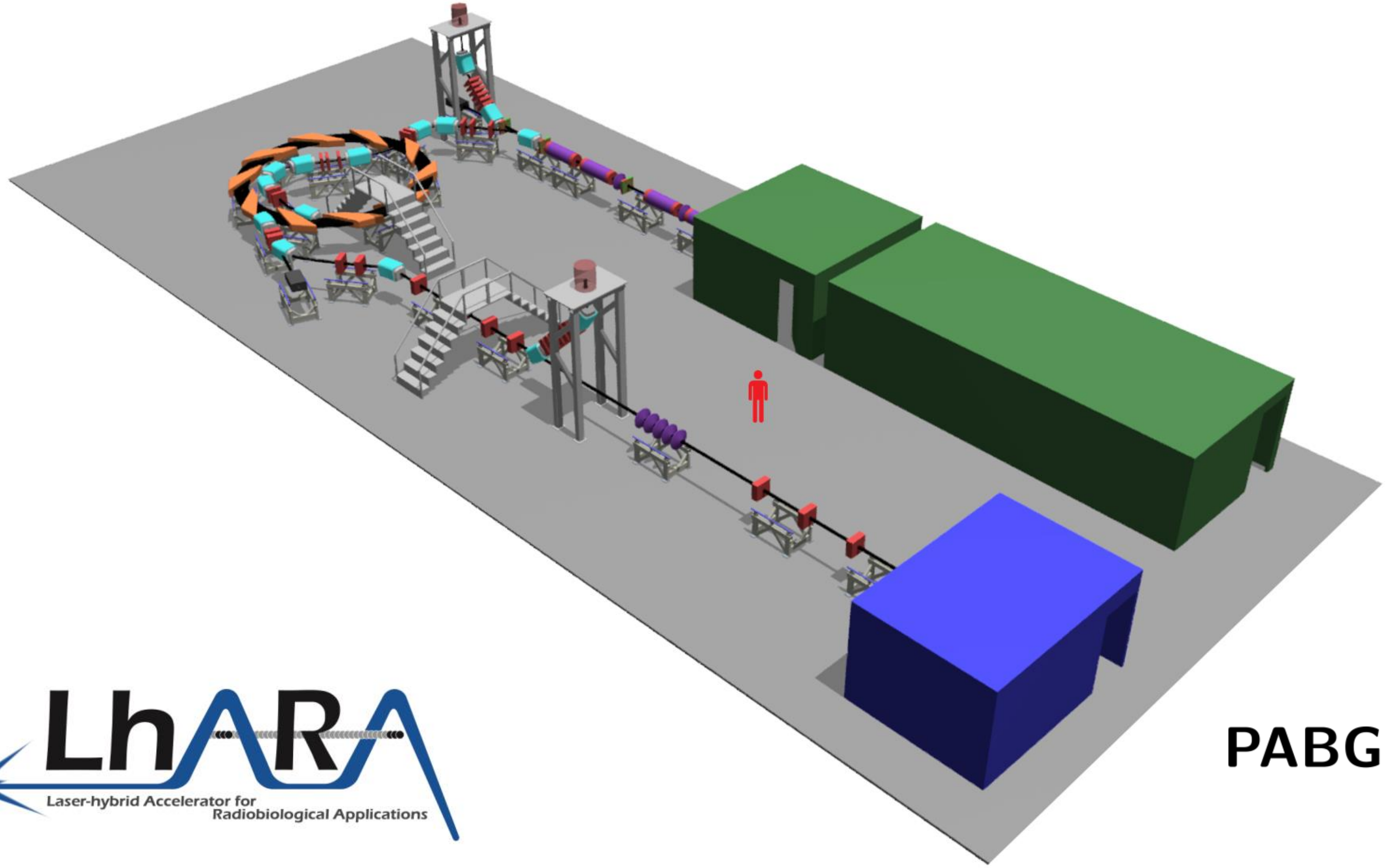
Imperial College London

Centre for the Clinical Application of Particles

The Laser-hybrid Accelerator for Radiobiological Applications (LhARA)



Titus-Stefan Dascalu

for the LhARA collaboration

Imperial College London

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PABG Annual Conference, *25th July 2022*

Laser-hybrid Accelerator for Radiobiological Applications

The collaboration

Partners

University · Clinical · Laboratory · Industry · Accelerator

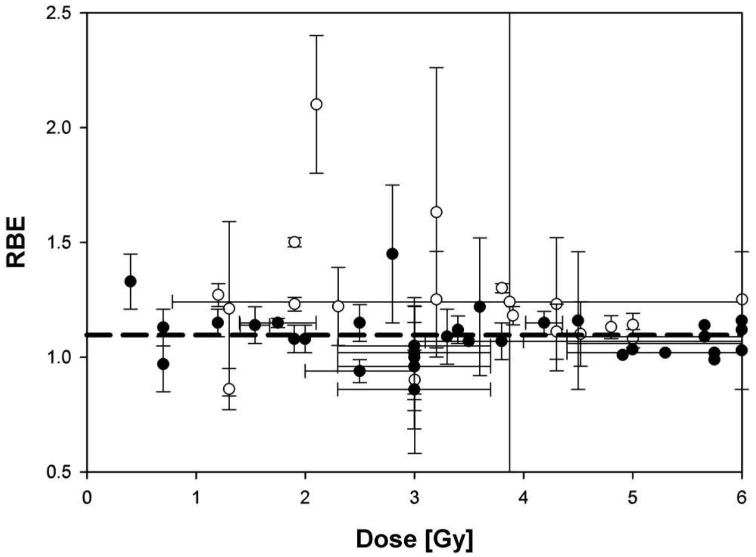
Mission

- **Deliver a systematic radiobiology programme**
- **Prove the laser-hybrid approach**
- **Lay the foundations for transformative ion-beam therapy**
  - Highly automated, patient-specific treatment

Motivation: strong case for...

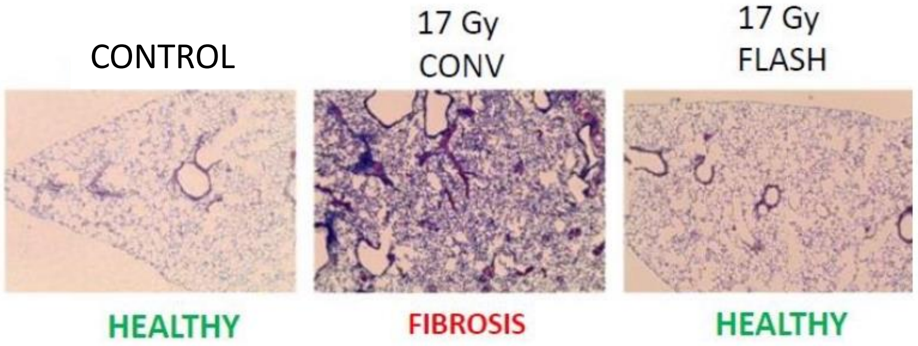
Systematic study of radiobiology

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



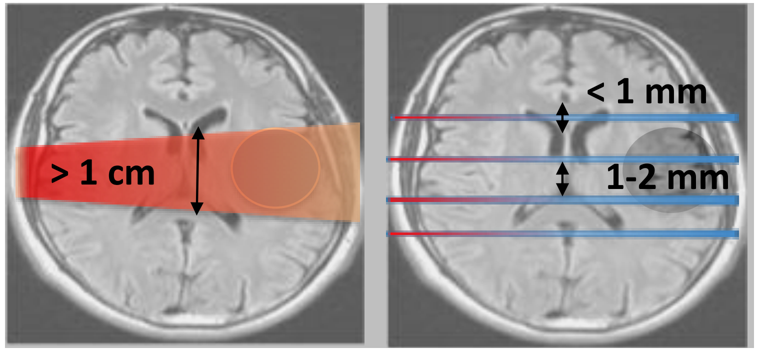
Novel beams for radiobiology

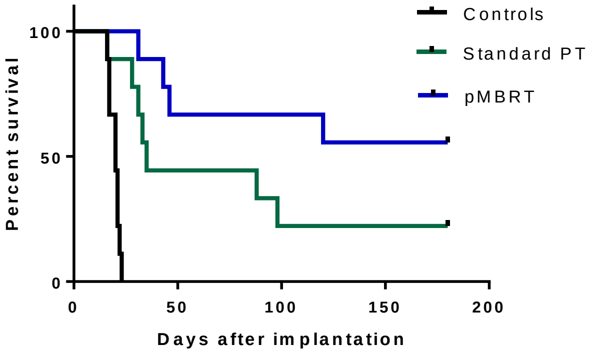
Favaudon et al., Sci. Transl. Med. 6, 245 (2014)
Prezado et al., Red Journal 2, 104 (2019)



FLASH

minibeams

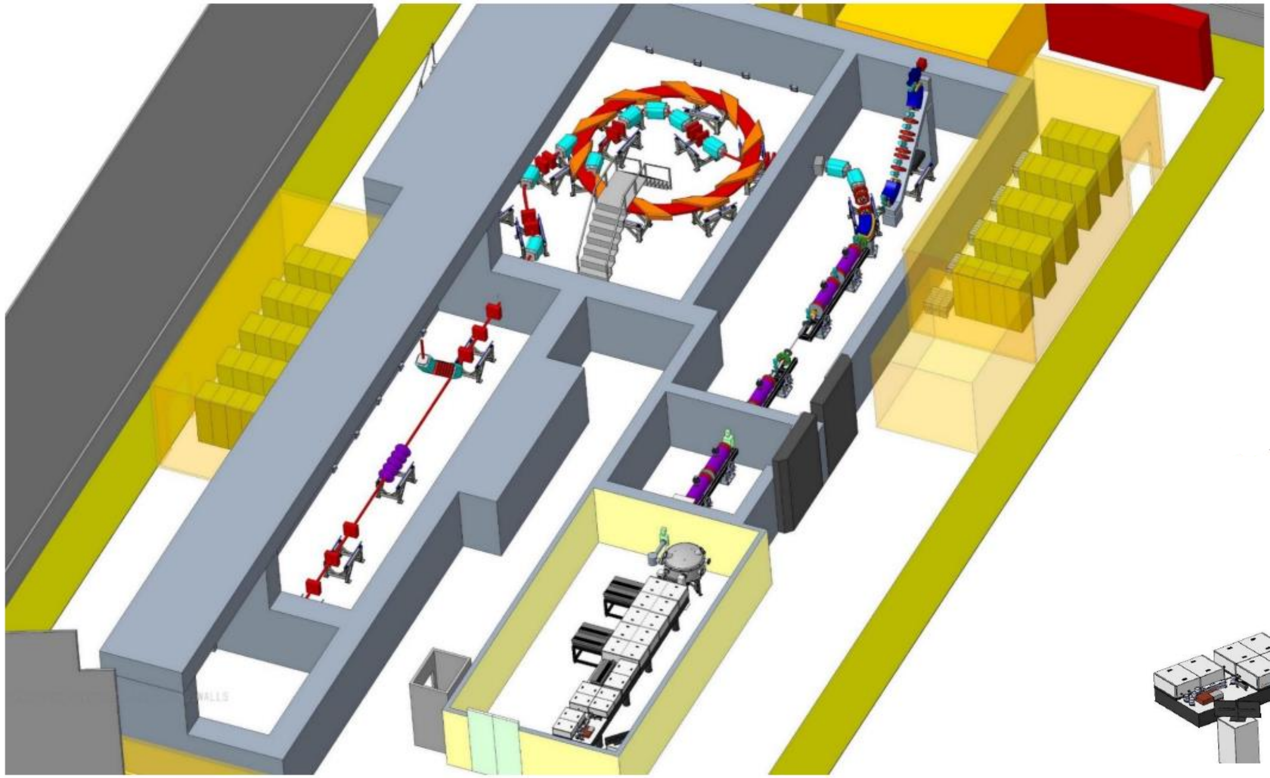




Transformative ion-beam therapy

- Radiotherapy (RT) used in $\sim 50\%$ of cancer patients and involved in 40% of cancer cures
- 17 million new cases per year at present $\Longrightarrow$ 27.5 million new cases per year by 2040
- Nearly 70% of patients globally do not have access to RT (facilities predominantly located in high-income countries)

Laser-hybrid approach



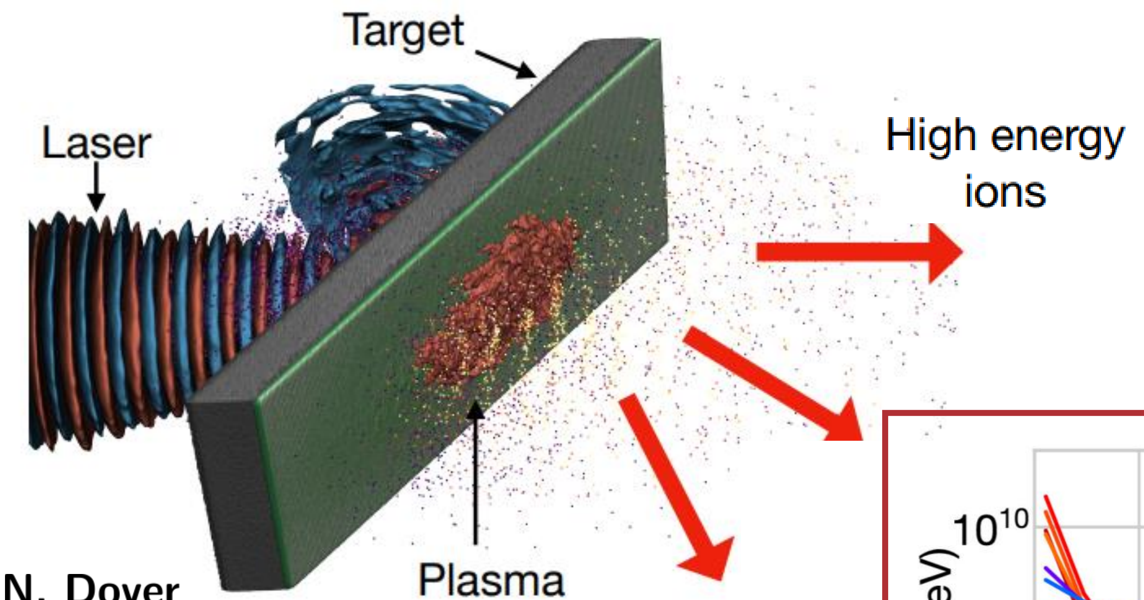
Front. Phys., 29 September 2020; DOI: 10.3389/fphy.2020.567738

LhARA: R&D proposal for the preliminary, pre-construction phases (link)

- **Laser-driven, high-flux proton/ion source**
  - multiple ion species & ultra-high dose rate
- **Electron-plasma lenses for capture and beam focusing**
- **Fast, flexible post-acceleration with an FFA**
  - Variable energy
    - Protons: 15–127 MeV
    - Ions: 5–34 MeV/u

The laser-driven source

target normal sheath acceleration (TNSA)



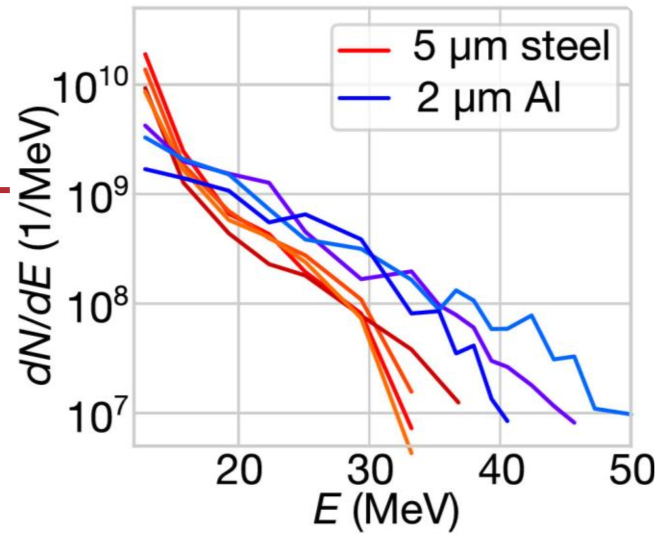
N. Dover

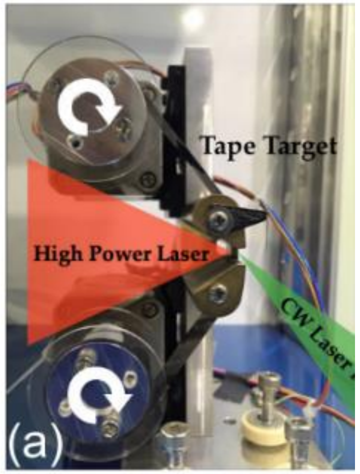
Initially approximately charge neutral

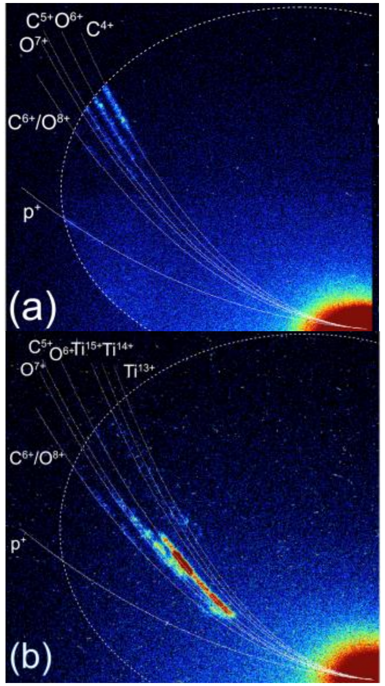
Protons (and ions) produced at "high energy"

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

Dover et al.,
High Energy Density Phys. 37, 100847 (2020)







Kondo et al.,
Crystals 10, 837 (2020)

High brightness

$10^{11} - 10^{13}$ particles/shot

Small emittance & short duration

rms emittance $\sim 0.01\pi$ mm-mrad

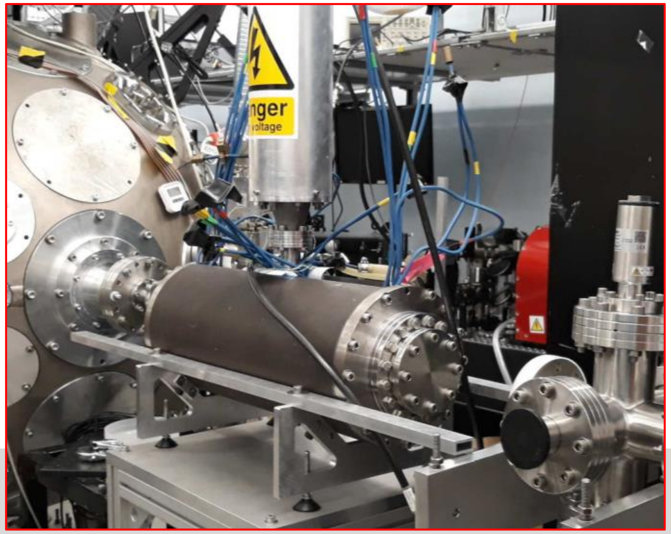
ps at source

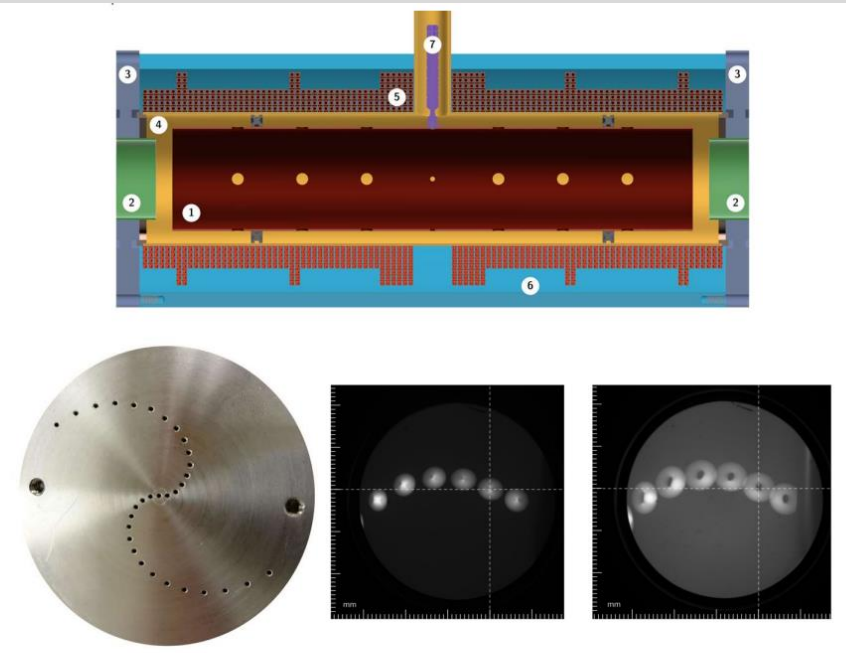
Triggerable and on-demand

Typically broadband energy

Highly divergent ($>10°$)

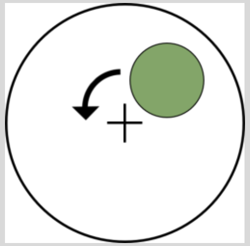
Development of a plasma lens for LhARA



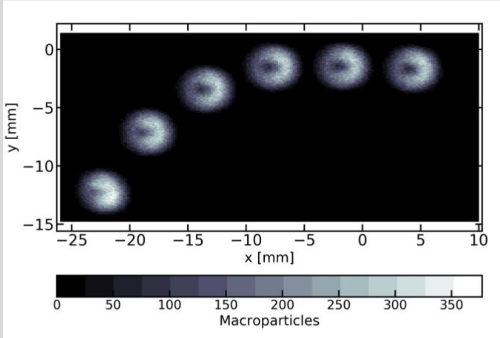


Nonnenmacher et al., Appl. Sci. 11(10), 4357 (2021)

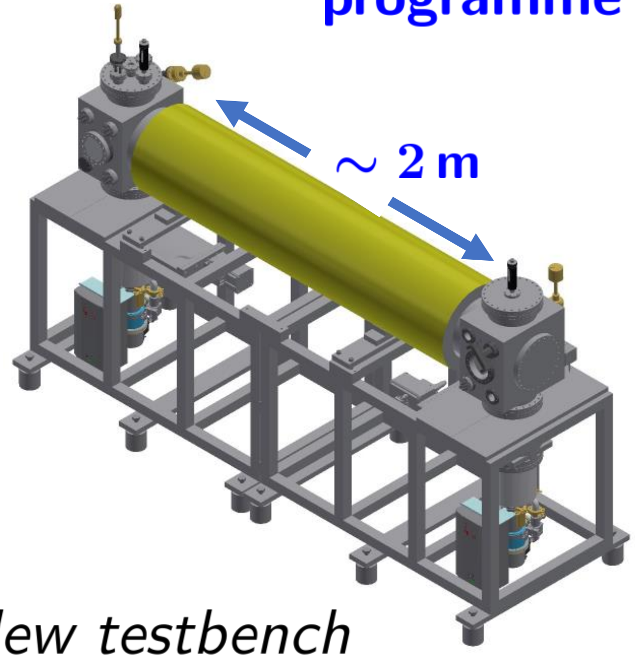
Plasma coherent rotation



+ beam-tracking



"Preliminary Phase" programme



New testbench

produce & study larger plasmas

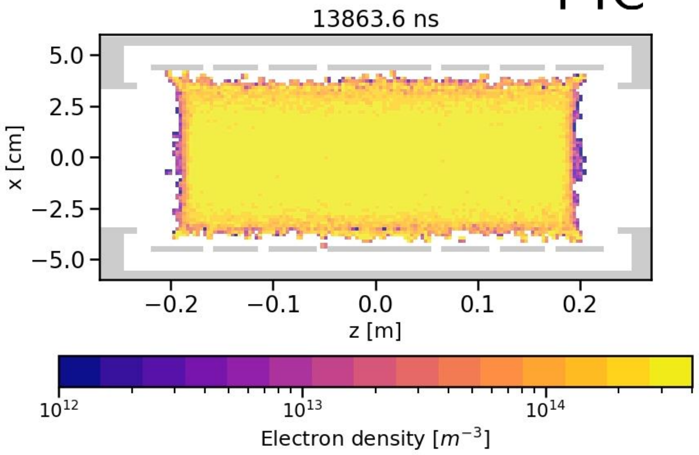
$r_w = 10\,\text{cm}$ $\quad L_p \sim 1\,\text{m}$

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

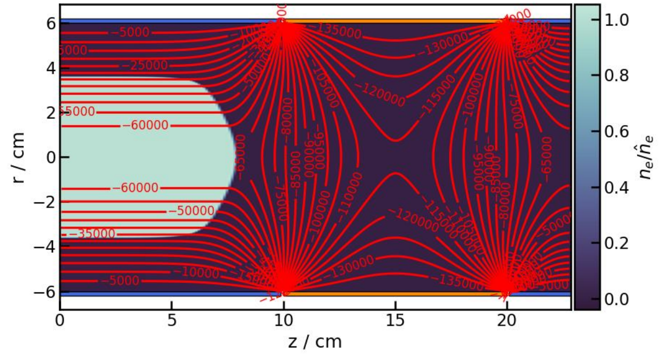
Development of the capture section

Plasma simulations

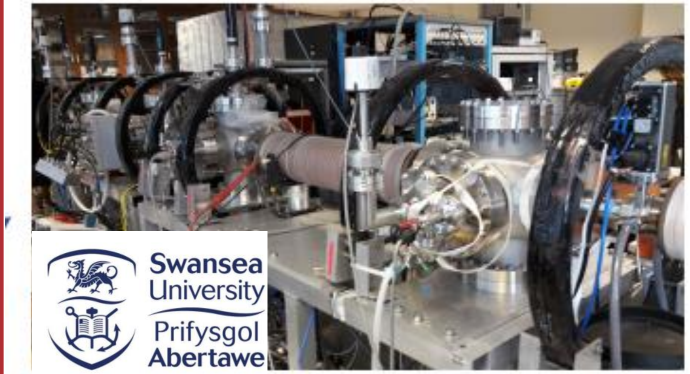
PIC

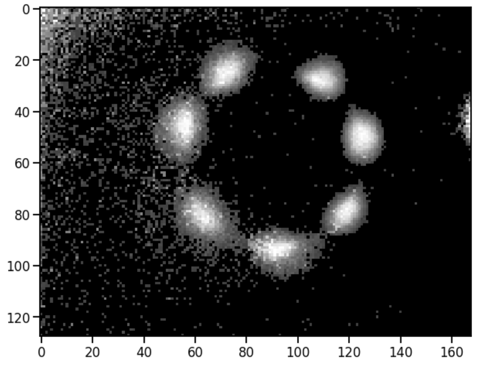


Numerical model



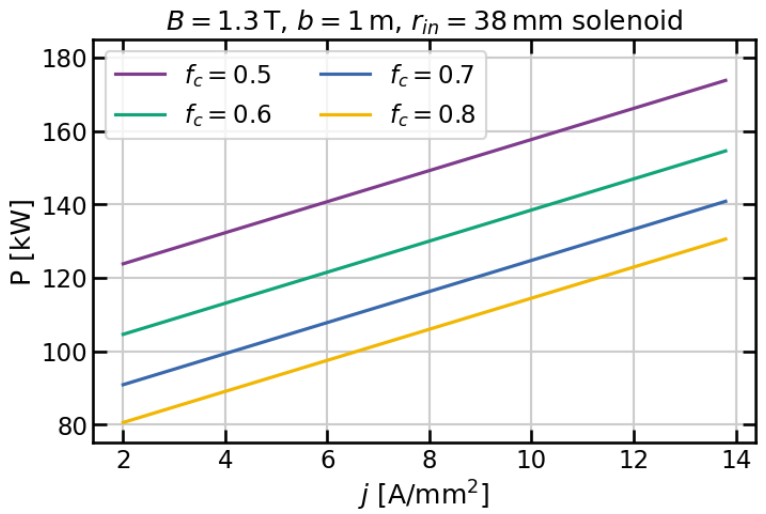
Measurements with confined electrons

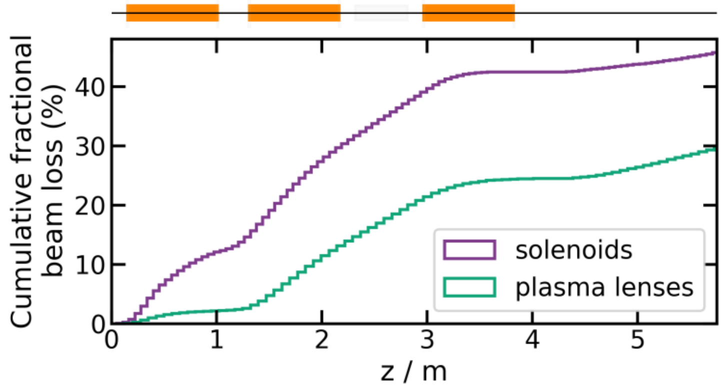




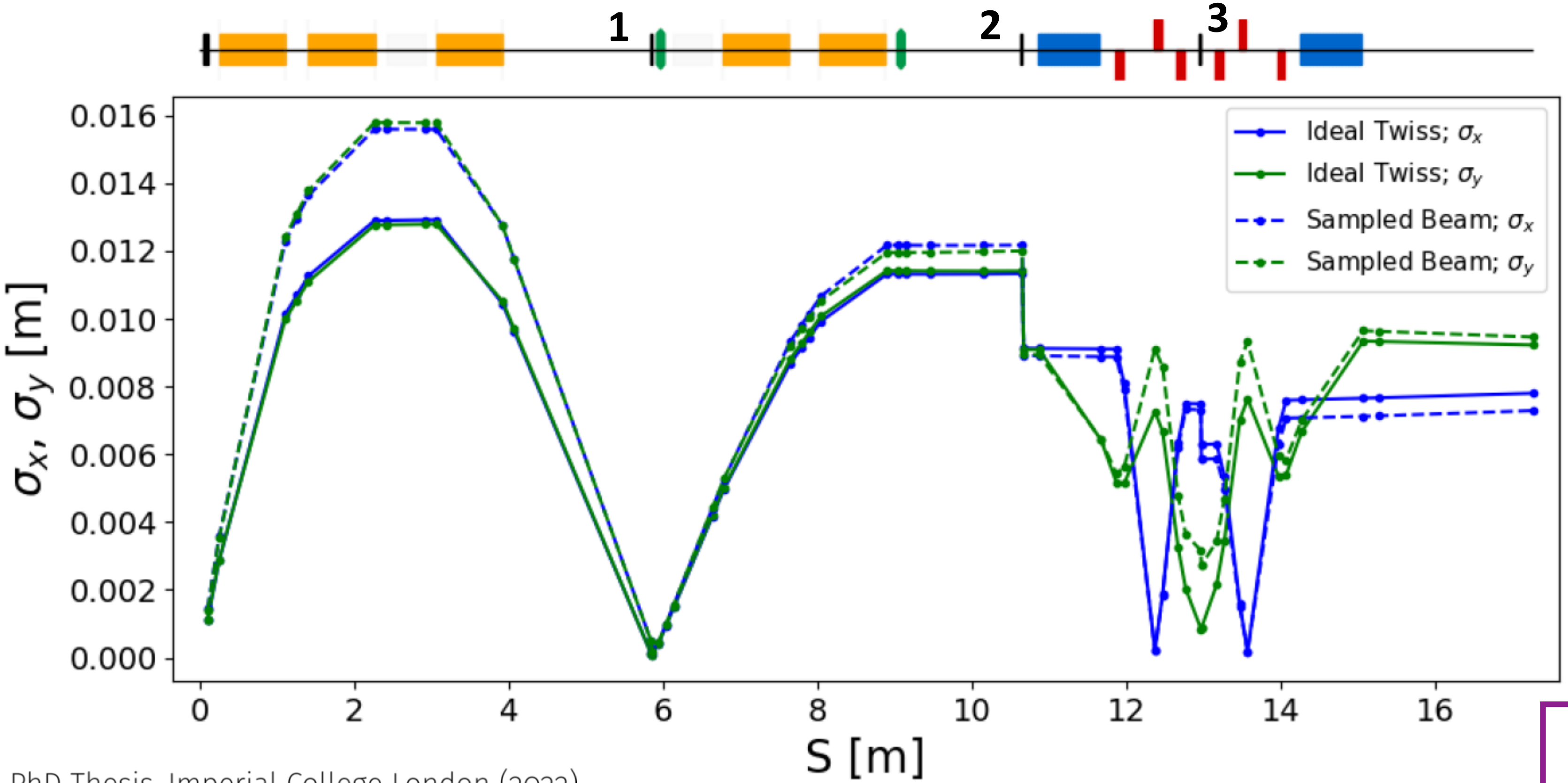
Design more conventional alternative

normal-conducting solenoids

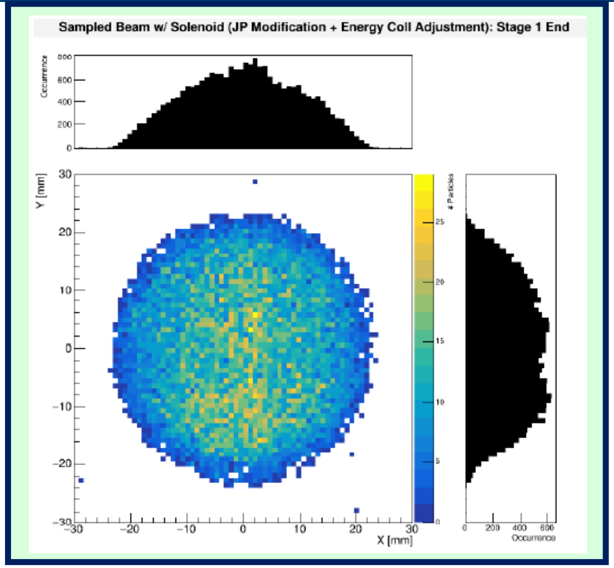




LhARA Stage 1 for *in-vitro* studies

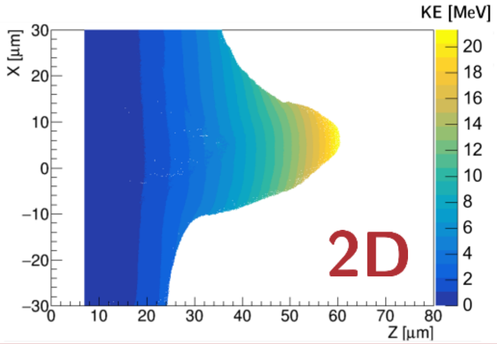


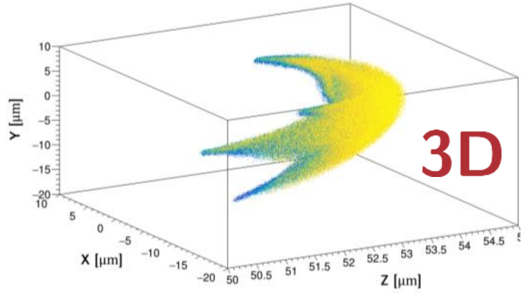
H.T.Lau, PhD Thesis, Imperial College London (2022)



Dose uniformity at end station

Protons at source

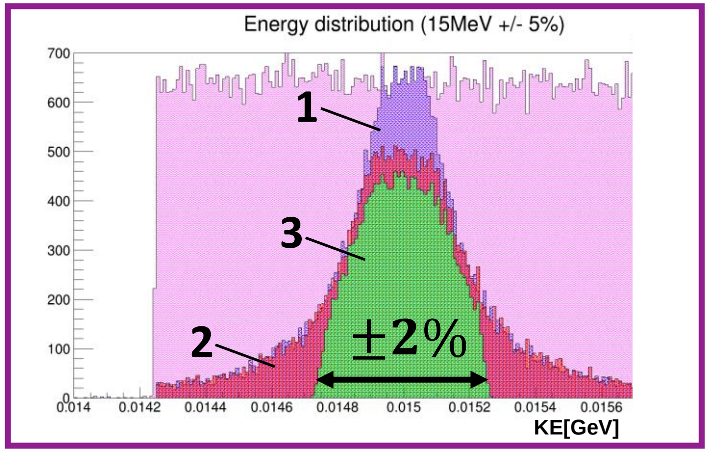




Smilei)

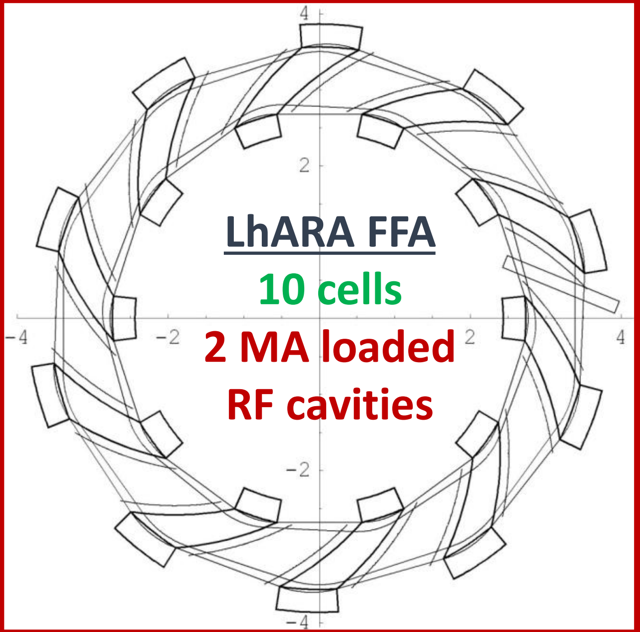
BDSIM Beam Delivery Simulation

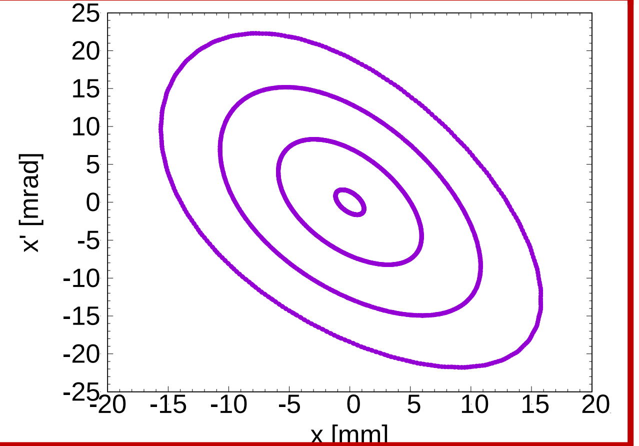
Energy collimation



Rapid, flexible acceleration for Stage 2

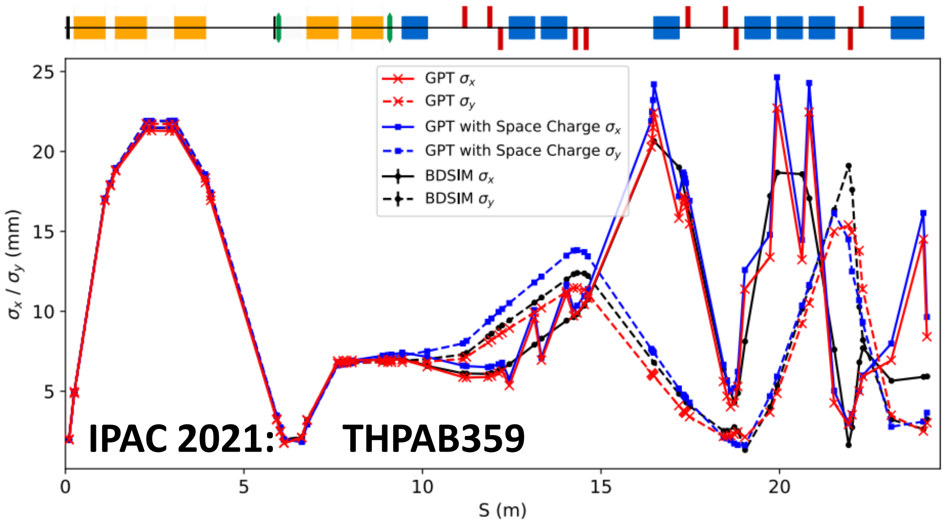
- **Baseline: $\times 3$ increase in momentum**
- **Spiral scaling FFA** shows a good performance in tracking studies.
  - Dynamical acceptances much larger than physical ones
  - FFA model with space charge in development
- Feasible ring injection, extraction and beam transport to the end stations have been designed.



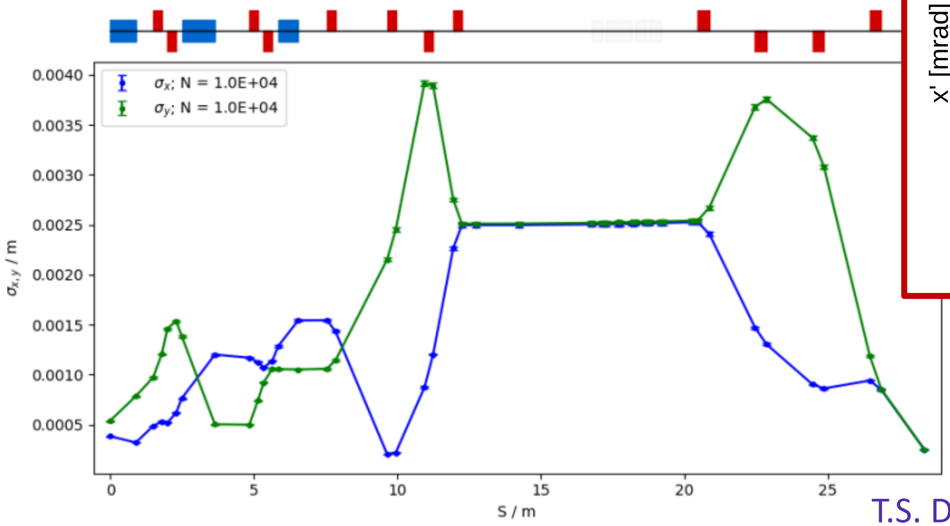


Aymar et al., Frontiers in Physics, 432 (2020)

Injection into FFA



To in vivo end-station



LhARA performance

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

Doses and dose rates

LhARA performance summary

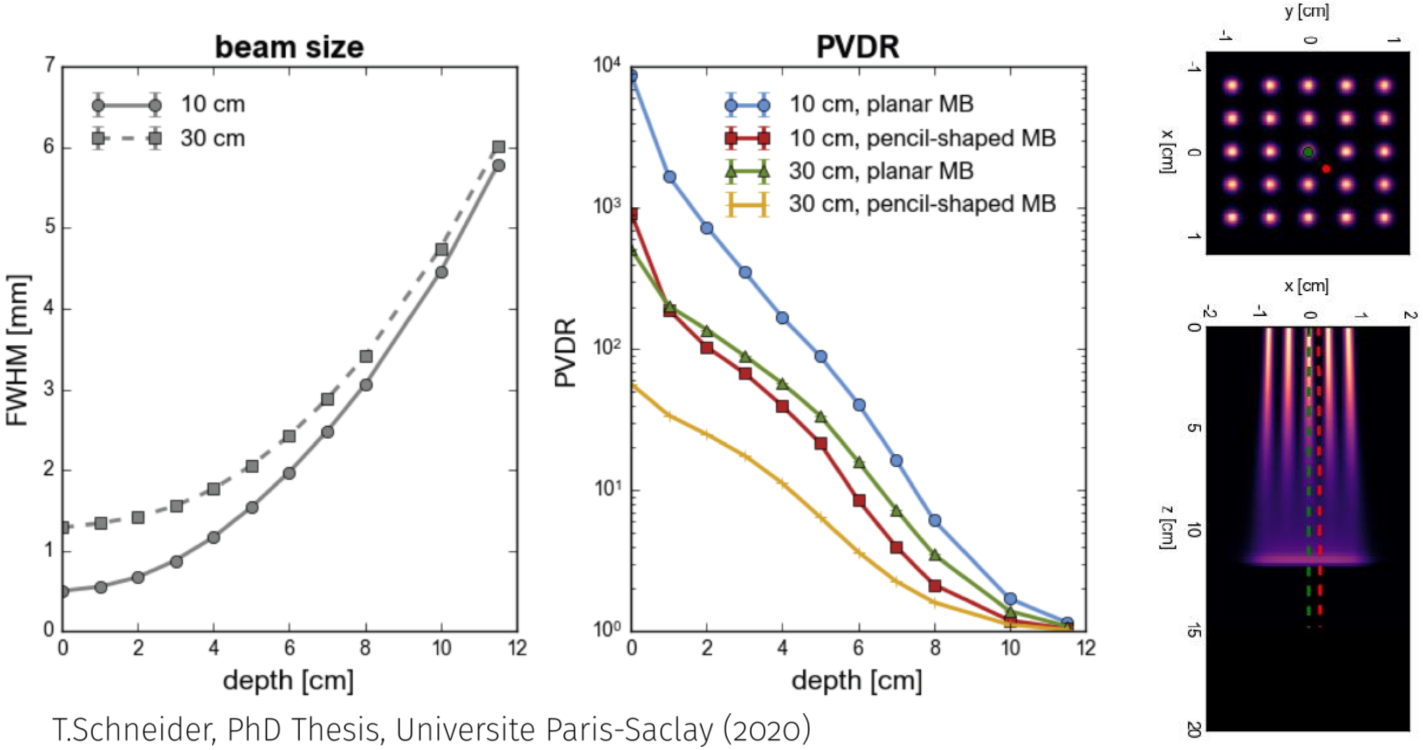
	12 MeV Protons	15 MeV Protons	127 MeV Protons	33.4 MeV/u Carbon
Dose per pulse	7.1 Gy	12.8 Gy	15.6 Gy	73.0 Gy
Instantaneous dose rate	1.0×10^9 Gy/s	1.8×10^9 Gy/s	3.8×10^8 Gy/s	9.7×10^8 Gy/s
Average dose rate	71 Gy/s	128 Gy/s	156 Gy/s	730 Gy/s

Worked example: FLASH

Conventional regime: ~ 2 Gy/min
FLASH regime: ≥ 40 Gy/s

Worked example: minibeams

LhARA + clinical nozzle for magnetically focused proton minibeams



T.Schneider, PhD Thesis, Universite Paris-Saclay (2020)

Conclusions

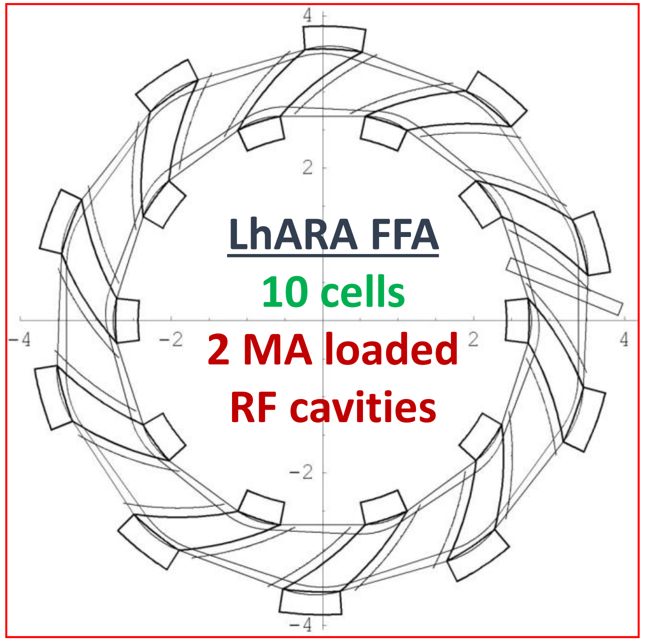
- **Laser-driven sources are disruptive technologies...**
  - with the potential to drive a step-change in clinical capability.
- **Laser-hybrid approach has potential to:**
  - Overcome dose-rate limitations of present proton and ion beam therapy sources.
  - Deliver a uniquely flexible facility:
    - **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.
- **Funding from the UKRI Infrastructure Fund has recently been announced**
  - 2-year "Preliminary Activity"
  - to deliver a CDR for the Ion Therapy Research Facility served by LhARA.

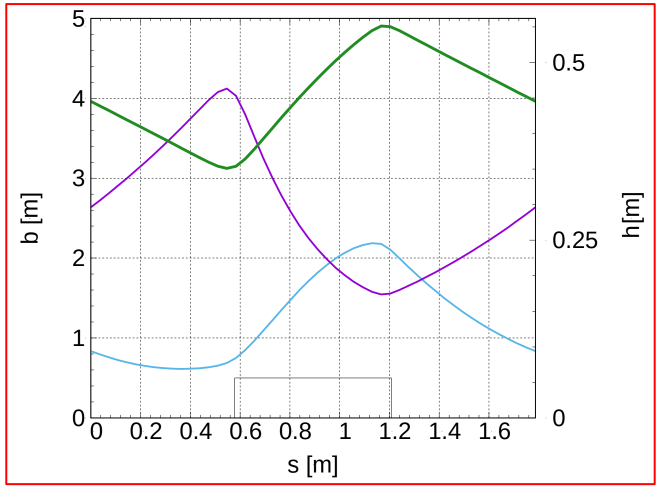
Backup Slides

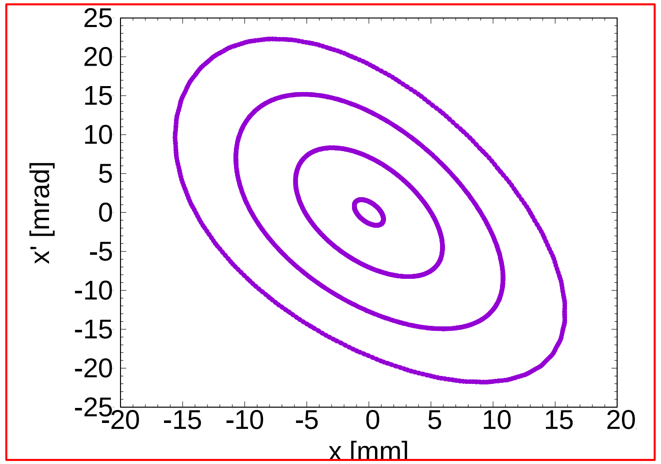
Rapid, flexible acceleration for Stage 2

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

- **Fixed-field alternating-gradient accelerator (FFA):**
  - Compact, flexible solution:
    - Multiple ion capability
    - Variable energy extraction
    - High repetition rate (10–100 Hz)
    - Large acceptance
  - Single scaling spiral FFA:
    - Baseline lattice type
    - Single magnet per lattice cell
    - Spiral magnet needed







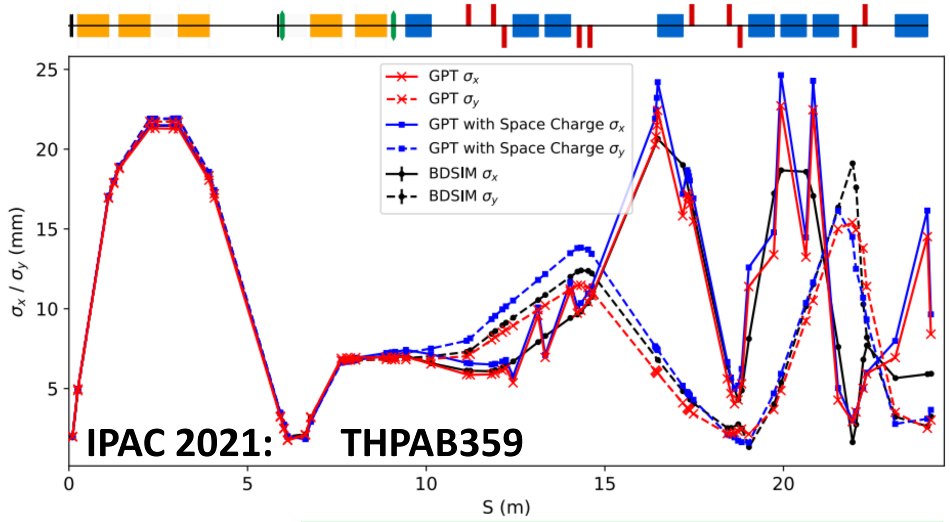
- Spiral scaling FFA shows a good performance in tracking studies.
  - Dynamical acceptances much larger than physical ones
  - FFA model with space charge in development

FFA in LhARA Stage 2

- **Baseline: $\times 3$ increase in momentum:**
  - 15 MeV protons accelerated to 127 MeV
  - 3.8 MeV/u carbon 6+ ions accelerated to 34 MeV/u
- Feasible ring injection, extraction and beam transport to the end stations have been designed.
- Preliminary ideas for slow extraction

Essential R&D:
– finalisation of lattice design
– main FFA magnet (parallel gap, distributed windings)
– technology transfer for Magnetic Alloy (MA) loaded RF cavities

Injection into FFA



To in vivo end-station