Very High Energy Electron (VHEE) Beams for Cancer Radiotherapy

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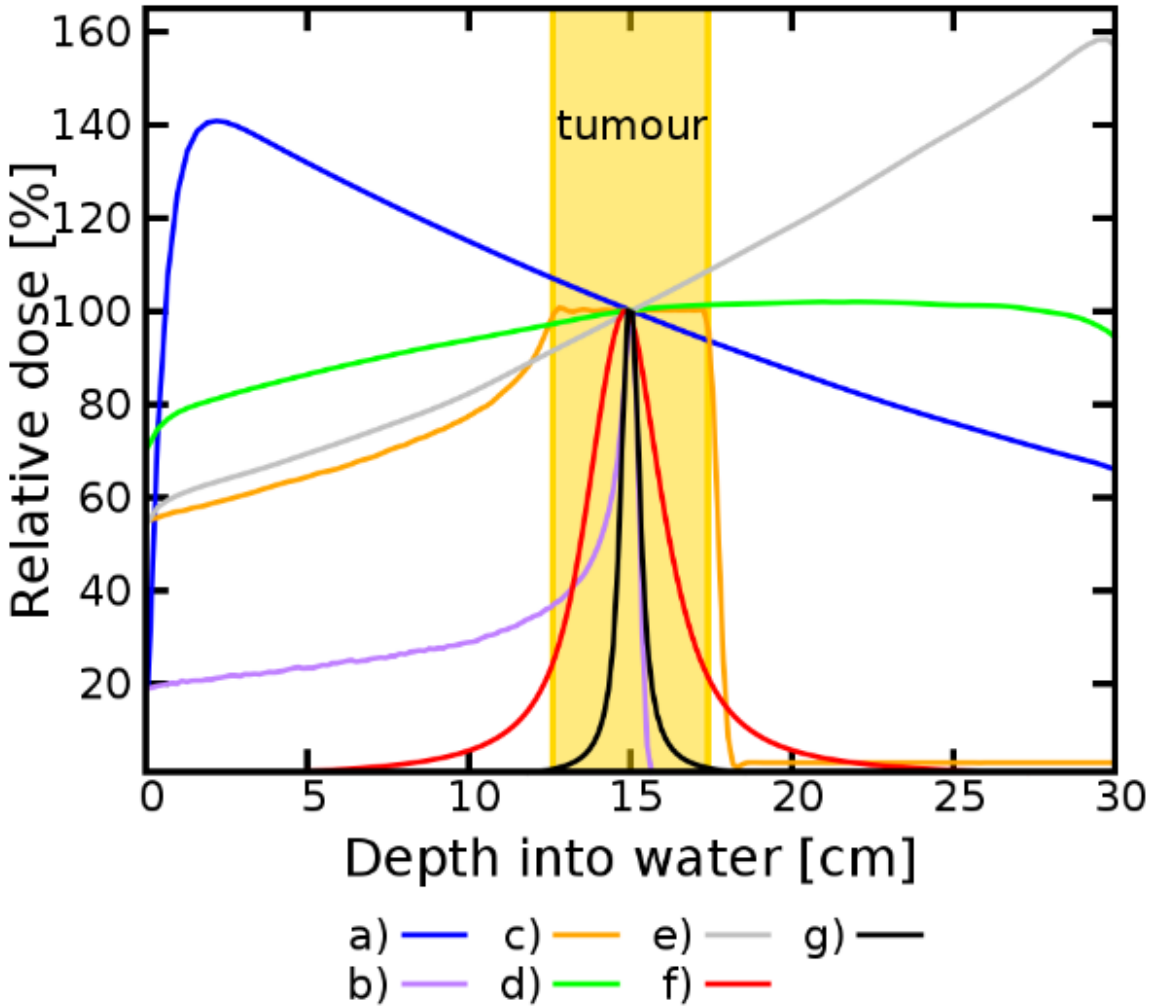

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SUPA: Scottish Universities Physics Alliance

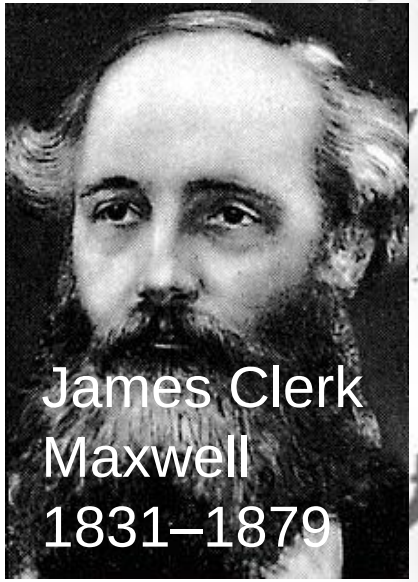
University of Strathclyde

SUPA: largest Physics Alliance in the UK consisting of 8 Scottish universities.

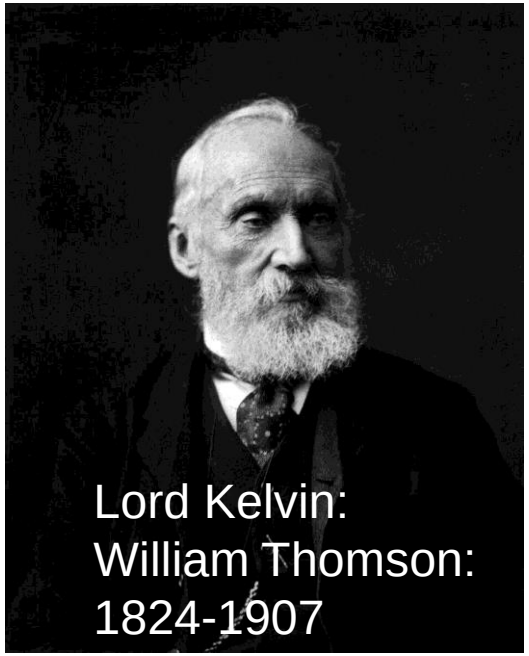
Physics Scotland

Schiehallion Experiment 1774

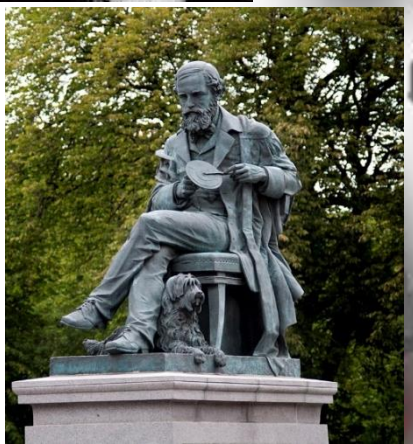
Funded by the Royal Society Charles Hutton invented contour lines



James Clerk Maxwell 1831–1879



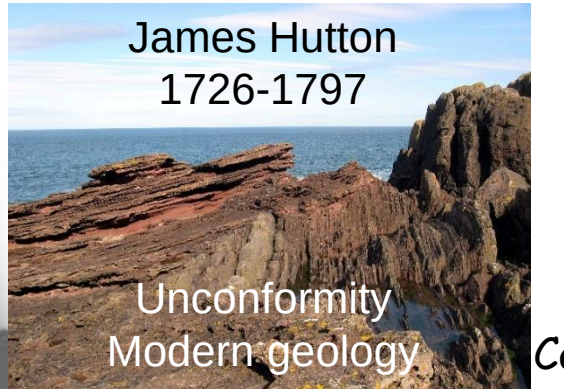
Lord Kelvin: William Thomson: 1824-1907



Maxwell's equations:

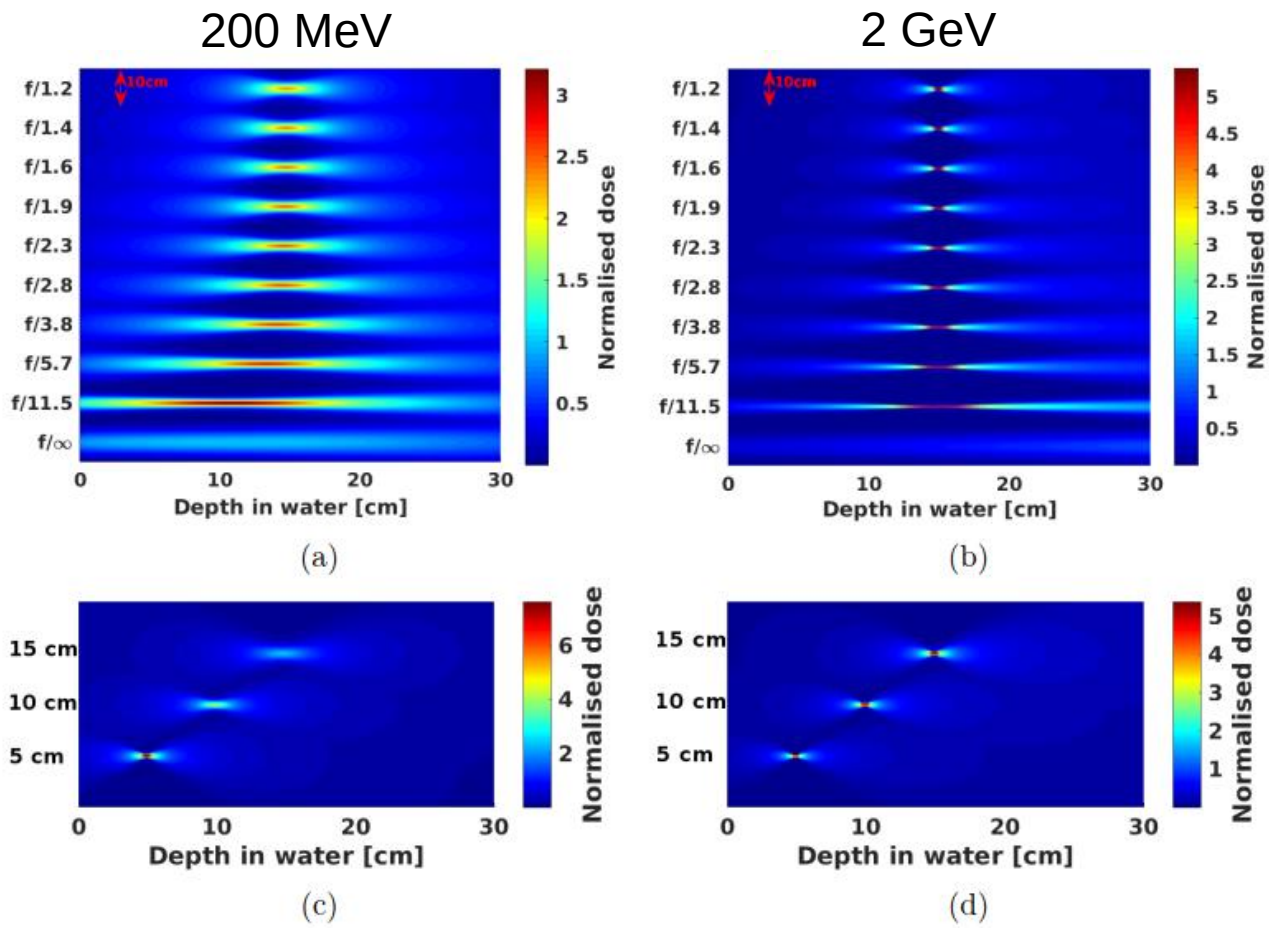
$dF = 0$

$d * G = j$



Cancer 2021

- Very High Energy Electron (VHEE) Beams for Radiotherapy
- Laser-Plasma Accelerators (LPAs): short bunches, low emittance, low energy spread and high charge
- **Focussed VHEE & X-ray beams**
- LPA – VHEE experiments
- Conventional Accelerator VHEE beams
- SCAPA



VHEE team: Dino Jaroszynski, Marie Boyd, Annette Sorensen, Natividad Gomez Roman, Enrico Brunetti, Antoine Maitrallain, Karolina Kokurewicz, Anna Subiel, Jason Mill + international collaborators

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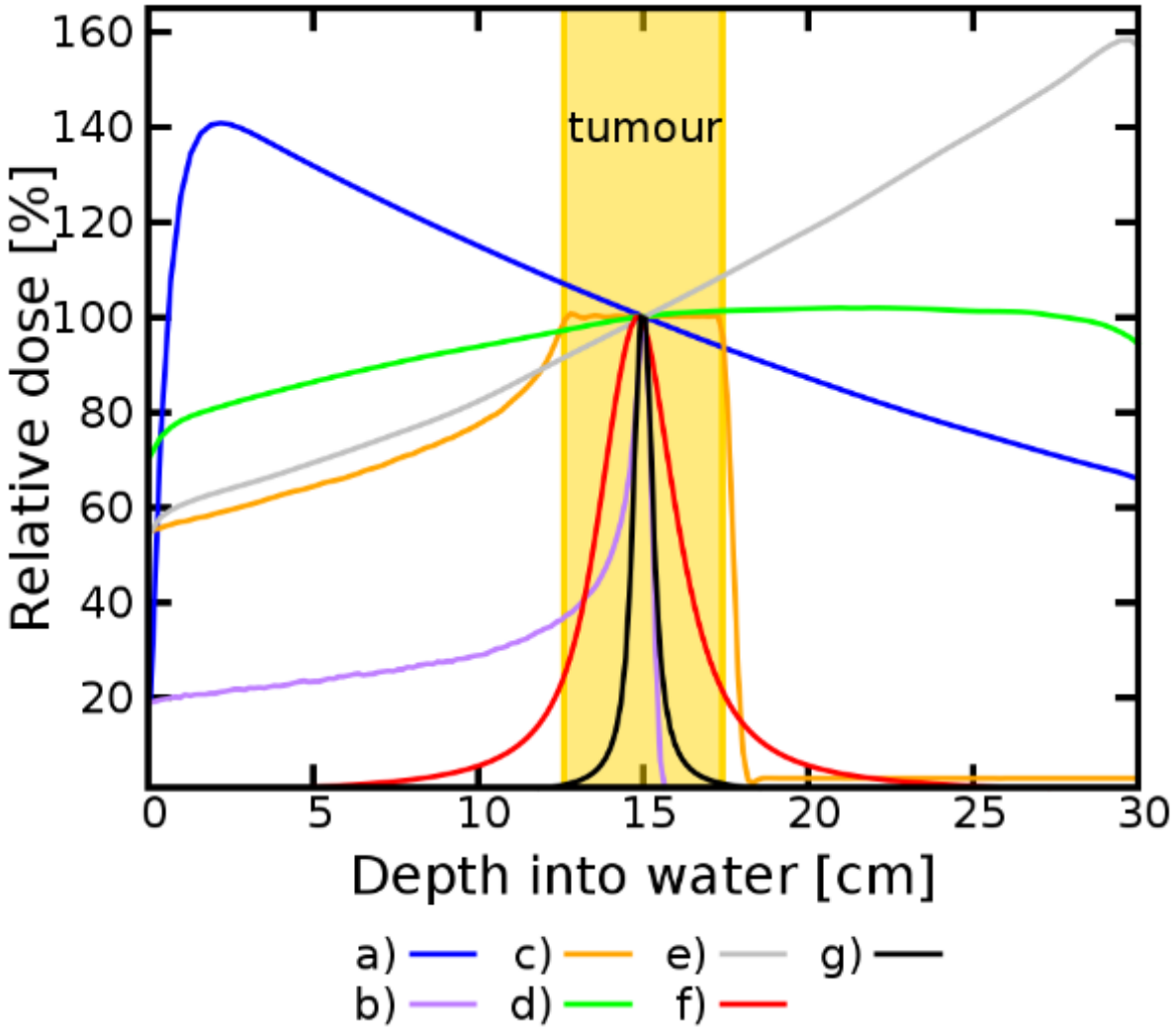
VHEE therapy

The percentage depth-dose distribution

a) 6 MV Photons,
b) Bragg peak 147 MeV protons,
c) spread-out Bragg peak,
d) collimated 200 MeV electrons,
e) collimated 2 GeV electrons
f) 200 MeV electrons focused at 15 cm in water for *f*/1.2,
g) 2 GeV electrons focused at 15 cm in water for *f*/1.2.



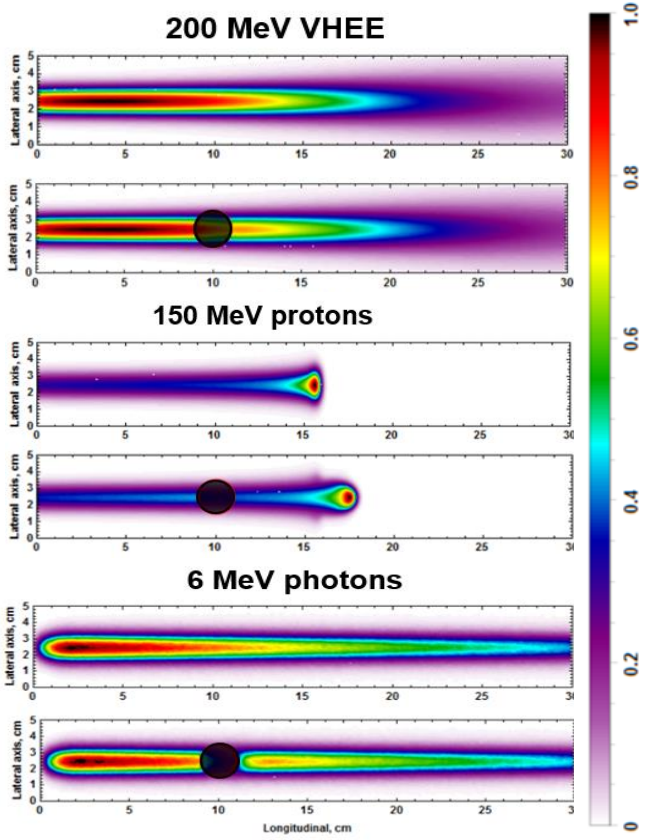
50-200 MeV VHEEs as a new RT modality

Deep penetration (>20 cm for 200 MeV)

Reach deep seated tumours

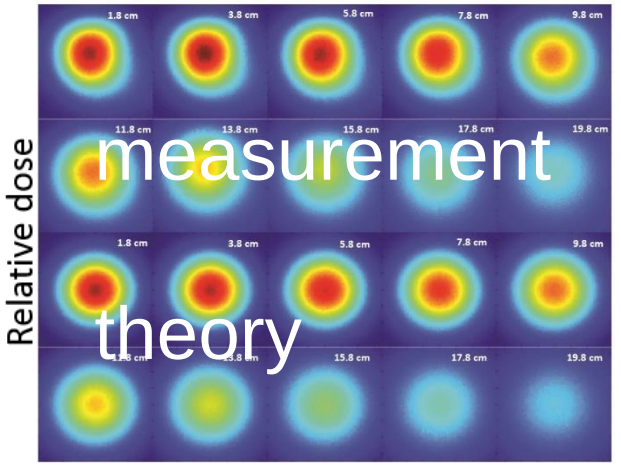
- Low scattering in tissue – high particle inertia
- Low sensitive to inhomogeneities
- Easily focussed beam

K. Kokurewicz et al., Sc. Rep. (2019)
K. Kokurewicz, K. et al., Commun. Phys. (2021)



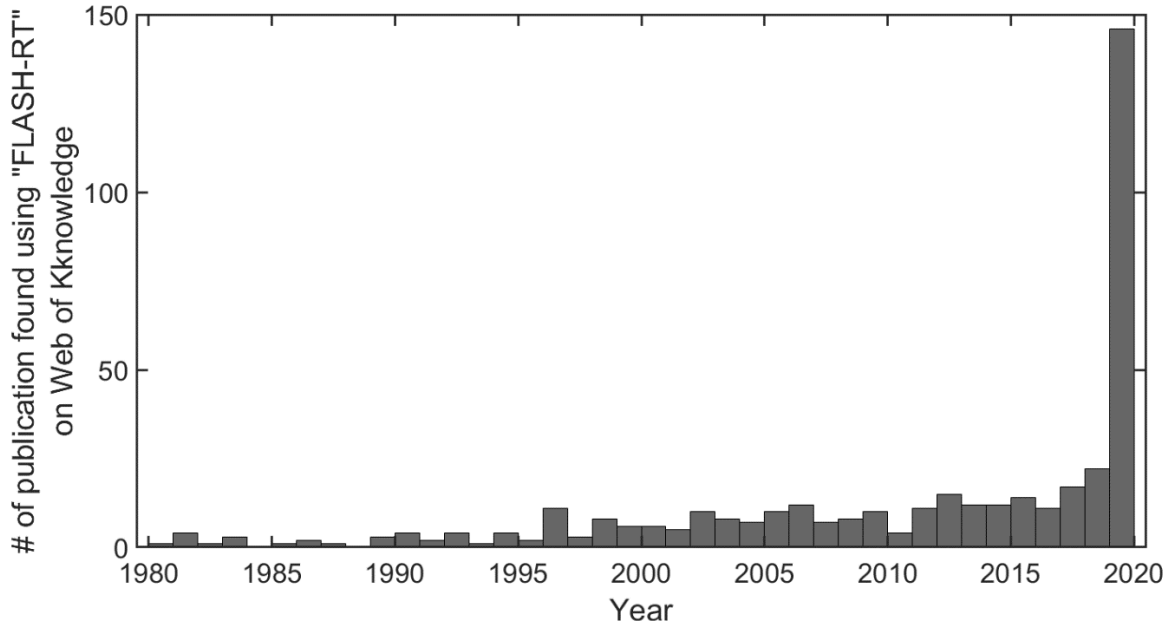
A. Lagzda, VHEE'17

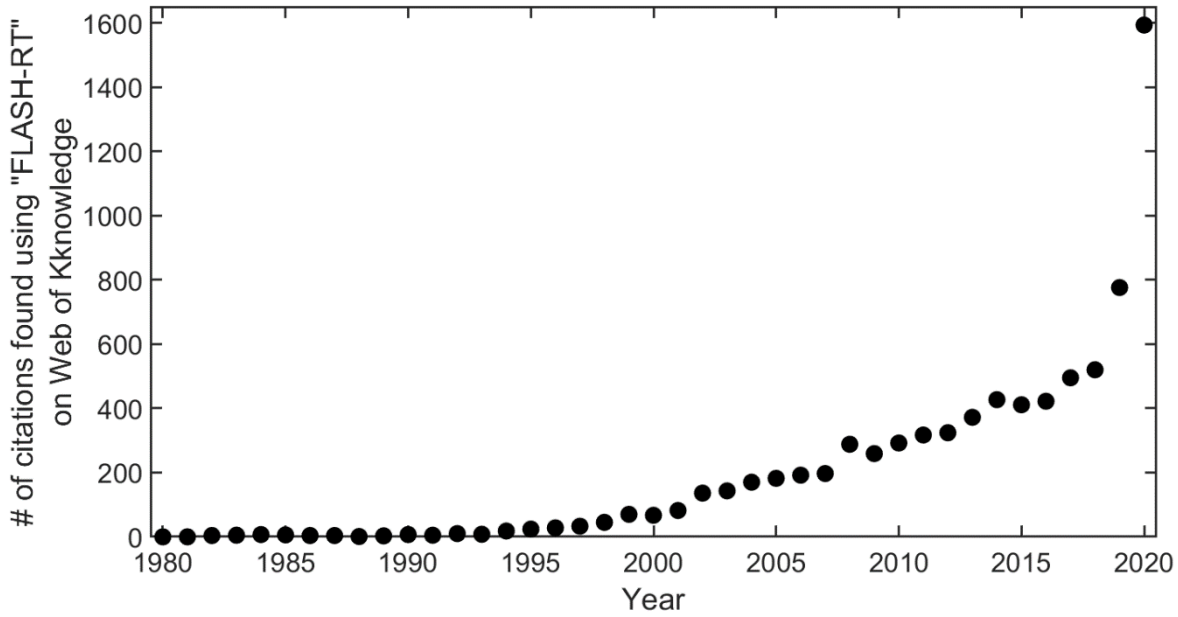
LPA produced VHEE beams



V. Moskvin et al., Medical Physics, 39, 3813 (2012)
Subiel, A. et. al. Phys. Med. Biol. 59, 5811 (2014)

FLASH RT



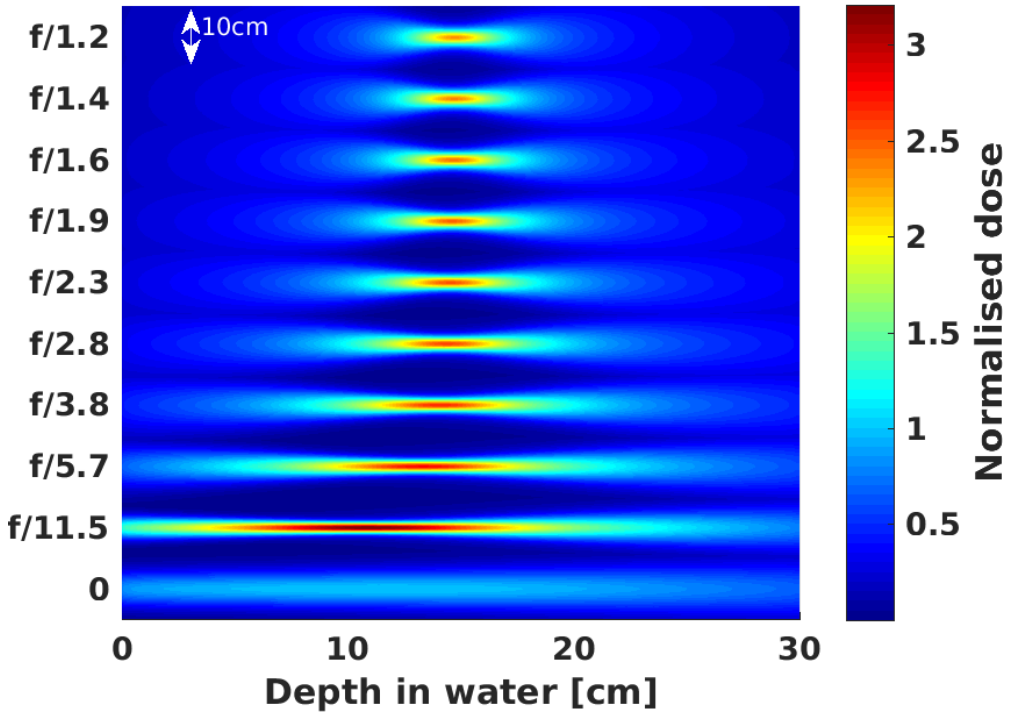


- FLASH: ≥10's Gy/s, high dose
- Prevent damage to healthy tissue (while toxic to tumours)
- Oxygen depletion may contribute to the FLASH effect?

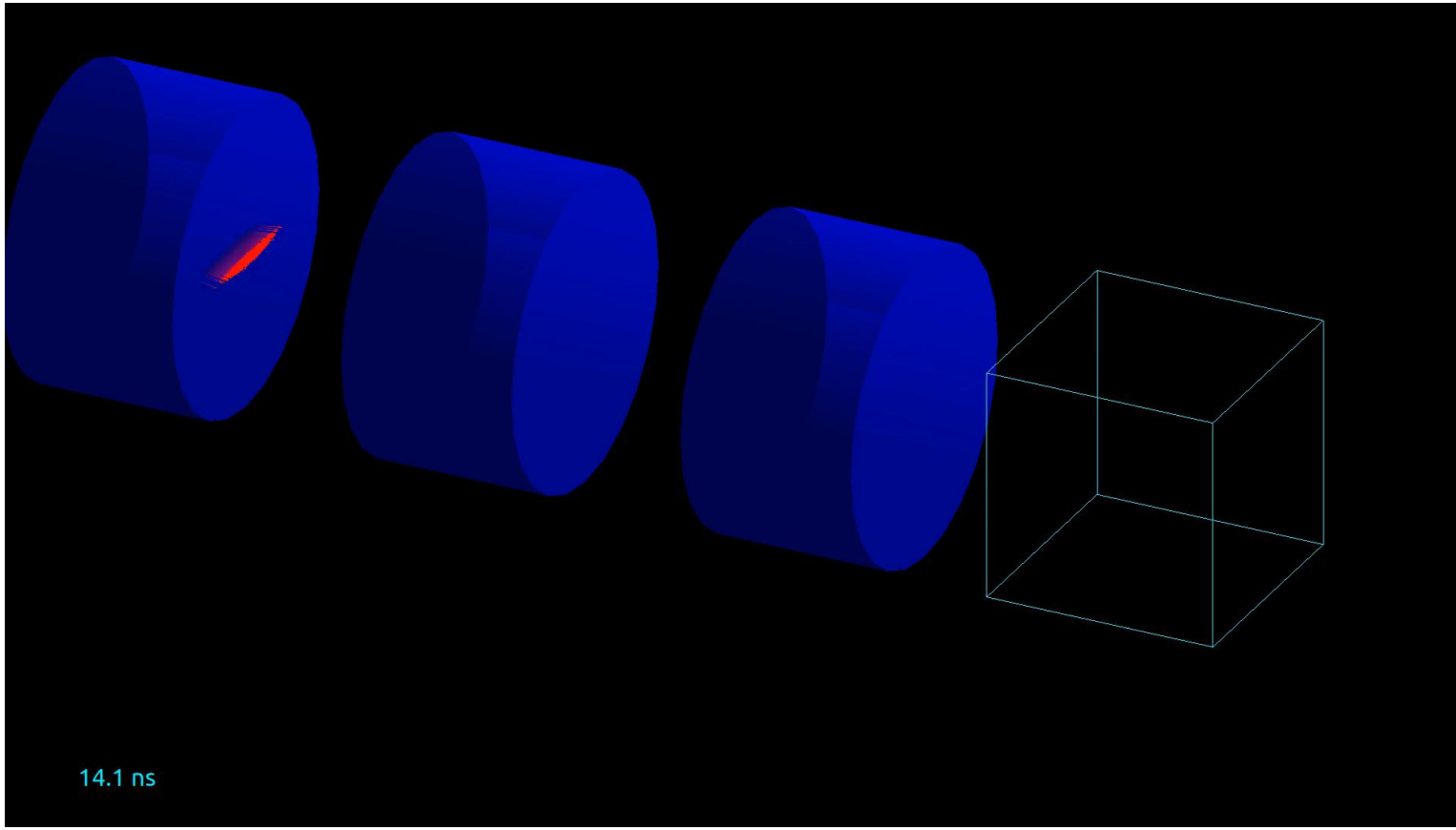
Wilson JD, et. al. Front. Oncol. 9:1563. (2020)

Focussed beams: concentrate dose into small volumetric element

200 MeV beam

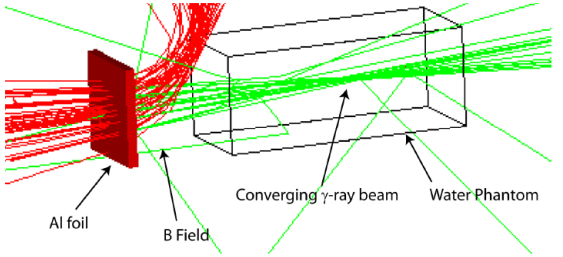


Line focus



Focussing replaces multiple beams with a single focussed beam – to concentrate dose

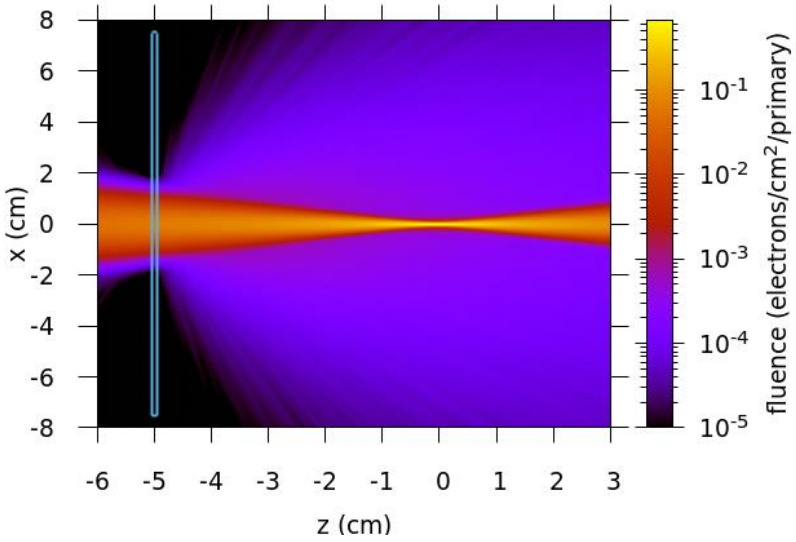
Focussed VHEE beams and photons

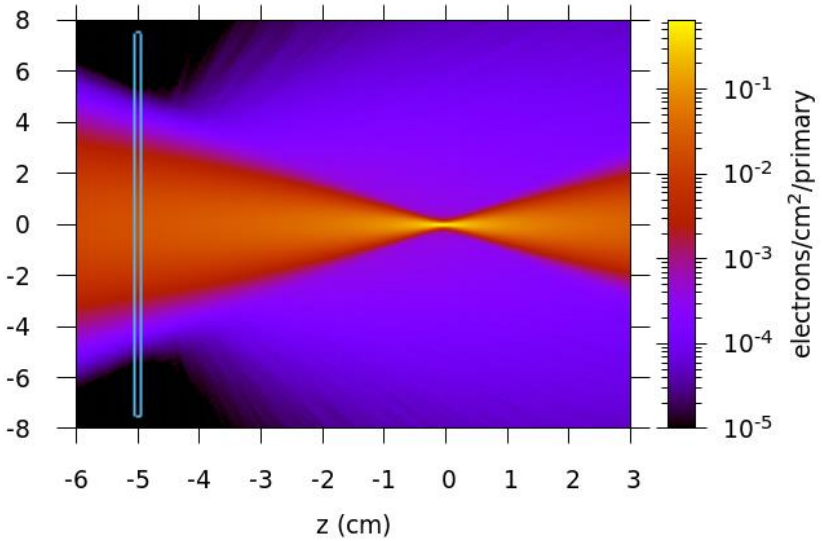


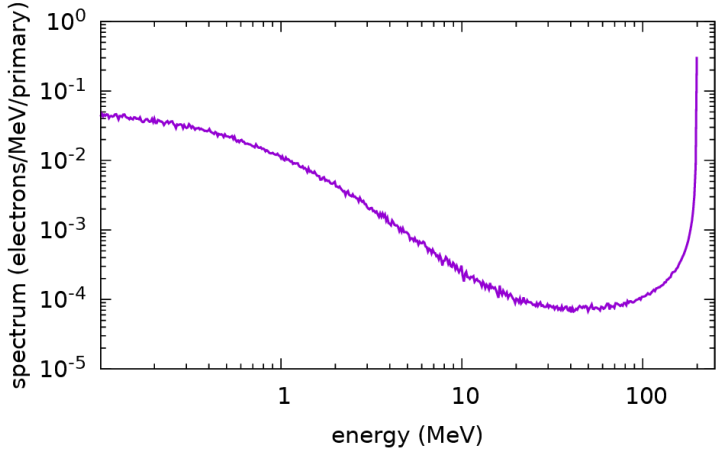
5° converging angle, 1 mm Al foil

15° converging angle, 1 mm Al foil

200 MeV electrons

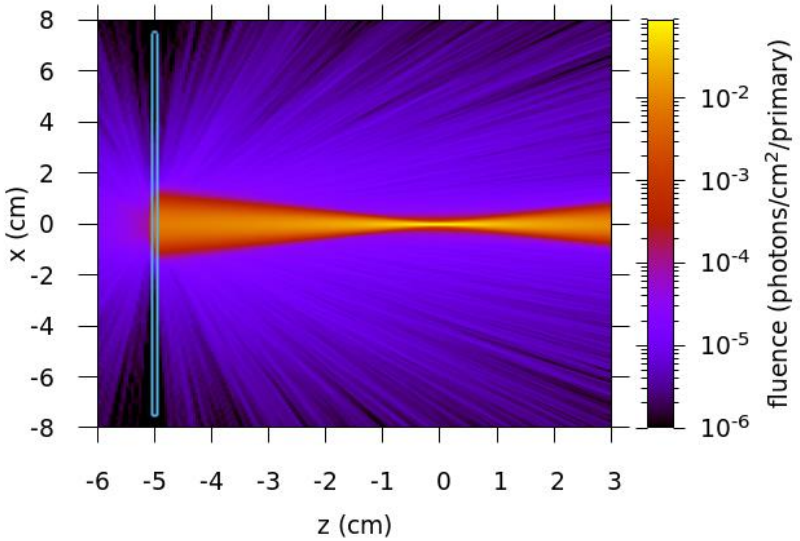


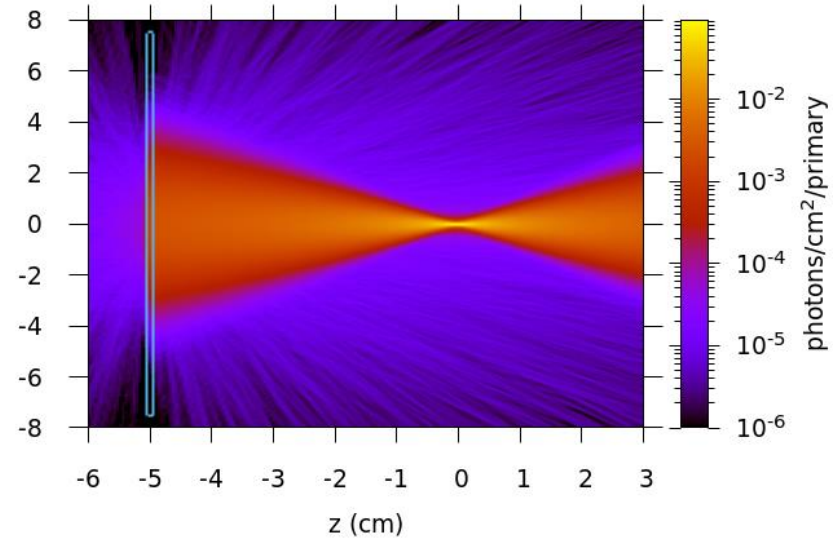


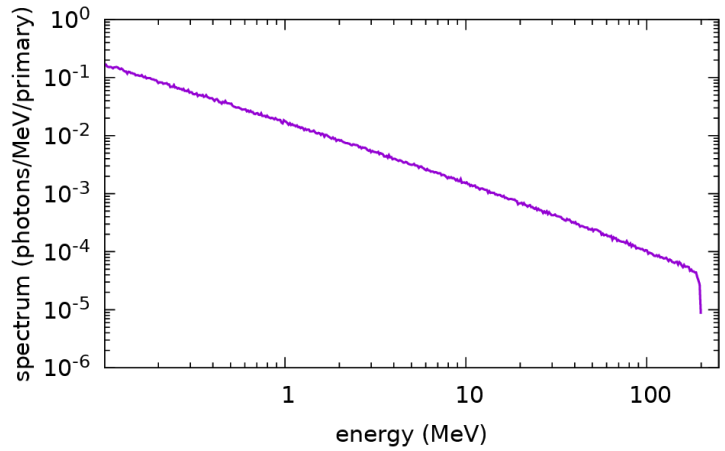


Brunetti et al., SPIE 2019

Photons

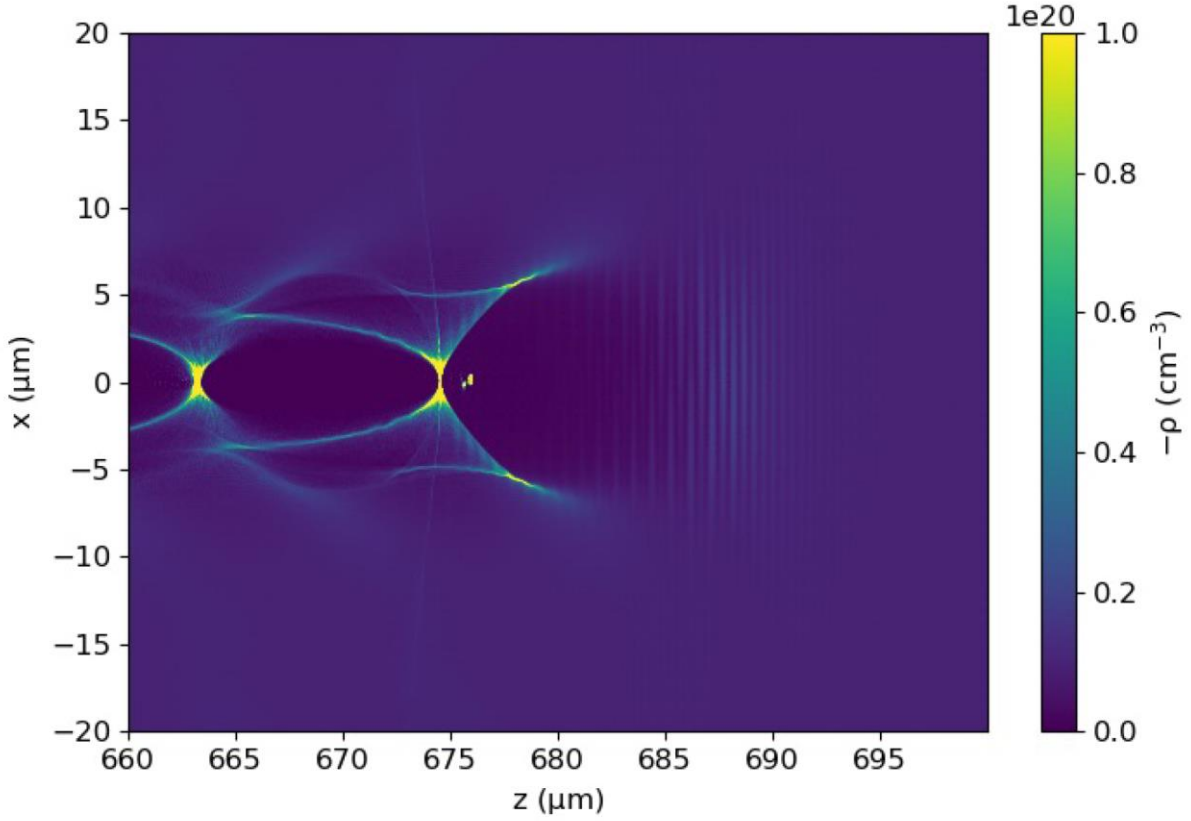


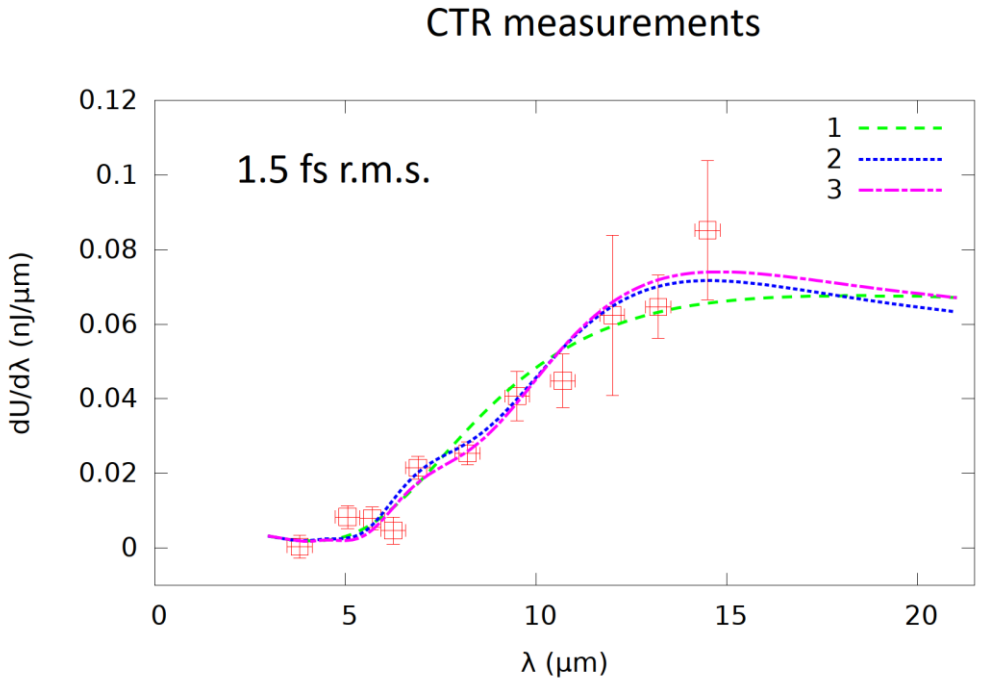




-Europe Lasers Fighting Cancer 2021

Laser Plasma Accelerator (LPA)





Femtosecond duration
M. Islam, et. al. New J. Phys. (2015)

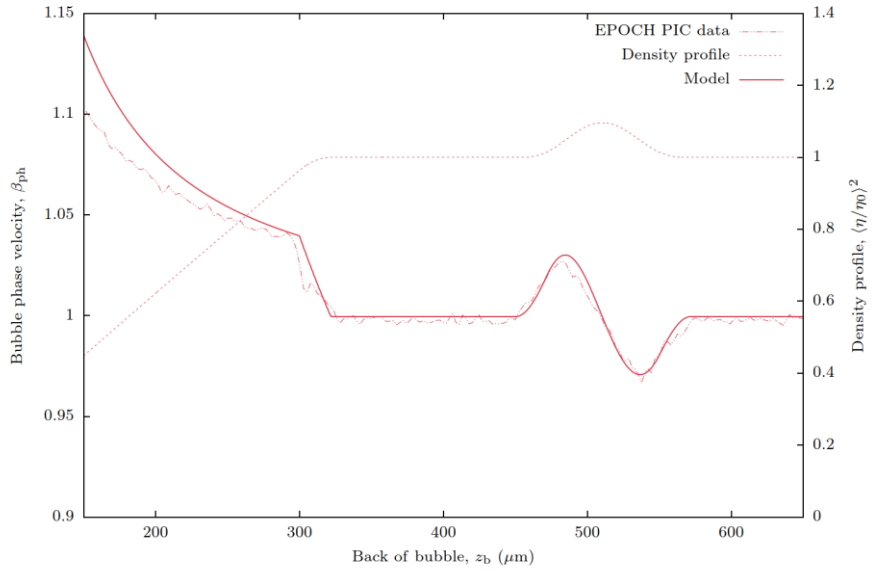
LPA – Bubble accelerating structure: can accelerate electrons up to GeV energies, femtosecond duration &100s pC charge

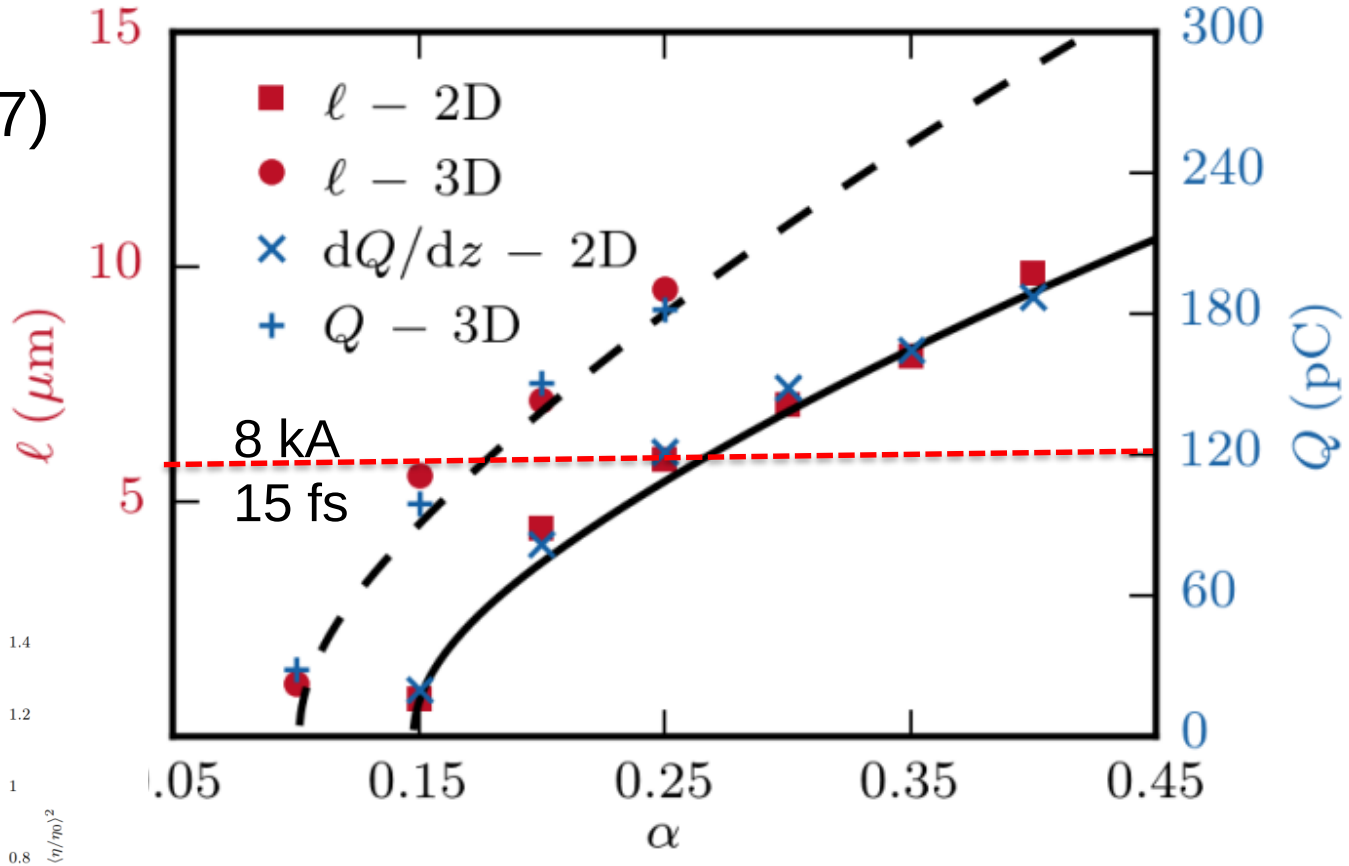
Electron beams for VHEE: 200 MeV at 10 Hz

Ultra-short, high charge bunch generation

M.P. Tooley et al., PRL (2017)
S. Yoffe et al., SPIE (2019)

Bump injection
Adjust injected charge up to 300 pC





Minimum bunch length: 260 attoseconds rms

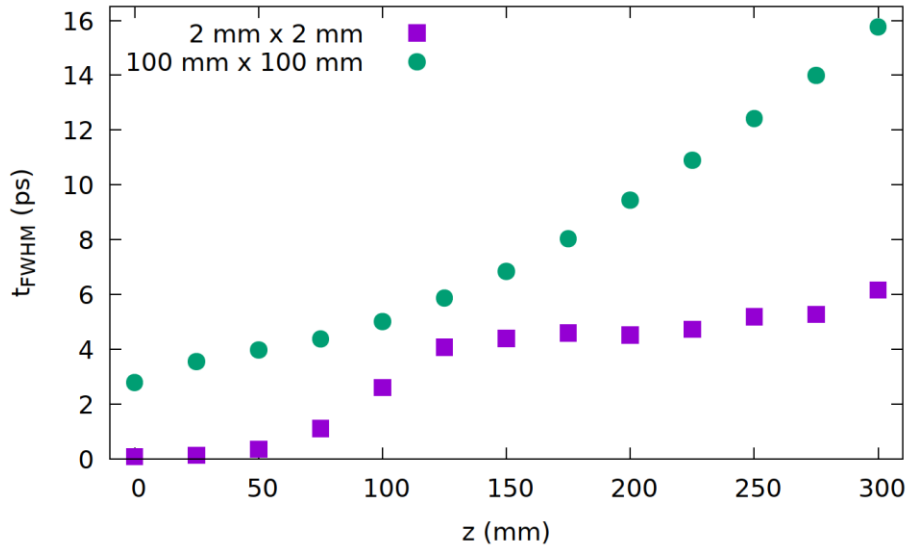
$$\ell \simeq \frac{1-\bar{\beta}_b}{\bar{\beta}_b}(z_1 - z_0) \simeq \frac{\Delta L}{2\bar{\gamma}_b^2},$$

$$\bar{\gamma}_b = (1-\bar{\beta}_b^2)^{-1/2}$$

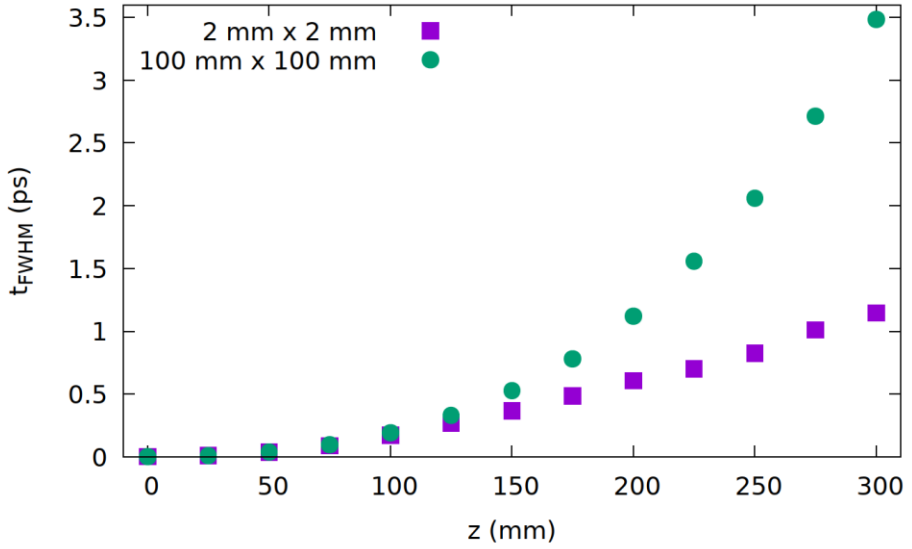
Bunch duration vs depth in phantom

E. Brunetti et al., SPIE (2021)

Focused beam



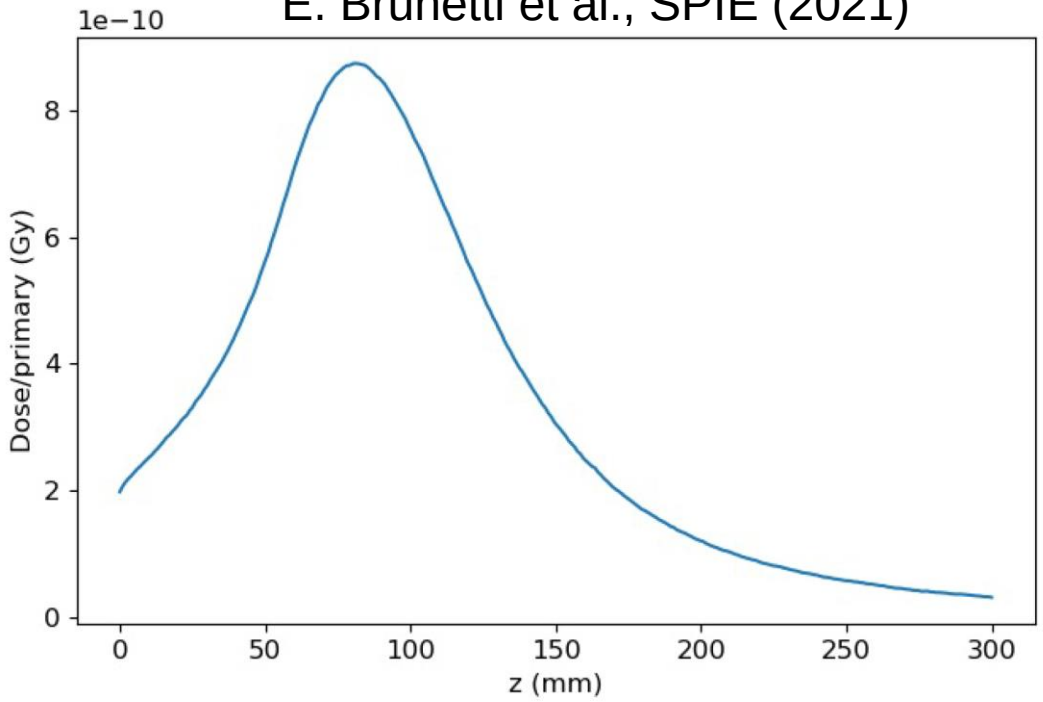
Collimated beam



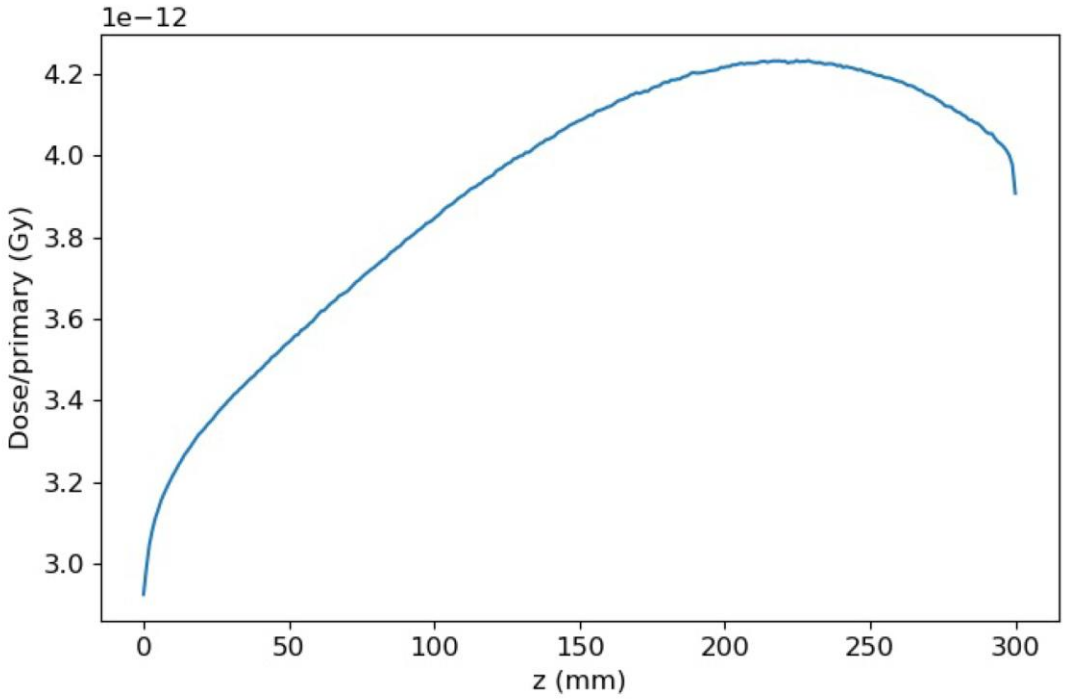
200 MeV bunch lengthens and loses energy because of multiple scattering:
1 Gy: 1-10 electrons per μm^2

Dose distribution for 200 MeV beam

K. Kokurewicz et al., Sc. Rep. (2019)
K. Kokurewicz, et al. Commun. Phys. (2021)
E. Brunetti et al., SPIE (2021)



2 mm x 2 mm x 300 mm volume

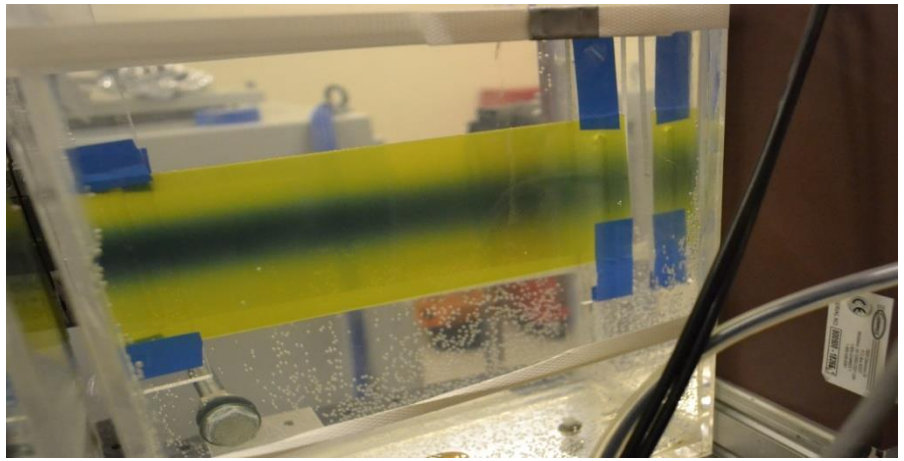


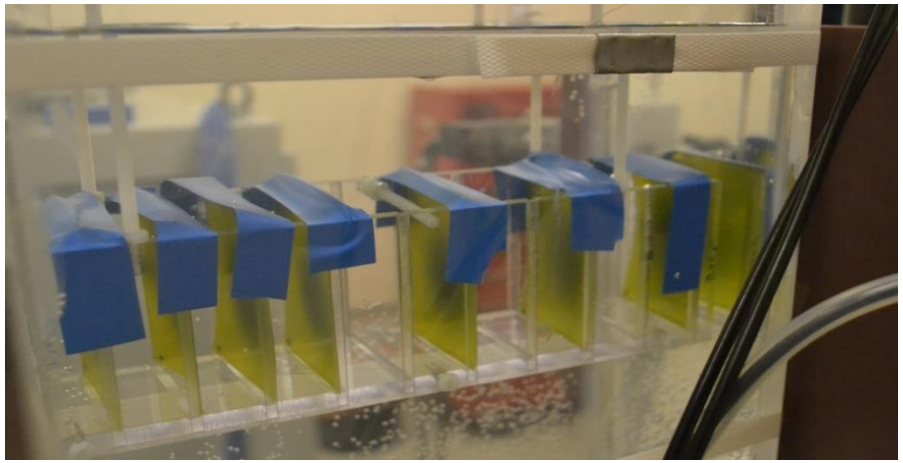
100 mm x 100 mm x 300 mm volume

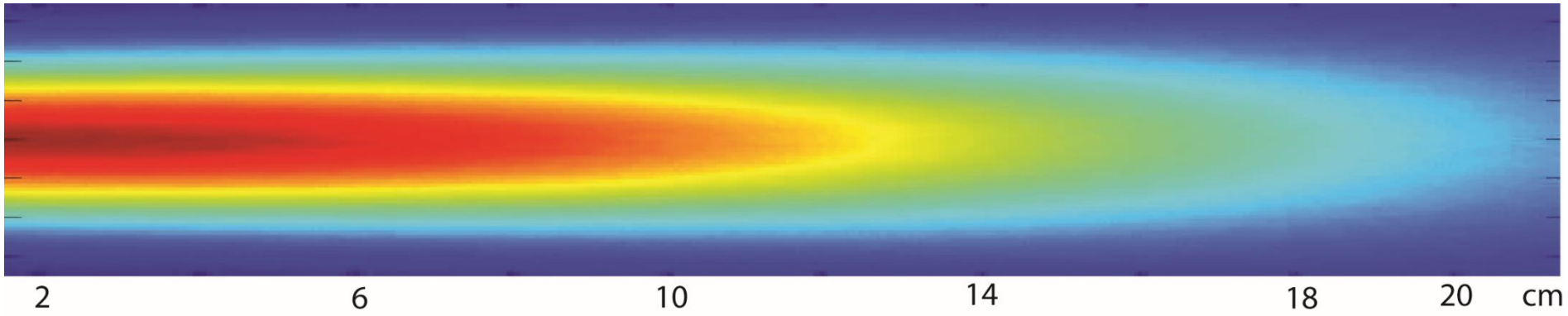
For 200-300 pC beam at 200 MeV @ 10 Hz, we reach the FLASH dose > 10 Gy/second when beam is focussed.

Objective: to deposit 10 Gy in a small volume in tumour and then scan

Dosimetry of LPA beams measured at Strathclyde: longitudinal and transverse profiles



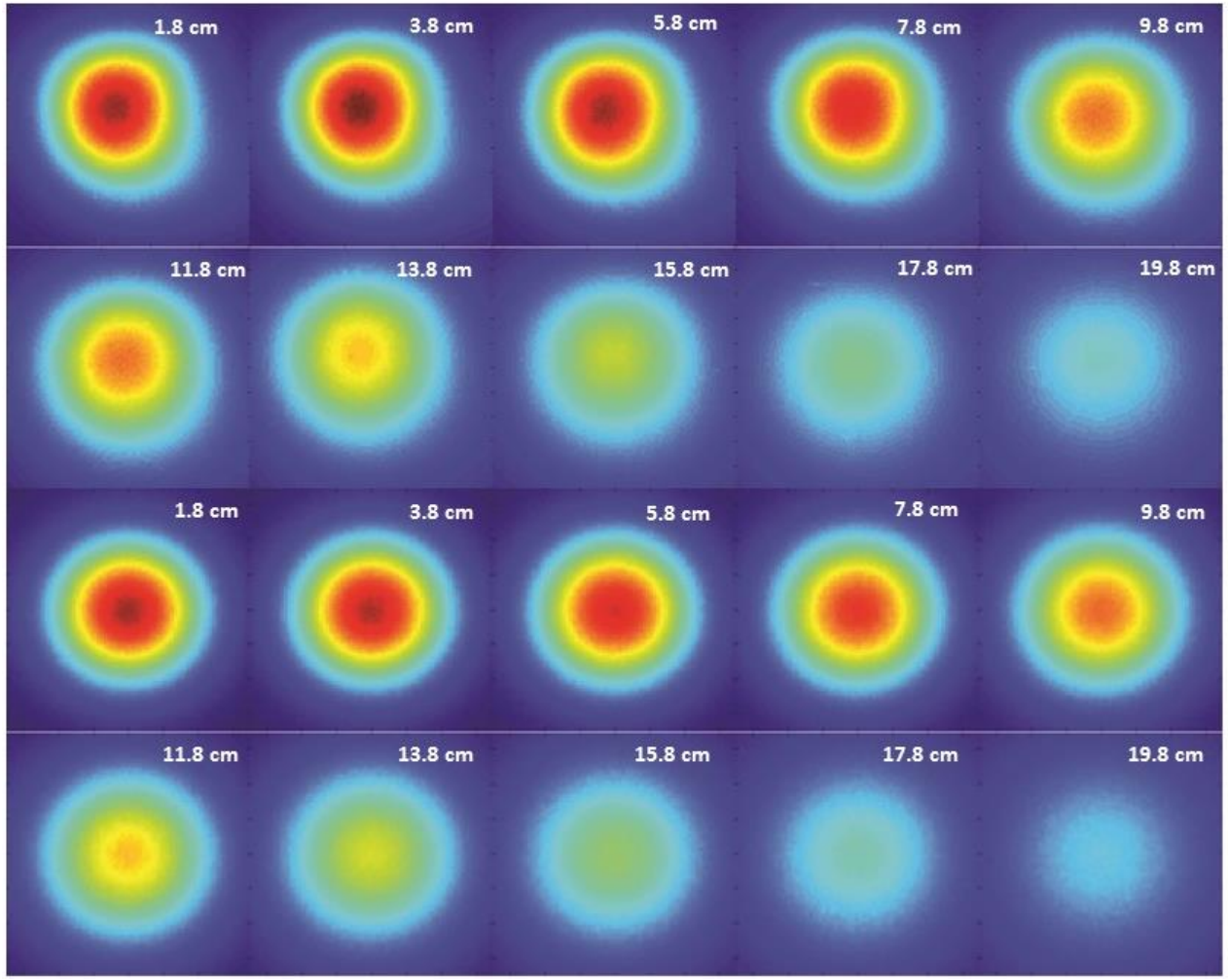




2D MC calculated longitudinal dose map for 142 MeV electron beam

A. Subiel et al., Phys. Med. Biol. 59, 5811 (2014).
V. Moskvin et al., Medical Physics, 39, 3813 (2012)

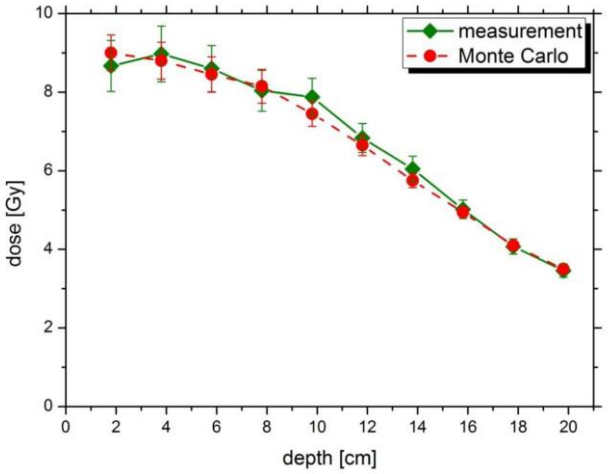
LPA - VHEE: Measured & calculated dose maps



LPA Measurement in phantom

Measurement (above) vs **MC simulated** (below) dose maps for several depths in water phantom for 142 MeV electron beam.

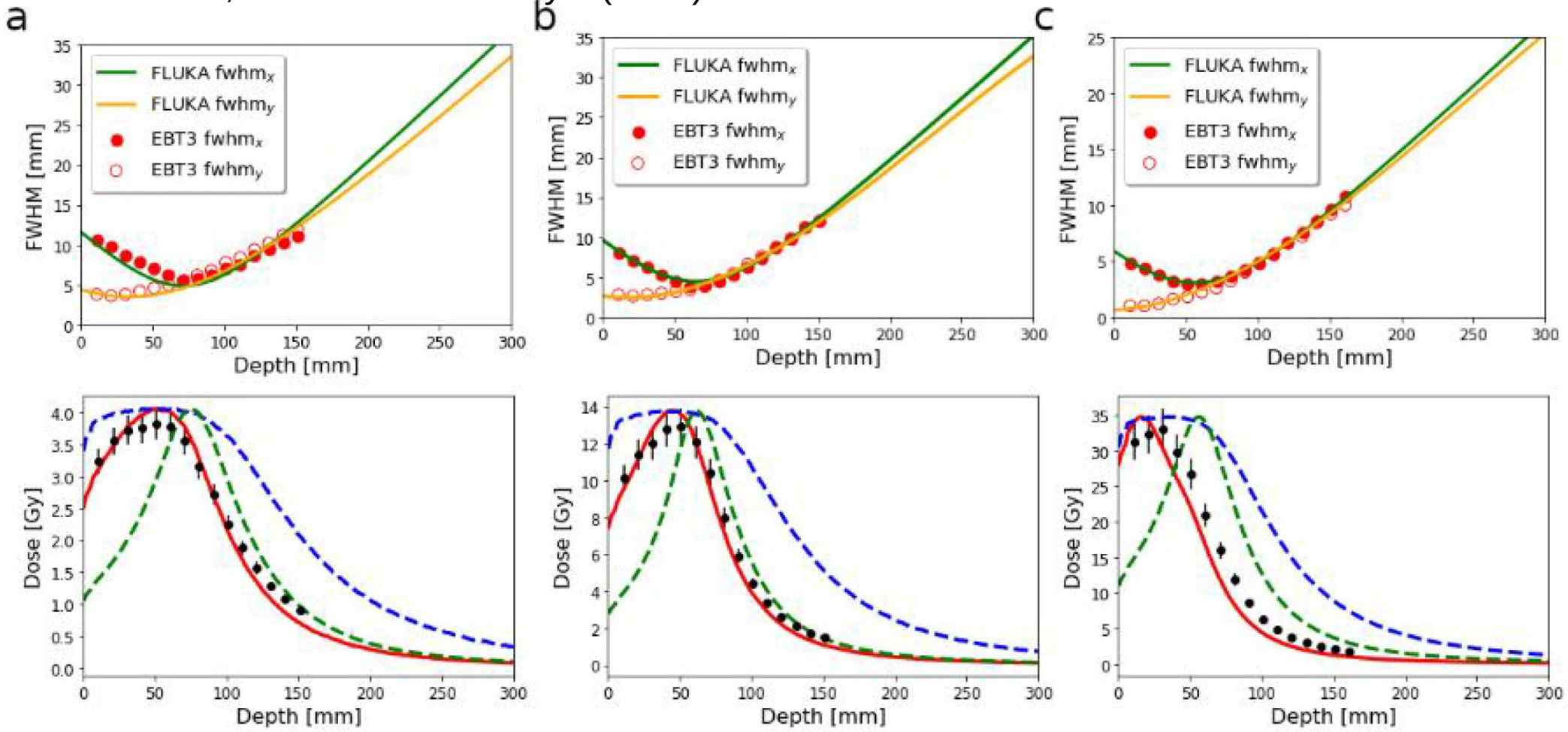
MC Simulation



A. Subiel et al., Phys. Med. Biol. 59, 5811 (2014).
V. Moskvin et al., Medical Physics, 39, 3813 (2012)

Measurements at CERN on CLEAR Facility

K. Kokurewicz, et al. Commun. Phys. (2021)



(a) 158 MeV, f/11.2,
(b) 158 MeV, f/12.3,
and
(c) 201 MeV, f/18.2

Solid red curves MC simulated depth dose profiles for beams focused only in the horizontal plane.
Dashed green lines MC simulated dose profiles obtained for symmetric focussing,
Dashed blue lines represent collimated beams. Depth-dose curves - collimated and symmetrically focused beams normalised to the peak dose of the line focus.

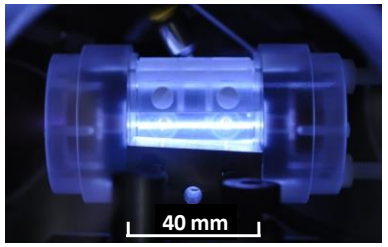
SCAPA

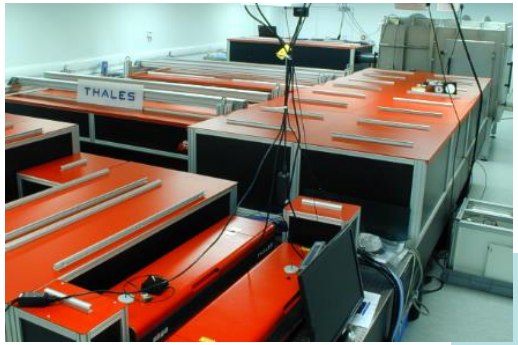
http://www.scapa.ac.uk/

University of Strathclyde

- **The Scottish Centre for the Application of Plasma-based Accelerators (SCAPA)**
- Expansion of **ALPHA-X** laser-plasma accelerator facilities at Strathclyde with newly constructed laboratories
- **Applications, Research & Development**.
- Knowledge Exchange & **Commercialisation** opportunities
- Engagement in European (ELI, Laserlab, AWAKE, EuPRAXIA)
- **Training**
- **3 shielded areas** containing **7 accelerator beam lines**
- High-intensity femtosecond laser systems:
  - a) 350 TW (with provision for expansion) @ 5 Hz
  - b) 40 TW @ 10 Hz PRF,
  - c) sub-TW @ kHz PRF.
- High-energy **proton, ion, electron, positron** bunches, High-brightness **X-ray and gamma-ray** pulses
- Control of particle beam polarisation.

Compact GeV electron accelerator and gamma-ray source





APPLICATIONS

- Radiobiology
- Ultrafast Probing
- High-Resolution Imaging
- Radioisotope Production
- Detector Development
- Radiation Damage Testing

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Thank You and Our Team

ALPHA-X *Strathclyde Team:* Dino Jaroszynski, Giorgio Battaglia, Enrico Brunetti, Bernhard Ersfeld, Lucas Gamiz, Andrjez Kornaszewski, Wen Tao Li, Erin Logan, Tom McCanny, Antione Maitrallain, Grace Manahan, Jason Mill, Adam Noble, Willow Pring, Mohammed Shahzad, Kiruththika Sivanathan, Annette Sorenson, Gregory Vieux, Mark Wiggins, Sam Yoffe

Strathclyde Collaborators: Marie Boyd, Natividad Gomez Roman, Annette Sorensen, Paul McKenna, Zheng Ming Sheng, Bernhard Hidding, Gordon Rob, Brian McNeil, & Ken Ledingham

ALPHA-X: Current and past academic and industrial collaborators:

Lancaster U., Cockcroft Institute / STFC - ASTeC, STFC – RAL CLF, U. St. Andrews, U. Dundee, U. Abertay-Dundee, U. Glasgow, Imperial College, Cochin University of Science & Technology U. Manchester, IST Lisbon, U. HH Dusseldorf, U. Paris-Sud - LPGP, Pulsar Physics, UTA, CAS Beijing, U. Tsinghua Beijing, Shanghai Jiao Tong U., Capital Normal U. Beijing, APRI, GIST Korea, UNIST Korea, LBNL, FSU Jena, U. Stellenbosch, U. Oxford, UCL, LAL, PSI, U. Twente, TUE, U. Bochum, IU Simon Cancer Center, Indianapolis, IRP, MGS Research, Inc., Madison, Royal Marsden, ELI-NP, ELI-ALPS, ELI-Beamlines ....

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FIN

Thank you

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University of Strathclyde

EPSRC

SUPA

Laserlab Europe

Science & Technology Facilities Council

NPL National Physical Laboratory

The Cockcroft Institute of Accelerator Science and Technology

EuPRAXIA

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