Imperial College London

Science and Technology Facilities Council

Development of a laser-hybrid approach to the delivery of ion beams for biomedical application

Laser-hybrid Accelerator for Radiobiological Applications to serve the Ion Therapy Research Facility

ITRF / LhARA

Laser-hybrid Accelerator for Radiobiological Applications

K. Long, 18 July, 2024

On behalf of the ITRF/LhARA collaboration

Radiotherapy; the challenge

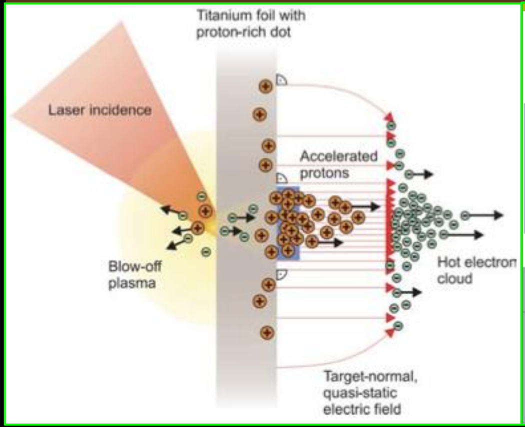
- Cancer: second most common cause of death globally
  - Radiotherapy indicated in half of all cancer patients
- Significant growth in global demand anticipated:
  - 14.1 million new cases in 2012 ⇢ 24.6 million by 2030
  - 8.2 million cancer deaths in 2012 ⇢ 13.0 million by 2030
- Scale-up in provision essential:
  - Projections above based on reported cases (i.e. high-income countries)
  - Opportunity: save 26.9 million lives in low/middle income countries by 2035
- Provision on this scale requires:
  - Development of new and novel techniques … integrated in a
  - Cost-effective *system* to allow a distributed network of RT facilities

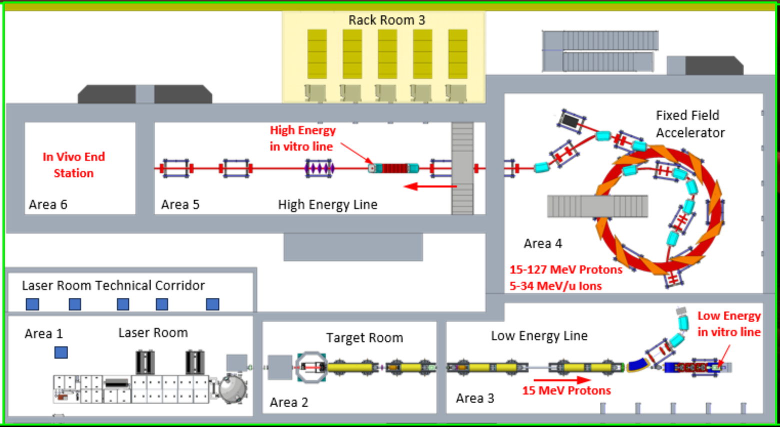
Atun, Lancet Oncol. 2015 Sep;16(10):1153-86

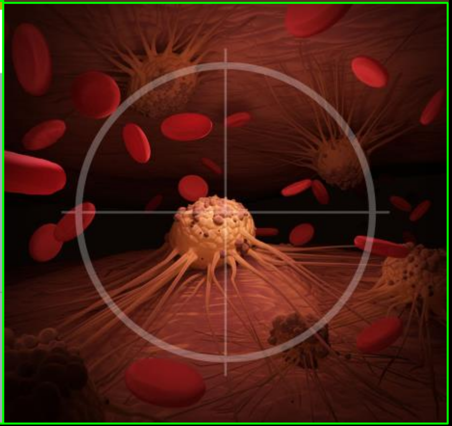
Our ambition is to:

- ***Deliver a systematic and definitive radiation biology programme***
- ***Prove the feasibility of laser-driven hybrid acceleration***
- ***Lay the technological foundations for the transformation of PBT***
  - automated, patient-specific proton and ion beam therapy

LhARA
Laser-hybrid Accelerator for Radiobiological Applications

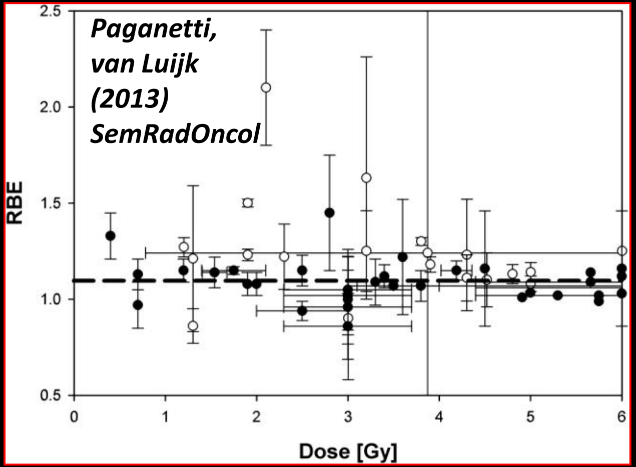


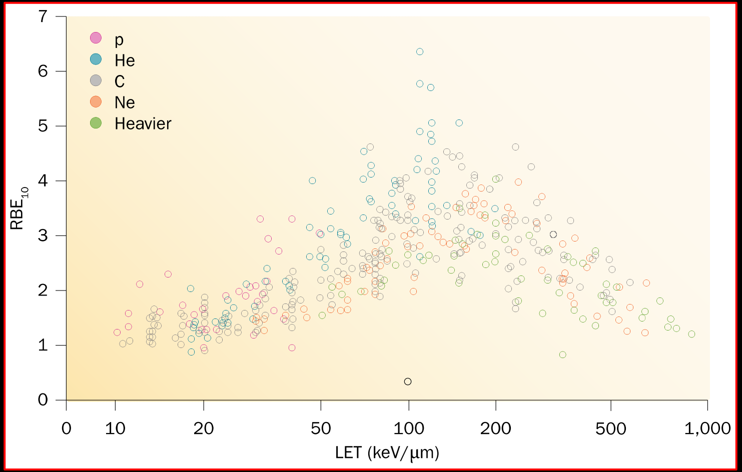




The case for fundamental radiobiology

- Relative biological effectiveness:
  - Defined relative to reference X-ray beam
  - Known to depend on:
    - Energy, ion species
    - Dose & dose rate
    - Tissue type
    - Biological endpoint
- Yet:
  - *p*-treatment planning uses 1.1
  - Effective values are used for C^{6+}
- Maximise the efficacy of PBT now & in the future:
  - Develop systematic programme of radiobiological measurements

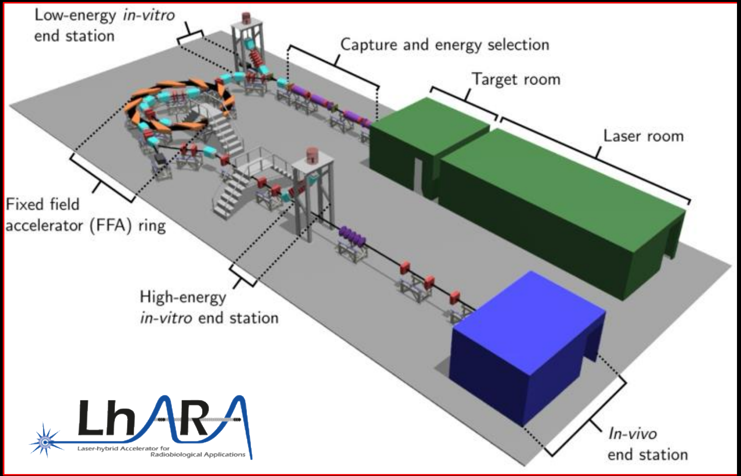




What is LhARA?

A novel, hybrid, approach:

- Laser-driven, high-flux proton/ion source
  - Overcome instantaneous dose-rate limitation
    - Capture at >10 MeV
  - Delivers protons or ions in very short pulses
    - Bunches as short as 10—40 ns
  - Triggerable; arbitrary pulse structure



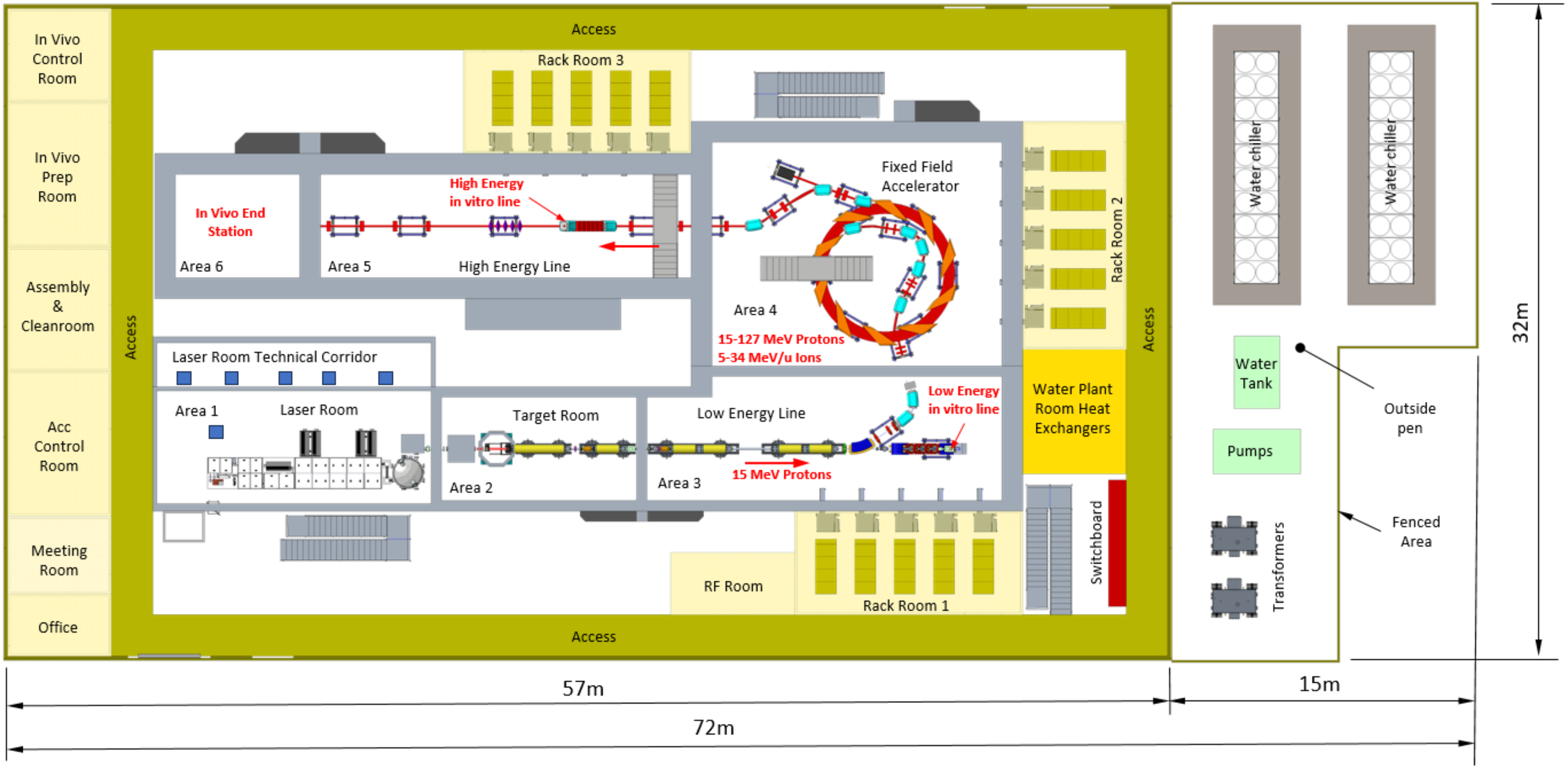
Front. Phys., 29 September 2020; DOI: 10.3389/fphy.2020.567738

- 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

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	1.0×10^9 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



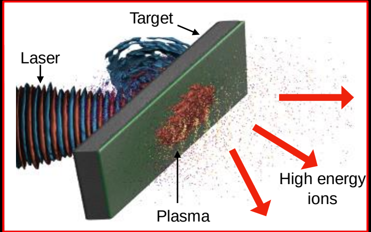
In Vivo Control Room
In Vivo Prep Room
Assembly & Cleanroom
Acc Control Room
Meeting Room
Office
Access
Access
Access
Access
Rack Room 3
Fixed Field Accelerator
High Energy in vitro line
In Vivo End Station
Area 6
Area 5
High Energy Line
Rack Room 2
Area 4
15-127 MeV Protons
5-34 MeV/u Ions
Laser Room Technical Corridor
Area 1
Laser Room
Target Room
Low Energy Line
Low Energy in vitro line
Water Plant Room Heat Exchangers
Area 2
Area 3
15 MeV Protons
Switchboard
RF Room
Rack Room 1
Water chiller
Water chiller
Water Tank
Pumps
Outside pen
Fenced Area
Transformers
32m
57m
15m
72m

Dascalu, Dover, Gray

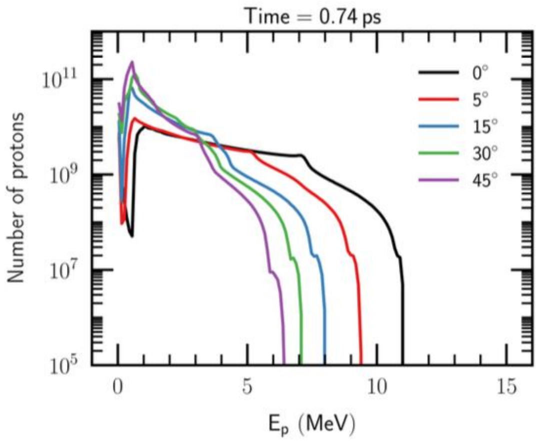
Source: simulation

R&D objectives:

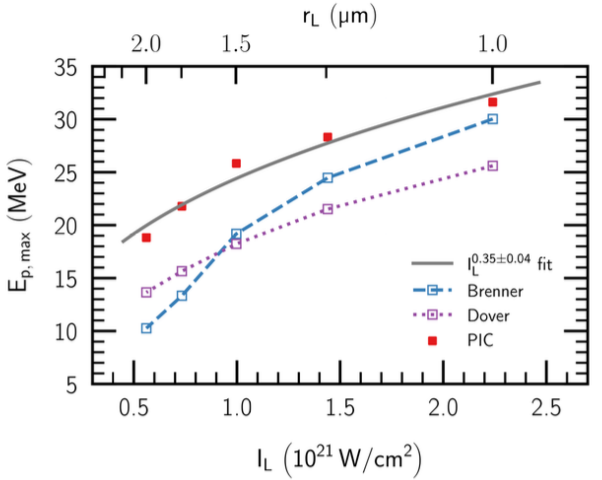
- "Full-scale" tests in conditions approaching LhARA specification
- LhARA-focused diagnostic and targetry development
- High-repetition rate, automation and longevity studies
- Accurate numerical modelling 3D simulation codes



Vary angle of incidence of laser



Vary f-number of focusing optic

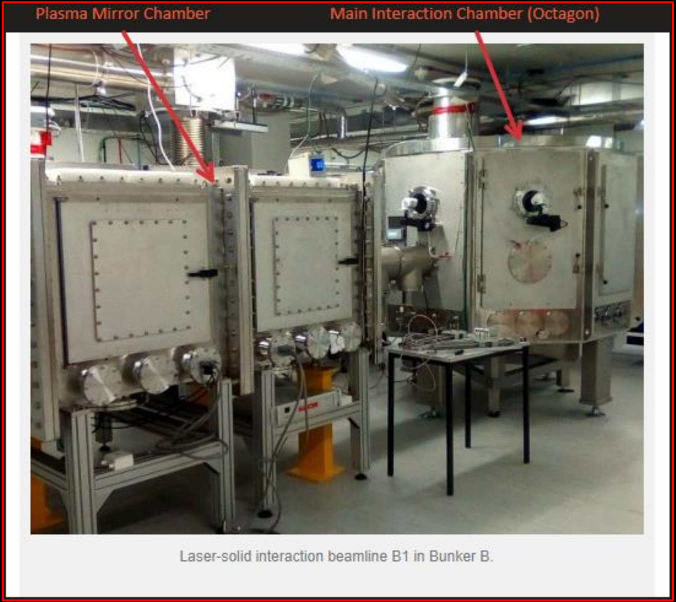


Realistic, 2-stage simulation on ARCHER2 using accurate "pre-plasma" profile

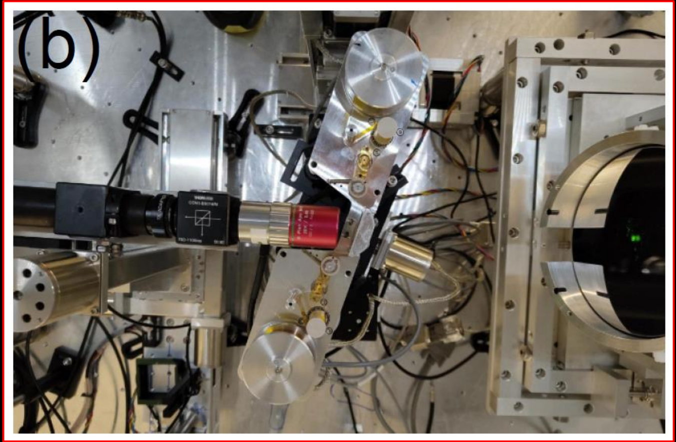
Study proton production as a function of angle of incidence, spot size, proton-layer thickness

Seek to benchmark against data

Source: experiment



Laser-solid interaction beamline B1 in Bunker B.



SCAPA Experiment Team....

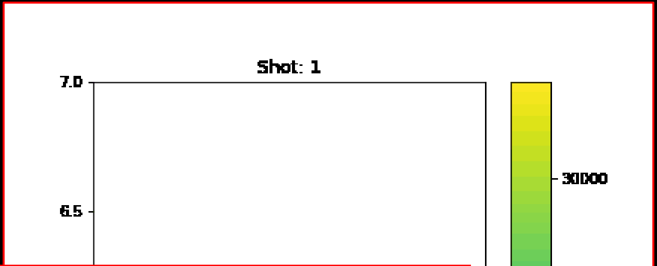
University of Strathclyde
R. Wilson, T. Frazer, E. Dolier, C. McQueen, B. Torrance, R. Nayli and P.McKenna

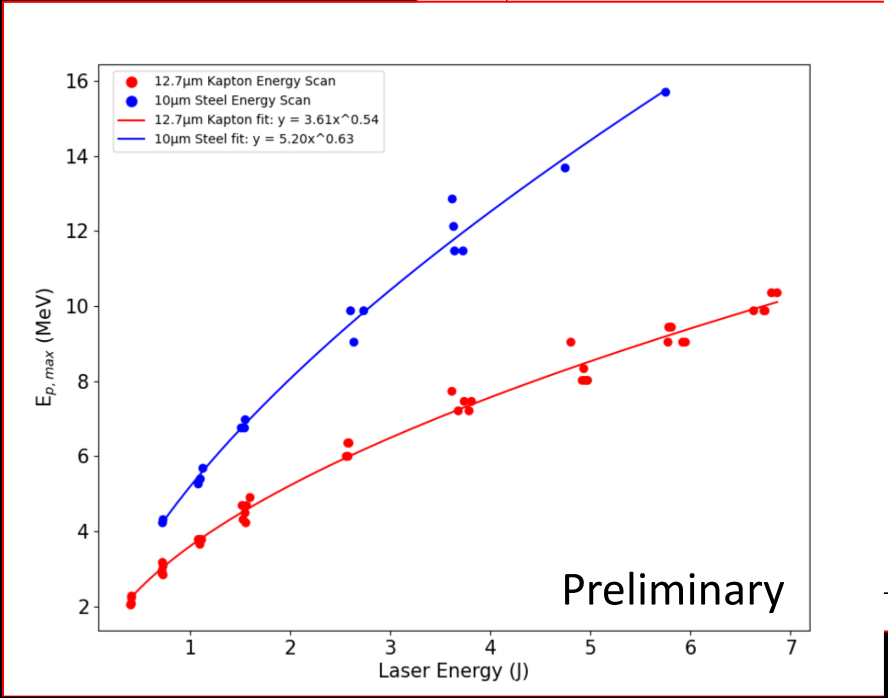
Imperial College
O. Ettlinger, G. Casati and N.P. Dover

Queens University Belfast
P. Parsons and C. Palmer

SCAPA, University of Strathclyde
M. Wiggins, E. Brunetti, G. Manahan, W. Li

Central Laser Facility
J. Green, C. Armstrong, C. Spindloe, W. Robins, S. Astbury



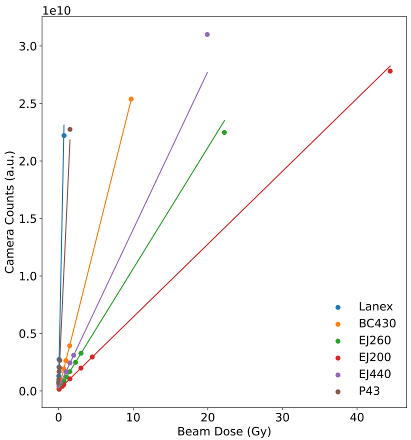


R. Gray

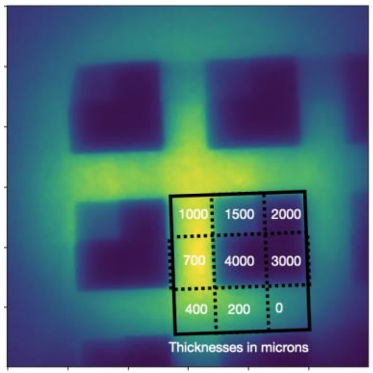
Source: diagnostics & high rep-rate

Diagnostics

Absolute calibration and dose linearity scan



Energy dependent emission scan



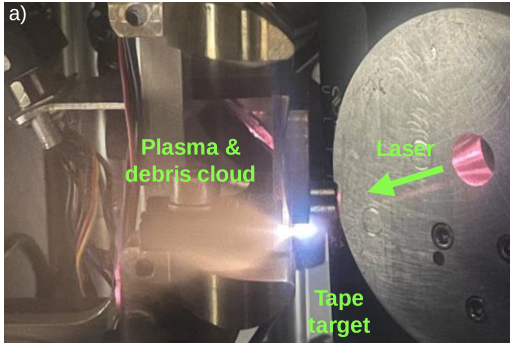
Scintillators: key for high rep rate operation

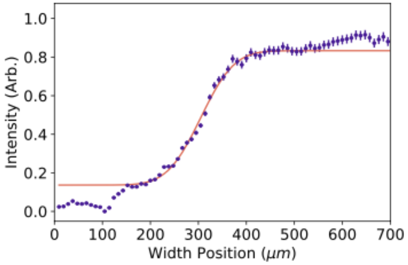
- **Dedicated calibration effort led by N. Dover (ICL):**
  - **Birmingham MC40 cyclotron**

Experimental team (with some missing) - from QUB, CLF, Strathclyde and Imperial

High-rep rate / longevity …

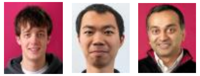
Experimental R&D at ICL - Initial results





- Preliminary experiments run at 5 mJ level (without final amplifier)
- Continuous operation at 100 Hz for 10s minutes
- Plasma formation, x-ray generation (and debris production!) observed

O. Ettlinger, N. Xu, Z. Najmudin



90 mJ of laser energy, 30 fs pulse width at 100 Hz

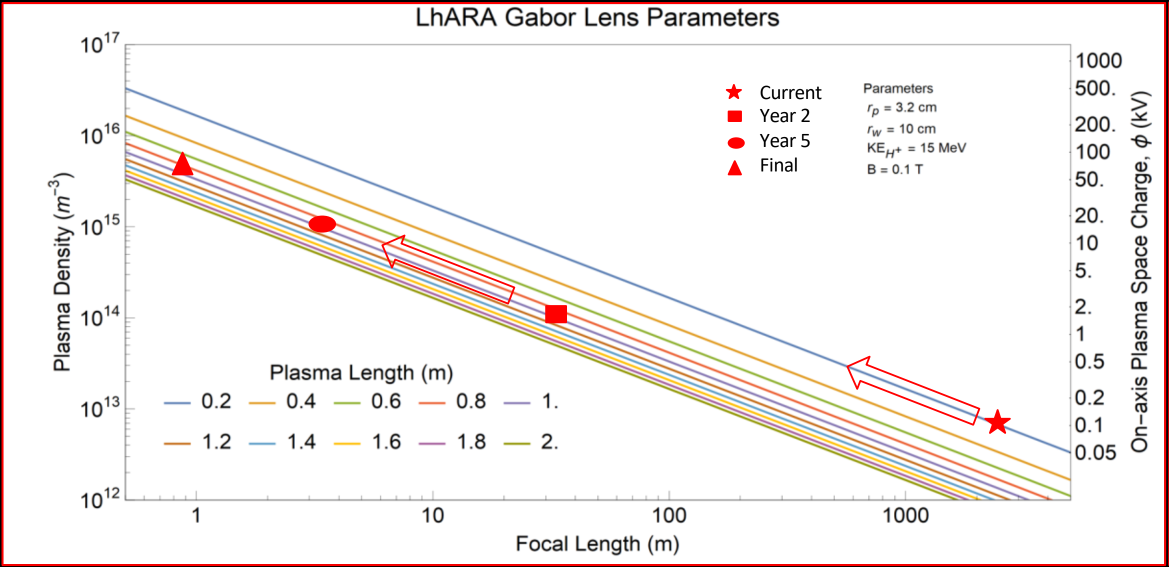
Predicted maximum proton energies ~ few MeV

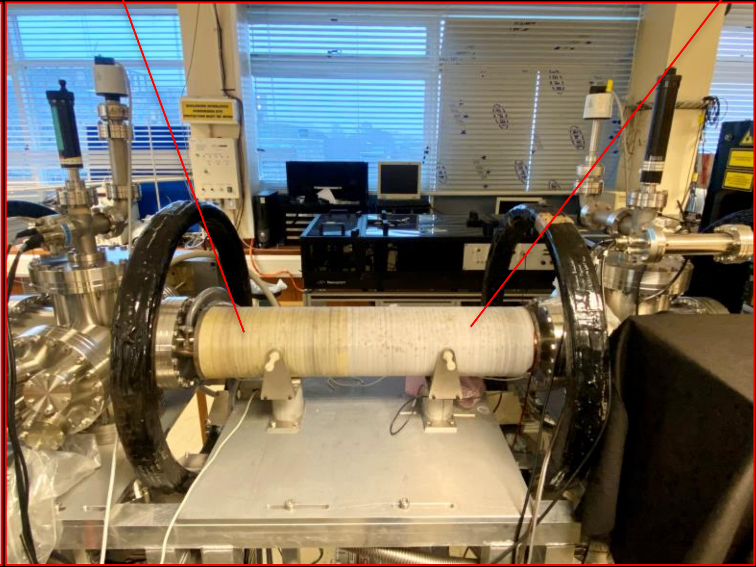
Semi-continuous access allows long term R&D into technical issues in stabilisation, debris, targetry, etc

Ruksasakchai, Isaac, Eriksson, Bertsche

Capture

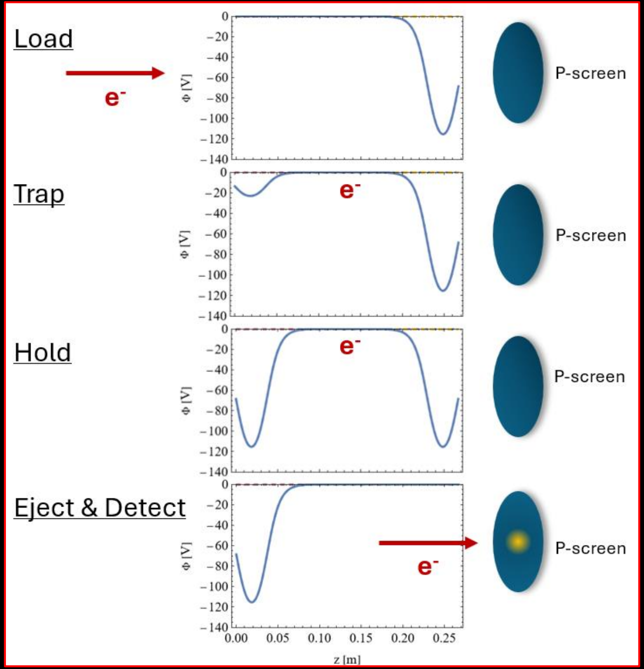
- "Electron-plasma" (Gabor) lens:
  - Strong focusing exploiting electron gas in "Penning/Malmberg" trap

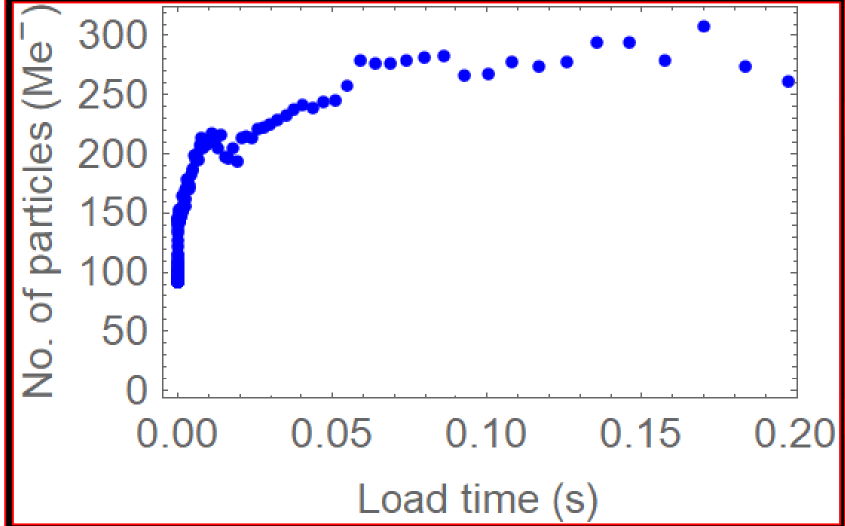


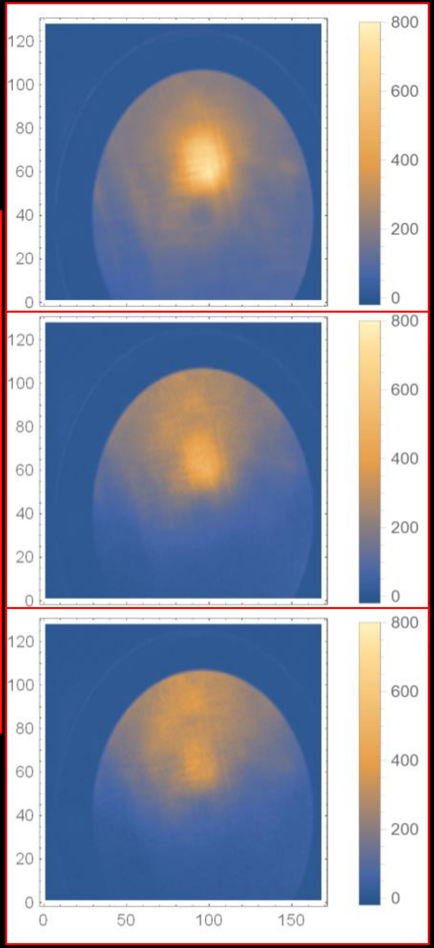


Capture

- **Key issues:**
  - Electron density, plasma stability
- **Measurements on Penning-Malmberg trap at Swansea University**
  - "Rotating wall" to "spin-up" plasma to gain stability







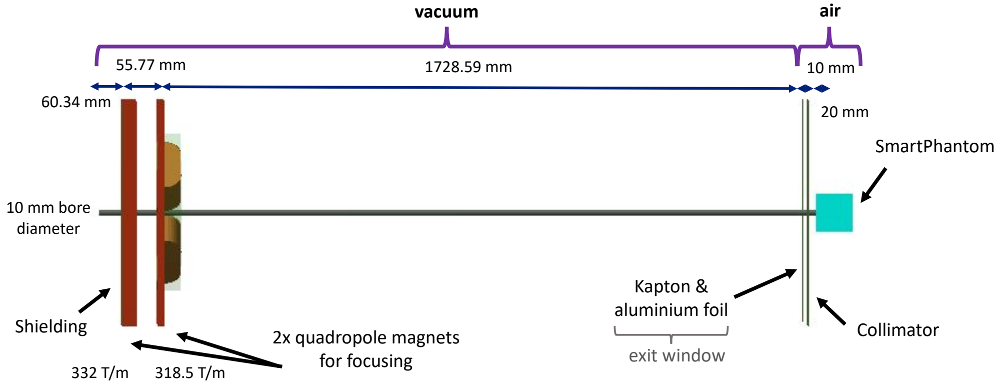
Ruksasakchai, Isaac, Eriksson, Bertsche

- **Ongoing campaign:**
  - Improved diagnostics
  - Numerical analysis to interpret and optimise experiments

Maxouti, Bamber, Cox, Hobson

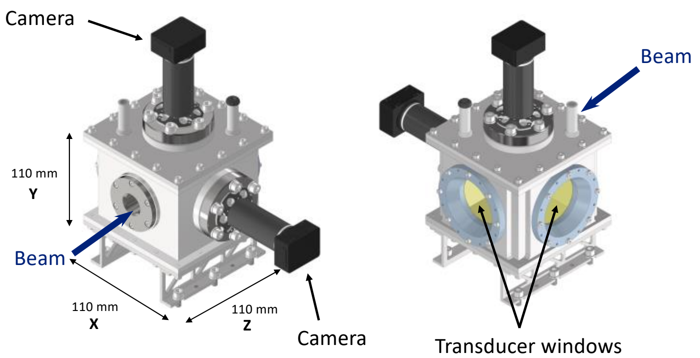
Real-time dose measurment

LION beamline - BDSIM



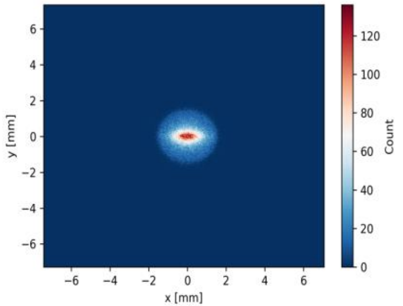
Proposed Instrumentation

The SmartPhantom

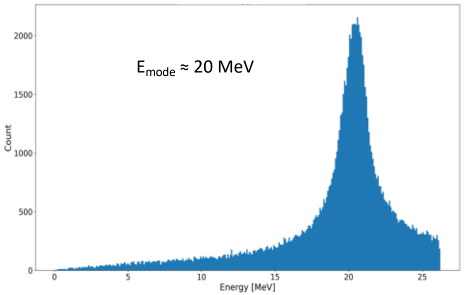


Proton Beam

Spot Size



Energy Spectrum



Bragg peak localization

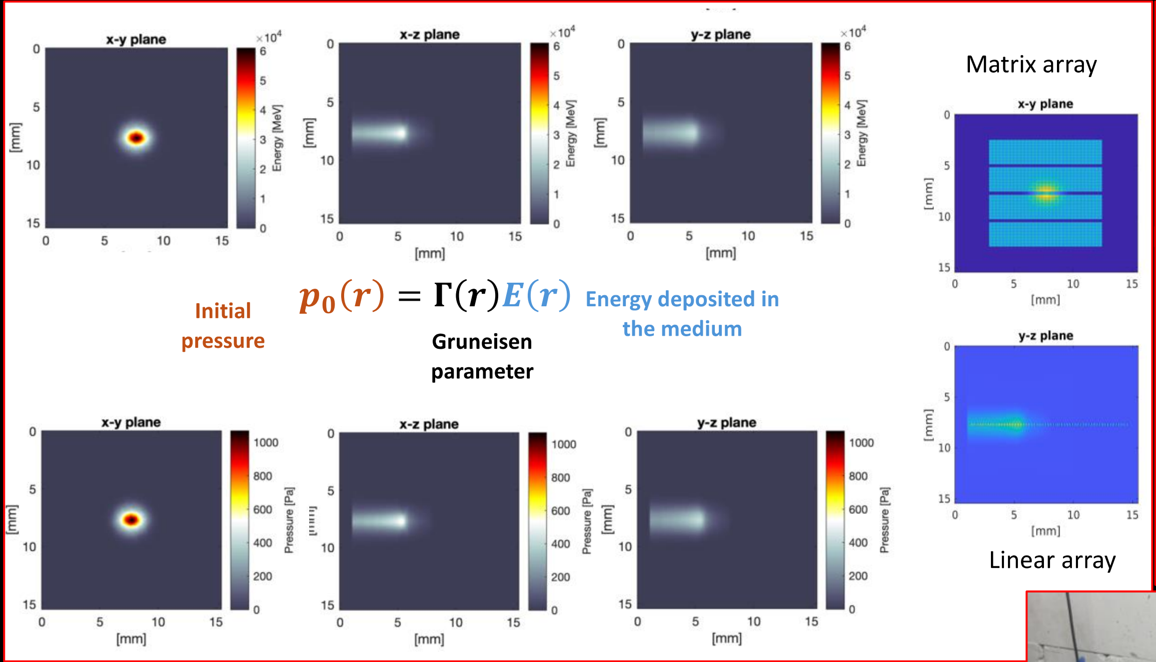
Quantitative 3D dose mapping

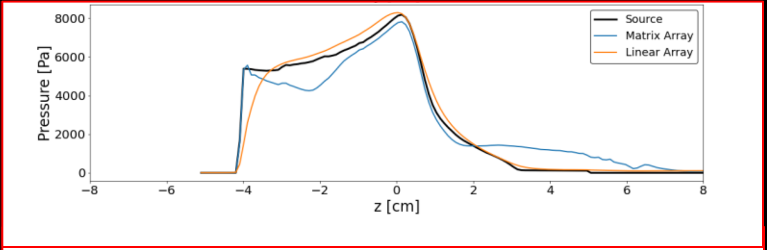
Pulse-to-pulse adaptive treatment

Simultaneous anatomical imaging

Ion-acoustic imaging

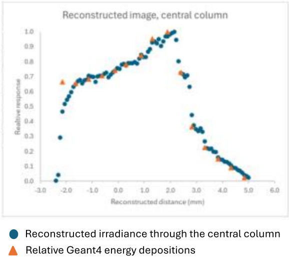
Real-time dose measurement



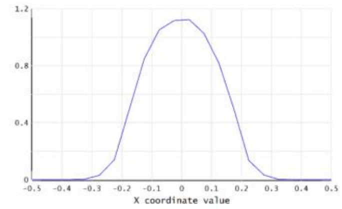


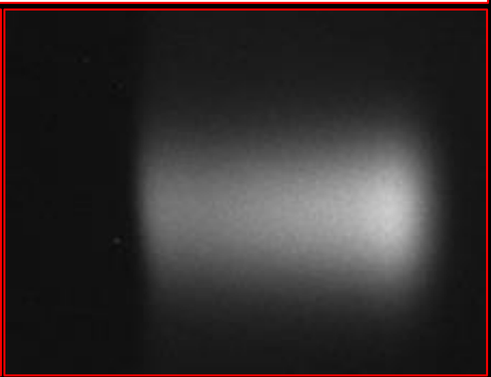
Optical Reconstruction

Central column reconstruction



Reconstruction across a row near the Bragg peak

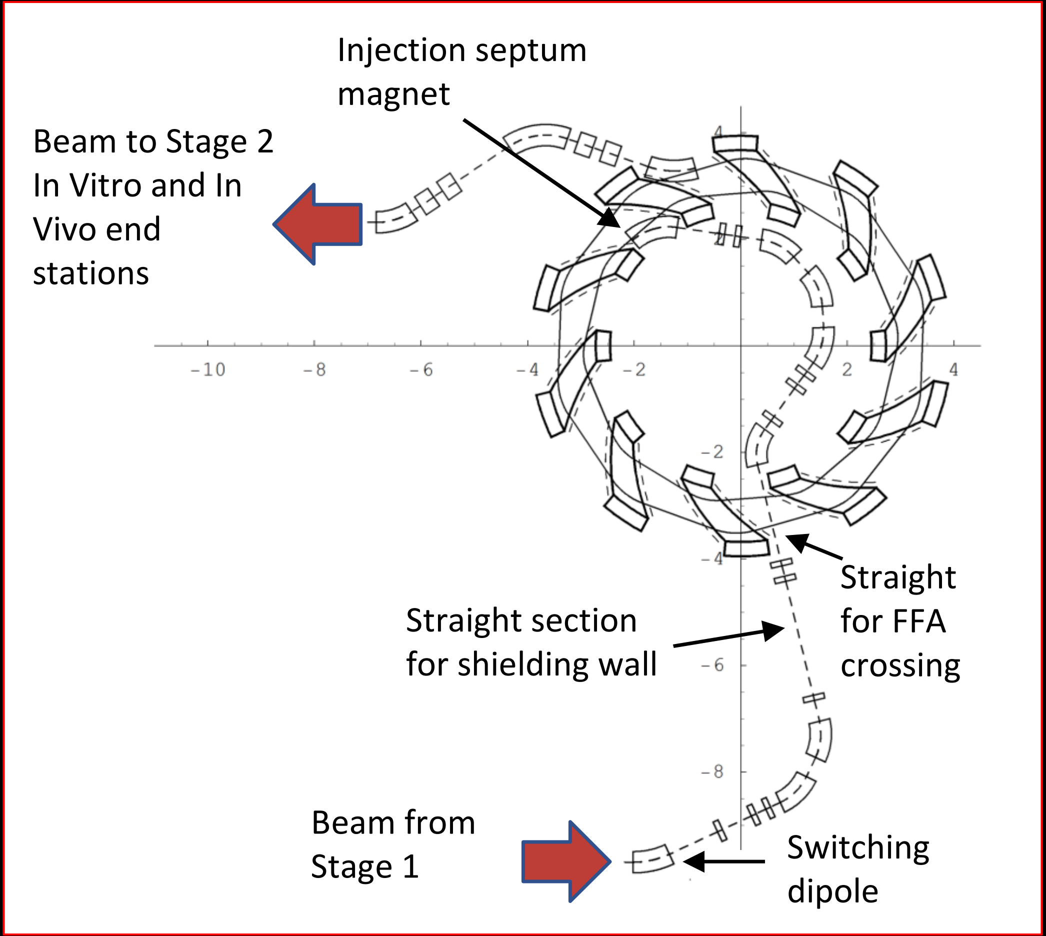




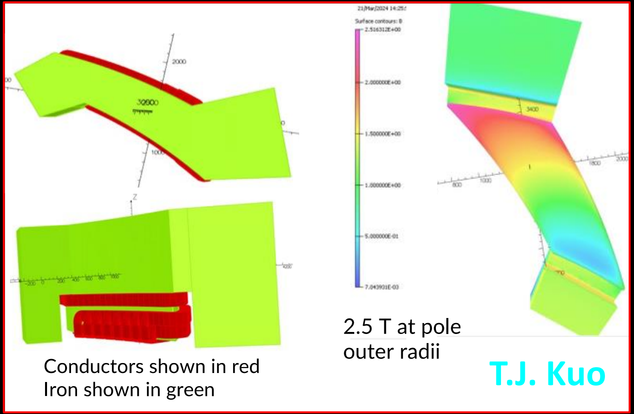
Maxouti, Bamber, Cox, Hobson

Pasternak, Shields, Kuo, Kurup, Hill

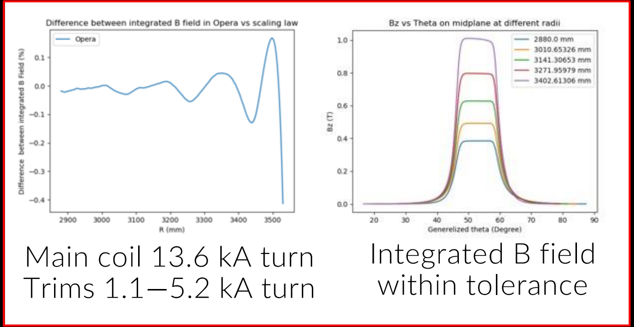
Stage 2: FFA & FFA magnet



FFA magnet



Emerging collaboration with ISIS u/g team



Conclusions

- Significant progress in ITRF/LhARA:
  - Beamline design and optimisation
  - Engineering, initial studies of FFA magnet
  - Initial characterisation of laser-driven source
  - Progress on understanding and stablisation of plasma for Gabor lens
  - Design of ion-acoustic proof-of-principle experiment
  - Peer-group consultation leading to specification of end-station

- Looking forward:
  - Recognition of importance of development of biological programme:
    - First steps in design and specification of proof-of-principle experiment as part of broader radiation-biology programme
  - Project programme for next two years defined

- Exciting programme, but, clear need to *make the case!*

Imperial College London

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

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

University
Clinical
Partners
Accelerator
Laboratory
Industry

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

Queen Mary University of London

UKRI
Science and Technology Facilities Council

CLF central laser facility

ASTeC
Daresbury Laboratory
Particle Physics Department
ISIS Neutron and Muon Source

University of Birmingham | Cyclotron Facility | Positron Imaging Centre

Corerain
鲲云科技

INFN
Catania

The Cockcroft Institute
of Accelerator Science and Technology

CERN

LEO
Cancer Care

Maxeler Technologies
Maximum Performance Computing

The Rosalind Franklin Institute

NPL
National Physical Laboratory

BACKUP

Learning from history

Radiology 47:487–91 (1946)

in tissue is … y, *i.e.*, 15
ev proton is 27 cm. It is and 85 per cent water.
protons can penetrate to can be easily extended t
ody. and densities.[2] The accu
oceeds through the tissue per cent. However, exa
traight line, and the tissue ious tissues can be quic

Wilson, then at Harvard designing 150 MeV cyclotron:

- Identified benefits and properties of proton beams for RT
- Pointed out potential of ions (carbon) and electrons

- **@BioTech:**
  - Develop the *system!*
- **@ energy frontier:**
  - *Innovate* through applications:
    - Can take greater technical risk
    - Reduced timescales, more & more novel machines
    - Recruitment & retention, education, and training