LhARA IAB Review
Accelerators and Technology
WP3: Proton and ion capture

Christopher Baker
(on behalf of WP3)

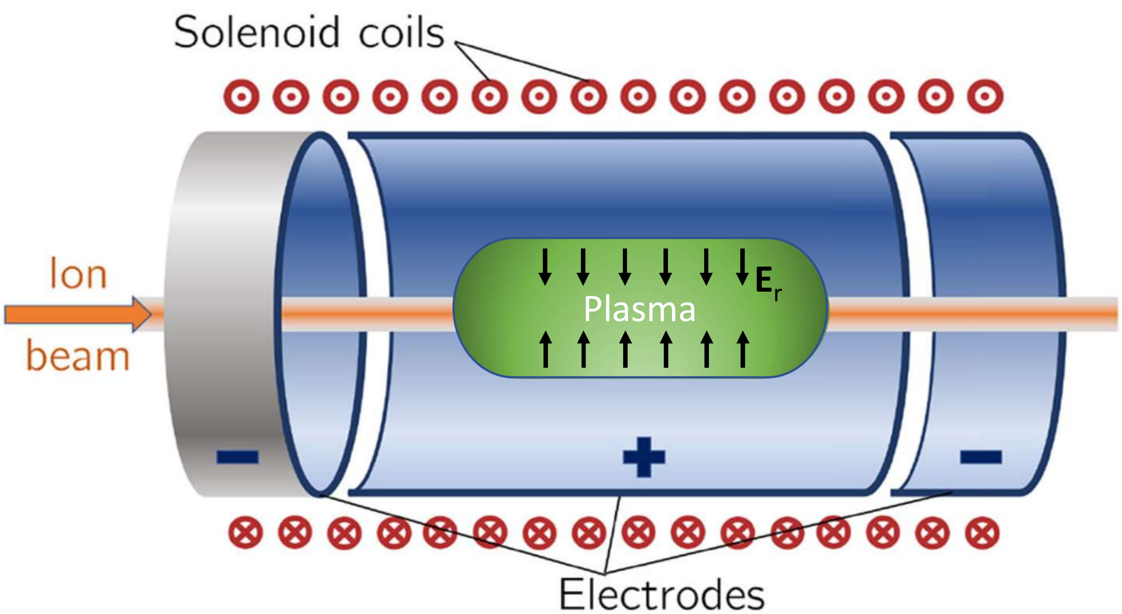
Capture work package

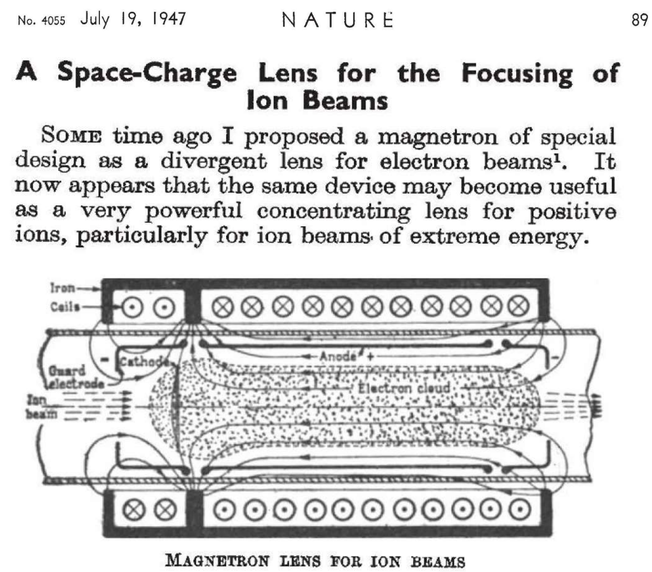
- Holistic approach to project, with feedback and synergy

1. Take output from upstream components, laser source (see WP2), as input

2. Tailor beam as required for transfer line capabilities (see WP6) and end-station requirements (WP4, WP5)

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:

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

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.

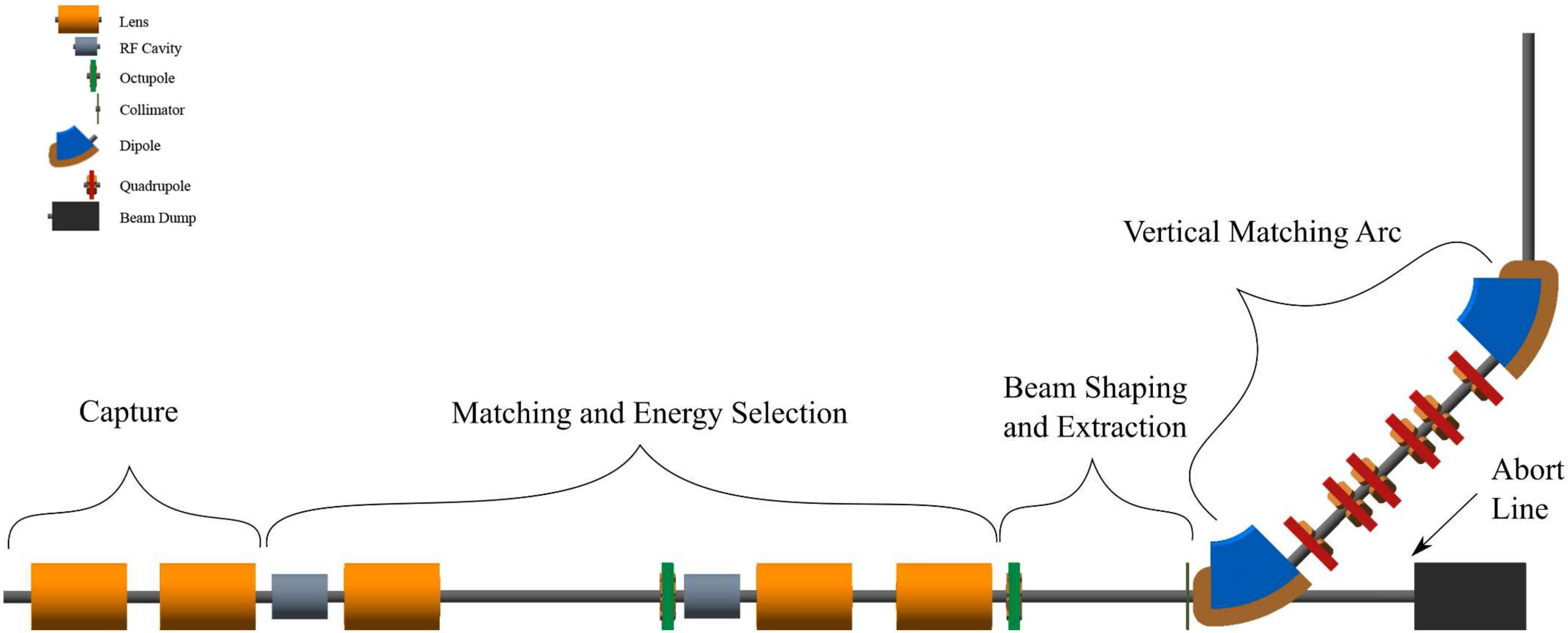
doi:10.1038/160089b0
doi: 10.3389/fphy.2020.567738

Illustrative Beam parameters for Capture section

- (see WP2 & WP6 for details)

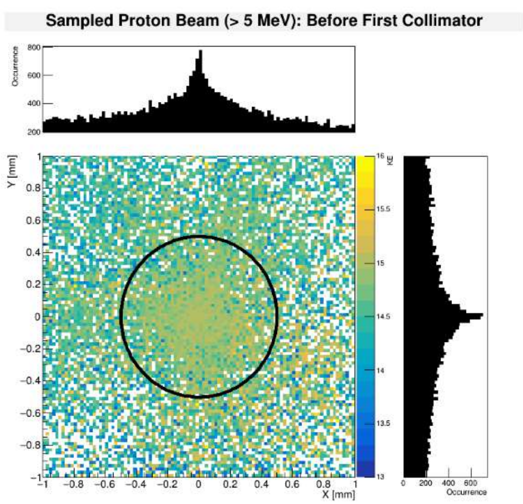
	Input	Output
Energy range	0 – 20 MeV	13 – 17 MeV
Divergence	50 mrad	~1E-6 mrad
Flux (proton no. / pulse)	10^{10}	$>10^{9}$
Radius	<1 cm	<4 cm
Length	~8ns	~8ns
Repetition rate	10 – 1000 Hz	10 – 1000 Hz

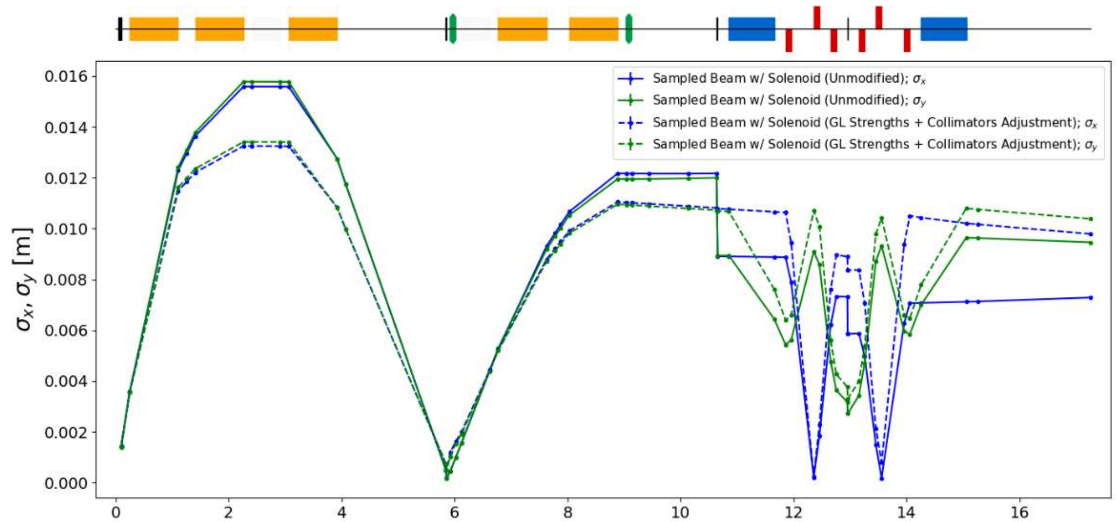
Capture system overview (see WP6)

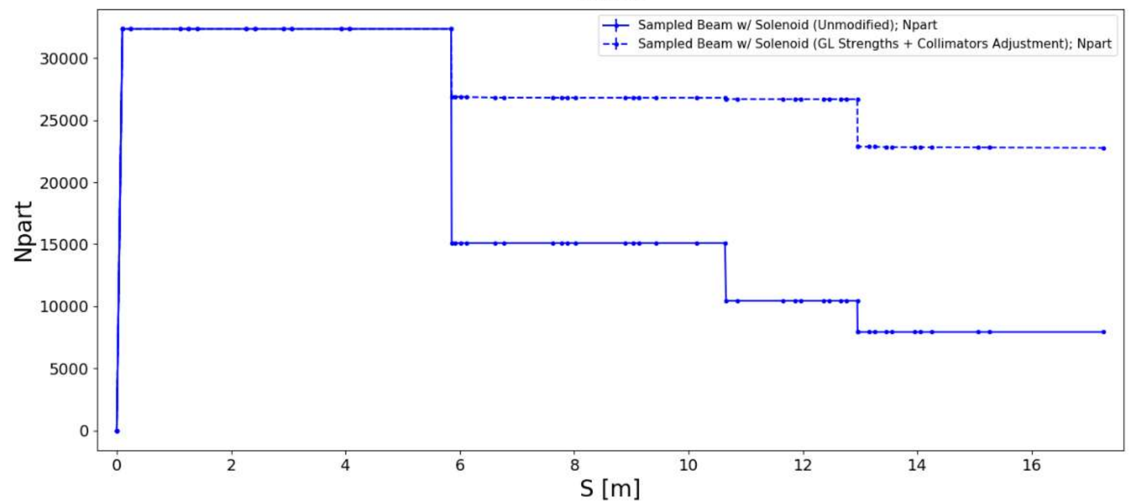


Simulations - Beam

- Particle tracking
  - BDSIM, GPT, VSIM
  - Ideal behaviour, approximated, & simulated fields

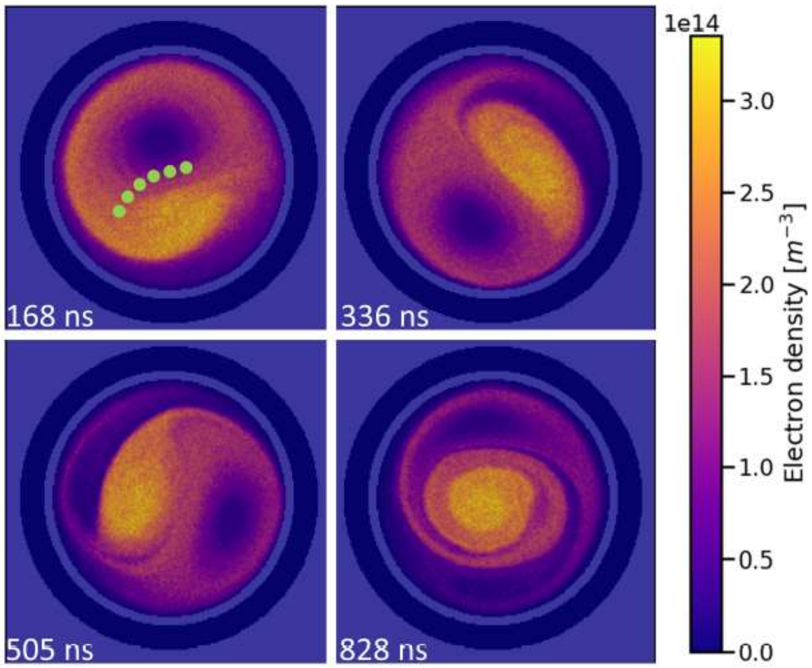


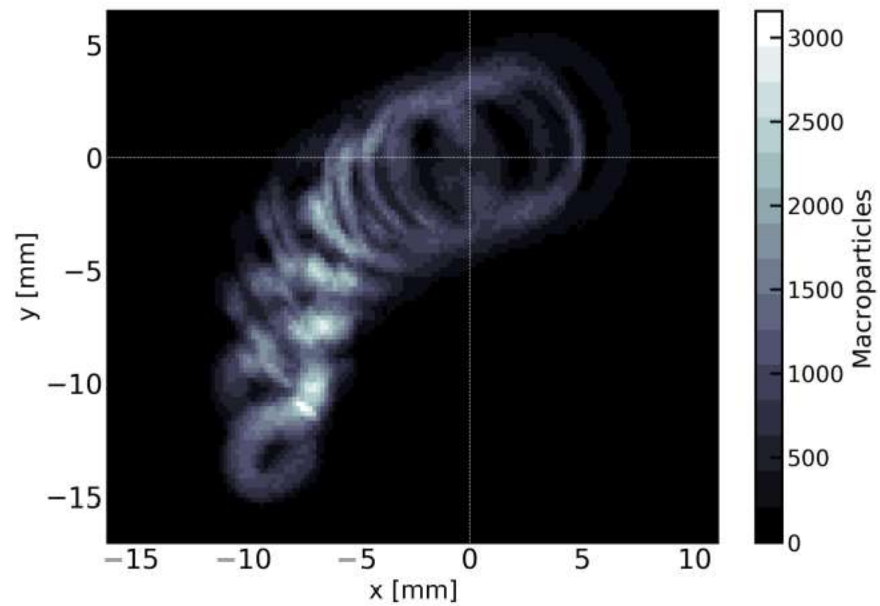




HT Lau PhD Thesis Imperial College London (2021)

Simulations – Plasma





Appl. Sci. 11 4357 (2021)

Lenses - Magnetic field (solenoid)

- Focussing strength proportional to square of magnetic field strength (current density)

- Normal conducting or Superconducting options
  - Non-trivial design – Windings, thermal, jackets, etc.
  - Financially expensive – Materials, specialists
  - Power intensive – Electrical and cooling
  - Limited flexibility

  - Well known technology
  - Commercially available

- Risk mitigation programme includes preliminary solenoid design efforts

Lenses - Electric field (plasma), Gabor Lens

- Focussing strength proportional to plasma density
  - V. high **E**-fields (& hence focussing strengths) possible
    - Dictated predominantly by applied voltages

- Existing Gabor lens attempts use high-temperature discharge plasma
  - Shot-by-shot synchronised with ion source
  - Each plasma is quasi-stable
  - Plasma established by limited control of initial conditions
  - No known successful implementation despite many decades of effort

- Proposed Gabor lens will take a <u>different approach</u> & build upon knowledge of equilibrated non-neutral plasmas

Existing experimental lens effort examples

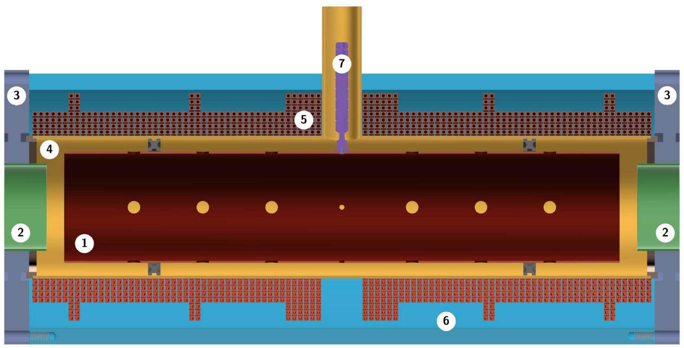
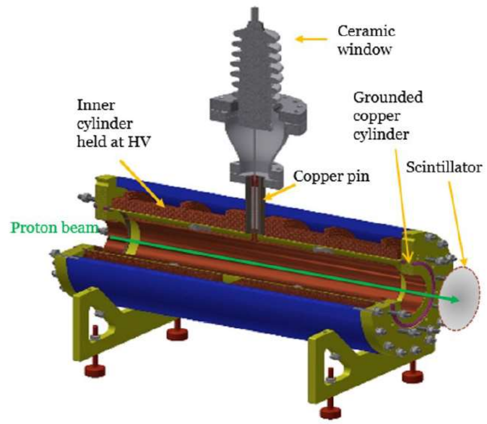
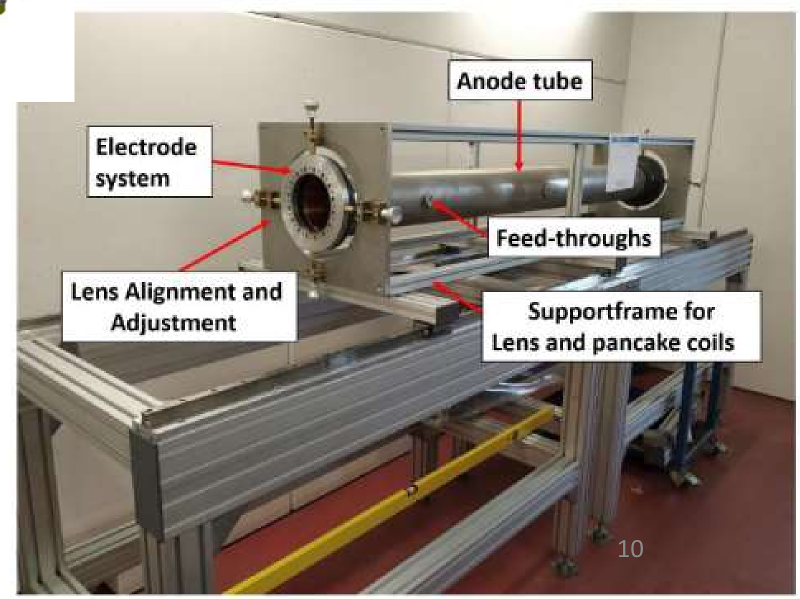
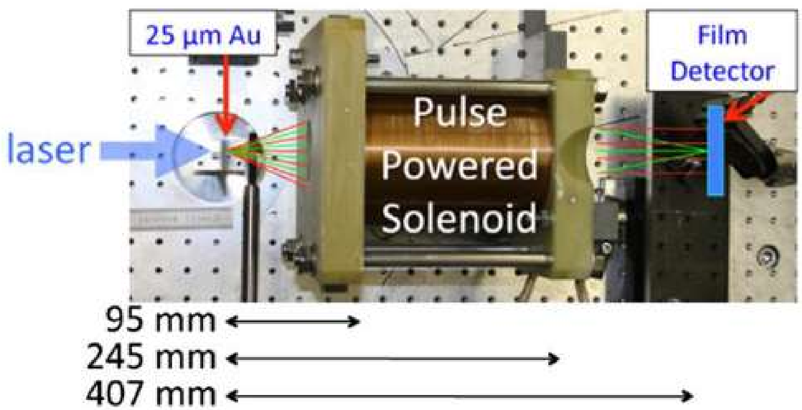


Figure 1. Internal structure of the IC Gabor lens viewed in longitudinal cross-section. The main components are: 1-central anode, 2-end electrodes, 3-end flanges, 4-vacuum tube, 5-pancake coils, 6-outer tube, 7-high-voltage feed-through.







Appl. Sci. **11** 4357 (2021)
Proc. IPAC2016 TUPMY024
Ecloud '18 Proc. 143 (2020)
Phys Rev STAB **14** 121301 (2011)

Existing non-neutral plasma

PHYSICS OF PLASMAS **13**, 022101 (2006)

Finding the radial parallel temperature profile in a non-neutral plasma using equilibrium calculations on experimental data

Grant W. Hart and Bryan G. Peterson

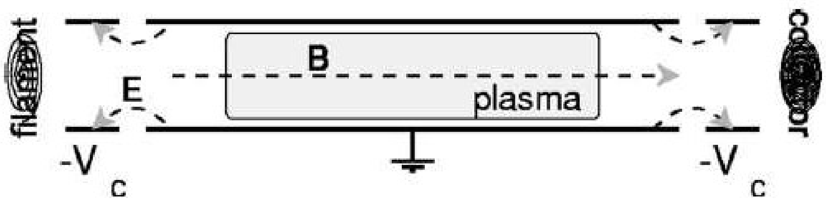


FIG. 1. Electric and magnetic fields in a Malmberg-Penning trap.

Our experiment is a fairly typical Malmberg-Penning trap with a nominal plasma length of 60 cm and a ring radius

of 4 cm. Typically our plasmas had a radius of about 2.5 cm. The central density in these data is near 7×10^{12} m^{-3}. Our neutral gas pressure is normally near 8×10^{-9} Torr. While we have not made the measurement for these specific data sets, a typical particle confinement time in this machine is 5–6 s.

Phys. Plasmas, Vol. 7, No. 7, July 2000 2776

Confinement and manipulation of non-neutral plasmas using rotating wall electric fields

E. M. Hollmann, F. Anderegg, and C. F. Driscoll

A "rotating wall" perturbation technique enables confinement of up to 3×10^9 electrons or 10^9 ions in Penning–Malmberg traps for periods of weeks. These rotating wall electric fields transfer torque

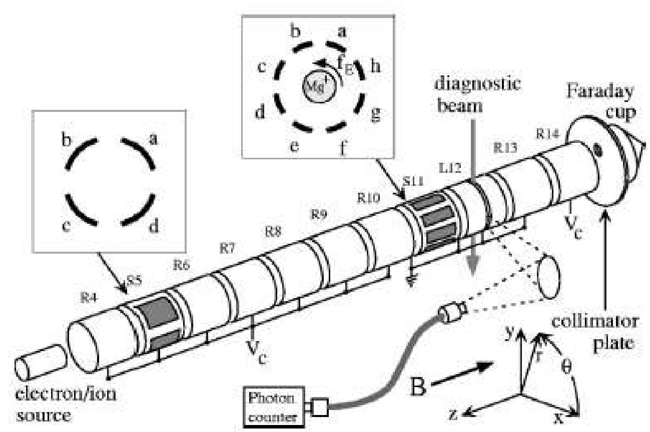
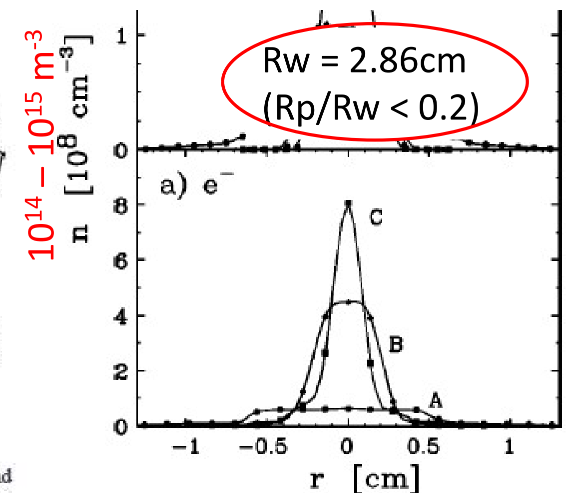
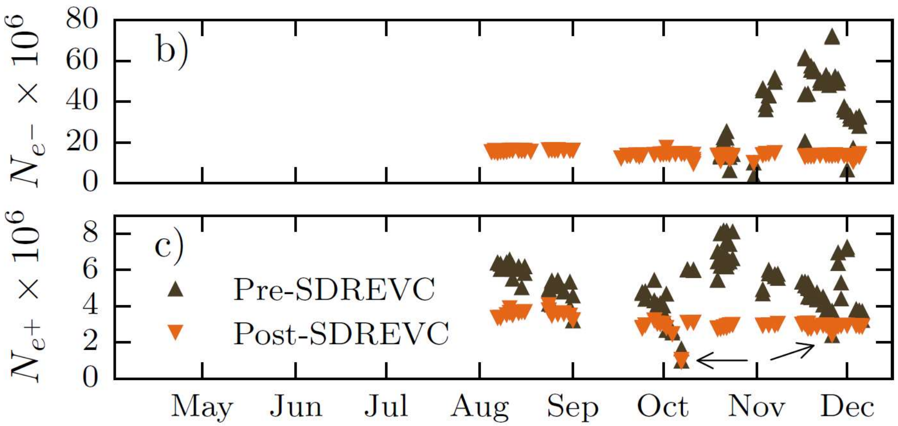


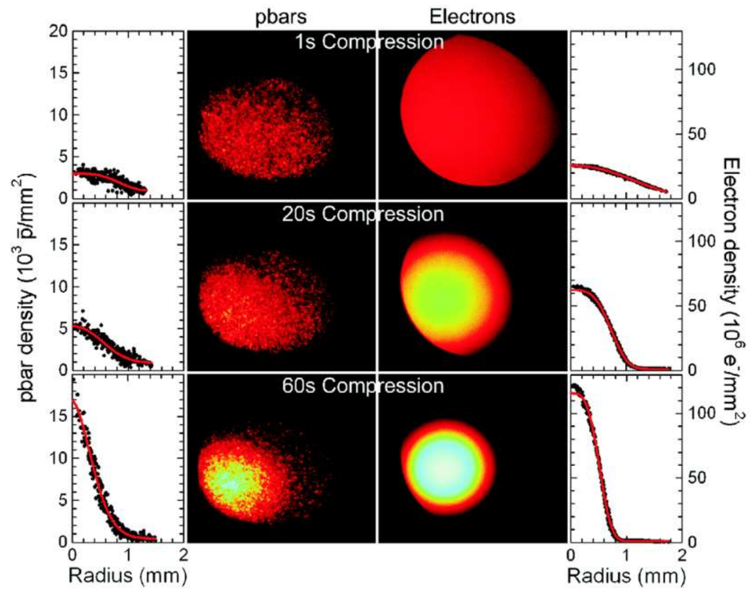
FIG. 1. Schematic of the IV Penning–Malmberg trap used for electron and ion plasma experiments. Electrons are typically confined in the region S5 →S11; Mg^+ ions (shown) are typically confined in the region S11→R13. A laser diagnostic is used for ion plasmas; a collimator plate and Faraday cup diagnostic is used for electron plasmas. Azimuthally-dependent modes are driven and detected with sectored rings (S5 and S11).



Existing plasma in ALPHA at CERN



- Length ~ 10 cm
- Radius ~ 0.5 mm (at 1T)
- Density 10^{12} -10^{14} m^{-3}



$10^{13} - 10^{14}$ m^{-3}

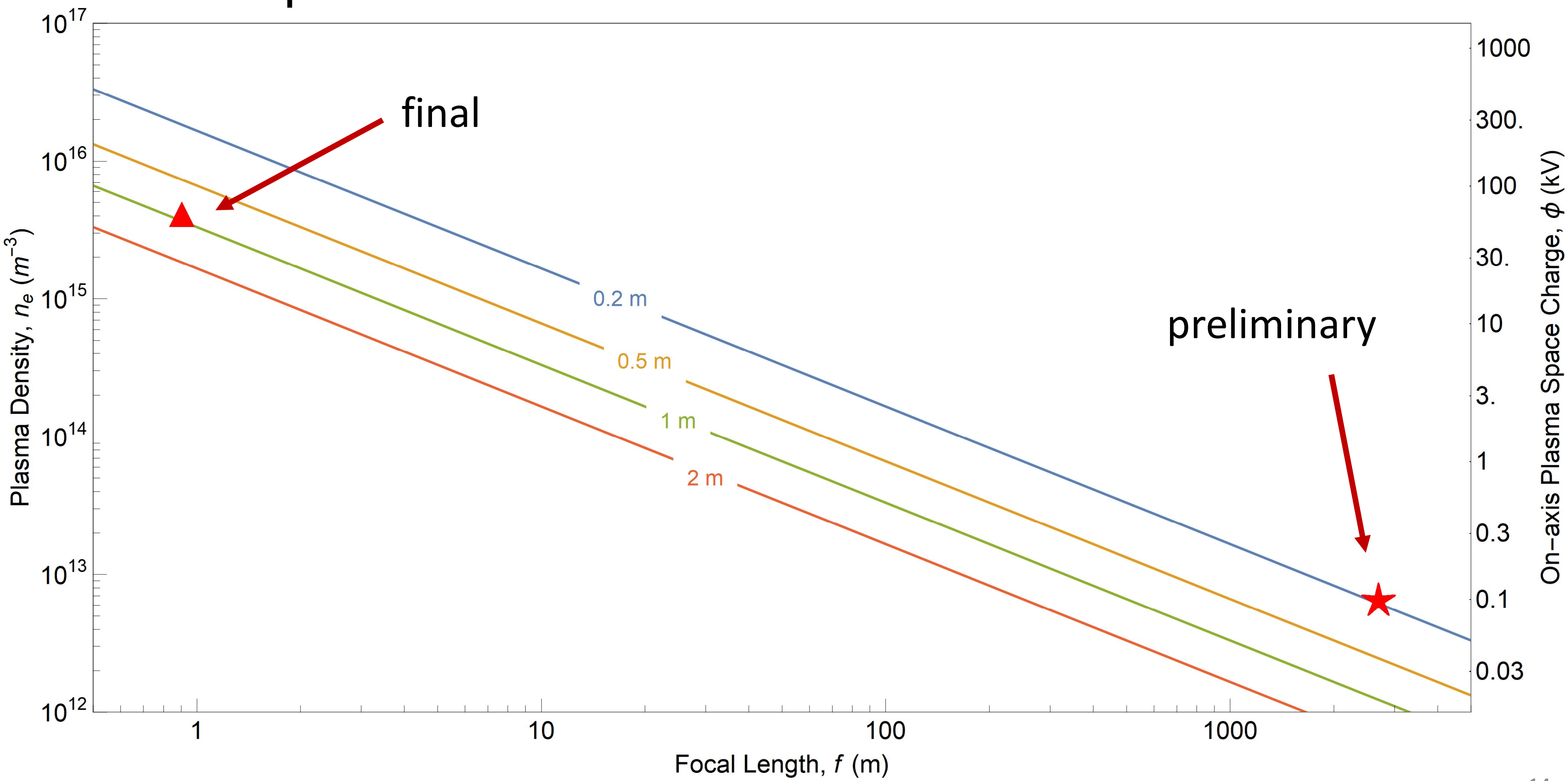
Phys Rev Lett 120 025001 (2018)

Plasma parameters

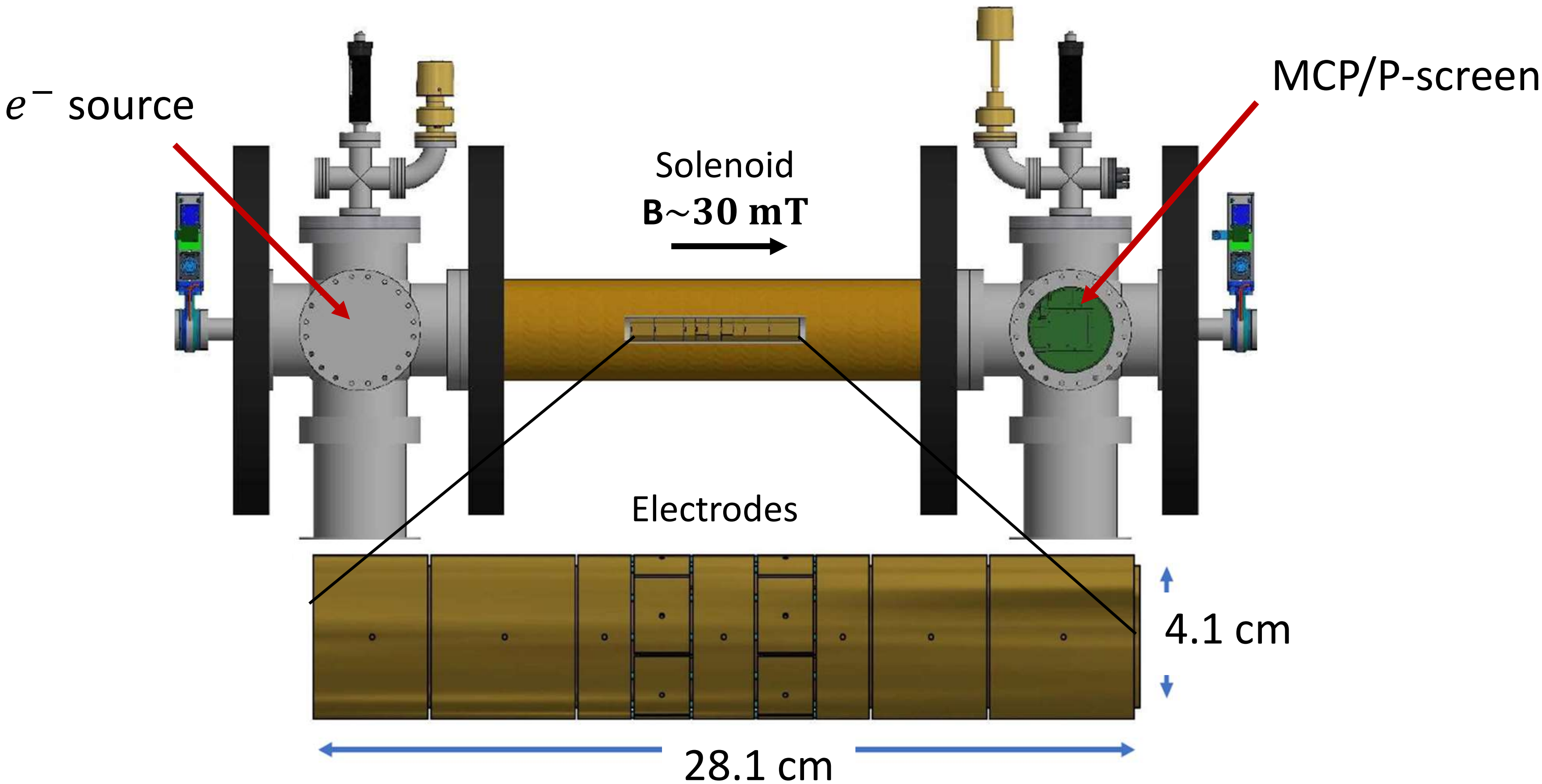
	Preliminary	Pre-construction	Final
Diameter	1 cm	3 cm	3.5 cm
Plasma Length	10 cm	1 m	1.2 m
Density	~10^{13} m^{-3}	$5x10^{14}$ m^{-3}	$5x10^{15}$ m^{-3}
Space-charge potential	20 V	2 kV	50 kV
Focal length	1000's m	10's m	1 m
B-field	0.03 T	0.1 T	0.15 T

Iterative & parameterised approach in preliminary & pre-construction phases

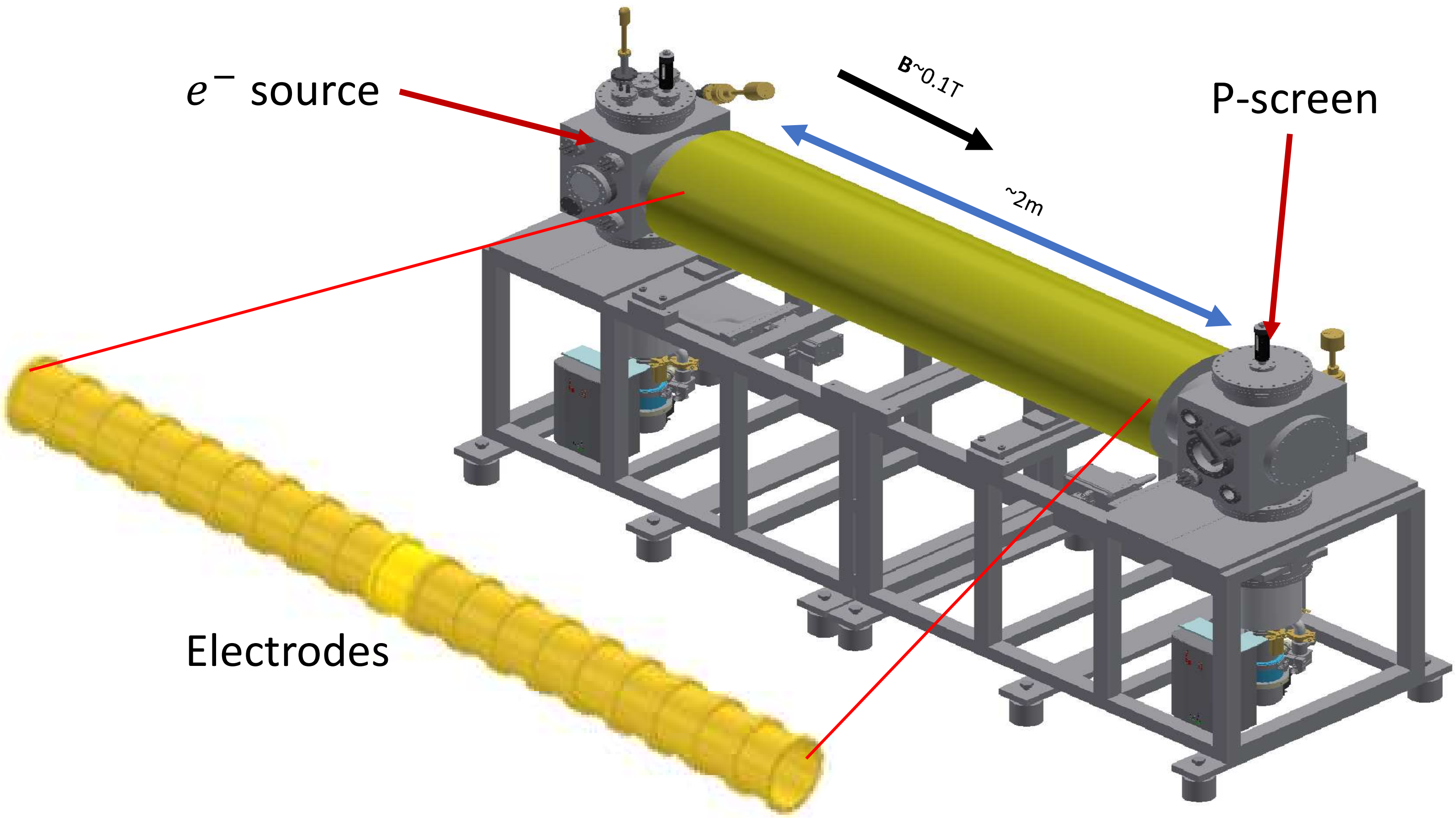
Plasma parameters



Current Apparatus (preliminary activity)



Proposed Apparatus (preconstruction phase)



R&D Philosophy

- Cautious approach
  - Built upon decades long experiences

- Iterative approach
  - Confirm simulation methods & feedback into multiple designs & apparatus upgrades
  - Vary single parameter (as far as possible)
    - Analyse using Machine Learning due to correlations
  - Confirm ‘known physics’ (scaling laws) in new apparatus

Risks / mitigations

Being unable to create a suitable plasma:

- Density
- Size (radius, length)
- Timescales

- Possible technical/engineering solutions
  - Utilise inbuilt redundancy – e.g. Increase confining fields, compartmentalise plasma
  - Modify designs – e.g. Increase apparatus size
- Should be identified in simulations!

Lens options

- End of preconstruction phase report to provide recommendation

- Why not implement magnetic from outset?
  - Magnetic lens implementation as challenging as electric lens
  - Electric lens lay some groundwork (magnet design)
  - Limited magnetic vs. significant electric flexibility
  - Significant lifetime cost savings using electric
  - Significant technology transfer opportunities for electric

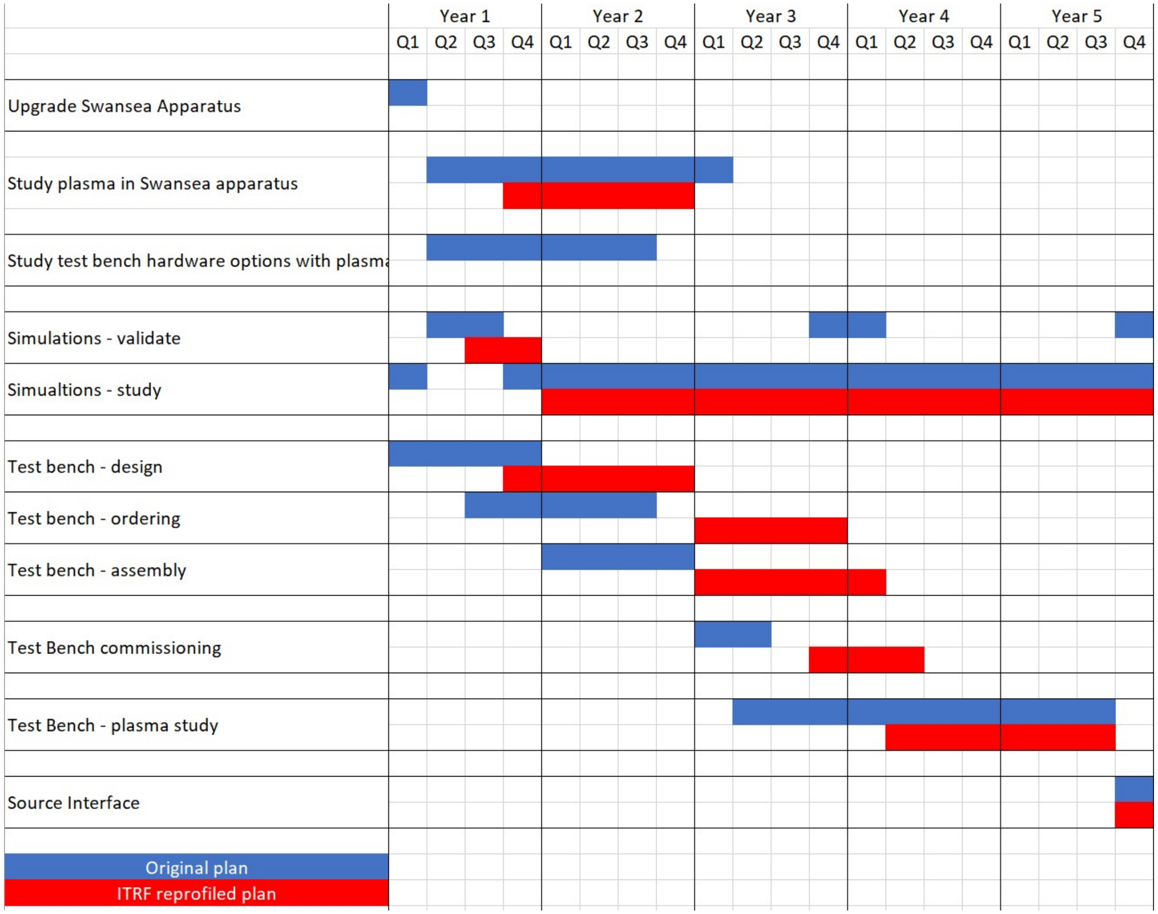
Resources

- Current ITRF Scoping project provides limited preliminary activity resources
  - Enables profitable studies for preconstruction phase apparatus design
  - Limited by one junior postdoctoral researcher
    - Enough for 4 FTE personnel!
- Existing apparatus at Swansea (& internationally) to be employed for studies
- Existing international expertise employed for efficiency

- Timeline identifies years 2, 5 (& 7) as critical
  - Resource shortfall early can be recovered at later stage (at non-linear & higher integrated cost)

Timeline

- Reprofile with ITRF resources
- Compressed timescale for detailed studies
- Required studies still achieved with additional personnel, outsourcing, & overspecifications
  - Increased costs



WP3 Personnel

- W. Bertsche
- M. Charlton
- S. Eriksson
- T. Dascalu
- J. Fajans
- J. Wurtele
- B. Bingham
- R. Hugtenburg
- J. Purden
- A. Knoll
- E. Bennet
- PDRA, etc.

Swansea University Prifysgol Abertawe

MANCHESTER 1824 The University of Manchester

Science & Technology Facilities Council Rutherford Appleton Laboratory

Imperial College London

SAC

SUPERCOMPUTING WALES UWCHGYFRIFIADURA CYMRU

Summary

- A breadth of personnel & support exist to ensure success of work package
  - Experimental, theoretical, medical, plasma, and accelerator physicists
  - HPC and supercomputer engineering support
  - Mechanical engineering support
  - Etc.
- No known fundamental physics issues foreseen
- Decades of large project experience available within the WP
- Significant experience developing non-neutral plasma, and techniques, for both study and use

- The risks and challenges (and opportunities) are recognised and constantly evaluated
  - associated with taking different approach (non-neutral vs. discharge)
  - associated with advancing individual non-neutral plasma aspects
  - associated with combining many state-of-the-art aspects
  - current non-ideal funding profile also increases overall risk

Questions?