LhARA;
the Laser hybrid Accelerator for Radiobiological Applications

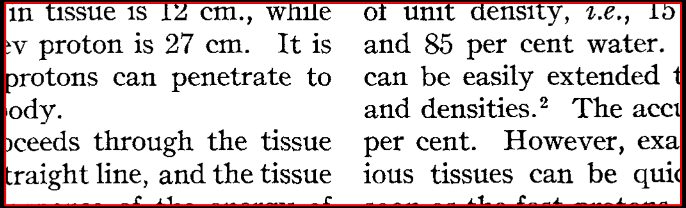
KENNETH LONG; IMPERIAL COLLEGE LONDON/STFC

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

Hadron beams for radiation therapy

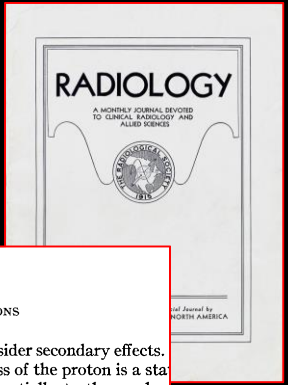
Robert R. Wilson

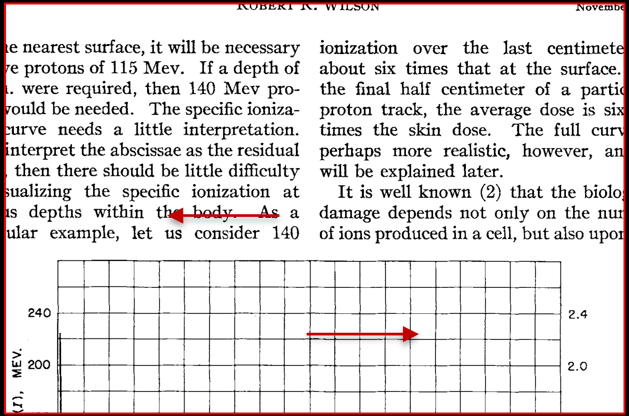
Radiology 47:487–91 (1946)



in tissue is 12 cm., while
ev proton is 27 cm. It is
protons can penetrate to
body.
oceeds through the tissue
traight line, and the tissue

of unit density, *i.e.*, 15
and 85 per cent water.
can be easily extended t
and densities.[2] The accu
per cent. However, exa
ious tissues can be quic



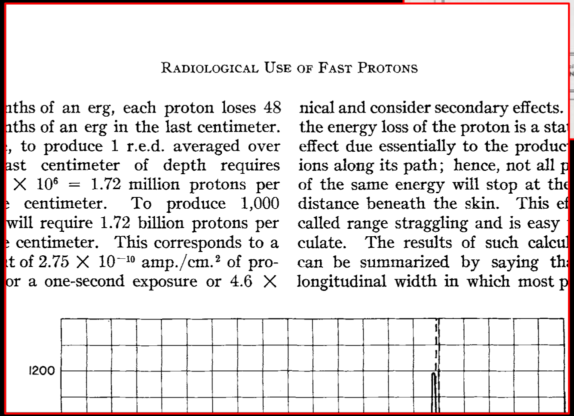


ROBERT R. WILSON

Novembe

e nearest surface, it will be necessary
e protons of 115 Mev. If a depth of
. were required, then 140 Mev pro-
would be needed. The specific ioniza-
curve needs a little interpretation.
interpret the abscissae as the residual
, then there should be little difficulty
sualizing the specific ionization at
s depths within the body. As a
ular example, let us consider 140

ionization over the last centimete
about six times that at the surface.
the final half centimeter of a partic
proton track, the average dose is six
times the skin dose. The full curv
perhaps more realistic, however, an
will be explained later.
It is well known (2) that the biolo
damage depends not only on the num
of ions produced in a cell, but also upon



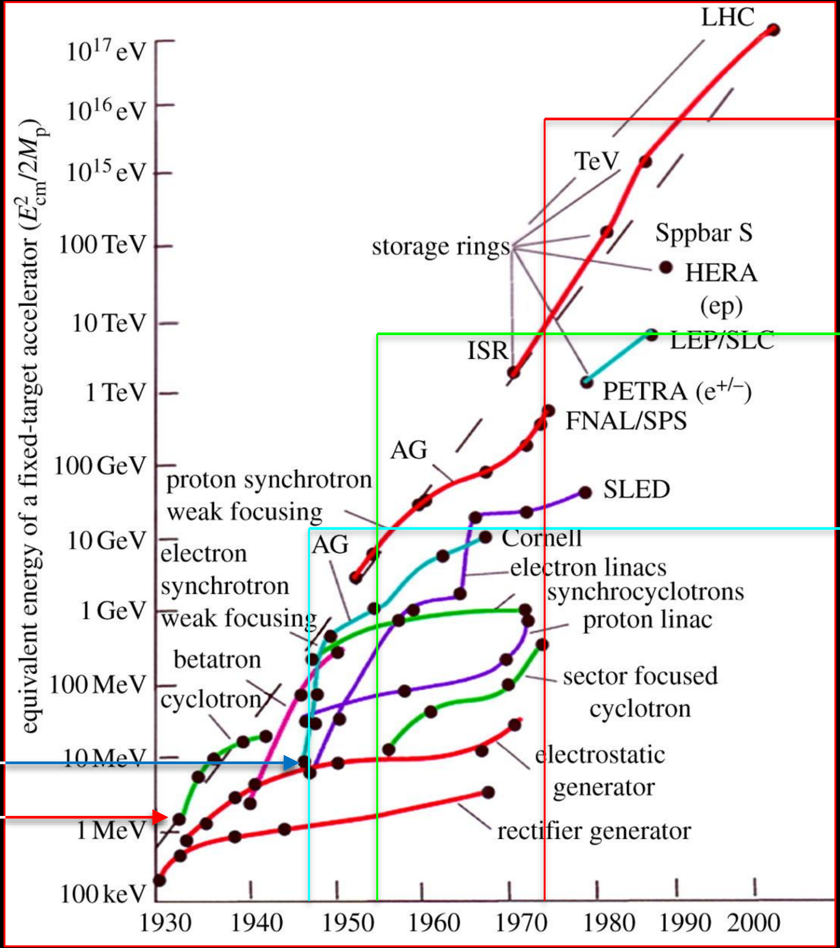
RADIOLOGICAL USE OF FAST PROTONS

nths of an erg, each proton loses 48
nths of an erg in the last centimeter.
, to produce 1 r.e.d. averaged over
ast centimeter of depth requires
$\times 10^6$ = 1.72 million protons per
e centimeter. To produce 1,000
will require 1.72 billion protons per
e centimeter. This corresponds to a
t of 2.75×10^{-10} amp./cm.[2] of pro-
or a one-second exposure or 4.6 $\times$

nical and consider secondary effects.
the energy loss of the proton is a sta
effect due essentially to the produc
ions along its path; hence, not all p
of the same energy will stop at the
distance beneath the skin. This ef
called range straggling and is easy
culate. The results of such calcul
can be summarized by saying tha
longitudinal width in which most p

- **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**

Evolving state of the art



Cancer therapy (Mass Gen Hosp) 1974

Clinical studies (pituitary gland); 1954

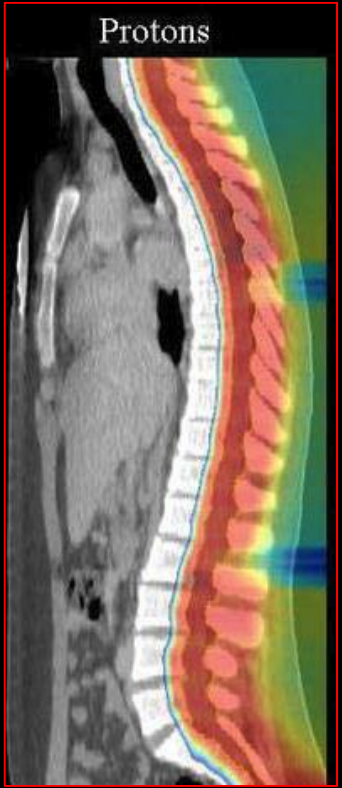
Biological studies; 1948

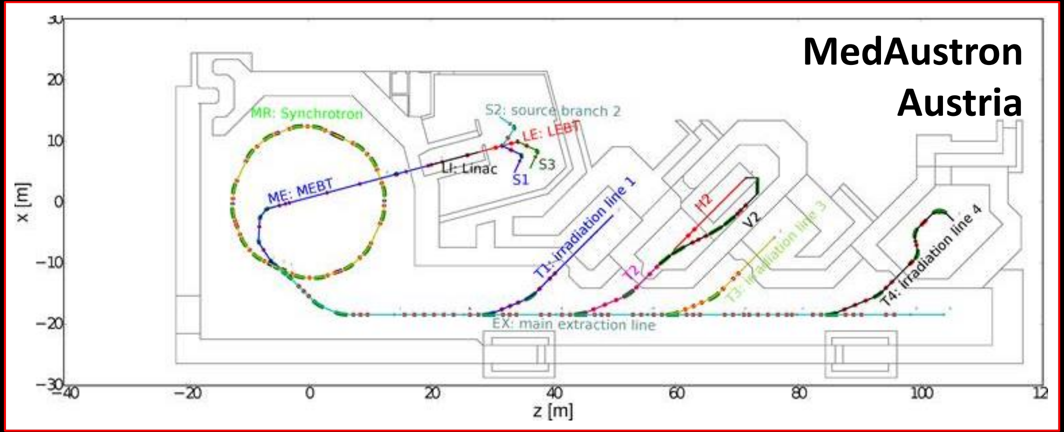
Synchrotron Goward, Barnes; 1946

Cyclotron Laurence; 1932

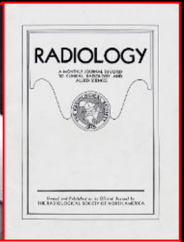
Particle beam therapy today

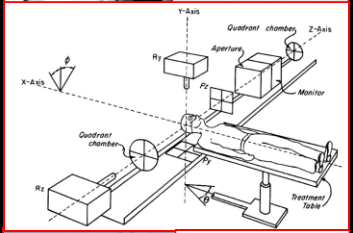
Cyclotron based





Synchrotron based

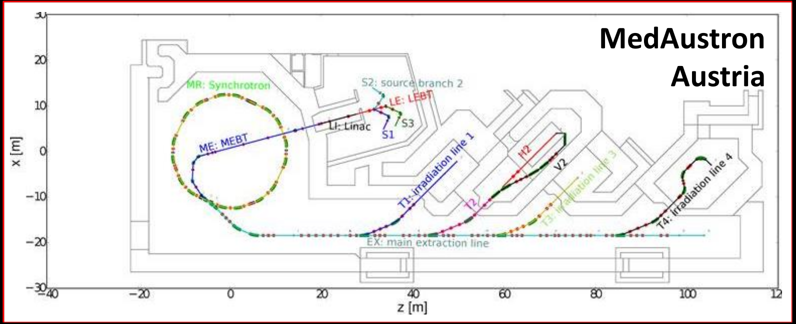




1946

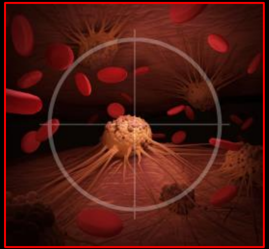
↓

1960



LhARA

Laser-hybrid Accelerator for Radiobiological Applications



1970 1980 1990 2000 2010 2020 2030 2040 2050

Plan

- Challenges and opportunities
- Radiobiology
- LhARA
- Conclusions

LhARA; the Laser-hybrid Accelerator for Radiobiological Applications

CHALLENGES AND OPPORTUNITIES

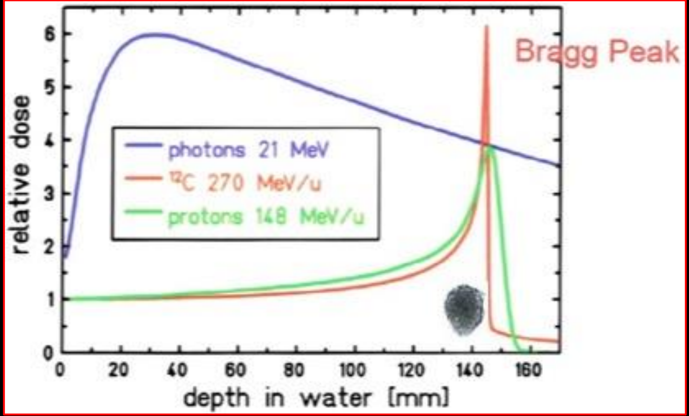
Radiotherapy; the challenge

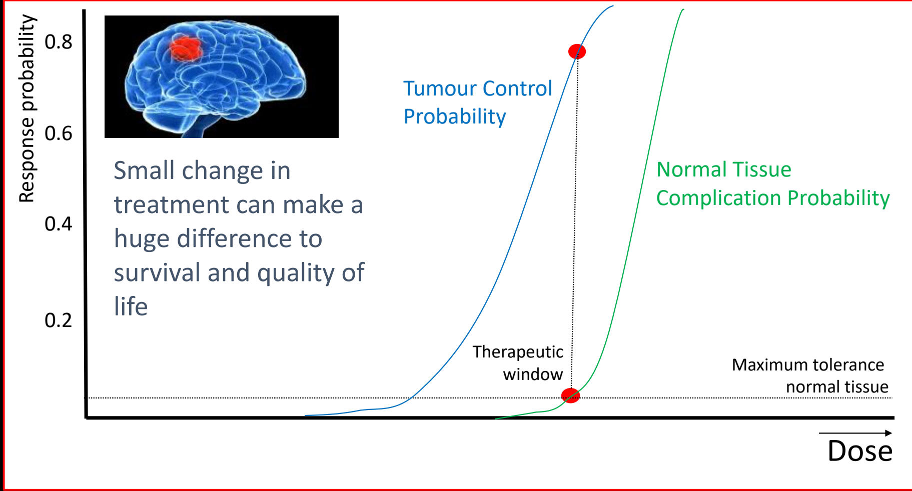
- Cancer: second most common cause of death globally
  - Radiotherapy indicated in half of all cancer patients
- Significant growth in global demand anticipated:
  - 14.1 million new cases in 2012 ⇢ 24.6 million by 2030
  - 8.2 million cancer deaths in 2012 ⇢ 13.0 million by 2030
- Scale-up in provision 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

The benefit of particles

- Maximise therapeutic benefit by:
  - Maximising damage to tumour
  - Minimising damage to healthy tissue





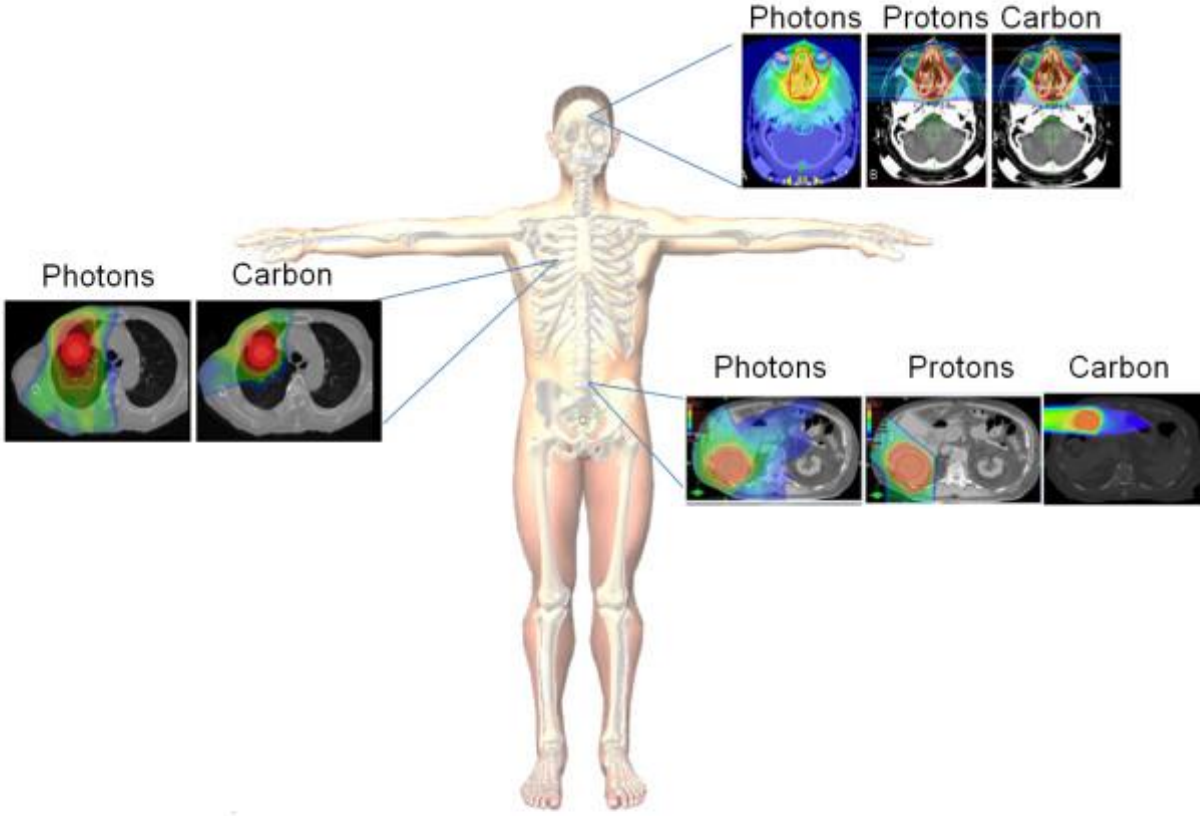
- X-ray therapy:
  - Modality used in most radiotherapy
  - Dose falls exponentially with depth
  - Proximity of sensitive organs limits dose to tumour

There is a strong rationale for the clinical benefit of proton and carbon therapies, but current evidence is limited

Therapy	Rationale for clinical benefit
Proton	▪ Deliver a higher, targeted radiation dose with decreased toxicity to surrounding tissue compared with photon therapy, especially near critical structures
Carbon	▪ Further increase target tissue damage with decreased secondary tissue affected compared with proton ▪ Specific potential benefit with intractable radio-resistant tumors

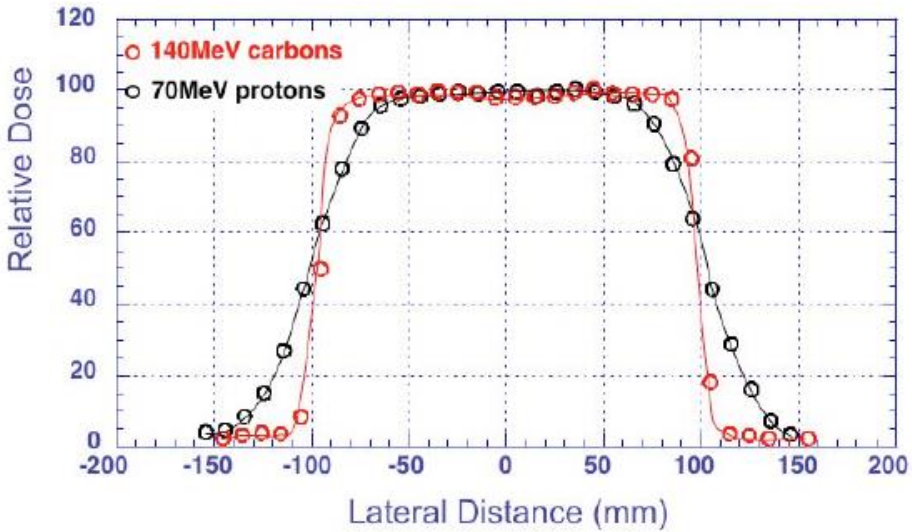
A. Giacca;
[RAL Lecture, 28Apr22]

Superior Dose Distribution of Carbon Ions Compared to Protons and Photons



A. Giacca;
RAL Lecture, 28Apr22

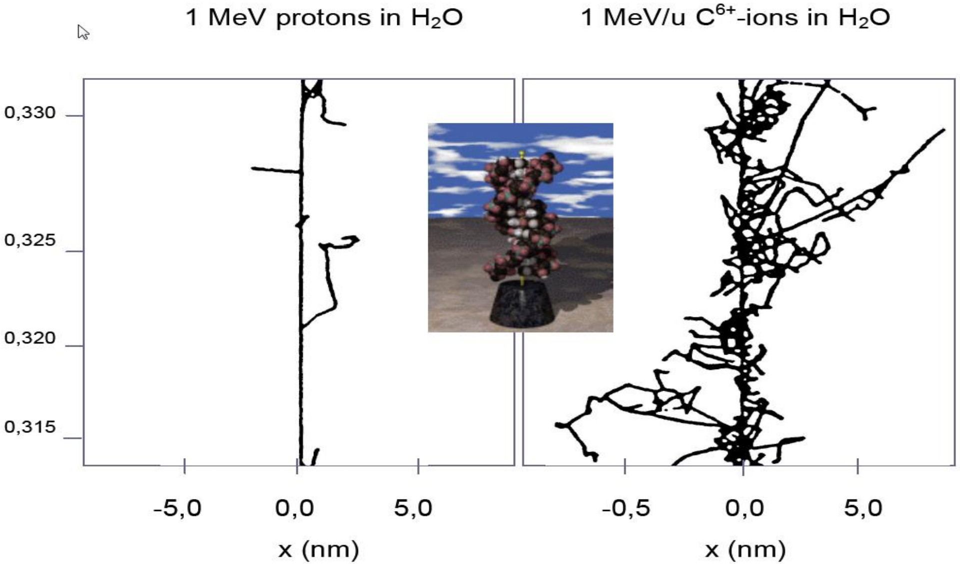
Carbon Ions Provide Highly Localized Tumor Deposition of Dose (Sharper Transverse Edge)



Better Localization

- Tighter deposition in depth (Bragg peak is narrower)
- Transverse deposition is more narrowly collimated
- **Less dose to the healthy tissue**

Carbon Ions Induce More Lethal Damage Per Unit Dose than Photons or Protons



Increased Biological Effectiveness:

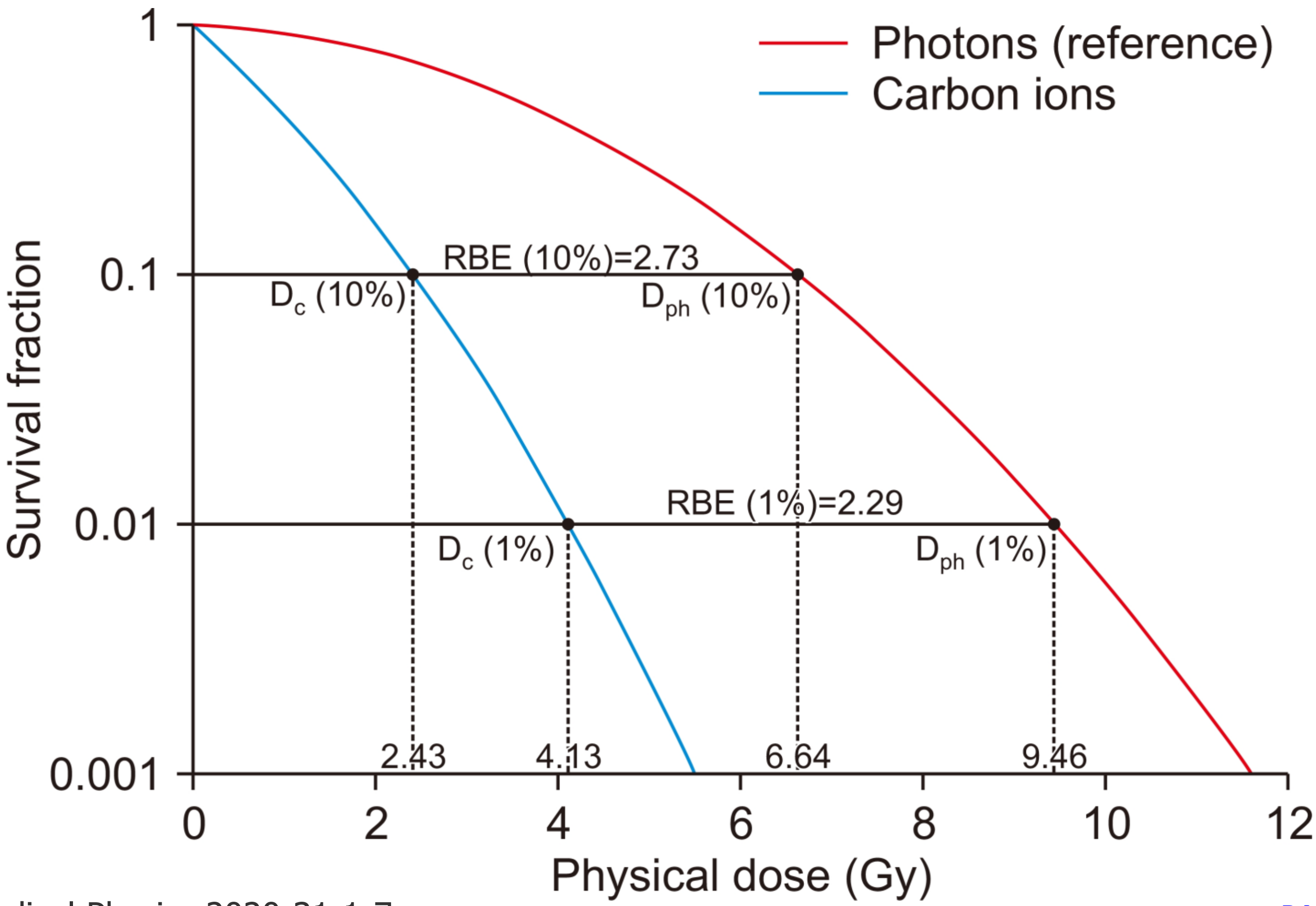
Relative Biological Effectiveness is 3 times protons

- Reduces # fractionations by ~ 2: greater patient throughput/compliance
- Countermands radio-resistance: non-repairable, double-strand breaks

Production of positrons permits active monitoring using PET

A. Giacca;
RAL Lecture, 28Apr22

Cell Survival Based on the LQ model



Progress in Medical Physics 2020;31:1-7

A. Giacca;
RAL Lecture, 28Apr22

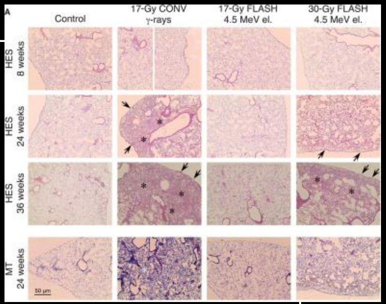
The need for a step-change in capability

- Growing recognition of benefits of PBT worldwide:
  - 70 PBT centres in operation; 40 under construction
- 'Incremental' development of technique
  - Existing suppliers
  - New initiatives

- To meet the Radiotherapy Challenge require transformative techniques:
  - LhARA!

Furthermore … exciting indications of additional benefits of novel beams …

The benefit of novel beams …



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

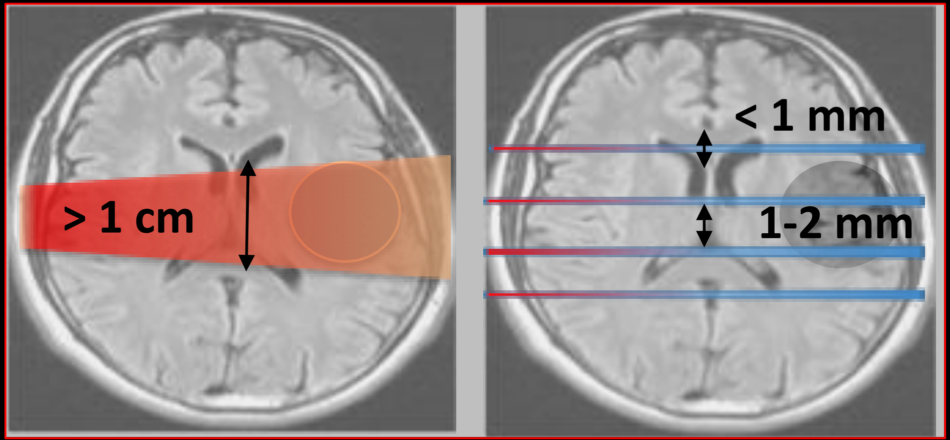
Time line:

- **Initial reports: 2014 (e.g. Flauvadon et al, STM Jul 2014)**
- **Confirmation in mini-pig & cat: 2018 (Clin. Cancer Research 2018)**
- **First treatment 2019 (Bourhis et al, Rad.Onc. Oct 2019)**

The benefit of novel beams …

Worked example: micro beams

Conventional regime : > 1 cm diameter; homogeous
Microbeam regime : < 1 mm diameter; no dose between 'doselets'



Remarkable increase of normal rat brain resistance.

[Dilmanian et al. 2006, Prezado et al., Rad. Research 2015]

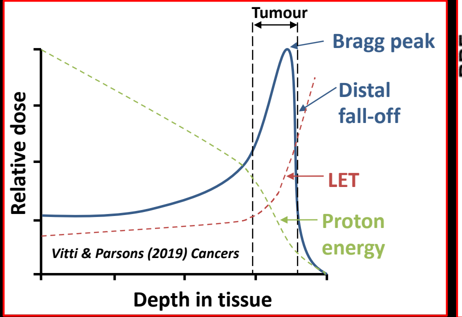
Dose escalation in the tumour possible – larger tumor control prob.

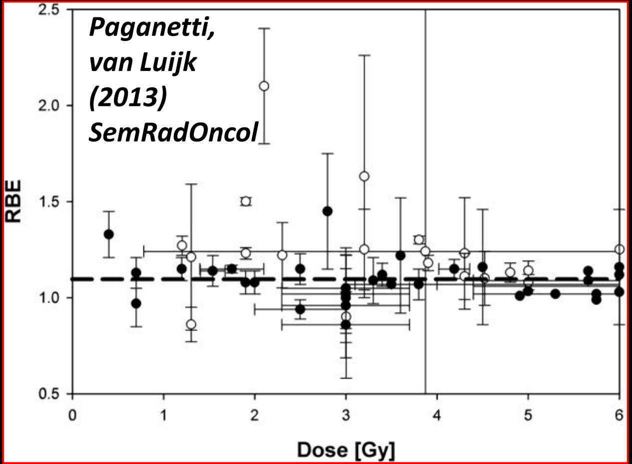
LhARA; the Laser-hybrid Accelerator for Radiobiological Applications

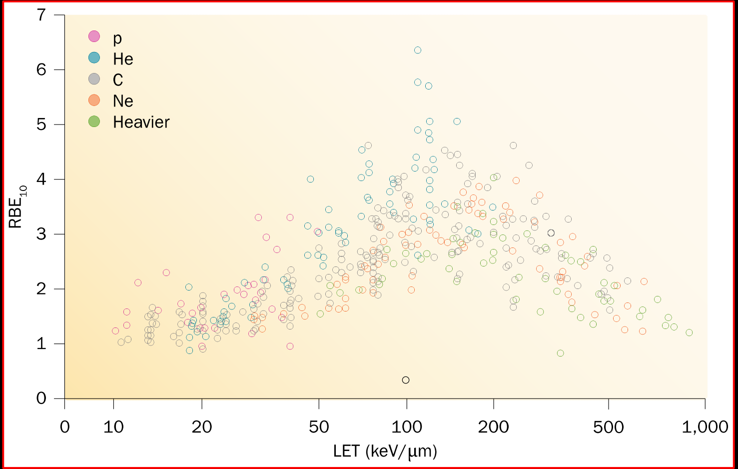
RADIOBIOLOGY

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:
  - Require systematic programme to develop full understanding of radiobiology

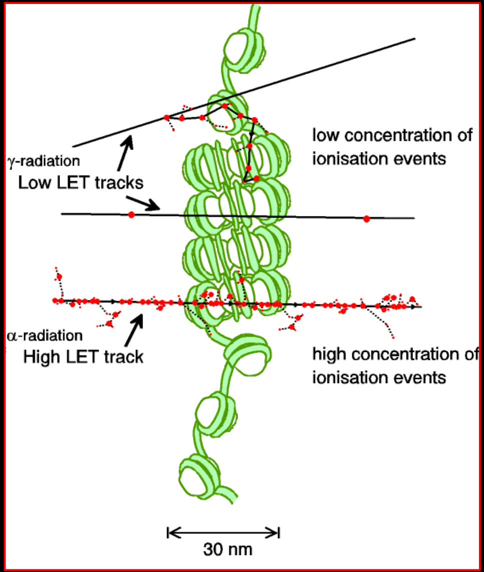


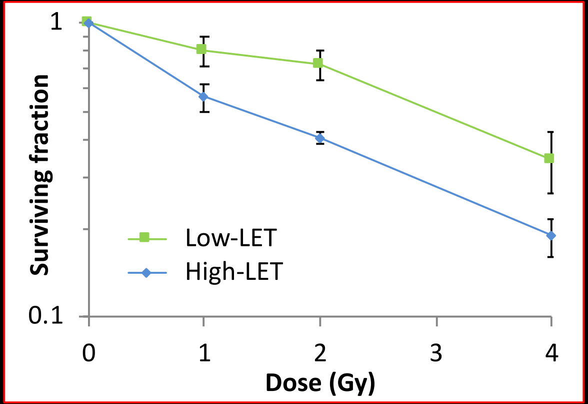




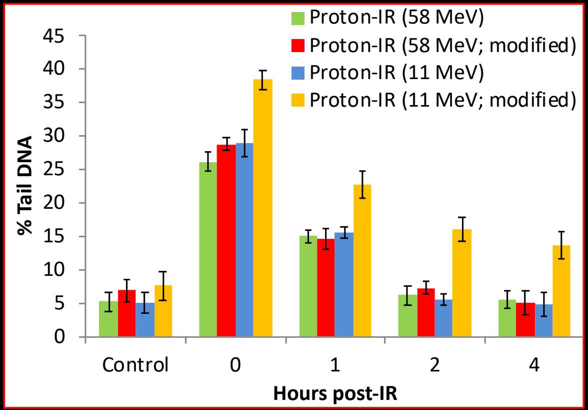
Biological impact from the physics of ionisation

- **Low-LET radiation:**
  - *Repairable* single/double strand breaks





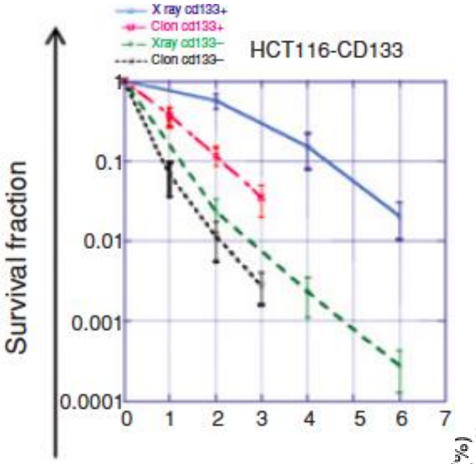
- **High-LET radiation:**
  - *Complex* DNA lesions
    - Multiple DNA pathways
    - More difficult to repair
    - Enhances cell death



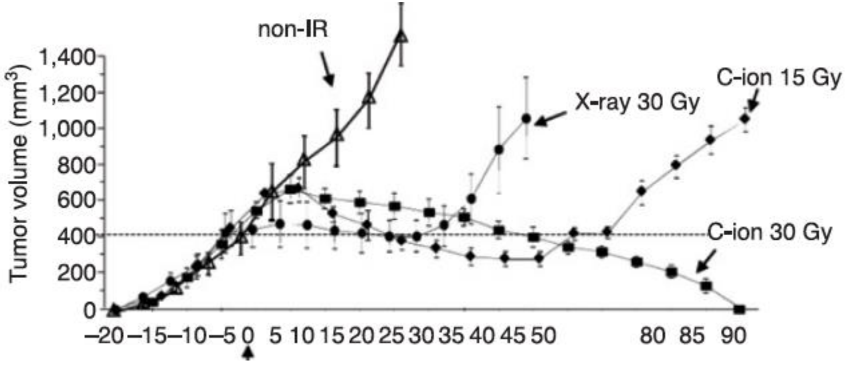
- **Programmatic approach:**
  - Dynamic studies of impact of radiation
  - Interpret with advanced computer models (e.g. G4DNA)

Carbon is More Effective In Killing Cancer Stem Cells

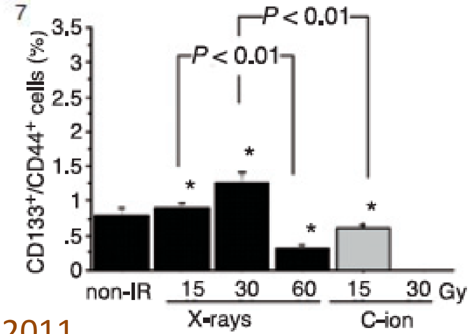
In vitro clonogenic survival

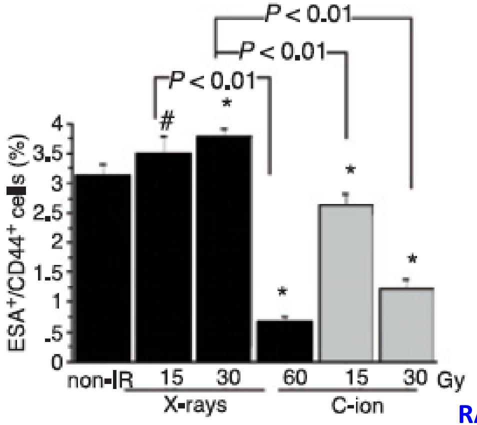


In vivo growth by beam type and dose



% putative CSC- like
in vivo after RT

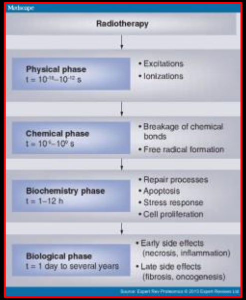




Cui X et al, Cancer Research 2011

A. Giacca;
RAL Lecture, 28Apr22

Radiobiology in new regimens



Time domain

Space domain

The ideally flexible beam facility can deliver it all!

⇒ substantial opportunity for a step-change in understanding!

Energy

Ion species

In combination and with chemo/immuno Therapies

Multidisciplinary approach essential

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
Partners
Accelerator
Laboratory
Industry

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

Central Laser Facility

Swansea University Prifysgol Abertawe

University of Birmingham | Positron Imaging Centre

University of Birmingham | Cyclotron Facility

The Cockcroft Institute of Accelerator Science and Technology

Corerain 鲲云科技

LEO Cancer Care

Maxeler Technologies Maximum Performance Computing

The Rosalind Franklin Institute

NPL National Physical Laboratory

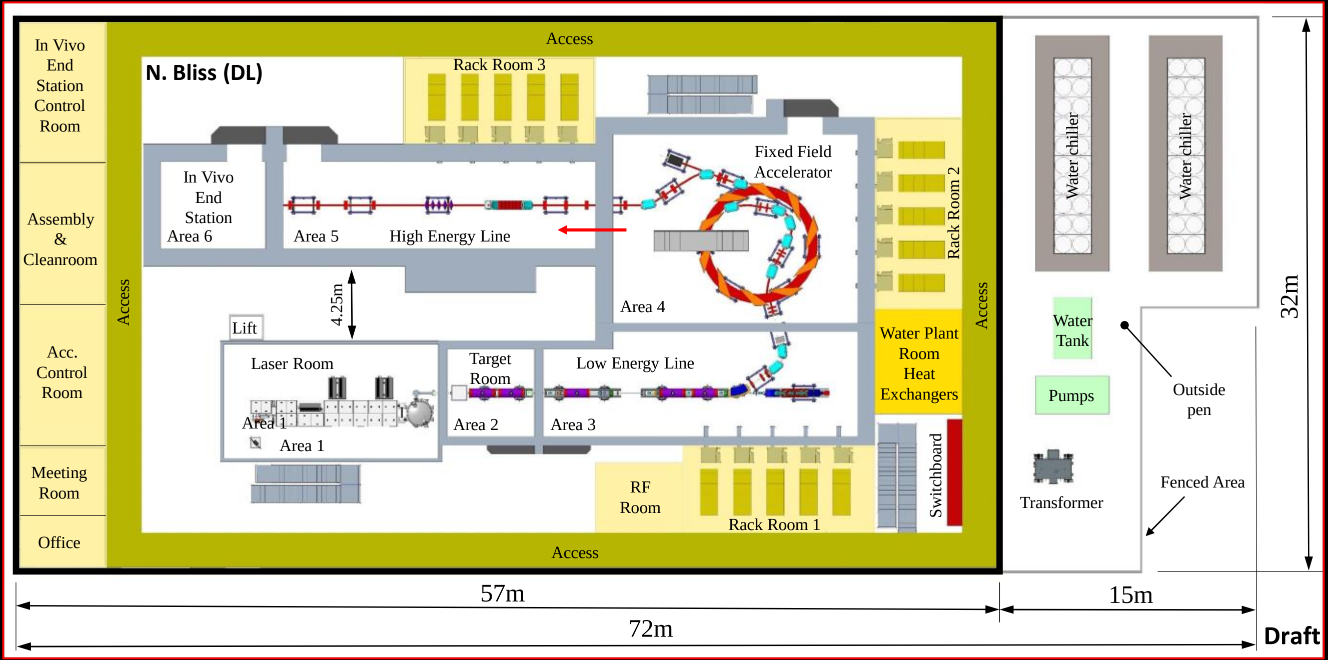
LhARA Laser-hybrid Accelerator for Radiobiological Applications

LhARA; the Laser-hybrid Accelerator for Radiobiological Applications

LHARA

Laser-hybrid Accelerator for Radiobiological Applications

- Novel, hybrid, approach:
  - High-flux, laser-driven proton/ion source:
    - Overcome instantaneous dose-rate limitation
    - Delivers protons or ions in very short pulses:
      - Pulse length 10 – 40 ns
    - Arbitrary pulse structure
  - Novel plasma-lens capture & focusing
  - Fast, fixed-field (FFA) post acceleration



⇒ compact, uniquely flexible facility

LhARA
Laser-hybrid Accelerator for Radiobiological Applications

Vision and ambition

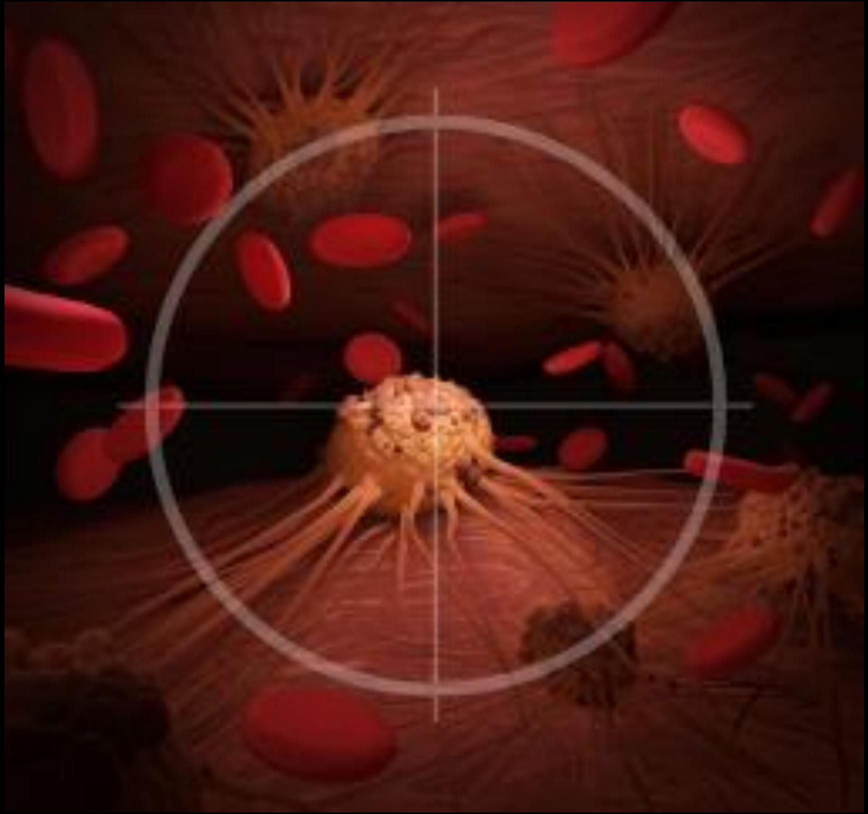
LhARA will be a uniquely-flexible, novel system that will:

- ***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**

LhARA collaboration's mission

Create a uniquely-flexible, novel system that will:

- Deliver a systematic and definitive radiobiology programme
- Prove the feasibility of the laser-hybrid approach
- Lay the foundations for transformative ion-beam therapy
  - Highly automated, patient-specific
    - Implies triggerable source, online imaging, integrated fast feedback and control



Laser-hybrid Accelerator for Radiobiological Applications

A novel, hybrid, approach:

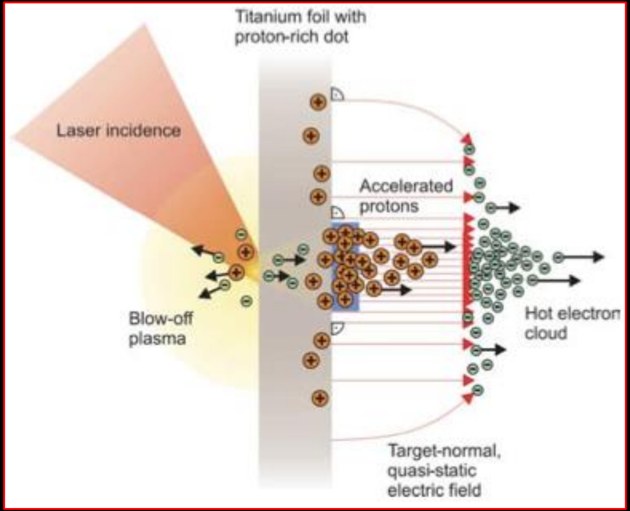
- Laser-driven, high-flux proton/ion source
  - Overcome instantaneous dose-rate limitation
    - Capture at >10 MeV
  - Delivers protons or ions in very short pulses
    - Bunches as short as 10—40 ns
  - Triggerable; arbitrary pulse structure
- Novel "electron-plasma-lens" capture & focusing
  - Strong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

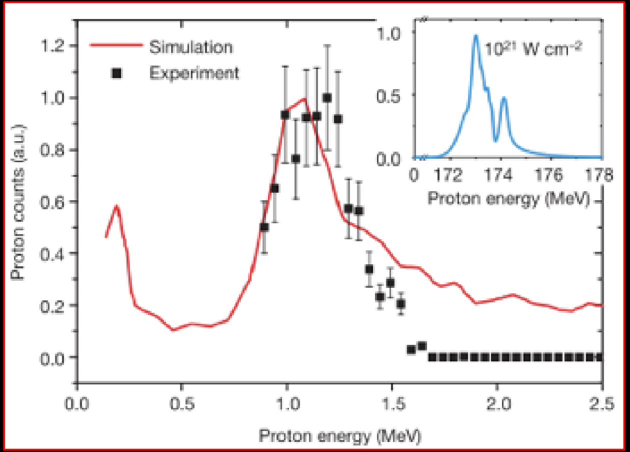
	12 MeV Protons	15 MeV Protons	127 MeV Protons	33.4 MeV/u Carbon
Dose per pulse	7.1 Gy	12.8 Gy	15.6 Gy	73.0 Gy
Instantaneous dose rate	1.0×10^9 Gy/s	1.8×10^9 Gy/s	3.8×10^8 Gy/s	9.7×10^8 Gy/s
Average dose rate	71 Gy/s	128 Gy/s	156 Gy/s	730 Gy/s

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

Sheath acceleration



Schwoerer, H. et al., 2006; Nature, 439(7075).



- 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

Many initiatives in Americas, Europe, Asia

Applications in biological research, ambition to push toward clinical application …

A selection …

- Phys Lett A. (2002) 299:240–7. doi: 10.1016/S0375-9601(02)00521-2
- Med Phys. (2003) 30:1660–70. doi: 10.1118/1.1586268
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- New J Phys. (2010) 12:85003. doi: 10.1088/1367-2630/12/8/085003
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- J Instrum. (2017) 12:C03084. doi: 10.1088/1748-0221/12/03/C03084
- A-SAIL Project. (2020). Available online at: https://www.qub.ac.uk/research-centres/A-SAILProject/
- Vol. 8779. Prague: International Society for Optics and Photonics. SPIE (2013). p. 216–25.
- Vol. 11036. International Society for Optics and Photonics. SPIE (2019). p. 93–103.
- Nuovo Cim C. (2020) 43:15. doi: 10.1393/ncc/i2020-20015-6
- 10th International Particle Accelerator Conference. Melbourne, VIC (2019). p. TUPTS005
- …

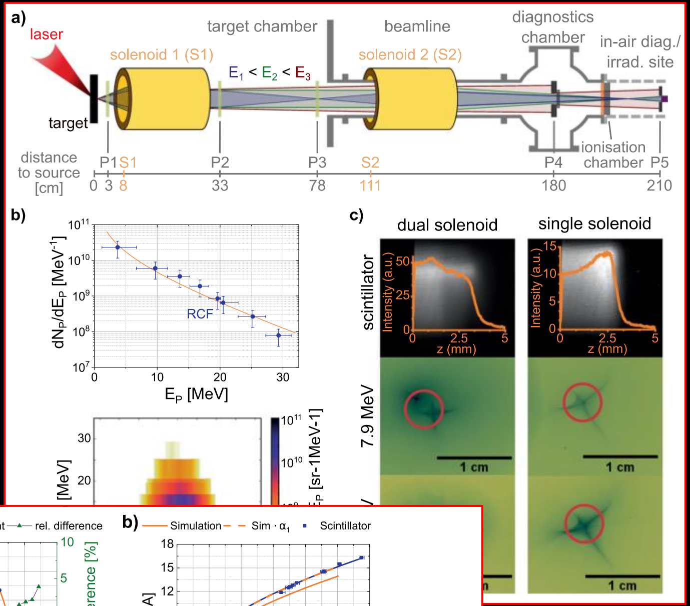
I will not attempt a review, choosing instead to focus on opportunity

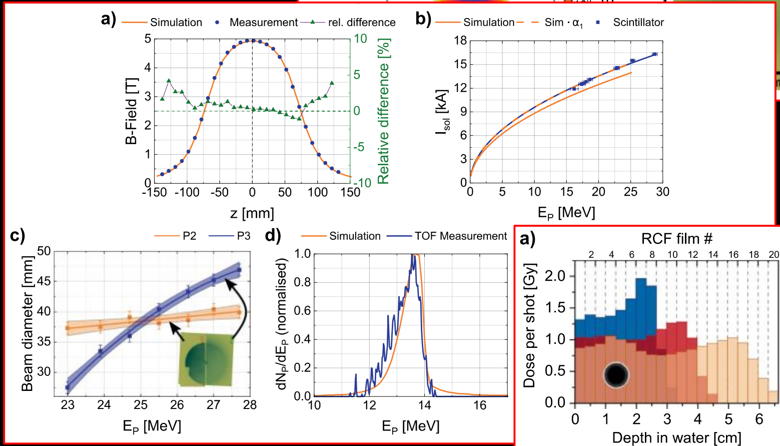
Laser-driven beams for rbio: example 1

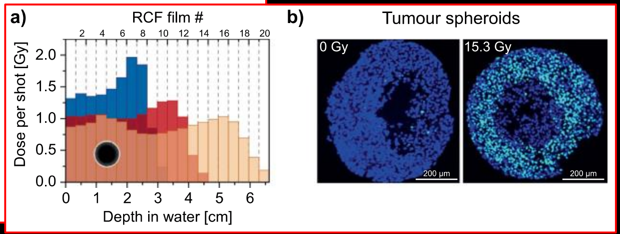
On Draco @ HZDR

DOI: 10.1038/s41598-020-65775-7

- **Draco:**
  - Petawatt laser
    - E = 13 J, τ = 30 fs, 3 μm FWHM
- **Beam line:**
  - Target Normal Sheath Acceleration (TNSA)
  - Pulsed solenoid focusing
    - 19.5T, 2 or 3 pulses/min.
    - S1, S2: 40 mm bore
    - Half angle acceptance 14°
  - Measured transmission (18.6 MeV *p*)
    - 50.6% (dual solenoid)
    - 28.6% (single solenoid)





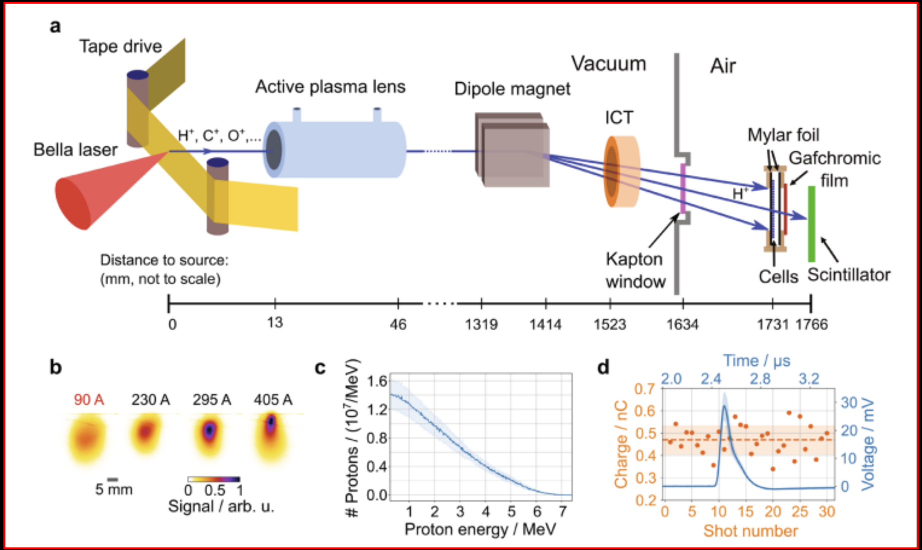


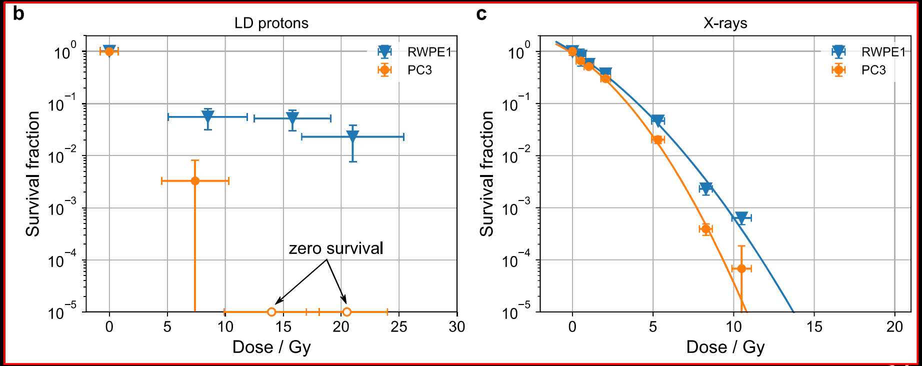
Laser-driven beams for rbio: example 2

On BELLA @ Berkeley

DOI 10.1038/s41598-022-05181-3

- Berkeley Lab Laser Accelerator (BELLA):
  - Petawatt laser
    - E = 35 J, τ = 35 fs, 52 μm FWHM
- Beam line:
  - Target Normal Sheath Acceleration (TNSA)
  - Active plasma lens focusing
    - 1 mm diameter Ar gas filled capillary
    - 33 mm length
    - 13 mm behind the tape drive target
    - ~0.2% transport efficiency for protons with *E* > 1.5 MeV





Variety of initiatives; some key examples

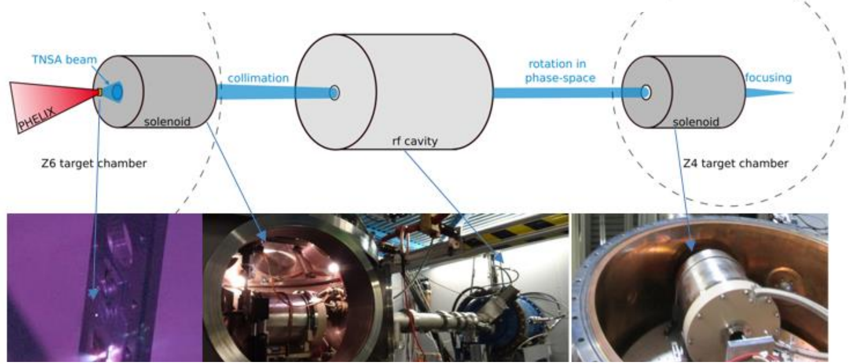
Capture

On PHELIX @ GSI

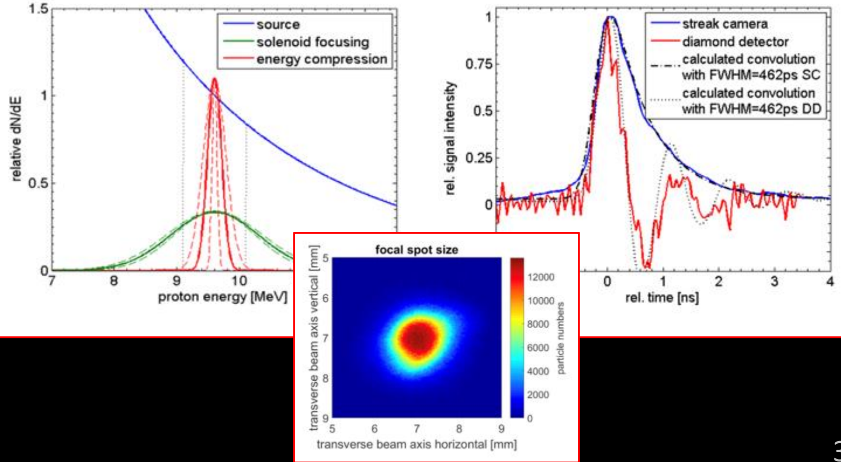
DOI: 10.1063/1.3299391
DOI: 10.1103/PhysRevSTAB.14.121301
DOI: 10.1103/PhysRevSTAB.16.101302
DOI: 10.1103/PhysRevSTAB.17.031302
NIMA 909 (2018) 173–176

- **PHELIX:**
  - Petawatt High-Energy Laser for Heavy Ion EXperiments
    - $E < 25$ J, $\tau = 500$ fs, $I > 10^{19}$ J/cm2
- **LIGHT:**
  - Target Normal Sheath Acceleration (TNSA)
  - Ion beam is collimated by a pulsed high-field solenoid
  - Phase rotation in RF cavity
  - Final focus with a second pulsed high-field solenoid

LIGHT – Laser Ion Generation, Handling and Transport



https://www.gsi.de/work/forschung/appamml/plasmaphysikphelix/experimente/light



Variety of initiatives; some key examples

Capture

On CLAPA @ Peking University

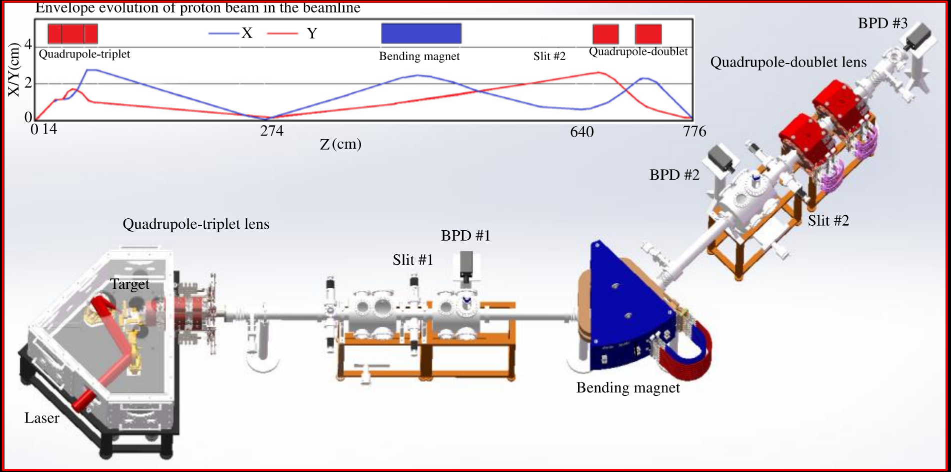
DOI: 10.1103/PhysRevAccelBeams.22.061302
DOI: 10.1103/PhysRevAccelBeams.23.121304

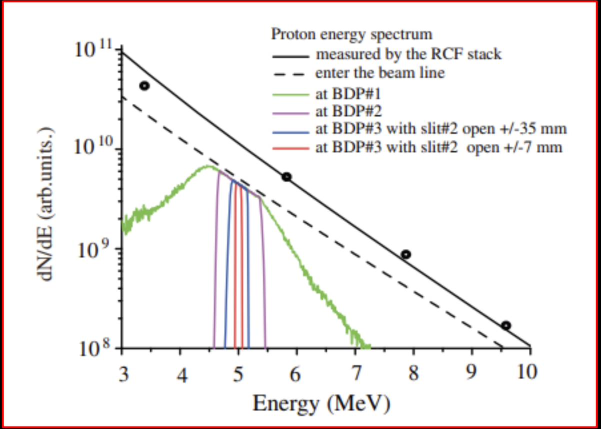
- **Compact Laser Plasma Accelerator (CLAPA):**
  - Petawatt laser
    - E = 1.3 J, τ = 30 fs, 5 μm FWHM
- **Beam line:**
  - Target Normal Sheath Acceleration (TNSA)
  - Quadrupole triplet focusing

TABLE I. The CLAPA beam line parameters.

Type	Length	Aperture	Max B	# turns	Current
Q1	100 mm	30 mm	5 KGs/cm	16	300 A
Q2	200 mm	64 mm	2.5 KGs/cm	20	540 A
Q3	100 mm	64 mm	2.5 KGs/cm	20	540 A

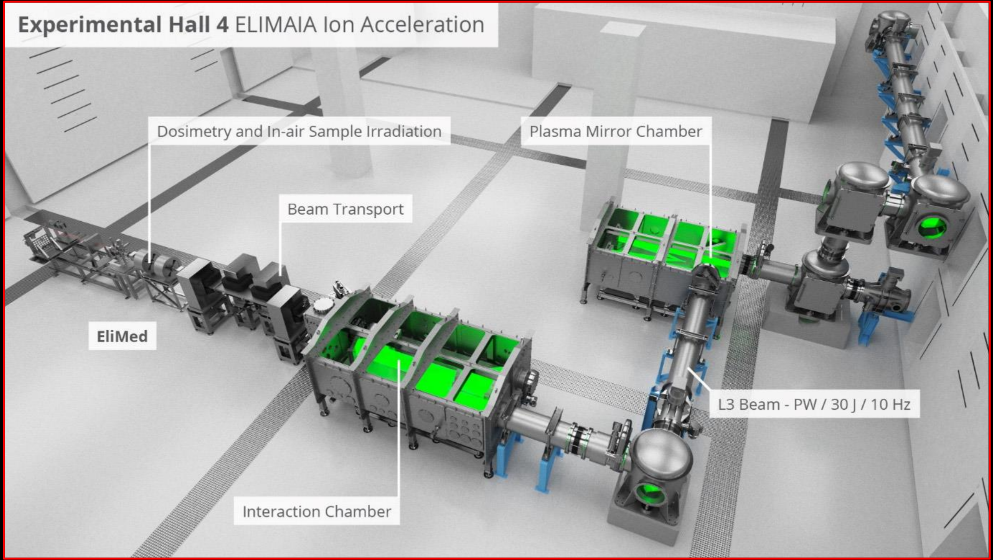
  - Measured transmission:
    - 88% transmission through triplet
    - ±50 mrad collection angle @ 5 MeV

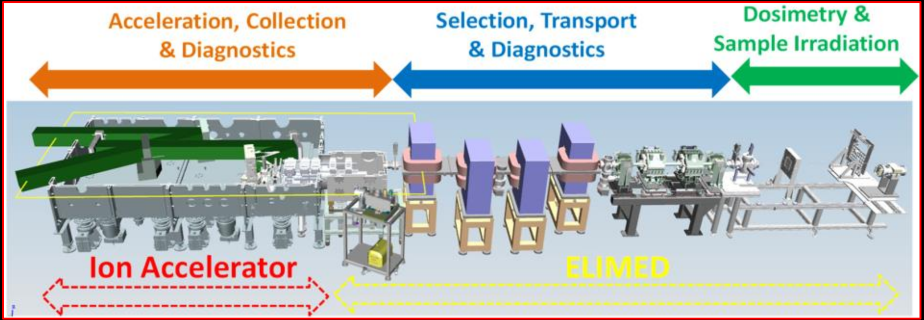


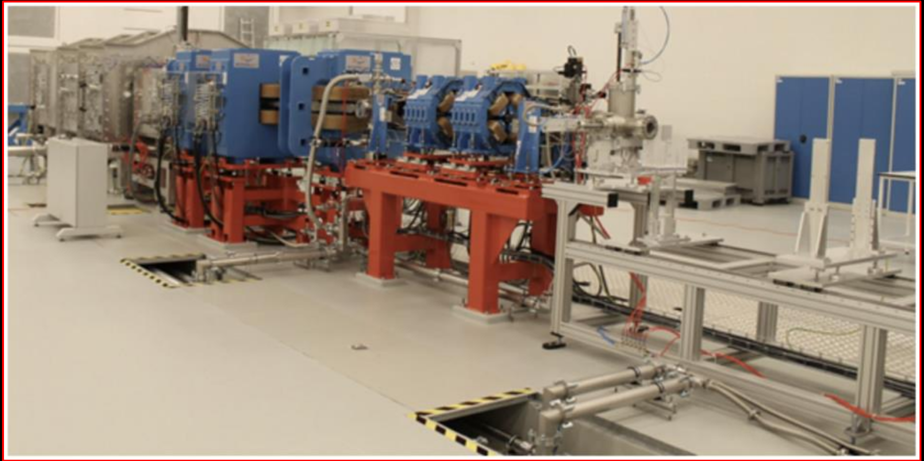


ELIMAIA-ELIMED

Quantum Beam Sci. 2018, 2, 8; doi:10.3390/qubs2020008
Frontiers in Phys. Med. Phys. & Imag. – doi: 10.3389/fphy.2020.564907





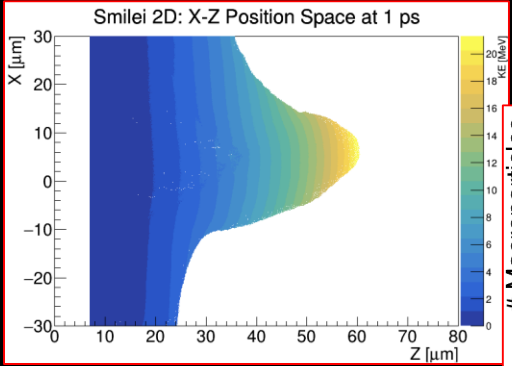


Extreme Light Infrastructure, Prague, Czech Republic:

- ELI Multidisciplinary Applications of laser-Ion Acceleration (ELIMAIA)
  - ELI MEDical and multidisciplinary applications (ELIMED)
    - ELIMAIA section dedicated to ion focusing, selection, characterization, and irradiation
  - Proton energies from 5 to 250 MeV transported to in-air section

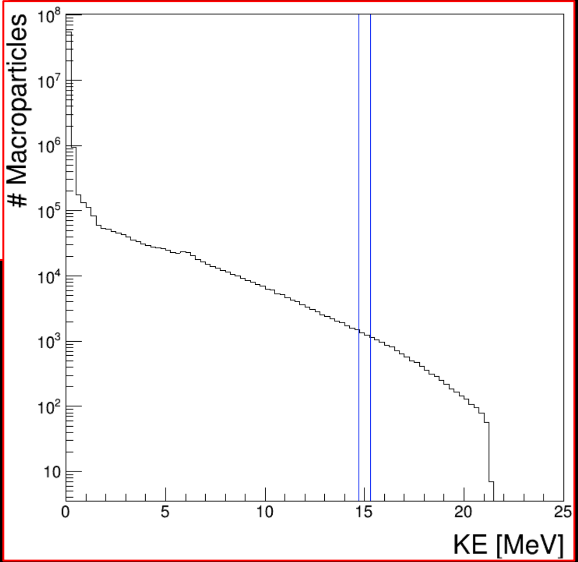
Laser-driven proton/ion source

- **Commercial laser:**
  - **Motivation: risk management**



HT Lau
Thesis, 2022

Smilei)



Ti:Sapphire commercial system >150TW
Pulse ~35 fs at rep-rate of at least 10Hz
At least 500mJ laser energy - $I_L \sim 10^{20}$ Wcm^{-2}

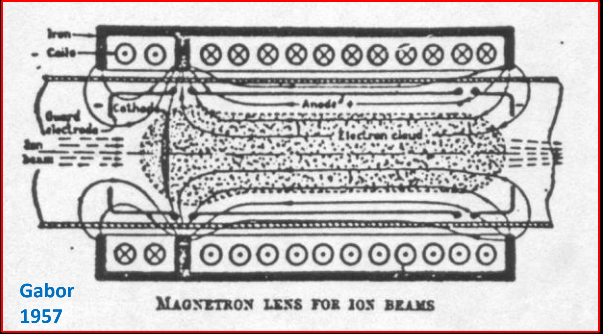
LhARA
Laser-hybrid Accelerator for Radiobiological Applications

H.T. Lau

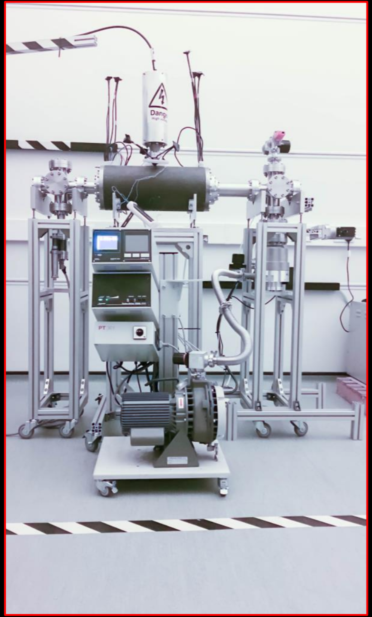
Posocco, Pozimski

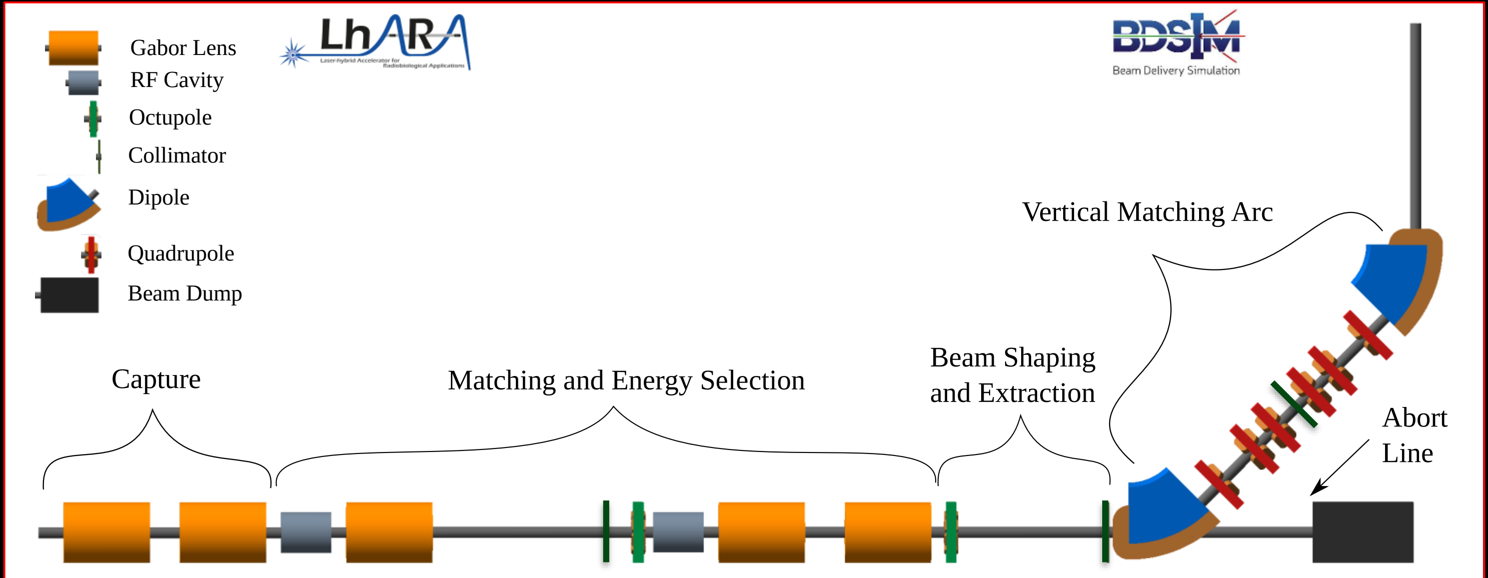
LhARA Capture

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



Gabor 1957





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

applied sciences

MDPI

Article

Anomalous Beam Transport through Gabor (Plasma) Lens Prototype

Toby Nonnenmacher [1,*], Titus-Stefan Dascalu [1,*], Robert Bingham [2,3], Chung Lim Cheung [1], Hin-Tung Lau [1], Ken Long [3,4], Jürgen Pozimski [3,4] and Colin Whyte [2]

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4 John Adams Institute for Accelerator Science, Imperial College London, London SW7 2AZ, UK
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Abstract: An electron plasma lens is a cost-effective, compact, strong-focusing element that can ensure efficient capture of low-energy proton and ion beams from laser-driven sources. A Gabor lens prototype was built for high electron density operation at Imperial College London. The parameters of the stable operation regime of the lens and its performance during a beam test with 1.4 MeV protons are reported here. Narrow pencil beams were imaged on a scintillator screen 67 cm downstream of the lens. The lens converted the pencil beams into rings that show position-dependent shape and intensity modulation that are dependent on the settings of the lens. Characterisation of the focusing effect suggests that the plasma column exhibited an off-axis rotation similar to the $m = 1$ diocotron instability. The association of the instability with the cause of the rings was investigated using particle tracking simulations.

Keywords: plasma trap; space-charge lens; beam transport; instability; proton therapy

Citation: Nonnenmacher, T.; Dascalu, T.S.; Bingham, R.; Cheung, C.L.; Lau, H.T.; Long, K.; Pozimski, J.; Whyte, C. Anomalous Beam Transport through Gabor (Plasma) Lens Prototype. *Appl. Sci.* **2021**, *11*, 4357. https://doi.org/10.3390/app11104357

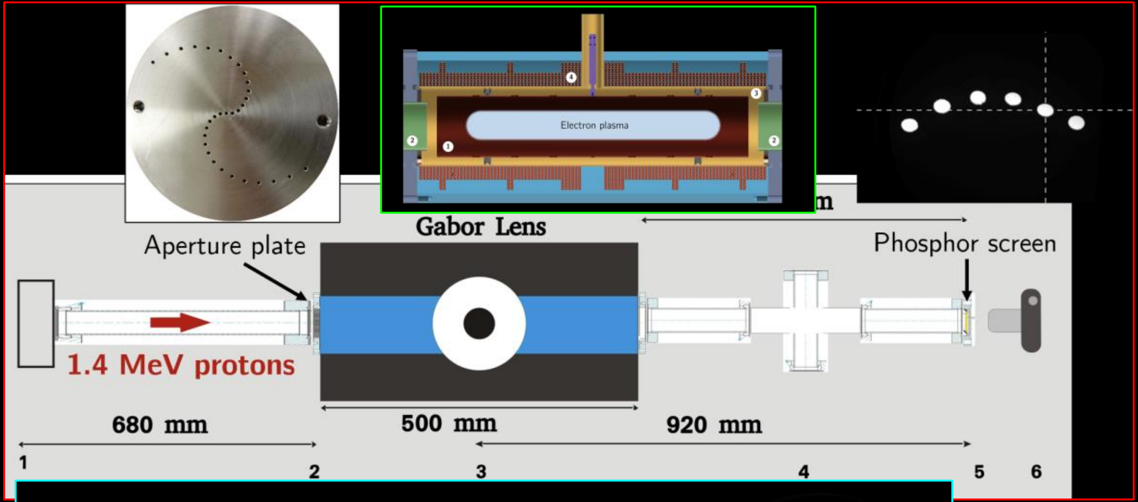
Academic Editor: Paolo Branchini

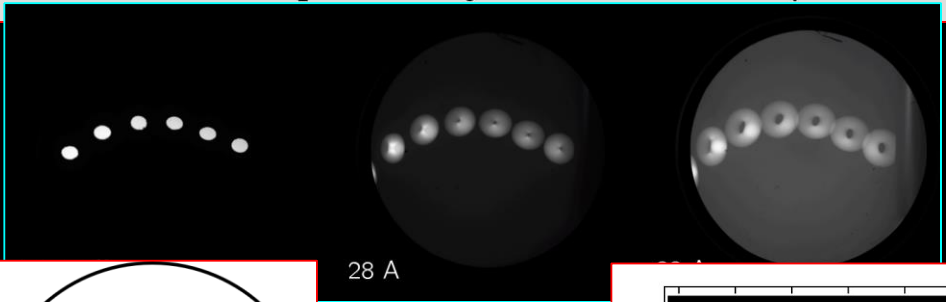
Received: 13 April 2021
Accepted: 4 May 2021
Published: 11 May 2021

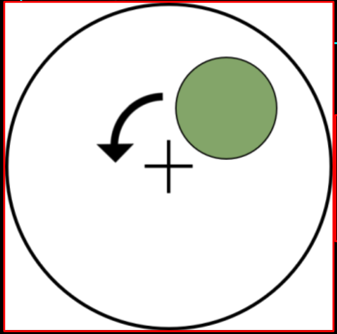
1. Introduction

One of the principal challenges that must be addressed to deliver high-flux pulsed proton or positive-ion beams for many applications is the efficient capture of the ions ejected from the source. A typical source produces protons with kinetic energies of approximately 60 keV [1–3] and ions with kinetic energies typically below 120 keV [4,5]. At this low energy the mutual repulsion of the ions causes the beam to diverge rapidly. Capturing a large fraction of this divergent flux therefore requires a focusing element of short focal length. Proton- and ion-capture systems in use today employ magnetic, electrostatic, or radio frequency quadrupoles, or solenoid magnets to capture and focus the beam [2,6–8].

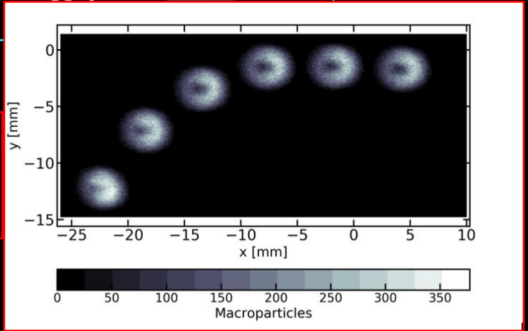
Laser-driven proton and ion sources are disruptive technologies that offer enormous potential to serve future high-flux, pulsed beam facilities [9–16]. Possible applications include proton- and ion-beam production for research, particle-beam therapy, radio-nuclide production, and ion implantation. Recent measurements have demonstrated the laser-driven production of large ion fluxes at kinetic energies in excess of 10 MeV [17–20]. The further development of present technologies and the introduction of novel techniques [21,22] makes it conceivable that significantly higher ion energies will be produced in the future [13,23,24]. By capturing the laser-driven ions at energies two orders of magnitude greater than those pertaining to conventional sources, it will be possible to evade the current space-charge limit on the instantaneous proton and ion flux that can be delivered. While in some situations the high divergence of laser-driven ion beams can be reduced [25,26], for the tape-drive targets proposed for medical beams [16,20] it necessary to capture the beam using a strong-focusing element as close to the ion-production point as possible.





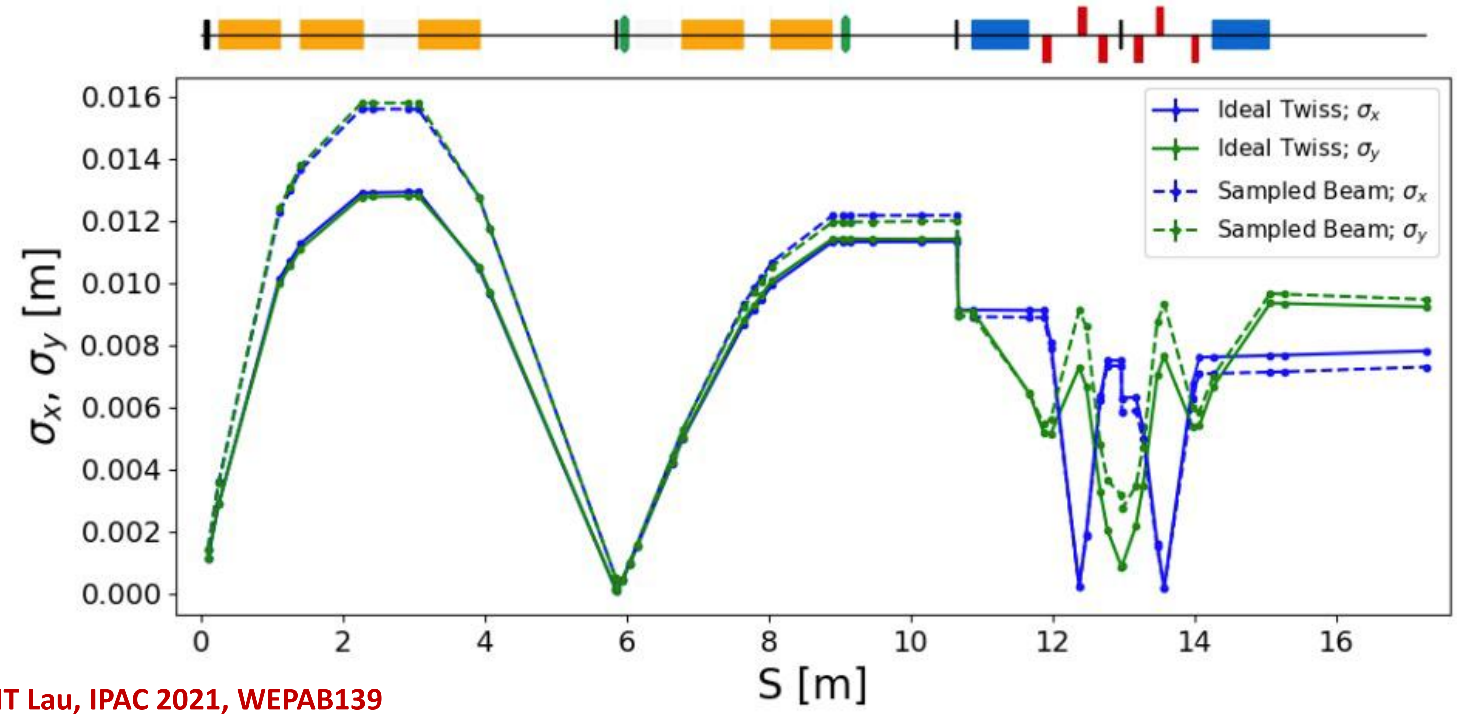


VSIM/BDSIM:
evaluation of m = 1 diocotron mode



Dascalu

Beam envelopes Stage 1



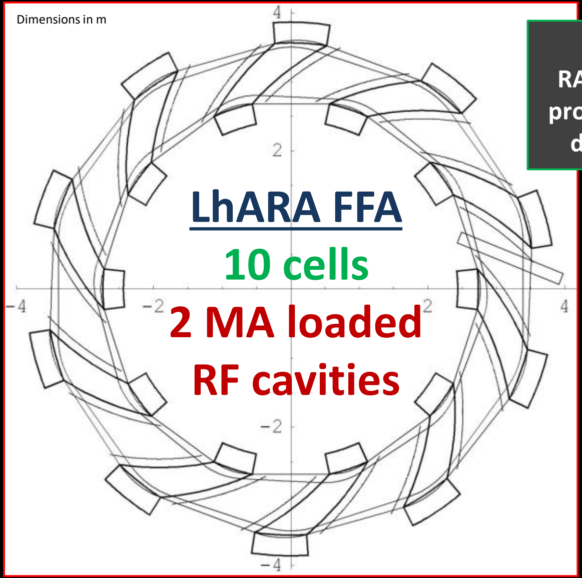
HT Lau, IPAC 2021, WEPAB139

- Propagation of "semi-realistic" source distribution:
  - Generated using SMILEI
  - Optimisation studies on going

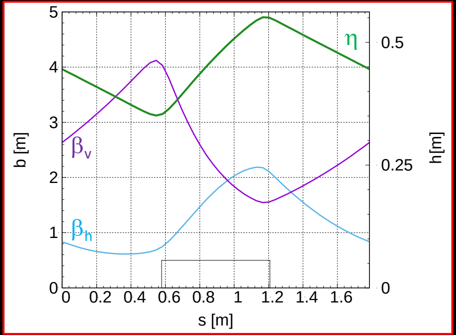
Laser-hybrid Accelerator for Radiobiological Applications

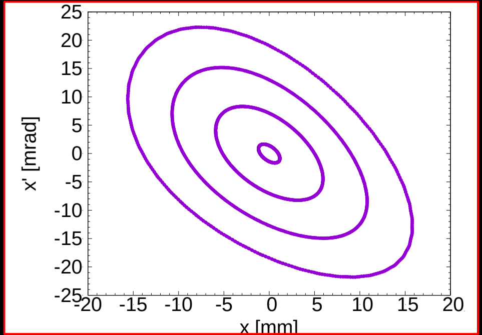
Rapid, flexible acceleration for stage 2

- 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 PofP EMMA (DL)



Evolution of RACCAM design; prototype magnet demonstrated





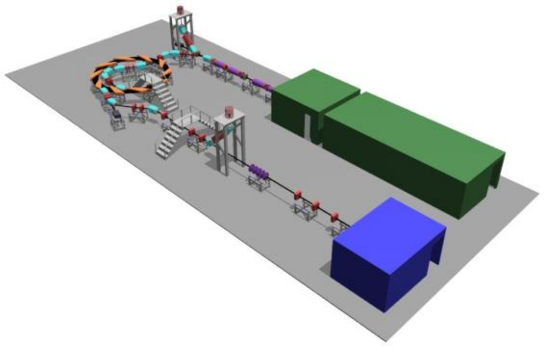
Front. Phys., 29 September 2020; DOI: 10.3389/fphy.2020.567738

LhARA @ the *Ion Therapy Research Facility*

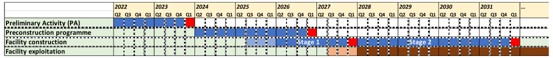
J, Clark, M. Noro, A. Woodcock 14Jun21

Ion Therapy Research Facility

1. Schematic diagram of the Ion Therapy Research Facility



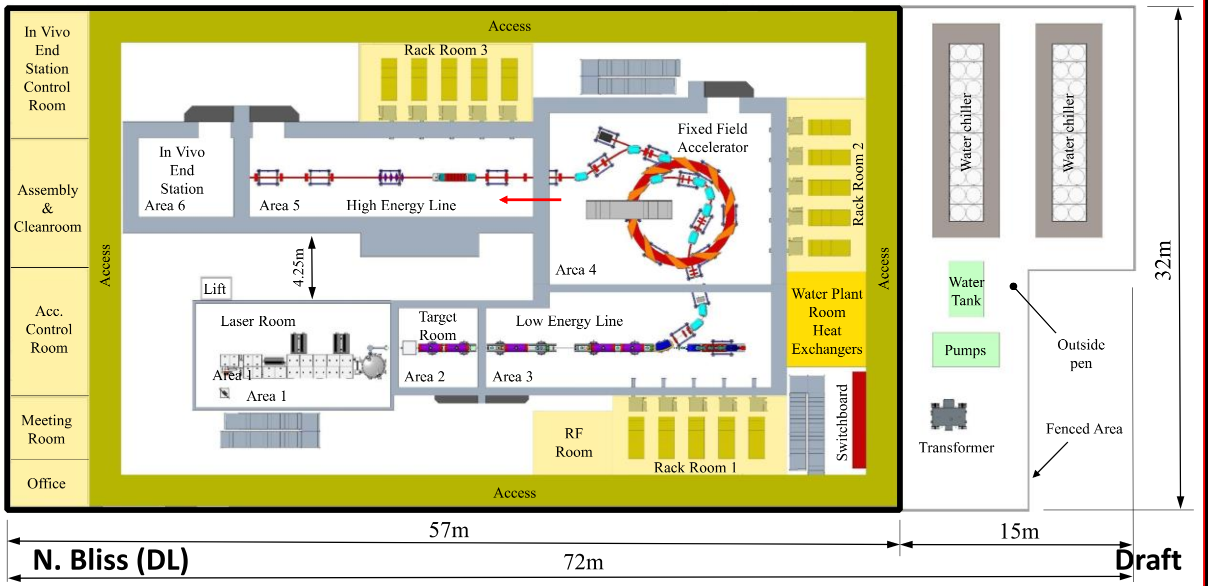
2. ITRF development timeline

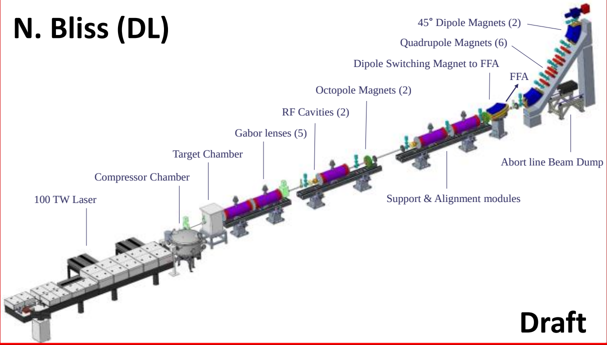


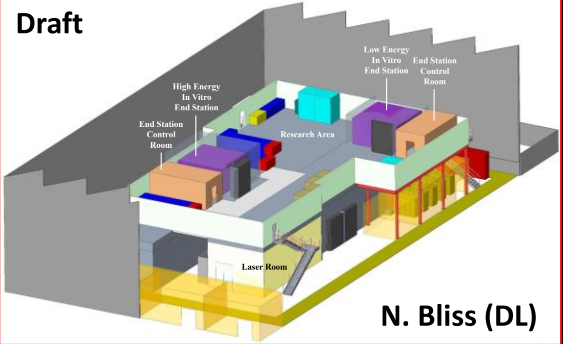
3. Institutes that make up the ITRF collaboration

Partners: University, Clinical, Laboratory, Industry, Accelerator

Submitted to UKRI Infrastructure Advisory Committee
14 June 2021







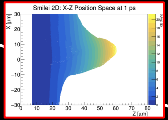
LhARA; the Laser-hybrid Accelerator for Radiobiological Applications

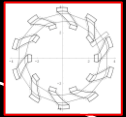
CONCLUSIONS

LhARA

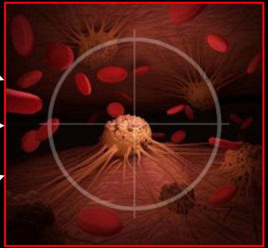
Laser-hybrid Accelerator for Radiobiological Applications

Novel accelerator techniques

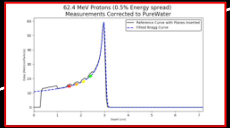




System: image processing fast feedback, control



Fundamental radiobiology



1970 1980 1990 2000 2010 2020 2030 2040 2050

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
  - Be used in automated, triggerable *system* → reduce requirement for large gantry
    - Disruptive/transformative approach to "distributed PBT for 2050"

- To serve the ITRF, 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
  - Create novel capabilities to 'spin back in' to science and innovation

LhARA Laser-hybrid Accelerator for Radiobiological Applications

CCAP Centre for the Clinical Application of Particles

Acknowledgements

Imperial College London
Department of Physics
Faculty of Medicine

ICR The Institute of Cancer Research

Imperial College Academic Health Science Centre

UKRI Medical Research Council
Oxford Institute for Radiation Oncology

University of Oxford

JAI John Adams Institute for Accelerator Science

CCAP Centre for the Clinical Application of Particles

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

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

LEO Cancer Care

Maxeler Technologies Maximum Performance Computing

LhARA Laser-hybrid Accelerator for Radiobiological Applications

ITRF team: N. Bliss, J. Clarke, M. Noro, H. Owen

"This material was prepared and presented within the HITRIplus **Specialised Course on Heavy Ion Therapy Research,** and it is intended for personal educational purposes to help students; people interested in using any of the material for any other purposes (such as other lectures, courses etc.) are requested to please contact the authors

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