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University of Strathclyde Glasgow

# LhARA

## Laser-hybrid Accelerator for Radiobiological Applications

C. G. Whyte. On behalf of the LHARA Collaboration

Laser-hybrid Accelerator for Radiobiological Applicatons

*LhARA will be a uniquely-flexible, novel system that will:*

- *Deliver a systematic and definitive radiobiology programme*
- *Prove the feasibility of the laser-driven hybrid-accelerator approach*
- *Lay the technological foundations for the transformation of PBT*
  - automated, patient-specific: implies online imaging & fast feedback and control

*A novel, hybrid, approach:*

- Laser-driven, high-flux proton/ion source
  - Overcome instantaneous dose-rate limitation
  - Delivers protons or ions in very short pulses
  - Triggerable; arbitrary pulse structure
- Novel "electron-plasma-lens" capture & focusing
  - Strong focusing (short focal length) without the use of high-field solenoid
- Fast, flexible, fixed-field post acceleration. - Variable energy
  - Protons: 15—127 MeV Ions: 5—34 MeV/u

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# LhARA

University of Strathclyde Glasgow

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

INFN Catania

ASTeC
Particle Physics Department
ISIS Neutron and Muon Source

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

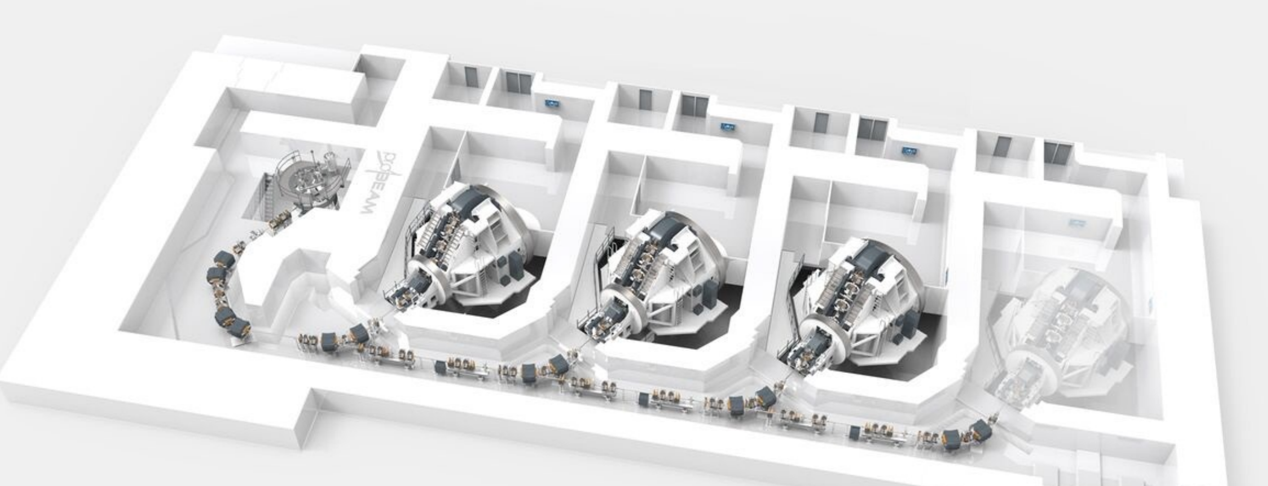
LEO Cancer Care

MAXELER Technologies Maximum Performance Computing

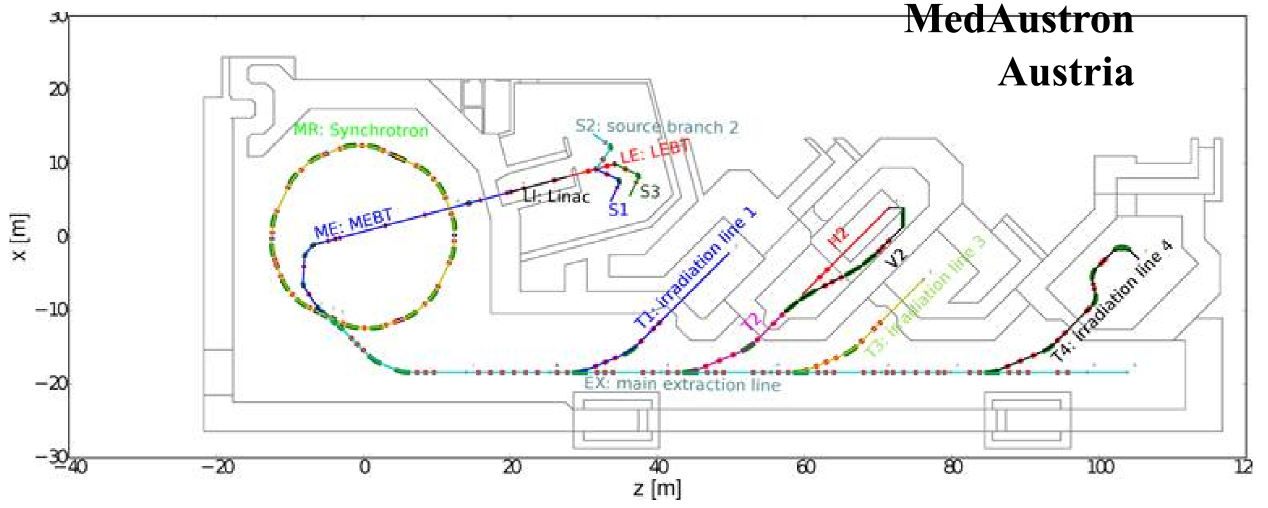
LhARA Laser-hybrid Accelerator for Radiobiological Applications

# Particle beam therapy today

- Cyclotron based:
  - Limitations:
    - Energy modulation
    - Instantaneous dose rate
- Synchrotron based:
  - Limitiations:
    - Complexity
    - Instantaneous dose rate

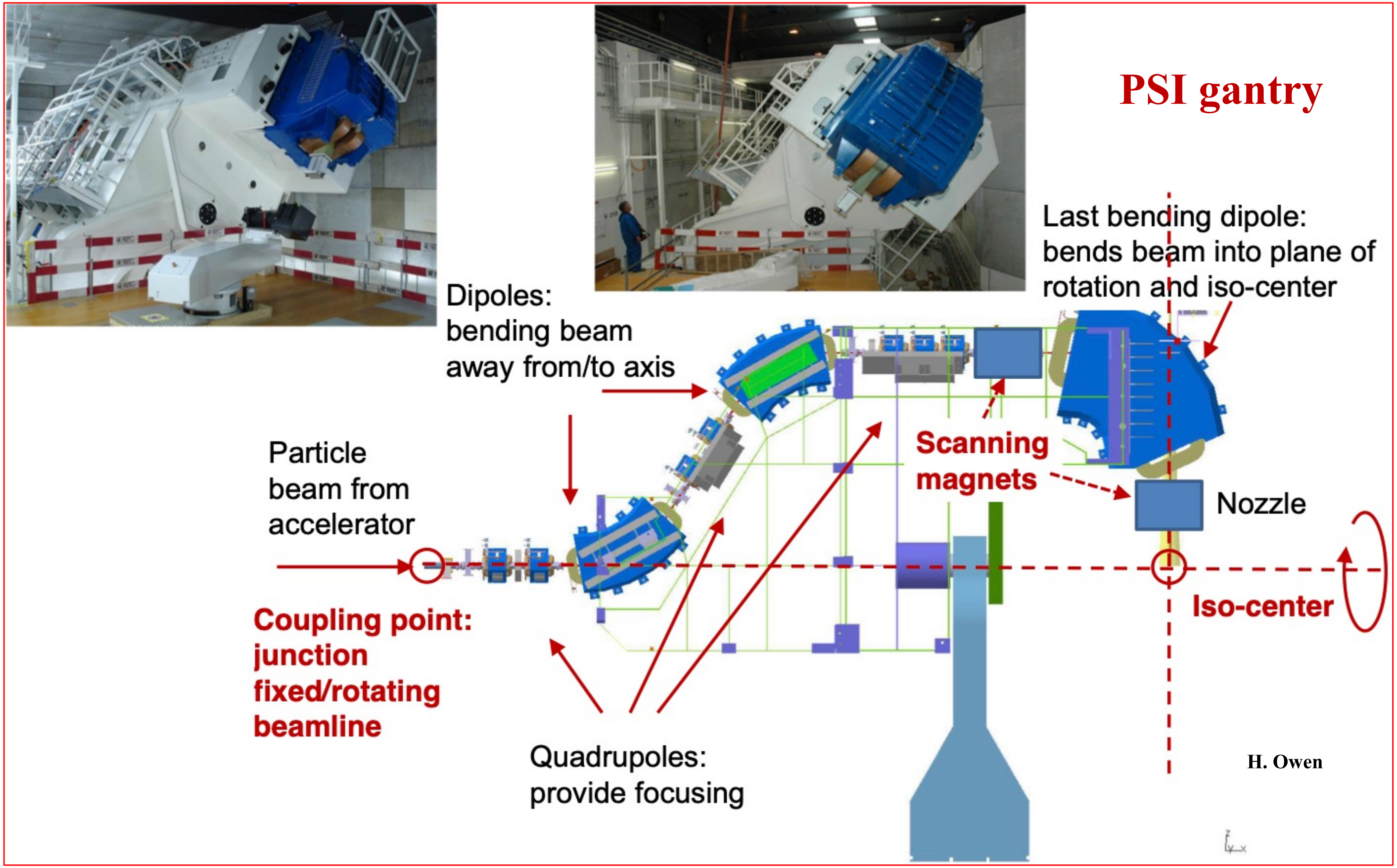


Christie Hospital Manchester




MedAustron
Austria

# *Beam delivery*

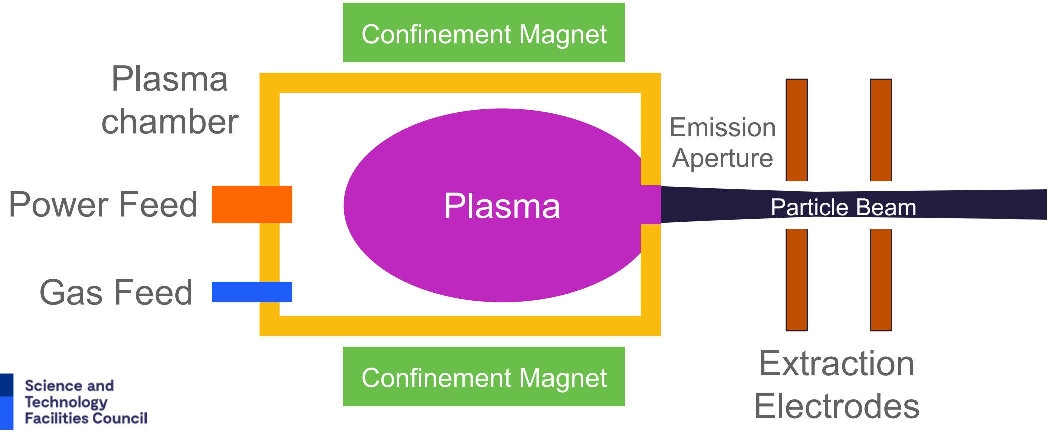


# Particle source

## The Typical Ion Source

S. Laurie

Every ion source basically consists of two parts:
1. **Ion production** inside a plasma
2. **Beam extraction** from the plasma

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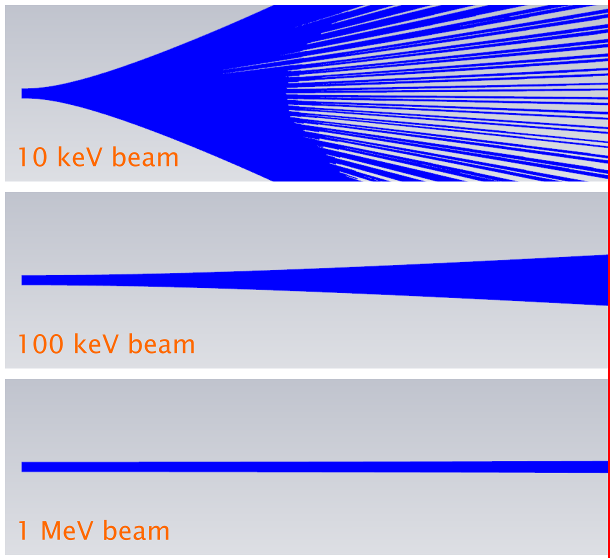
## Space Charge

S. Laurie

- 50 mA proton beam
- 5 mm initial radius
- 1000 mm drift distance
- Expands due to its own 'space charge'
- Space charge forces velocity dependent

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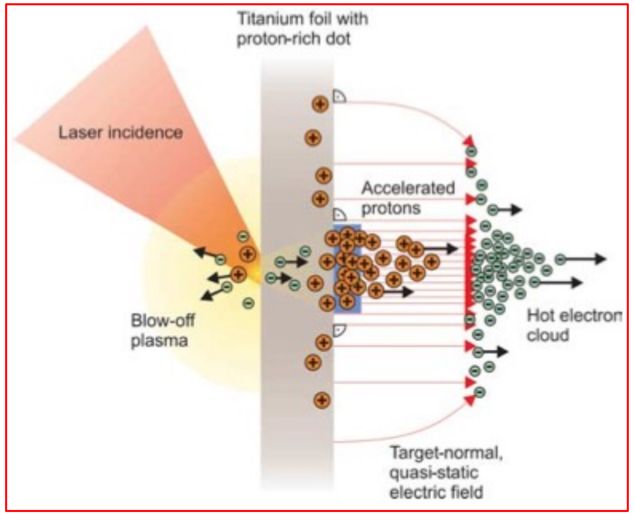
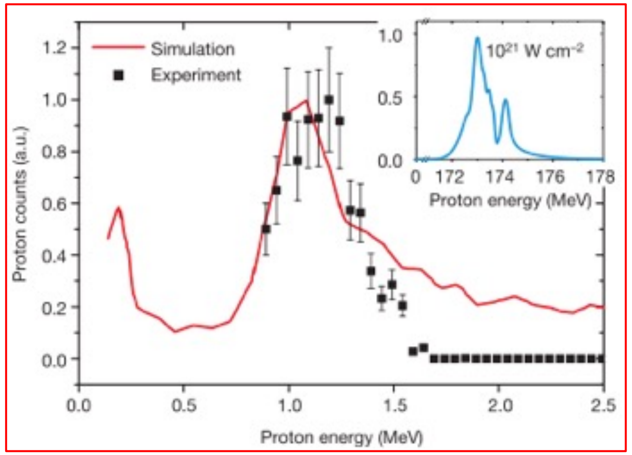
- Extraction energy:
  - 30—80 keV
    - Limited by extraction voltage
- Instantaneous flux (current or dose):
  - Determined by acceptance of first accelerator structure
    - Limited by mutual repulsion of protons (ions) … "space-charge effect"

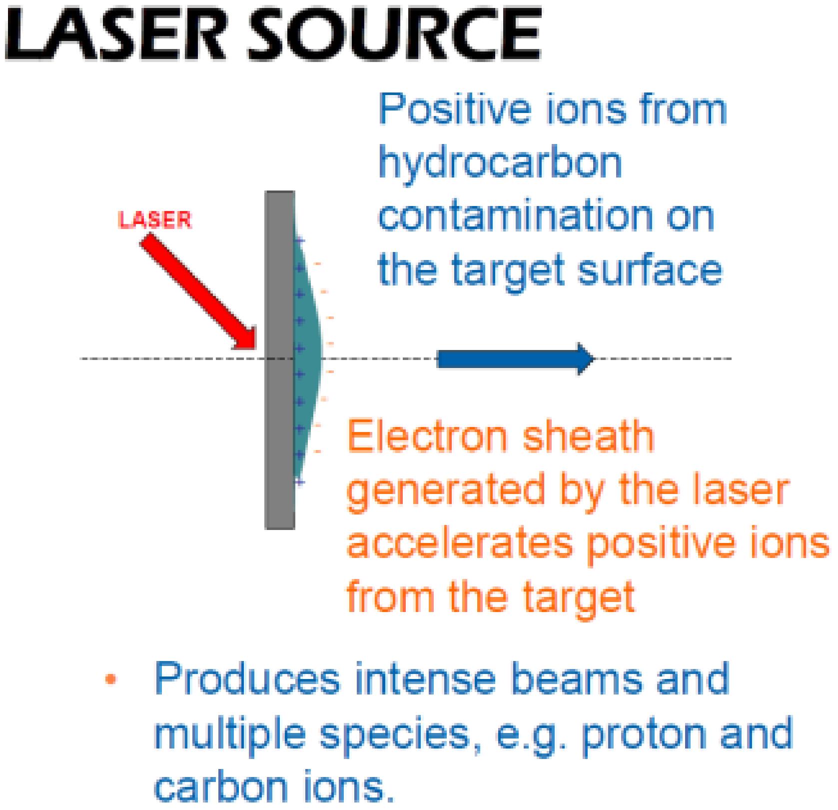
# Sheath acceleration

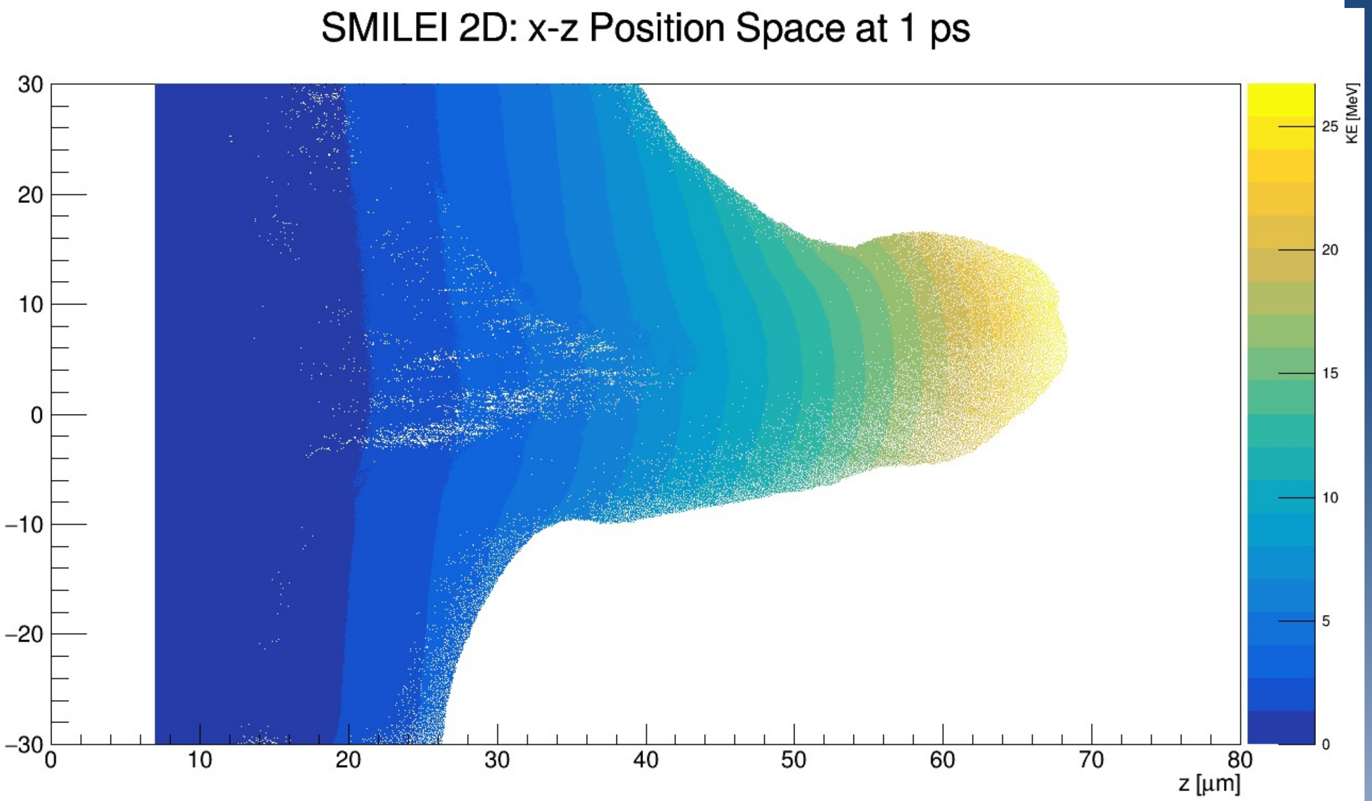



- Laser incident on foil target:
  - Drives electrons from material
  - Creates enormous electric field
- Field accelerates protons/ions
  - Dependent on nature of target
- Active development:
  - Laser: power and rep. rate
  - Target material, transport

# Initial Beam from the Laser Source

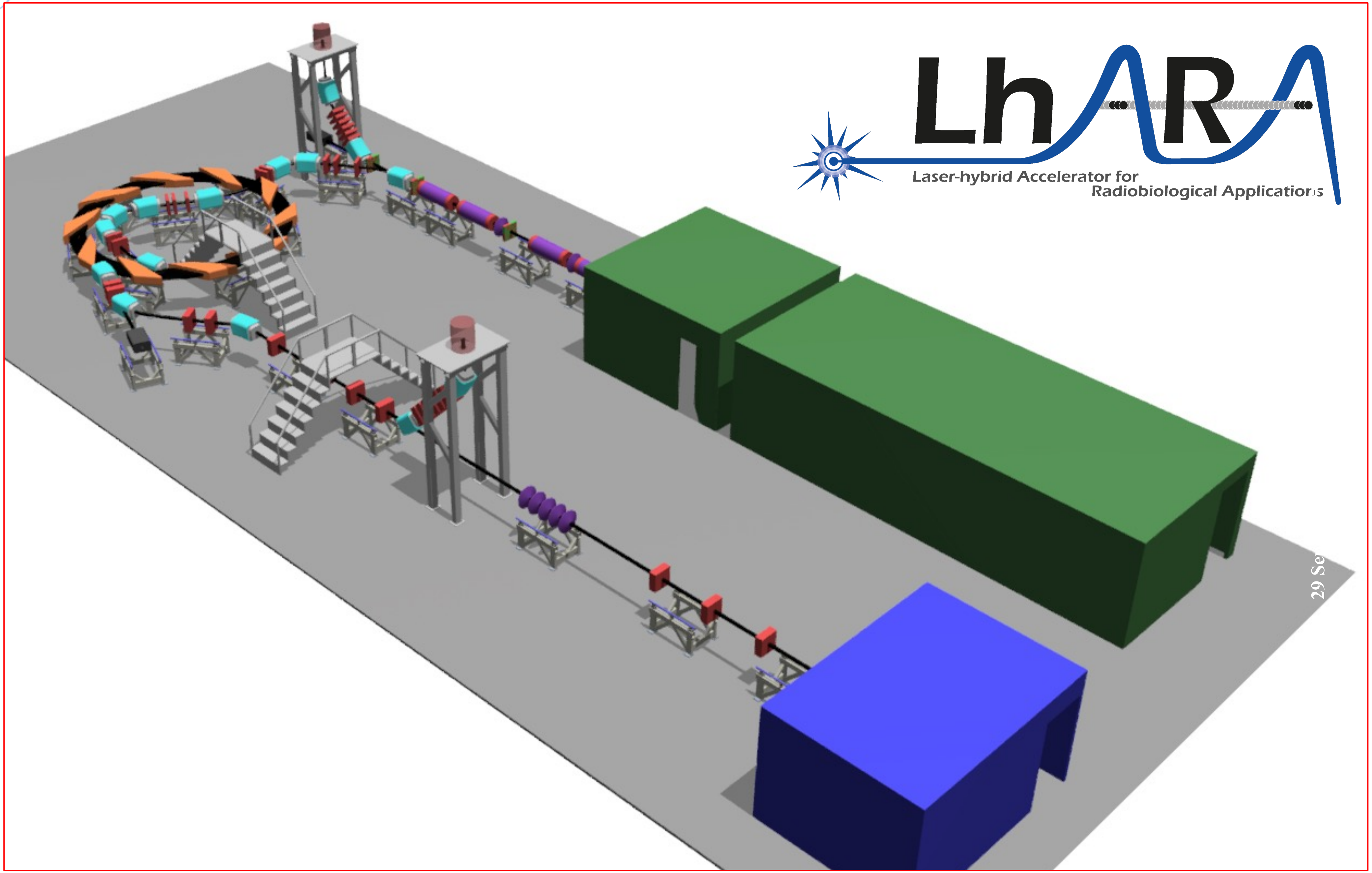



- Small emittance ($\sim 4.1\times10^{-7}$ □.m.rad)
- Huge energy spread
- Very small beam size
- Very large divergence
- Neutral at the beginning then space charge dominated
- Mixture of states

# Advantages

- Protons (and ions) produced at "high energy":
  - e.g. 15 MeV → 250 times energy of conventional proton source
    - High energy substantially reduced impact of space charge
      - Allows evasion of instantaneous dose-rate limitation of today's sources
- Pulsed operation "natural":
  - Discharge sources are DC; accelerator imposes time structure
  - Pulsed operation determined by laser:
    - A triggerable, "on demand", source
- Critical issues:
  - Efficient capture of divergent, high-energy ion flux
  - Transformation of captured flux into useful beam


LhARA
Laser-hybrid Accelerator for
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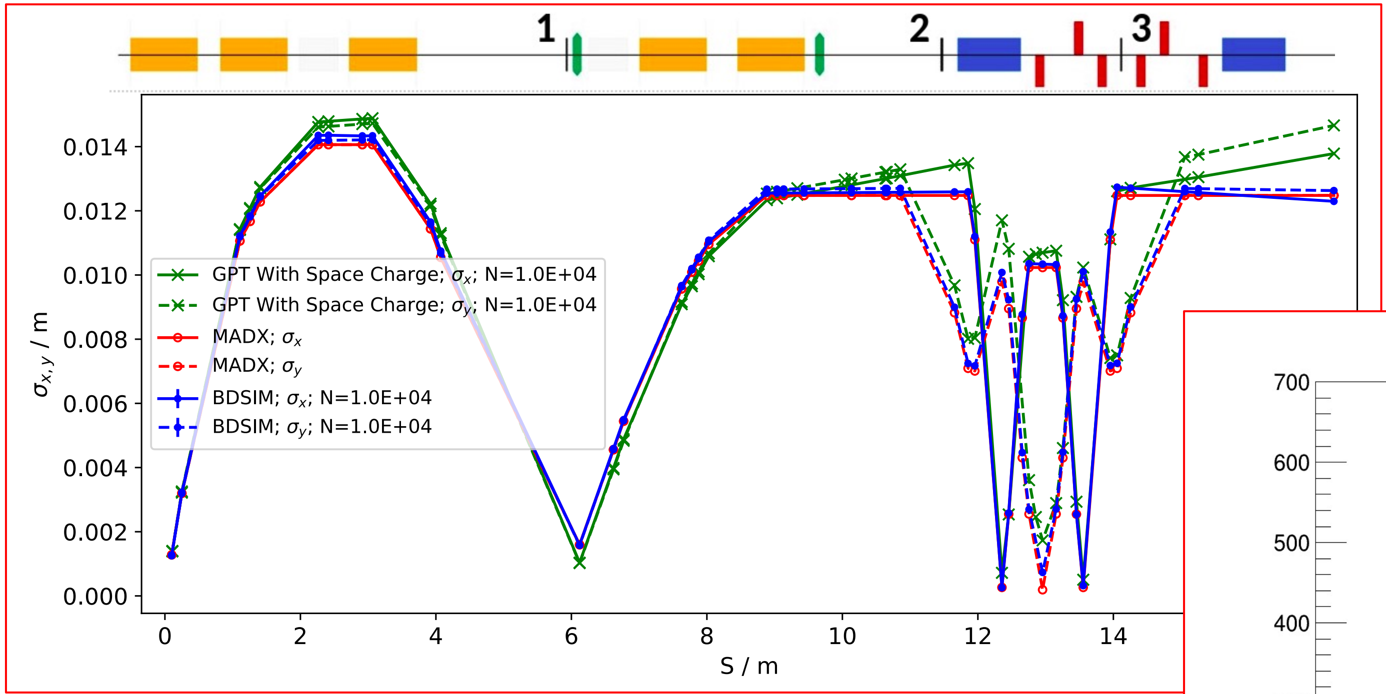
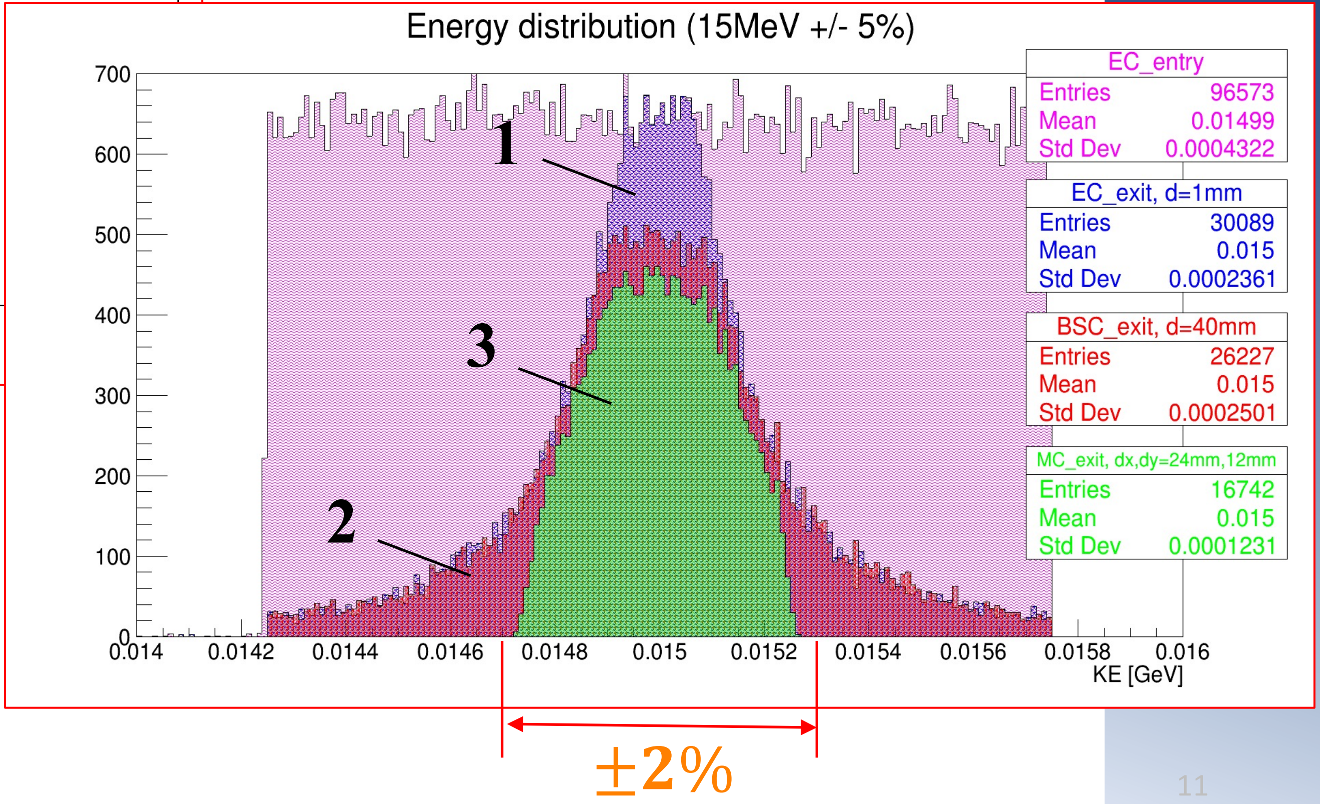
# Energy collimation



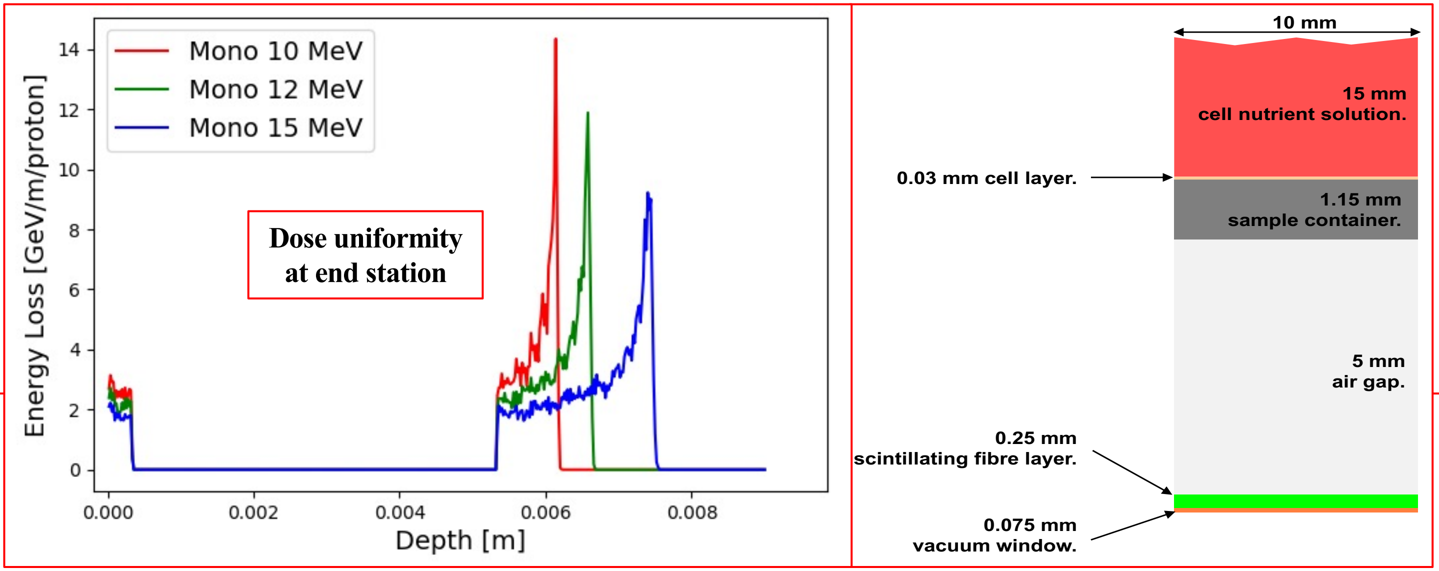

Flat initial energy profile

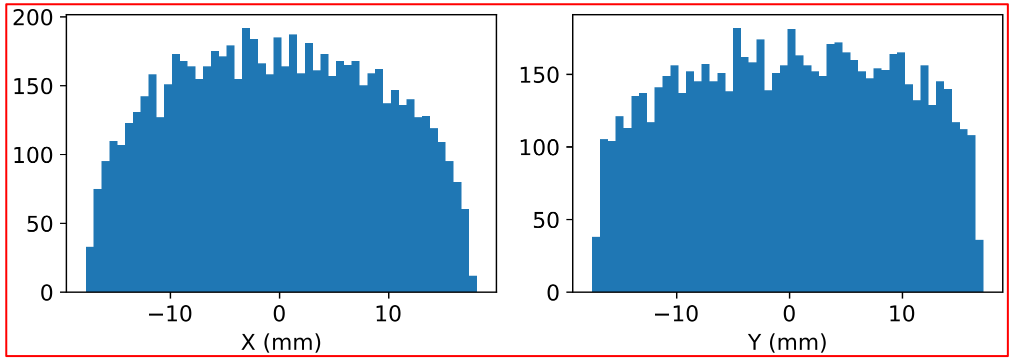
**15 MeV ± 15%**

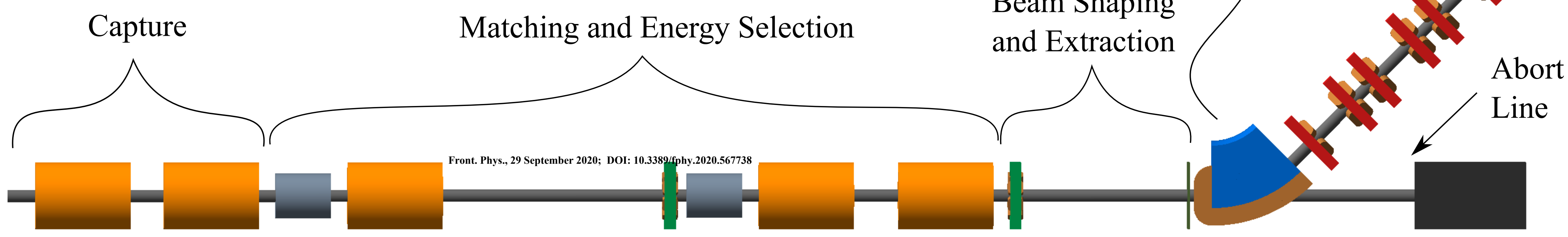



- 3 collimators
  1. Energy collimation (at beam focus)
  2. Beam shaping
  3. Momentum cleaning (removes energy tails)

# LhARA stage 1



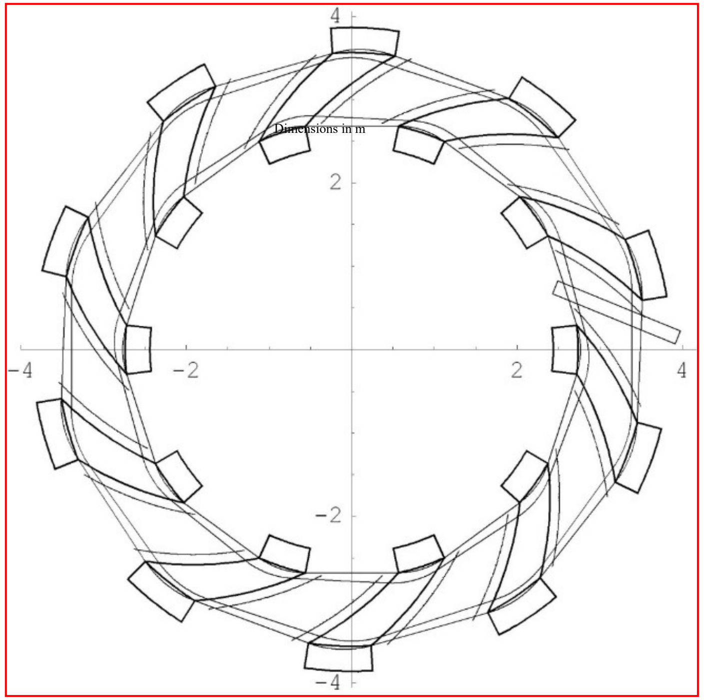




Front. Phys., 29 September 2020; DOI: 10.3389/fphy.2020.567738

# 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 DL

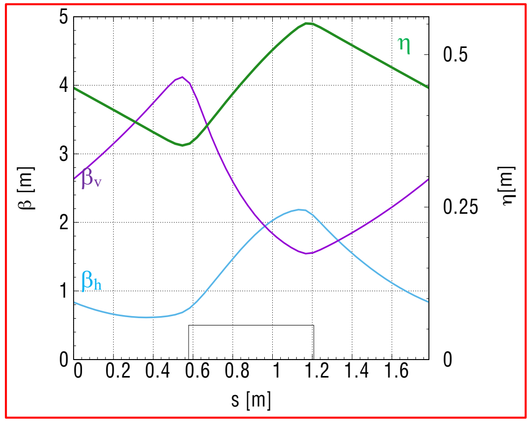


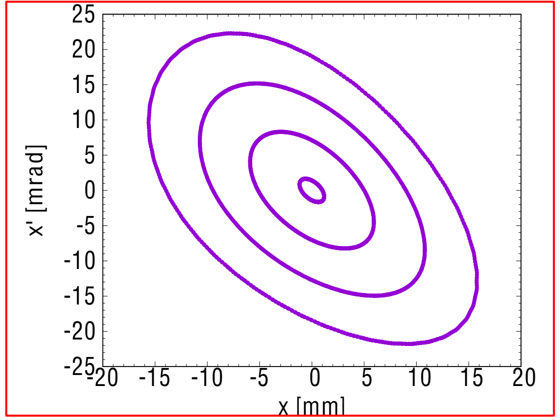

Evolution of RACCAM design; prototype magnet demonstrated

**LhARA FFA**

**10 cells**

**2 MA loaded RF cavities**

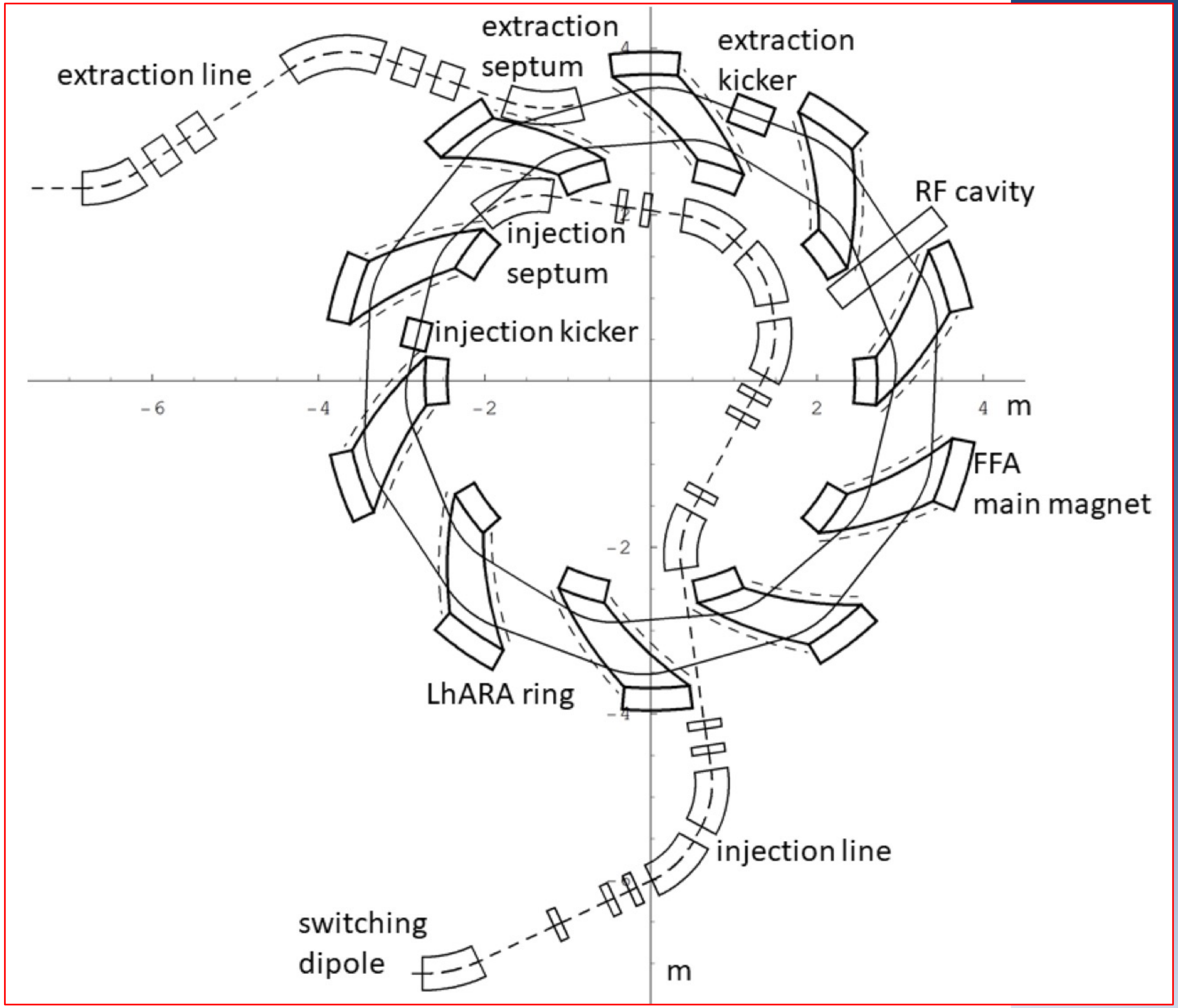


# FFA LhARA – Stage 2

Baseline:

- x3 increase in momentum
  - 15 MeV protons accelerated to 127 MeV
  - 3.8 MeV/u carbon 6+ ions accelerated to 34 MeV/u

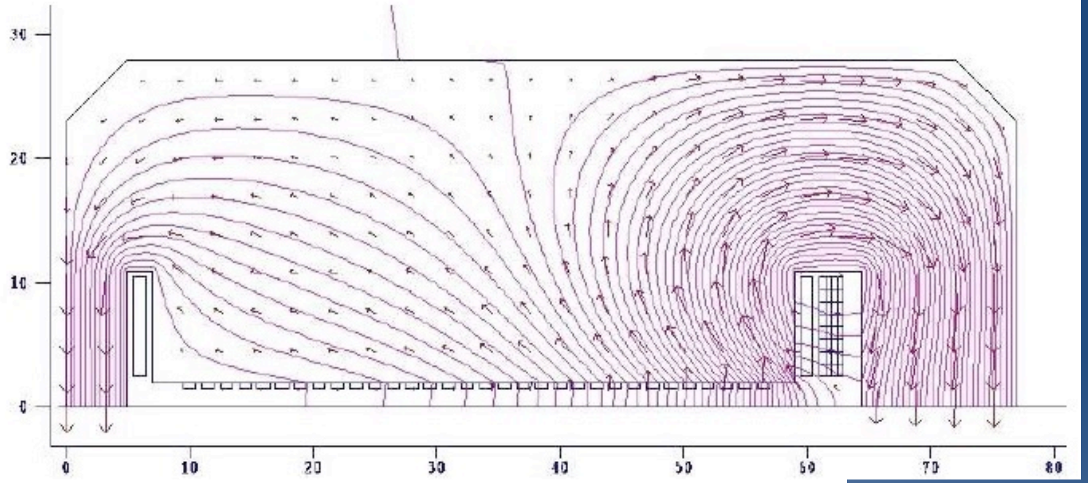


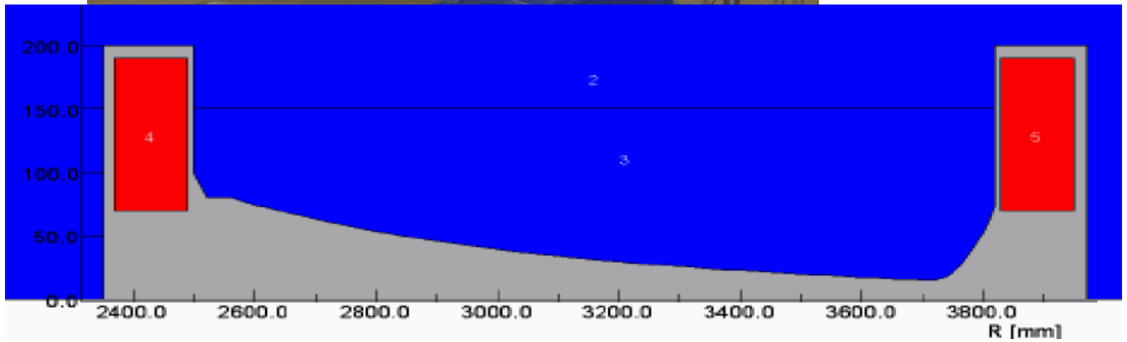
# Essential R&D – Magnets

Magnet with distributed conductors:

• Parallel gap – vertical tune more stable,

• Flexible field and k adjustment,




"Gap shaping" magnet:

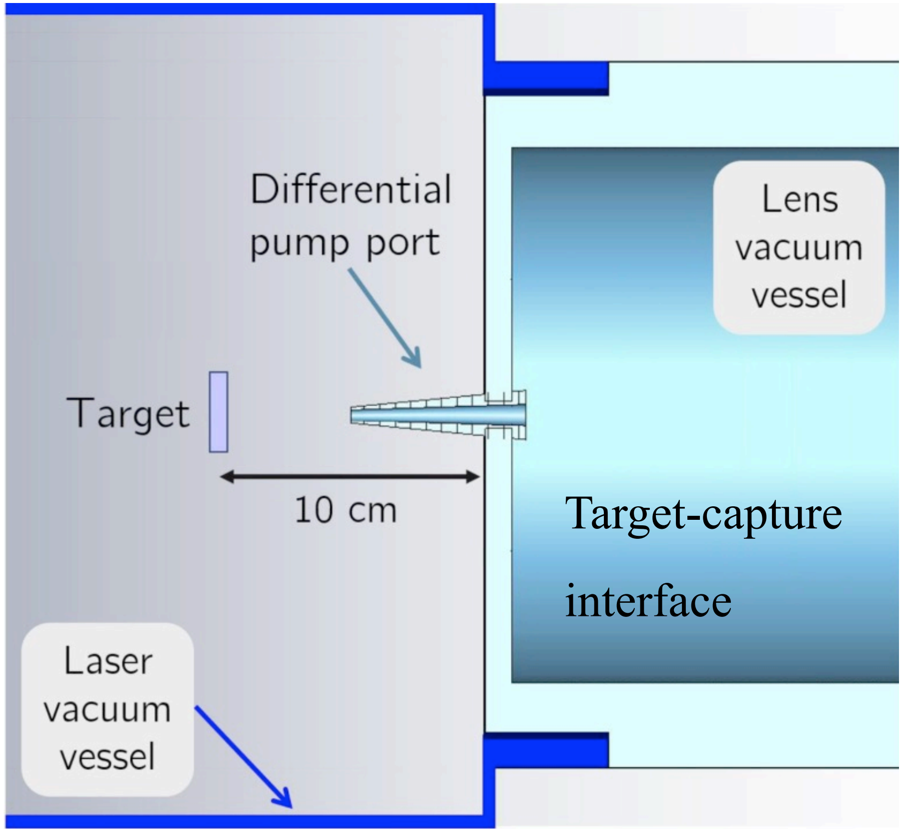
•Developed by SIGMAPHI for RACCAM project

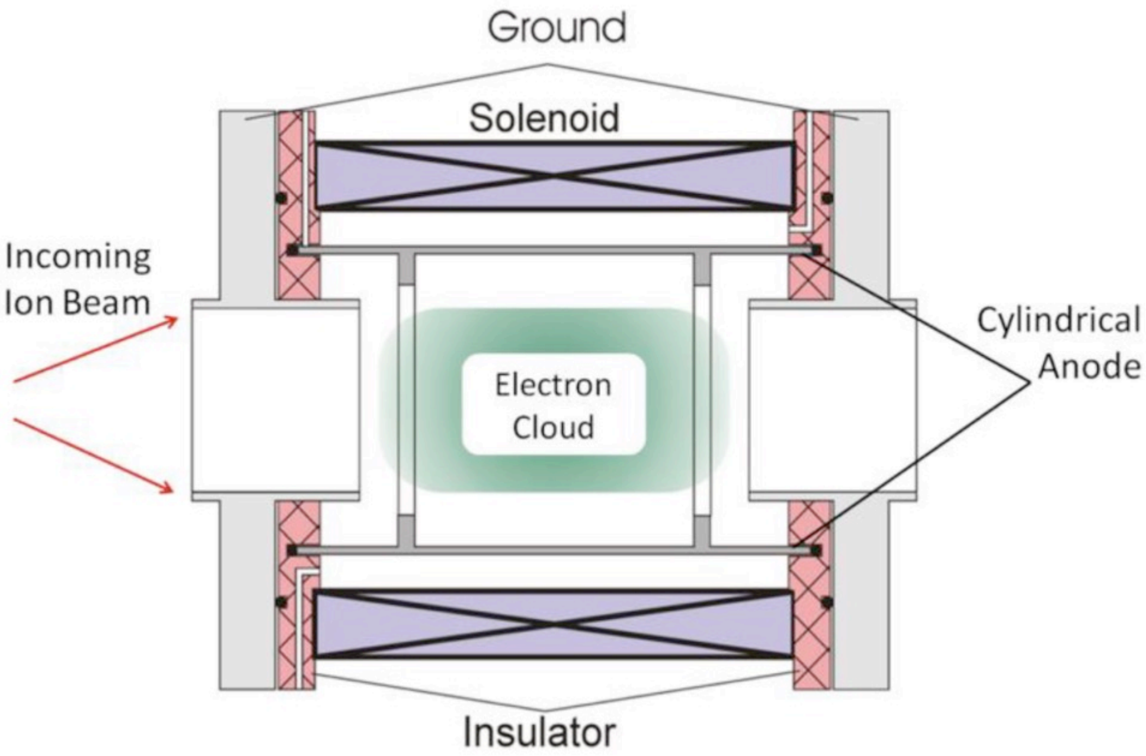
•Initialy thought as more difficult - behaves very well

•Chosen for the RACCAM prototype construction

- For LhARA magnet with parallel gap with distributed windings (but a single current) would be of choice with gap controlled by clamp. Concepts like an active clamp could be of interest too.
- Magnetic Alloy (MA) loaded RF cavities for the ring also important

# Gabor Lenses for strong focusing



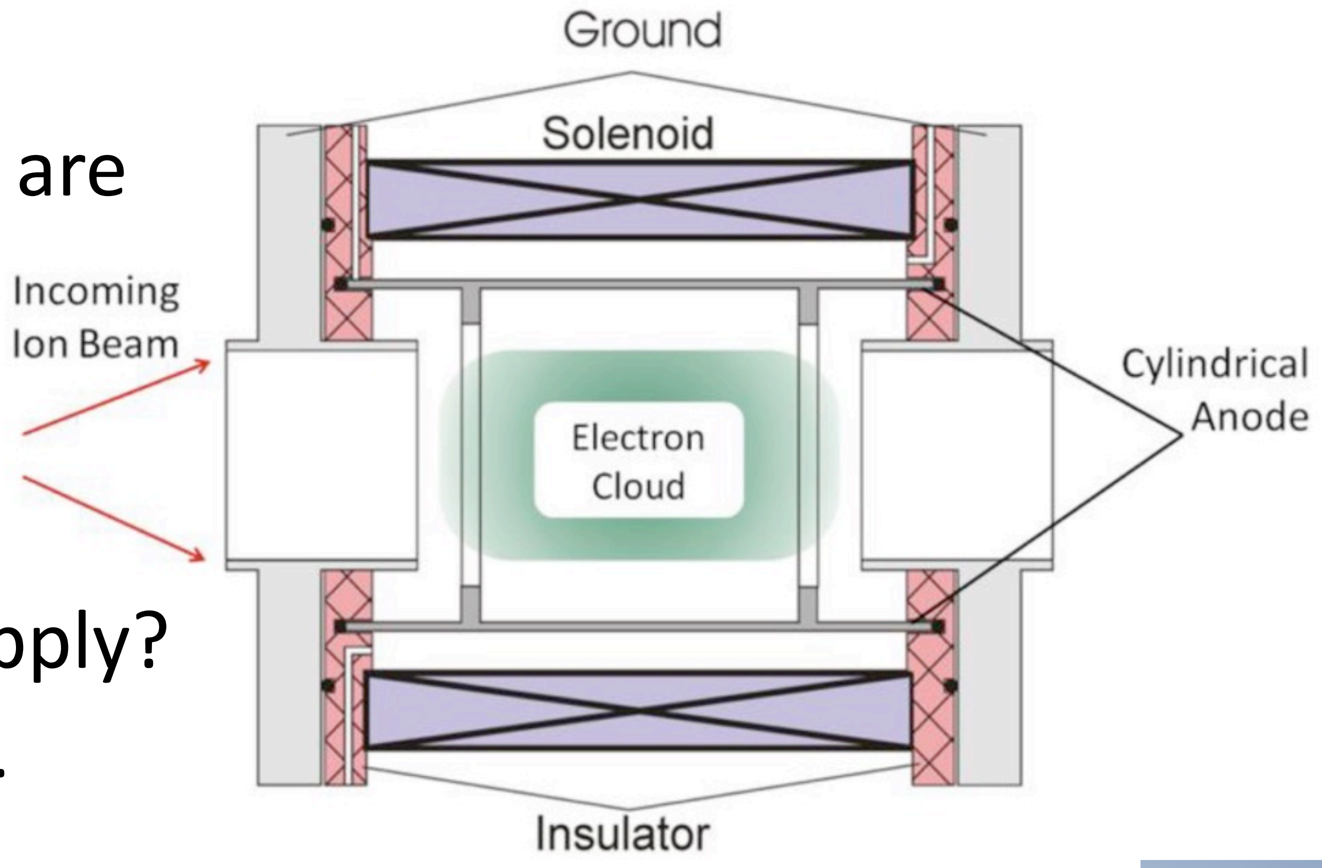

- Focus in both planes simultaneously, strength is energy dependent
  - Cost effective solution compared to SC solenoids
- Chosen as a baseline solution for the capture system and focusing in Stage 1
- Design based on Penning-Malmberg trap

- Require high vacuum to operate
- Subject to intensive 3D PIC simulation effort to inform a stable solution (to mitigate diocotron instability)
- Can be replaced by solenoids, if needed.

# Gabor Lens – Stability

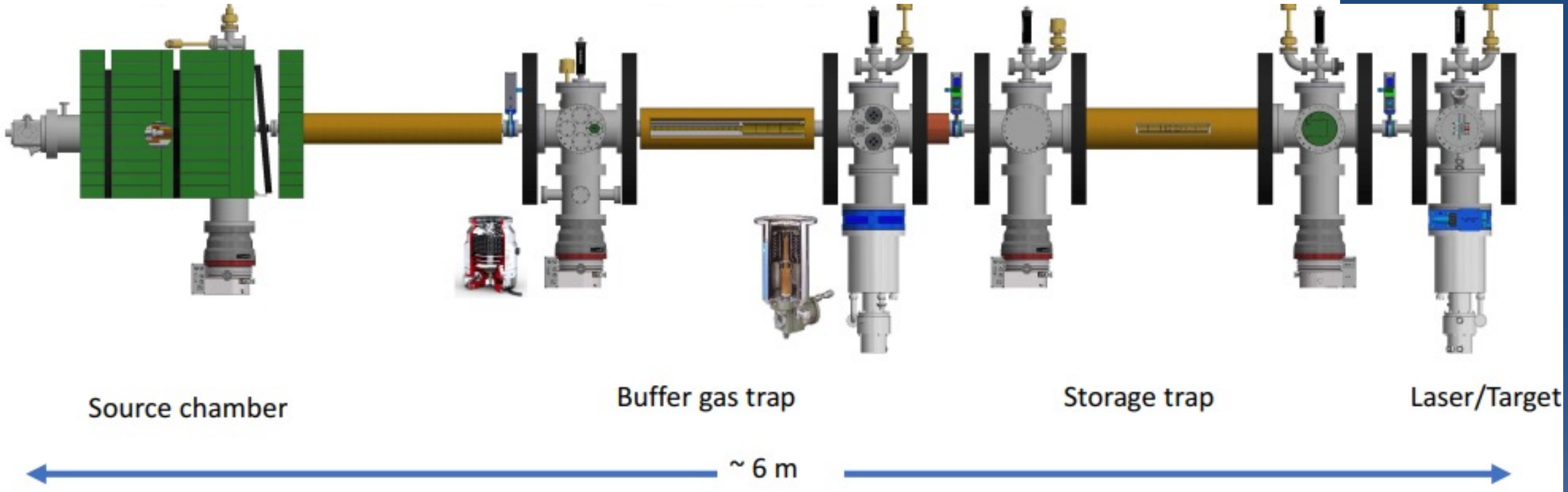
Diocotron Instability

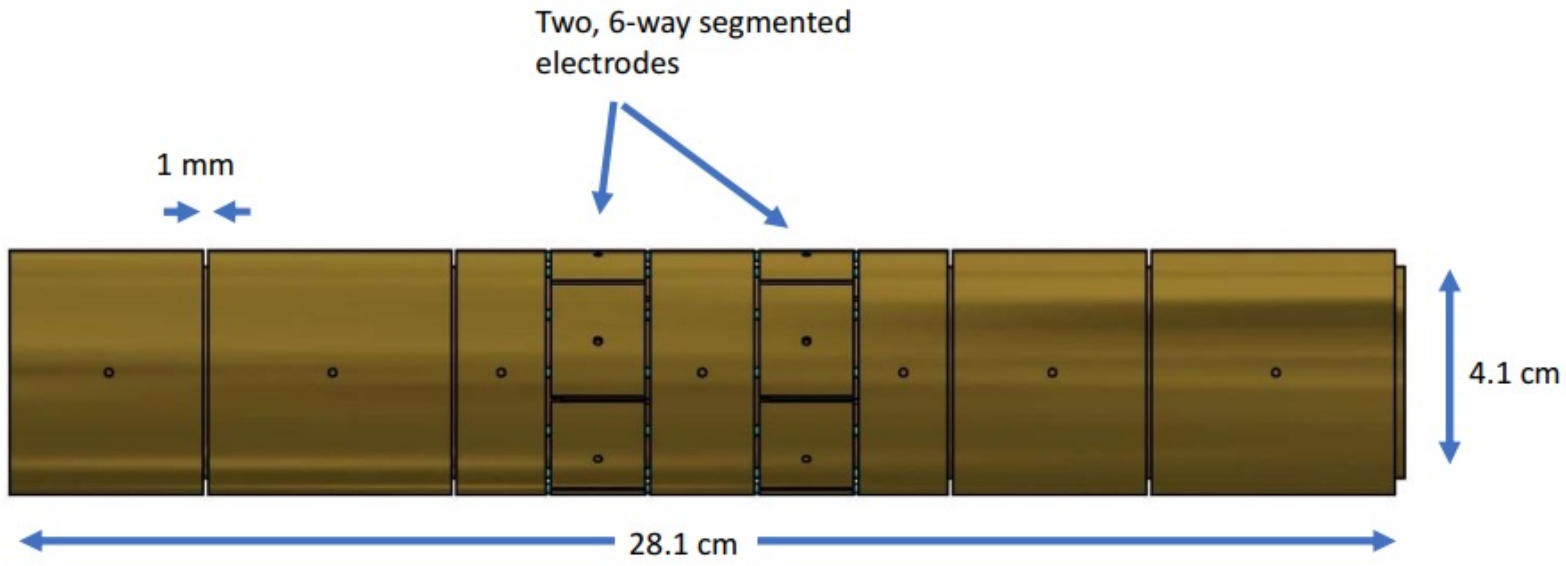
- ‘hollow’ particle distributions are vulnerable to diocotron
- Observed in experiment
- Modelled in Vsim/BDSim
- Driven by off-axis electron supply?
  - Possible on-axis electron filling.



# *Gabor Lens*

- ‘New’ collaborators
  - University of Swansea (Anti-hydrogen Expt. @ Cern)
  - Cockroft Insitute
- Non-neutral Plasma confinement.
- Plasma trapping and cooling
- Extended trapping times – hours to days
- Experimental apparatus at Swansea



# Project Design – Risk - Reward

‘New but established’ laboratory research

→ satisfy treatment requirements.

*Balance the total risk while retaining research relevance*

| Risk | Mitigation | Justification |
|---|---|---|
| Laser source | Buy-able | Heading toward mainsteam |
| Gabor Lens focussing | Alternate solution – Solenoid | Cost |
| FFA accelerator | Conventional accelerator | Better solution |
| ‘Live’ diagnostics | Solutions exist – laboratory level | Required – implicit in choice of Laser source |

# LhARA performance: doses and dose rates

**LhARA performance summary**

arXiv:2006.00493

| | 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 | $1.0 \times 10^9$ Gy/s | $1.8 \times 10^9$ Gy/s | $3.8 \times 10^8$ Gy/s | $9.7 \times 10^8$ 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

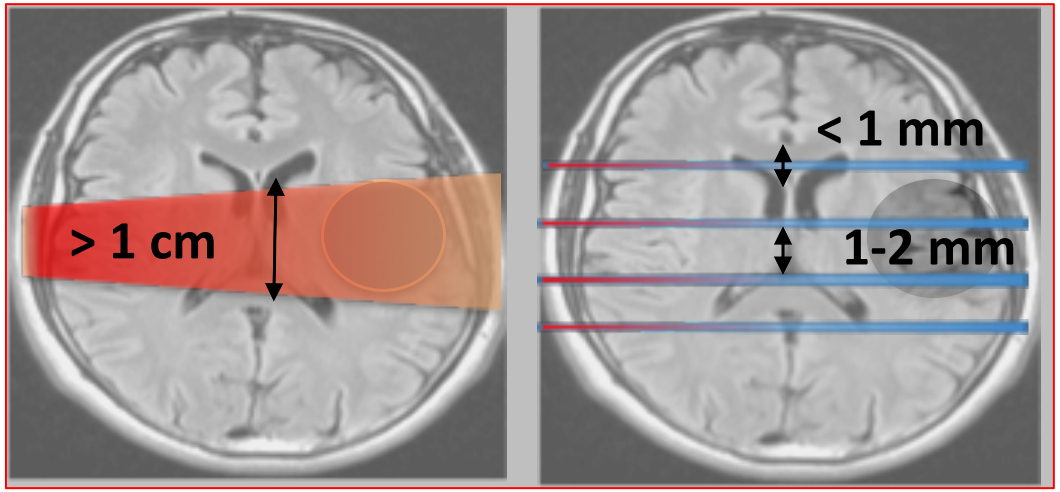
FLASH regime >40 Gy/s

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

## *Worked example: micro beams*

Conventional regime : > 1 cm diameter; homogenous

Microbeam regime : < 1 mm diameter.



# 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 PBT sources
  - Deliver uniquely flexible facility:
    - Range of: ion species; energy; dose; dose-rate; time; and spatial distribution
  - LhARA design is compact and flexible.
    - FFA-type ring as a post-accelerator enabling variable energy beams of various types of ions.
    - Good performance in tracking studies.
    - Feasible ring injection, extraction and beam transport designed.

- The LhARA collaboration now seeks to:
  - Prove the novel laser-hybrid systems in operation
  - Contribute to the study of the biophysics of charged-particle beams
    - Enhance treatment planning

# Review and publications

- LhARA team performed an intensive design work culminated by the international review last March
  - very positive feedback received
  - Pre-CDR completed
- Recent work summarised in article published in ‘Frontiers in Physics’

July 12, 2020 Final—revision 2 CCAP-TN-01

**Laser-hybrid Accelerator for Radiobiological Applications (LhARA)**

*Conceptual Design Report*

**The LhARA collaboration**

G. Aymar[1], T. Becker[2], S. Boogert[3], M. Borghesi[4], R. Bingham[5,1], C. Brenner[1], P.N. Burrows[6], T. Dascalu[7], O.C. Ettlinger[8], S. Gibson[3], T. Greenshaw[9], S. Gruber[10], D. Gujral[11], C. Hardiman[11], J. Hughes[9], W.G. Jones[7,20], K. Kirkby[12], A. Kurup[7], J-B. Lagrange[1], K. Long[7,1], W. Luk[7], J. Matheson[1], P. McKenna[5,14], R. Mclauchlan[11], Z. Najmudin[8], H.T. Lau[7], J.L. Parsons[9,21], J. Pasternak[7,1], J. Pozimski[7,1], K. Prise[4], M. Puchalska[13], P. Ratoff[14], G. Schettino[15,19], W. Shields[3], S. Smith[16], J. Thomason[1], S. Towe[17], P. Weightman[9], C. Whyte[5,14], R. Xiao[18]

https://ccap.hep.ph.ic.ac.uk/trac/raw-attachment/wiki/Communication/Notes/CCAP-TN-01.pdf

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Check for updates

**LhARA: The Laser-hybrid Accelerator for Radiobiological Applications**

*Galen Aymar[1], Tobias Becker[2], Stewart Boogert[3], Marco Borghesi[4], Robert Bingham[1,5], Ceri Brenner[1], Philip N. Burrows[6], Oliver C. Ettlinger[7], Titus Dascalu[8], Stephen Gibson[3], Timothy Greenshaw[9], Sylvia Gruber[10], Dorothy Gujral[11], Claire Hardiman[11], Jonathan Hughes[9], W. G. Jones[8,12], Karen Kirkby[13], Ajit Kurup[8]*, Jean-Baptiste Lagrange[1], Kenneth Long[1,8], Wayne Luk[8], John Matheson[1], Paul McKenna[5,14], Ruth McLauchlan[11], Zulfikar Najmudin[7], Hin T. Lau[8], Jason L. Parsons[15,16], Jaroslaw Pasternak[1,8], Juergen Pozimski[1,8], Kevin Prise[17], Monika Puchalska[18], Peter Ratoff[14,19], Giuseppe Schettino[20,21], William Shields[3], Susan Smith[22], John Thomason[1], Stephen Towe[23], Peter Weightman[8], Colin Whyte[5] and Rachel Xiao[24]*

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# Acknowledgements

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