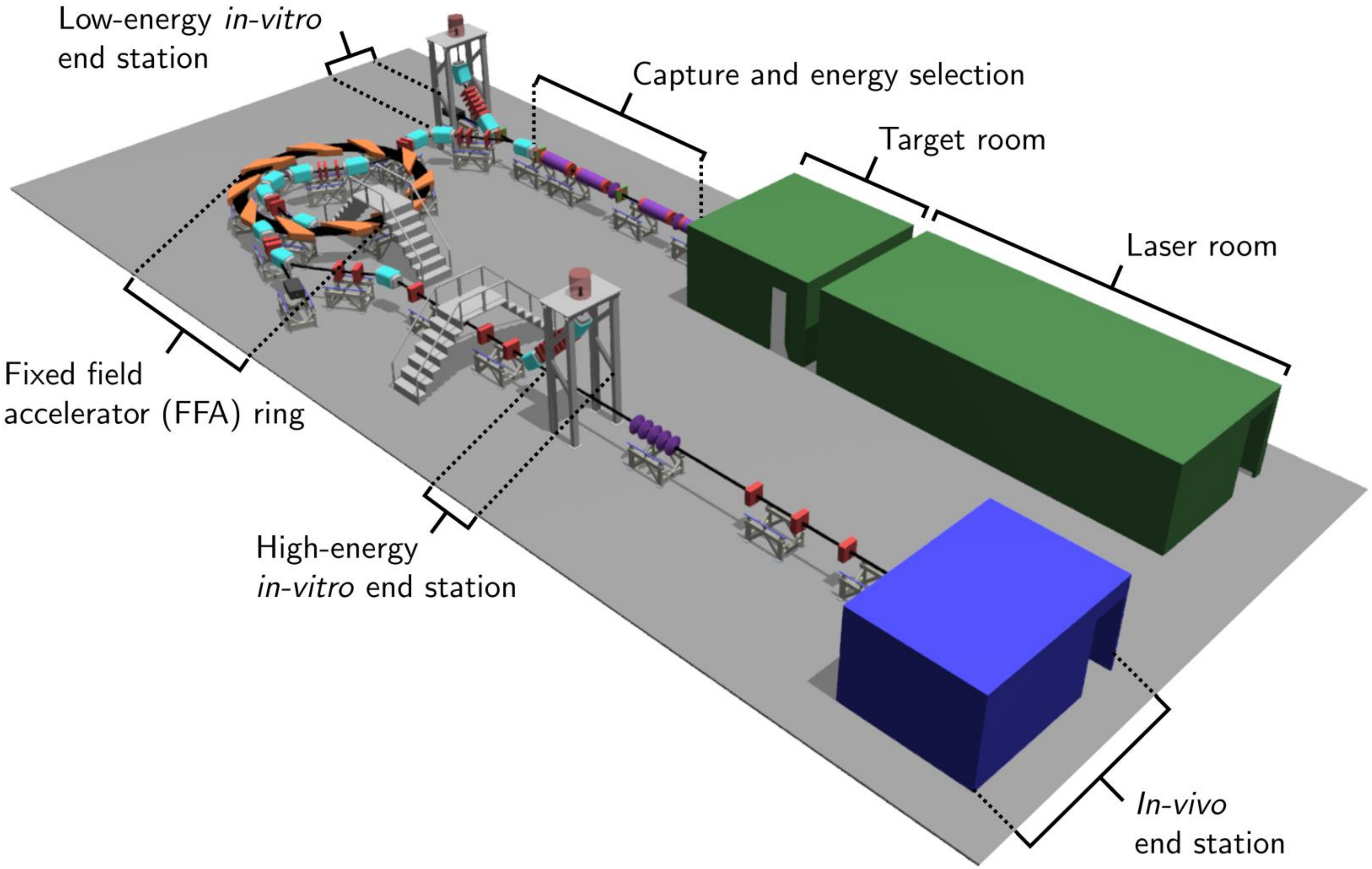
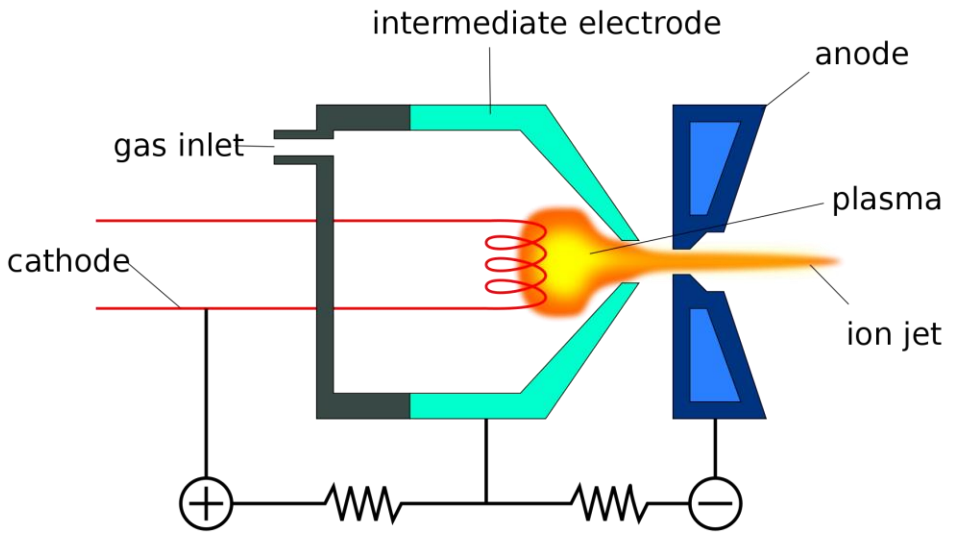
LhARA
Laser-hybrid Accelerator for Radiobiological Applications

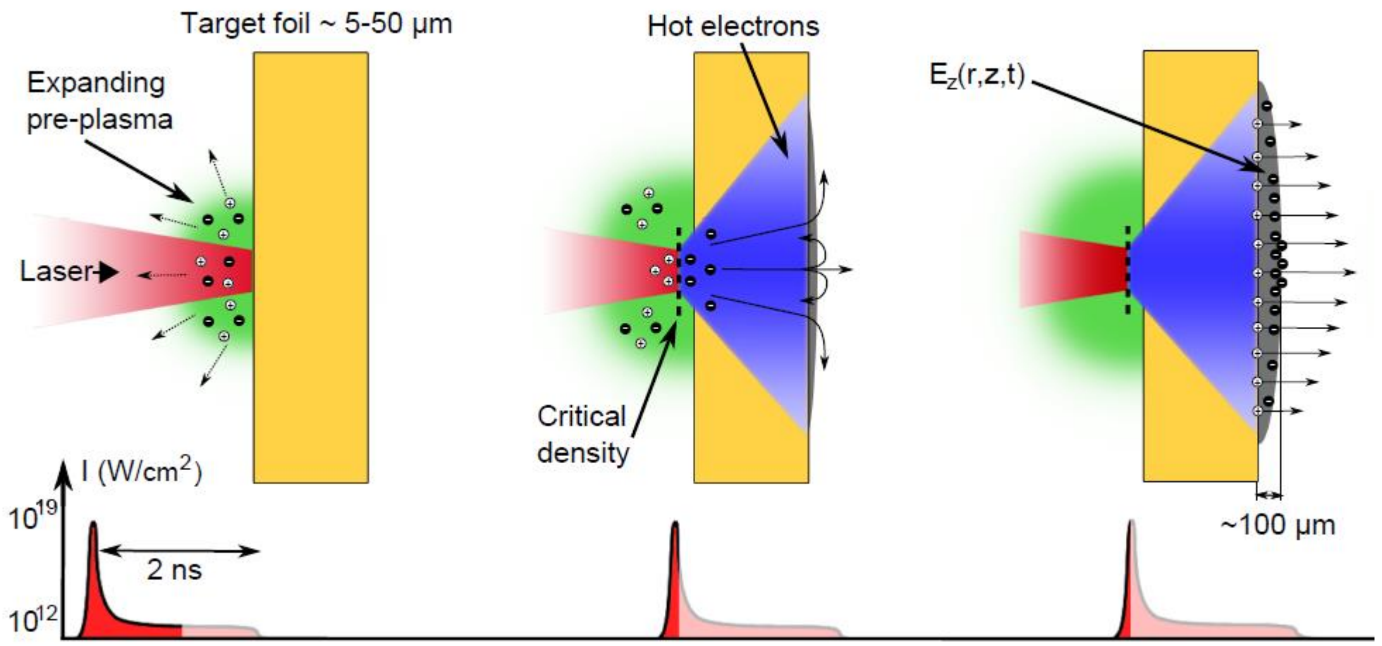


Ion production space charge

- Ions experience the electric field due to their neighbours – space charge – and repel each other.
- Effect is worst when ions have low energy – faster acceleration = better beam.
- Conventional ion sources extract ions with energies of a few 10's of keV and accelerate that beam over several metres.
- Laser-target system accelerates ions to MeV energies over distance of 100's of μm – space charge effect is much reduced.



Duoplasmatron – source Evan Mason 7/7/16



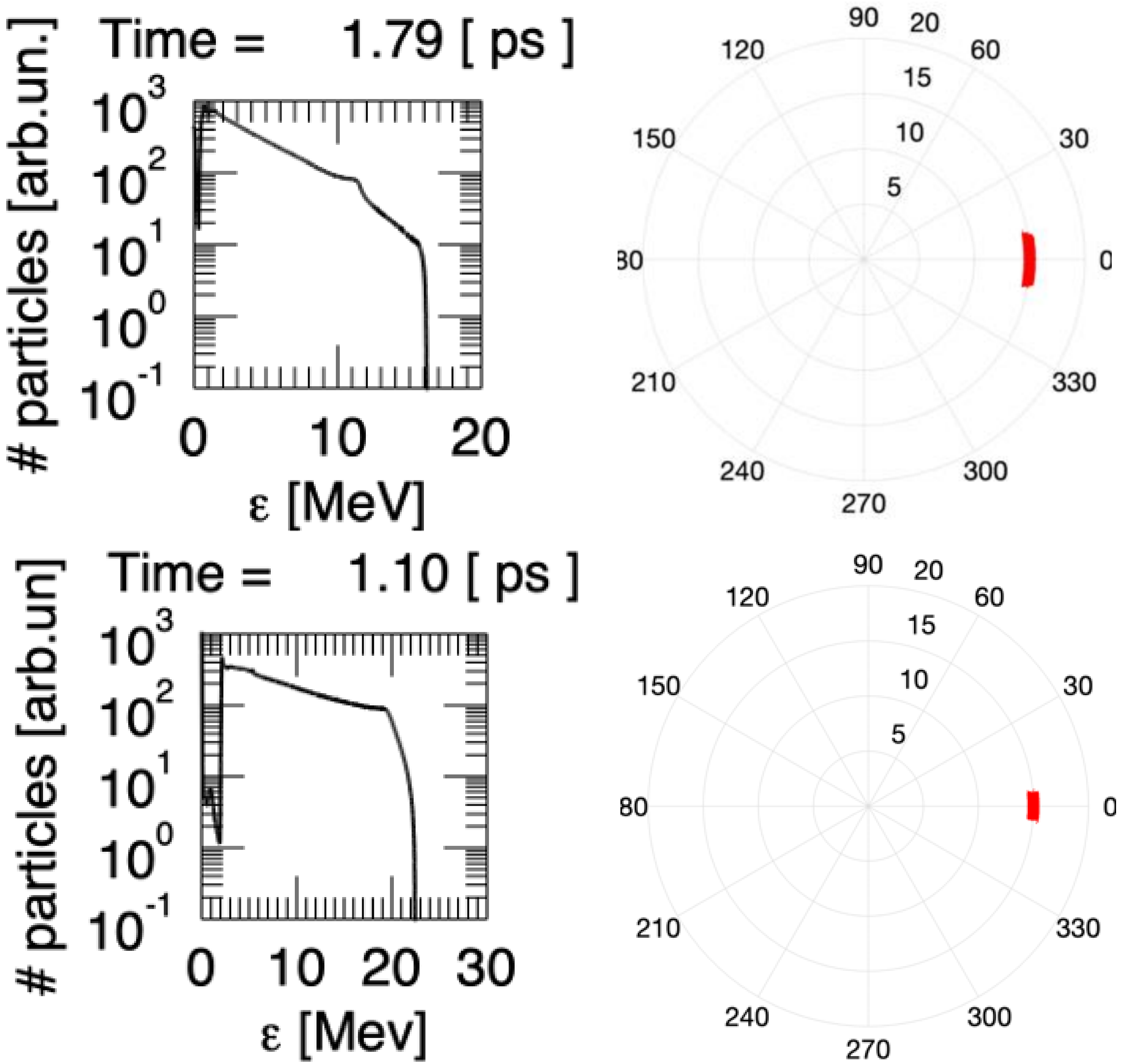
4 Objectives

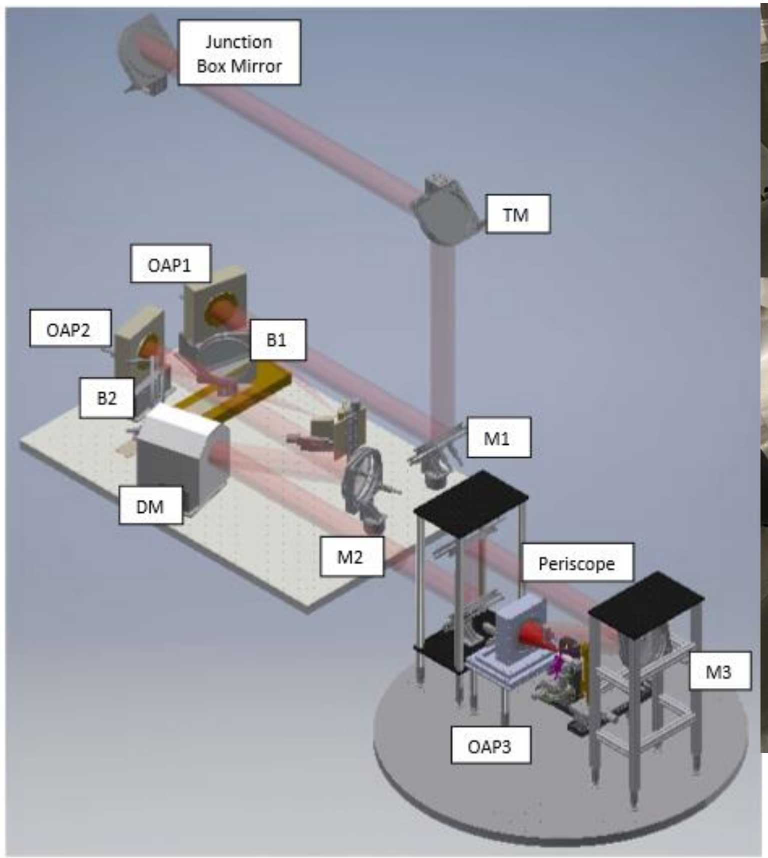
Simulation

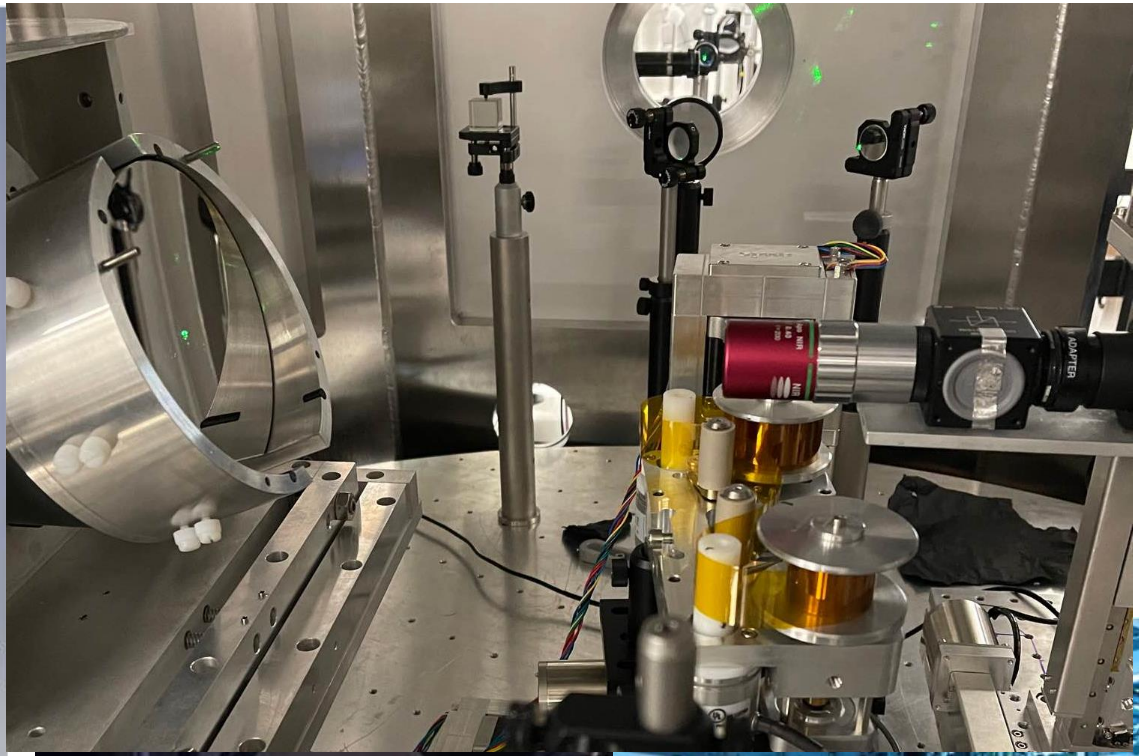
Scapa

- Diagnostics
- Tests

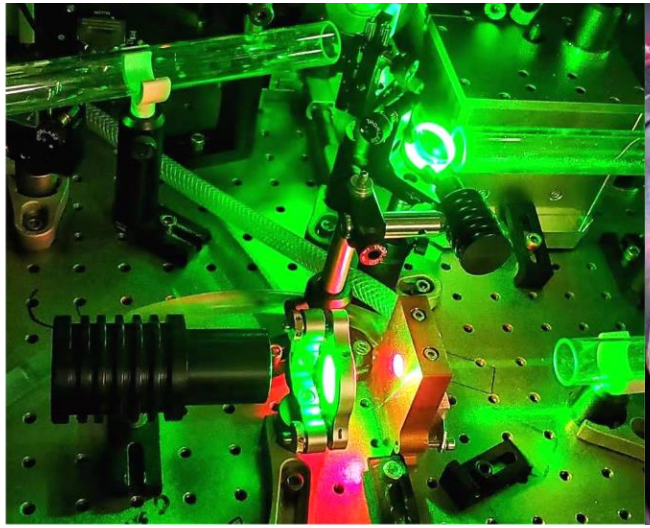
High rate tests

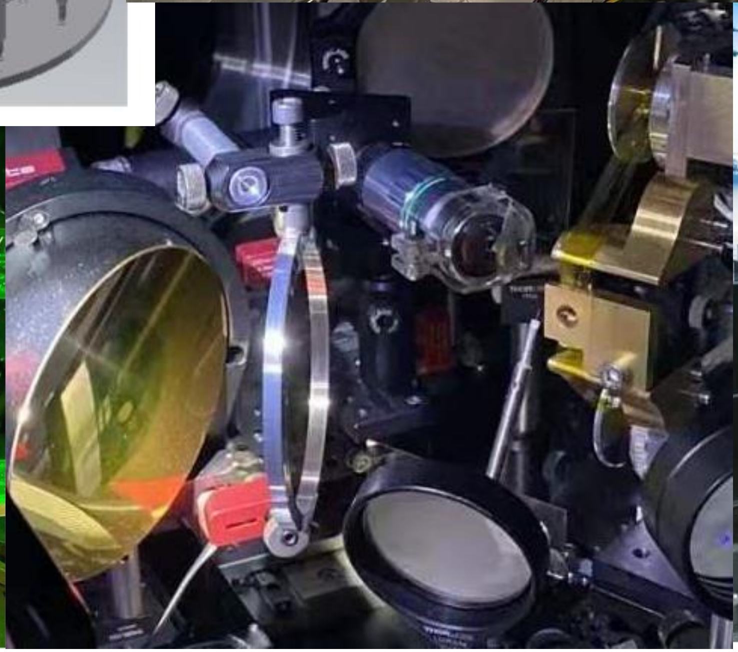






SCAPA
Cerberus
Zhi





Experiments & Technology Development in 2-year Programme: Characterising Source and Benchmarking Simulations

Established Diagnostics…

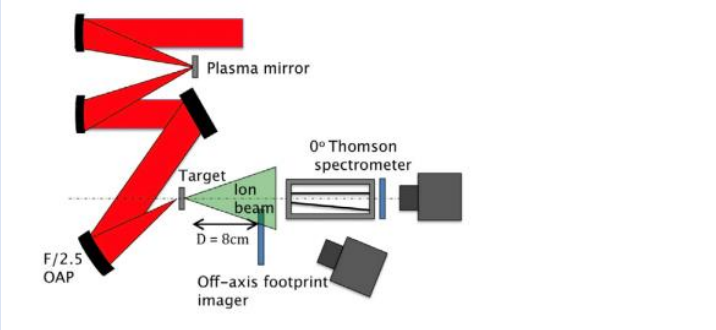
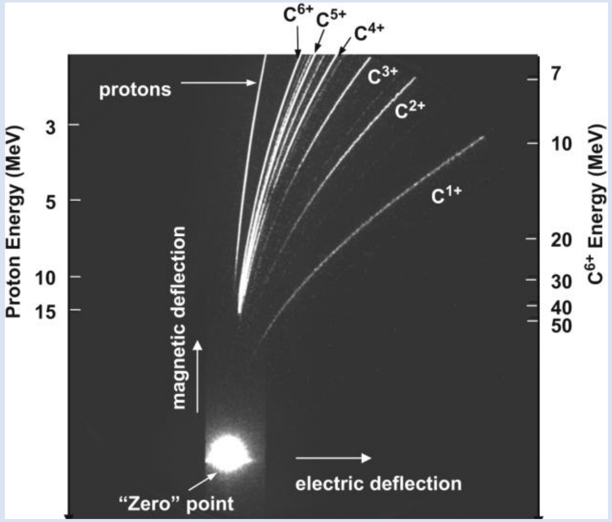


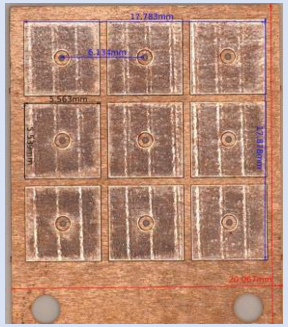
Figure 1. Experimental setup. A Thomson spectrometer deflects the ions onto a piece of plastic scintillator, which is imaged using an EMCCD camera. A second sheet of scintillator images the off-axis portion (>6° off-target normal) of the ion beam.

J.S Green *et al.,* NJP. 12 (2010) 085012

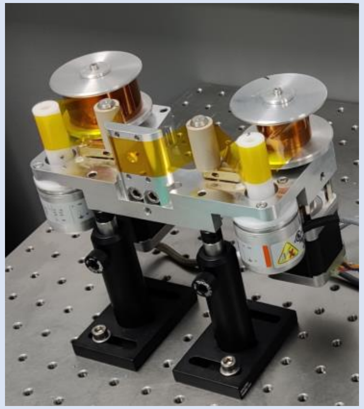


R. Prasad *et al.,* Nucl. Instrum. Methods. 623.2 (2010): 712-715.

Established Targetry…moving toward Hz-level targetry



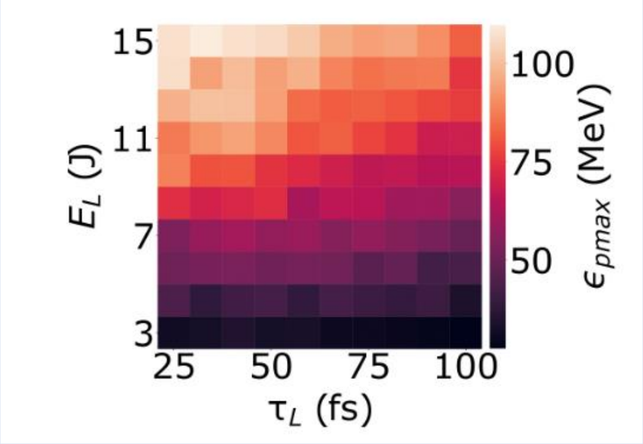
Typical 9-target array



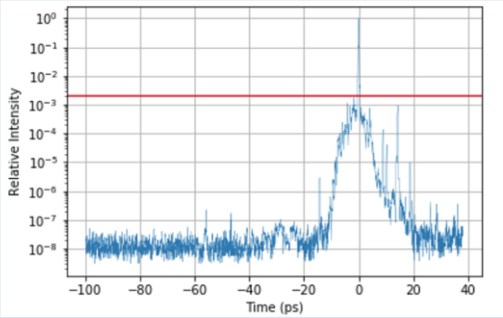
Tape targetry system (online in SCAPA 2022)

….to build a systematic parameter space map of the source performance

- Energy, Flux, Divergence across multiple ion species

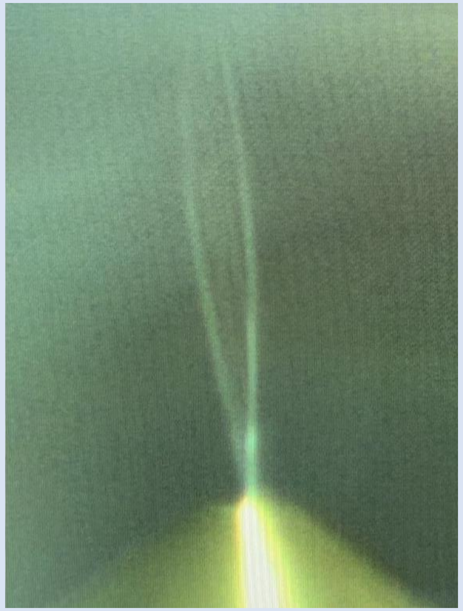


..but also need to consider some other experimental contributions like temporal contrast



Experiments & Technology Development in 3-year Programme: Producing a stable, high-rep source

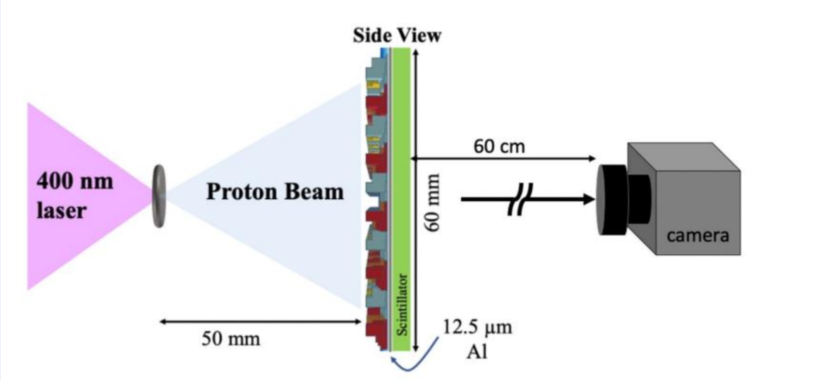
Novel Liquid Targetry



Courtesy of C. Palmer

- Reduces production of debris
- Increases operational time and possible rep rate

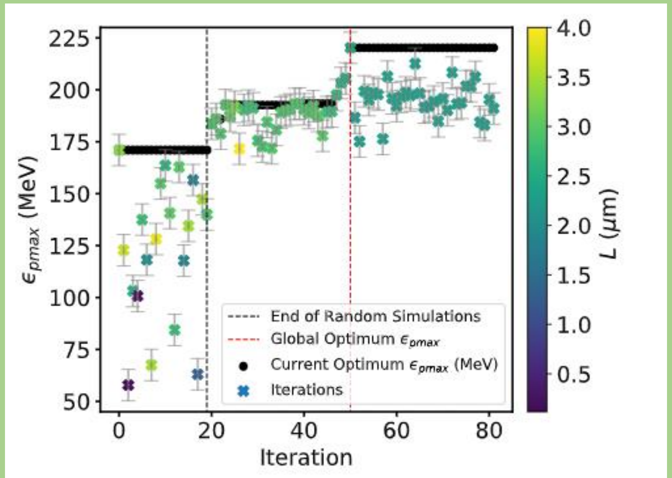
Advanced Particle & Laser Diagnostics



D. Marsical *et al.* , Plasma Phys. Control. Fusion 63 (2021) 114003

- Implementation of advanced (existing) particle diagnostics, taking account of long term operation.
- Implementation of full laser diagnostic suite to support automation, stabilisation.

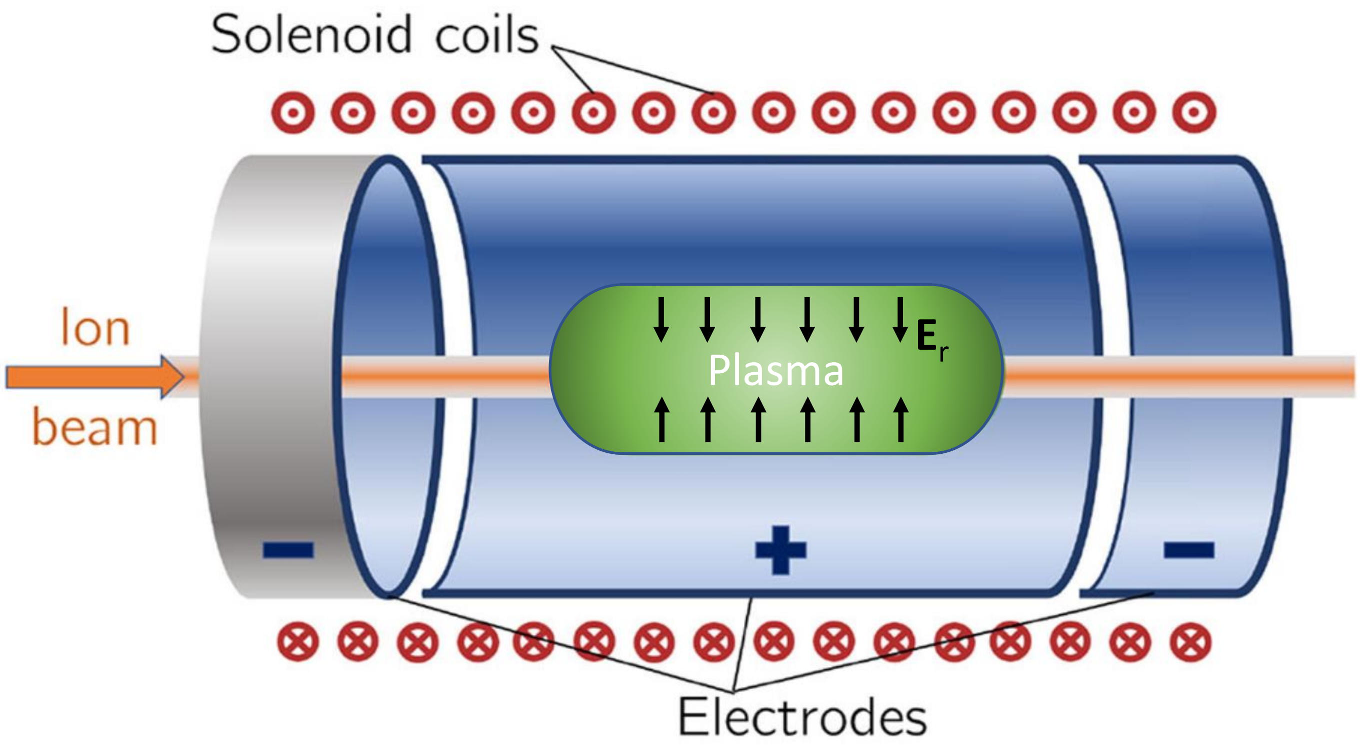
ML/AI Control & Optimisation



- Application of ML techniques (e.g Bayesian Optimisation) for parameter space
- Application of AI techniques (DNNs, CNNs) for system control and virtual diagnostics

Number	Name	Description	Likelihood	Impact	Score	mitigation	Mitigated Likelihood	Mitigated Impact	Mitigated score
1	PM - Unable to secure laser beamtime	SCAPA schedule does not allow for beamtime access	2	4	8	Pay for beamtime access/ Perform scaled experiments at other laser systems (e.g. Imperial)	2	3	6
2	Laser - Technical issues with laser prevent access	SCAPA/Imperial laser has technical issues that cause delays	3	4	12	Use different laser facility for similar experiments/ pay for beamtime access	3	3	9
3	Simulations - Insufficient HPC resource	Simulations take long or are more costly than planned	1	3	3	Included mitigation costs to pay for access to the Hartree HPC system	1	0	0
4	Source output - Energy	Unable to deliver sufficient beam energy from source	2	4	8	Early testing regime. Adjust laser cond	2	2	4
5	Source output - Intensity	Unable to deliver sufficient beam intensity.	3	3	9	Early testing regime. Multiple shot treatment	3	2	6
6	Source output - divergence	Unable to capture sufficient particles in beam due to un/mis understood source dynamics	3	3	9	Early testing regime. Close engagement with WP3	3	2	6
7	Source output - particle type	C6 / other ion yield low	4	3	12	Investigate experimental techniques to increase yield (i.e target cleaning)	4	2	8
8	Source output - stability is too low	Source parameters are unstable shot-to-shot	4	4	16	Apply active stabilisation techniques	4	2	8
9	Source design - Target debris	Target debris for optimal source is too high for long term operation	2	4	8	Reduce target thickness, capture as much debris as possible	2	2	4
10	Source design - activation	Unsustainable activation of materials surrounding interaction	2	4	8	Change design to minimise potential for activated materials around interaction point	2	2	4
11	Source design - vacuum	Targetry unable to perform in vacuum required by capture system	2	4	8	Design differential pumping system capable of maintaining adequate vacuum levels	2	2	4

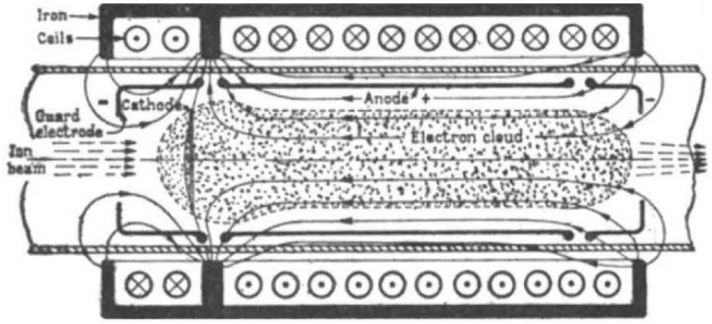
WP3 - Proton and Ion Capture
Gabor lens



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

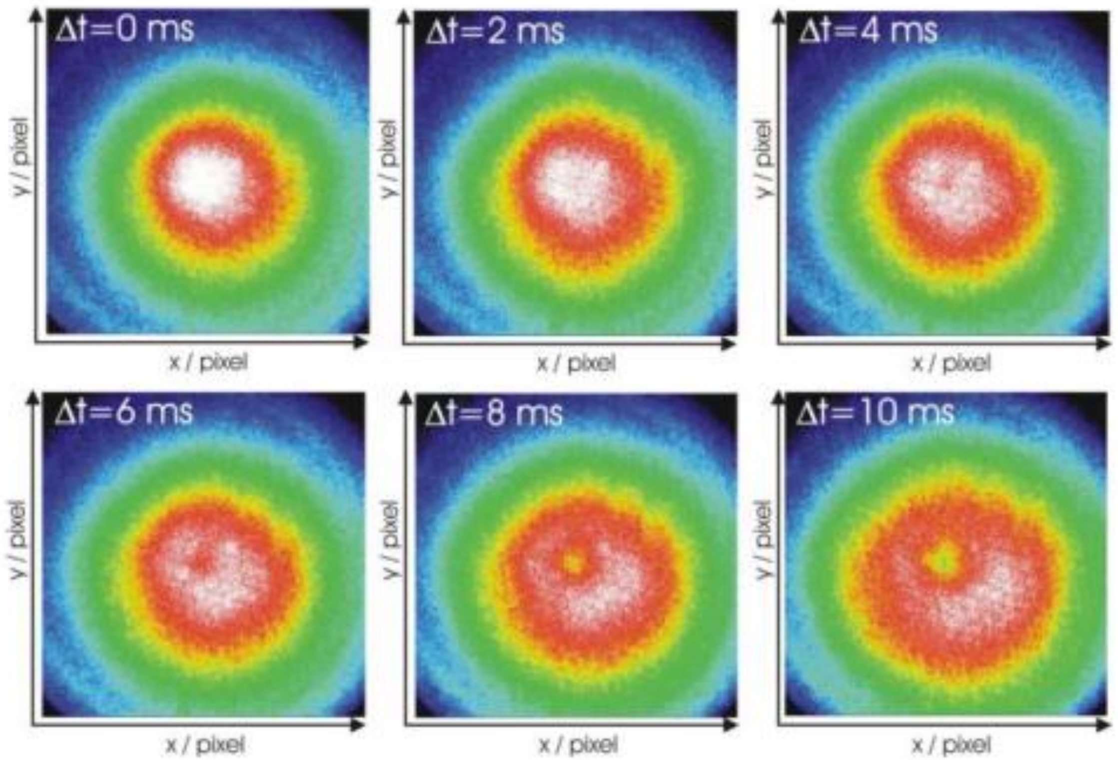
The focal length of a Gabor lens of length l is given in terms of the electron number density by:

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

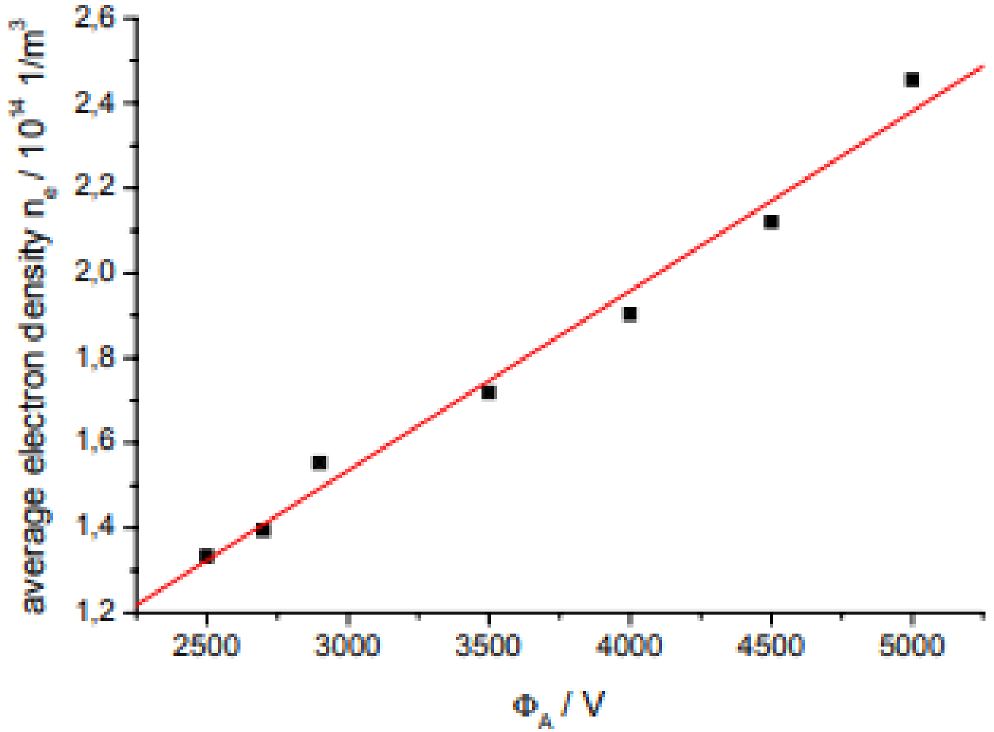
where e is the magnitude of the electric charge of the electron, n_e is the number density of the electrons confined within the lens, ϵ_0 the permittivity of free space, and U the kinetic energy of the particle beam.

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

Stability



Density



Objectives.

Initial experiments – establish stable high 'fill factor' plasmas

Phase 2. New apparatus to access higher densities - Tests at SCAPA

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

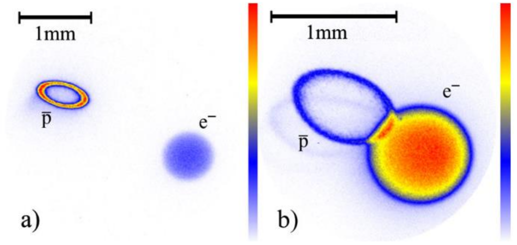
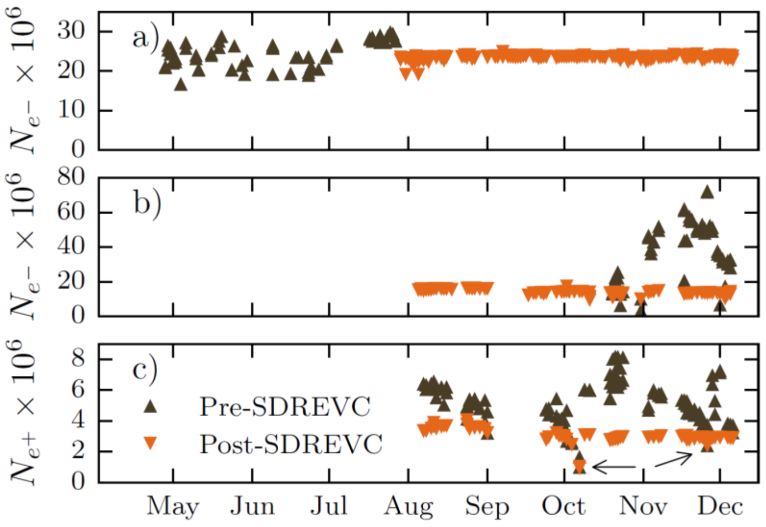
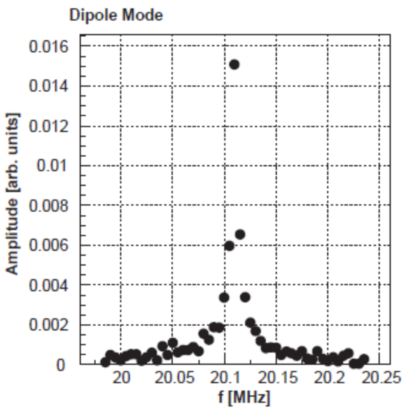
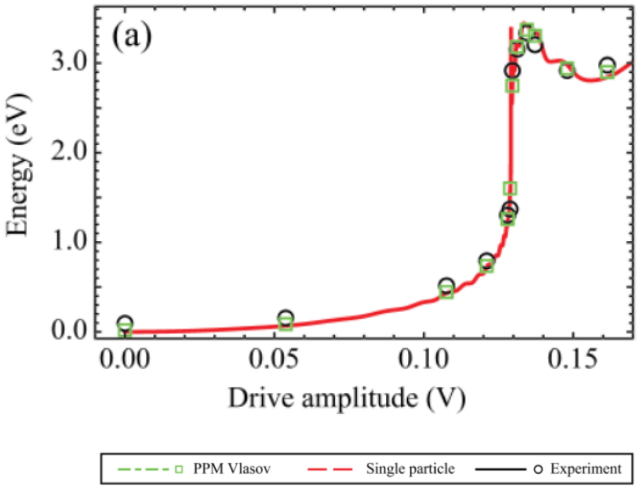
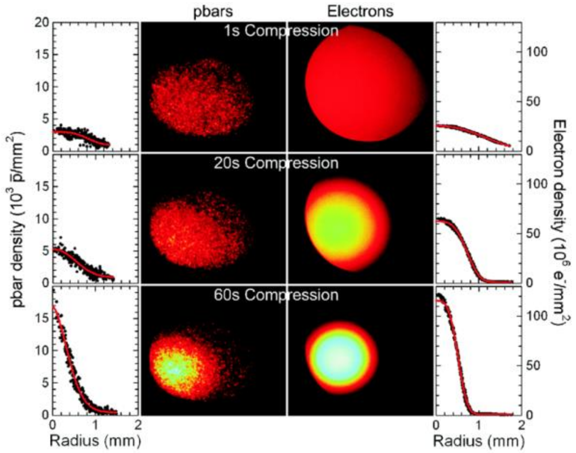


FIG. 1 (color online). Images of centrifugally separated plasmas trapped in (a) a 1 T and (b) a 3 T solenoidal field. In both









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

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

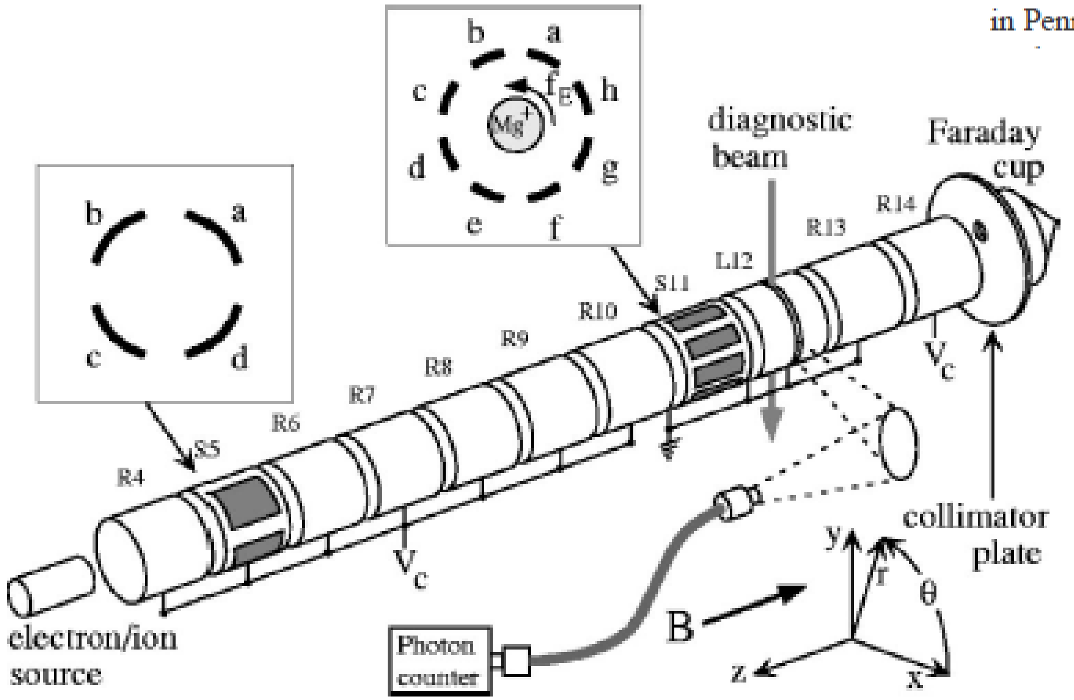
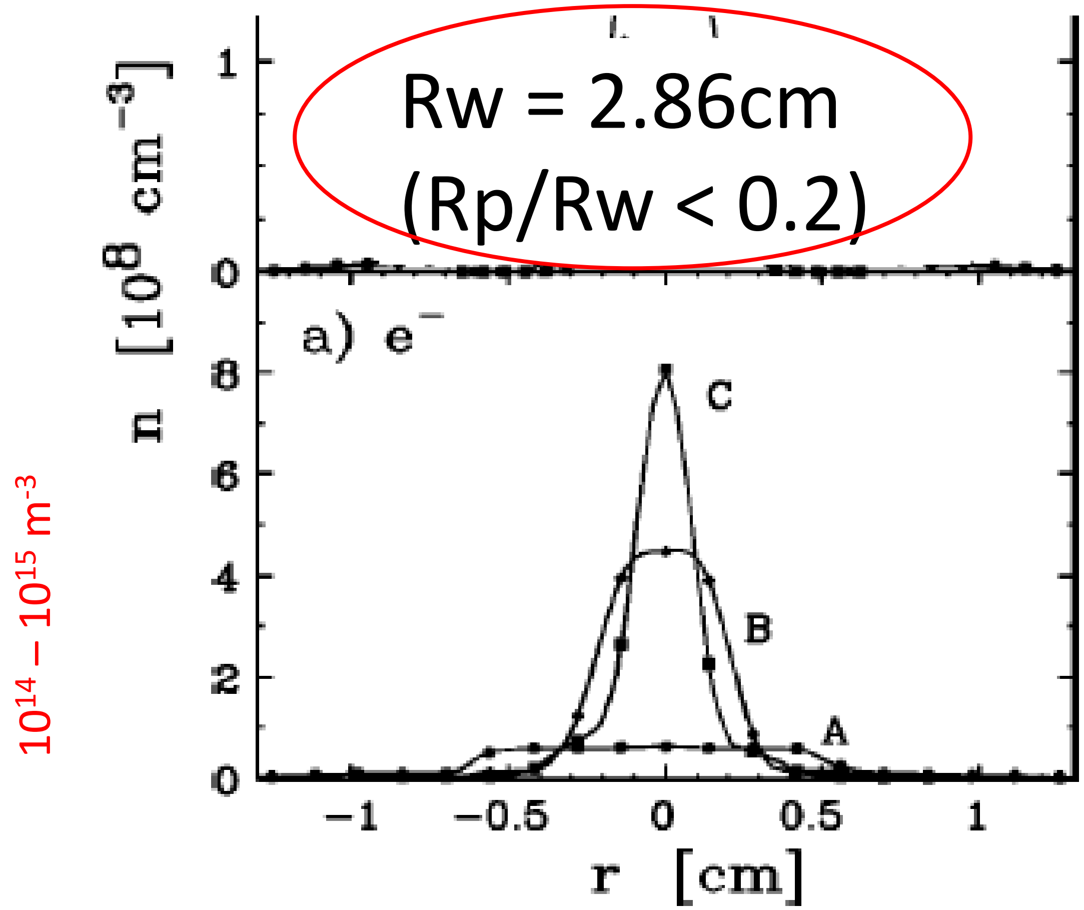
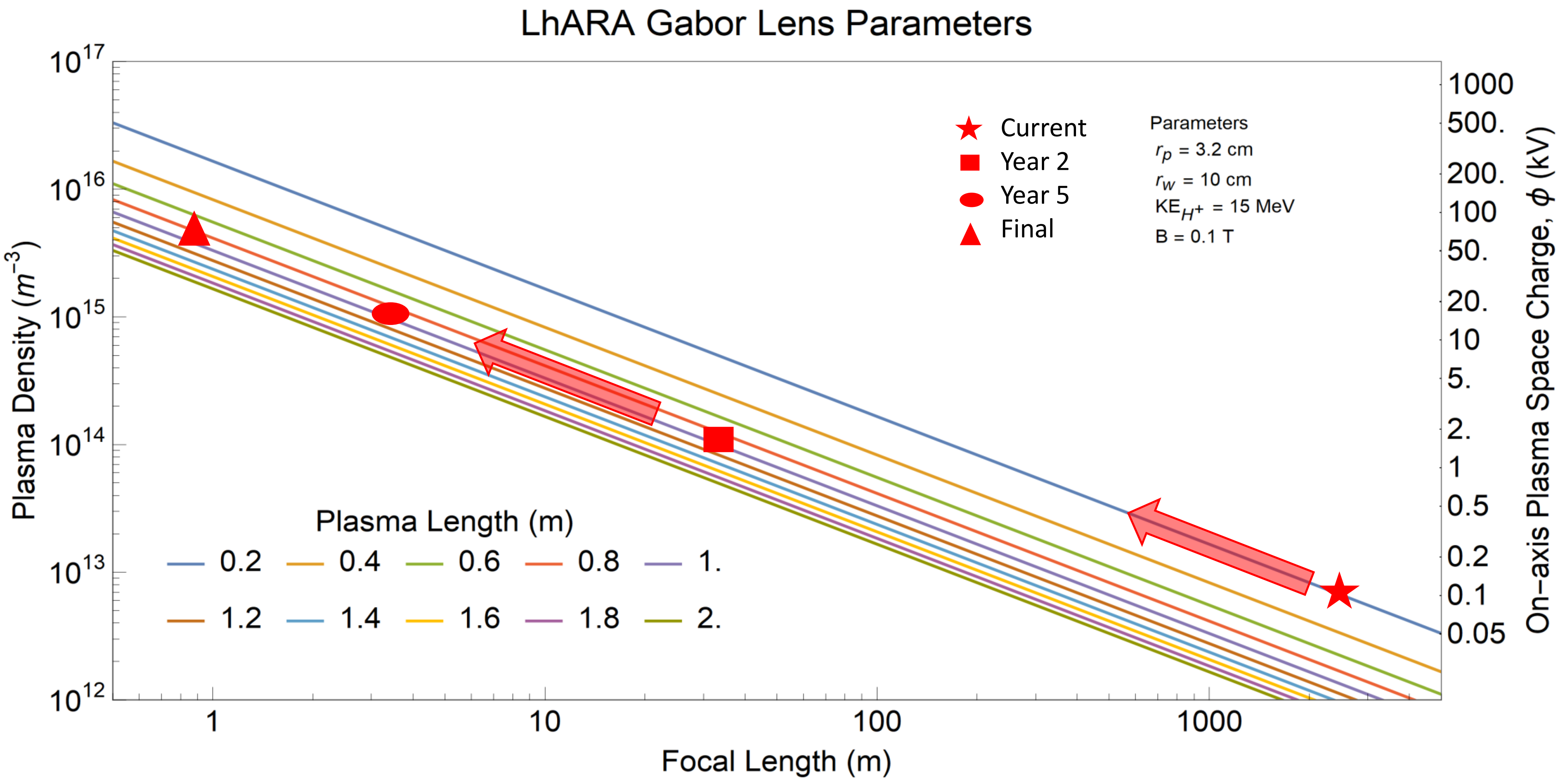


FIG. 1. Schematic of the IV Penning–Malmberg trap used for electron and ion plasma experiments. Electrons are typically confined in the region S5 →S11; Mg^+ ions (shown) are typically confined in the region S11→R13. A laser diagnostic is used for ion plasmas; a collimator plate and Faraday cup diagnostic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

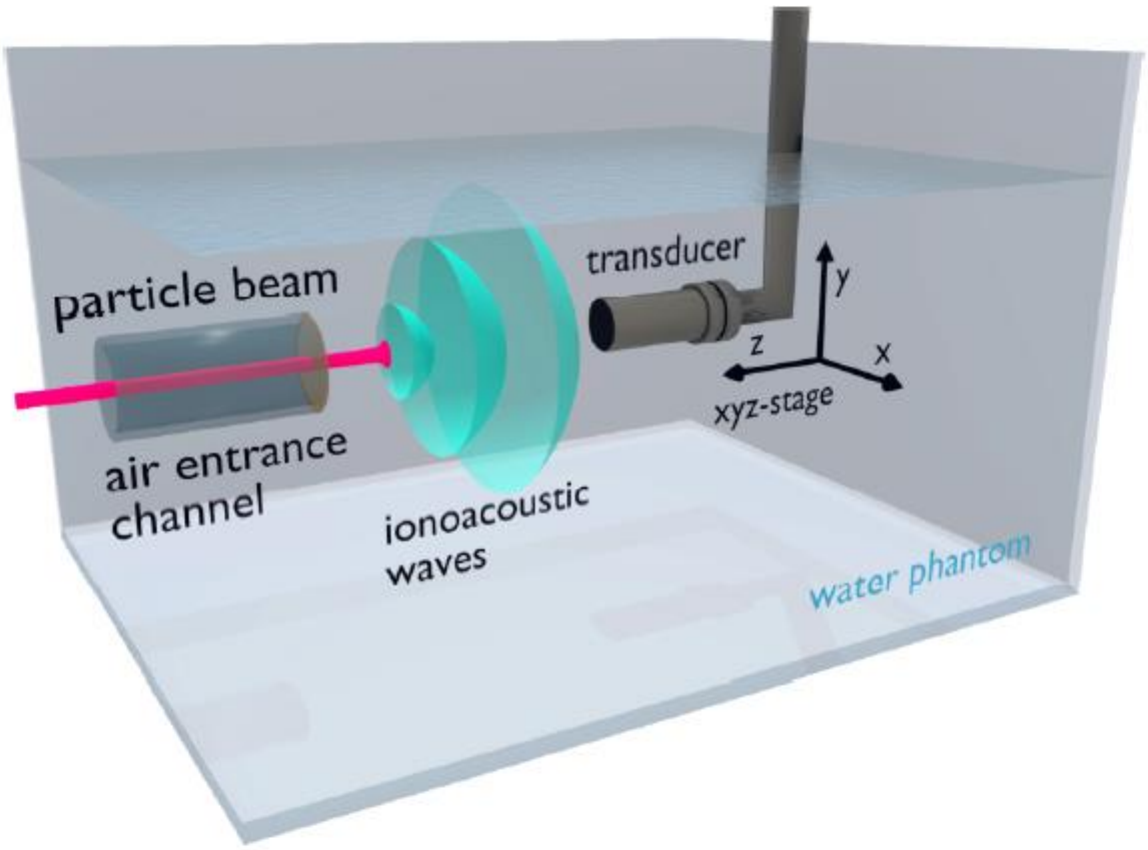


Year 5 milestone



Plasma initialisation	Slow load / long stabilisation time	3	3	9	Design / Purchase improved electron source	3	1	3	Interplay between various experimental components prevents this being known for sure a priori	Yr 1, 3	Yr 3
Plasma lifetime	A short lifetime might adversely effect the ability to suitably study the plasma	3	4	12	Careful design and study to increase lifetime. Multiple causes can be identified:	3	3	9			
Plasma Density	A low density will result in too long a focal length (& beamline)	4	4	16	Careful design and study to ensure a suitable density can be reached:	4	3	12			
Acceptance	An insufficiently large plasma radius to focus all the ion beam	3	3	9	Increase electrode radius		2	6	Increasing the electrode radius to accommodate a larger plasma radius maintains a plasma to wall radius ratio <<1, a well studied parameter regime. Although initial designs will have large radii electrodes, these can be increased further, perhaps with vacuum system & confining solenoid redesign. As initial plans intend to use exisiting solenoids (at Swansea & Strathclyde), the	Yr 4	Yr5+
Delivery delays	Delays in sourcing / receiving equipment	3	3	9	Appropriate personnel to source off-the-shelf equipment		2	6	Although bespoke apparatus might be available commercially, it can often be time consuming to source a suitable supplier (considering competency, cost, & leadtime). Some advanced equipment may need to be	Yr 1, 3	Yr 3

Ion Acoustic Dose Mapping



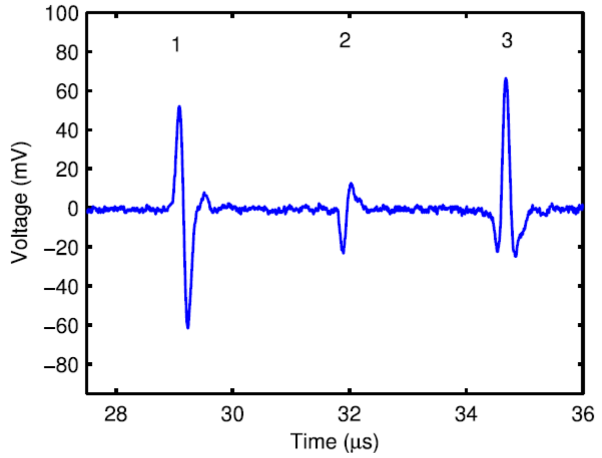


FIG. 2. Example of an ionoacoustic signal from a 110 ns ion pulse with 2×10^6 protons, recorded with a 3.5 MHz ultrasound transducer (pulse average of 16 samples, see also text).

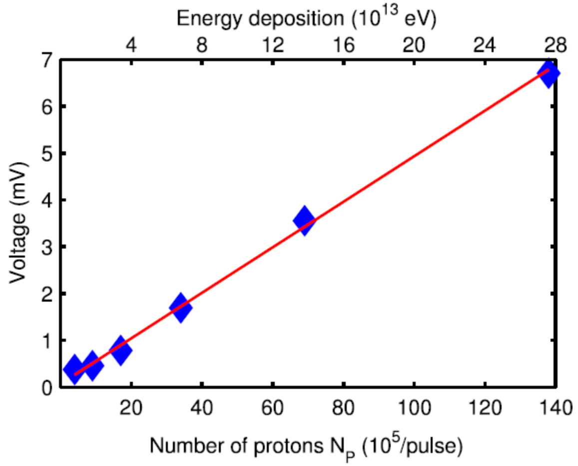


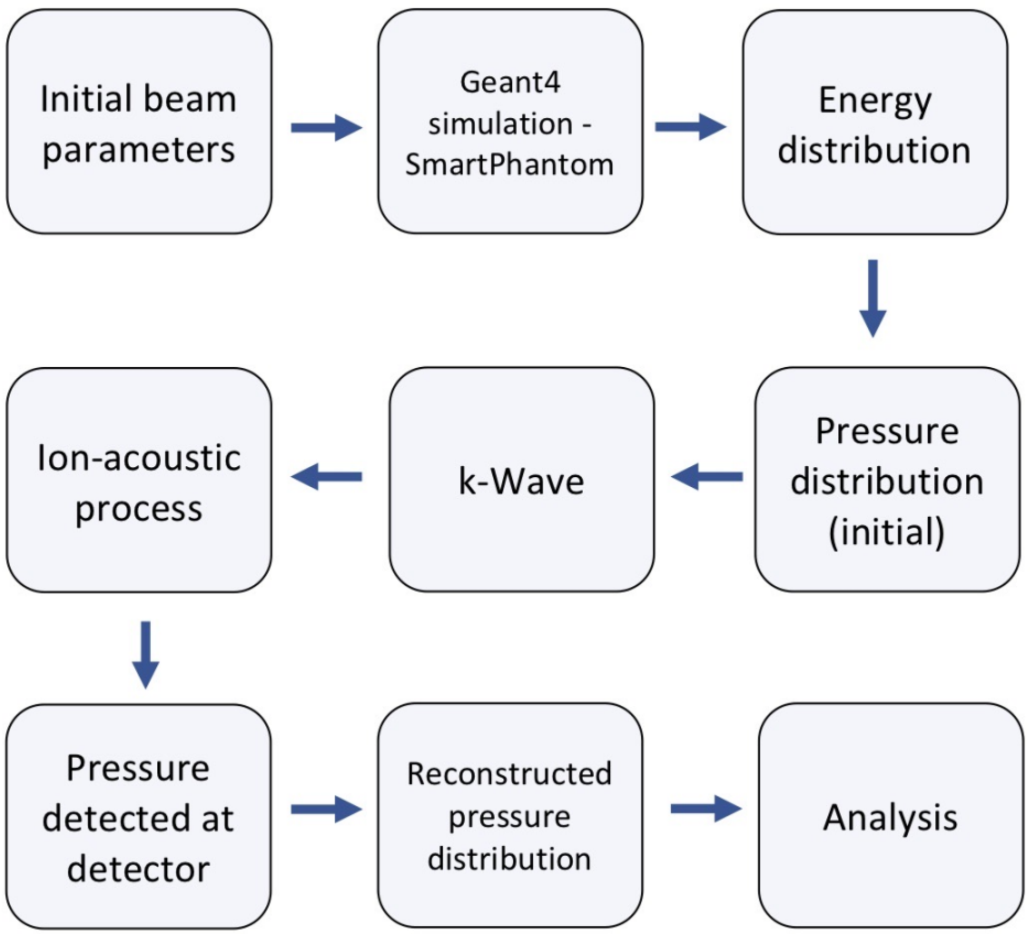
FIG. 5. Acoustic signal amplitude of a 473 ns proton bunch (16 pulses average) as function of particle number and total energy deposition per pulse, along with a linear polynomial fit (red line).

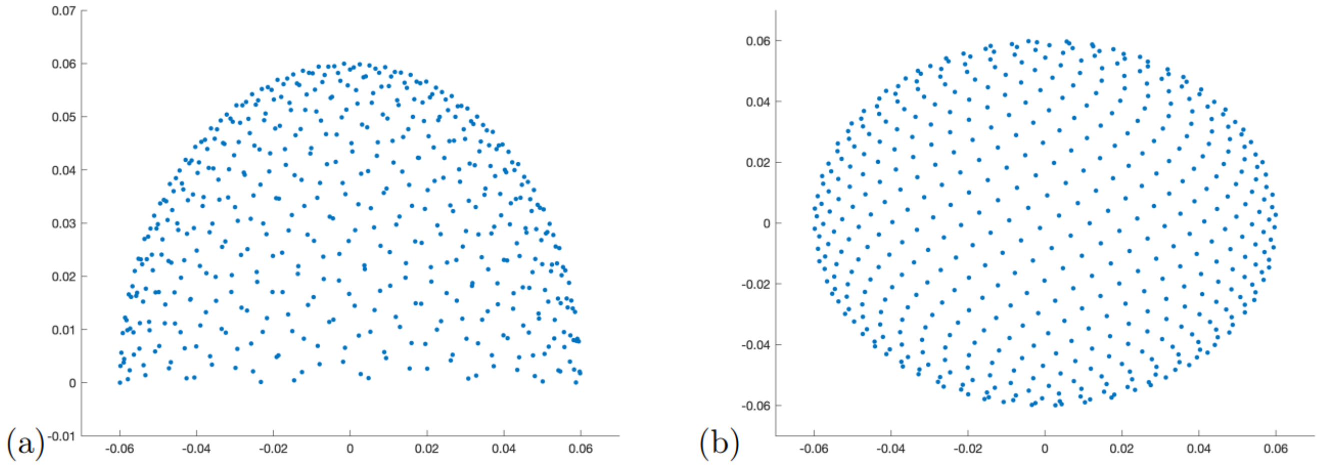
- Is it possible to get the deposited dose using acoustic measurements ?
- Compatibility with medical ultrasound and possibility of use in vivo

Ionoacoustic characterization of the proton Bragg peak with submillimeter accuracy

W. Assmann, S. Kellnberger, S. Reinhardt, S. Lehrack, A. Edlich, P. G. Thirolf, M. Moser, G. Dollinger, M. Omar, V. Ntziachristos, and K. Parodi

Ion Acoustic imaging



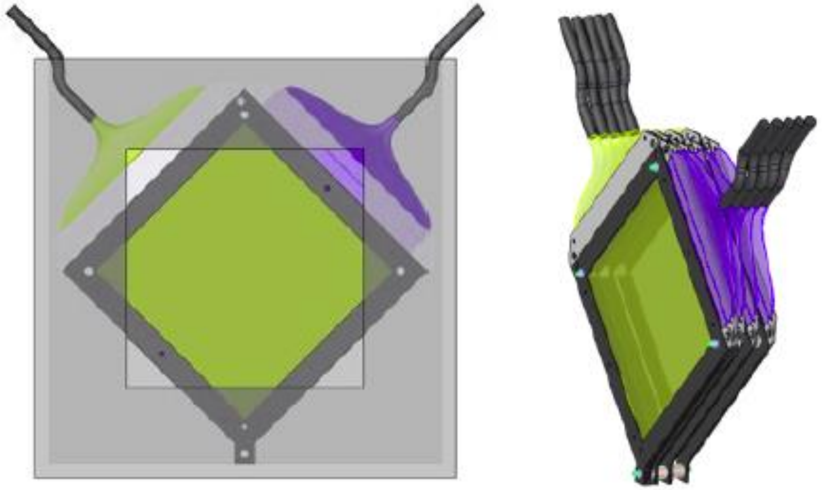


Time reversal
Model based minimisation
Back projection

The SmartPhantom

Water-filled phantom useful for protons, few 10s of MeV up

www.ptwdosimetry.com
http://www.k-wave.org/
https://geant4.web.cern.ch/



Beam is measured using scintillating fibre planes
Scintillating fibre -> clear fibre -> detector
Aiming to use the edge of the plane as a connector
Clear fibres bundled and sent to CMOS camera
For faster readout, could use photodiodes

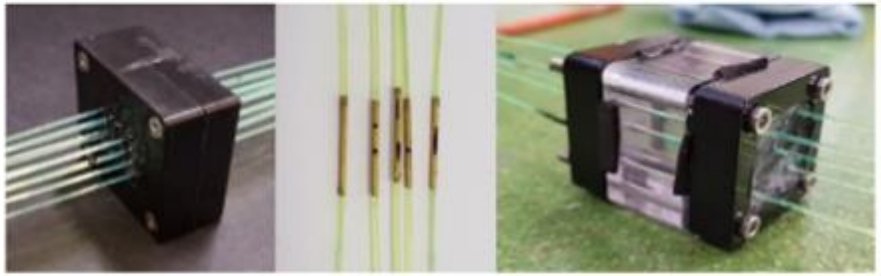
SmartPhantom is a tool go on the endstations, to compare simulations of beam interactions with experiment

Aim is to compare measurements:
- proton acoustic
- scintillating fibre
- dosimetry

Compare measurements & simulations:
- protons in water (GEANT4)
- protons in detectors (GEANT4)
- acoustic signals (k-Wave)

k-Wave
A MATLAB toolbox for the time-domain simulation of acoustic wave fields

GEANT4
A SIMULATION TOOLKIT

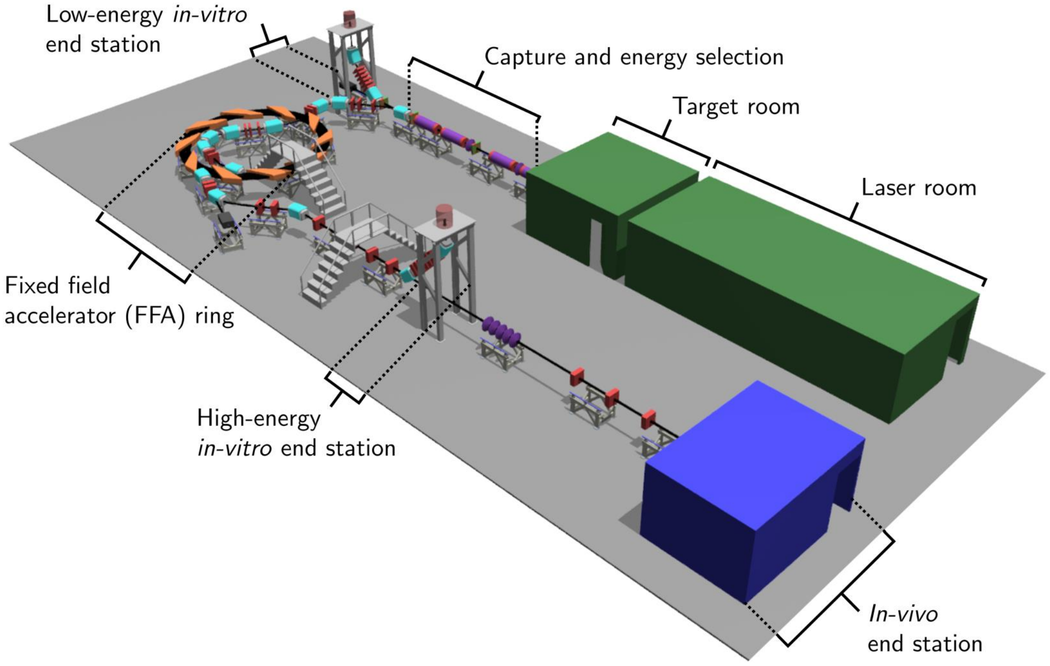


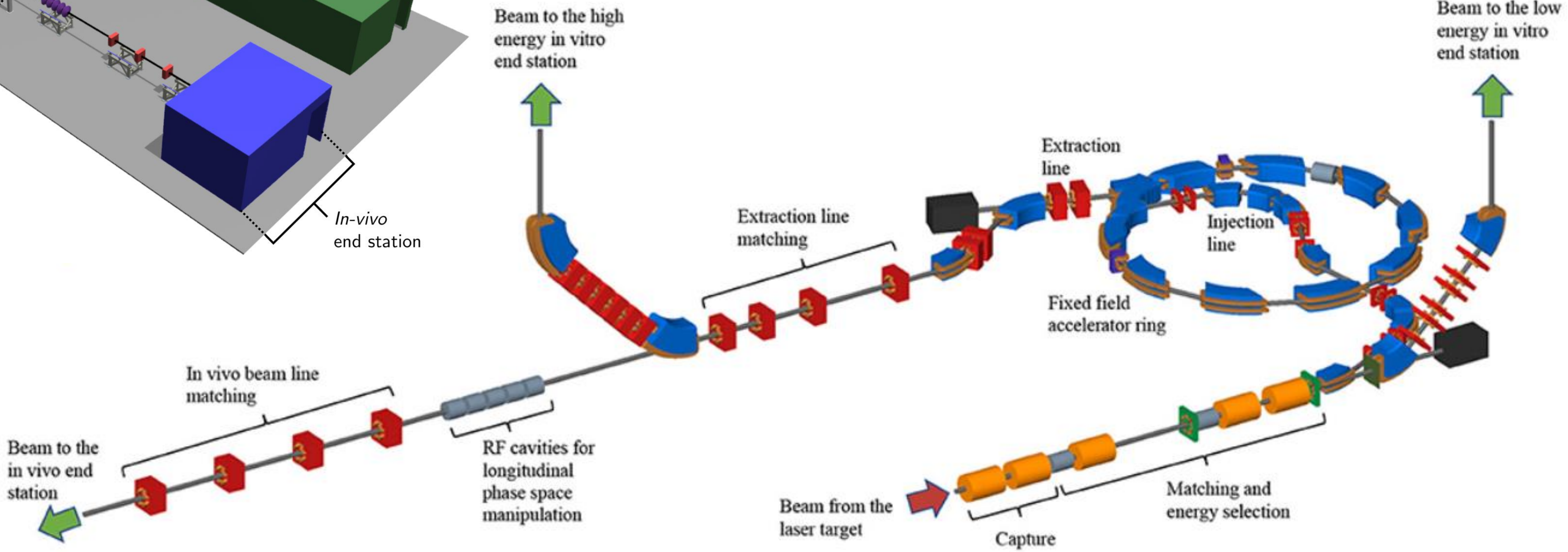
Methods of joining fibres – Jeff Sykora, ISIS

From: Medical Applications for Particle Physics (PhD Thesis), H.T.Lau, Imperial College (2021)

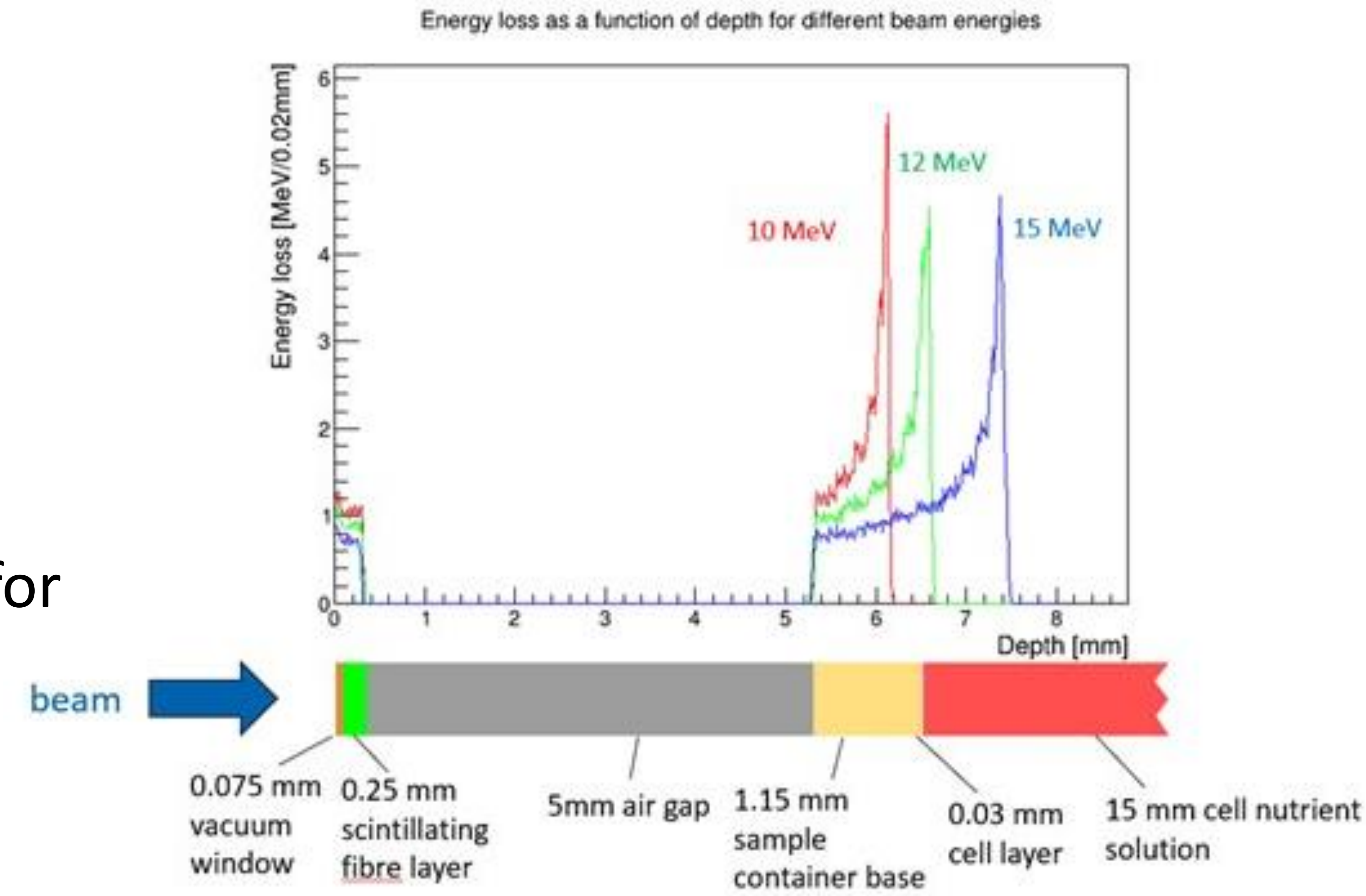
1	Low acoustic signal	Insufficient acoustic signal to noise ratio (SNR) (i.e., low amplitude acoustic emission)	3	5	15	Frequency optimisation, large sensor elements in a prefocused large array, 1024 elements for noise averaging, averaging over multiple pulses, adaptive reconstruction with priors and optimisation of frequency with element location, adaptively trade dose-map resolution for SNR	3	3	9
2	Low resolution	Insufficient dose-map spatial resolution (due to loss of high frequency components via attenuation or acoustic scattering)	4	3	12	Predominantly water-path propagation, model-based solutions, replace real-time dose mapping with off-line characterisation (as is done in radiobiology currently).	1	4	4
3	Sample holders	Multi-well sample holder unsuitable due to lack of field of view/acoustic access/acoustic reverberations	4	3	12	2D and 3D spatial biology readout, reduce throughput, use single samples on conveyor/robot.	2	2	4
3	CMOS	CMOS approach not adequate for scintillator field standard	3	2	6	Higher cost splicing solution possible.	3	1	3
4	Interference	Interference from RF noise (unlikely to matter as likley to be 1 GHz) and/or pulse switching transients	1	2	2	Sheilding of experiment, use of optical fibre connection between electronic components, use of optical sensors.	1	4	4
5	Beam Line access	Lack of access to validation beam line	5	3	15	Several possible sources	3	3	9
6	Lack of information from collaborators	Dependency on other WPs to provide information regarding Lhara in time	2	3	6	This WP has been designed to provide results which adapt to the modelling outputs of other WPs. A modelling coordinator will be appointent across all such WPs.	1	3	3
7	Overall project delay	Lhara construction running late - no final testing	2	4	8	Alternative sources that are similar - Avo, Lawerence Berkley?	1	4	4
9	Staff recruitment	Not being able to recruit people	2	4	8	Re-prioritise/limit tasks so that most important achievements may be met with fewer staff members	1	4	4

WP5 – End station development & Instrumentation



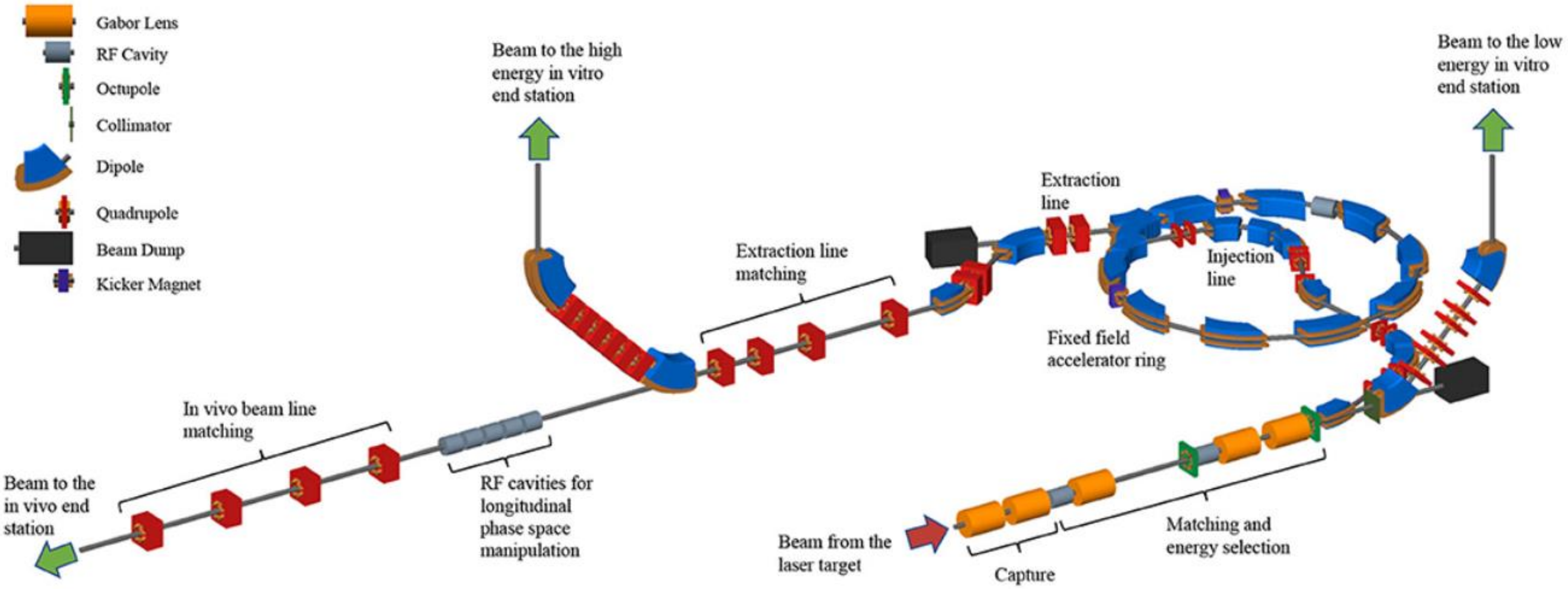


- User engagement – Peer group consultation.
- Automated Handling
- Controlled atmosphere
- Acoustic Imaging
- Cellular imaging
- In-vivo irradiation
- MC40 cyclotron operation for testing and de-risking.
- Beamline instrumentation
- Gas jet beam profiler.
- Dosimetry verification



Number	Name	Description	Likelihood	Impact	Score	Mitigation	Mitigated Likelihood	Mitigated Impact	Mitigated score
1	End Station Specification	End station specification does not clearly specify requirements.	5	5	25	Approved escalation route from light corporal discipline to public vilification on social media	1	5	5
2	Beam instrumentation	Beam instrumentation specification and delivery delays	3	3	9	Progress montoring and effort supplementation from LhARA project expertise	2	3	6

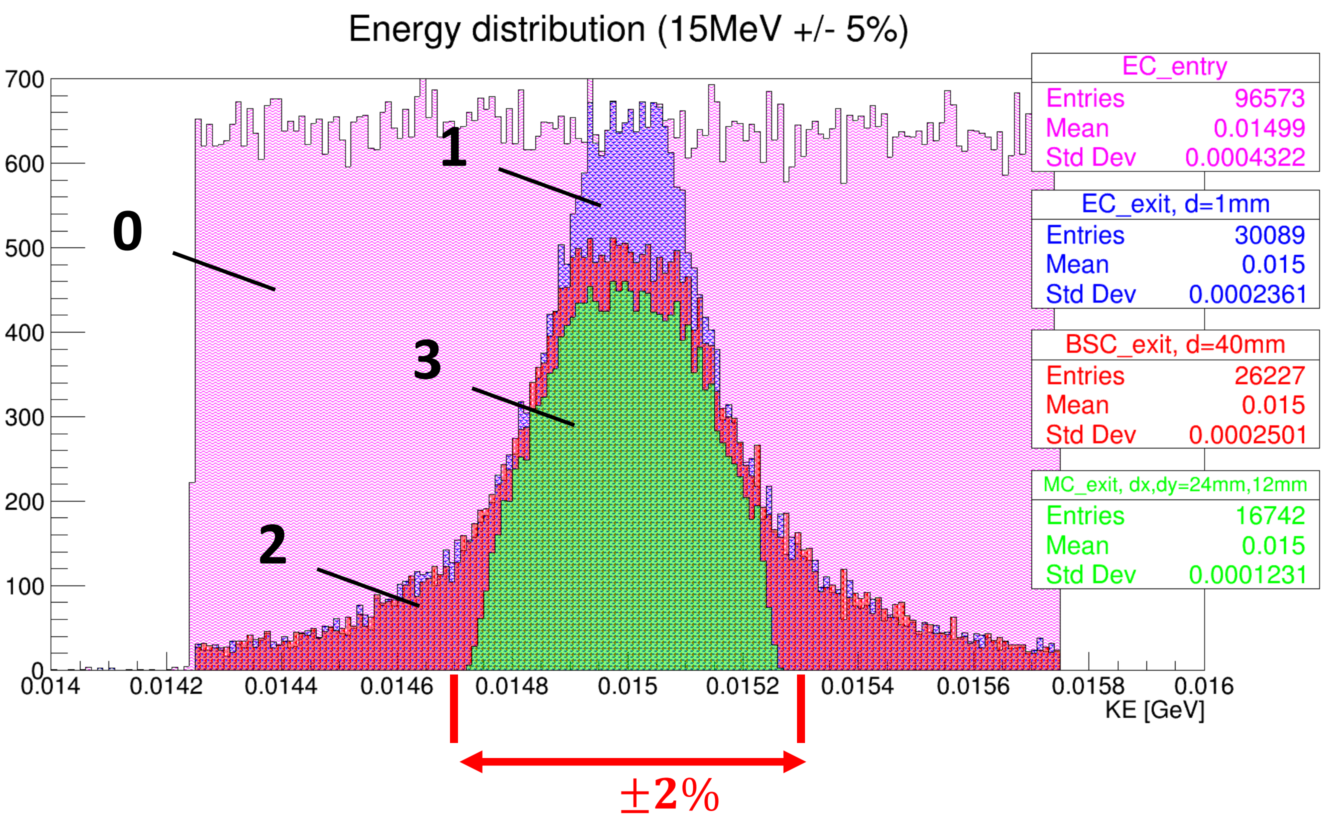
WP6 – Facility design and integration



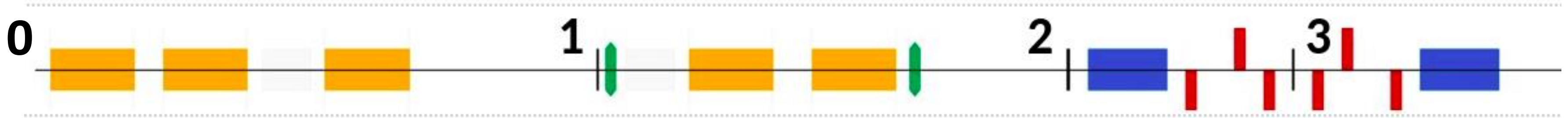
Controlling energy spread in LhARA

- 3 collimators
  1) Energy collimation
  2) Beam shaping
  3) Momentum cleaning

- Momentum cleaning is required to remove the tails of energy distribution



Schematic of the accelerator

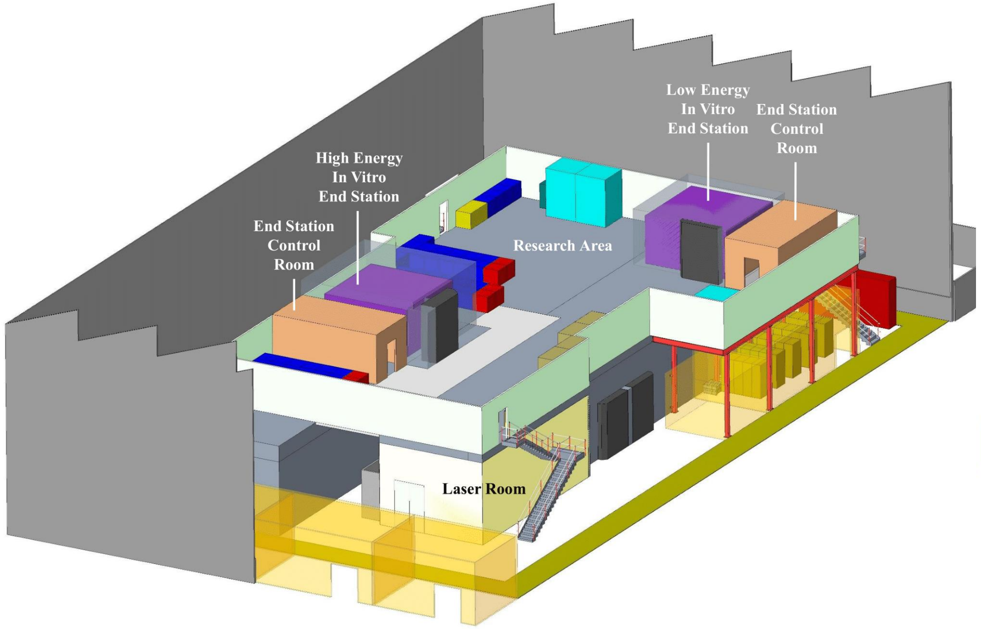


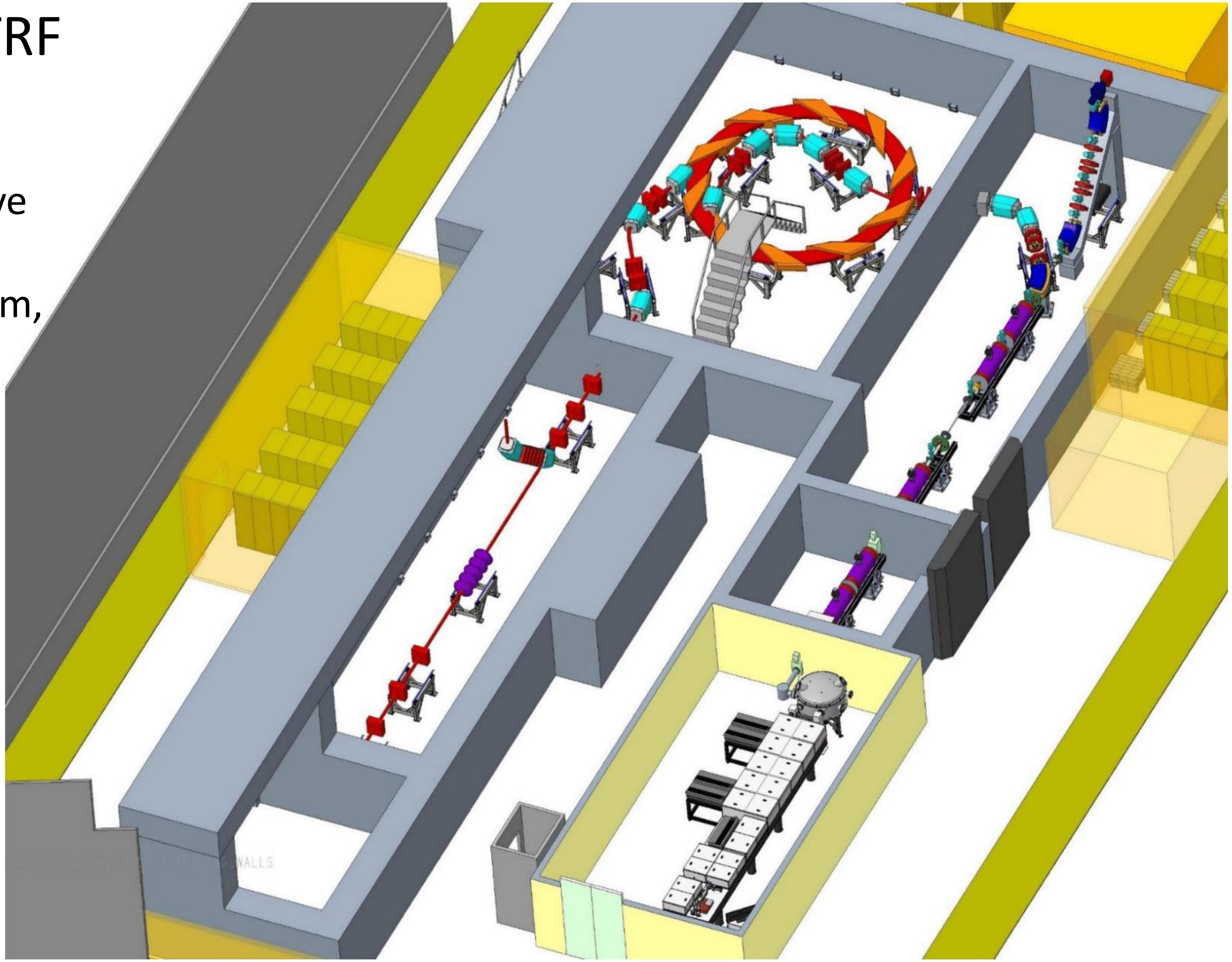
Facility – planning - development

Ion therapy Research Facility ITRF

£2M budget, of which

- £1.5M LhARA – as presented
- £500k Facility Engineering plus alternative technologies. 3.35FTE: Mechanical, Electrical, Controls, Tech Services, Vacuum, Radiation Protection





Number	Name	Description	Likelihood	Impact	Score	Mitigation	Mitigated Likelihood	Mitigated Impact	Mitigated score
1	Fixed Field Accelerator (FFA)	FFA does not deliver parameters in performance specification.	3	5	15	Continue R&D on the critical item that is the FFA spiral magnet. Construct a prototype before production of 10	1	5	5
2	Gabor lens performance	Gabor lens does not deliver parameters in performance specification.	4	5	20	Continue a R&D plan that involves the construction of a prototype Gabor lens and have a back up plan available that uses solenoid magnets in the place of	2	5	10
3	MA Cavity construction	Delay or technical difficulties in construction of Magnet Alloy (MA) cavity	5	4	20	Establish close collaboration with CERN, J-PARC & KURNS institutes, where similar systems have been constructed and are in operation. Component parts	5	1	5
4	Injection and extraction magnets	Insufficient availablility of injection and extraction magnets suppliers.	3	4	12	Design and construct of injection and extraction magnets by STFC national laboratorie expertise. Component parts manufactured by industry.	3	2	6
5	Facility infrastructure	Facility infrastructure is not fit for purpose.	4	4	16	Include facility infrastructure design during the Conceputal Design Report (CDR) stage to provide a fit for purpose design that will inform the project cost and schedule	1	4	4
6	Radiation protection	Radiation bulk shielding thickness, labyrinths and services penetrations are inadequate to meet specification.	4	5	20	Conduct radiation protection assessment during the CDR phase of the project to satisfy safety leglislation and identify construction method to inform cost and schedule.	1	5	5

Top Level Risks

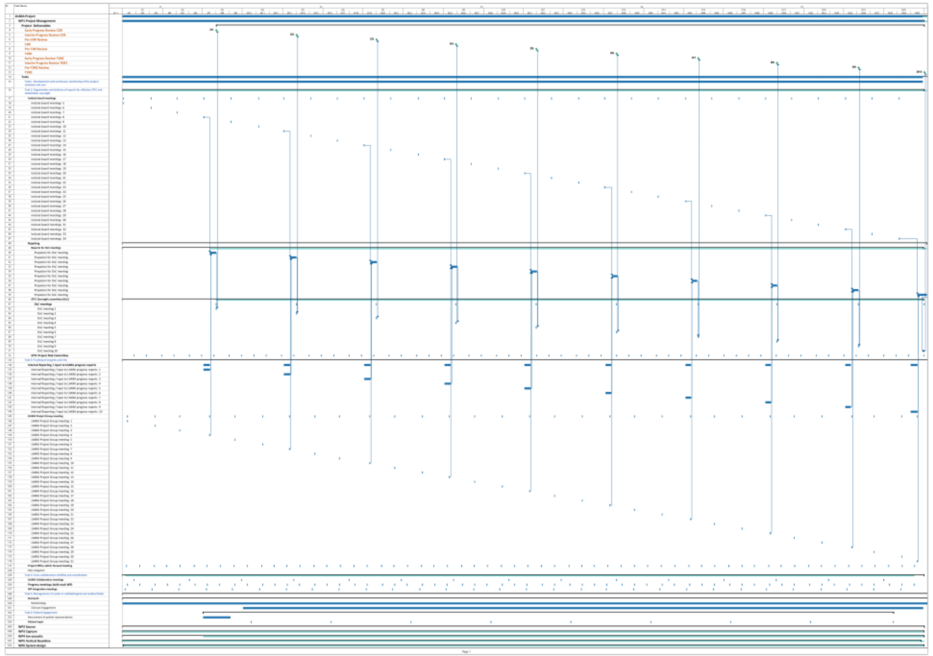
	Number	WP Number	Name	Description	Likelihood	Impact	Score	Mitigation	Mitigated Likelihood	Mitigated Impact	Mitigated score
WP1	1	1.5	Resources	Insufficient resources secured to deliver the project aims, project scope, quality or specifications to the required timescale.	5	4	20	Request adequate resources based on experience of delivering similar multidicipline facilities with comparable technical complexity. Use pre - CDR outputs to inform work towards Conceptual Design Report (CDR).	4	4	16
WP1	2	1.3	Performance specification parameters	Inadequate ion beam parameters specification to meet the Physics and Biolology requirements for the facility.	3	5	15	The project consortium consists of all the multidiscipline experts to understand the required parameters.	2	5	10
All	3	9	Key specialist staff	Availability of key specialist staff critical to delivering the project.	4	5	20	Identify potential single point failure risks, apply cover and succession planning where appropriate.	2	5	10
WP2	4	2.7	Source output	Unable to deliver desired beam.	4	3	12	Investigate experimental techniques to increase yield	4	2	8
WP2	5	2.1	Source design - activation	Unsustainable activation of materials surrounding interaction	2	4	8	Change design to minimise potential for activated materials around interaction point	2	2	4
WP3	6		Plasma Density	A low density will result in too long a focal length (& beamline)	4	4	16	Careful design and study to ensure a suitable density can be reached:	4		
WP4	7	4.1	Low acoustic signal	Insufficient acoustic signal to noise ratio (SNR) (i.e., low amplitude acoustic emission)	3	5	15	Frequency optimisation, prefocused large array, averaging over multiple pulses, adaptive reconstruction with priors and optimisation of frequency with element location. Adaptively trade dose-map resolution for SNR	3	3	9
WP6	8	6.6	Facility Integration	Delayed start/insufficient early resource to progress Integration work	3	5	15	Prioritise integration work package	1	4	4
WP5	9	5.1	End Station Specification	End station specification does not clearly specify requirements.	5	5	25	Approved escalation route from light corporal discipline to public vilification on social media	1	5	5

LhARA - Project organisation

- WP1 – Project management
- WP2 – Laser Driven proton and ion source
- WP3 – Proton and Ion Capture
- WP4 – Real-time dose-deposition profiling
- WP5 – End station development & Instrumentation
- WP6 – Facility design and integration

Project management

All the boring but essential planning and organisation, but also..



Engagement and outreach:

Stakeholder

Peer group

User community

Public

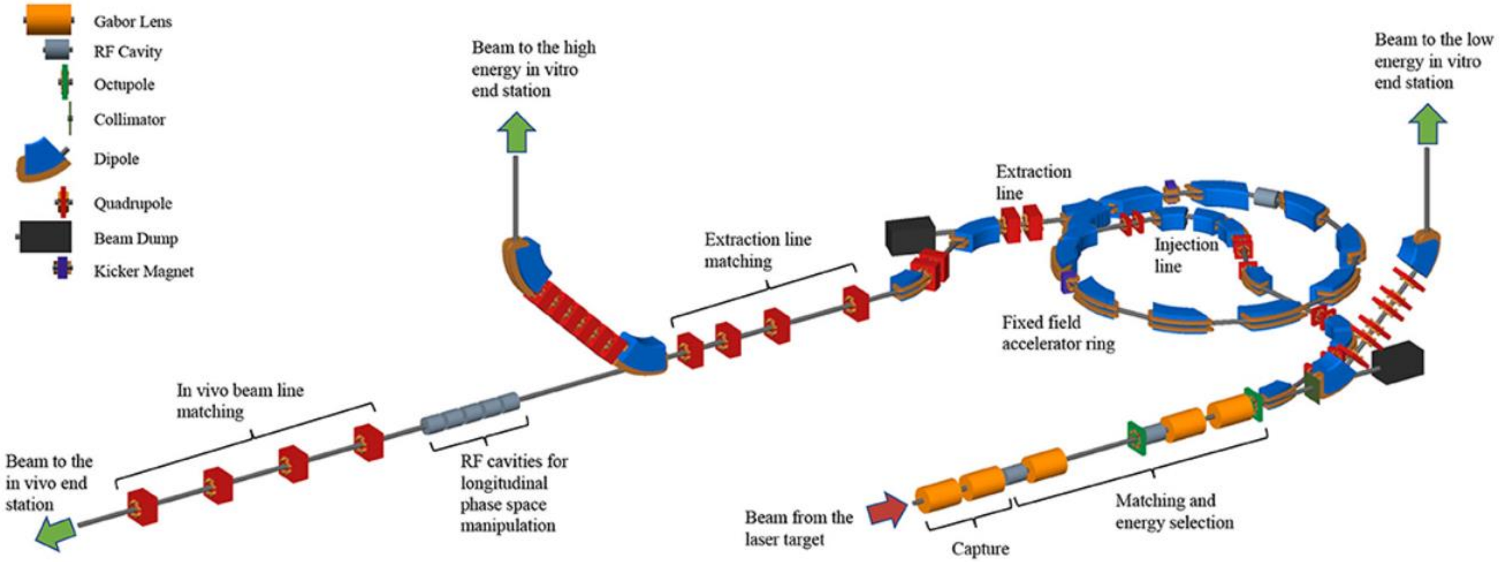
Patient

Diversification of LhARA funding

	Number	WP Number	Name	Description	Likelihood	Impact	Score	Mitigation	Mitigated Likelihood	Mitigated Impact	Mitigated score
WP1	1	1.5	Resources	Insufficient resources secured to deliver the project.	5	4	20	Pursue additional sources of funds.	4	4	16
WP1	2	1.3	Performance specification parameters	Inadequate ion beam parameters to meet the Physics and Biolology requirements.	3	5	15	The project consortium includes the required experts to improve performance and adapt requirements to maximise convergence of capability and need.	2	5	10
All	3	9	Key specialist staff	Availability of key specialist staff critical to project.	4	5	20	Identify potential single point failure risks, apply cover and succession planning where appropriate.	2	5	10
WP2	4	2.7	Source output	Unable to deliver desired beam.	3	4	12	Investigate experimental techniques to increase yield	2	2	4
WP2	5	2.1	Laser Access	Laser schedule does not allow sufficient access.	3	4	12	Apply for access to other,similar, laser systems e.g Gemini	2	3	6
WP3	6		Plasma Density	A low density will result in too long a focal length (& beamline)	4	4	16	Expert experimental design coupled with established and novel mitigation measures	4	3	12
WP4	7	4.1	Low acoustic signal	Insufficient acoustic signal to noise ratio.	3	5	15	Employ range of established techniques. Adaptively trade dose-map resolution for enhanced signal	3	3	9
WP6	8	6.6	Facility Integration	Delayed start/insufficient early resource.	3	5	15	Prioritise integration work package	1	4	4
WP5	9	5.1	End Station Specification	End station specification does not clearly specify requirements.	5	5	25	Early progress review, input from system designers to user consultation exercise	1	5	5

Work Package Managers : Expectations

- Progress meetings ever 2 weeks, plus any extra required – minuted on Wiki
- Monthly update to LhARA PM – to STFC PRC
  - Simple format – fill the blanks.
- Milestones
- Collaboration Meetings
- Deliverables.



LhARA Wiki

wiki: Research / DesignStudy / ITRF / Documents

- Research/DesignStudy/ITRF/Documents/PA1
- Research/DesignStudy/ITRF/Documents/PA2?
- Research/DesignStudy/ITRF/Documents/Construction?

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wiki: Research / DesignStudy / ITRF / Documents / PA1

- Research/DesignStudy/ITRF/Documents/PA1/WP1.1 LhARA Project management
- Research/DesignStudy/ITRF/Documents/PA1/WP1.2 Laser driven proton and ion source
- Research/DesignStudy/ITRF/Documents/PA1/WP1.3 Proton and ion capture
- Research/DesignStudy/ITRF/Documents/PA1/WP1.4 Ion-acoustic dose mapping
- Research/DesignStudy/ITRF/Documents/PA1/WP1.5 Novel end-station development
- Research/DesignStudy/ITRF/Documents/PA1/WP1.6 Design and Integration
- (wp0) ITRF Project Mangement
- Research/DesignStudy/ITRF/Documents/PA1/wp2 ITRF Facilities and Costing work package management
- Research/DesignStudy/ITRF/Documents/PA1/wp3 Conventional Technology work package management
- Research/DesignStudy/ITRF/Documents/PA1/she? Safety Health and Environment
- Research/DesignStudy/ITRF/Documents/PA1/CERN? CERN
- Research/DesignStudy/ITRF/Documents/PA1/ac Advisory Committee
- Research/DesignStudy/ITRF/Documents/PA1/Para? LhARA Parameters
- Research/DesignStudy/ITRF/Documents/PA1/CDR? Conceptual Design Review
- Research/DesignStudy/ITRF/Documents/PA1/ITRF? Documents copied to ITRF Server

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wiki: Research / DesignStudy / ITRF / Documents / PA1 / WP1.1

- Research/DesignStudy/ITRF/Documents/PA1/WP1.1/agn Agendas
- Research/DesignStudy/ITRF/Documents/PA1/WP1.1/cal? Calculations
- Research/DesignStudy/ITRF/Documents/PA1/WP1.1/code? computer program/code/source etc.
- Research/DesignStudy/ITRF/Documents/PA1/WP1.1/dsn? Design Notes
- Research/DesignStudy/ITRF/Documents/PA1/WP1.1/dwg? Drawings
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- Research/DesignStudy/ITRF/Documents/PA1/WP1.1/qual? Quality Assurance
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- Research/DesignStudy/ITRF/Documents/PA1/WP1.1/tn? Technical Note
- Research/DesignStudy/ITRF/Documents/PA1/WP1.1/tend? Tender Documentation

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Documentation

Level1-level2-level3-level4-number-version-description.document type

ITRF – pa1 – wp1.1 – rpt – 0002 – v0.3 – LhARA document naming convention.docx

Documents generated by the LhARA collaboration that are to be stored in the ITRF documentation store must be converted to .pdf format. The copy on the ITRF server must be treated as a **read only pdf copy** that **must not be modified** to avoid multiple copies of the same document, protecting version control.

When a document is to be transferred to ITRF it will be given a second ITRF document name which will be recorded above its original LhARA name. This second name must be recorded in the original LhARA document to link the two documents.

Deliverables

D1. Early review of progress towards CDR.

D2. Interim review of progress towards CDR.

D3. Early draft of LhARA CDR.

D4. Complete LhARA CDR.

Milestones

A total of 16 spread across 5 work packages – all reviewed at Collaboration meetings and all feeding into above Deliverables.

LhARA Review

Review of the collaboration's "R&D proposal for the preliminary and pre-construction phases"

Review panel

The review is being organised under the auspices of the CCAP International Advisory Board. The review panel is made up of the CCP IAB Board:

- Mile Lamont (CERN) (Chair);
- Michael Baumann (DKFZ);
- Paul Bolton (LMU);
- Brita Singers Sørensen (Aarhus); and

Expert reviewers:

Gianluigi Arduini (CERN)
Christian Carli (CERN)
Malek Haj-Tahar (PSI)

Terms of reference

Terms of reference

Meetings

Next meeting: 29/30 September 2022

30Aug22:

- https://indico.cern.ch/event/1194925/ (Access code: CCAP3008)

02Sep22: Preliminary notes prepared by KL following a meeting with G.Arduini and P.Bolton to consider the next steps in the review.

1st session – 30th August 2022

2nd, 3rd sessions 29th and 30th September

https://ccap.hep.ph.ic.ac.uk/trac/wiki/Research/DesignStudy/Reviews/AugSep22/Review