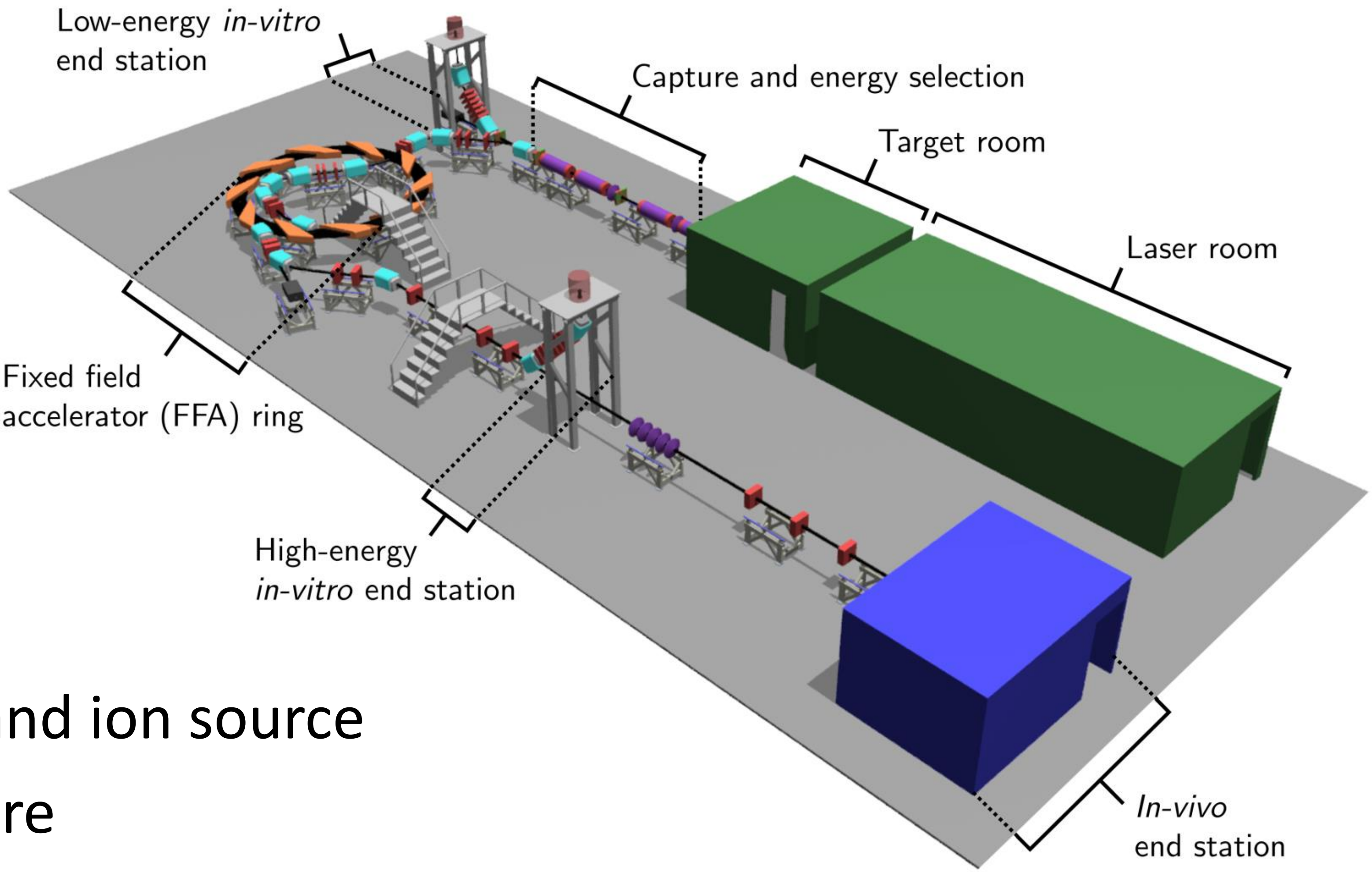
LhARA

Laser-hybrid Accelerator for Radiobiological Applications

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

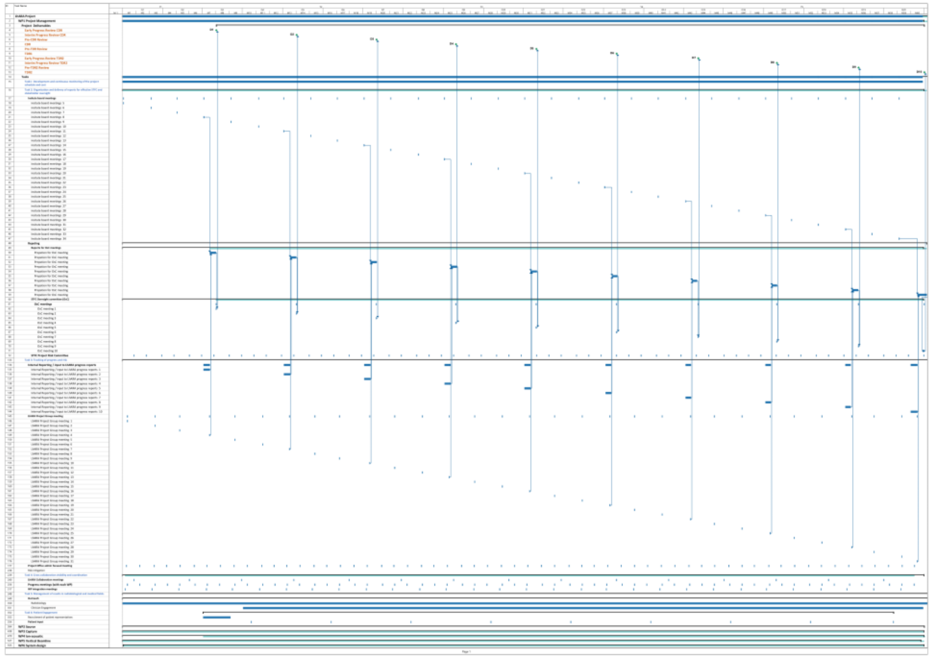
Peer group

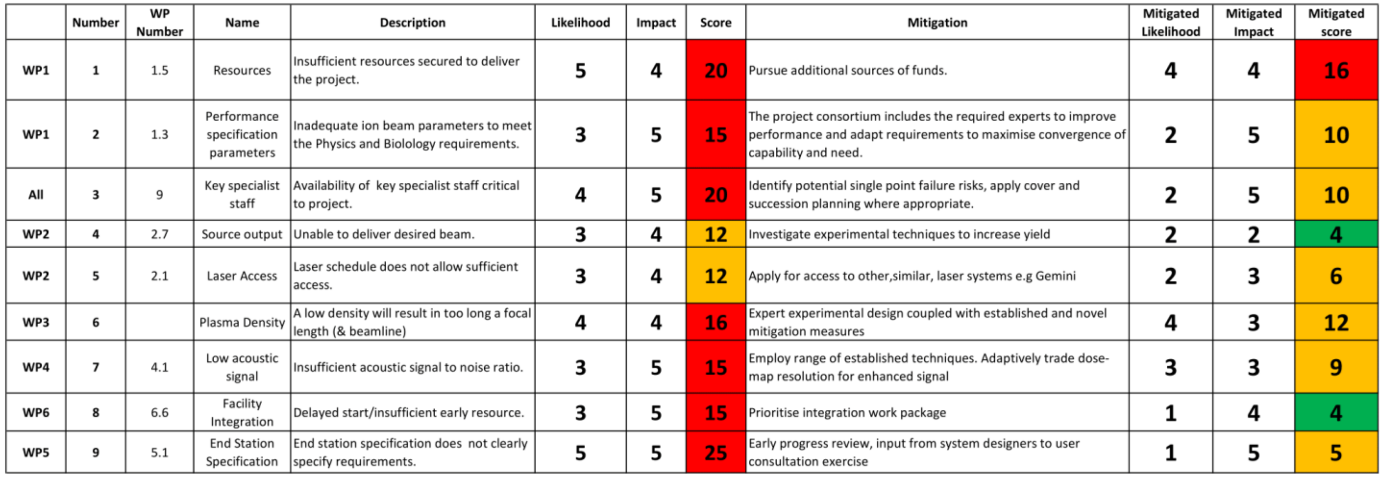
User community

Public

Patient

Diversification of LhARA funding

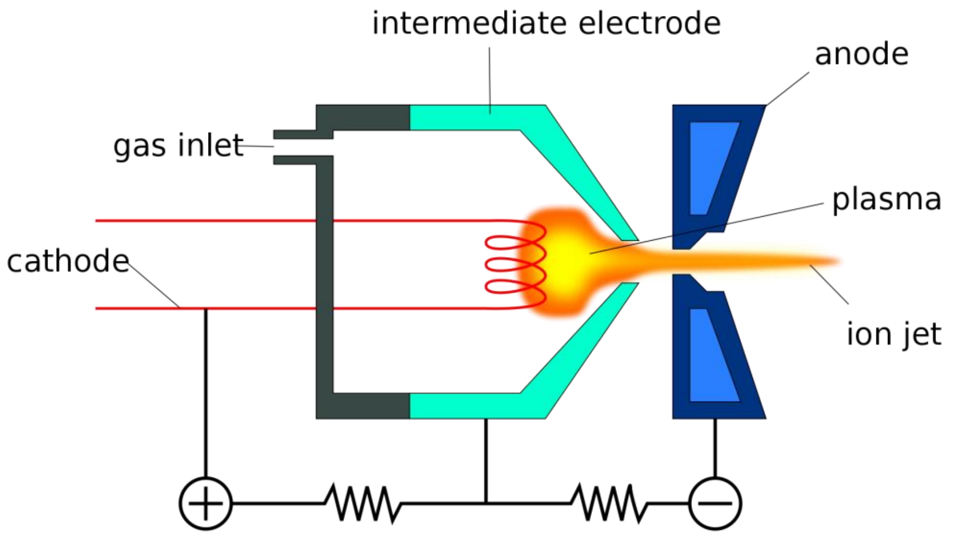




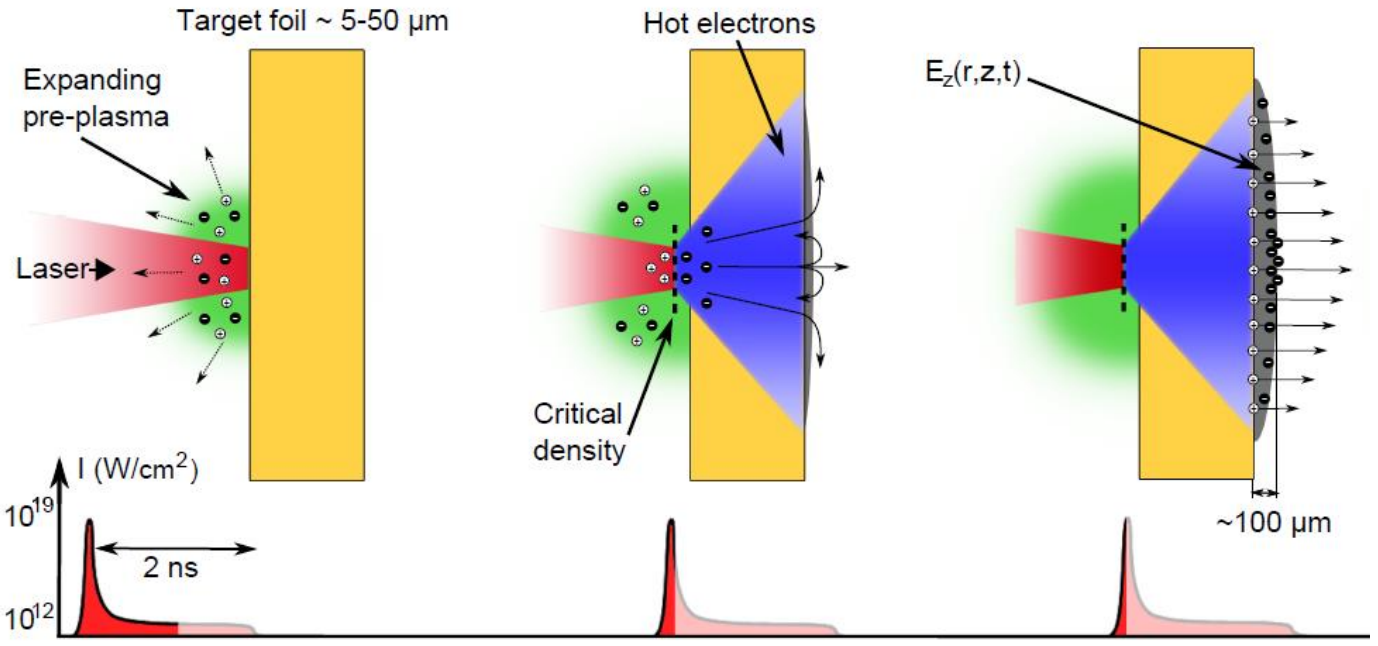
	Number	WP Number	Name	Description	Likelihood	Impact	Score	Mitigation	Mitigated Likelihood	Mitigated Impact	Mitigated score
WP1	1	1.5	Resources	Insufficient resources secured to deliver the project.	**5**	**4**	**20**	Pursue additional sources of funds.	**4**	**4**	**16**
WP1	2	1.3	Performance specification 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**

Ion production space charge

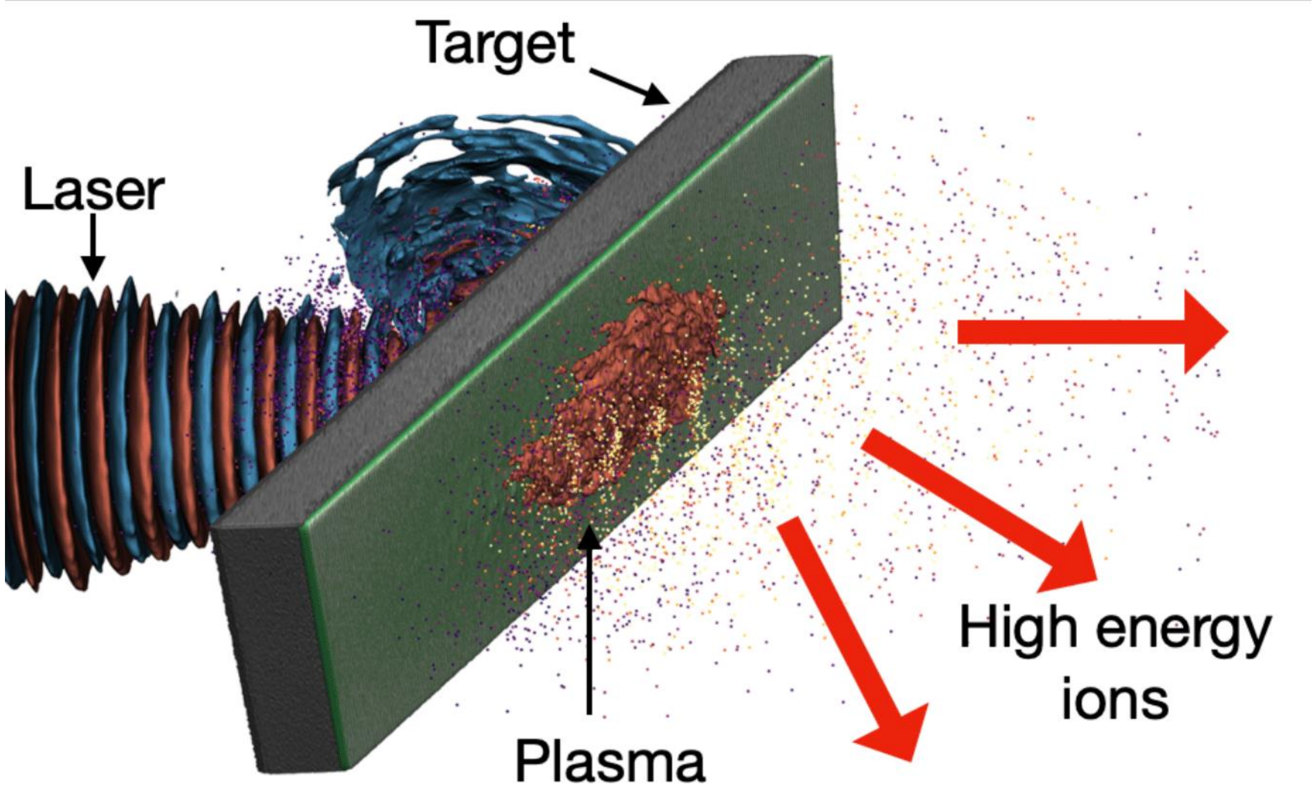
- Ions experience the electric field due to their neighbours – space charge – and repel each other.
- Effect is worst when ions have low energy – faster acceleration = better beam.
- Conventional ion sources extract ions with energies of a few 10's of keV and accelerate that beam over several m.
- Laser-target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

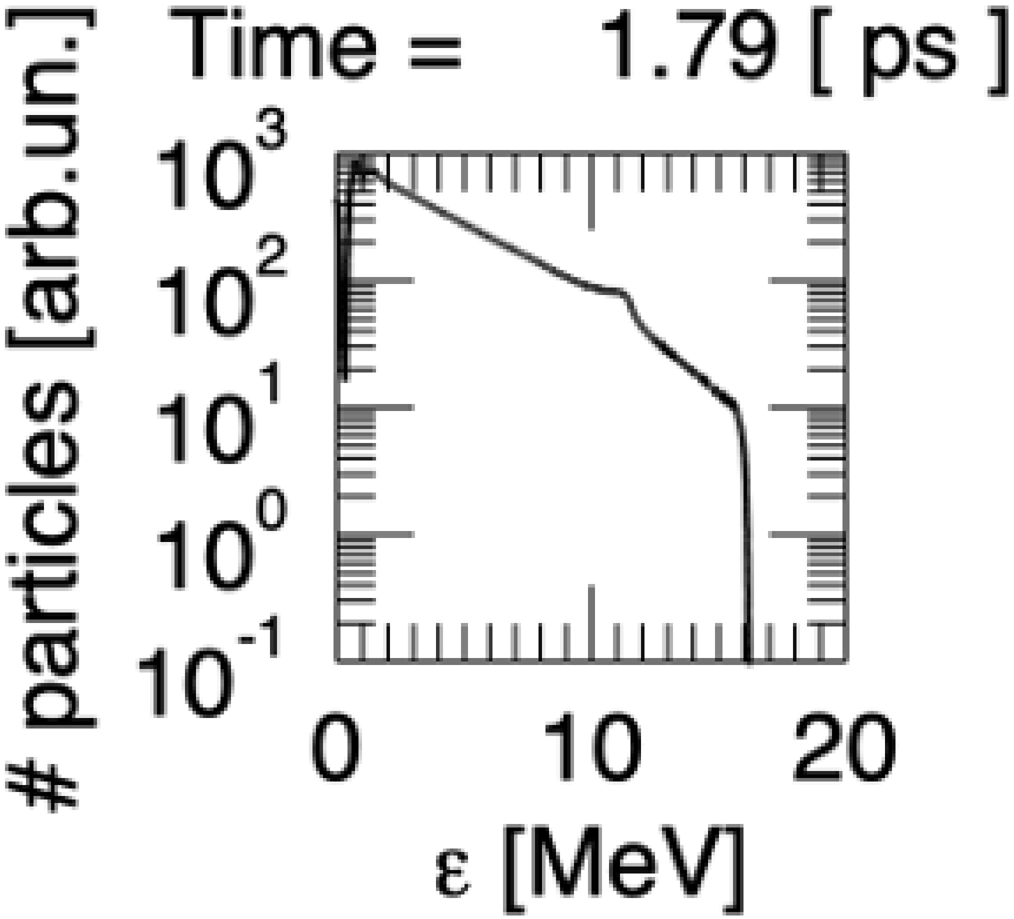


Duoplasmatron – source Evan Mason 7/7/16



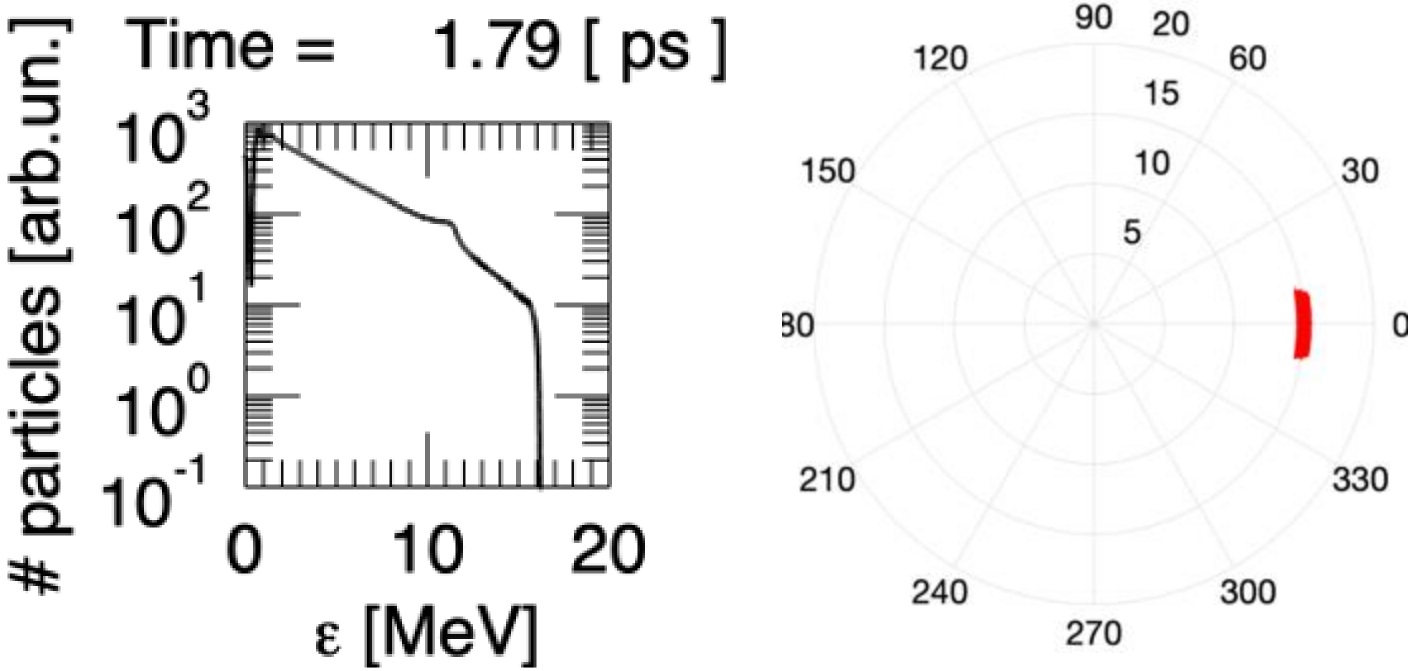
WP Laser Driven proton and ion source

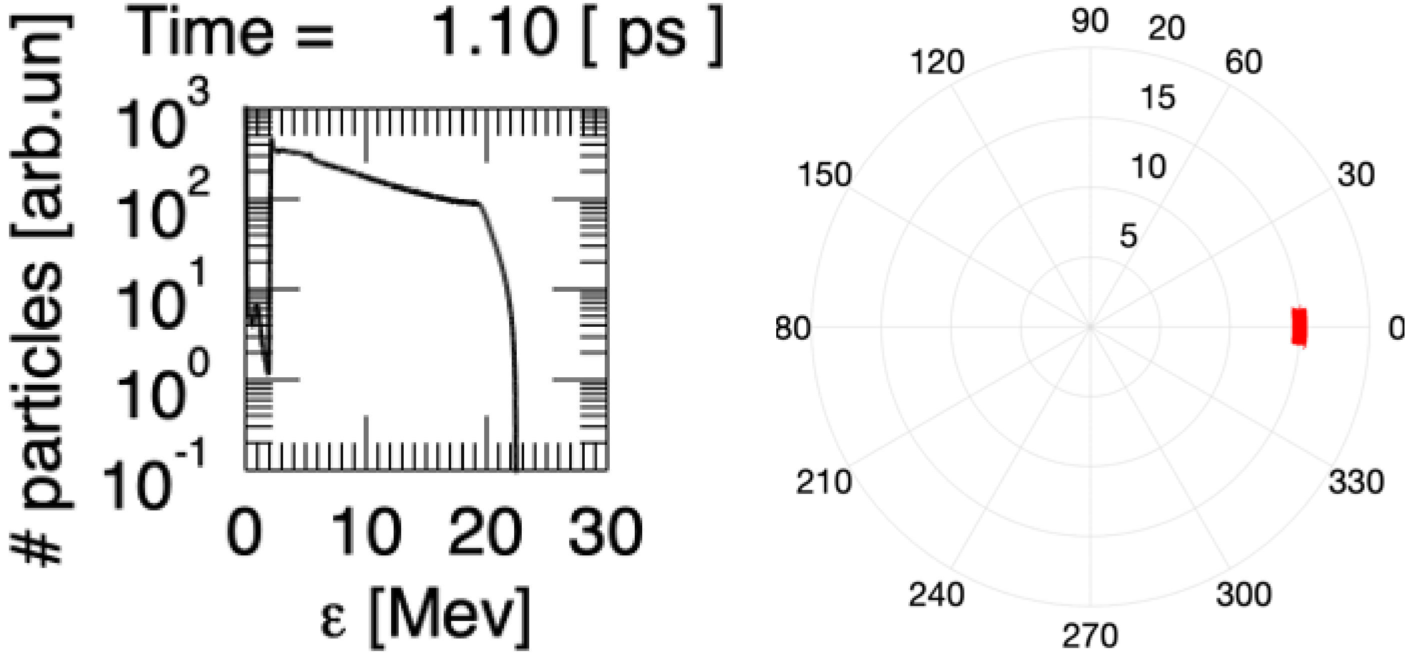




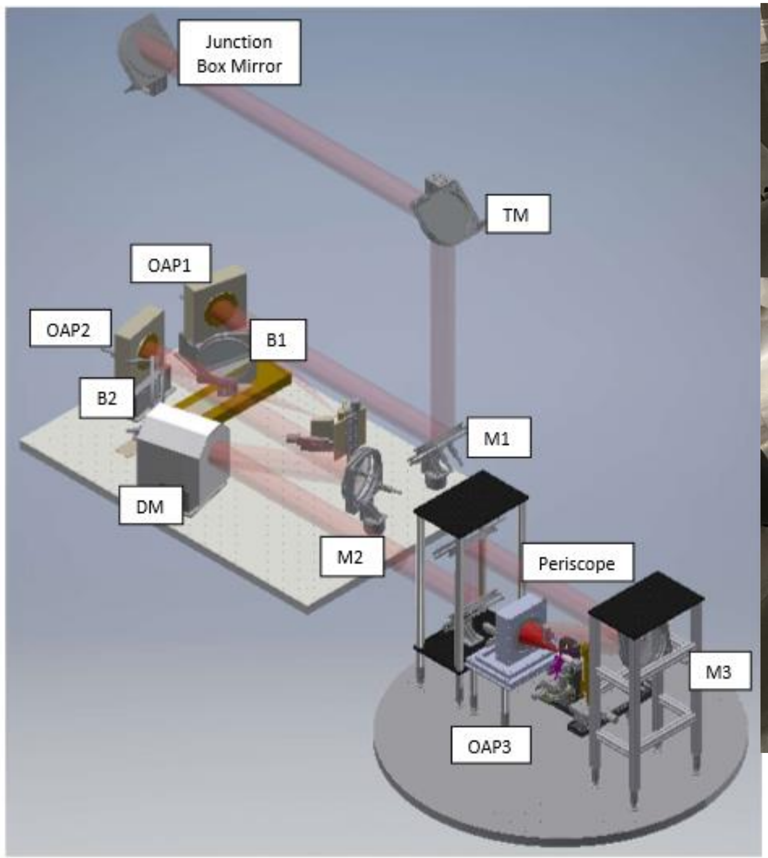
4 Objectives

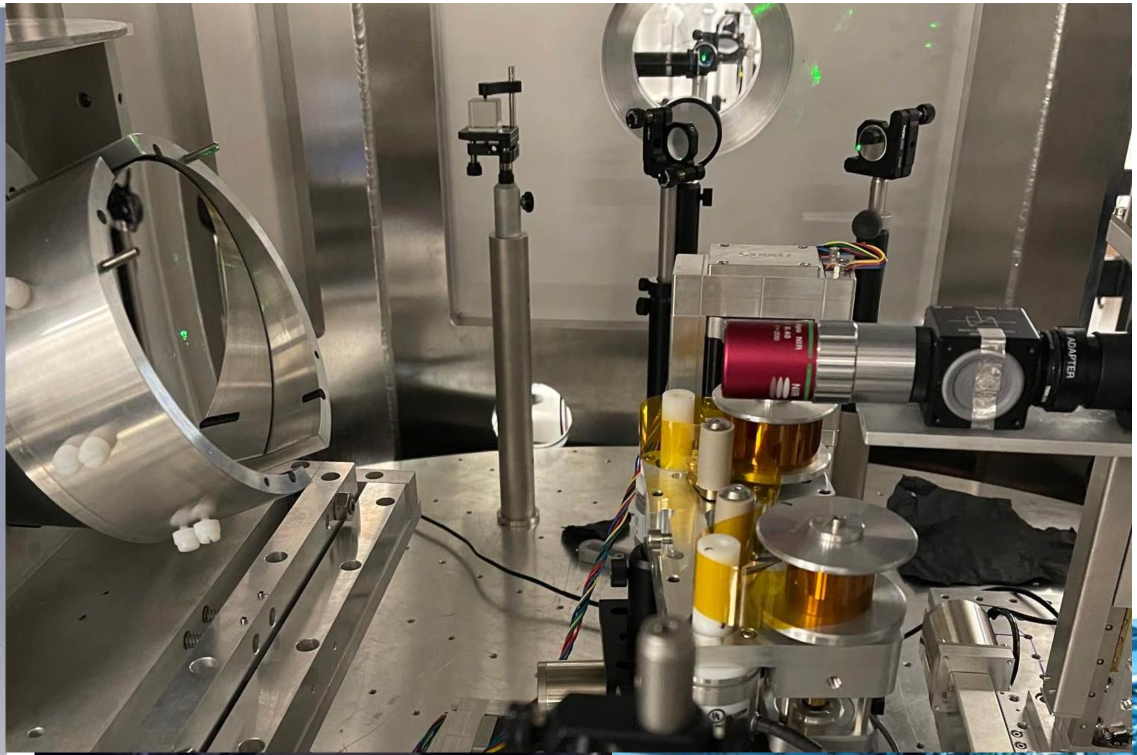
- Simulation
- Scapa
    - Diagnostics
    - Tests
- High rate tests

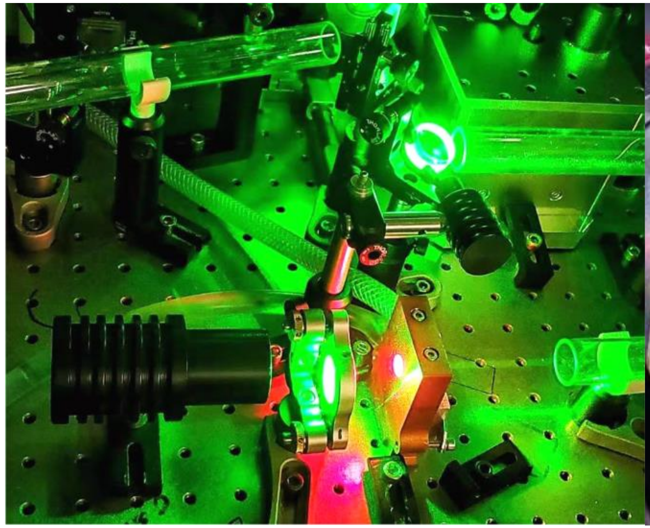


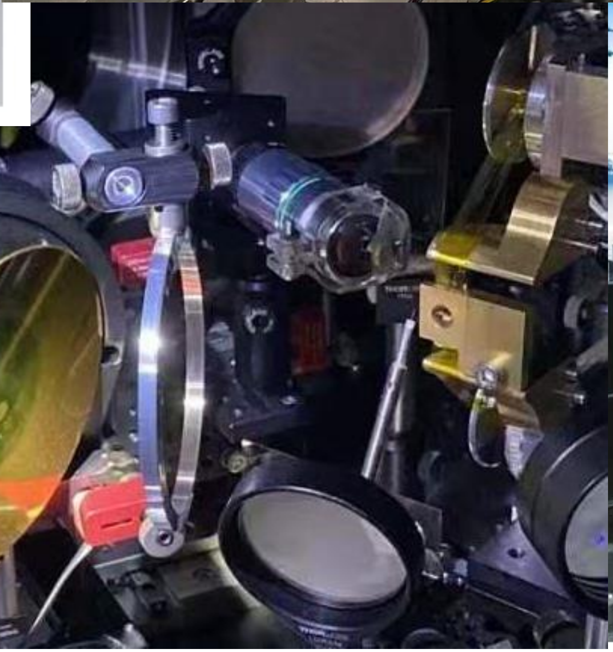


SCAPA
Cerberus
Zhi









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

Established Diagnostics…

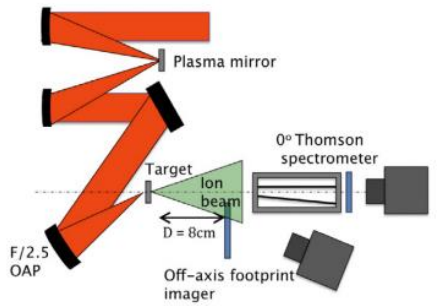
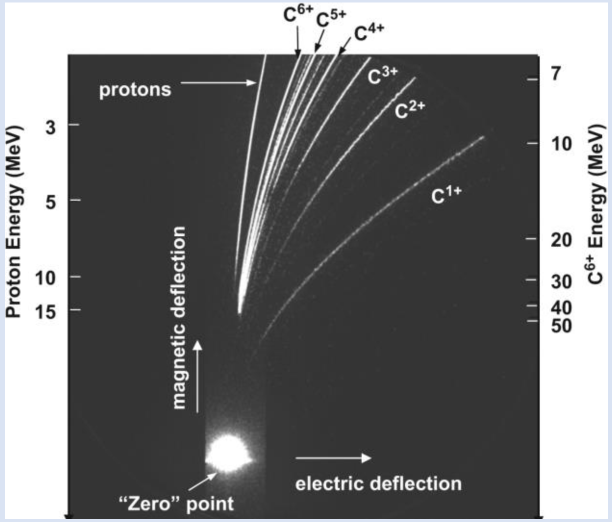


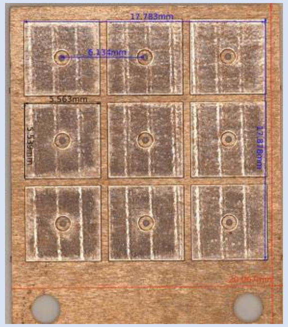
Figure 1. Experimental setup. A Thomson spectrometer deflects the ions onto a piece of plastic scintillator, which is imaged using an EMCCD camera. A second sheet of scintillator images the off-axis portion (>6° off-target normal) of the ion beam.

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

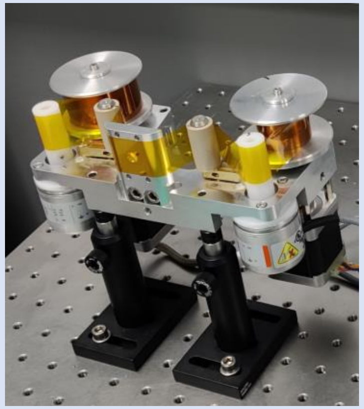


R. Prasad *et al.,* Nucl. Instrum. Methods. 623.2 (2010): 712-715.

Established Targetry…moving toward Hz-level targetry



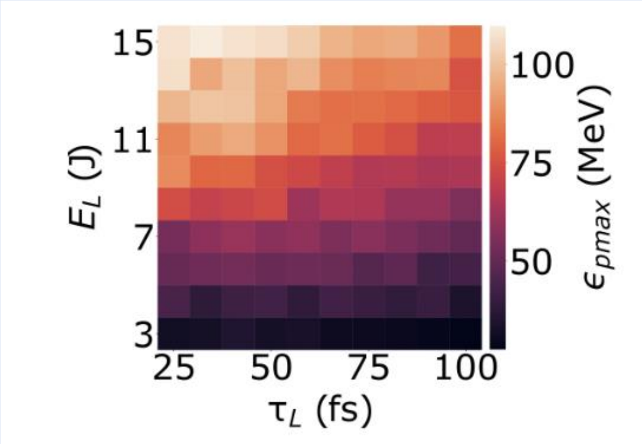
Typical 9-target array



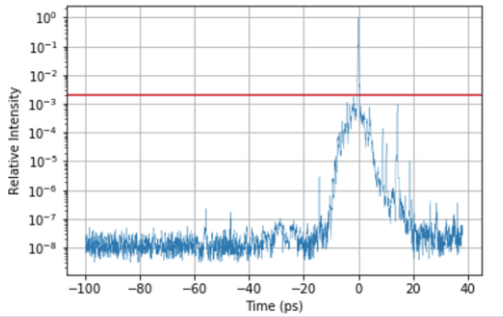
Tape targetry system (online in SCAPA 2022)

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

- Energy, Flux, Divergence across multiple ion species

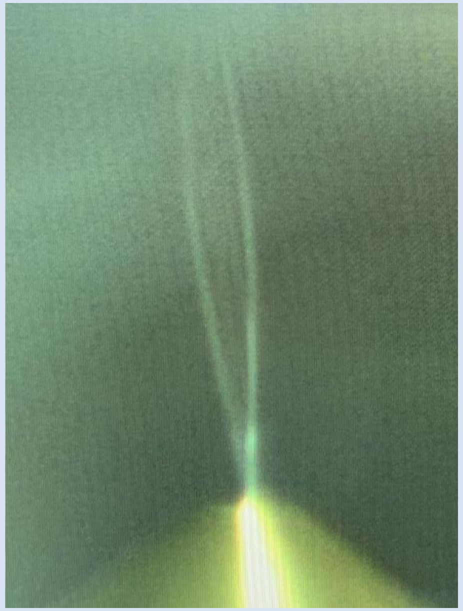


..but also need to consider some other experimental contributions like temporal contrast



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

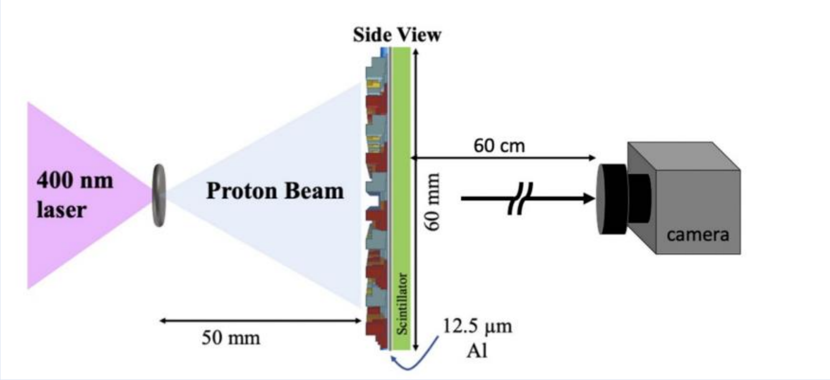
Novel Liquid Targetry



Courtesy of C. Palmer

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

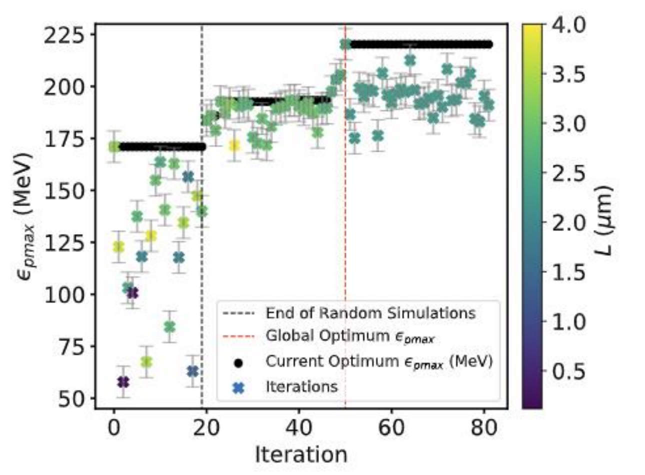
Advanced Particle & Laser Diagnostics



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

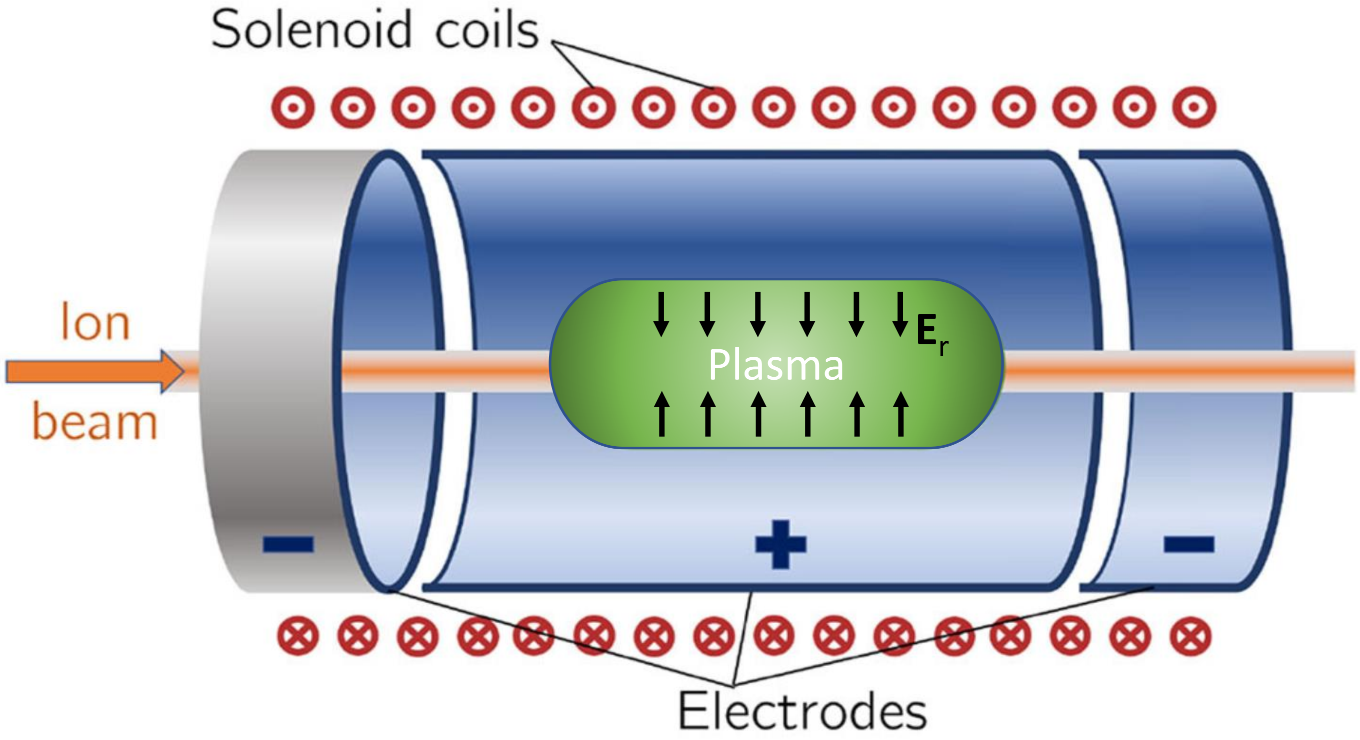
- Implementation of advanced (existing) particle diagnostics, taking account of long term operation.
- Implementation of full laser diagnostic suite to support automation, stabilisation.

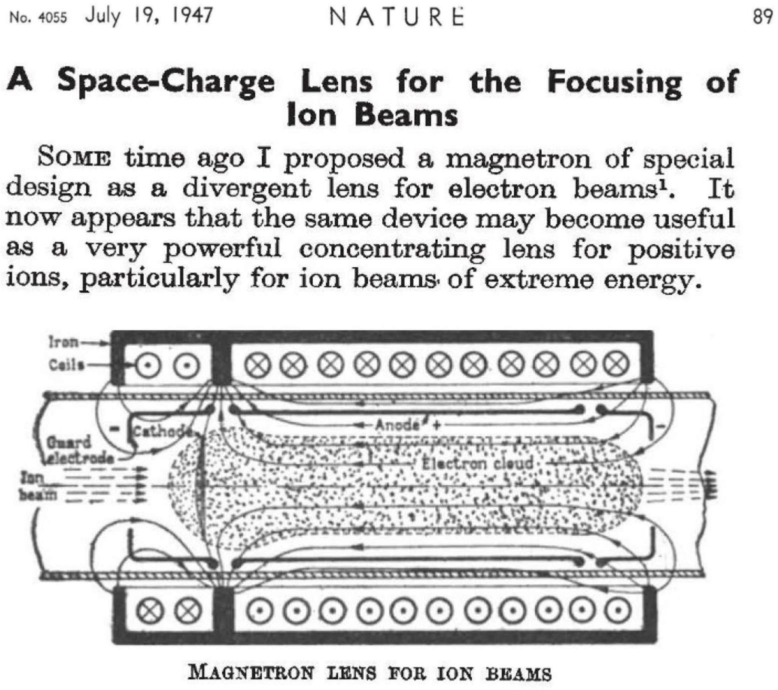
ML/AI Control & Optimisation



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

WP3 - Proton and Ion Capture
Gabor lens

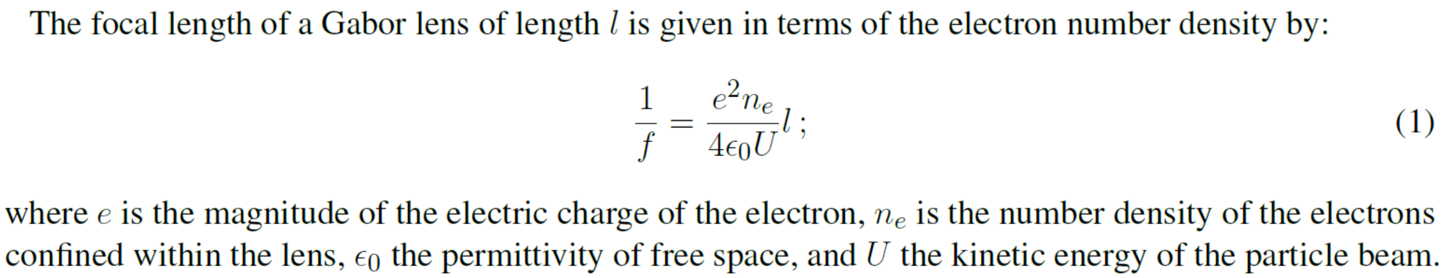



No. 4055 July 19, 1947 NATURE 89

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 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

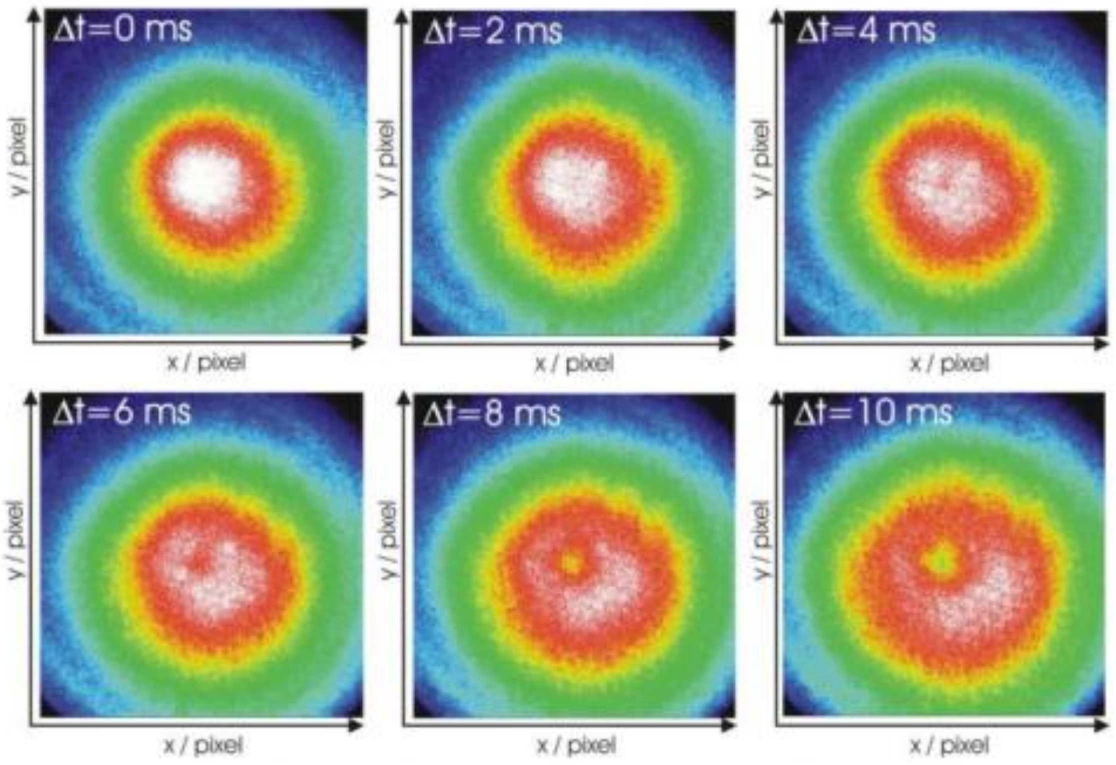

The focal length of a Gabor lens of length l is given in terms of the electron number density by:

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

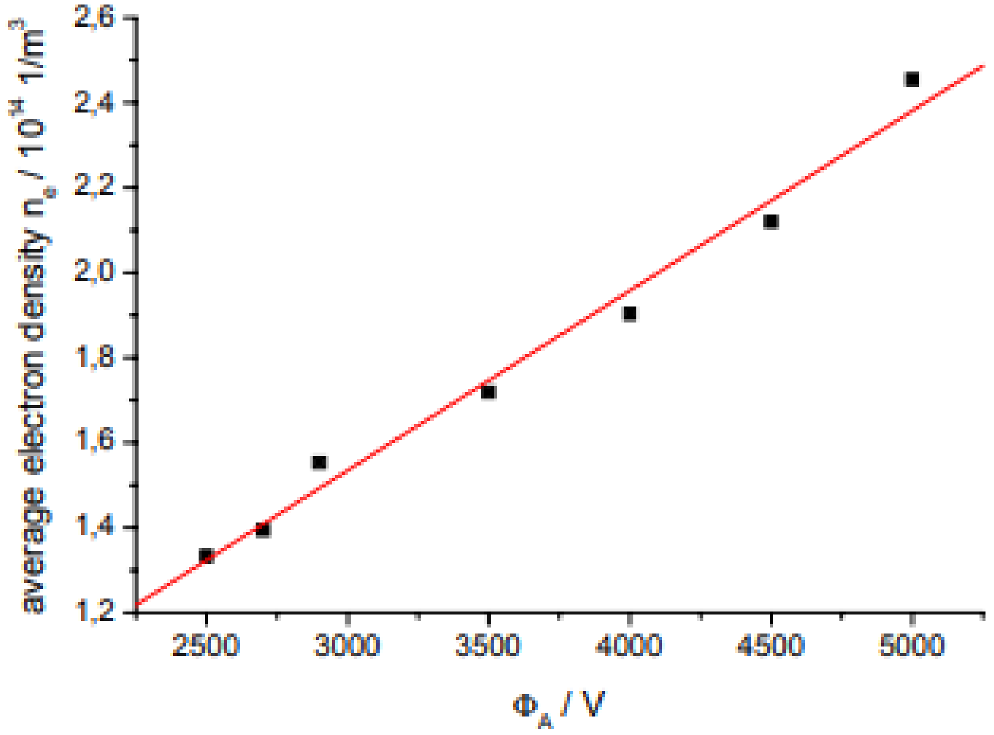
where e is the magnitude of the electric charge of the electron, n_e is the number density of the electrons confined within the lens, ϵ_0 the permittivity of free space, and U the kinetic energy of the particle beam.

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

Stability



Density



Objectives.

Initial experiments – establish stable high ‘fill factor’ plasmas

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

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

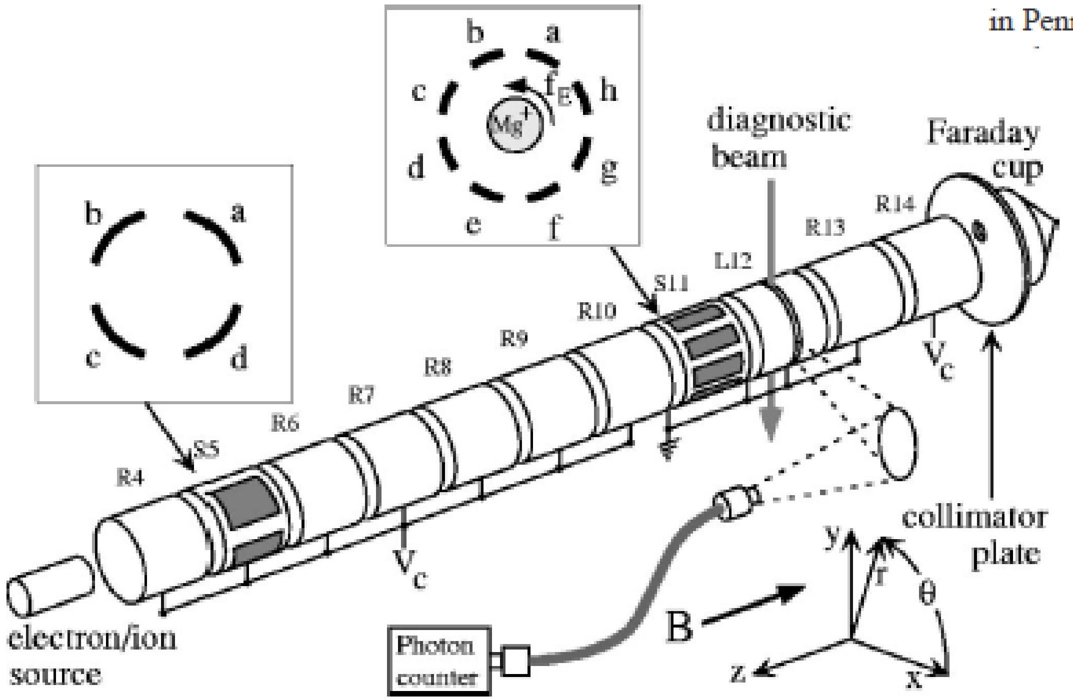
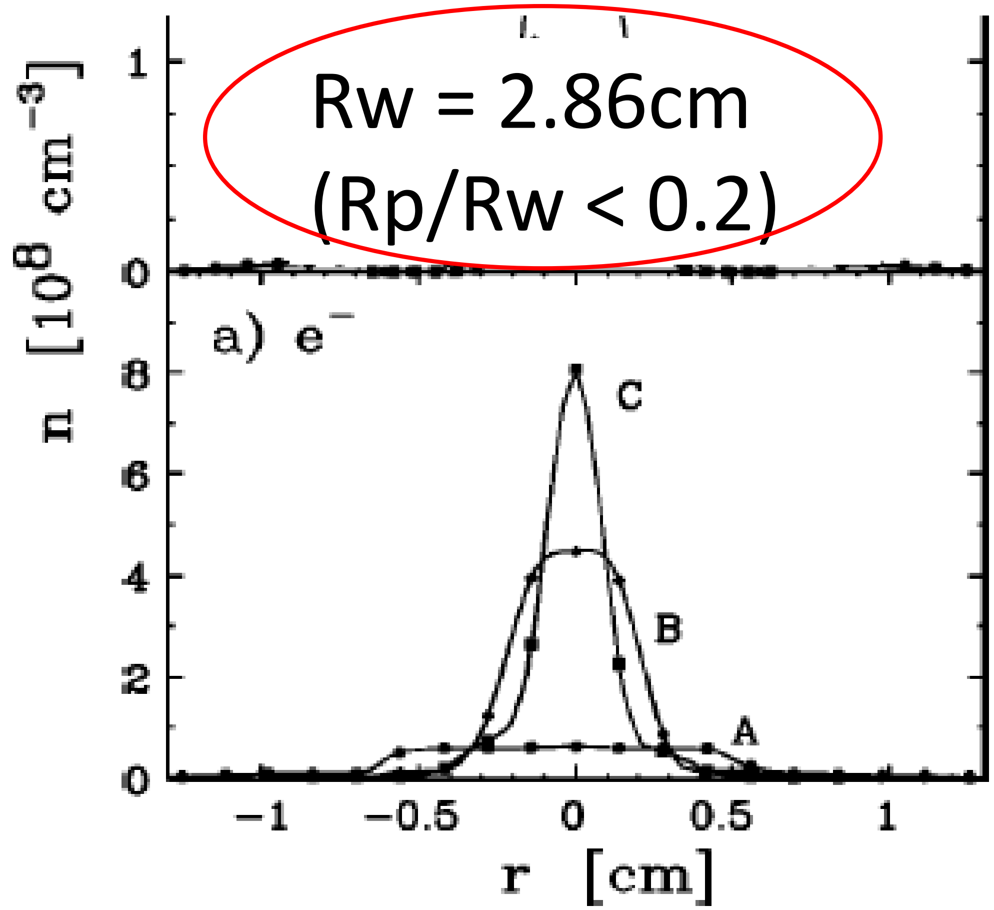


FIG. 1. Schematic of the IV Penning–Malmberg trap used for electron and ion plasma experiments. Electrons are typically confined in the region S5 → S11; Mg$^+$ ions (shown) are typically confined in the region S11→R13. A laser diagnostic is used for ion plasmas; a collimator plate and Faraday cup diagnostic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



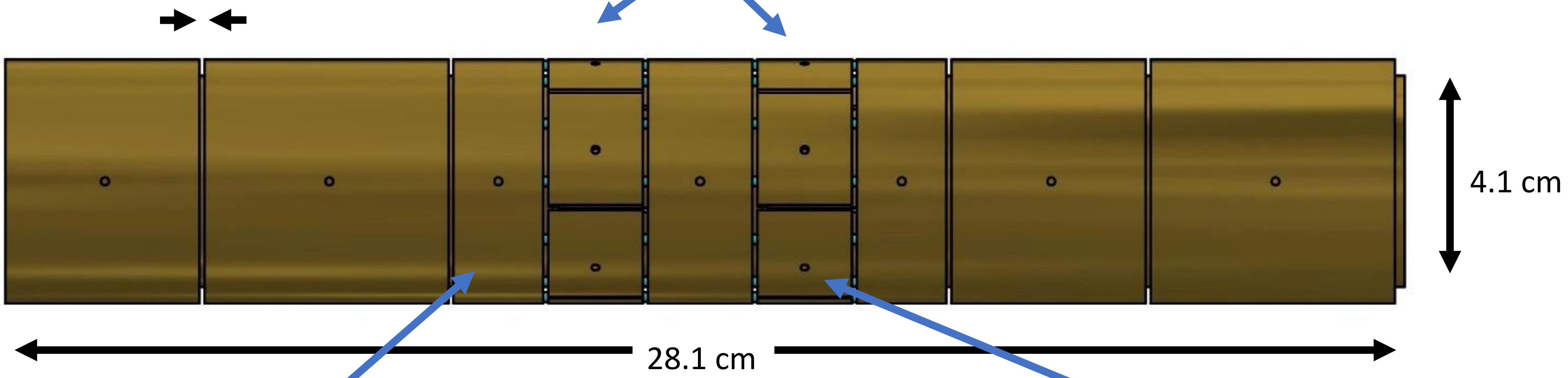
Rw = 2.86cm

(Rp/Rw < 0.2)

$10^{14} – 10^{15}\ \mathrm{m}^{-3}$

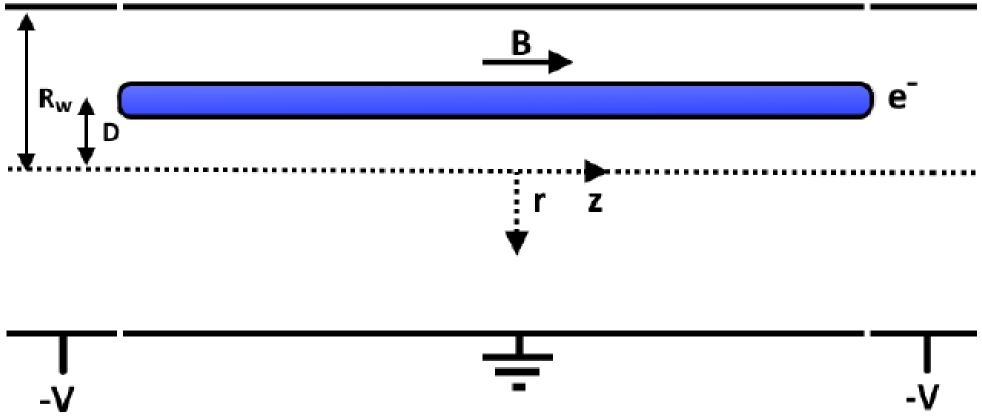
Storage trap assembly - current

Two, 6-way segmented electrodes



For Example:

Monitor axial image charge induced on 1 ring electrode



Monitor azimuthal image charge induced on 1 segment

Plasma in ALPHA for $\overline{\mathrm{H}}$ 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

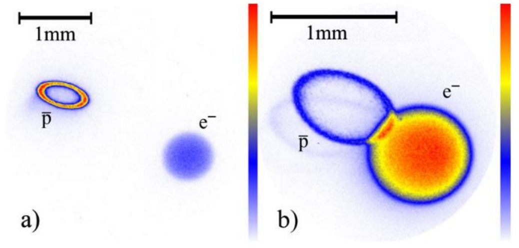
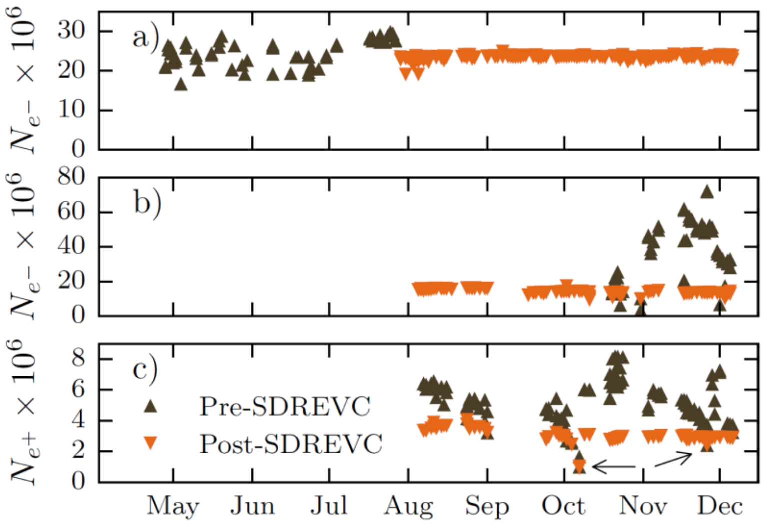
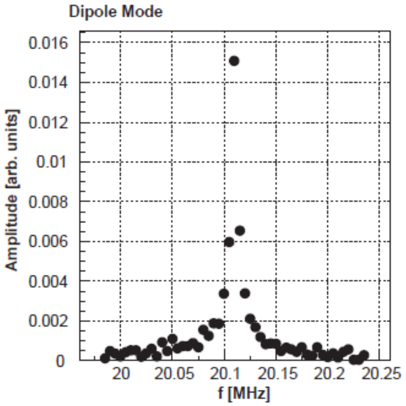
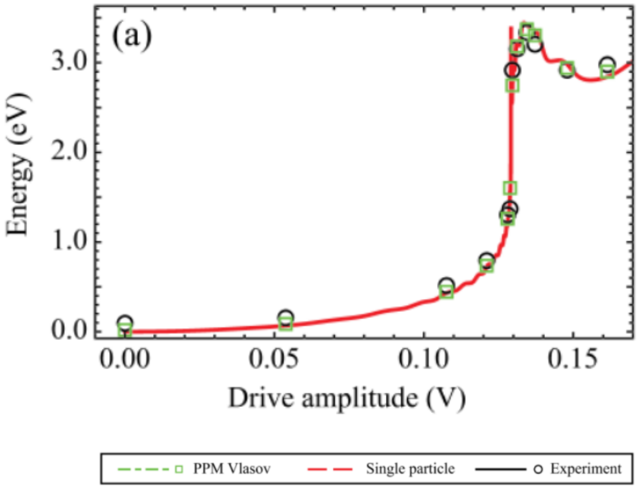
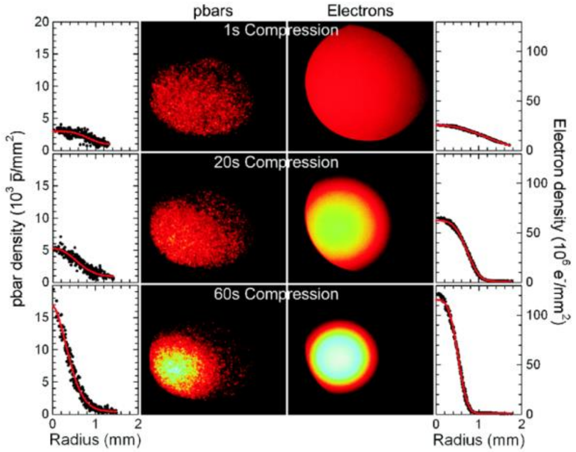


FIG. 1 (color online). Images of centrifugally separated plasmas trapped in (a) a 1 T and (b) a 3 T solenoidal field. In both



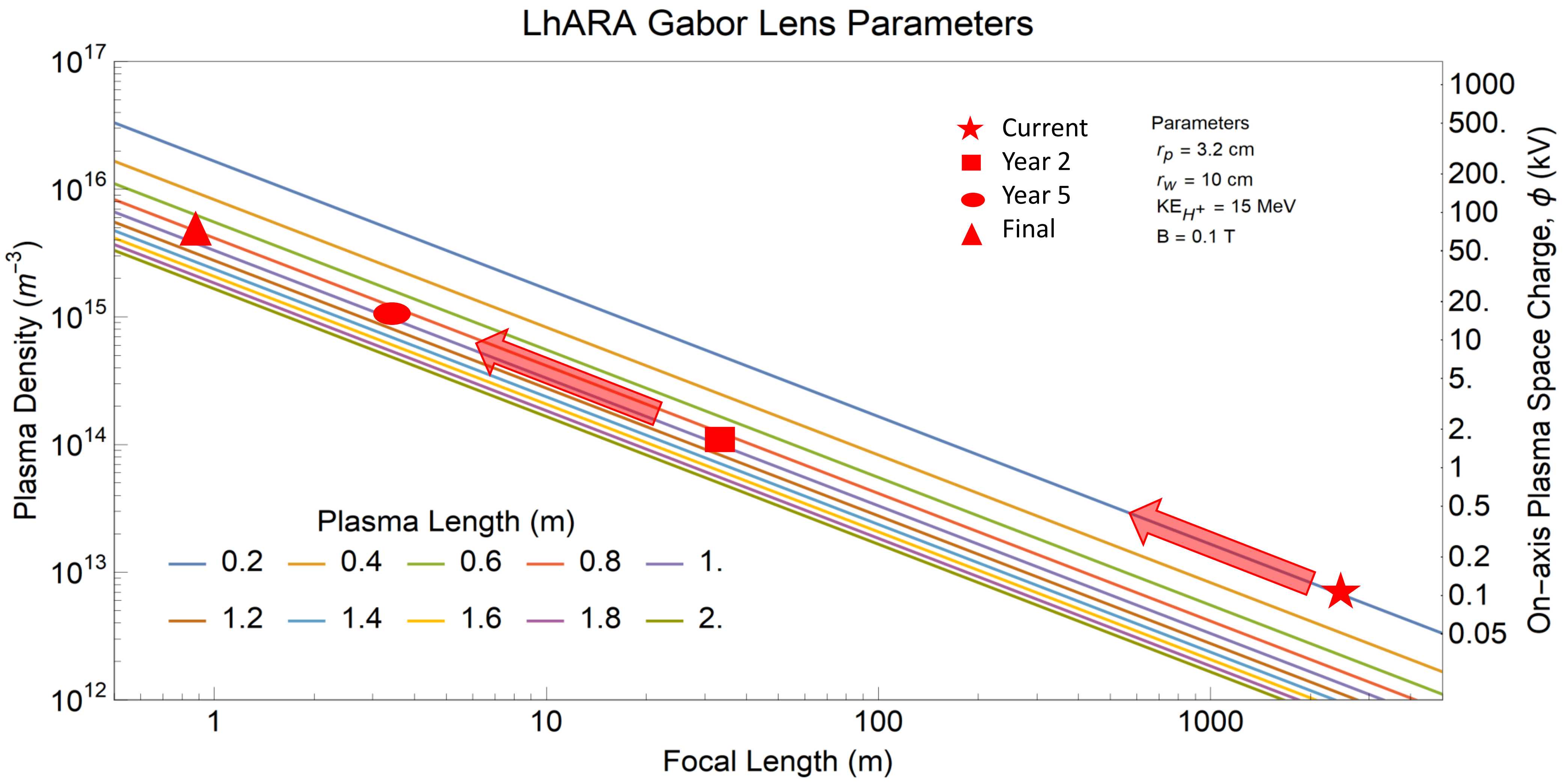




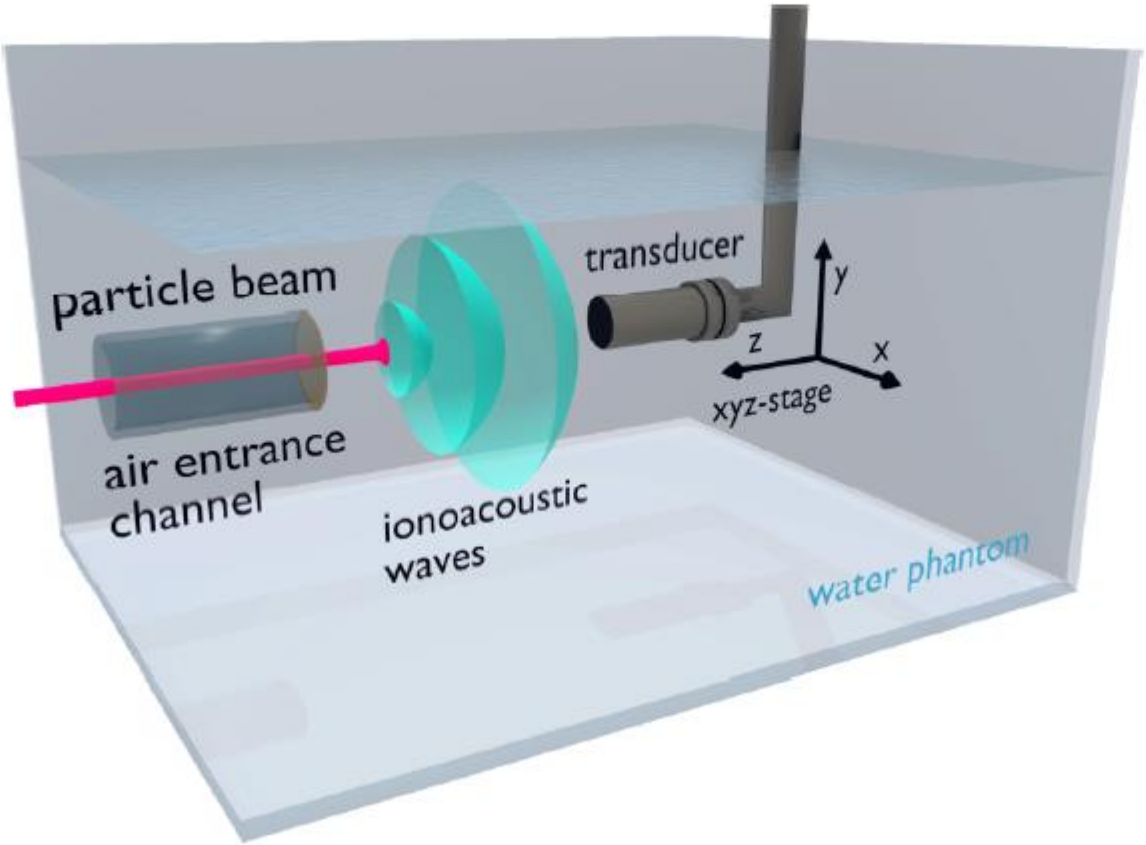


doi: 10.1103/PhysRevLett.120.025001
doi: 10.1063/1.4801067
doi: 10.1103/PhysRevLett.100.203401
doi: 10.1016/j.nima.2003.09.052
doi: 10.1103/PhysRevLett.106.145001

Year 5 milestone



Ion Acoustic Dose Mapping



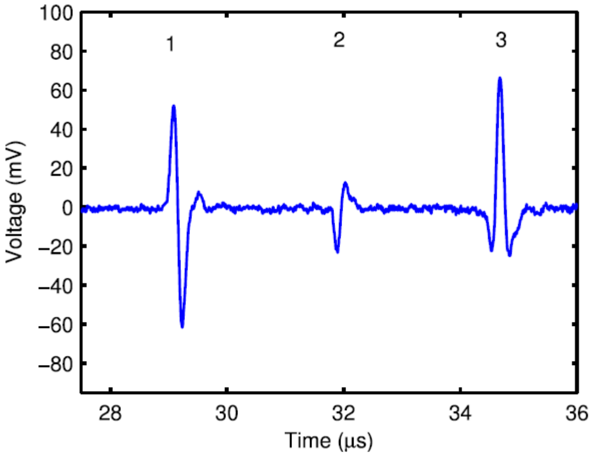


FIG. 2. Example of an ionoacoustic signal from a 110 ns ion pulse with 2×10^6 protons, recorded with a 3.5 MHz ultrasound transducer (pulse average of 16 samples, see also text).

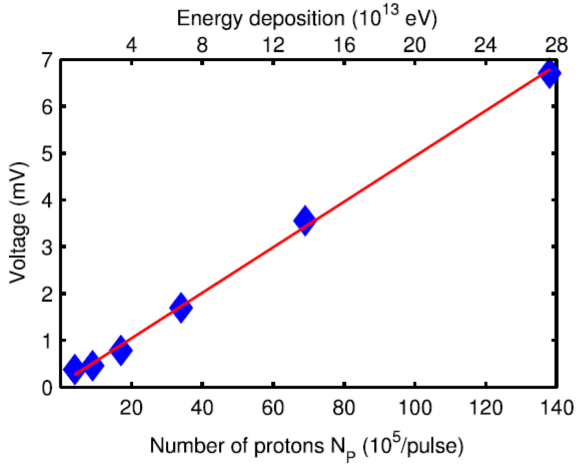


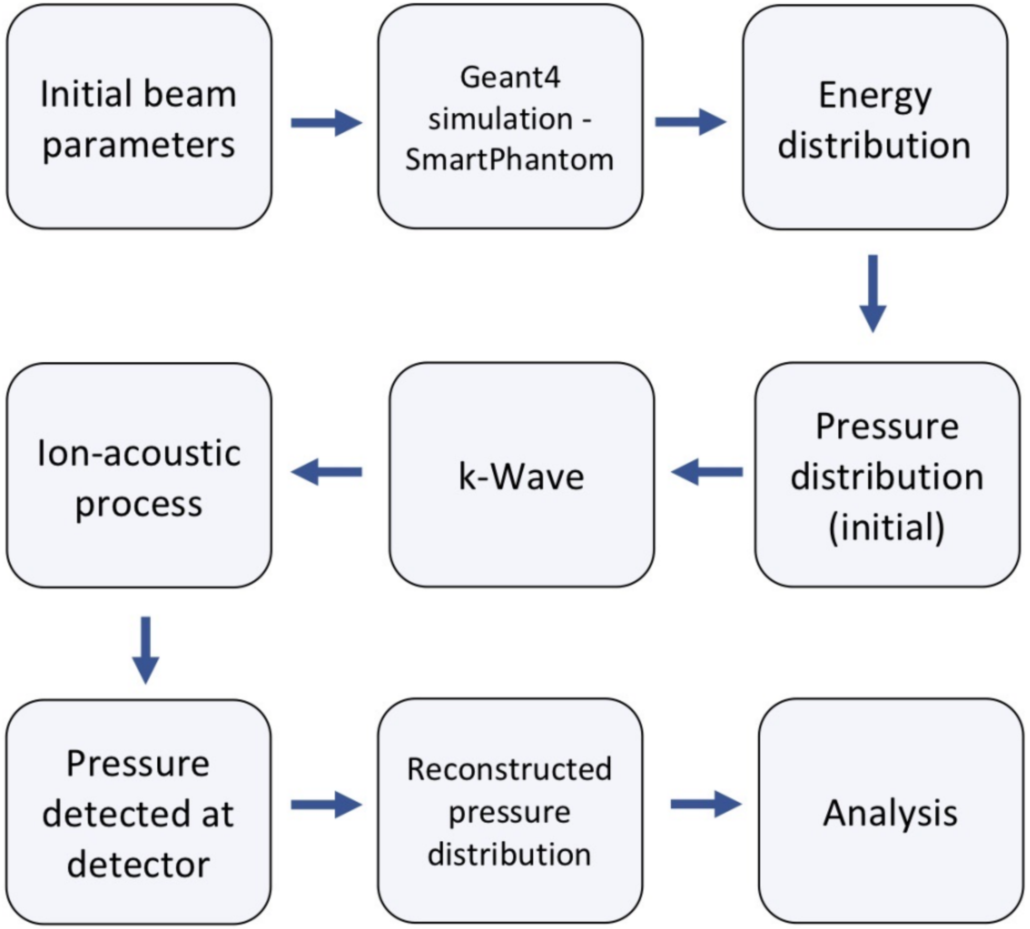
FIG. 5. Acoustic signal amplitude of a 473 ns proton bunch (16 pulses average) as function of particle number and total energy deposition per pulse, along with a linear polynomial fit (red line).

- 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



Initial beam parameters

Geant4 simulation - SmartPhantom

Energy distribution

Pressure distribution (initial)

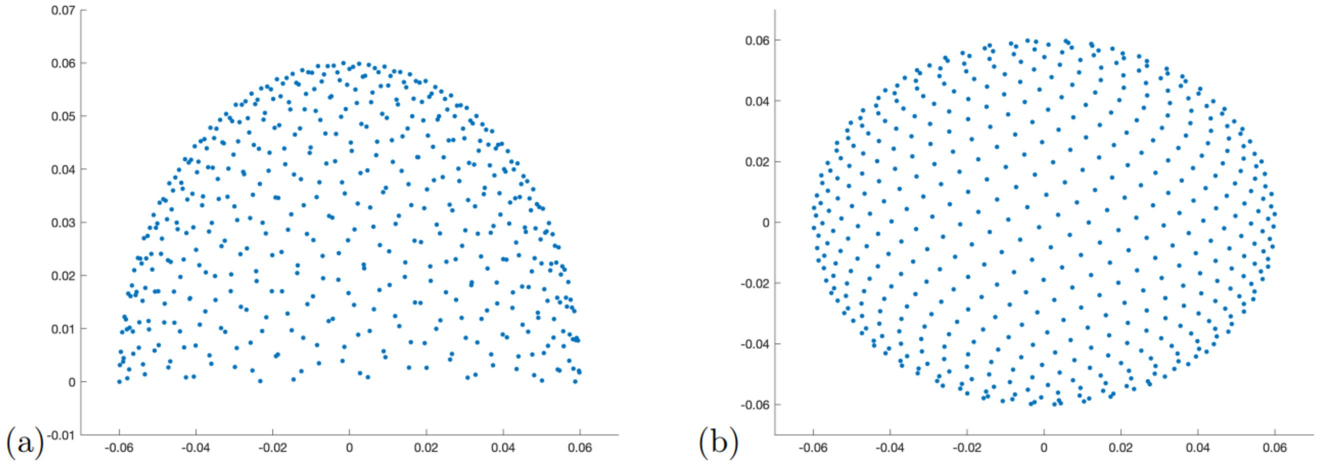
k-Wave

Ion-acoustic process

Pressure detected at detector

Reconstructed pressure distribution

Analysis



Time reversal

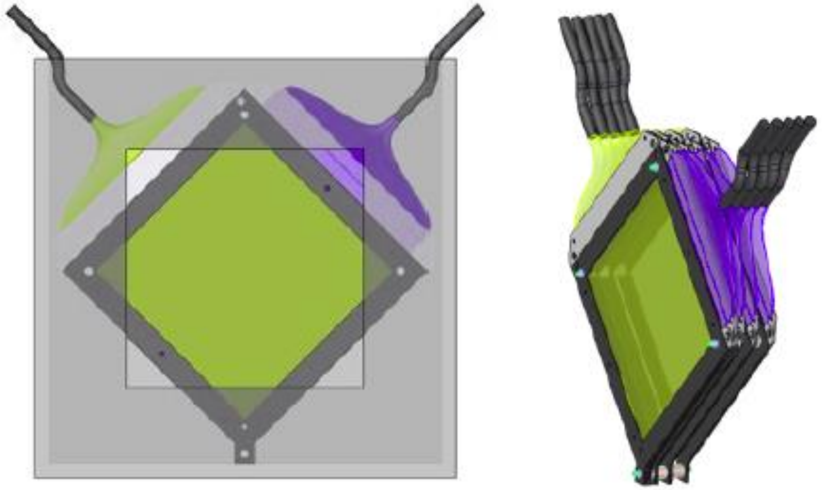
Model based minimisation

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/



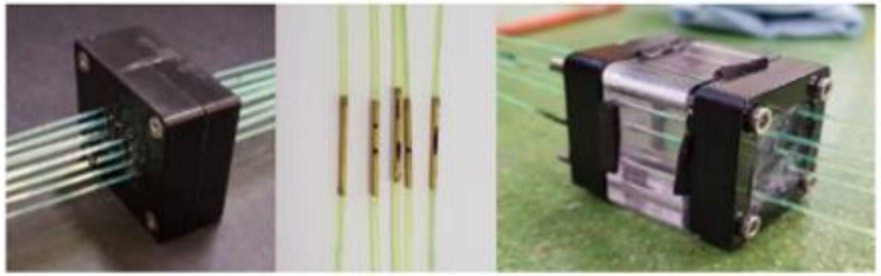
Beam is measured using scintillating fibre planes
Scintillating fibre -> clear fibre -> detector
Aiming to use the edge of the plane as a connector
Clear fibres bundled and sent to CMOS camera
For faster readout, could use photodiodes

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

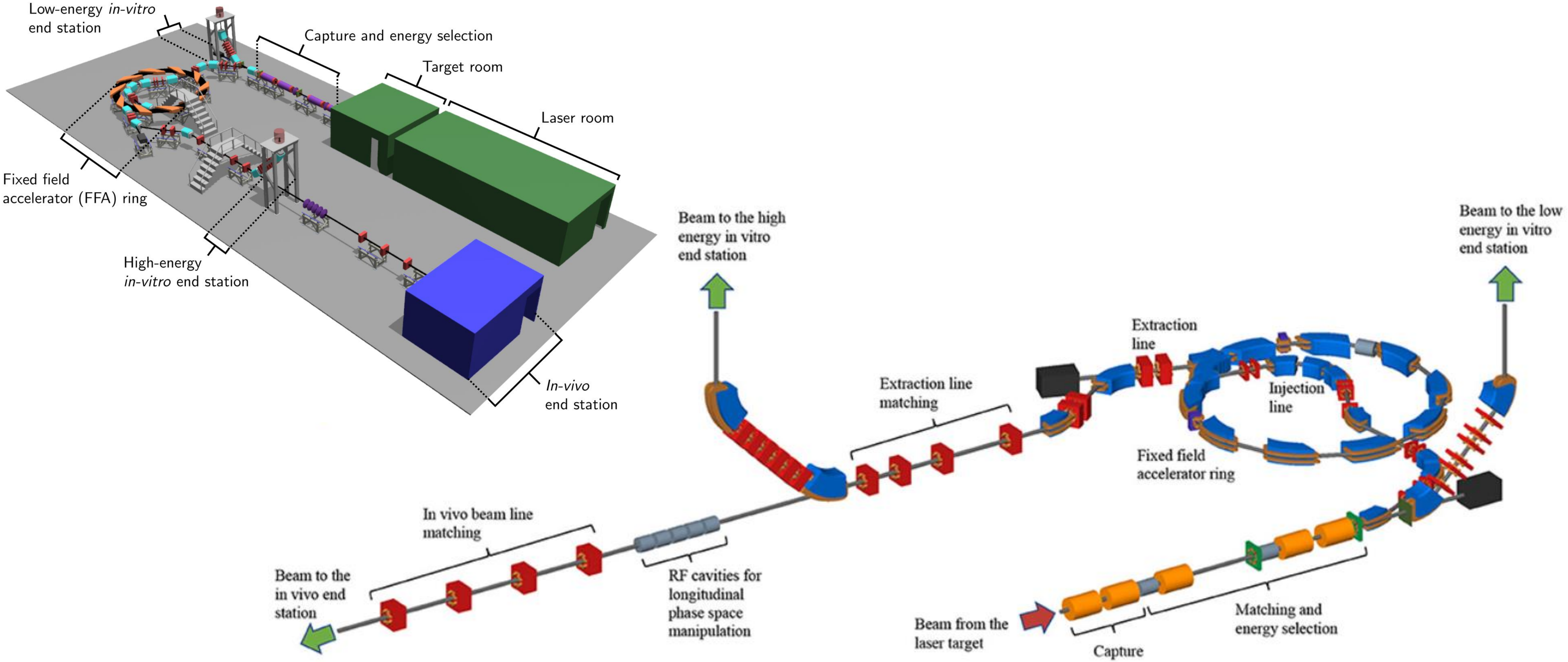
GEANT4
A SIMULATION TOOLKIT



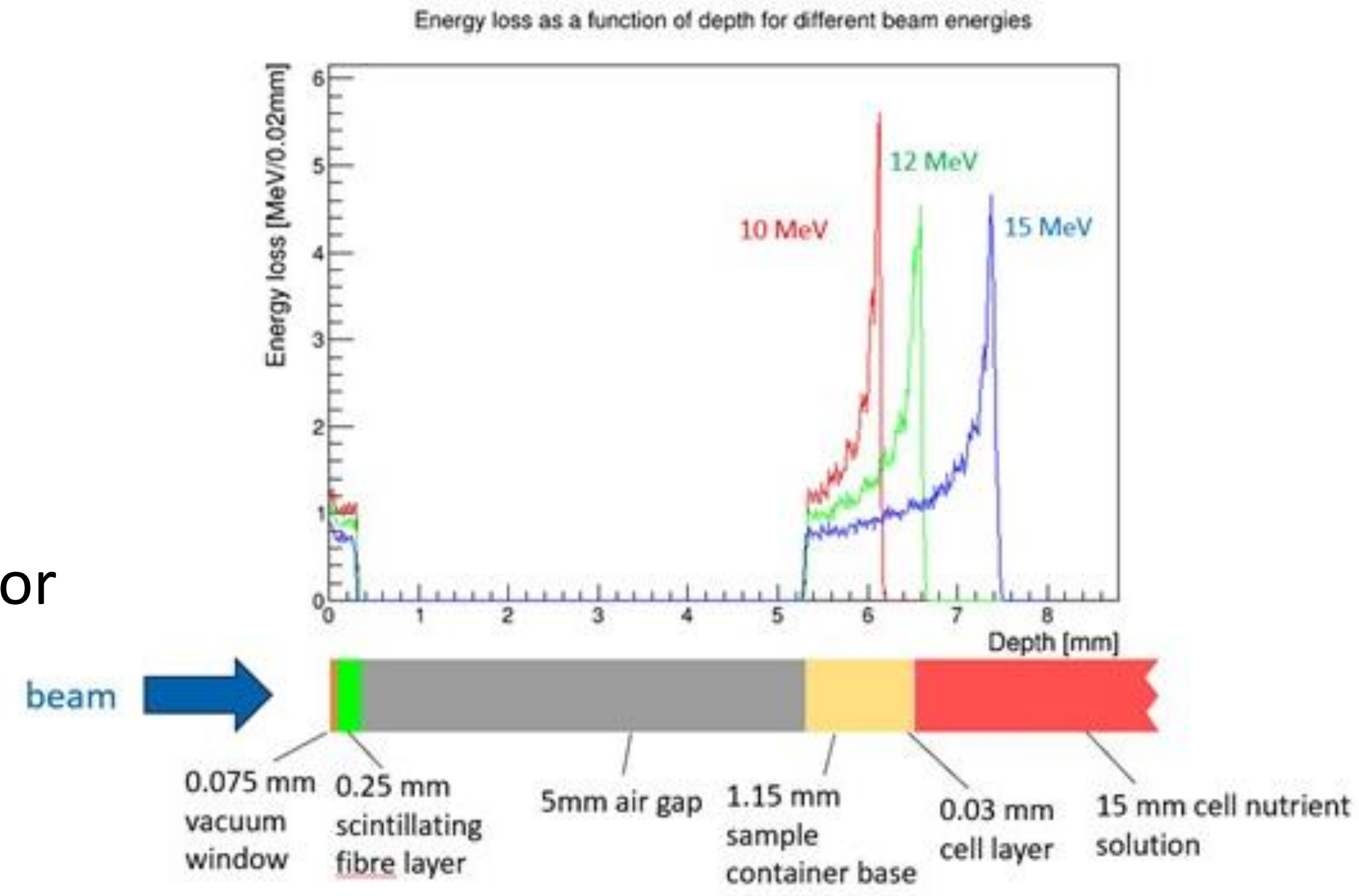
Methods of joining fibres – Jeff Sykora, ISIS

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

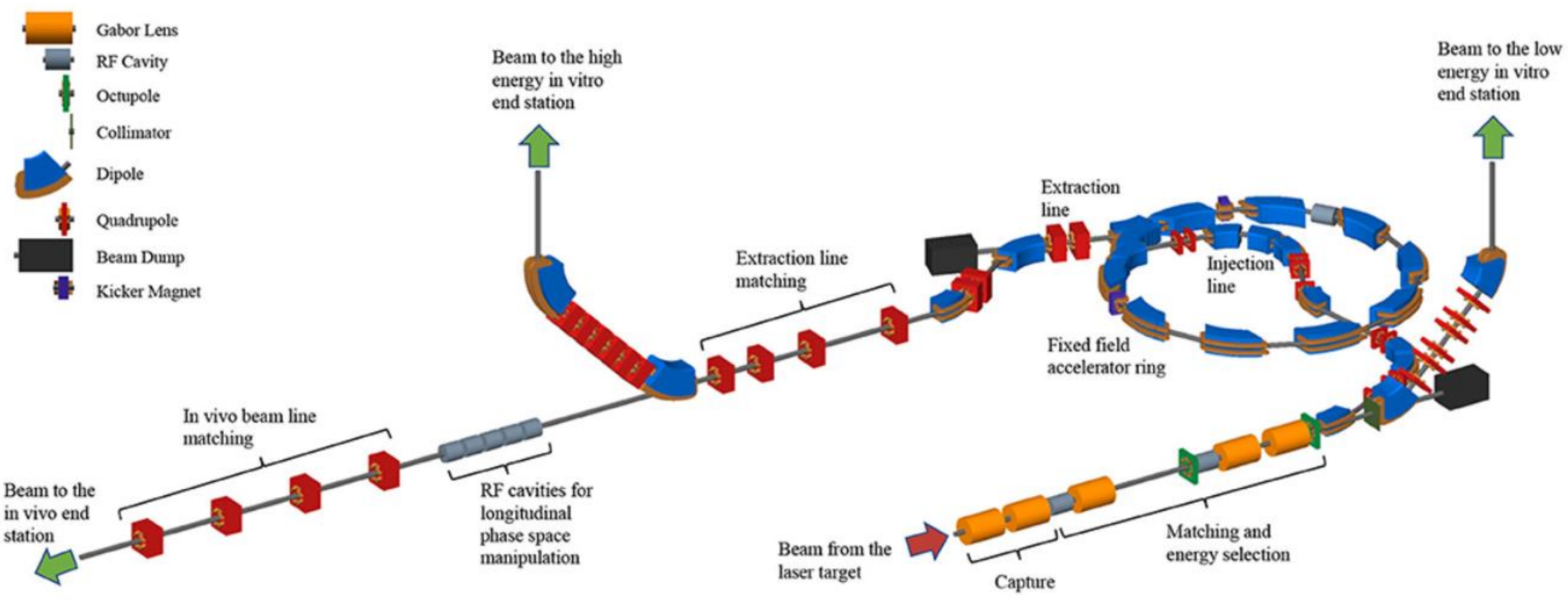
WP5 – End station development & Instrumentation



- 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



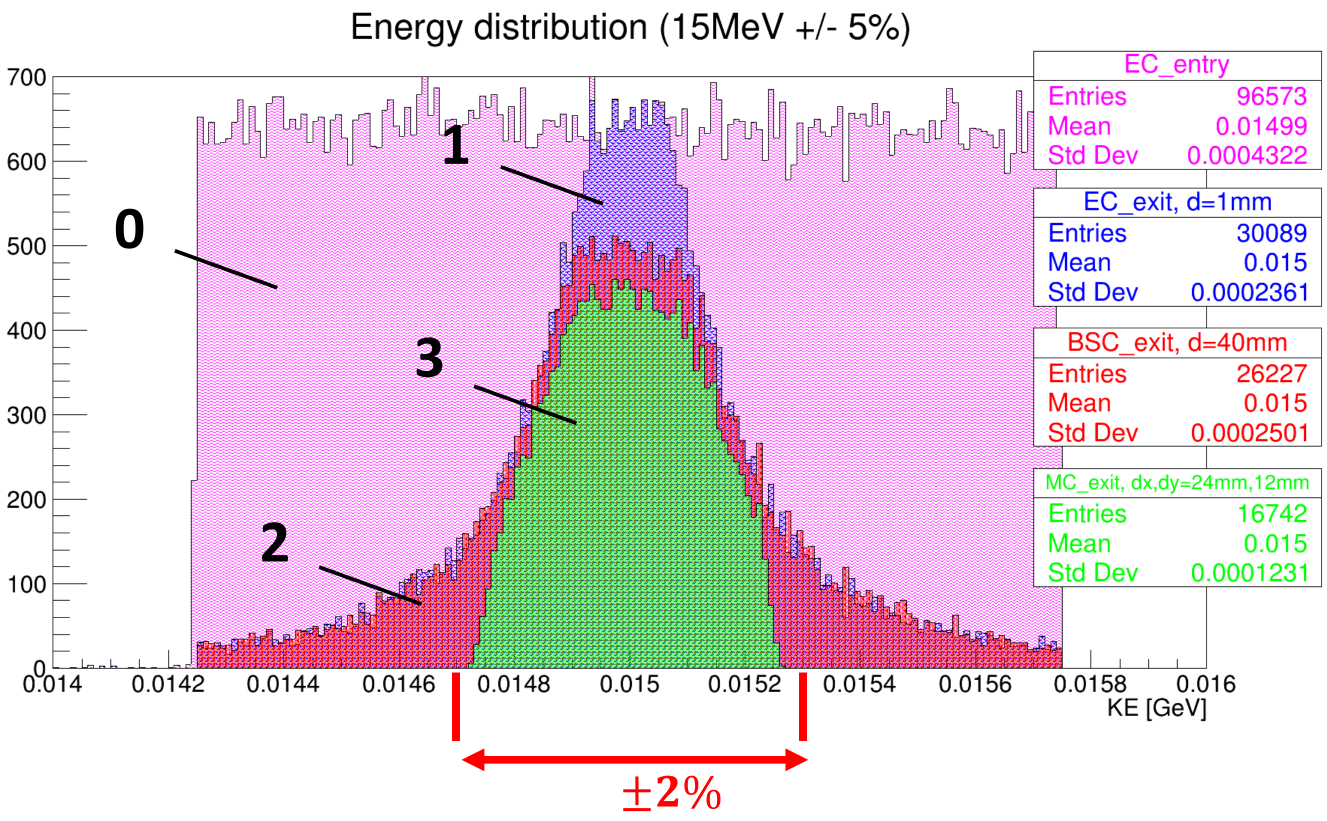
WP6 – Facility design and integration



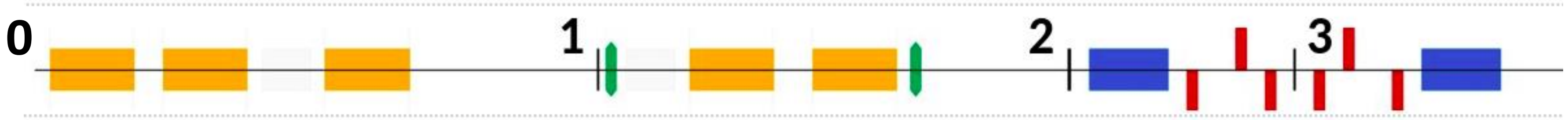
Controlling energy spread in LhARA

- 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

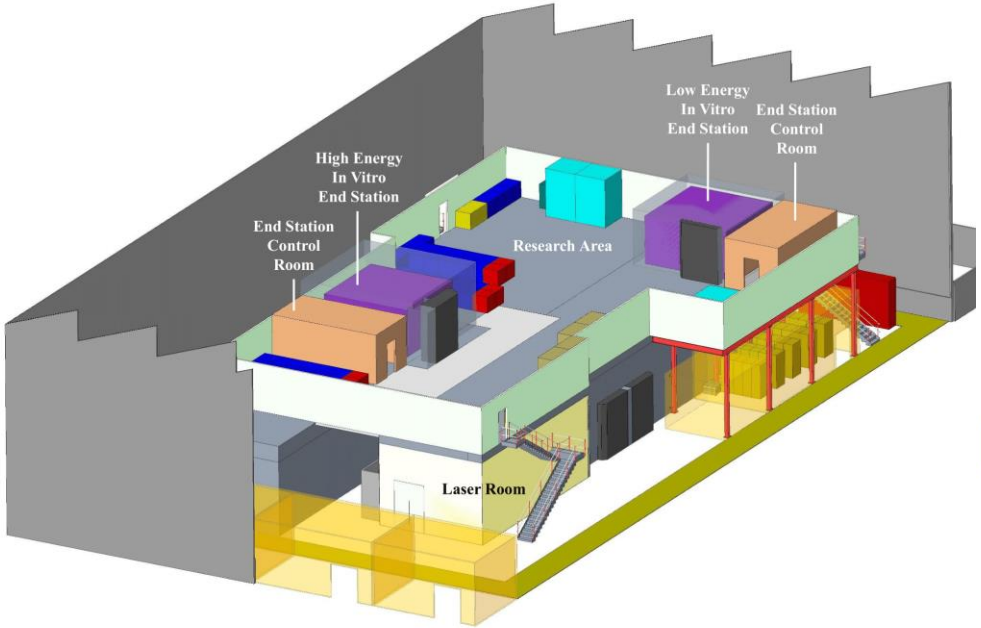


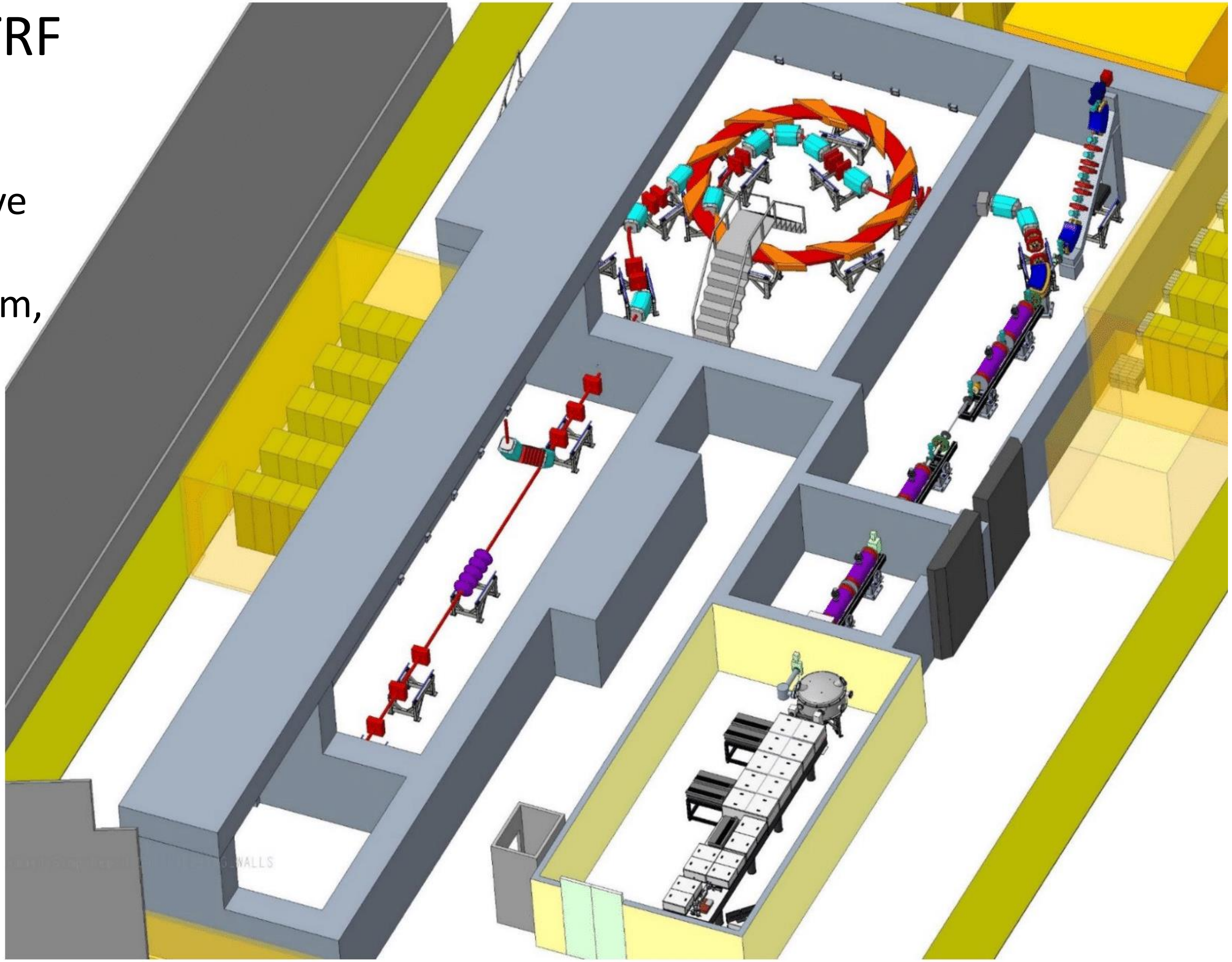
Facility – planning - development

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





Imperial College London

ICR The Institute of Cancer Research

Medical Research Council
Oxford Institute for Radiation Oncology

UNIVERSITY OF OXFORD

JAI John Adams Institute for Accelerator Science

LhARA
Laser-hybrid Accelerator for Radiobiological Applications

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

UNIVERSITY OF LIVERPOOL

NHS
University Hospitals Birmingham
NHS Foundation Trust

NHS
The Clatterbridge Cancer Centre
NHS Foundation Trust

NHS
The Christie
NHS Foundation Trust

institut Curie

QUEEN'S UNIVERSITY BELFAST

Swansea University
Prifysgol Abertawe

UCL
MEDICAL PHYSICS & BIOMEDICAL ENGINEERING

Partners

University
Clinical
Laboratory
Industry
Accelerator

NETHERLANDS CANCER INSTITUTE
ANTONI VAN LEEUWENHOEK

HAMPTON UNIVERSITY
PROTON THERAPY INSTITUTE
FIGHTING CANCER. SAVING LIVES

University of Strathclyde Glasgow
DEPARTMENT OF PHYSICS

ROYAL HOLLOWAY UNIVERSITY OF LONDON

Lancaster University

UKRI Science and Technology Facilities Council

ASTeC
Daresbury Laboratory
Particle Physics Department
ISIS Neutron and Muon Source

CLF central laser facility

UNIVERSITY OF BIRMINGHAM | CYCLOTRON FACILITY | POSITRON IMAGING CENTRE

INFN CATANIA

The Cockcroft Institute
of Accelerator Science and Technology

CERN

Corerain
鲲 云 科 技

LEO Cancer Care

MAXELER Technologies
Maximum Performance Computing

The Rosalind Franklin Institute

NPL
National Physical Laboratory