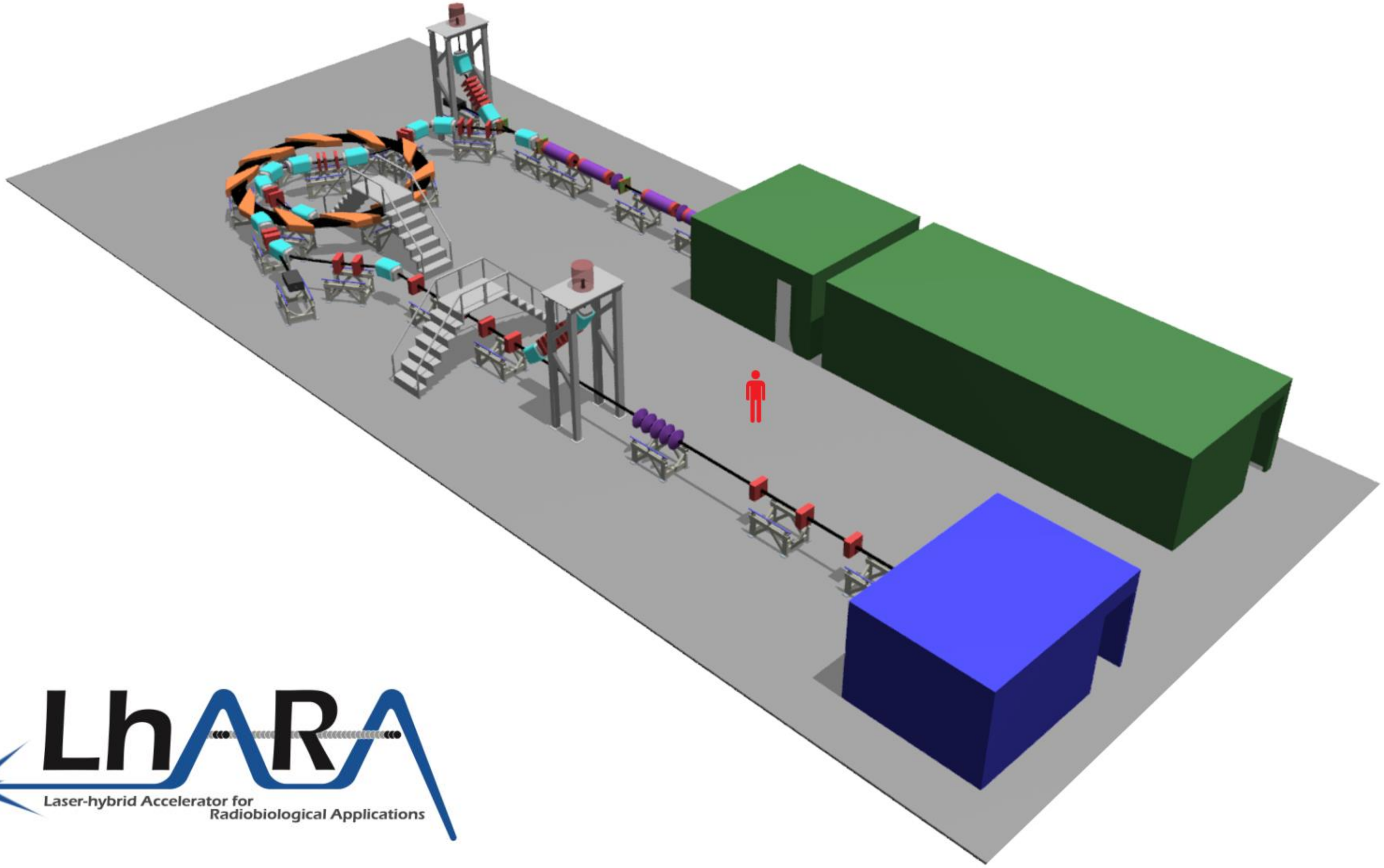
Imperial College London

CCAP Centre for the Clinical Application of Particles

The Laser-hybrid Accelerator for Radiobiological Applications (LhARA)



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for the LhARA collaboration

Imperial College London
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APS April Meeting, *9th April 2022*

LhARA Laser-hybrid Accelerator for Radiobiological Applications

Motivation

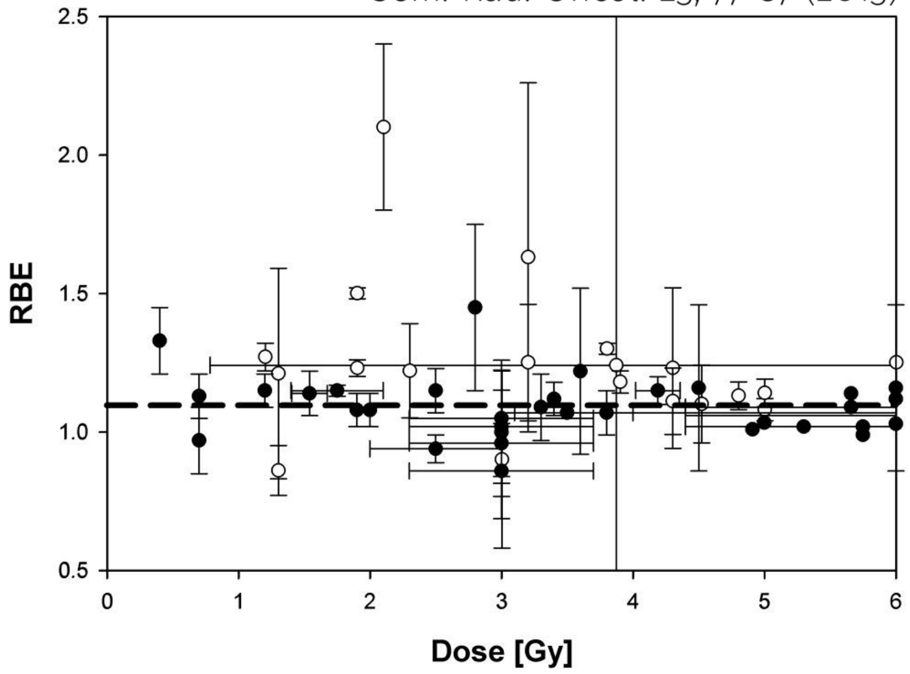
The challenge in radiotherapy

Growing global requirement → Scale-up in provision is essential → Development of **new technologies and cost-effective systems**

Essential: systematic radiobiology programme

- **Relative Biological Effectiveness**
  - A **range of RBE values** *in vitro* and *in vivo* have been reported
  - A value of **1.1 is used clinically (protons)**
  - Effective values are used for C^{6+}
  - Known to **depend on many factors**, including:
    - Energy
    - Ion species
    - Dose
    - Dose rate
    - Dose spatial distribution
    - Tissue type

Paganetti and van Luijk, Sem. Rad. Oncol. 23, 77-87 (2013)



The collaboration

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

Swansea University
Prifysgol Abertawe

University of Birmingham | Positron Imaging Centre

University of Birmingham | Cyclotron Facility

The Cockcroft Institute of Accelerator Science and Technology

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

Corerain
鲲云科技

The Rosalind Franklin Institute

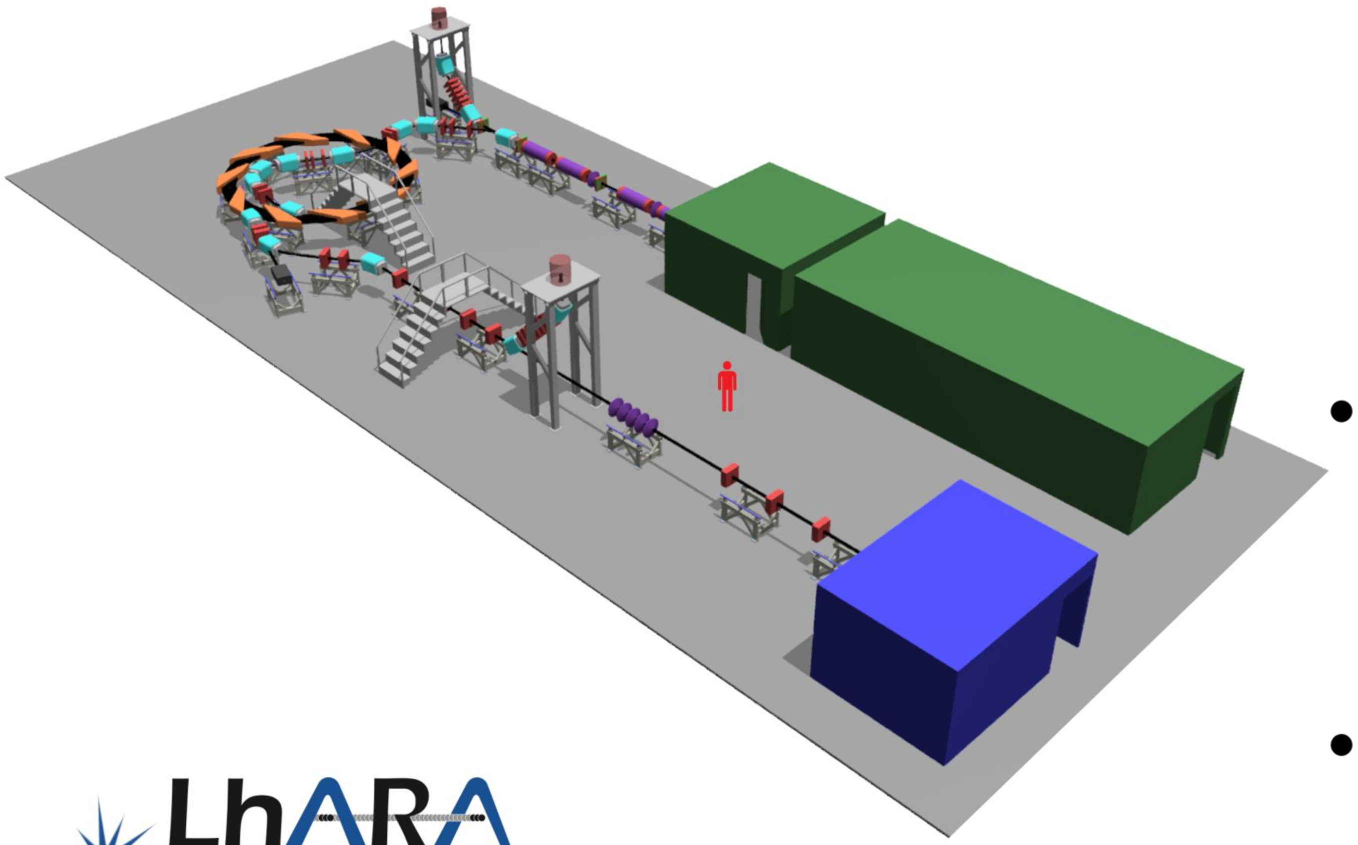
NPL National Physical Laboratory

LEO Cancer Care

MAXELER Technologies
Maximum Performance Computing

LhARA
Laser-hybrid Accelerator for Radiobiological Applications

Laser-hybrid approach



LhARA
Laser-hybrid Accelerator for Radiobiological Applications

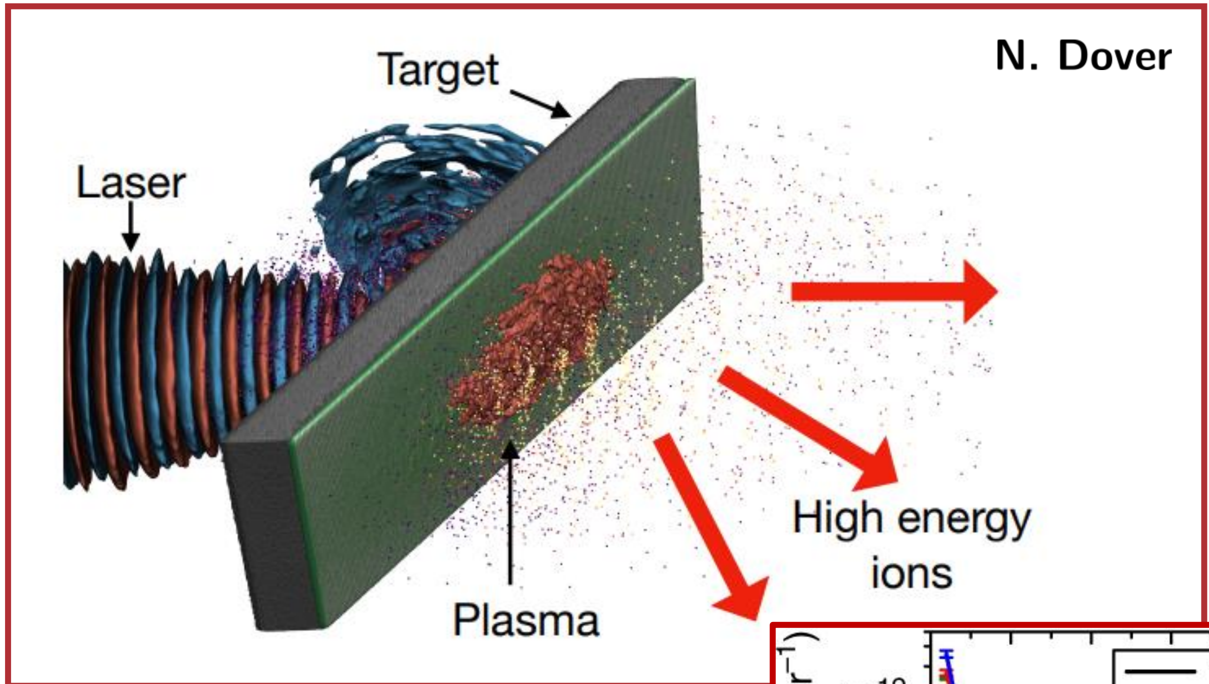
arXiv:2006.00493

A novel, hybrid approach:

- **Laser-driven, high-flux proton/ion source**
  - Overcome instantaneous dose-rate limitations (capture at > 10 MeV)
  - 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

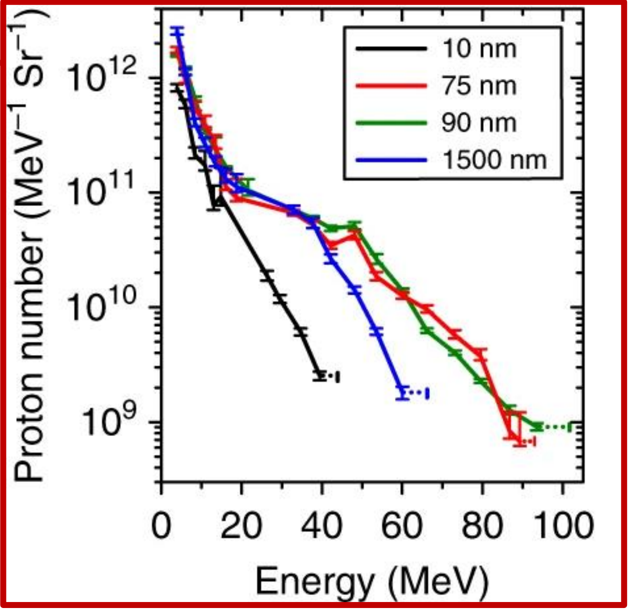
Front. Phys., 29 September 2020; DOI: 10.3389/fphy.2020.567738

Laser-driven source



Well understood technique:

target normal sheath acceleration (TNSA)



Higginson et al.,
Nat. Commun. 9, 724 (2018)

Protons (and ions) produced at "high energy"

e.g. $15\,\text{MeV} \rightarrow \mathbf{250}\times$ energy of conventional proton source

reduce impact of space-charge → **high instantaneous dose-rate**

Small emittance & short duration

rms emittance $\sim 4 \times 10^{-7}\,\pi$ m-rad; ps at source

Initially approximately charge neutral

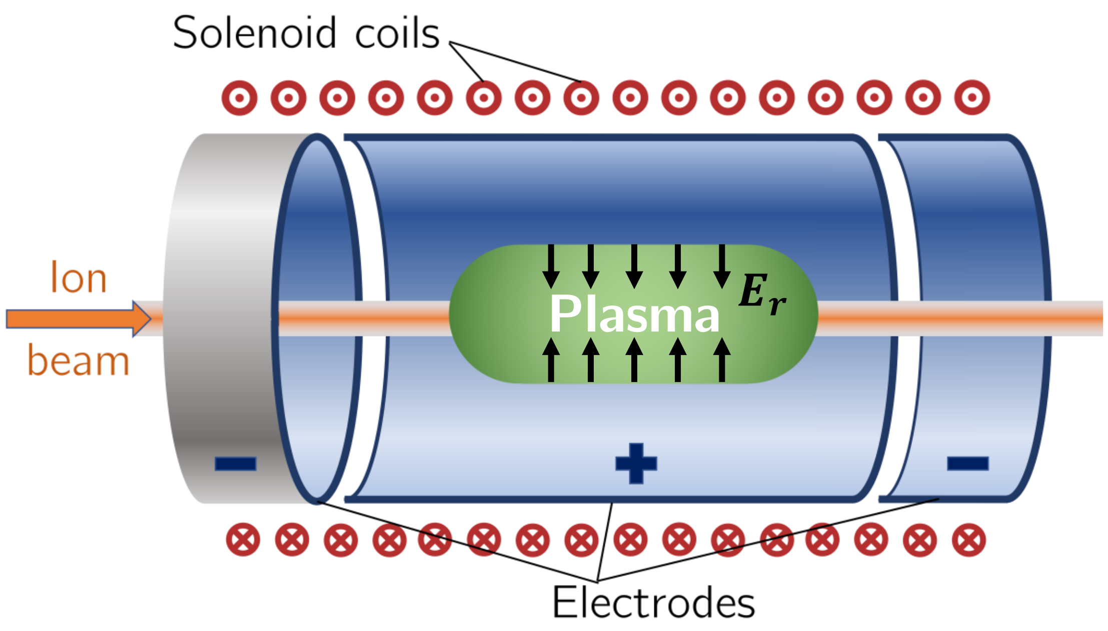
Triggerable and on-demand

Critical issue:

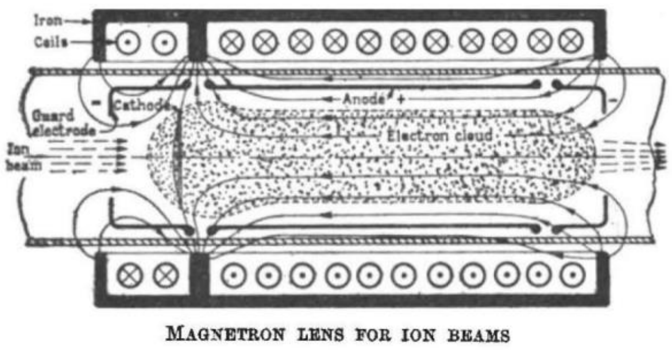
efficient capture of **highly divergent, broadband energy** proton/ion flux

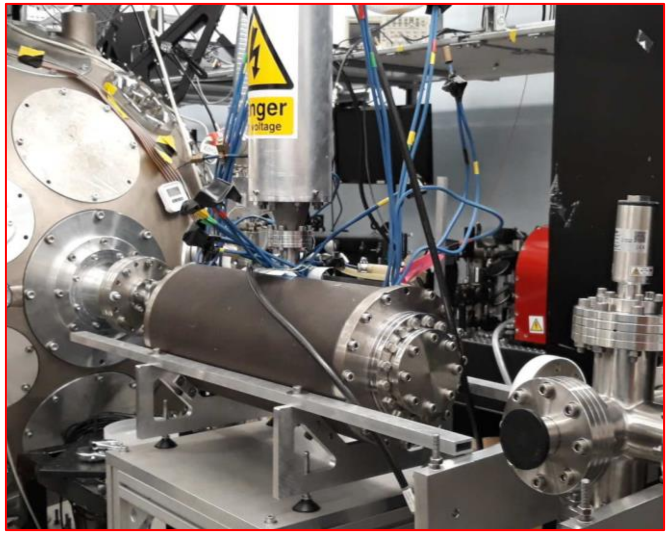
Plasma (Gabor) lenses for strong focusing

Penning-Malmberg trap design



Gabor, Nature 160, 89-90 (1947)





$$B_{GPL} = B_{sol}\sqrt{\frac{m_e}{m_{ion}}Z}$$

Pozimski, Laser Part. Beams 31, 723-733 (2013)

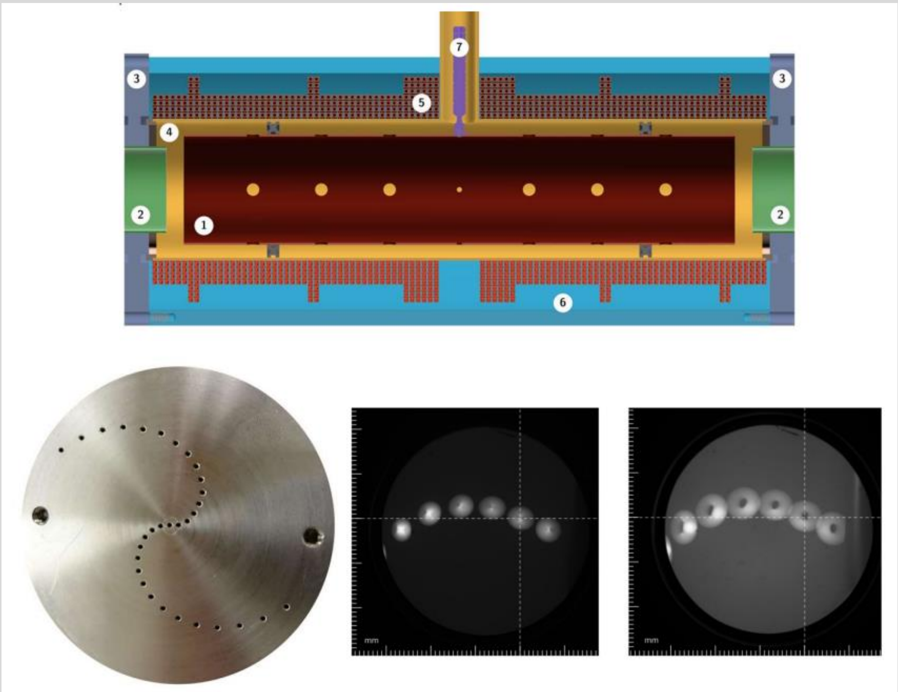
- Focus in both planes simultaneously
- Energy dependent focusing strength
- Cost effective alternative to solenoids

Baseline solution for capture and focusing

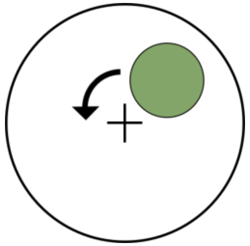
- Requires high-vacuum to operate
- Can be replaced by solenoids, if needed.

Development of a Gabor lens for LhARA

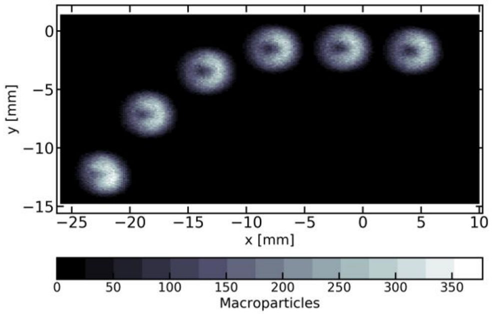
Nonnenmacher et al., Appl. Sci. 11(10), 4357 (2021)



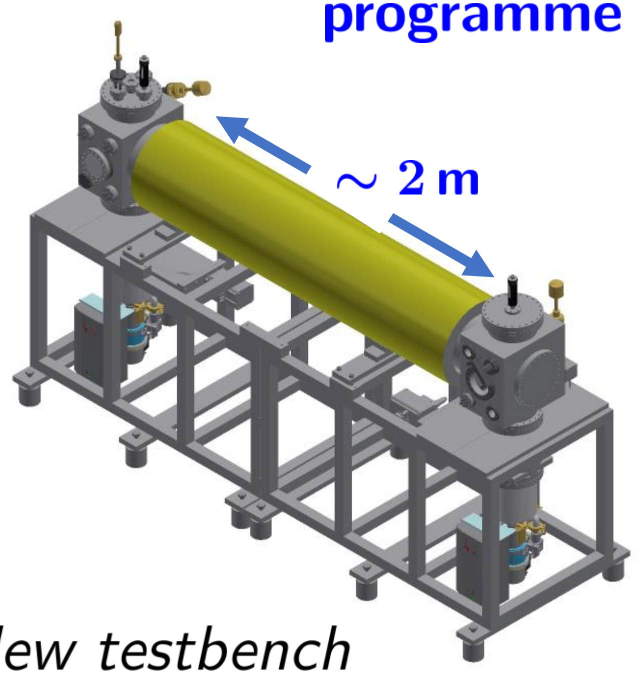
Plasma coherent rotation



+ beam-tracking



"Preliminary Phase" programme



New testbench

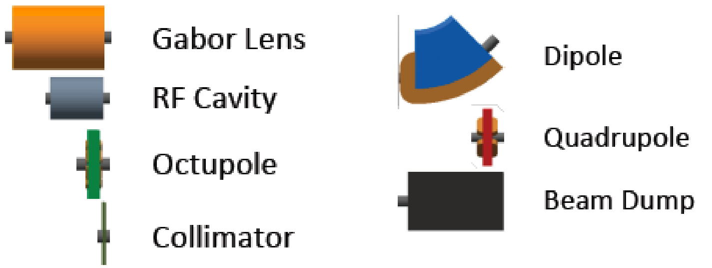
produce & study larger plasmas

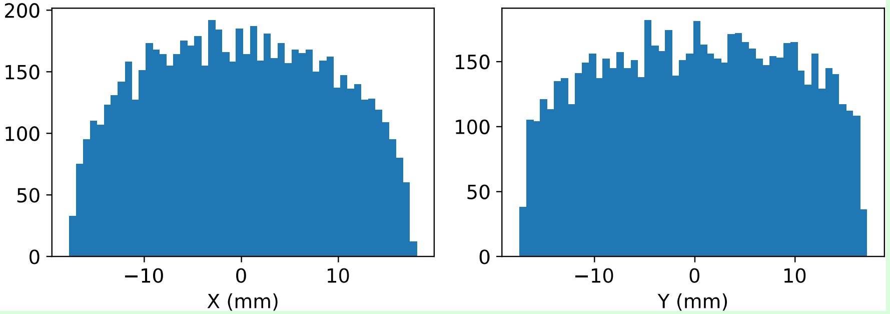
$r_w = 10\,\text{cm} \qquad L_p \sim 1\,\text{m}$

$\phi_{sc} \sim 2\text{–}10\,\text{kV}$

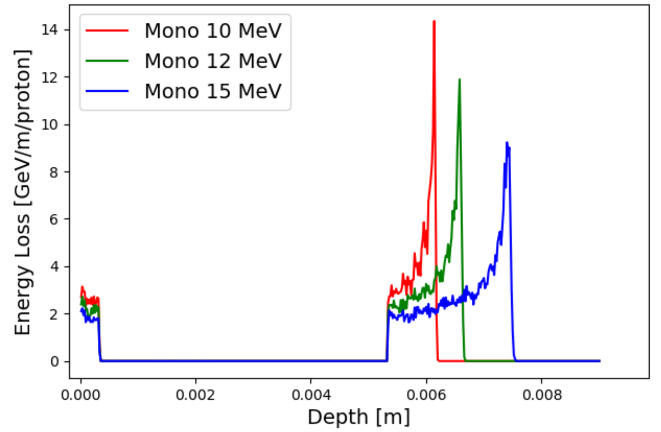
- Anomalous focusing observed in test of a lens prototype with proton beams
- Observations were modelled based on diocotron instability
- Intensive 3D PIC simulation effort to inform a stable solution (to mitigate plasma instabilities)

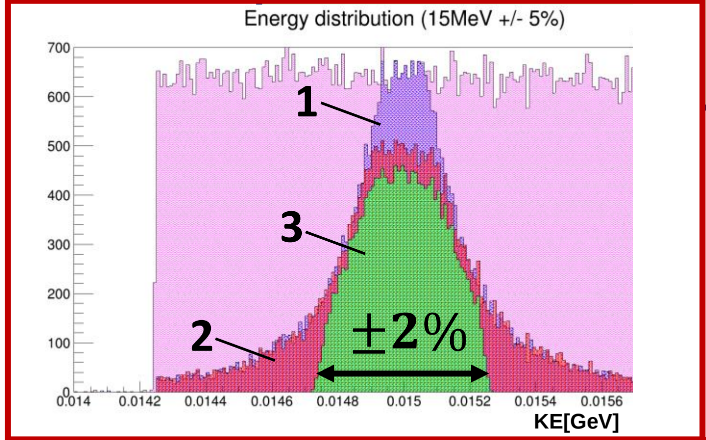
LhARA Stage 1 for *in-vitro* studies



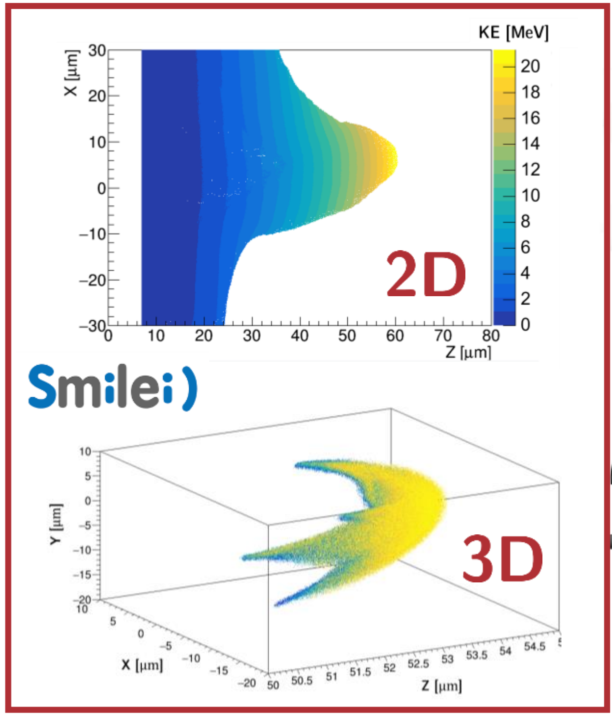


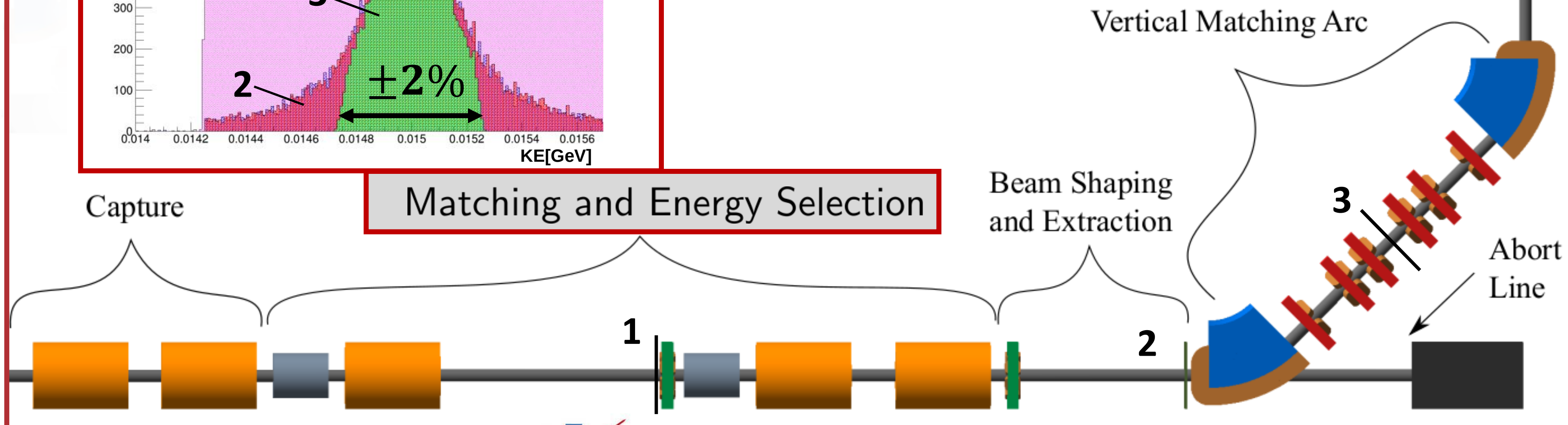
Dose uniformity at end station





H.T.Lau, PhD Thesis,
Imperial College London (2022)





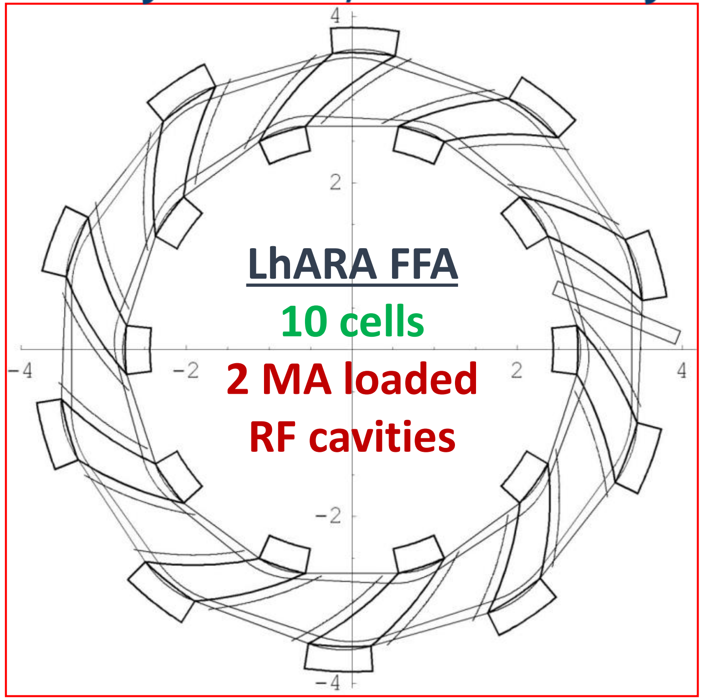
Beam Delivery Simulation

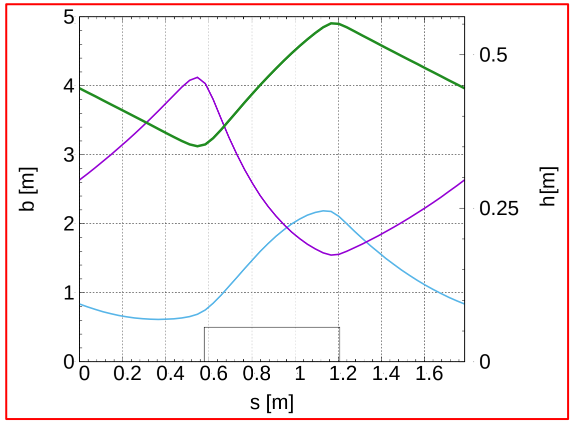
Rapid, flexible acceleration for Stage 2

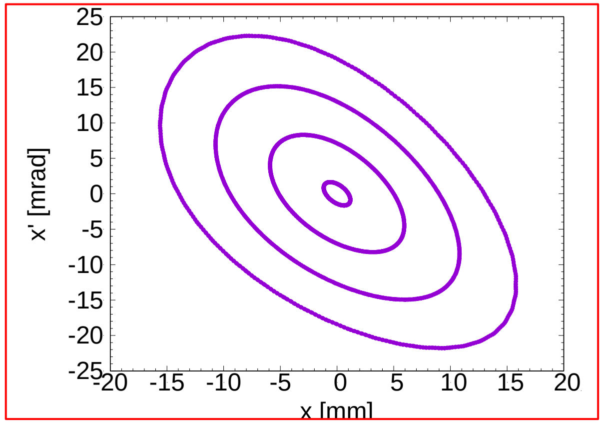
- **Fixed-field alternating-gradient accelerator (FFA):**
  - Invented in 1950s
    - Kolomensky, Okhawa, Symon
  - Compact, flexible solution:
    - Multiple ion species
    - Variable energy extraction
    - High repetition rate (rapid acceleration)
    - Large acceptance
  - Successfully demonstrated:
    - Proof of principle at KEK
    - Machines at KURNS
    - Non-scaling pop., EMMA, at Daresbury Lab., UK

- Spiral scaling FFA shows a good performance in tracking studies.

Aymar et al., Frontiers in Physics, 432 (2020)

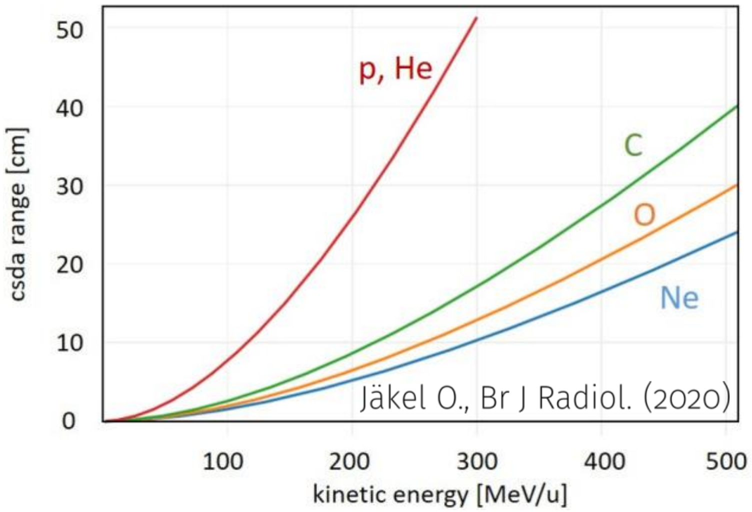






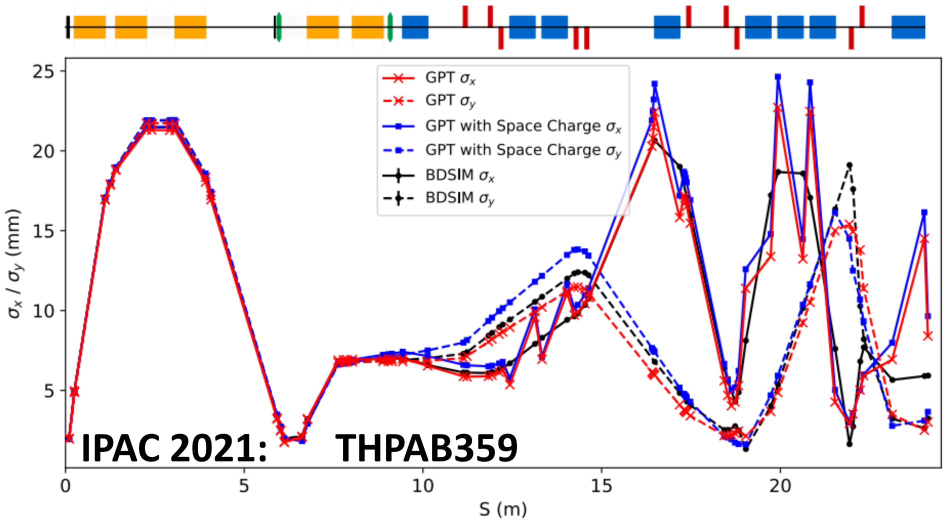
FFA in LhARA Stage 2

- **Baseline: $\times 3$ increase in momentum:**
  - $15\,\mathrm{MeV}$ protons accelerated to $127\,\mathrm{MeV}$
  - $3.8\,\mathrm{MeV/u}$ carbon 6+ ions accelerated to $34\,\mathrm{MeV/u}$



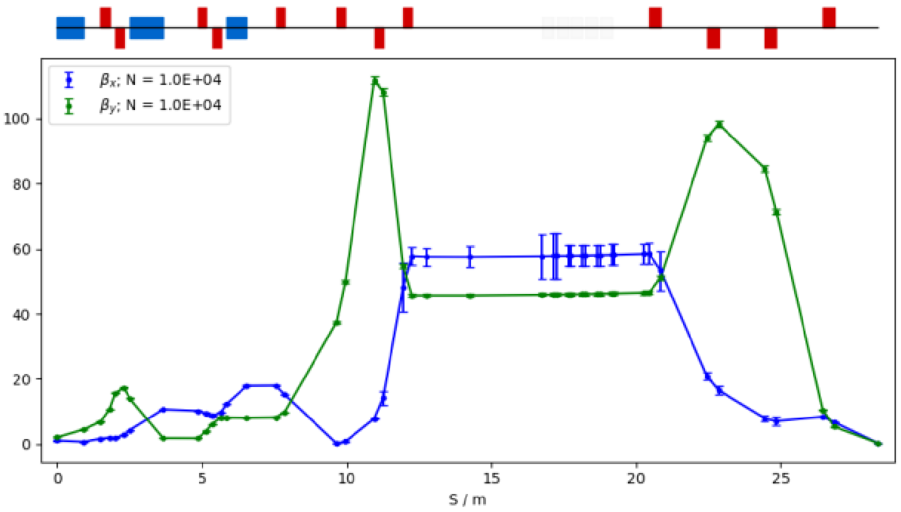
- Feasible ring injection, extraction and beam transport to the end stations have been designed.

Injection into FFA



IPAC 2021: THPAB359

To in vivo end-station



Essential R&D:
main FFA magnet

+ technology transfer for Magnetic Alloy (MA) loaded RF cavities

LhARA performance

Aymar et al., *Frontiers in Physics* (2020):432

Doses and dose rates

LhARA performance summary

	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

Worked example: FLASH

Conventional regime: ~ 2 Gy/min

FLASH regime: ≥ 40 Gy/s

Evidence of normal-tissue sparing while tumour-kill probability is maintained: i.e. **enhanced therapeutic window**

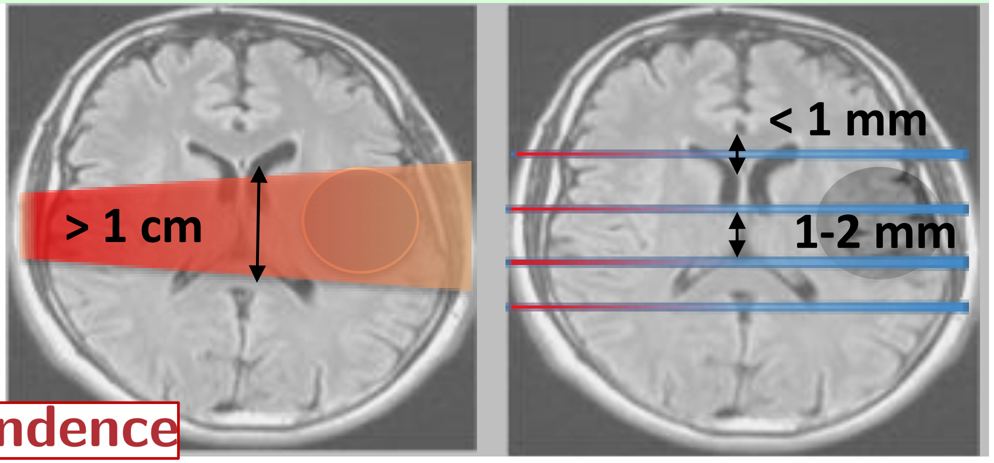
Temporal dependence

Worked example: minibeams

Standard RT: ≥ 1 cm, laterally homogeneous

Minibeam regime: < 1 mm diameter

Increase of **normal tissue tolerance**



Spatial dependence

Conclusions

- **Laser-driven sources are disruptive technologies...**
  - with the potential to drive a step-change in clinical capability.
- **Laser-hybrid approach has potential to:**
  - Overcome dose-rate limitations of present proton and ion beam therapy sources.
  - Deliver a uniquely flexible facility:
    - **Range of ion species, energy, dose, dose-rate, time and spatial distribution**
- **LhARA design is flexible and compact.**
  - Good performance in tracking studies.
  - Feasible FFA ring, injection, extraction, and beam transport designed.
- **Collaboration and UK's STFC labs now developing "Preliminary Phase" programme for the opportunity to:**
  - Prove the novel laser-hybrid systems in operation,
  - Contribute to the study of the biophysics of charged-particle beams.