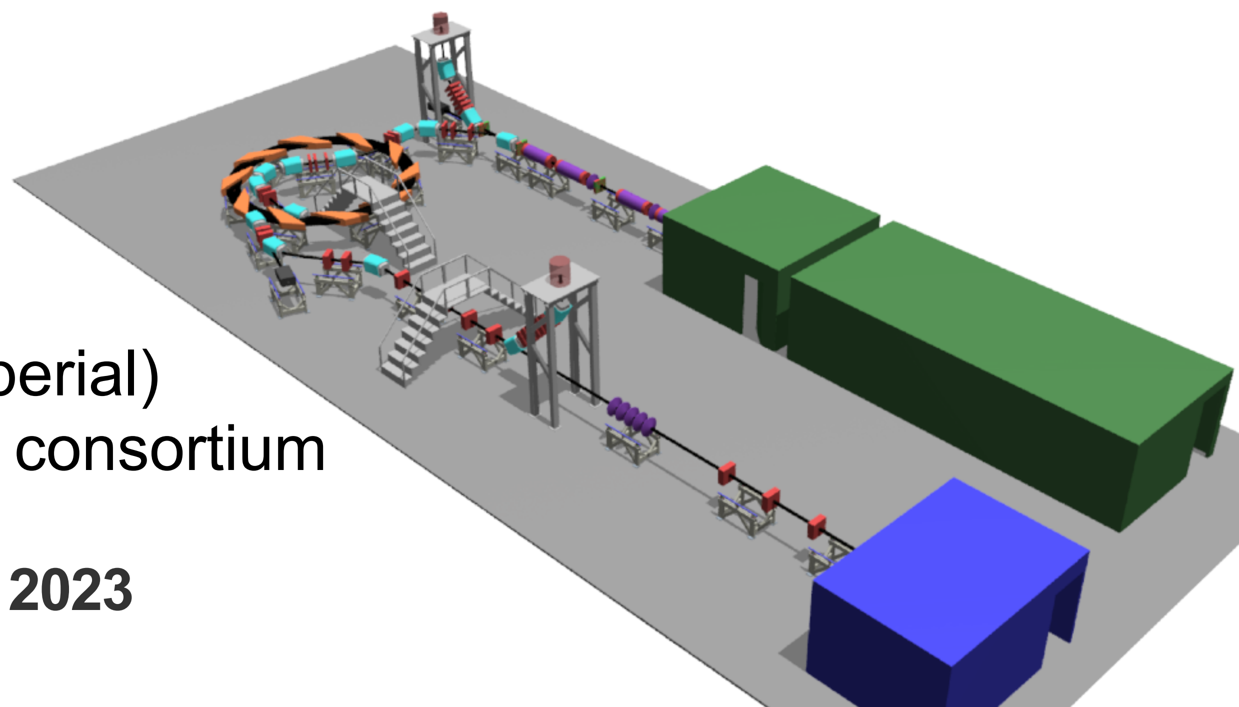
Laser-hybrid Accelerator for Radiobiological Applications (LhARA)

N. P. Dover on behalf of K. Long (Imperial College London)

Acknowledgements:
E. Boella (Lancaster)
R. Gray (Strathclyde)
W. Shields (Royal Holloway)
T. Dascalu, J. Pasternak (Imperial)
… and the rest of the LhARA consortium

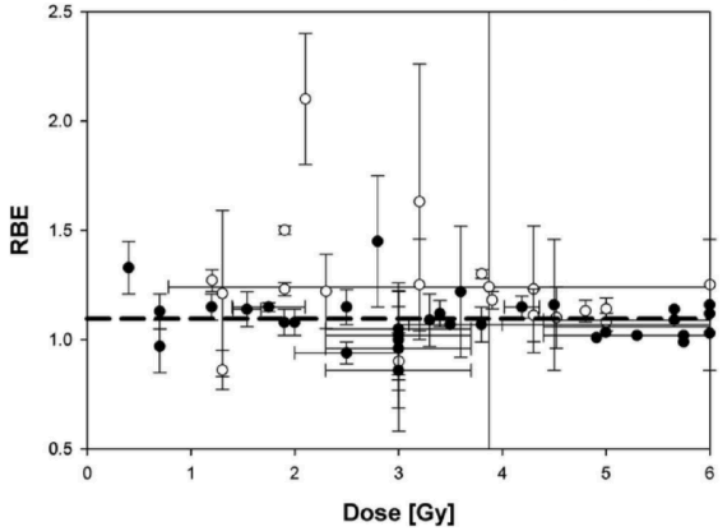


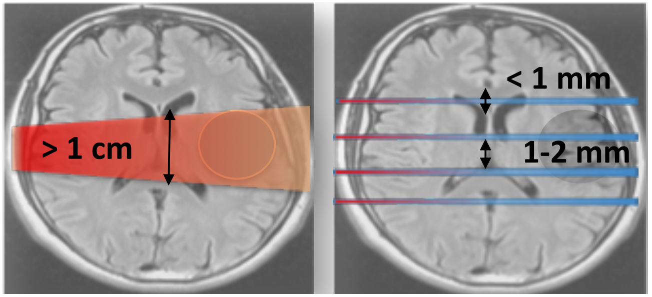
SPIE Optics & Optoelectronics 2023
24-27th April 2023

The case for LhARA

- **Growing global requirement for RT**
  - Scale up in provision is essential
  - Development of new technologies and cost effective systems
- **Systematic study of the radiology of ion beams**
  - Accurate treatment planning relies on RBE
  - For ions, uncertainty due to many factors:
    - Energy, dose, dose rate, dose spatial distribution, ion species…
- **Novel beams for radiobiology**
  - Therapeutic benefits for ultrahigh dose rates ("FLASH" RT) and microbeam therapy
  - Requires extensive further study both *in vitro* and *in vivo*

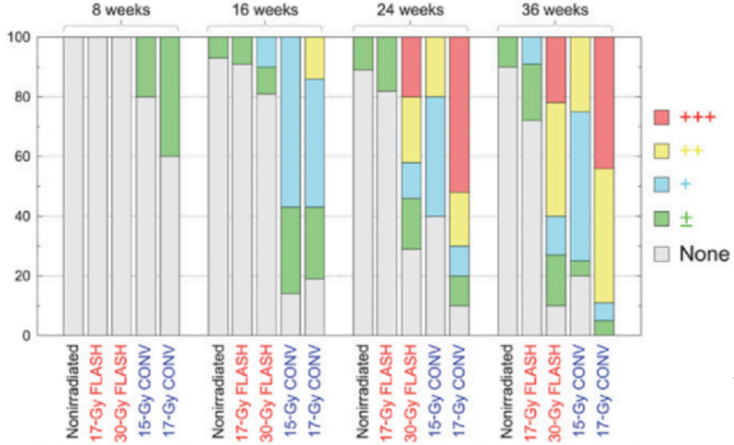
Paganetti and van Luijk, Sem. Rad. Oncol. 23, 77 (2013)





Prezado et al., Sci. Rep. 7, 14403 (2017)

Favaudon et al., Sci. Transl. Med. 6, 245 (2014)



Towards a novel facility to answer critical questions in radiobiology

Time domain

Space domain

A flexible new beam facility is necessary to explore radiobiology in new regimes

Ion energy

Ion species

In combination with chemo/immuno therapy

<u>Goals:</u>

- Deliver a systematic and definitive radiobiology programme
- Lay the foundation for transformative, highly automated and patient specific ion beam therapy

The LhARA consortium

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 · Laboratory · Industry · Accelerator

Partners

NHS University Hospitals Birmingham NHS Foundation Trust

NHS The Clatterbridge Cancer Centre NHS Foundation Trust

institut Curie

UKRI Science and Technology Facilities Council
ASTeC
Particle Physics Department
ISIS Neutron and Muon Source

INFN Catania

CLF central laser facility

Swansea University Prifysgol Abertawe

University of Birmingham | Positron Imaging Centre

University of Birmingham | Cyclotron Facility

Corerain 鲲云科技

The Rosalind Franklin Institute

NPL National Physical Laboratory

The Cockcroft Institute of Accelerator Science and Technology

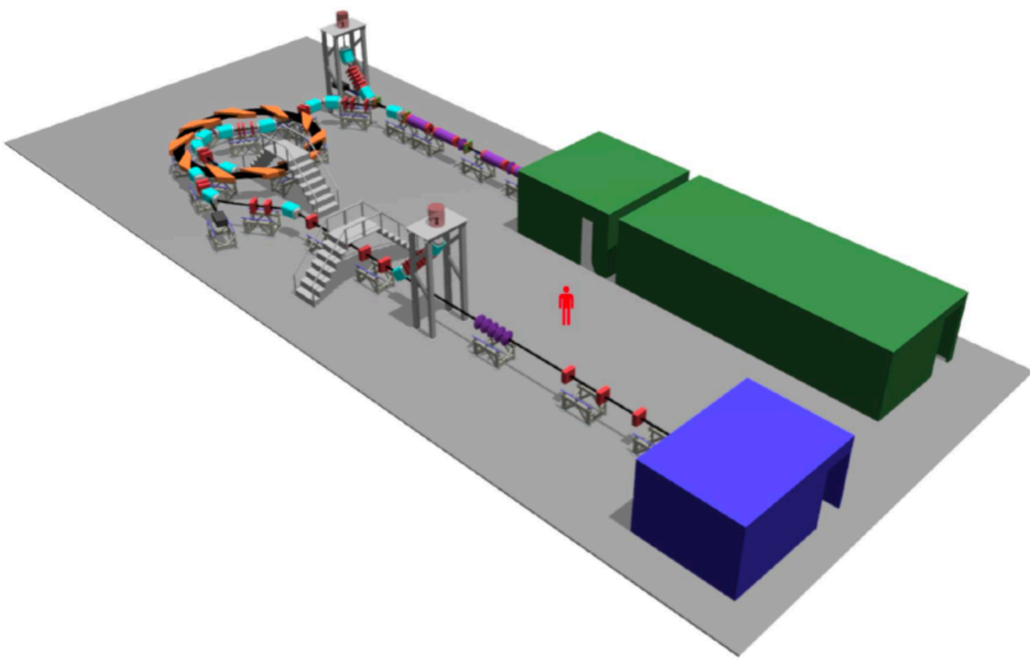
University of Surrey Ion Beam Centre

LEO Cancer Care

Maxeler Technologies Maximum Performance Computing

LhARA Laser-hybrid Accelerator for Radiobiological Applications

The LhARA approach

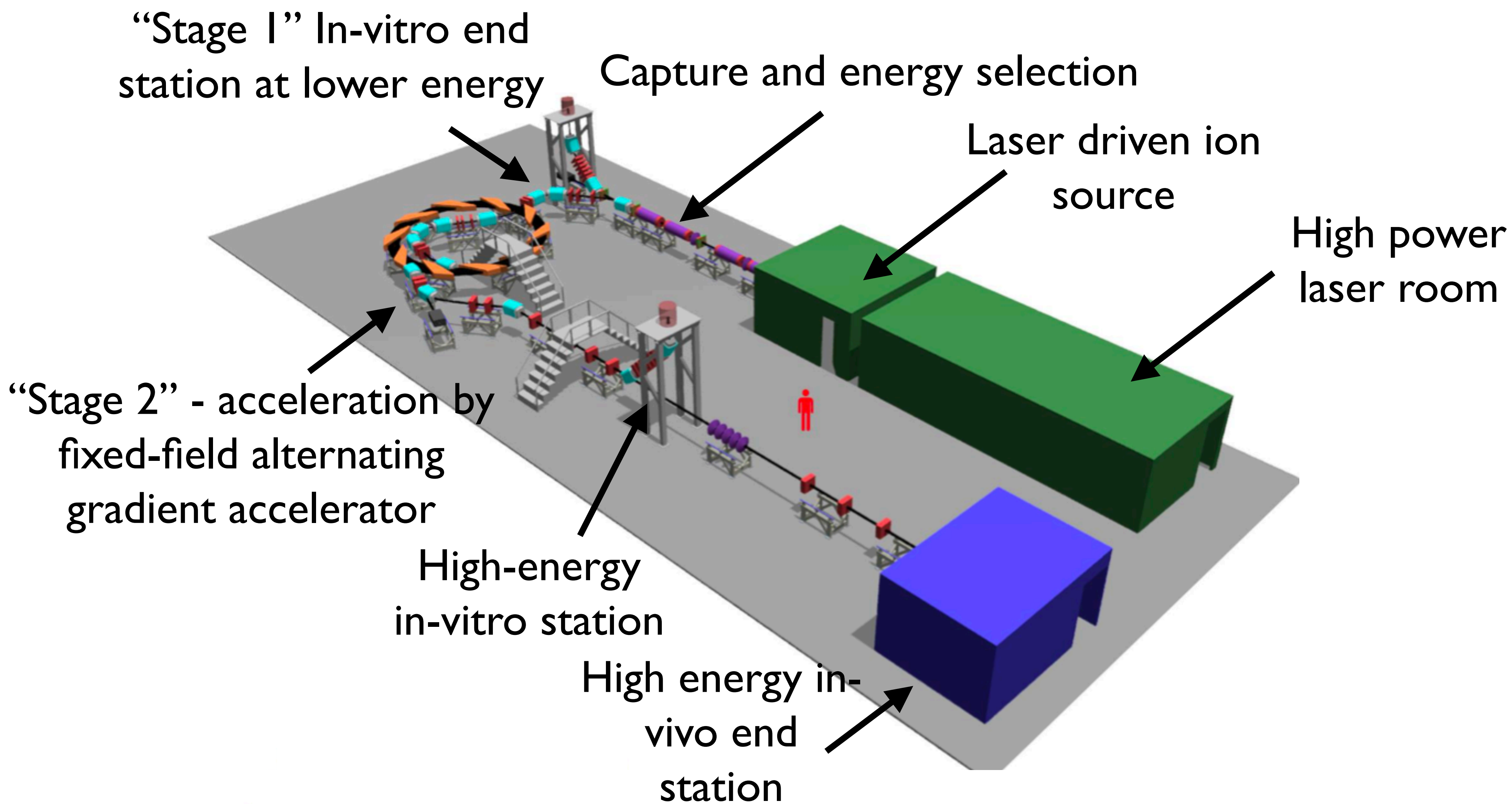


A novel laser-hybrid approach

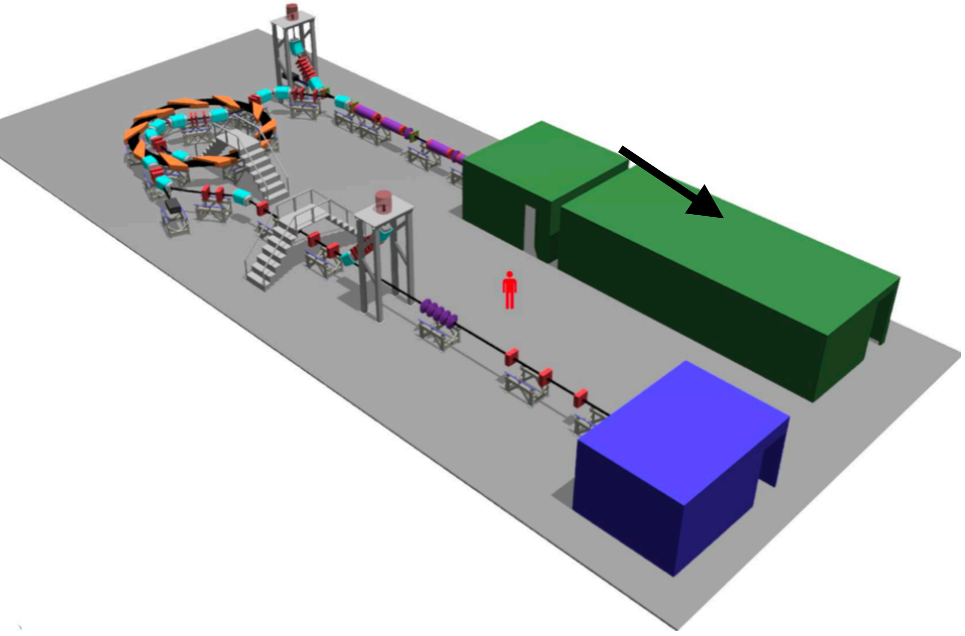
- **Laser-driven high-flux proton/ion source**
  - Overcome instantaneous dose-rate limitations
  - Proton/ion bunches as short as 10-40 ns
  - Triggerable
- **Electron-plasma lenses for capture and beam focusing**
  - Short focal length without the use of high field solenoids
- **Fast post acceleration with an FFA**
  - Variable energy:
    - ➡Protons 15-127 MeV
    - ➡Ions 5-34 MeV/u

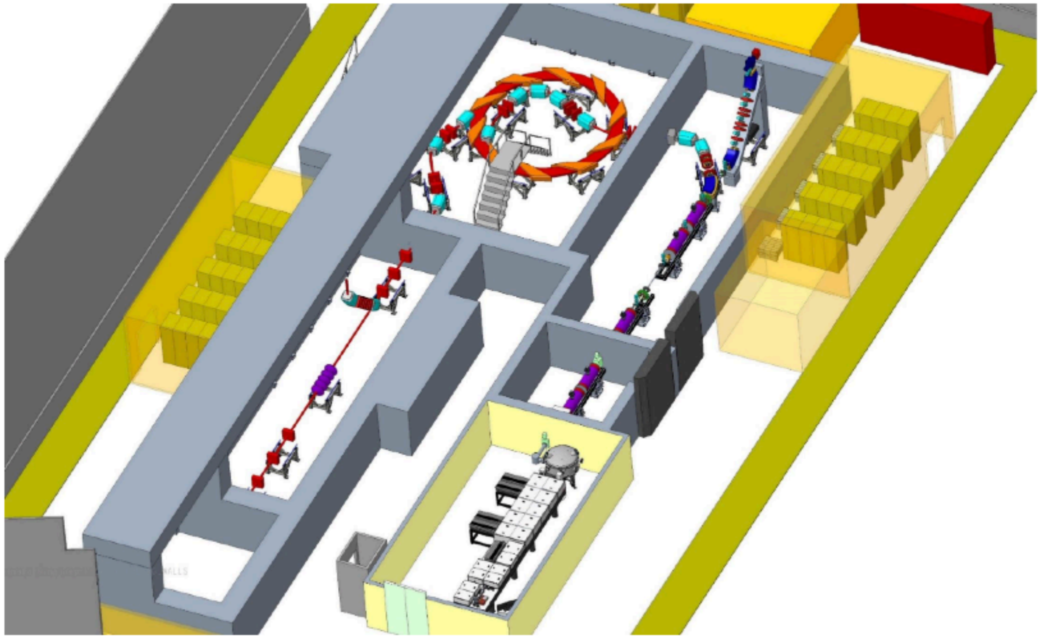
Conceptual design for LhARA: Aymar et al. Frontiers in Physics **8**, 567738 (2020)

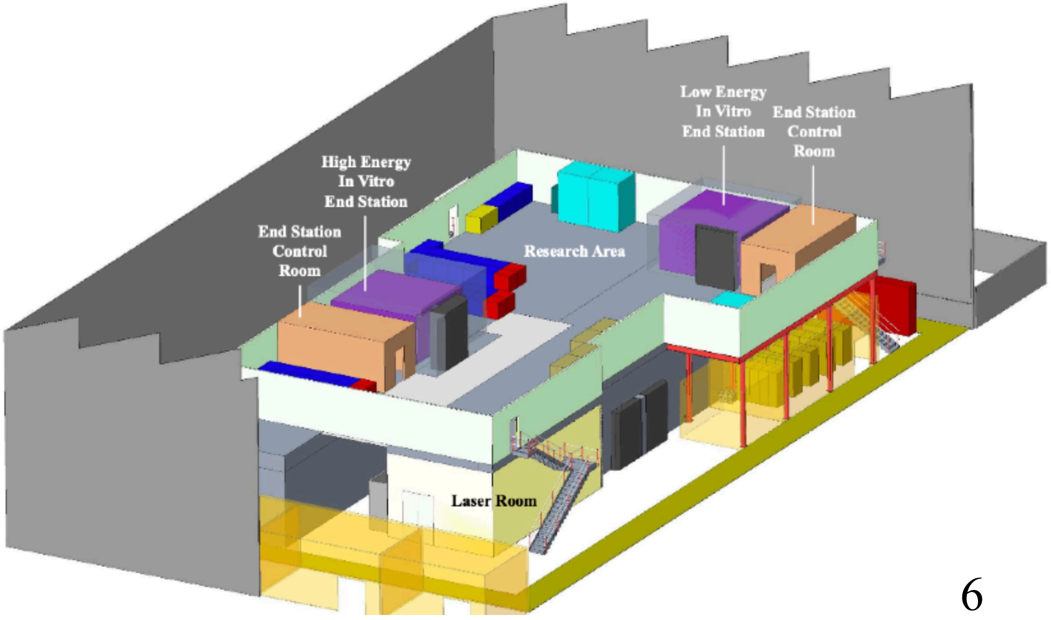
LhARA beamline overview



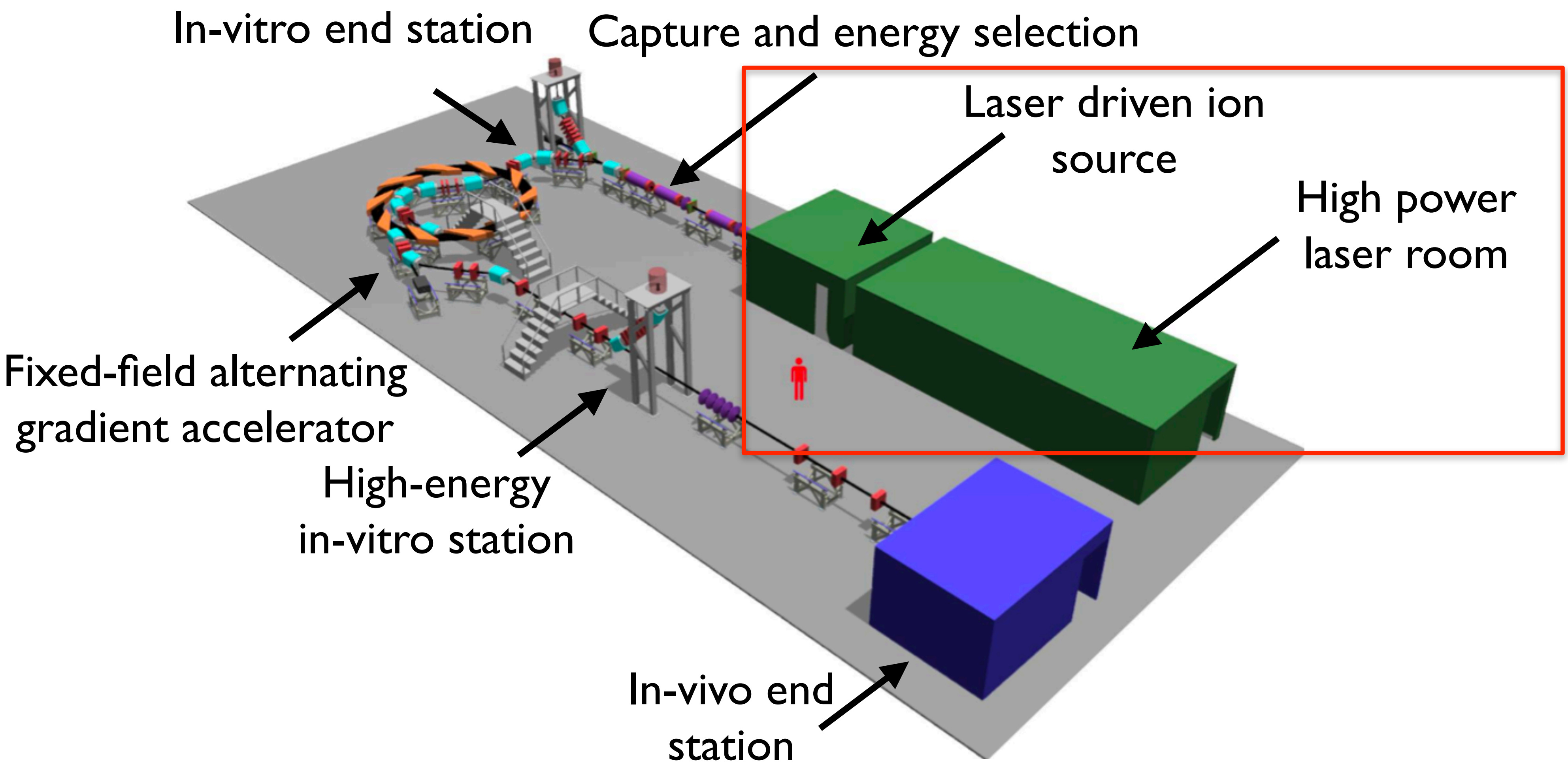
LhARA beamline overview



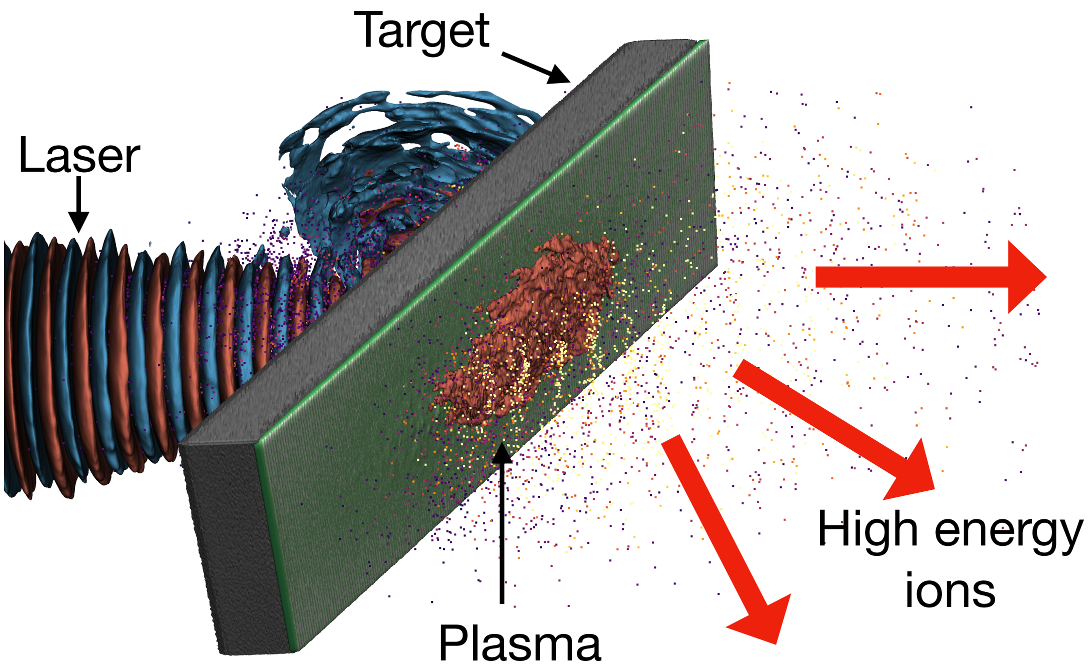




LhARA beamline overview



Laser driven ion source for LhARA



- High energy (e.g. ~15 MeV p+, 4 MeV/u C6+) from source
- Minimised space charge issues, enabling high peak current
- Needs to operate at 10 Hz for long periods
- Aiming to deliver 10^9 protons or 10^8 carbon ions per shot, eventually other ions
- Initially tape targets, but developing other options, e.g. water jet

University of Strathclyde Glasgow
Imperial College London
Lancaster University
QUEEN'S UNIVERSITY BELFAST
central laser facility

Full 3D Particle-in-Cell simulations of LhARA laser-driven ion source

$I = 9 - 10 * 10^{20}$ W/cm^2

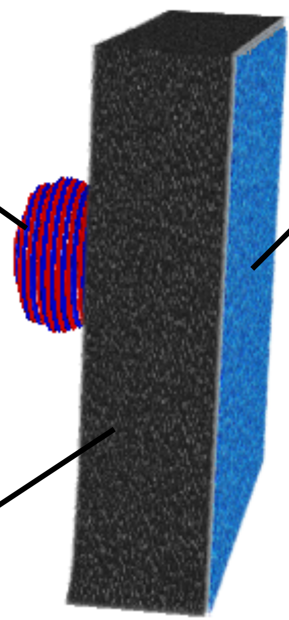
$\lambda_0 = 800$ nm

$a_0 = 20.52 - 21.60$

$\tau_{FWHM} = 25$ fs

$w_0 = 1.5$ μm

p - polarised



H^+ layer

$n_{H+} = 1.15\ n_c$

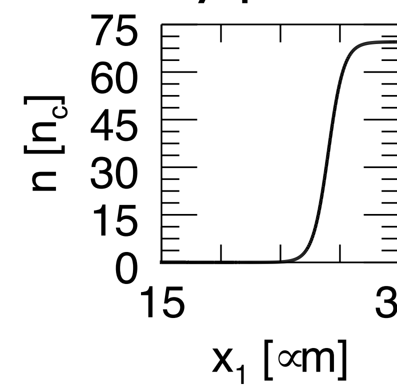
$L_{H+} = 31.83$ nm

Al^{3+} foil

$n_{Al3+} = 70\ n_c$

$L_{Al3+} = 2 - 6$ μm

Initial density profile detail



$$n_{Al^{3+}} = 70\frac{n_c}{2}\left[\tanh\left(\frac{x_1 - x_{1,0}}{L_g}\right) + 1\right]$$

$x_{1,0} = 25.5$ μm

$L_g = 0.08 - 1$ μm

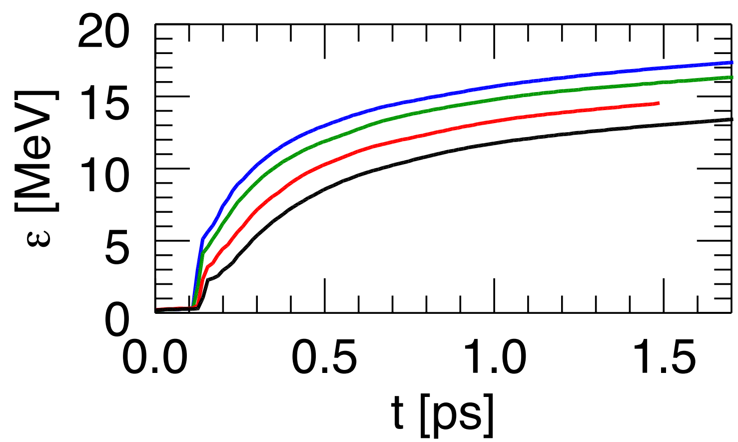
Lancaster University

Simulations by Elisabetta Boella

Osiris 4.0

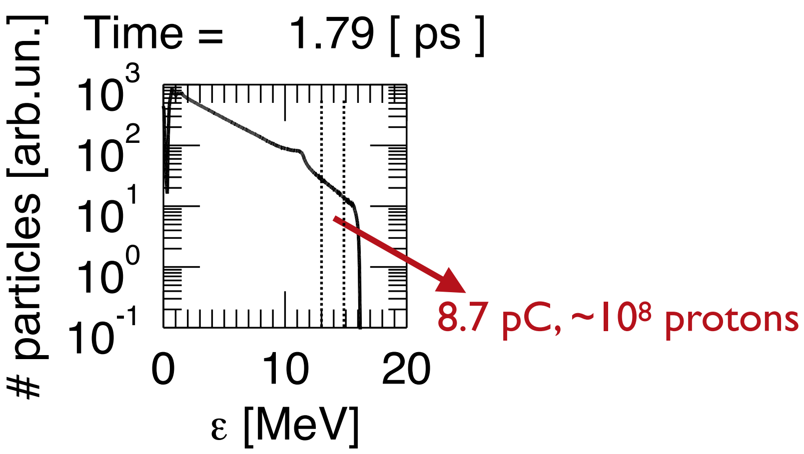
With no preplasma, only relatively thin targets achieve LhARA target energy

Proton cutoff energy vs time for different target thicknesses



— 6 μm — 4 μm — 2 μm — 1 μm

2 μm thick target, L_g = 0 μm



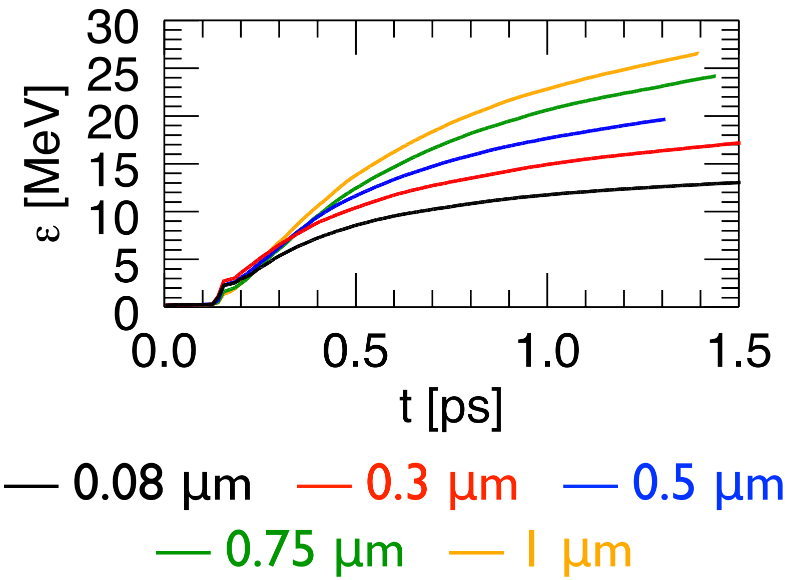
Lancaster University

Simulations by
Elisabetta Boella

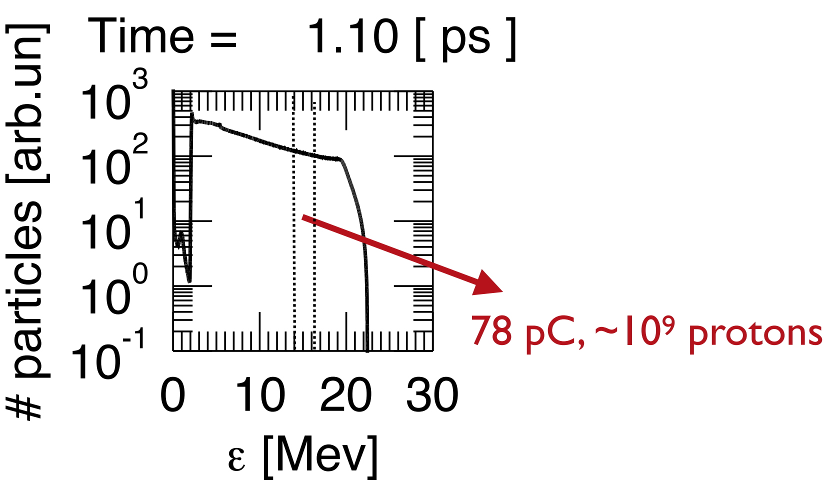
Osiris 4.0

Optimising preplasma enables doses close to requirements with thicker targets

Proton cutoff energy vs time for 6 µm thick targets with pre-plasma scale-lengths



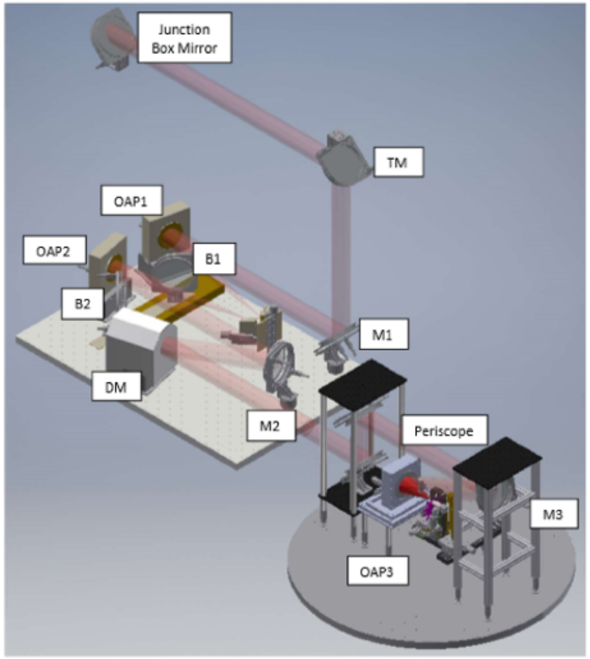
6 µm thick target, L_g = 1 µm

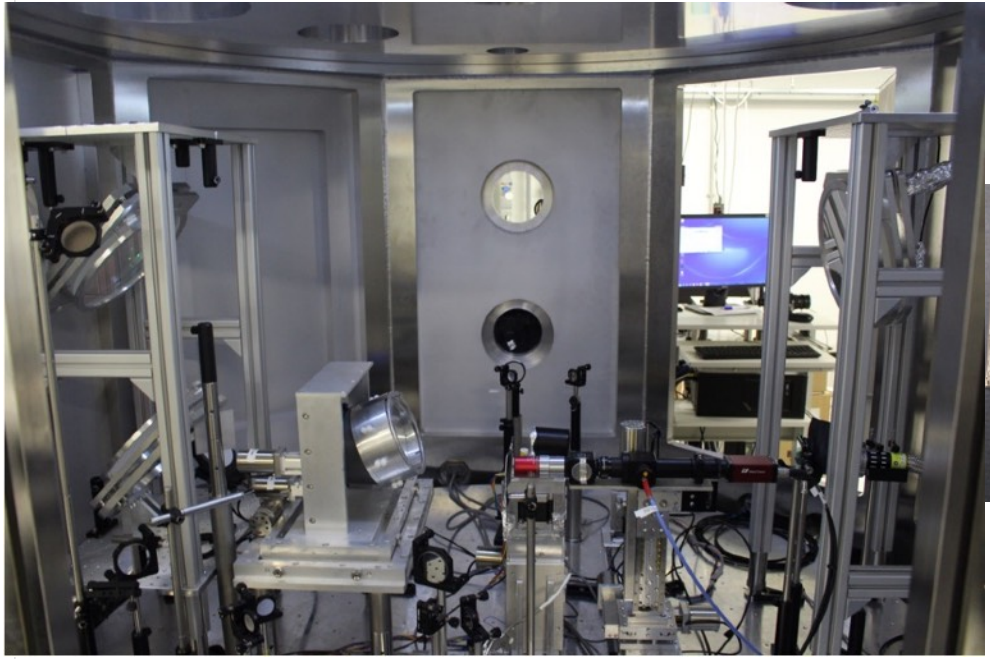


Simulations by Elisabetta Boella

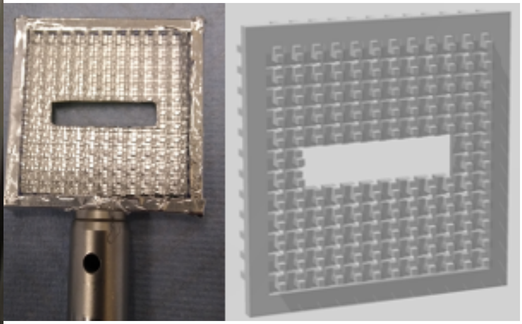
Experimental R&D programme for LhARA ion source - SCAPA

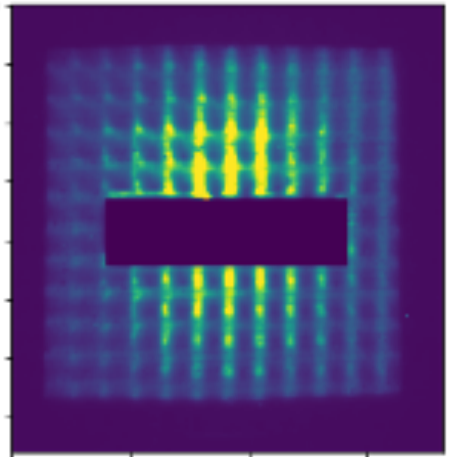
SCAPA 8 J, 25 fs at 5 Hz repetition rate up to ~10^{20} W/cm^2





Online beam spatial & spectral profile monitor

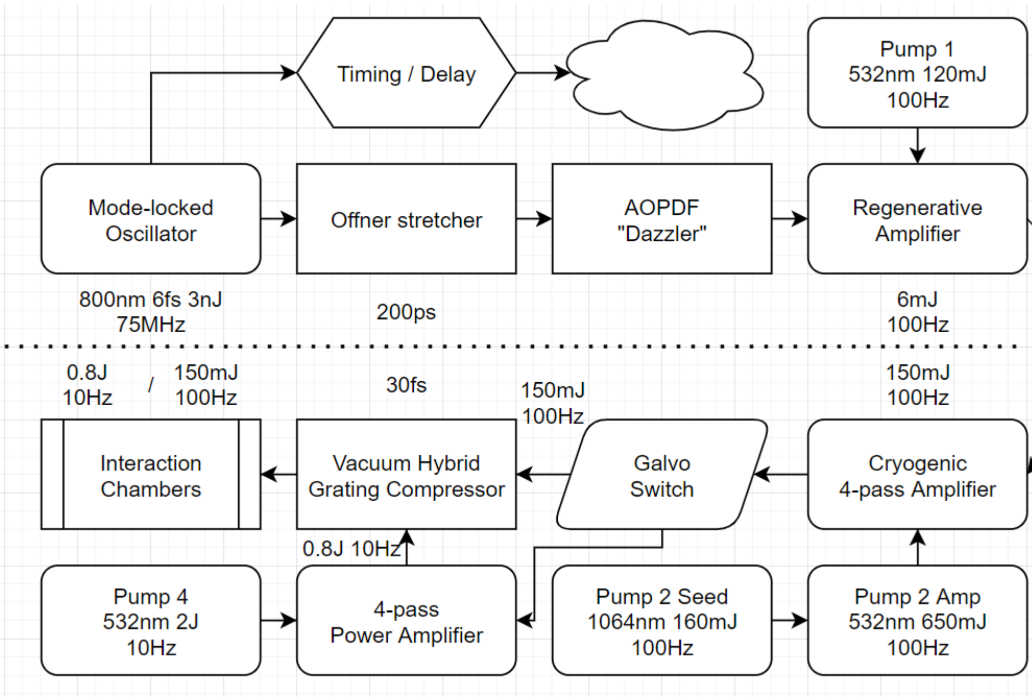


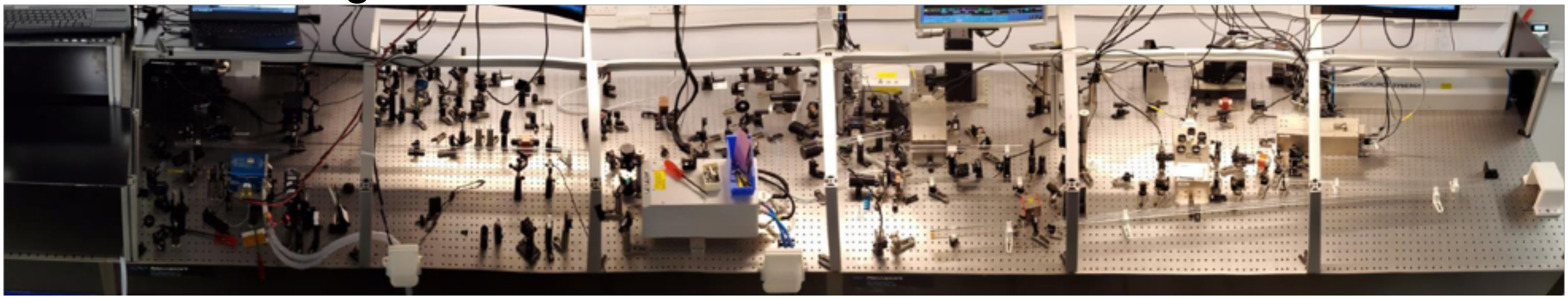


- Initial ion source experiments performed at SCAPA using tape drive - see talk by M. Alderton - Wed 2.20 in Tycho
- LhARA dedicated beamline planned for July 2023 for parametric source optimisation
- Diagnostic & hardware development ongoing

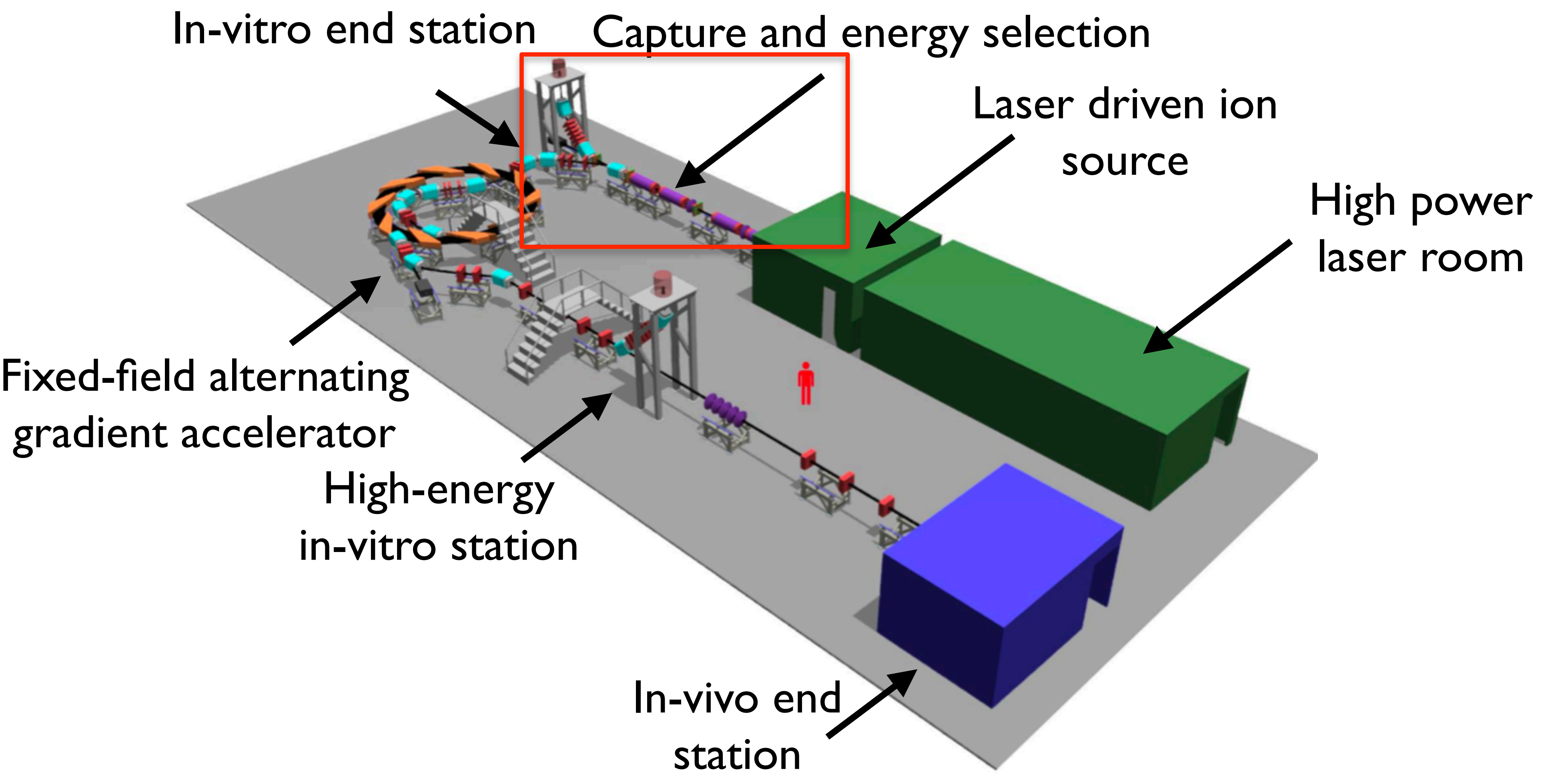
Experimental R&D programme for LhARA ion source - Zhi laser

- **Development of high repetition ion acceleration facility at ICL**
  - Driven by in-house 100 Hz, ~100 mJ, 40 fs laser, to address issues related to high repetition rate
  - High repetition ion source commissioning experiments have now begun

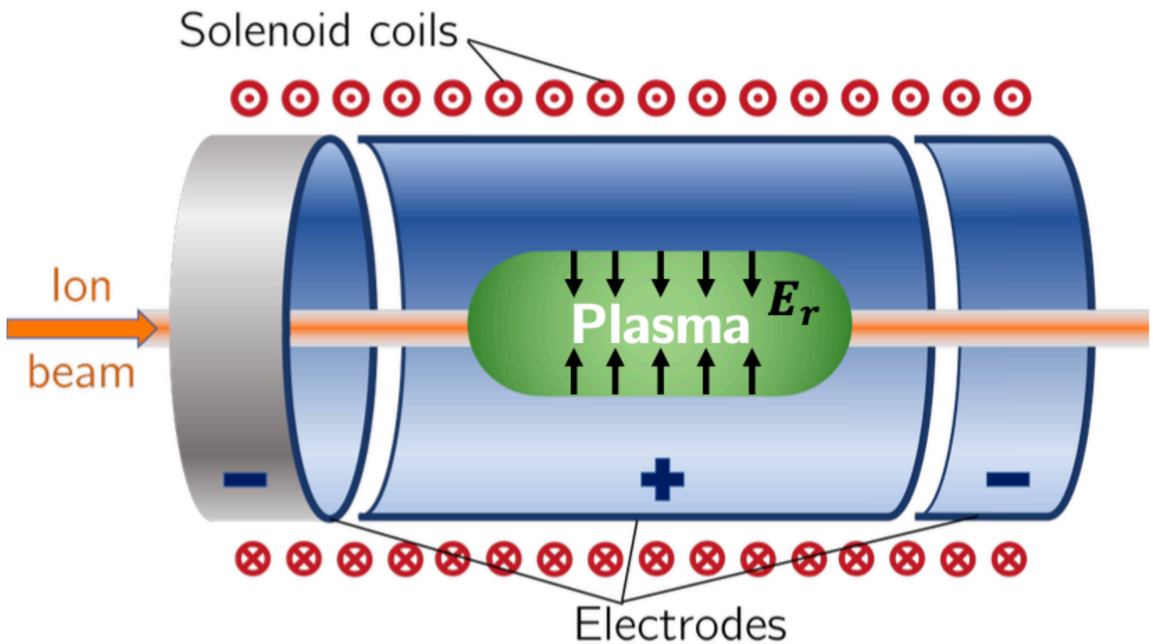




LhARA beamline overview

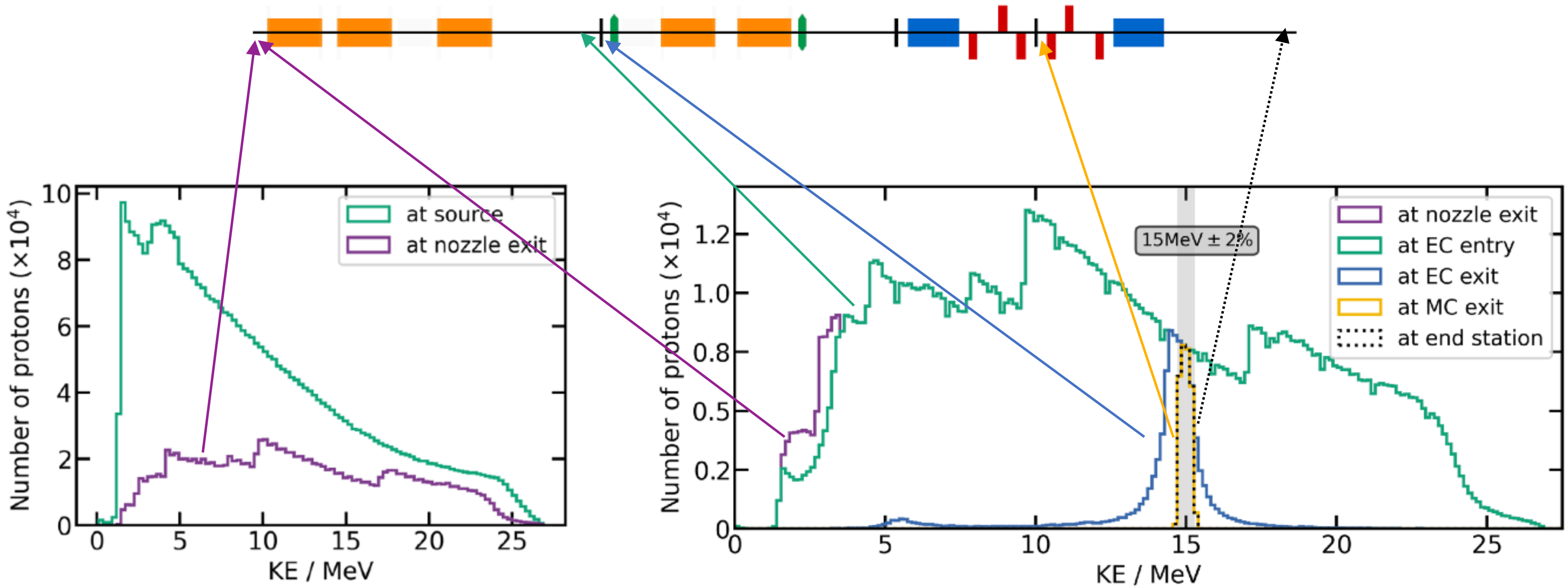


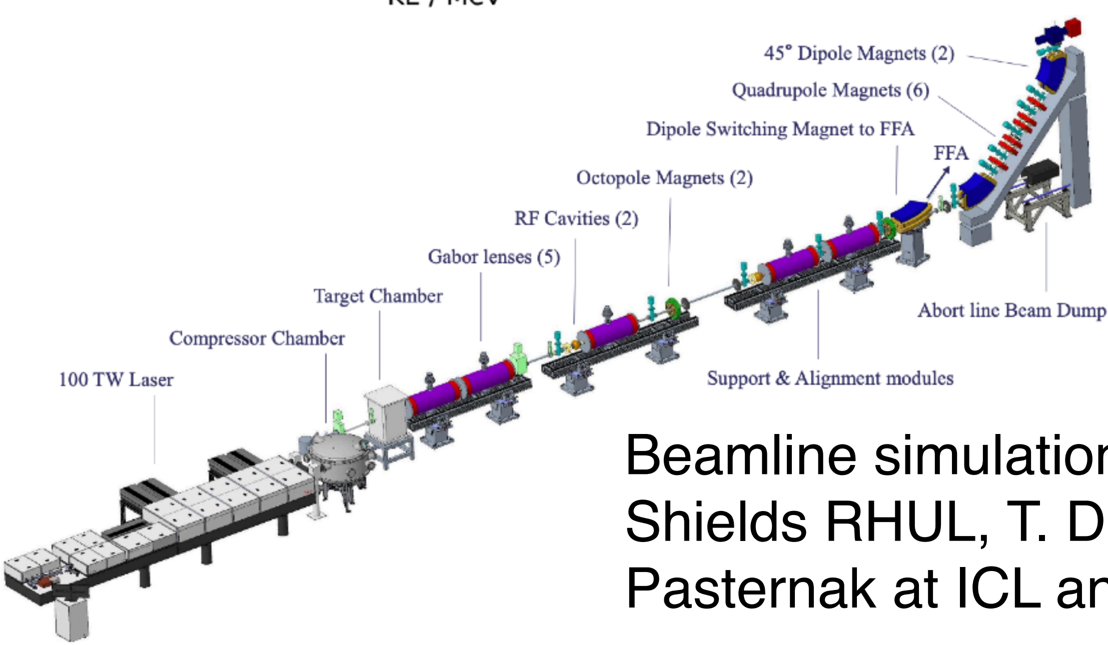
Ion capture and focused obtained using innovative Gabor lenses



- Focus in both planes simultaneously
- Can operate continuously
- Energy-dependent focusing strength
- Easily tunable focusing power
- Cost effective solenoid alternative - requires orders of magnitude lower B-field than equivalent solenoid

Ion capture and focused obtained using innovative Gabor lenses

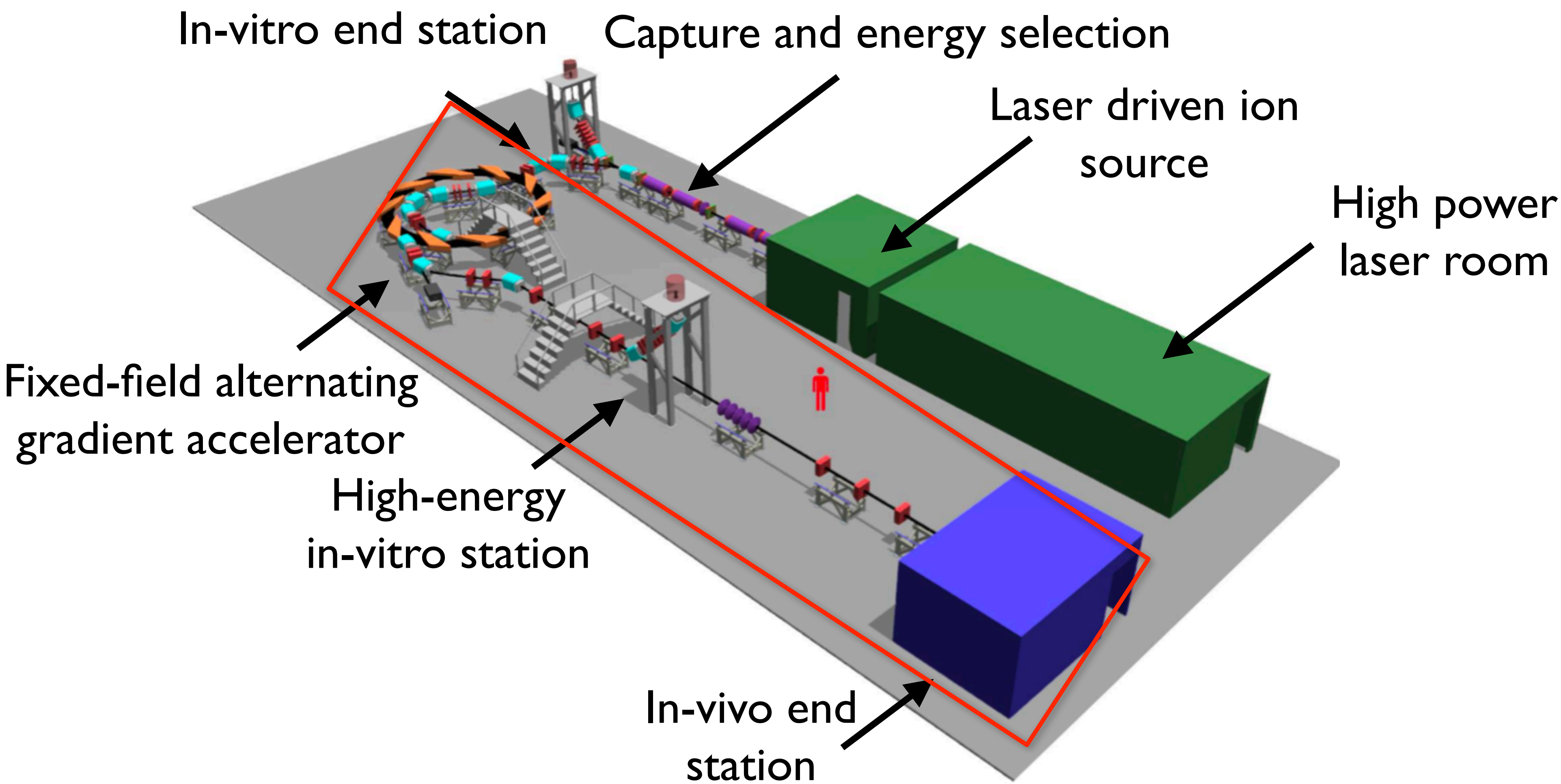




Beamline modelling shows high transmission of target ions to low-energy in vitro end station

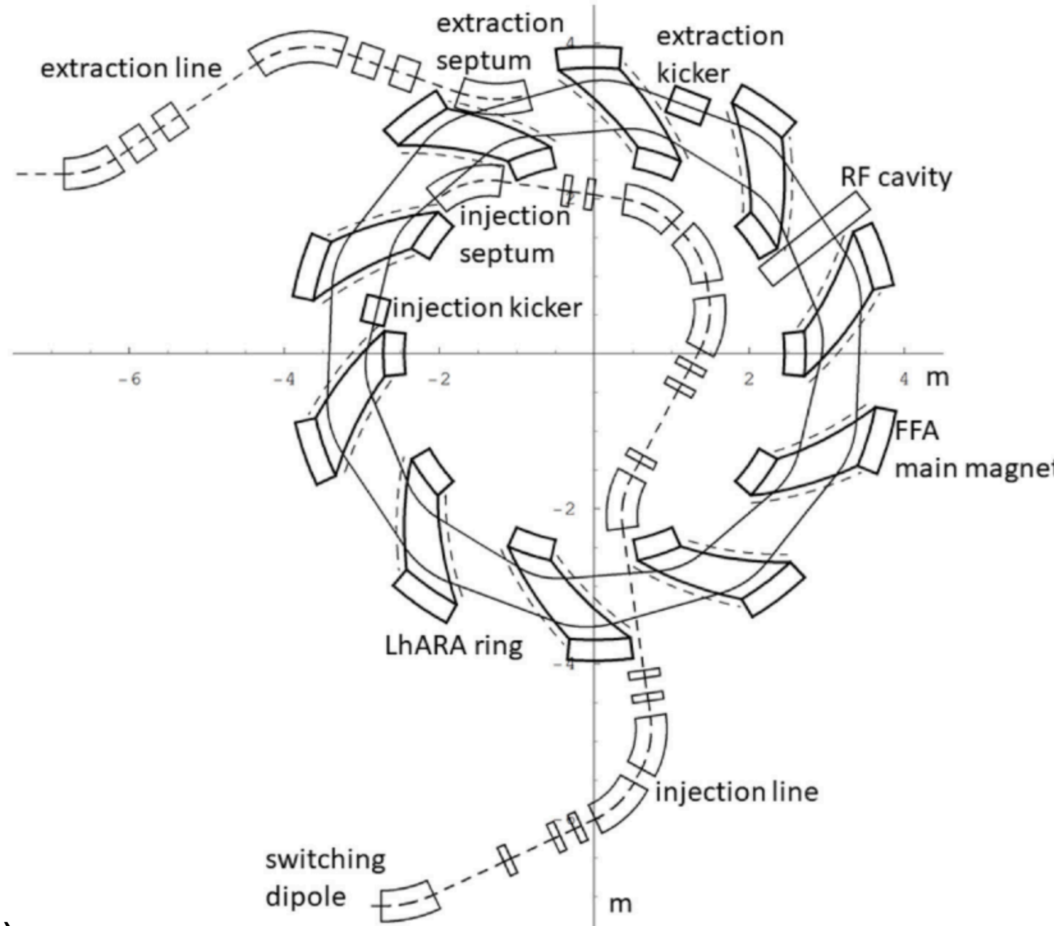
Beamline simulations and design - W. Shields RHUL, T. Dascalu, K. Long, J. Pasternak at ICL and others

LhARA beamline overview



LhARA Stage 2 - higher ion energies

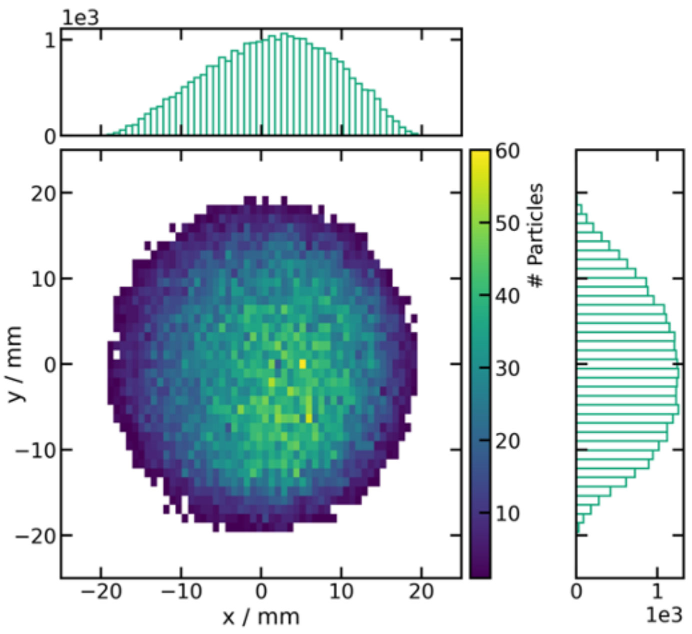
- Fixed-field alternating-gradient accelerator (FFA):
  - Compact, flexible solution:
    - Multiple ion species
    - Variable energy extraction
    - High repetition rate (rapid acceleration)
    - Large acceptance
  - Successfully demonstrated:
    - Proof of principle at KEK
    - Machines at KURNS
    - Non-scaling PofP EMMA (DL)
- **Up to 127 MeV protons, 33 MeV/u C**
- Delivery to *in vitro* and *in vivo* end stations currently being investigated



Predictions for final beam delivery

	12 MeV protons	15 MeV protons	127 MeV protons	33.4 MeV/u carbon
Dose per pulse	7.1 Gy	12.8 Gy	15.6 Gy	73.0 Gy
Instantaneous dose rate	1.0×10^9 Gy/s	1.8×10^9 Gy/s	3.8×10^8 Gy/s	9.7×10^8 Gy/s
Average dose rate	71 Gy/s	128 Gy/s	156 Gy/s	730 Gy/s

These estimates are based on Monte Carlo simulations using a bunch length of 7 ns for 12 and 15 MeV proton beams, 41.5 ns for the 127 MeV proton beam and 75.2 ns for the 33.4 MeV/u carbon beam. The average dose rate is based on the 10 Hz repetition rate of the laser source.



- Stage 1 delivery of protons has been designed using realistic source parameters to deliver ~cm scale beam
- Deliverable dose rates are sufficient for FLASH radiobiology studies

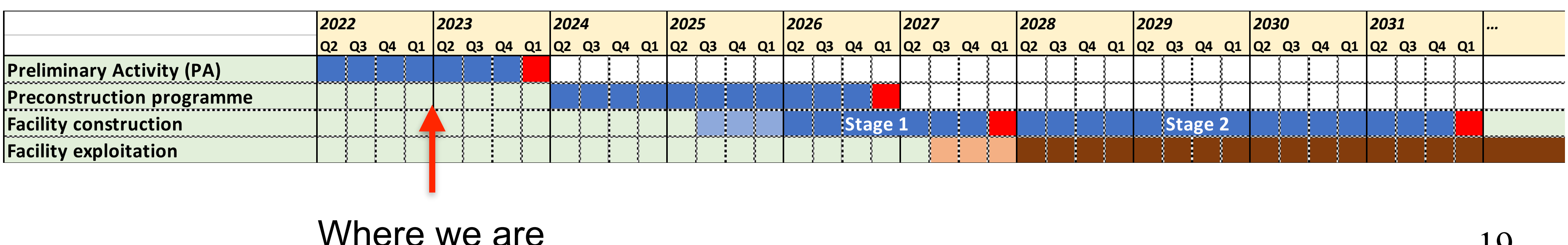
Currently designing LhARA for the “Ion Therapy Research Facility”

Ion Therapy Research Facility (ITRF):

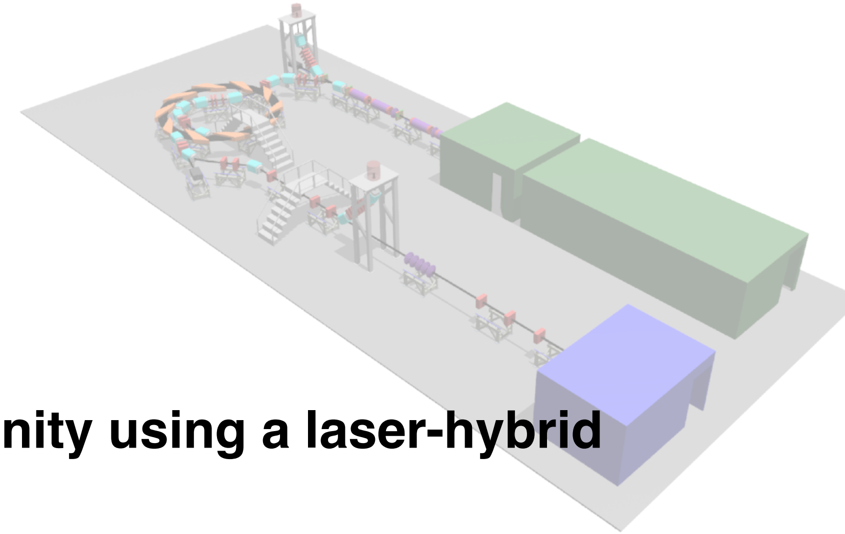
- Compact, single-site national research infrastructure delivering ions (protons through oxygen and beyond) at high dose rates (FLASH)
- Energies sufficient for both in-vitro and in-vivo studies
- Facility will answer cancer biology questions for better clinical care

Now performing critical R&D to show suitability of LhARA for ITRF

- 2 year preliminary activity underway
- Working towards completion of Conceptual Design Review in 2024



Summary



- **LhARA will serve the radiobiology community using a laser-hybrid approach**
  - Overcome dose-rate limitations of present and ion beam therapy sources
  - Deliver a range of ion species, energies, dose, dose-rate and time and spatial distribution
  - Used in an automated, triggerable system
- **The LhARA collaboration working with the ITRF to develop a Conceptual Design Review and do mission critical R&D**
  - Prove the novel laser-hybrid system in operation
  - Design a facility capable of delivering broad radiation biology programme
  - Create the novel capabilities required to transform proton and ion therapy

LhARA
Laser-hybrid Accelerator for Radiobiological Applications