LhARA Collaboration Meeting
WP3 – Ion Capture

15th December 2021

Chris, Mike, Will, Stefan, Titus, HT

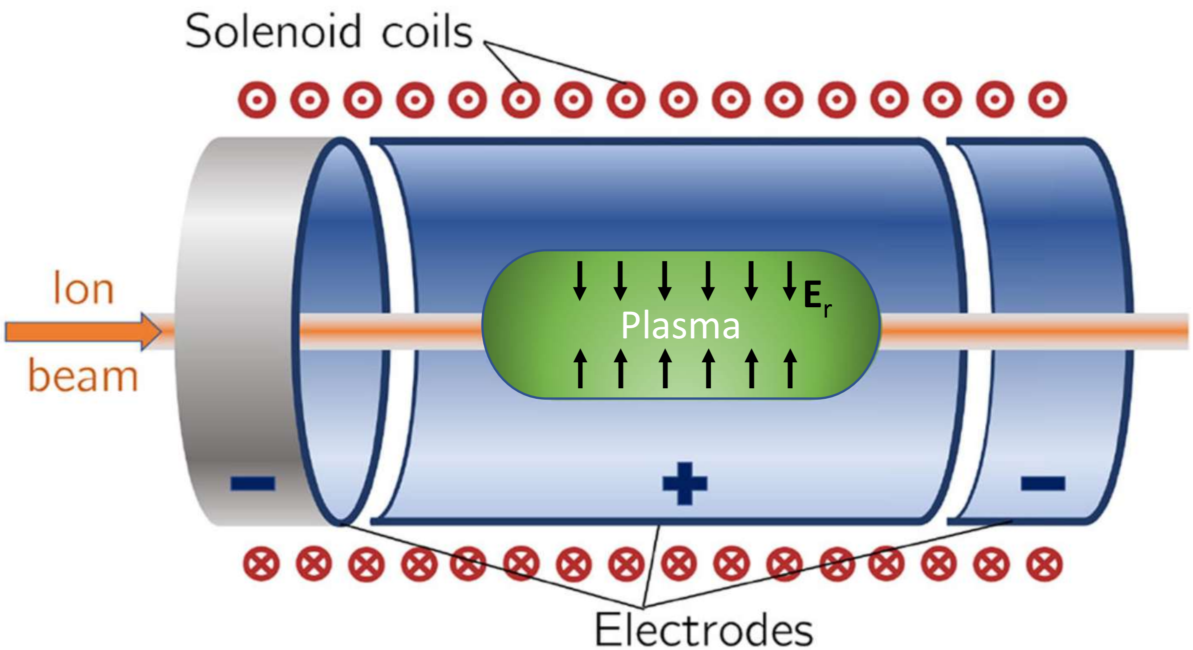
Introduction

Chris

Ion Capture Requirements

- Take output from laser source (WP2), tailor output, transmit downstream
  - Focus 15 MeV proton beam to a reasonable distance (metres)
- Use conventional, off-the-shelf technology (WP)
  - Magnets, electronics, etc
- Ensure operational stability & reliability over multiple time-scales
  - Shot-to-shot of high reptation rate source
  - Day-to-day & beyond clinician use

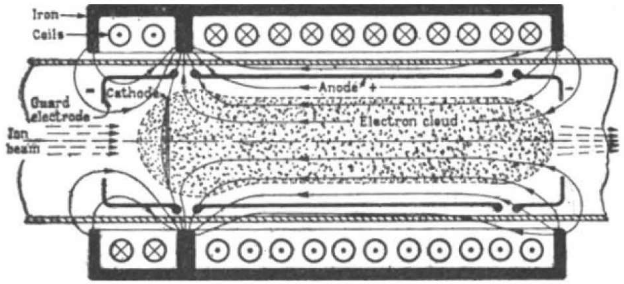
Gabor lens



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

The focal length of a Gabor lens of length l is given in terms of the electron number density by:

$$\frac{1}{f} = \frac{e^2 n_e}{4\epsilon_0 U} l \; ; \qquad (1)$$

where e is the magnitude of the electric charge of the electron, n_e is the number density of the electrons confined within the lens, ϵ_0 the permittivity of free space, and U the kinetic energy of the particle beam.

doi: 10.1038/160089b0
doi: 10.3389/fphy.2020.567738

Plasma in ALPHA for $\bar{\mathrm{H}}$ production

- E-field & large radius deleterious
  - Low density
  - Small radius
- Experimental diagnosis
  - MCP imaging
  - Mode analysis
- Modelling
- Manipulation techniques
  - Cooling (evaporative)
  - Rotating wall
  - Feedback/damping

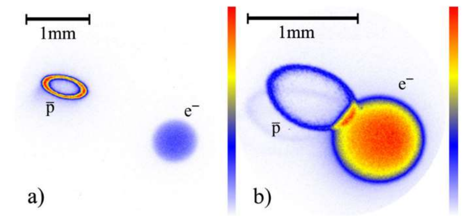
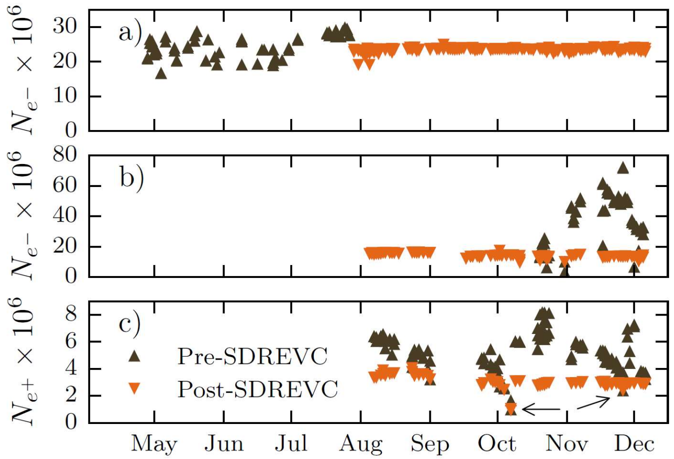
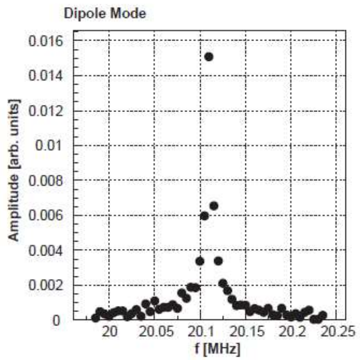
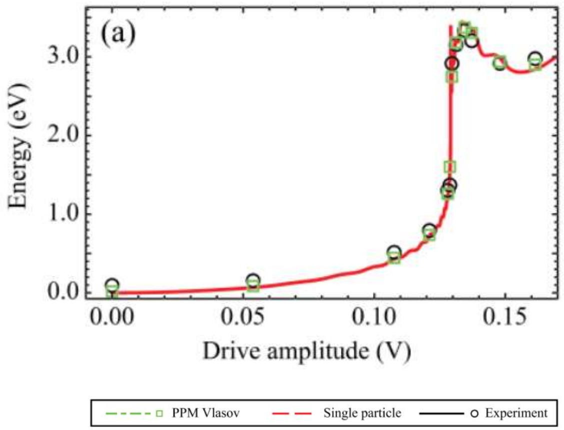
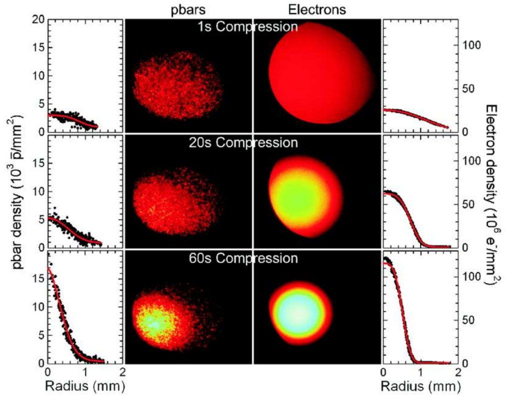


FIG. 1 (color online). Images of centrifugally separated plasmas trapped in (a) a 1 T and (b) a 3 T solenoidal field. In both









doi: 10.1103/PhysRevLett.120.025001 doi: 10.1016/j.nima.2003.09.052
doi: 10.1063/1.4801067 doi: 10.1103/PhysRevLett.106.145001
doi: 10.1103/PhysRevLett.100.203401

Beamline

HT

Vacuum Nozzle Interface

- The aperture of the nozzle collimates the particle flux from target.
  - Opening has a radius of 2 mm and widens to an exit radius of 2.87 mm.
- Simulations show the highest energy particles come off the target at an angle.
  - Adjustments of target with reference to the nozzle improves the transmission for the particles of interest.
- Simulations so far have neglected the electron population.
  - Investigations to study these electrons are ongoing.

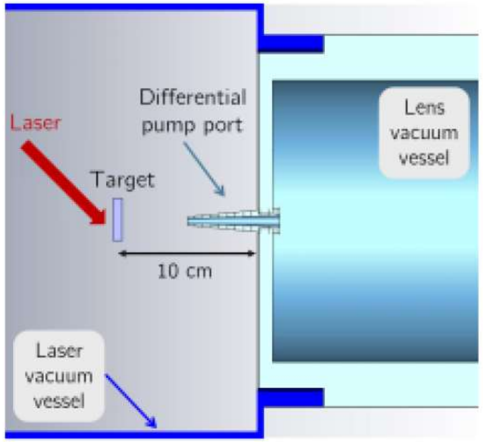


Figure: Schematic diagram of the interface between the target and the first Gabor lens.

Stage 1 Beamline Simulations

- An approximate 3D proton beam was simulated from the laser source through the Stage 1 Beamline.
  - Good match between solenoids and field maps in modelling Gabor lens.
  - Energy collimation shown to be effective.
  - Adjustments to beamline improves the transmission while still retaining a good comparison to an ideal beam.
- Next steps are to simulate and track a fully 3D beam to corroborate the results.

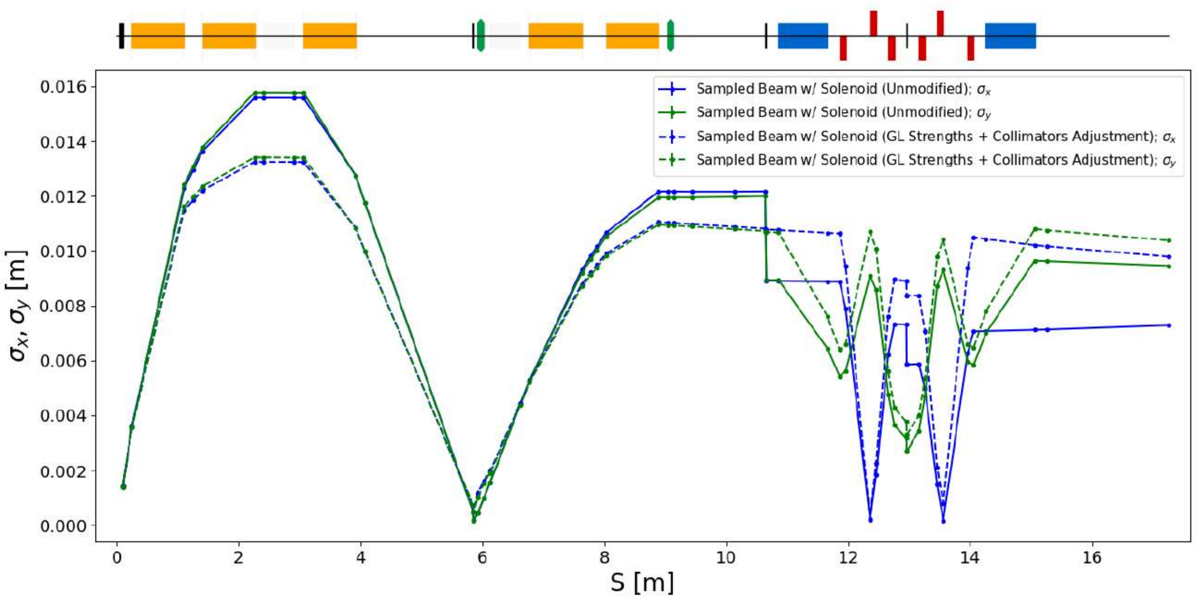
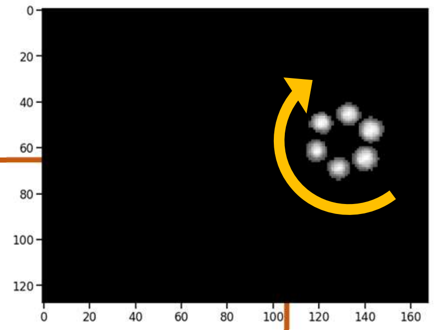


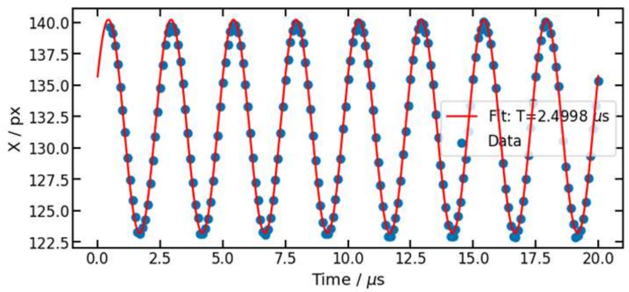
Figure: Beam size evolution comparison. Modifications decrease initial beam size, improving the transmission of the sampled beam (dashed) to the end station, with a comparison to an ideal Gaussian beam (solid).

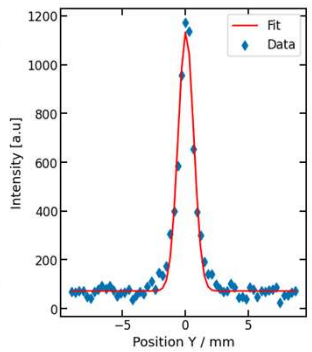
Recent results

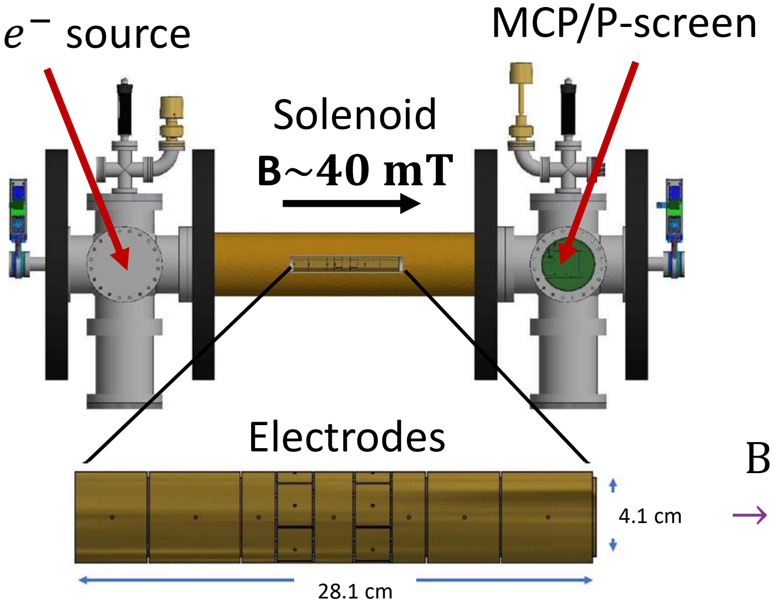
Titus

Experiment at Swansea









Beam catching

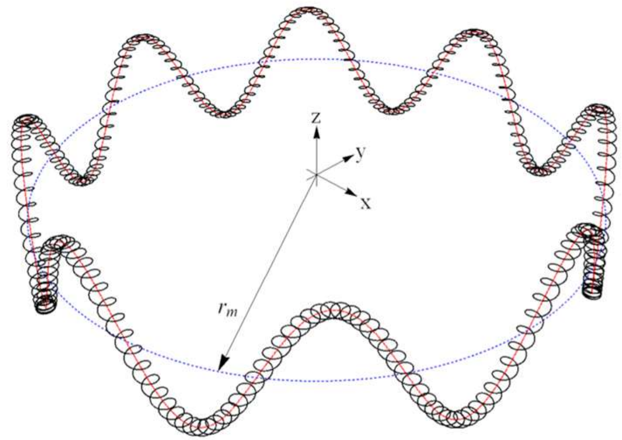
$\rightarrow N_e \sim 10^5 - 10^6$

6 m positron beamline

- e^+ / e^- trapped plasma (cooling & compression)
- Destructive/non-destructive diagnostics
- Variable trap length

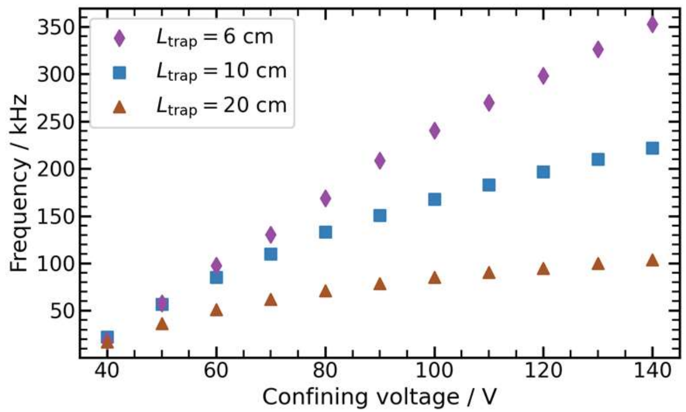
Single-particle motion

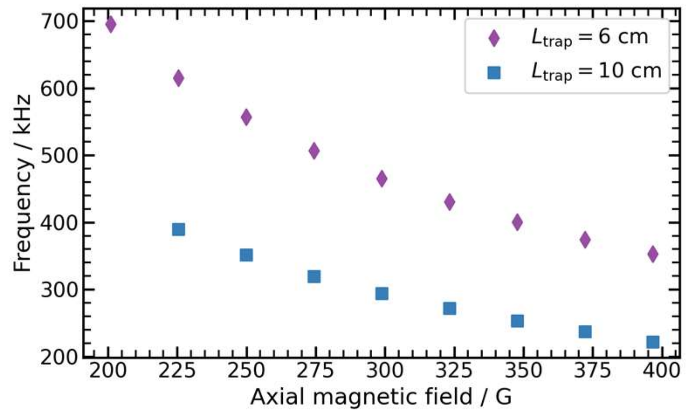
- Axial motion (∼5– 25 MHz)
- Modified cyclotron motion (∼1 GHz)
- Magnetron rotation (∼5– 500 kHz)
  $\mathbf{E} \times \mathbf{B}$ drift

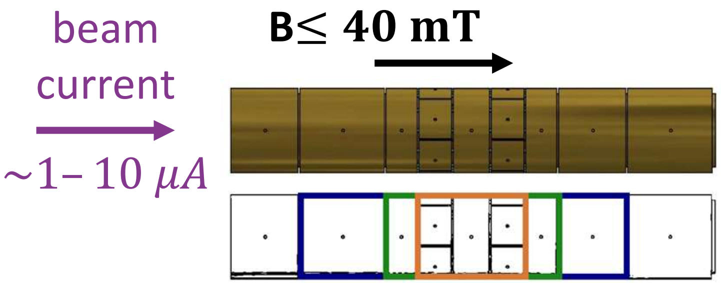


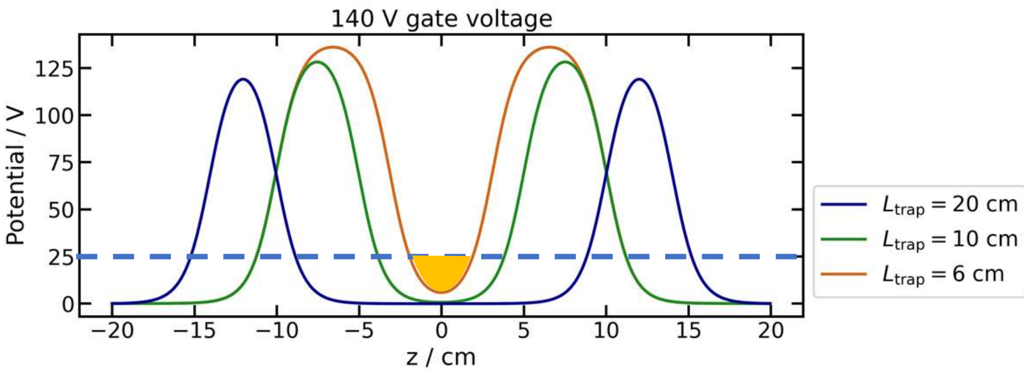
A. Deller, PhD Thesis, Swansea University, 2013

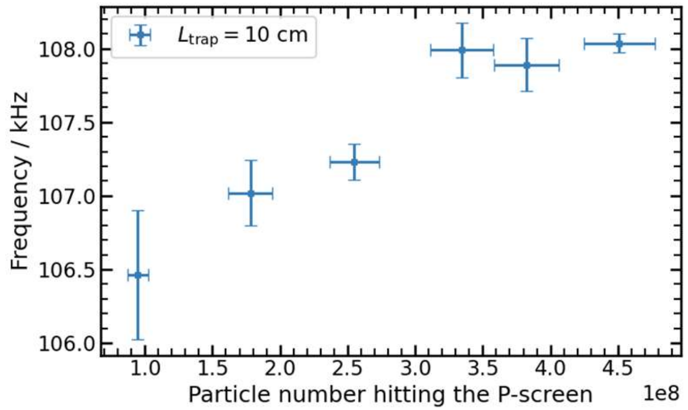
Main results







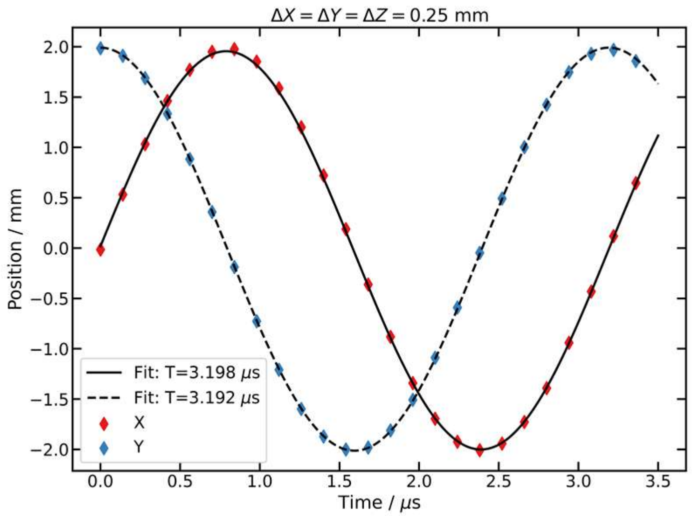


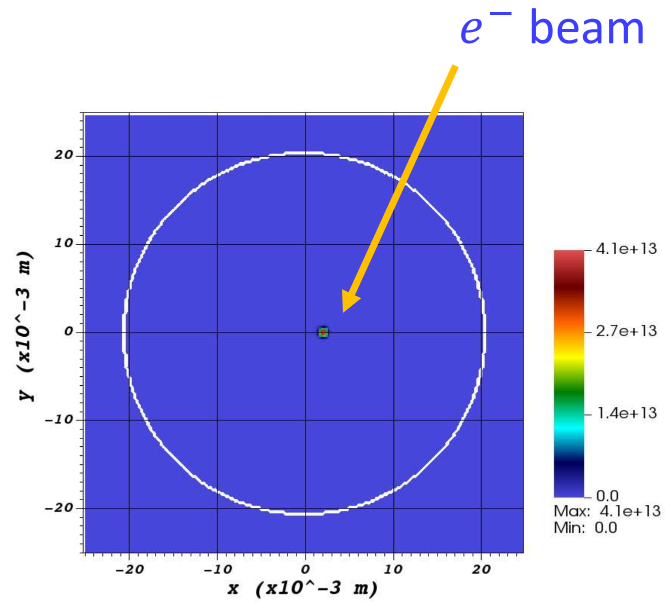


- Magnetron frequency measured under various trapping conditions
- Catch-hold-dump sequences
  - Destructive measurements on P-screen

Status of simulations

- PIC code previously used to model stable/unstable plasmas in a Gabor lens prototype
  - Validate the PIC code against the measurements from Swansea
- Ongoing work to reproduce the change in magnetron frequency observed in the experiment
  - Preliminary simulation shows agreement within 10%



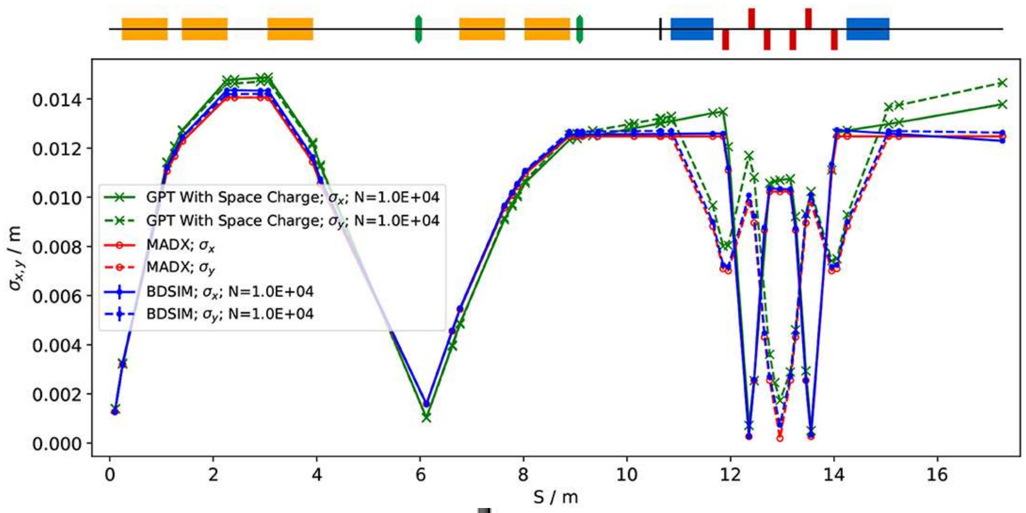


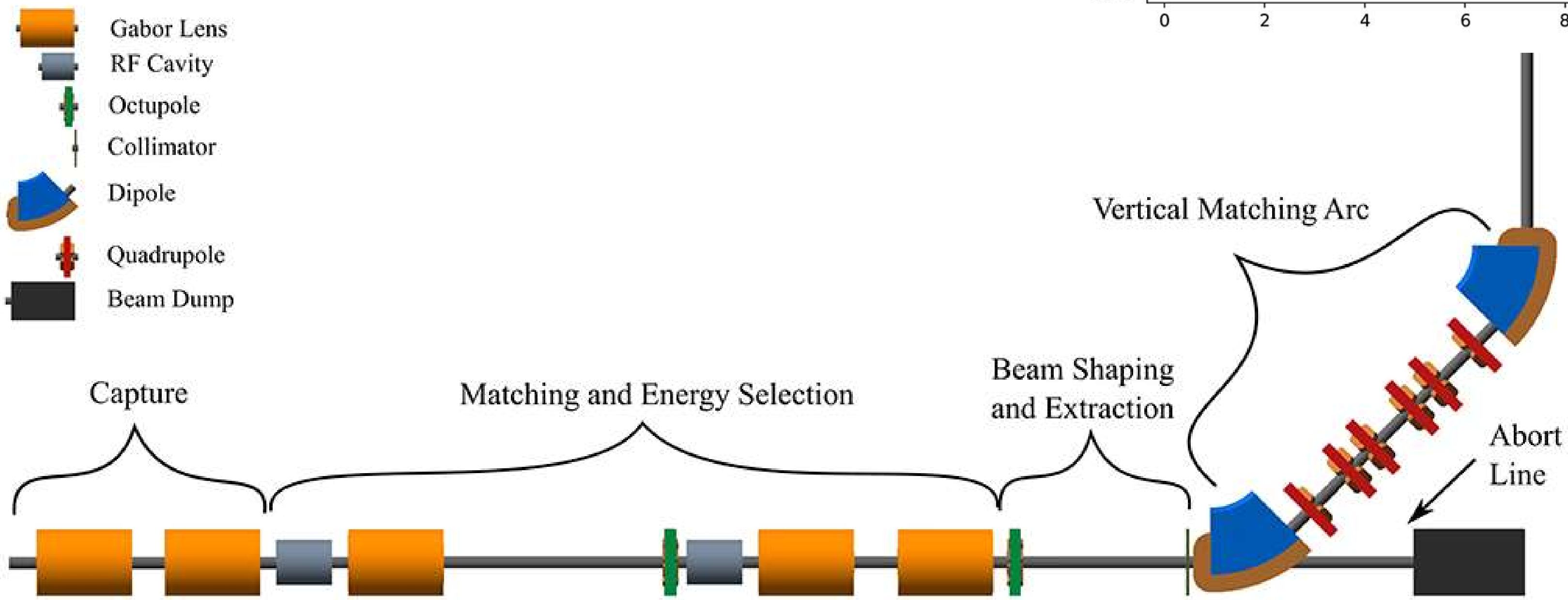
WP3 Project plan

Chris

Ion Capture overview

- 5 lens elements expected



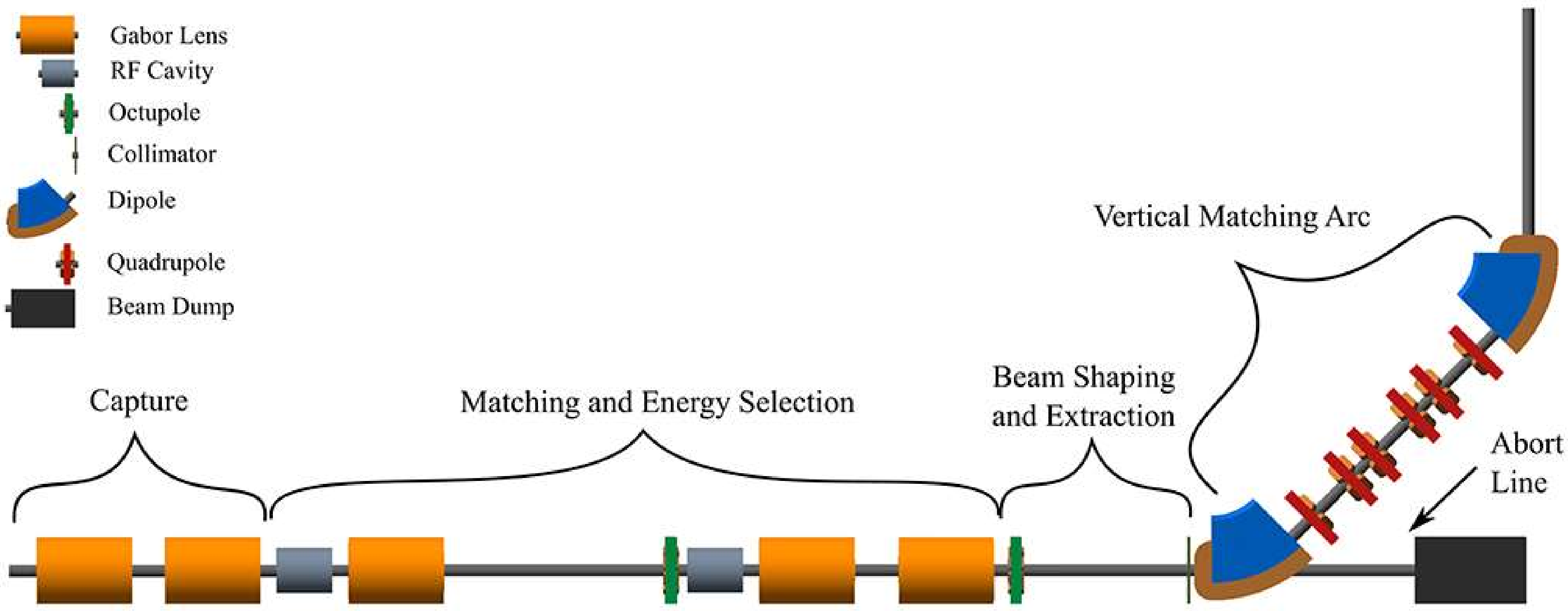


doi: 10.3389/fphy.2020.567738

Ion Capture overview

- 5 lens elements expected
- Preliminary & preconstruction phases focus on 1 element

Lens	Equivalent solenoid field† B_{sol} [T]	Focal length [m]	Electron density‡ [m^{-3}]	Lens solenoid field‡ B_{GL} [T]
GL1*	1.2868	1.05	4.3×10^{15}	0.032
GL2*	0.6671	3.46	1.2×10^{15}	0.017
GL3	0.8139	2.37	1.7×10^{15}	0.021
GL4	0.6852	3.29	1.2×10^{15}	0.017
GL5	0.6541	3.59	1.1×10^{15}	0.017



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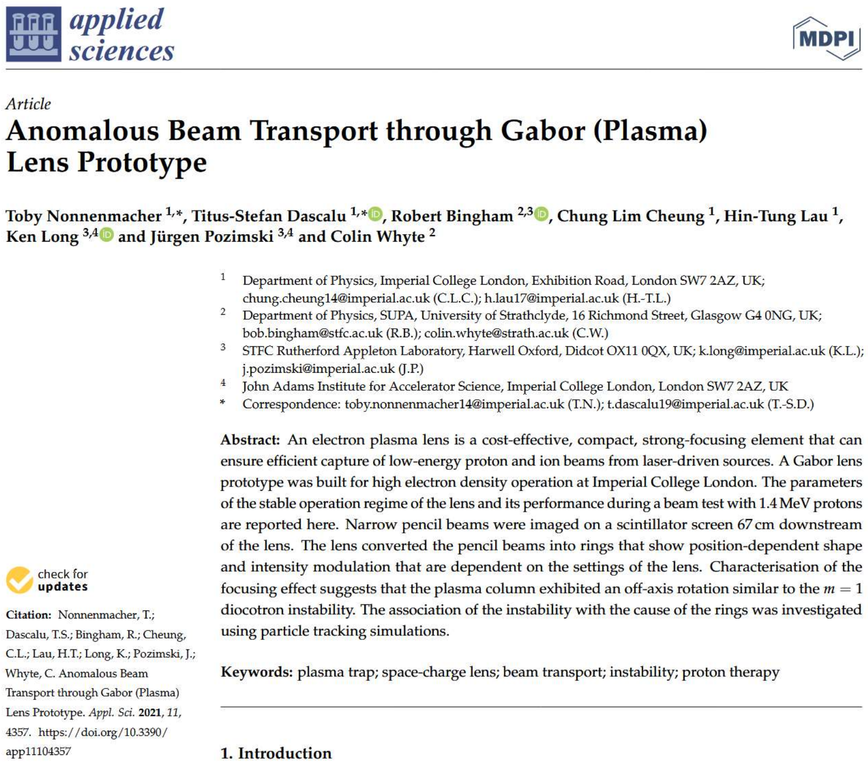
Previous efforts



applied sciences MDPI

Article

Anomalous Beam Transport through Gabor (Plasma) Lens Prototype

Toby Nonnenmacher [1,*], Titus-Stefan Dascalu [1,*], Robert Bingham [2,3], Chung Lim Cheung [1], Hin-Tung Lau [1], Ken Long [3,4] and Jürgen Pozimski [3,4] and Colin Whyte [2]

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4 John Adams Institute for Accelerator Science, Imperial College London, London SW7 2AZ, UK
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Abstract: An electron plasma lens is a cost-effective, compact, strong-focusing element that can ensure efficient capture of low-energy proton and ion beams from laser-driven sources. A Gabor lens prototype was built for high electron density operation at Imperial College London. The parameters of the stable operation regime of the lens and its performance during a beam test with 1.4 MeV protons are reported here. Narrow pencil beams were imaged on a scintillator screen 67 cm downstream of the lens. The lens converted the pencil beams into rings that show position-dependent shape and intensity modulation that are dependent on the settings of the lens. Characterisation of the focusing effect suggests that the plasma column exhibited an off-axis rotation similar to the $m = 1$ diocotron instability. The association of the instability with the cause of the rings was investigated using particle tracking simulations.

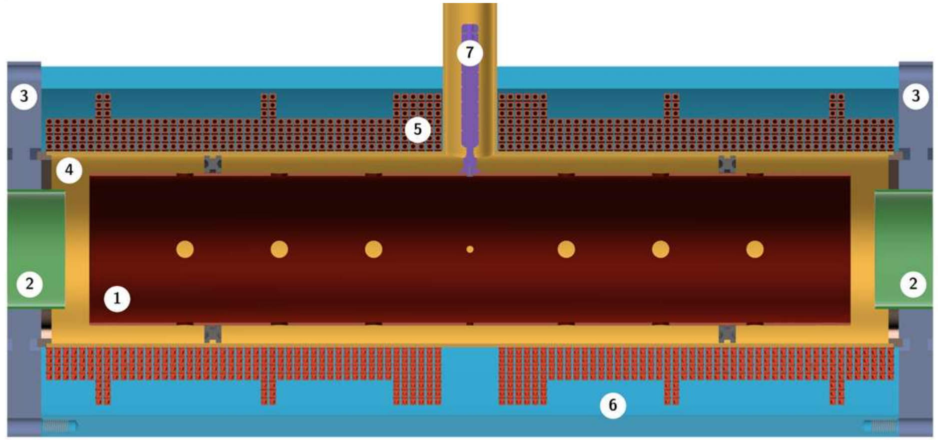
Keywords: plasma trap; space-charge lens; beam transport; instability; proton therapy

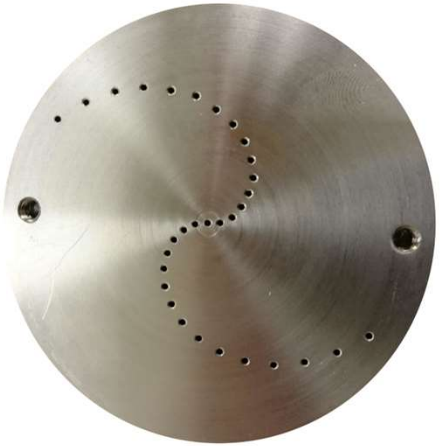
check for updates

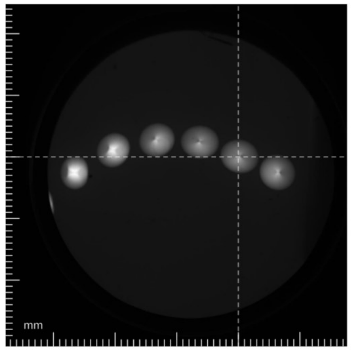
Citation: Nonnenmacher, T.; Dascalu, T.S.; Bingham, R.; Cheung, C.L.; Lau, H.T.; Long, K.; Pozimski, J.; Whyte, C. Anomalous Beam Transport through Gabor (Plasma) Lens Prototype. *Appl. Sci.* **2021**, *11*, 4357. https://doi.org/10.3390/app11104357

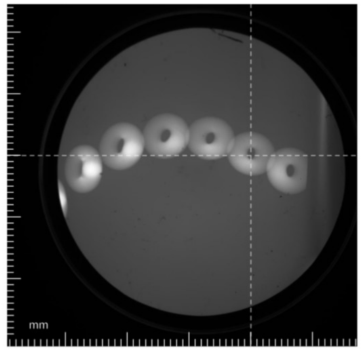
1. Introduction

Plasma in the lens was produced by increasing the high voltage applied to the anode and the current in the magnetic coils. A significant increase in pressure was observed when a stable plasma was first established in the lens. Simulation of the plasma discharge within the lens indicated that a high electron density, ~5×10^{-7} cm^{-3}, was produced.









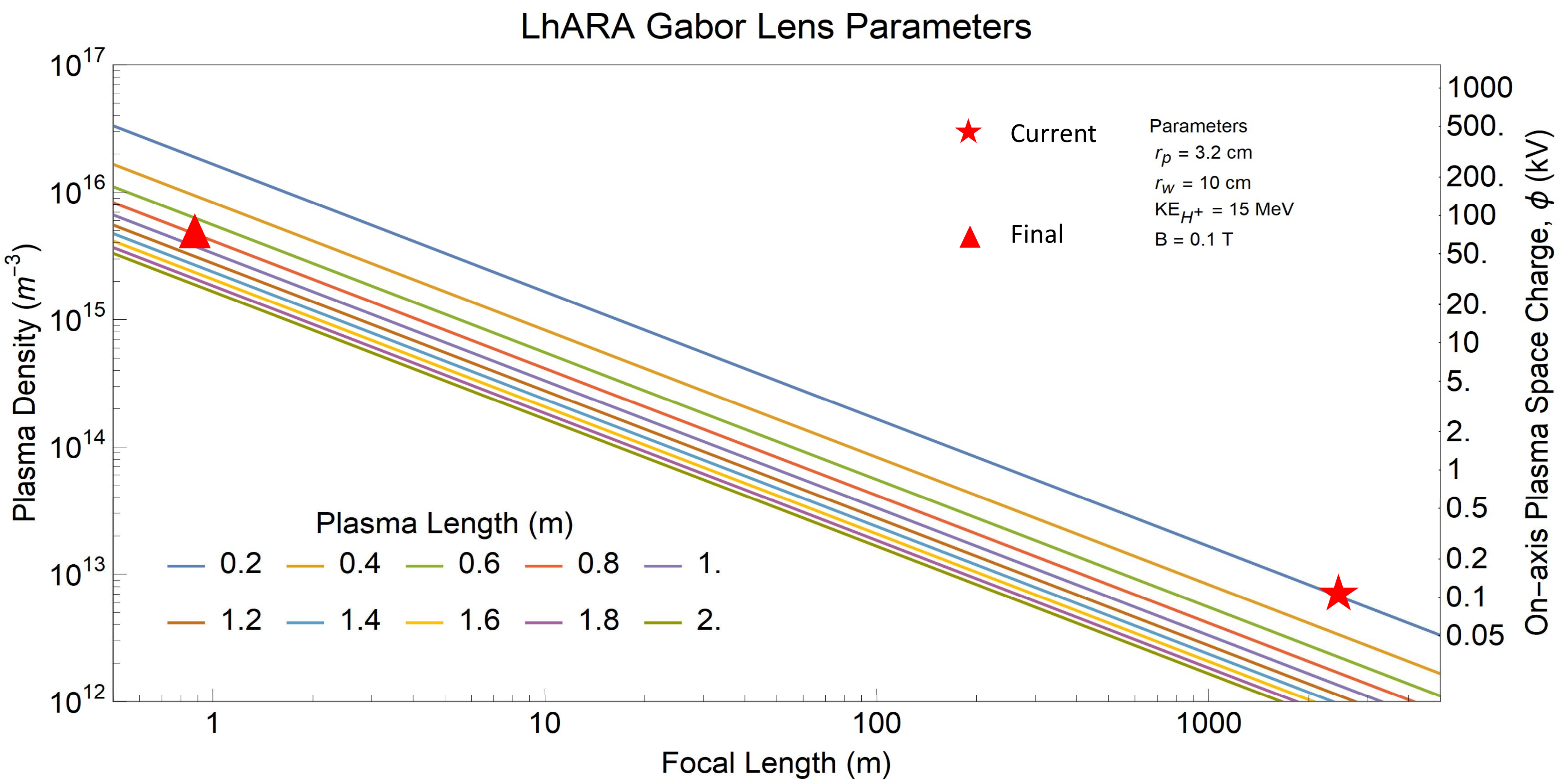
Appl. Sci. **11** 4357 (2021)
https://ccap.hep.ph.ic.ac.uk/trac/wiki/Research/GaborLens/Meetings/2021/01/28

Full-proposal plan

- Build upon experience and techniques of low temperature non-neutral plasma community
  - Clean, controlled, heavily diagnosed environment

- Year 1-2 plan: upgrade existing apparatus & design new apparatus
- Year 3-5 plan: use new apparatus to push multiple limits currently present in non-neutral plasma field, with off-the-shelf components
- Year 5+ plan to design & build focussing element (Gabor lens)

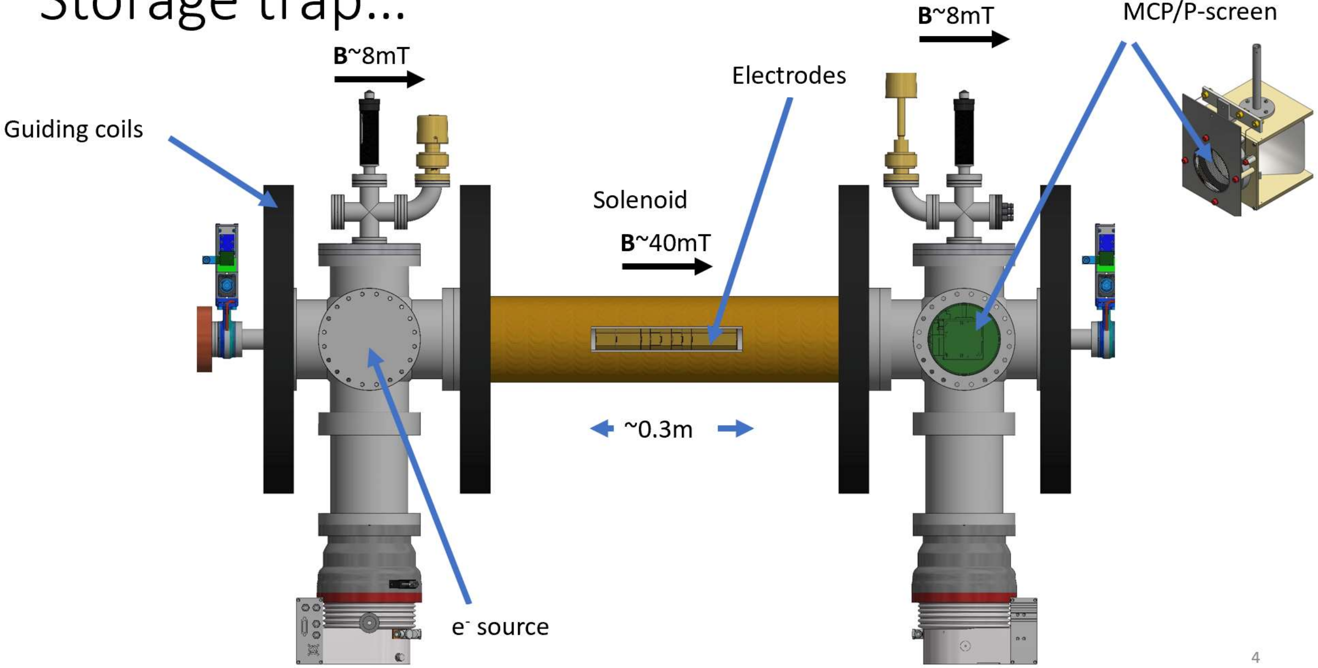
Why is this cautious development necessary?



Year 1-2 plan

- Existing apparatus is currently limited as designed for ‘single particle’ / low density / small volume ensemble

Storage trap...

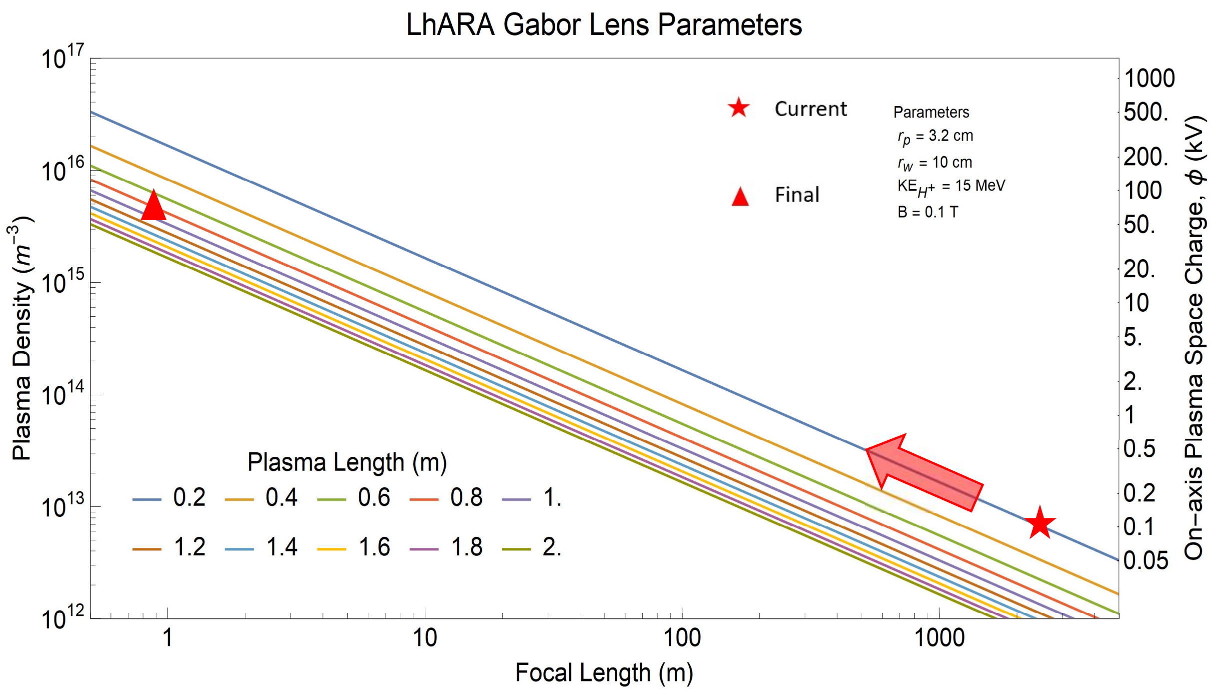


Year 1-2 plan

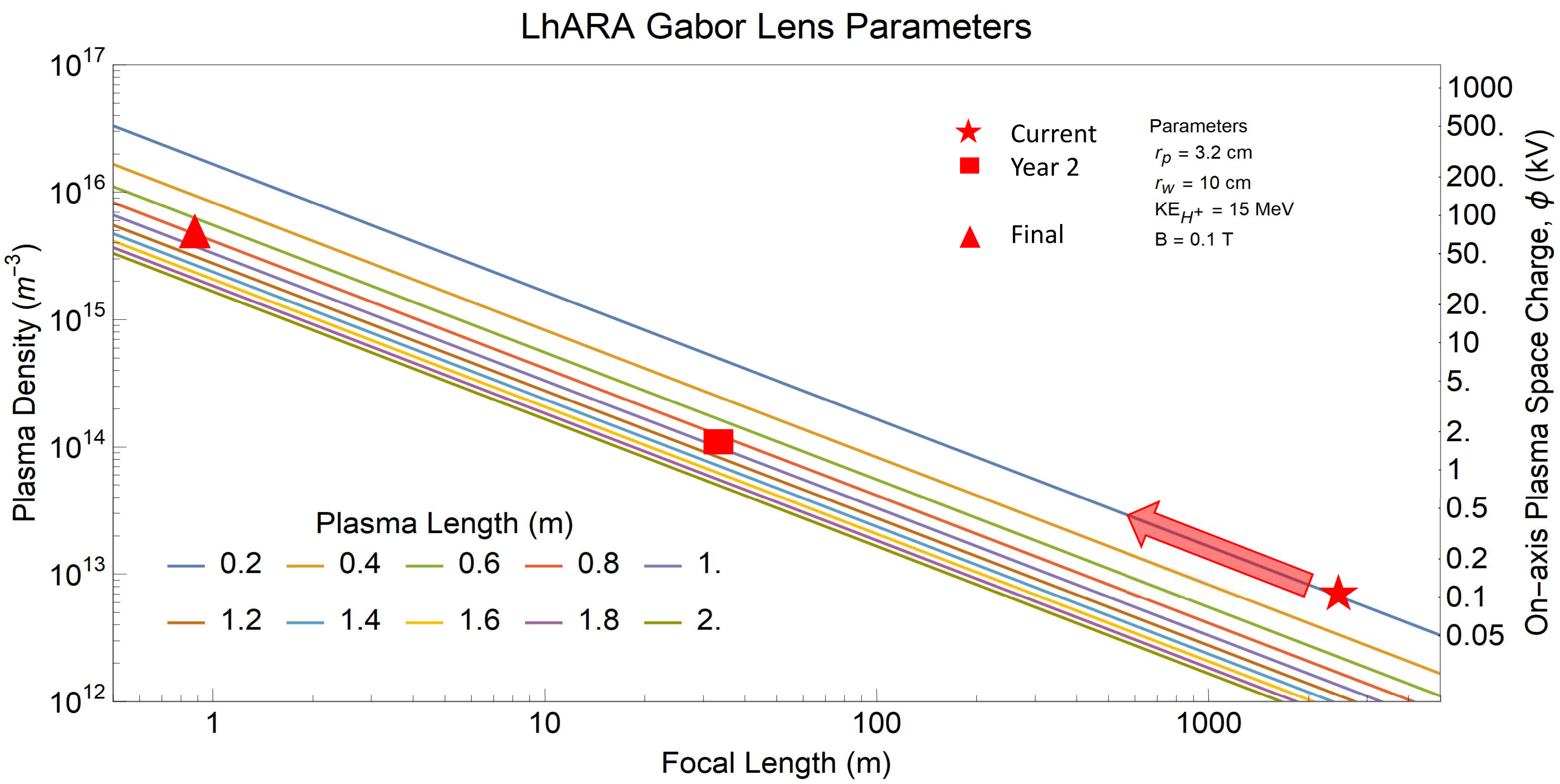
- Existing apparatus is currently limited as designed for 'single particle' / low density / small volume ensemble
- Parallel Stream: Modest upgrades enable time to be used efficiently, invaluable early information will be obtained & fed into design process
- Parallel Stream: Simulation of upgraded apparatus & new system
- Parallel Stream: Design & purchasing of new system

Upgraded apparatus

- New electrodes (geometry, size, electrical insulation, etc.)
- New electronics for confining higher space-charge plasma
- New electron source
- Upgraded magnet
  - Utilities
  - <u>Homogeneity control</u>
- Debug new control system

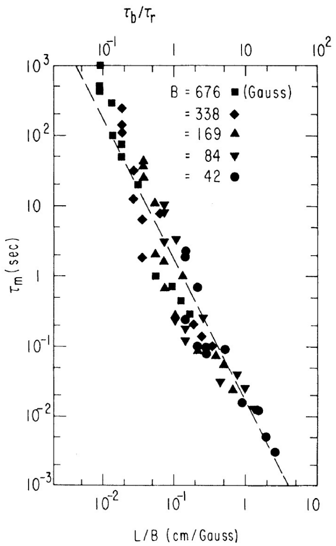


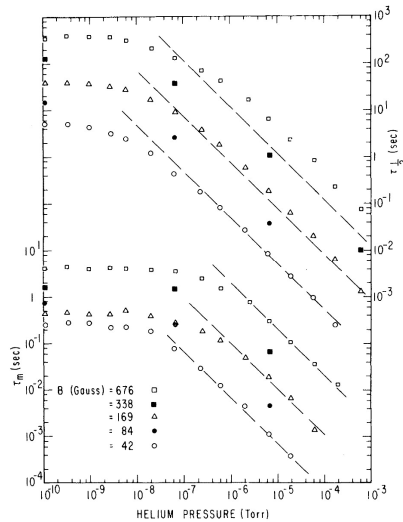
Year 2 milestone



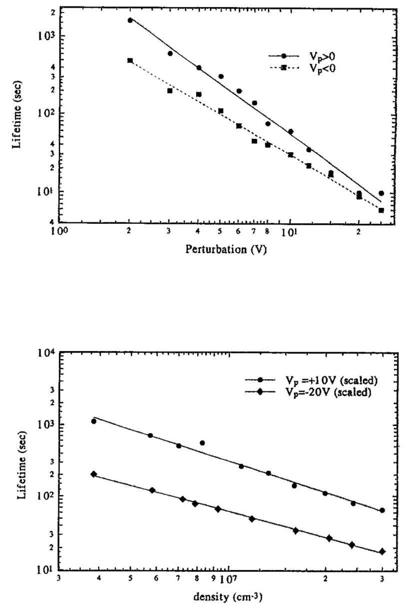
Year 3-4 plan

- Use new apparatus to study ‘medium’ scale plasma (confirm & advance literature)
  - Length behaviour
  - Density & lifetime behaviour
    - Static & dynamic
  - Fill factor
  - Pressure
  - B-field
  - Number



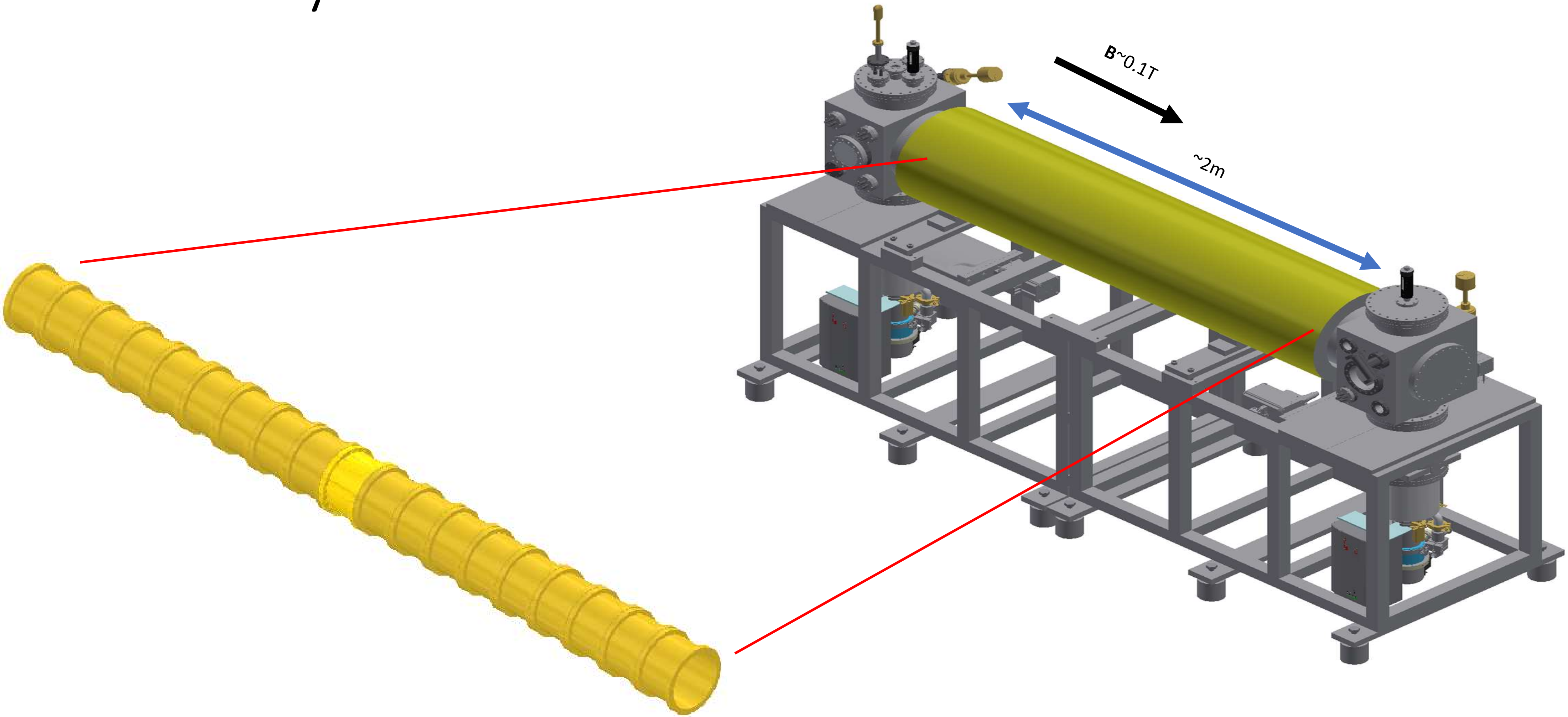


Phys. Rev. Lett. **50** 167 (1983)
Phys. Plasmas **1** 1123 (1994)

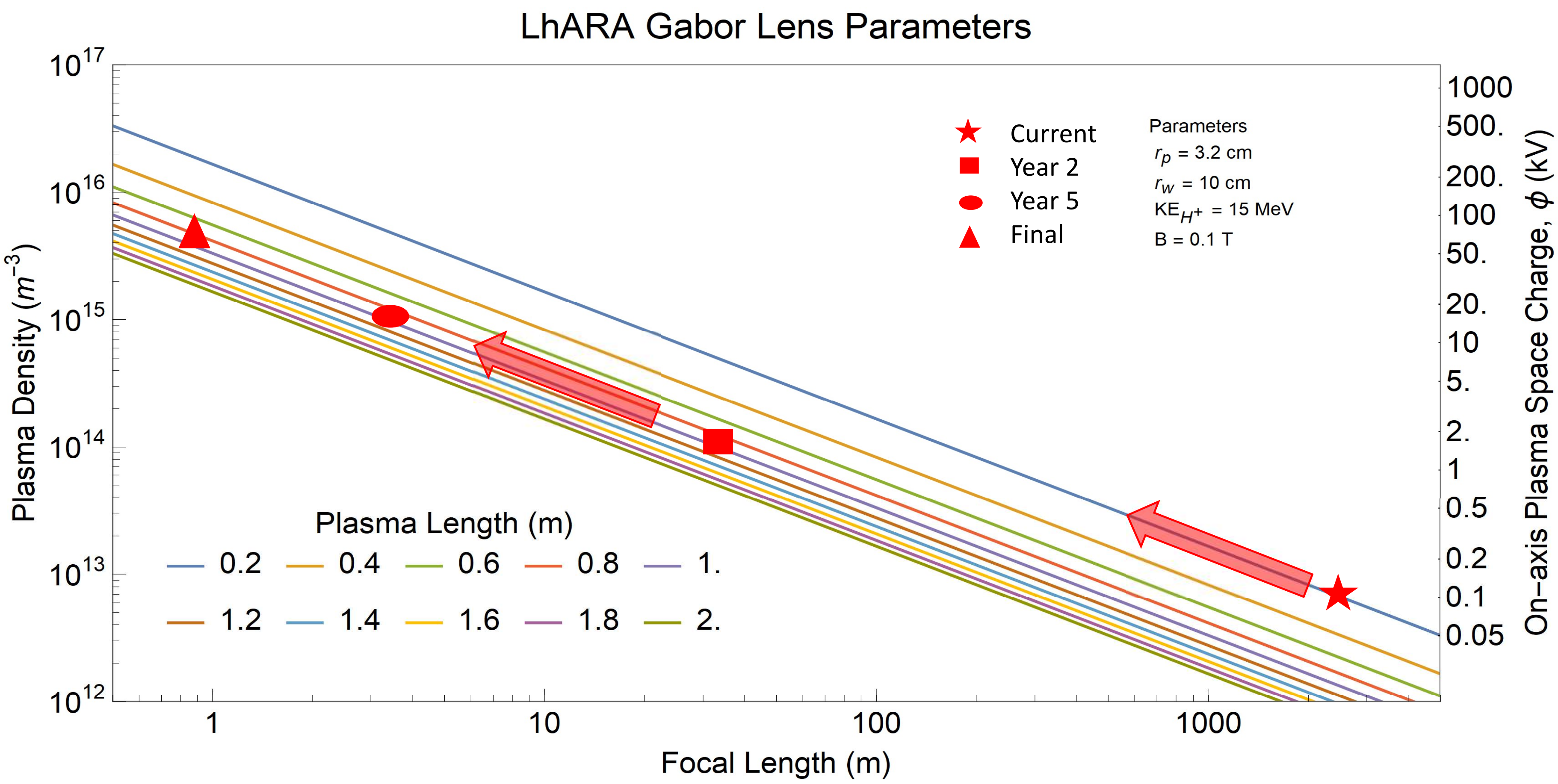


Phys. Rev. Lett. **44** 654 (1980)

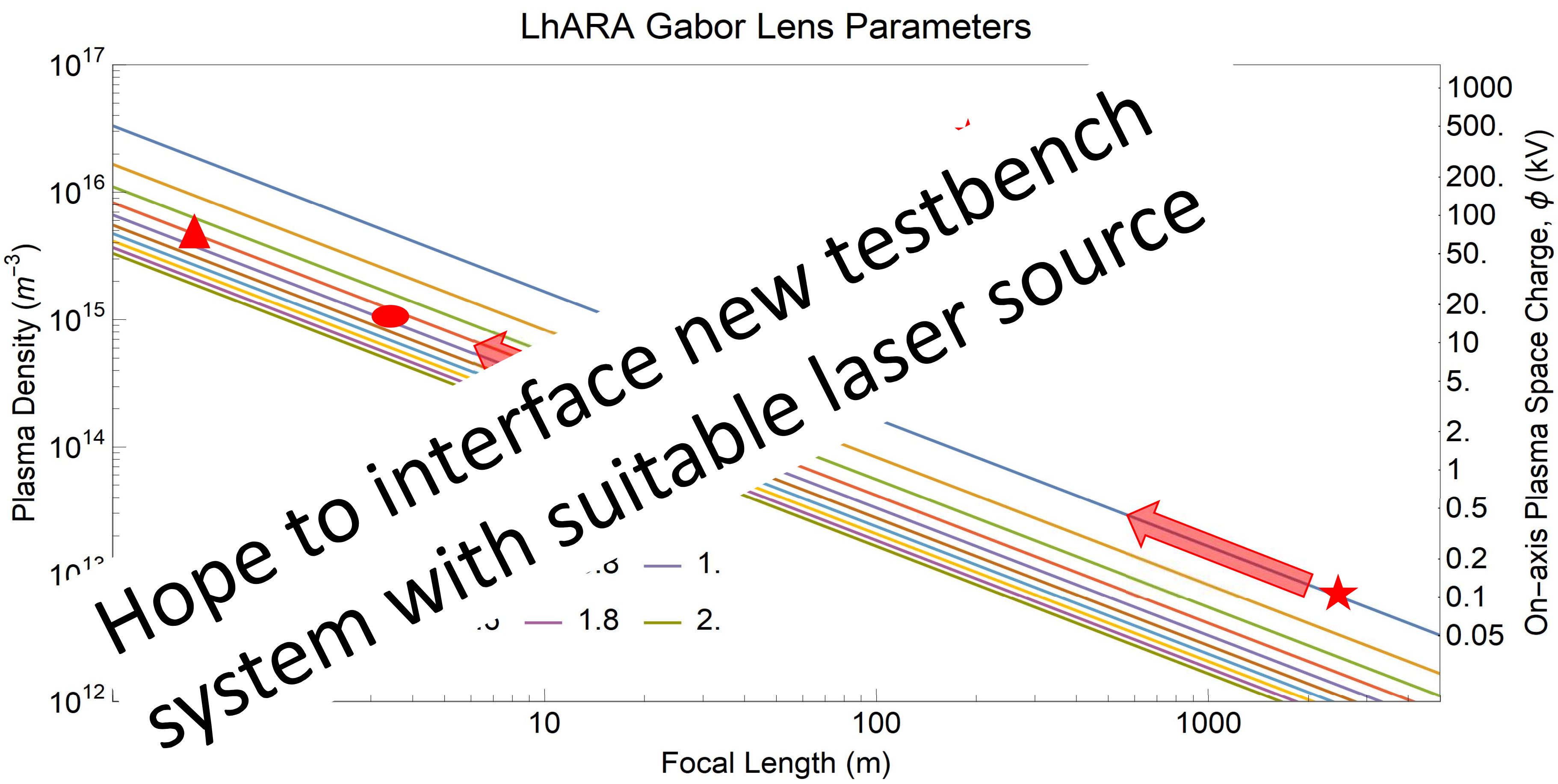
New System



Year 5 milestone



Year 5 milestone



Hope to interface new testbench system with suitable laser source

WP3 Proposal update

Chris

Current Proposal Status – Staff requirements

Staff	2022/23 Fraction	£k	2023/24 Fraction	£k	2024/25 Fraction	£k	2025/26 Fraction	£k	2026/27 Fraction	£k	Total Fraction	£k
All												
Manchester Physics												
Man-Phys-PDRA-1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00	5	500.00
Man-Phys-Stf-1	0.2	20.00	0.2	20.00	0.2	20.00	0.2	20.00	0.2	20.00	1	100.00
Swansea Physics												
Swns-Phys-PDRA-1	1	100.00	1	100.00	1	100.00	1	100.00	1	100.00	5	500.00
Swns-Phys-Stf-1	0.3	30.00	0.3	30.00	0.3	30.00	0.3	30.00	0.3	30.00	1.5	150.00
Swns-Phys-PG-1	1	100.00	1	100.00	1	100.00	0.5	50.00	0	0.00	3.5	350.00
Swns-Phys-PG-2	0	0.00	0.5	50.00	1	100.00	1	100.00	1	100.00	3.5	350.00
Swan-Phys-Tech-1	0.5	50.00	0.5	50.00	0.5	50.00	0.5	50.00	0.5	50.00	2.5	250.00
Swan-Phys-Tech-2	1	100.00	1	100.00	0	0.00	0	0.00	0	0.00	2	200.00
Berkeley												
Consultant	0.04	4.00	0.04	4.00	0.04	4.00	0.04	4.00	0.04	4.00	0.2	20.00
Task 1 - Preliminary Measurements												
Task 2 - Gabor testbench												
Cost of risk mitigation, staff (not yet implemented):		0.00		0.00		0.00		0.00		0.00		0.00
Staff total:	5.04	**504.00**	**5.54**	**554.00**	**5.04**	**504.00**	**4.54**	**454.00**	**4.04**	**404.00**	**24.2**	**2420.00**

Current Proposal Status – Equipment costs

Non staff	£k	£k	£k	£k	£k	£k
Task 1 - Preliminary Measurements						
Vacuum Generation	23	0	0	0	0	23
Vacuum Hardware	2.5	0	0	0	0	2.5
Trap/Expt. Hardware	16.5	0	0	0	0	16.5
Diagnostics	54.5	0	0	0	0	54.5
Control	28	0	0	0	0	28
Magnet(s)	10	0	0	0	0	10
Misc.	1	1	1	1	1	5
Task 2 - Gabor testbench						
Vacuum Generation	88.1	0	0	0	0	88.1
Vacuum hardware	41.86	0	0	0	0	41.86
Trap/Expt. Hardware	34.1	0	0	0	0	34.1
Diagnostics	46.5	0	10	10	0	66.5
Control	198	0	0	0	0	198
Magnet(s)	185	0	0	0	0	185
Misc.	1	1	1	1	1	5
of risk mitigation (equipment)	0	0	172	0	0	172
pment total	730.06	2	184	12	2	930.06
Consumables	186	13	13.5	18	14.5	245
Travel	32	32	32	32	42	170
PI, engagement, outreach	2	2	2	2	2	10
n-staff costs	950.06	49	231.5	64	60.5	1355.06

Teledyne LeCroy HDO4104A-MS Bench Mixed Signal Oscilloscope, 1GHz, 4, 16 Channels — 1 — Update | Remove — £17,611.00 Each — £17,611.00

RS Stock No. 136-8343
Brand Teledyne LeCroy
Mfr. Part No. HDO4104A-MS
RoHS status: Compliant

Ref	Description	Qty	Unit Price (£)	Total (£)
1 Photonis PS35518	Advanced Performance Long-Life™ Microchannel Plate Detector APD 2 PS 40/12/10/8 I 60:1 P43	1	6,190.00	6,190.00
2 P+P	Shipment and packaging	1	50.00	50.00

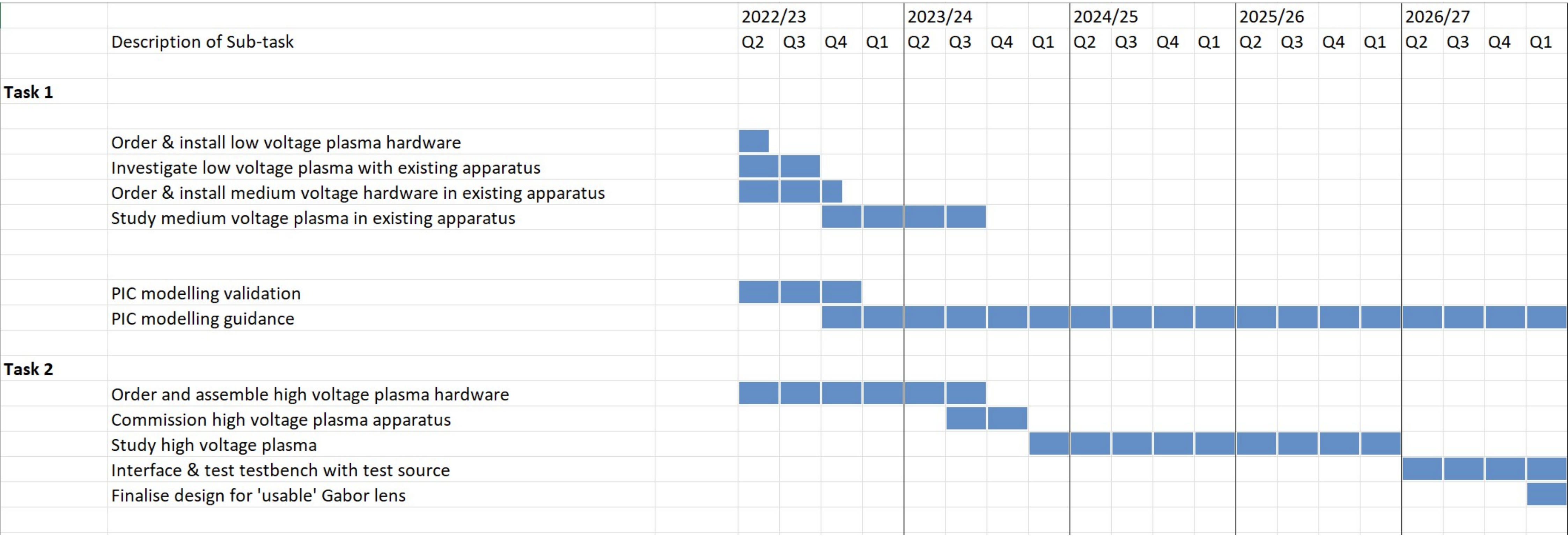
633-10HVA24-BP1-BNC-10KV-ND
10HVA24-BP1-BNC-10KV
Advanced Energy
HVA-SERIES DC-TO-HVDC AMPLIFIER, — 5 — Backorder — 2,175.60000 — £10,878.00

633-1HVA24-N1-F-25PPM-SHV-5KV-ND
1HVA24-N1-F-25PPM-SHV-5KV
Advanced Energy
HVA-SERIES DC-TO-HVDC AMPLIFIER, — 8 — Backorder — 1,190.62000

Subtotal: £20,4

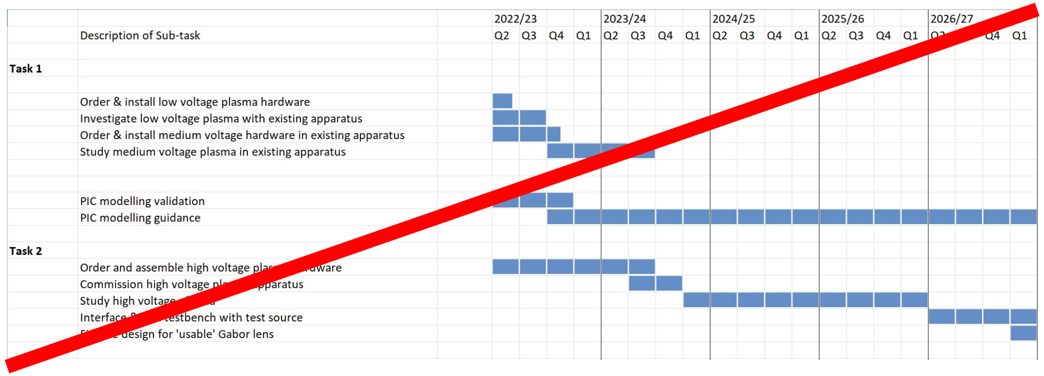
My Configuration
Total Price: £ 96,137.80

Current Proposal Status – Timeline



ITRF call re-profiling…

Staff	2022/23 Fraction	£k	2023/24 Fraction	£k	2024/25 Fraction	£k	2025/26 Fraction	£k	2026/27 Fraction	£k	[illegible] Fraction	£k
All												
Manchester Physics												
Man-Phys-PDRA-1	1	100.00	1	100.00	1	100.00	1	[illegible]	1	100.00	5	500.00
Man-Phys-Stf-1	0.2	20.00	0.2	20.00	0.2	20.00	[illegible]	20.00	0.2	20.00	1	100.00
Swansea Physics												
Swns-Phys-PDRA-1	1	100.00	1	100.00	[illegible]	100.00	1	100.00	1	100.00	5	500.00
Swns-Phys-Stf-1	0.3	30.00	0.3	[illegible]	0.3	30.00	0.3	30.00	0.3	30.00	1.5	150.00
Swns-Phys-PG-1	1	100.00	[illegible]	100.00	1	100.00	0.5	50.00	0	0.00	3.5	350.00
Swns-Phys-PG-2	0	[illegible]	0.5	50.00	1	100.00	1	100.00	1	100.00	3.5	350.00
Swan-Phys-Tech-1	[illegible]	50.00	0.5	50.00	0.5	50.00	0.5	50.00	[illegible]	[illegible]	[illegible]	[illegible]
Swan-Phys-Tech-[illegible]	1	100.00	1	100.00	0	0.00	0	0.00	[illegible]	[illegible]	[illegible]	[illegible]
Berkeley												
Consultant	0.04	4.00	0.04	4.00	0.04	4.00	0.04	4.00	[illegible]	[illegible]	[illegible]	[illegible]
[illegible] - Preliminary Measurements												
Task 2 - Gabor testbench												
C[illegible] risk mitigation, staff (not yet implemented):		0.00		0.00		0.00		0.00	[illegible]	[illegible]	[illegible]	[illegible]
Staff total:	5.04	**504.00**	5.54	**554.00**	5.04	**504.00**	4.54	**454.00**	[illegible]	[illegible]	[illegible]	[illegible]

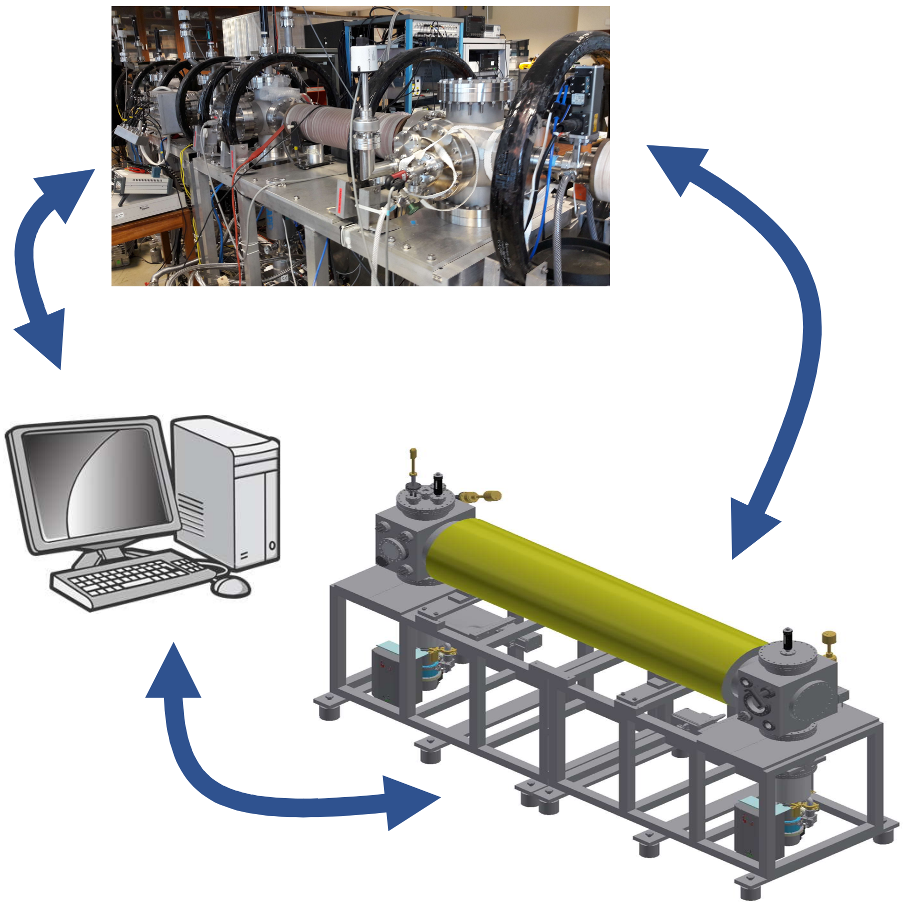


Non staff	£k	£k	£k	£k	£k	£k
Task 1 - Preliminary Measurements						
Vacuum Generation	23	0	0	0	0	23
Vacuum Hardware	2.5	0	0	0	[illegible]	2.5
Trap/Expt. Hardware	16.5	0	0	0	[illegible]	16.5
Diagnostics	54.5	0	0	[illegible]	0	54.5
Control	28	0	0	[illegible]	0	28
Magnet(s)	10	0	0	0	0	10
Misc.	1	1	[illegible]	1	1	5
Task 2 - Gabor testbench						
Vacuum Generation	88.1	[illegible]	0	0	0	88.1
Vacuum hardware	41.86	0	0	0	0	41.86
Trap/Expt. Hardware	[illegible]	0	0	0	0	34.1
Diagnostics	[illegible]	0	10	10	0	66.5
Control	198	0	0	0	0	198
Magn[illegible]	185	0	0	0	0	185
Misc.	1	1	1	1	1	5
Cost of risk mitigatio[illegible] equipment)	0	0	172	0	0	172
Equipment total	730.06	2	184	12	2	930.06
Consumables	186	13	13.5	18	14.5	245
Travel	32	32	32	32	42	170
PPI, engagement, outreach	2	2	2	2	2	10
[illegible]otal non-staff costs	950.06	49	231.5	64	60.5	1355.06

Concluding Remarks

Chris

Summary



- Ambitious but cautious and reasonable plan based on 20+ year Antihydrogen programme, and experience with plasma at CERN & elsewhere
- Right personnel identified
  - Swansea, Manchester, UC Berkley
- Some work remains on proposal text
- Reprofiling will reduce 2 & 5 year milestones
  - Details still being discussed & digested
- We’re eager to begin the programme – it’s very exciting!!!