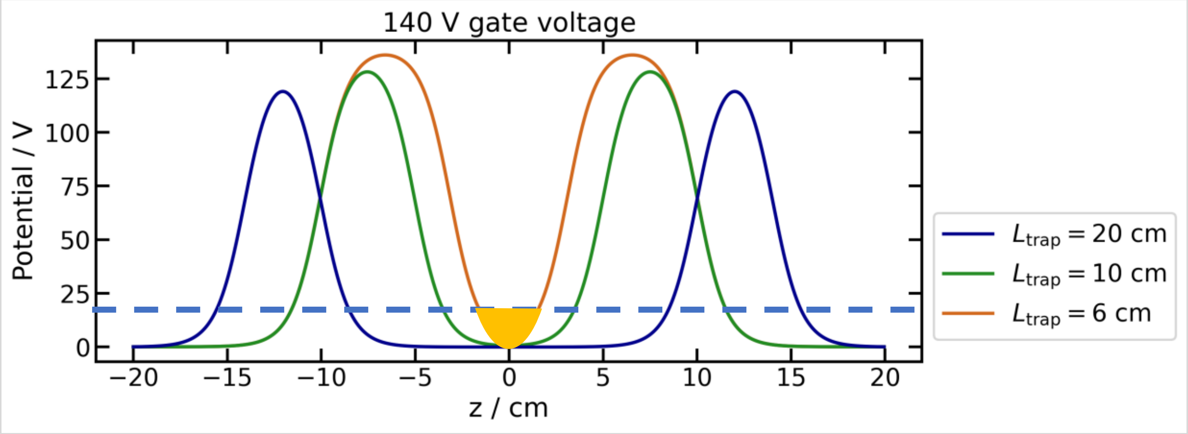
A.Deller, PhD Thesis, Swansea University (2013)

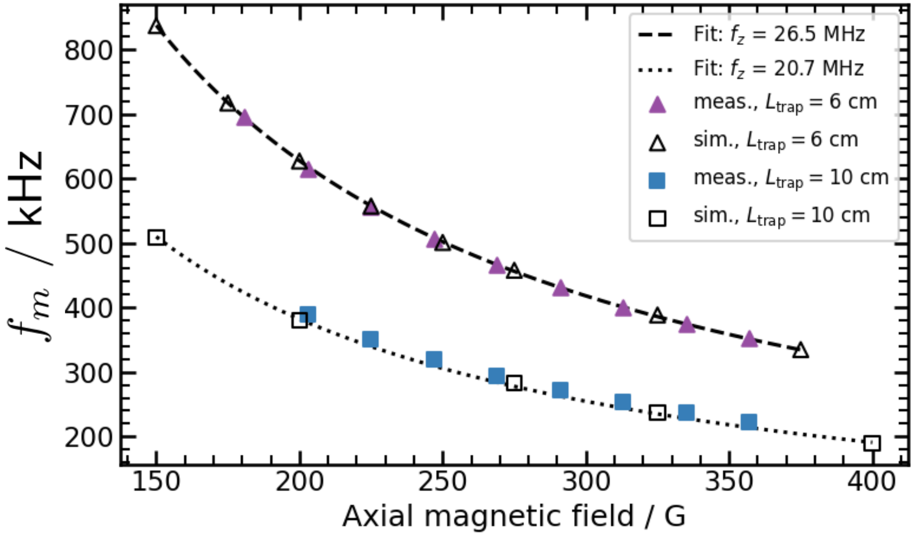
Measurements with trapped electrons–2

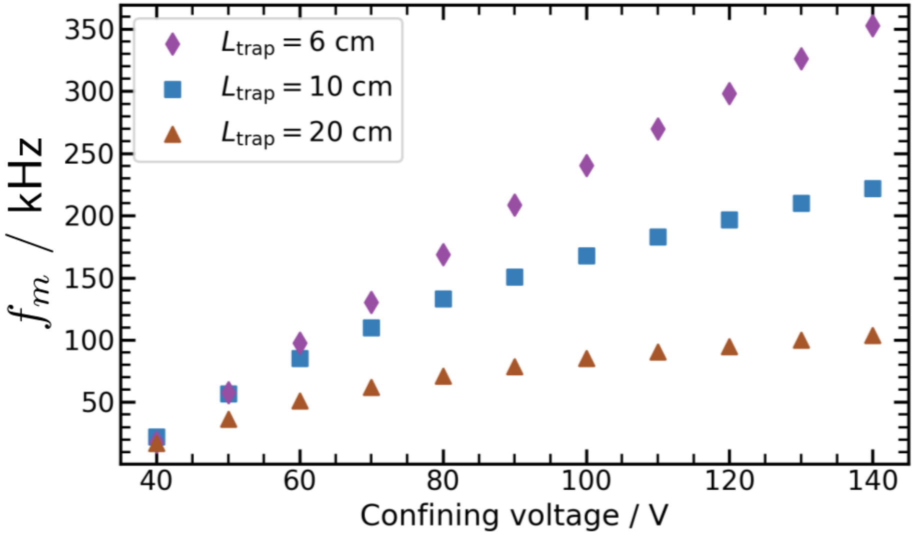
Magnetron frequency f_m measured for several configurations of the trap :

- **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**

Imperial College London

CCAP Centre for the Clinical Application of Particles

LhARA Laser-hybrid Accelerator for Radiobiological Applications

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
Laboratory
Industry

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

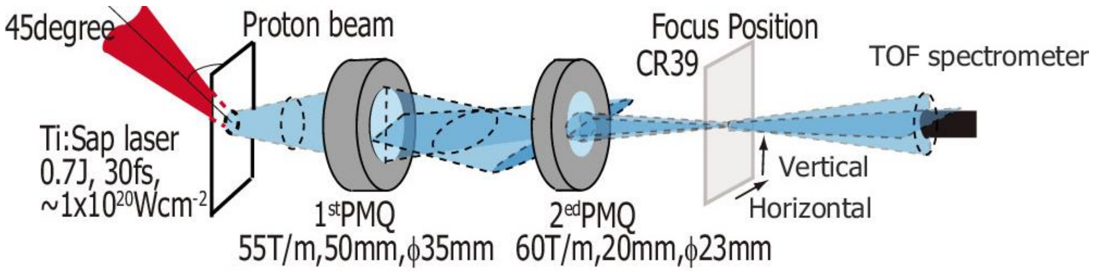
NPL National Physical Laboratory

LhARA
Laser-hybrid Accelerator for Radiobiological Applications

Back-up slides

Solutions for ion capture and transport

PMQ



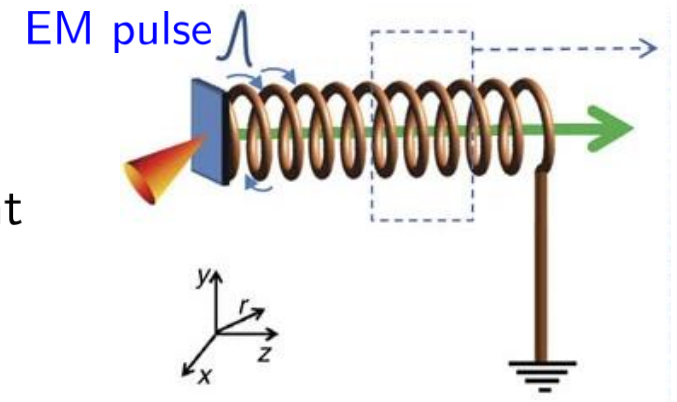
transmission $\sim 30\%$

field gradients 50–500 T/m

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

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

Helical coil targetry



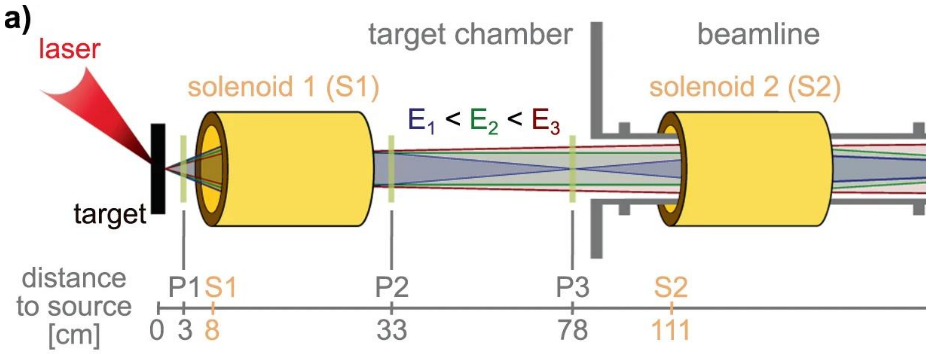
acceleration gradient ~ 2 GeV/m

divergence $< 1^\circ$

repeatability, rep. rate

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

High-field pulsed solenoids

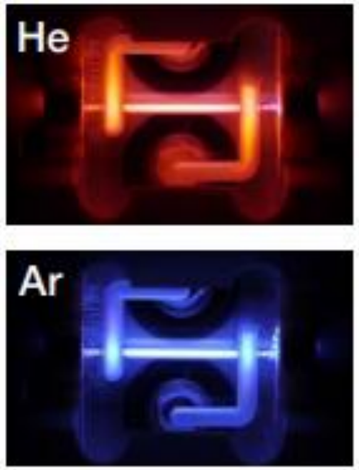


transmission $\leq 50\%$

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



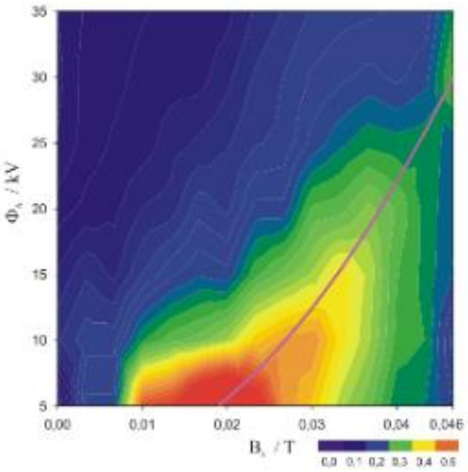
field gradient 3.6 kT/m

beam-driven plasma wakefields

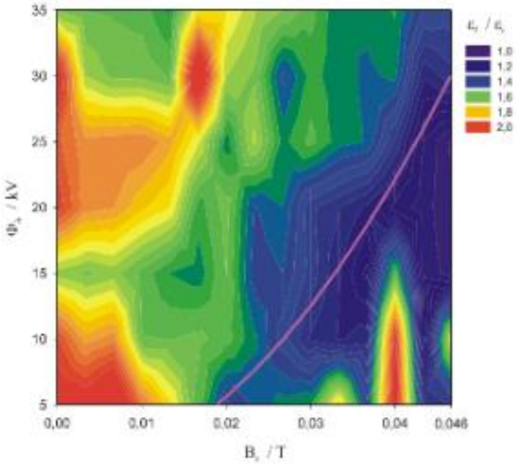
Previous studies of Gabor lenses

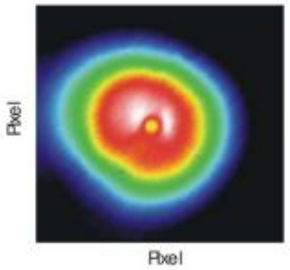
- Previous designs and experiments: performance lower than predicted
  - focusing strength (low filling factors)[1,4]
  - aberrations (focusing quality)[1]
  - emittance growth[2]
- Previous numerical simulations
  - state of the plasma strongly depends on the external field strengths
  - plasma instabilities[3,4]

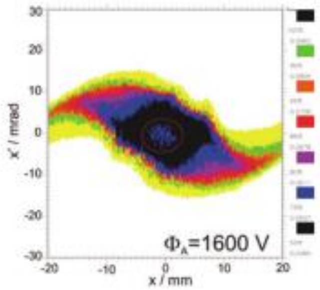
filling factor



emittance growth

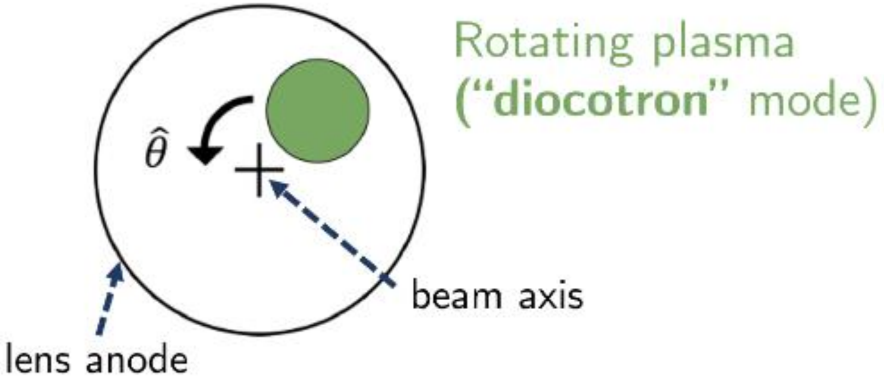




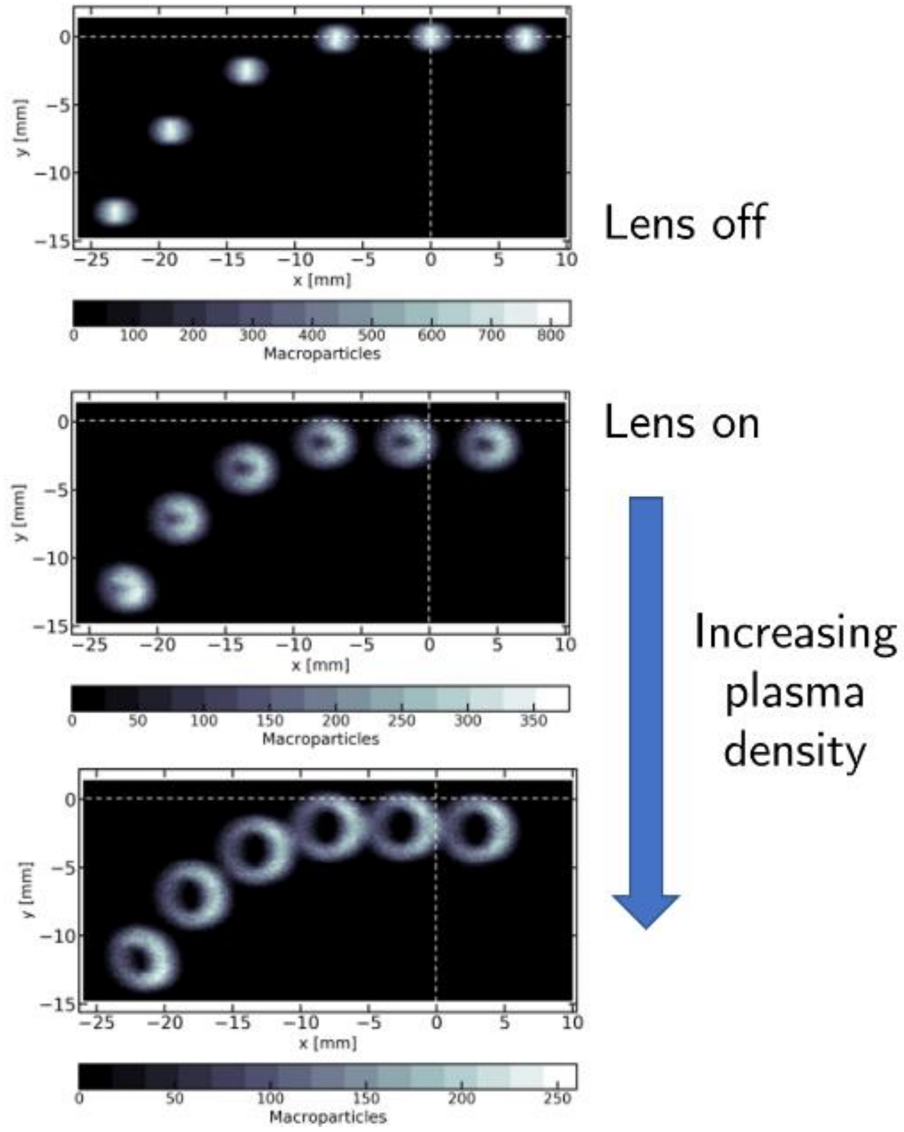


[1] O. Meusel, arXiv:1309.4654
[2] J.A. Palkovic, FERMILAB-CONF-88-177, 88-10-03
[3] M. Droba, IPAC 2013, TUPWO008
[4] K. Schulte, IPAC 2012, TUPPC007

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



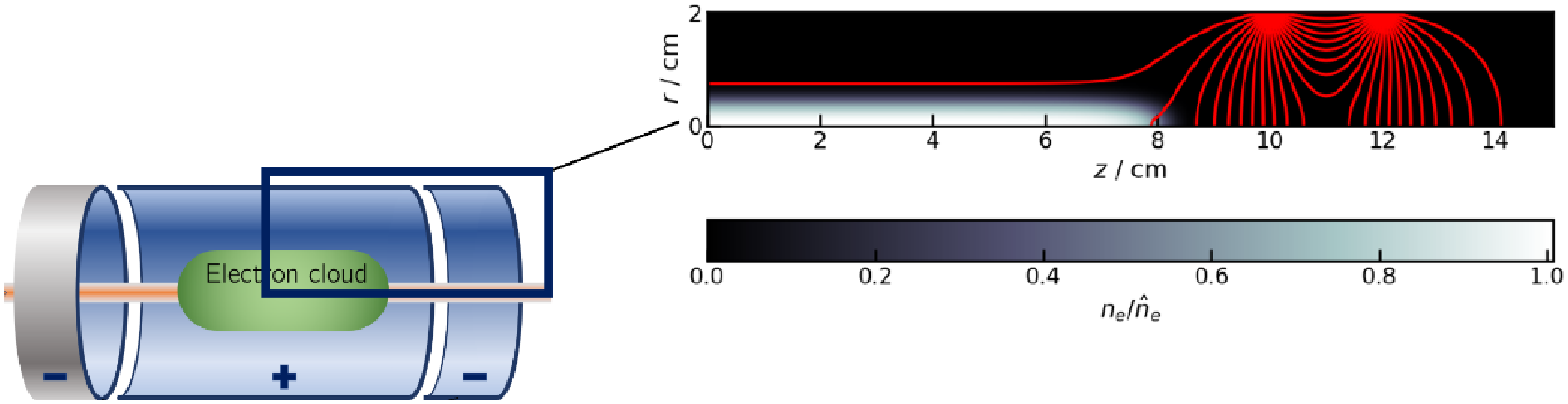
Lens off

Lens on

Increasing plasma density

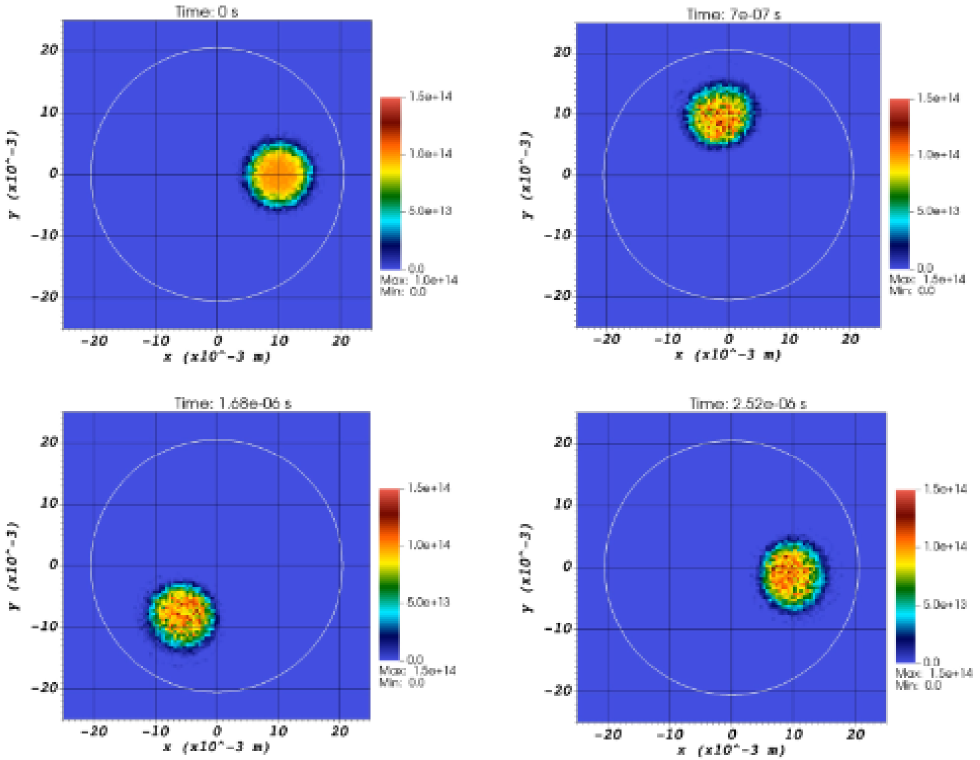
Modelling the stable state of the plasma

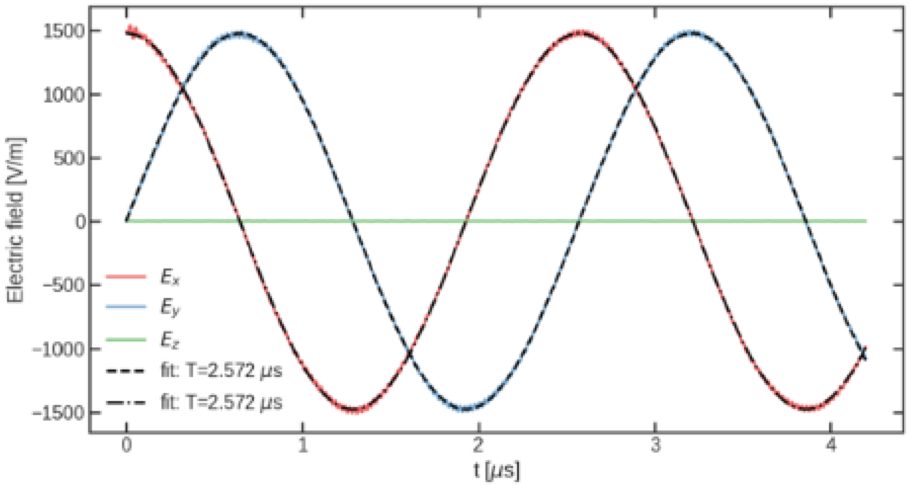
- PIC simulations are limited to short time scales $\sim 10\,\mu s$
  - Absence of collisions
- Alternative for fully thermalised plasma
  - Numerically solve a highly non-linear 2-D Poisson equation



- 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