Applications of very High Energy Electron (VHEE) Beams for Radiotherapy and PANAMA

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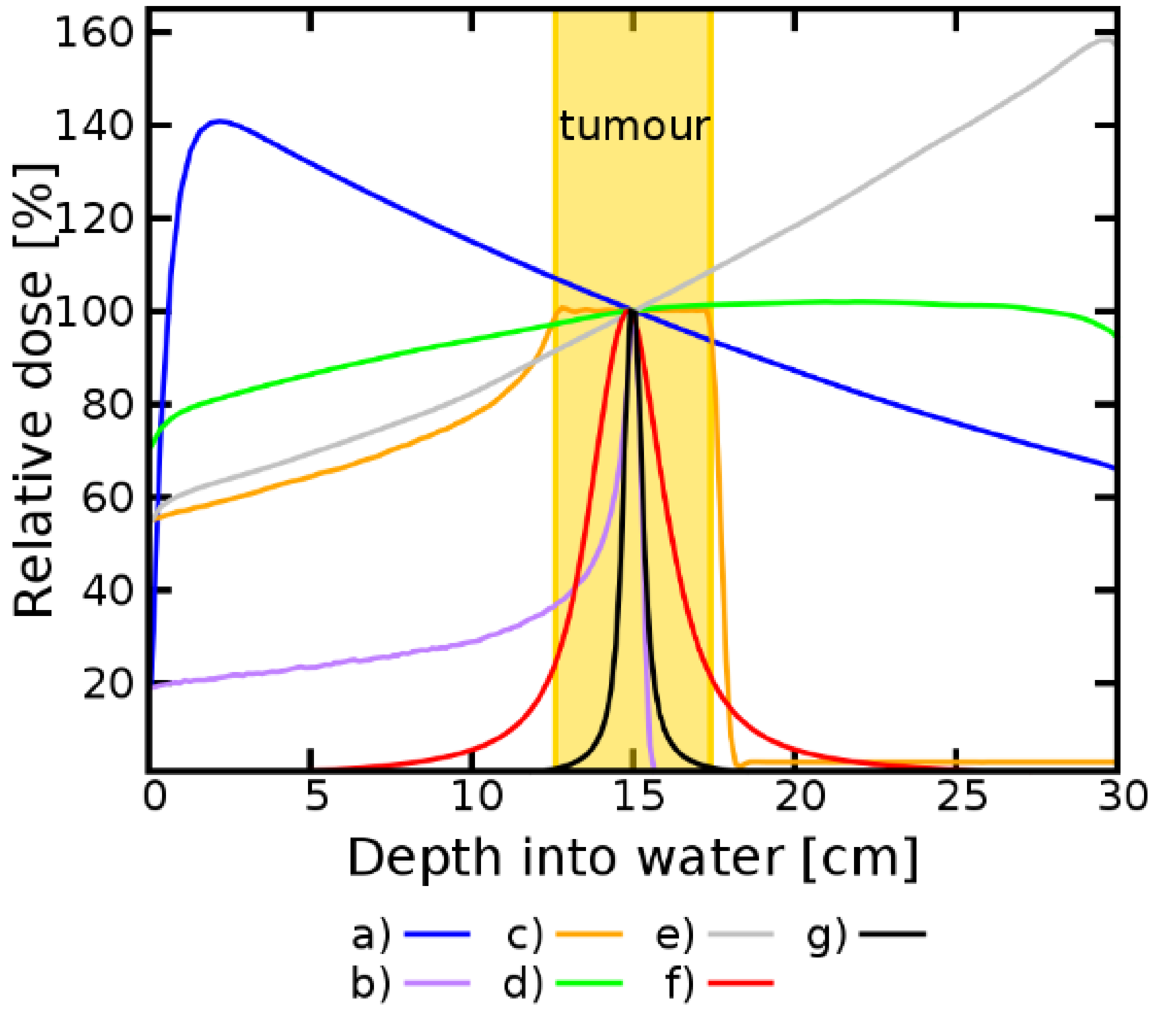

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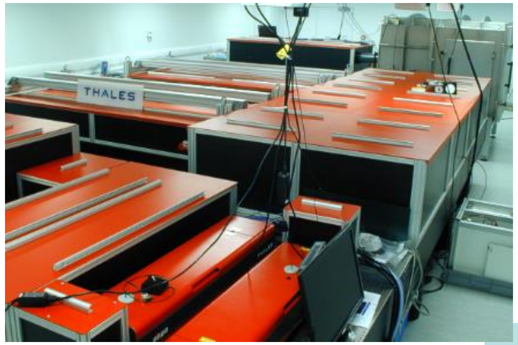
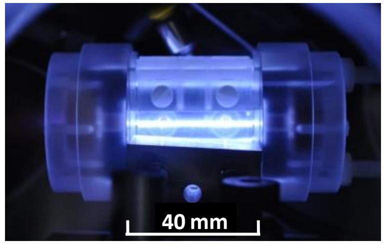
- **The Scottish Centre for the Application of Plasma-based Accelerators (SCAPA)**
- Expansion of **ALPHA-X** laser-plasma accelerator facilities at Strathclyde with newly constructed laboratories
- **Applications, Research & Development**.
- Knowledge Exchange & **Commercialisation** opportunities
- 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
- Dense matter

First stage - Bunker layout

Started with three beamlines:

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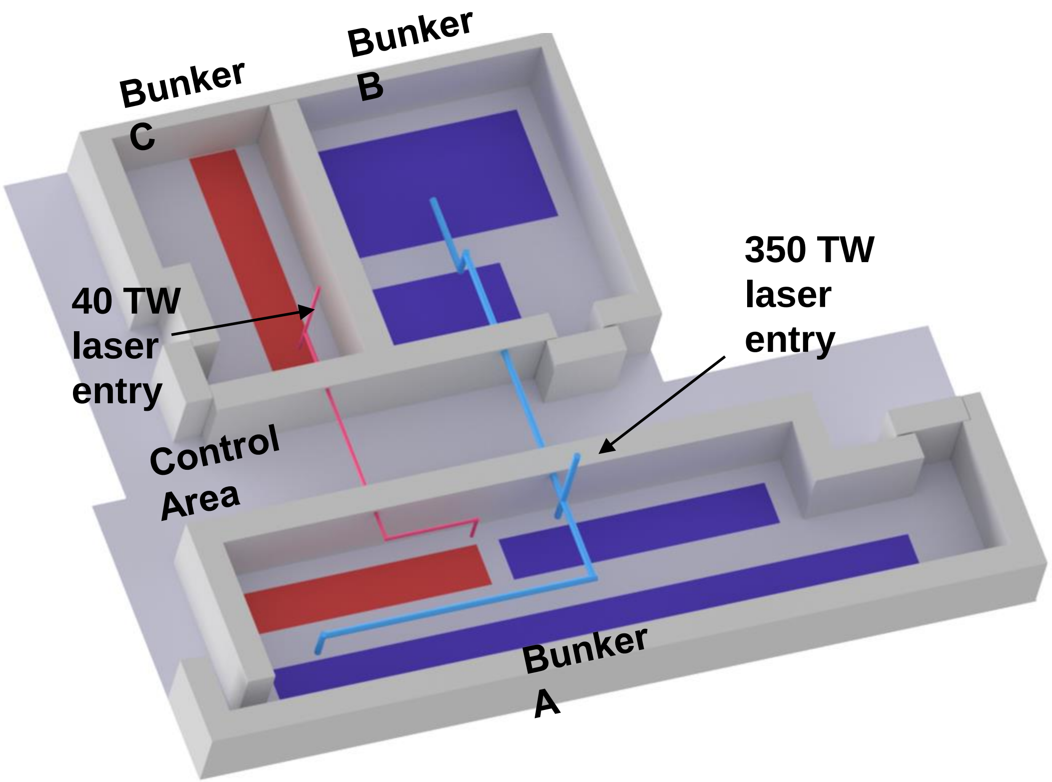
- **Bunker A:** mainly for laser wakefield acceleration studies and undulators – FEL and plasma undulator studies
- **Bunker B:** configured for laser-solid target interactions towards the generation of proton and ion beams.
- **Bunker C:** Medical applications - laser-plasma accelerator radiotherapy and undulators

SCAPA is open to user engagement across all areas of research:

- Development of primary or secondary sources
- Proof-of-principle demonstrations
- Application of sources
- Industry engagement



Layout: two laser labs located on top of the three bunkers

***Bunker C**, 40 TW @ 10Hz (1.5 J, 45 fs):*

- Successful experiment runs with the internal users since **August 2017**.

- Corresponding beamline is currently undergoing an upgrade.

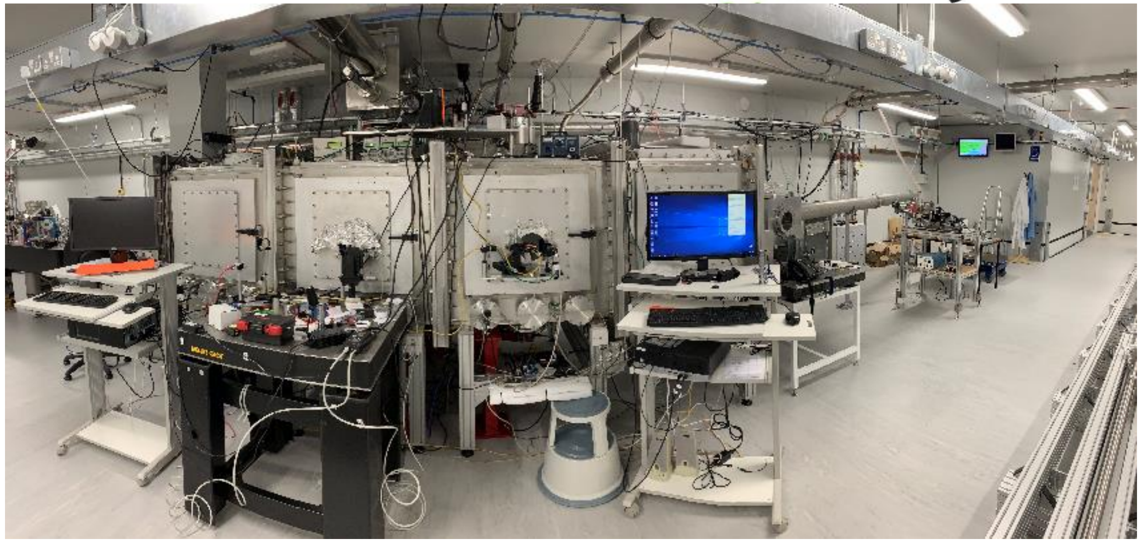
***Bunker A**, 350 TW @ 5Hz (8.5 J, 25 fs):*

- LWFA beamline has two focal length configuration: *f*# 33 (*f* = 4 m) and *f*#16 (*f* = 2 m).

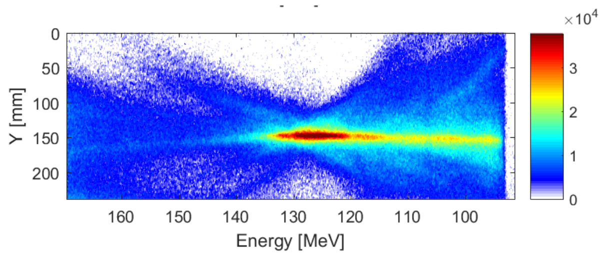
- First electron beams produced in **June 2019**, which leads to experiment campaigns with internal users.

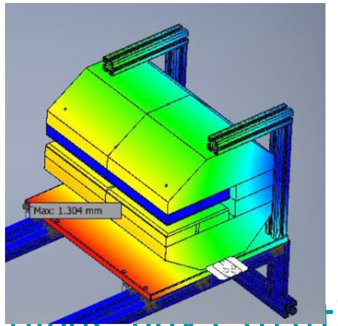
- First industrially-funded campaign (Oct 2020) providing SCAPA with KE links.

LWFA beamline at Bunker A

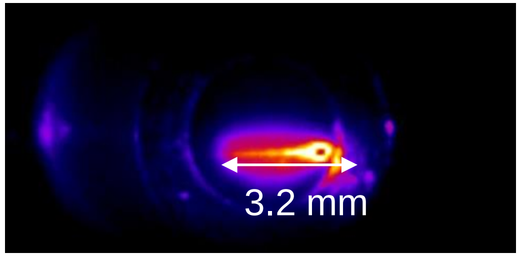


Spectrum of electron beam @ 130 MeV

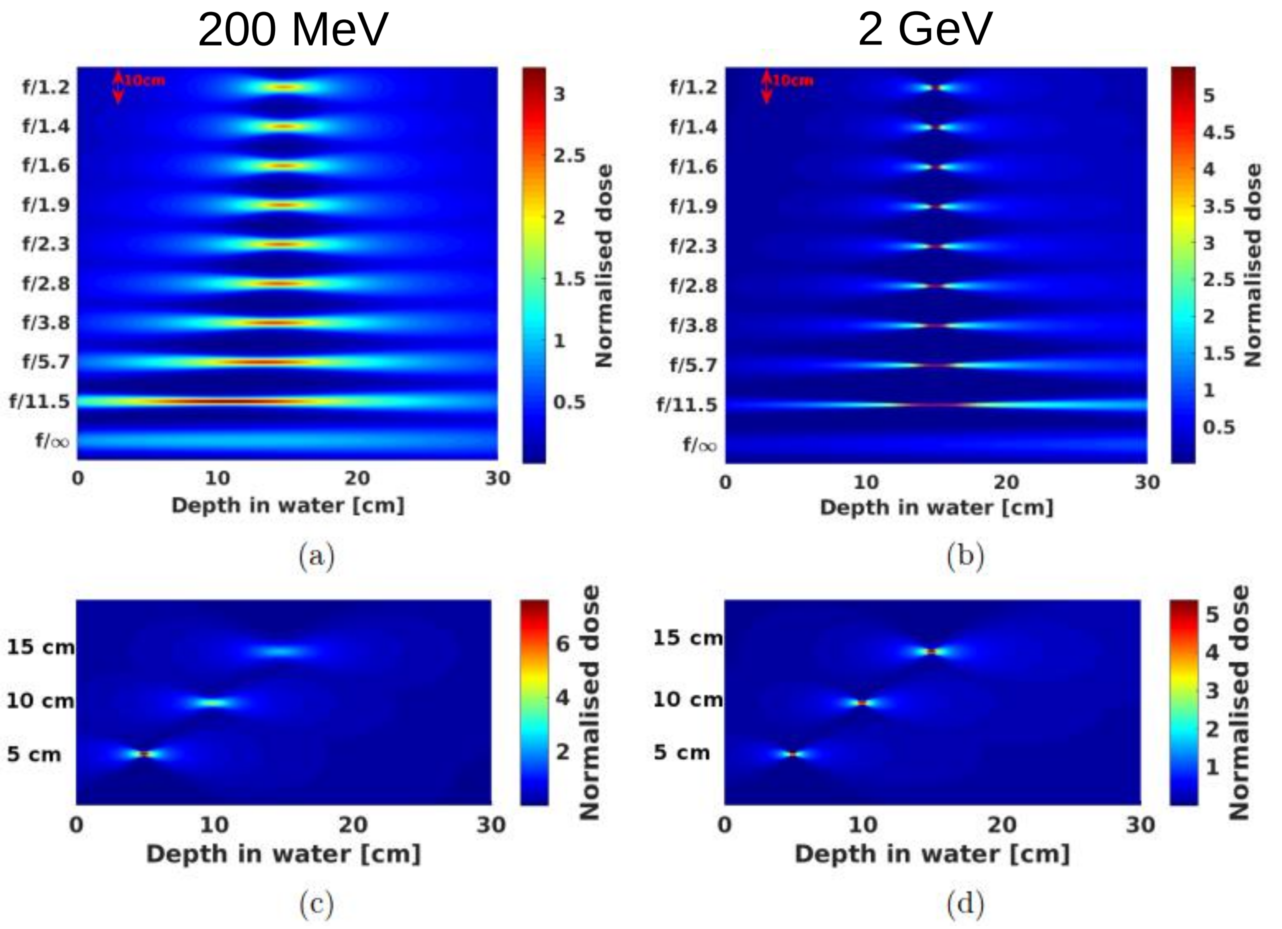




plasma filament from a 3.2 mm He gas jet



- 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
- PANAMA

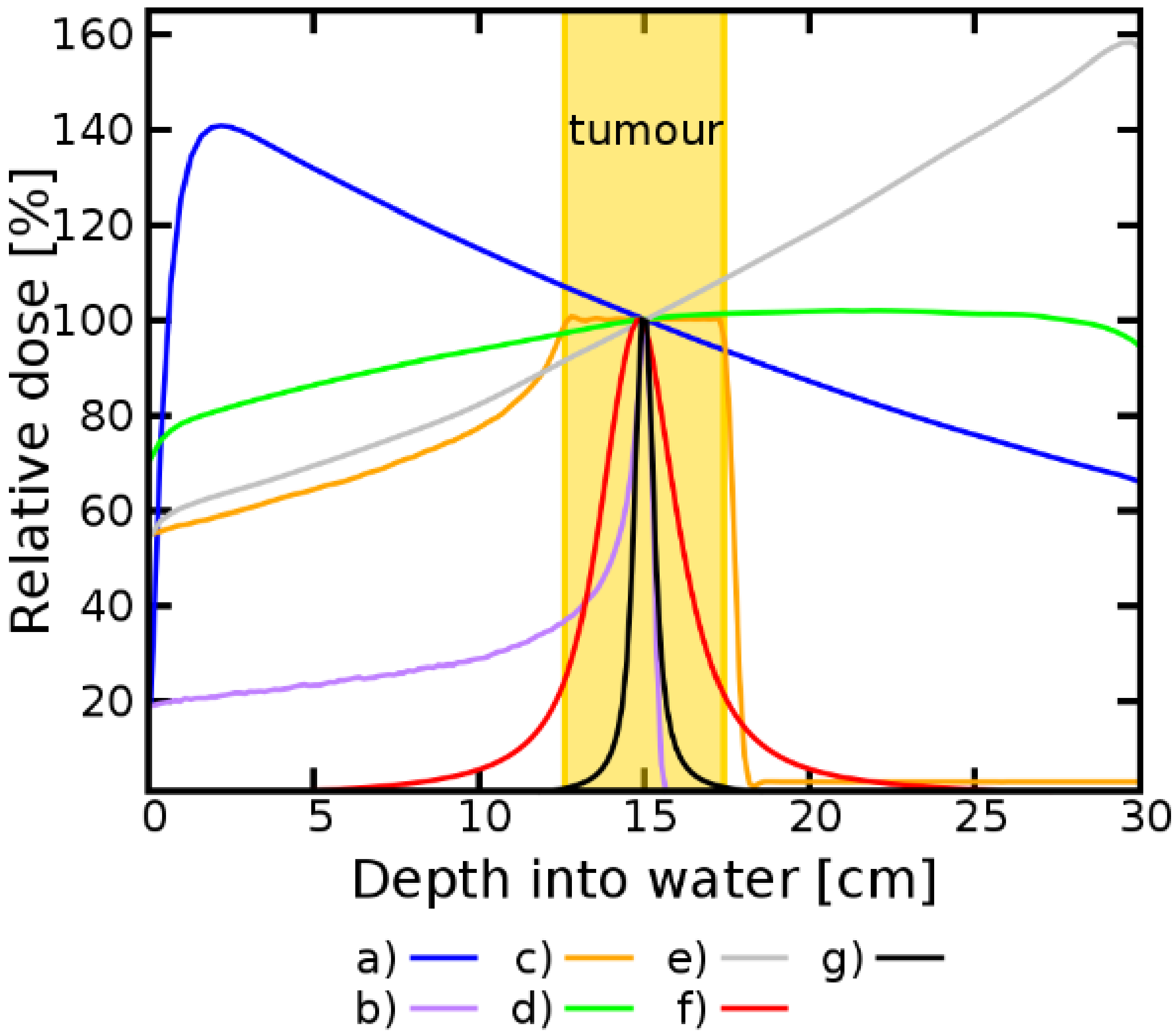


VHEE team: Dino Jaroszynski, Marie Boyd, Annette Sorensen, Natividad Gomez Roman, Enrico Brunetti, Antoine Maitrallain, Karolina Kokurewicz, Anna Subiel, Jason Mill + international collaborators

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.



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50-200 MeV VHEEs as a new RT modality

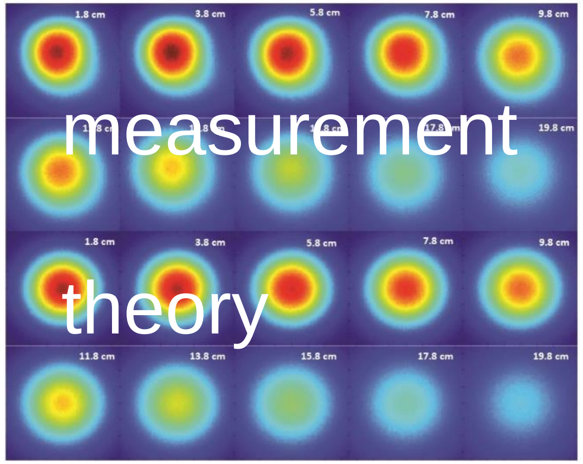
Deep penetration (>20 cm for 200 MeV)

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)

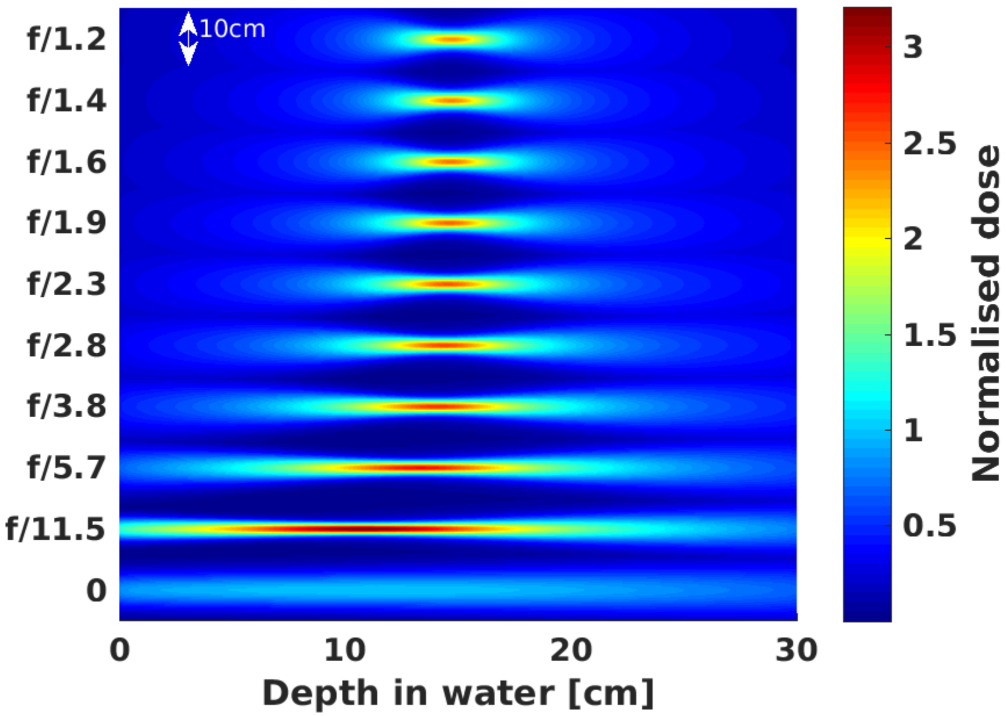
LPA produced
VHEE beams



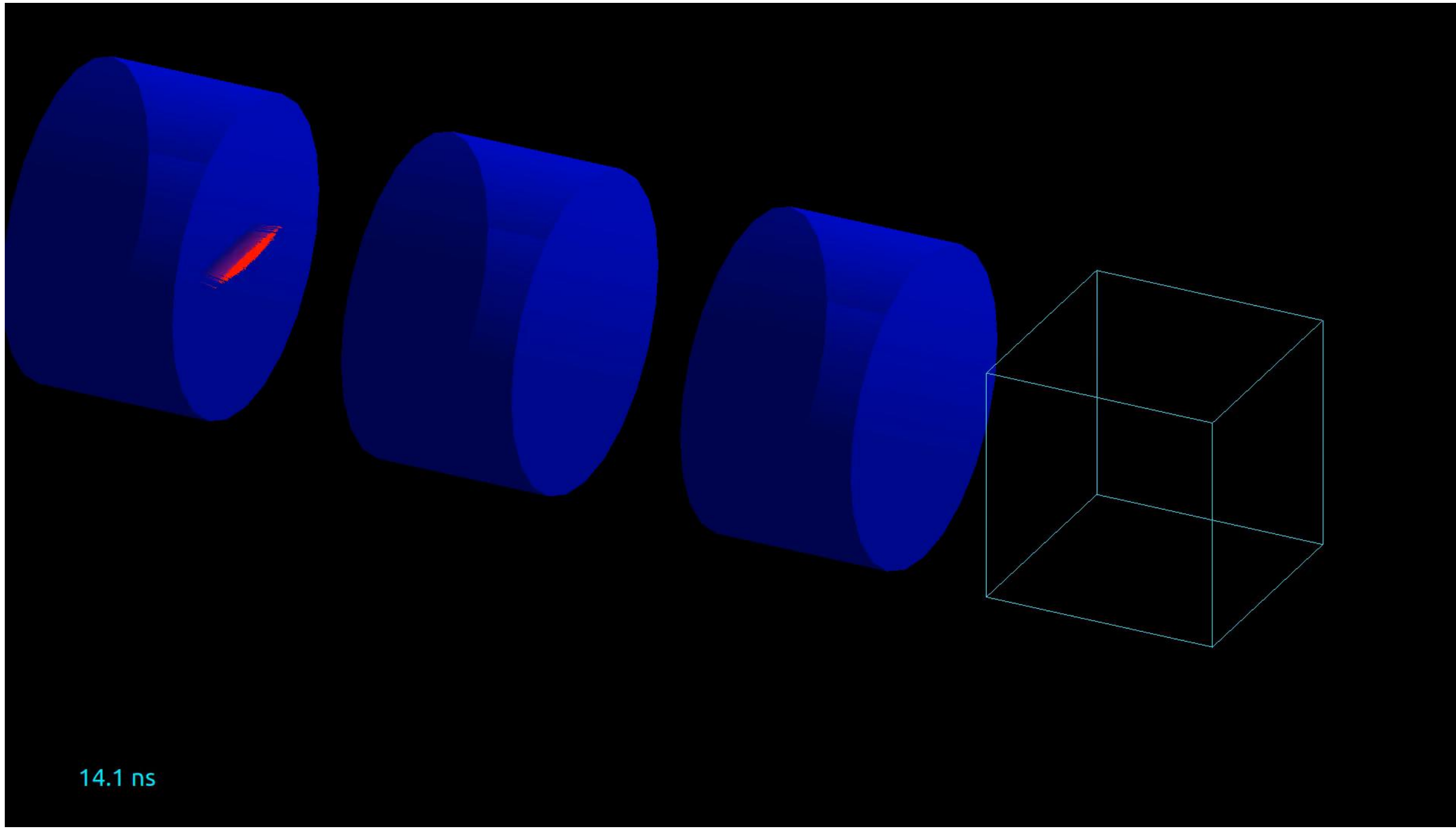
V. Moskvin et al., Medical Physics, 39, 3813 (2012)
Subiel, A. et. al. Phys. Med. Biol. 59, 5811 (2014)

Focussed beams: concentrate dose into small volumetric element

200 MeV beam

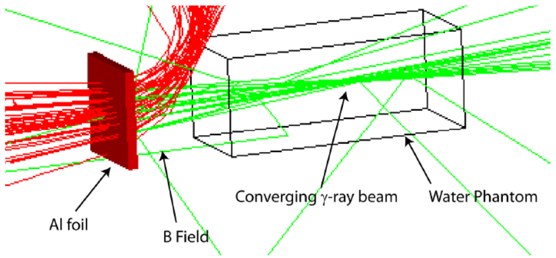


Line focus



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

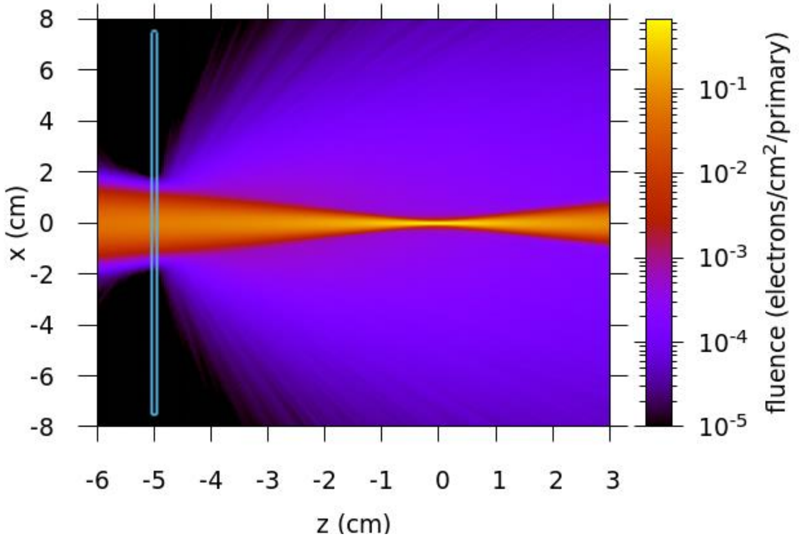
Focussed VHEE beams and photons

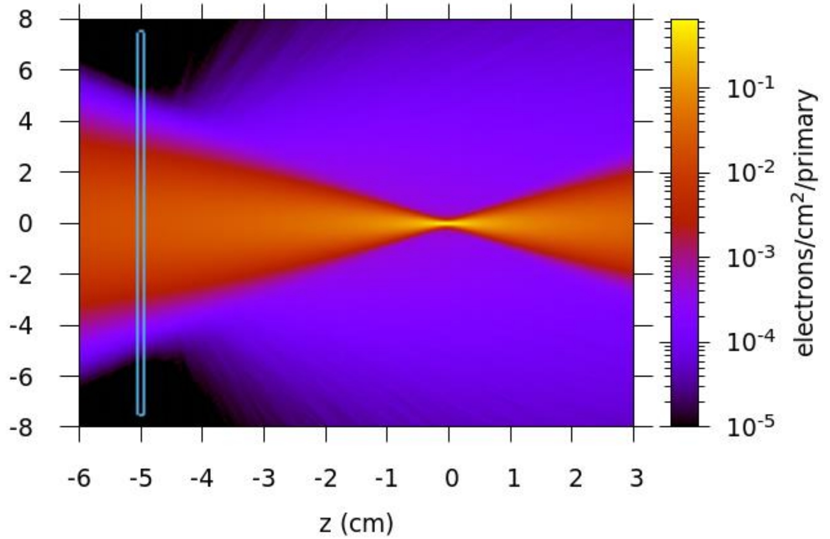


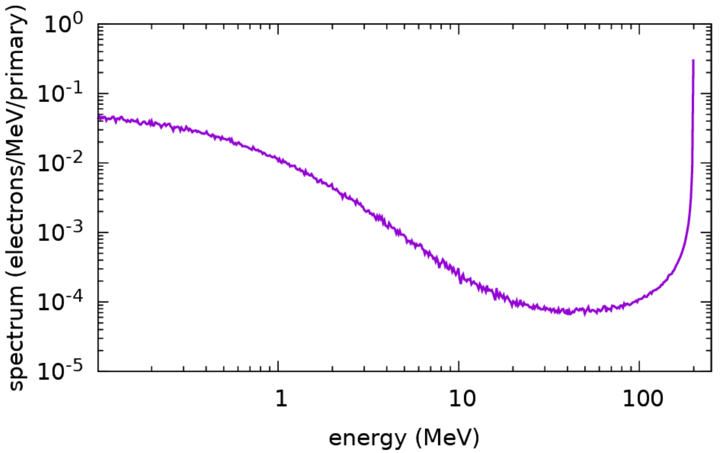
5° converging angle, 1 mm Al foil

15° converging angle, 1 mm Al foil

200 MeV electrons

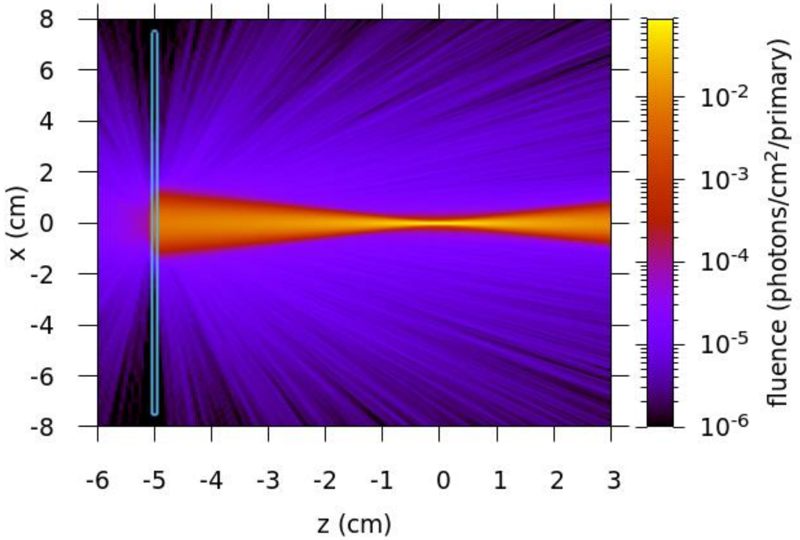


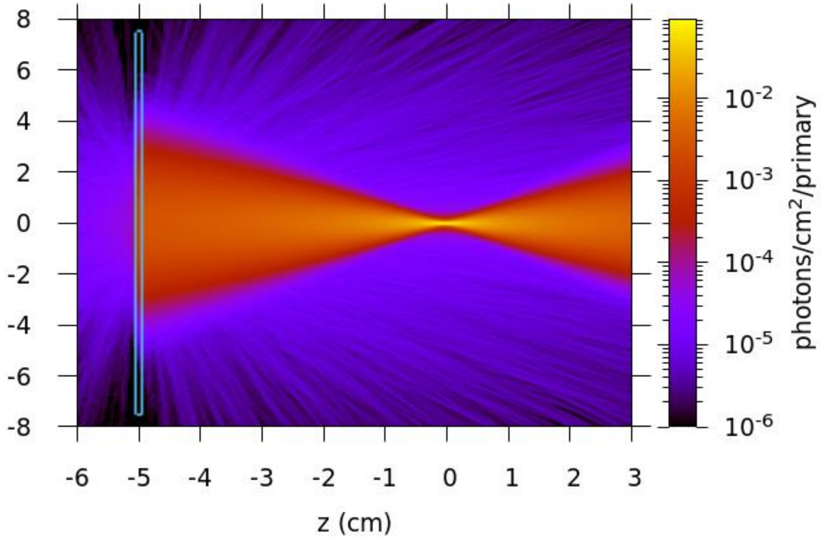


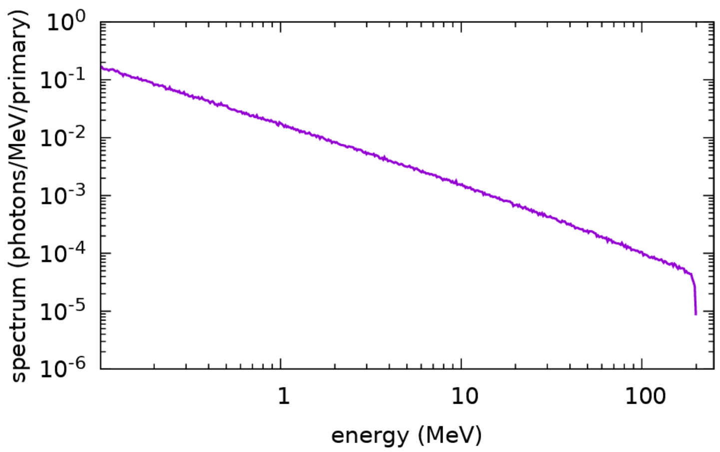


Brunetti et al., SPIE 2019

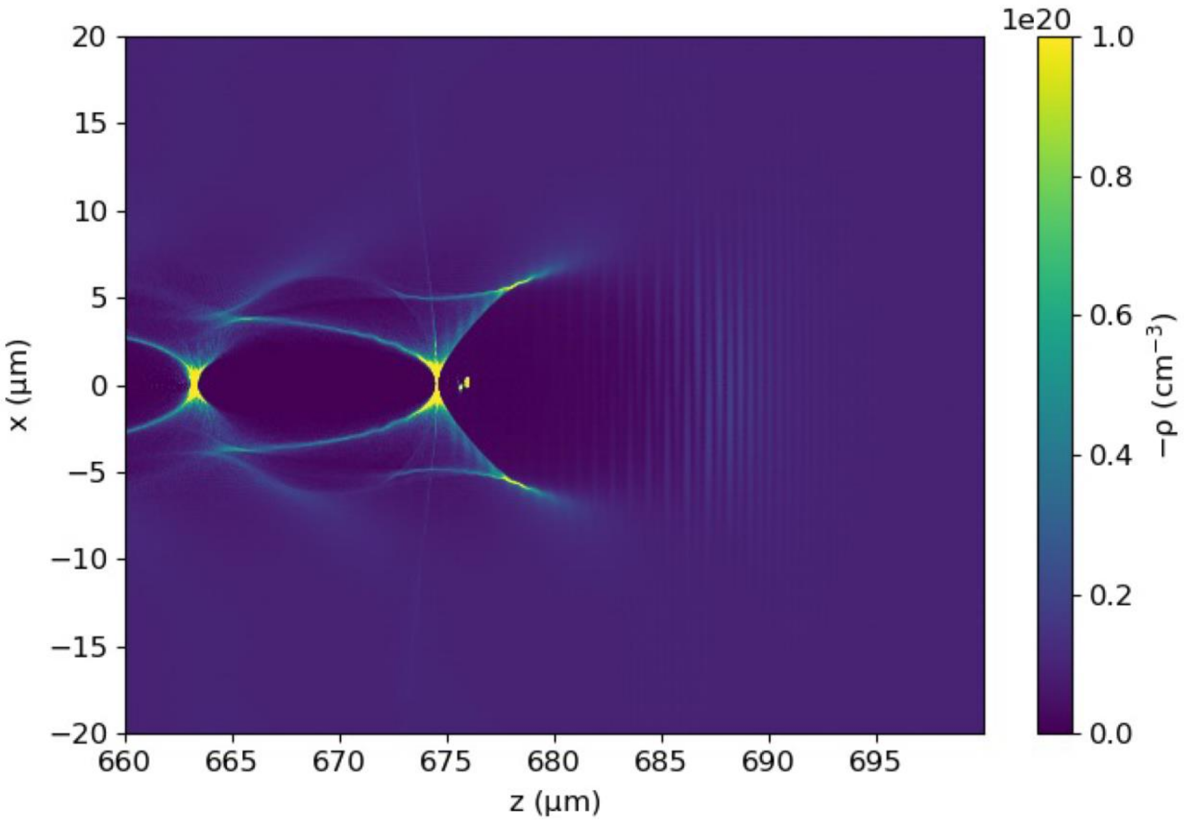
Photons

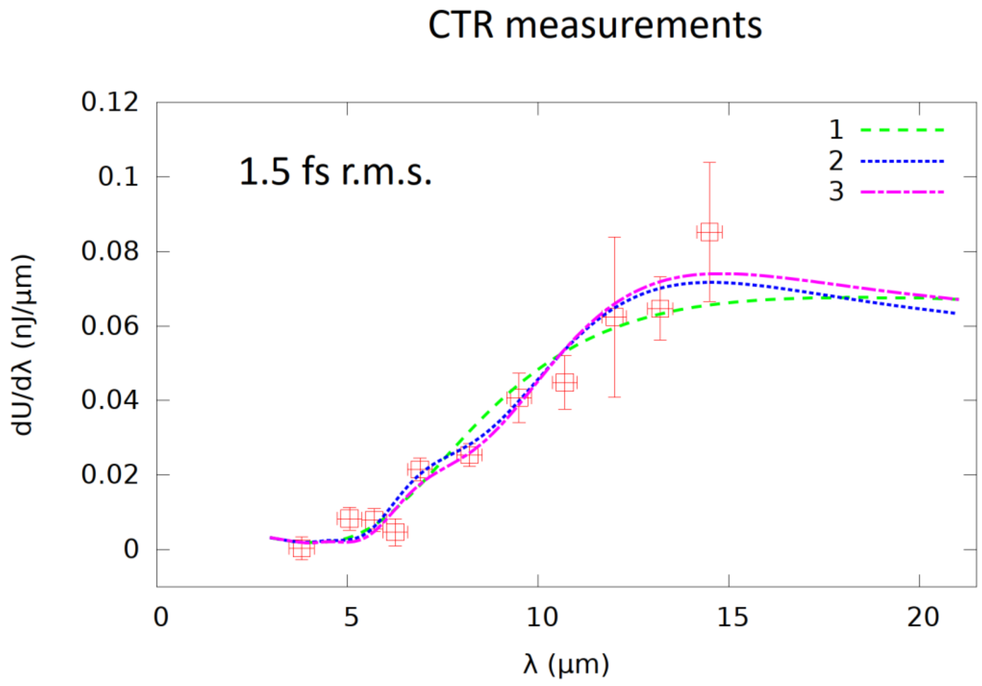






Laser Plasma Accelerator (LPA)





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

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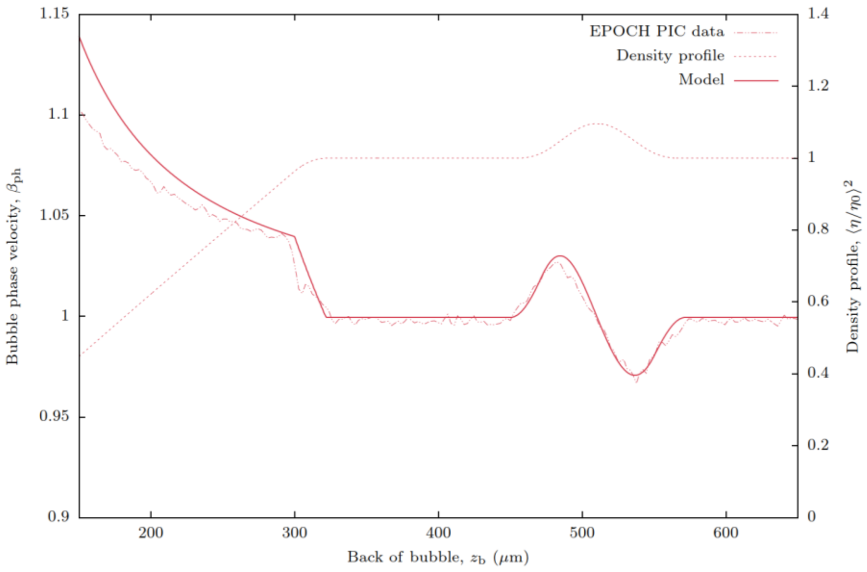
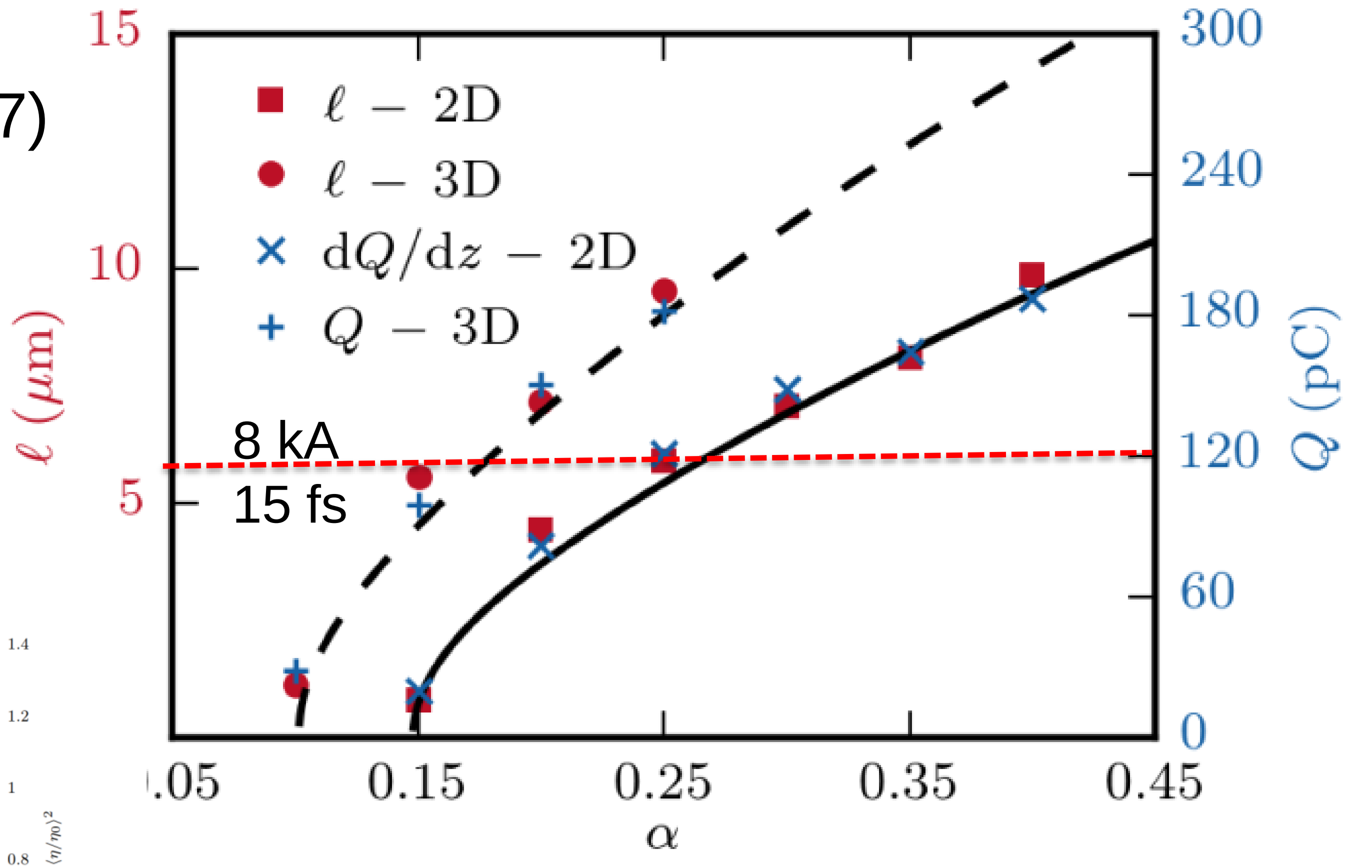
M.P. Tooley et al., PRL (2017)
S. Yoffe et al., SPIE (2019)

Bump injection
Adjust injected
charge up to 300 pC



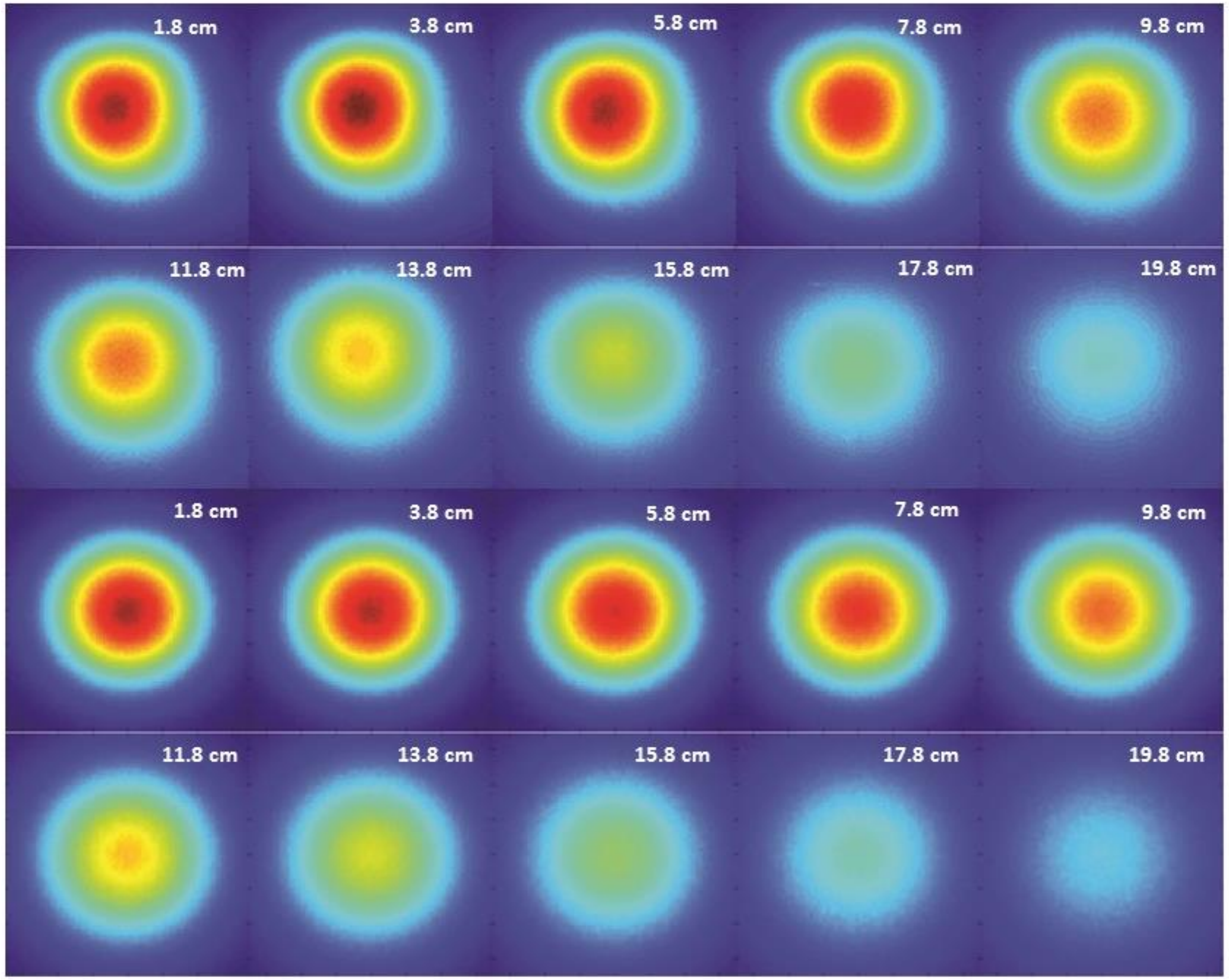


Minimum bunch length: 260 attoseconds rms

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

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

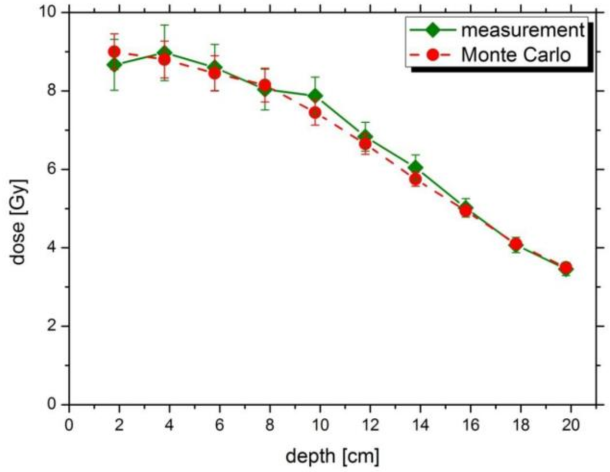
LPA - VHEE: Measured & calculated dose maps



LPA Measurement in phantom

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

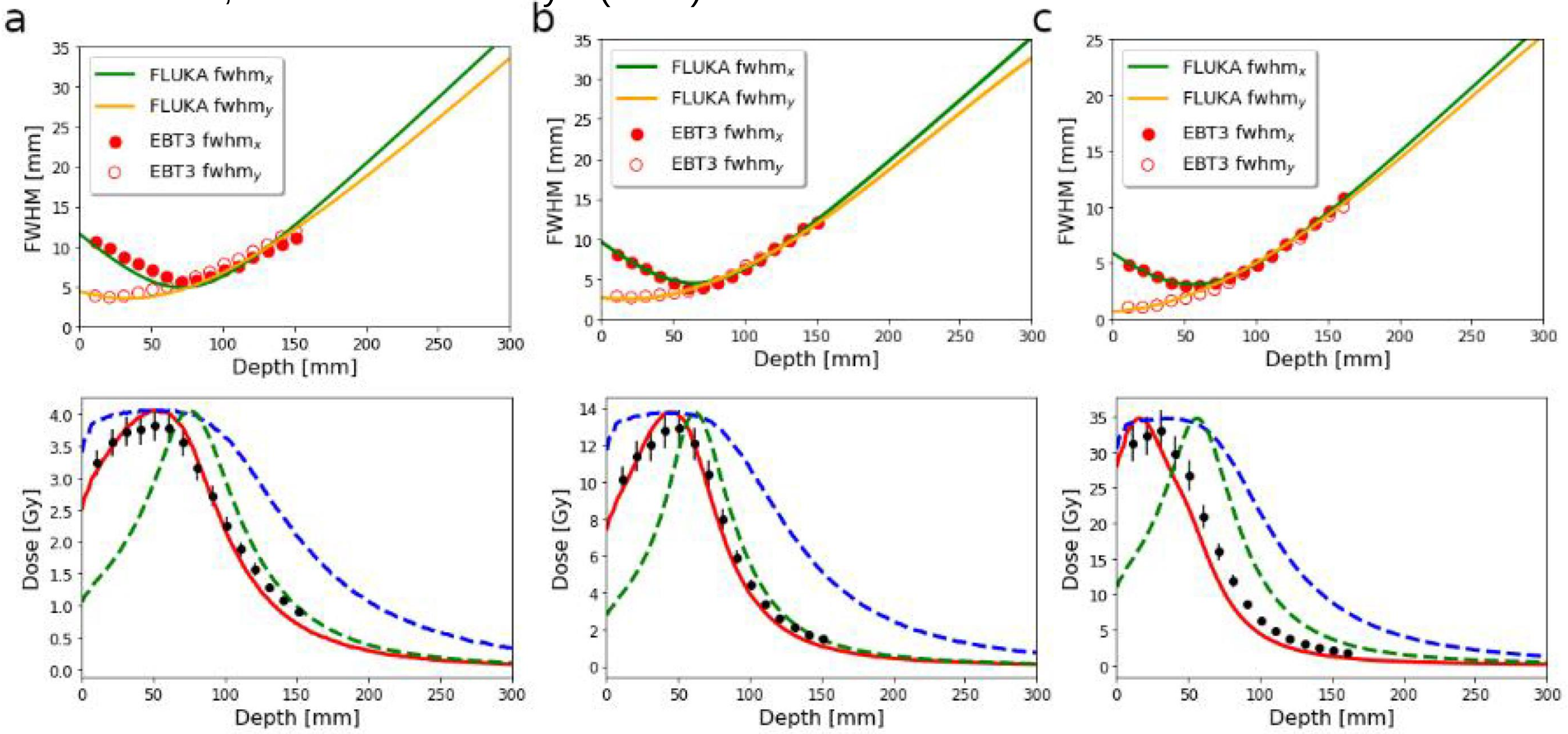
MC Simulation



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

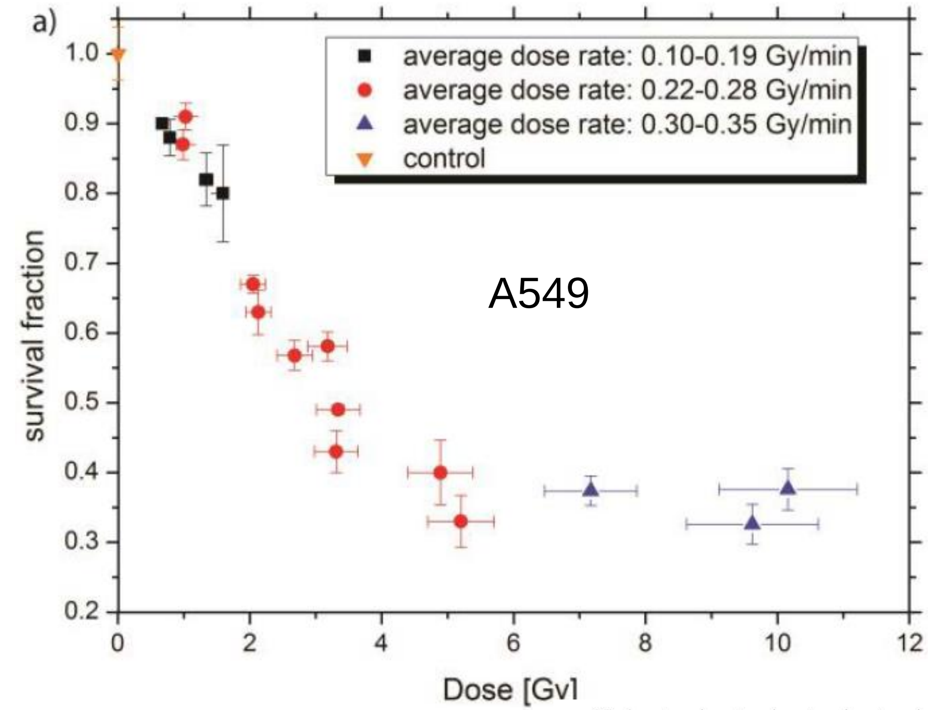
K. Kokurewicz, et al. Commun. Phys. (2021)

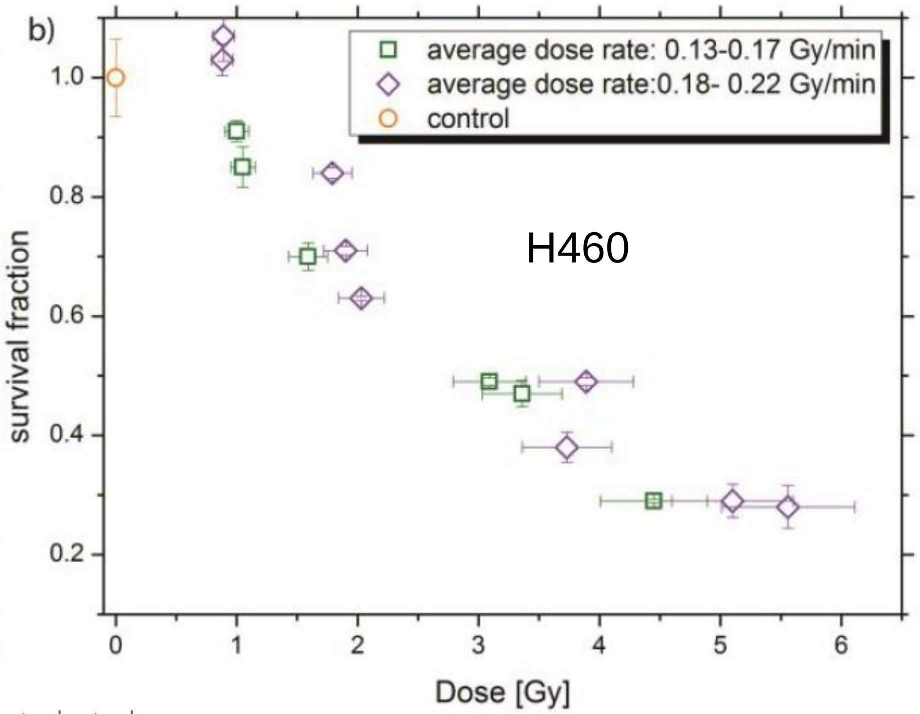


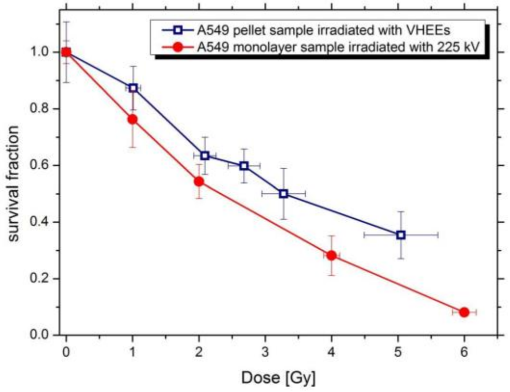
(a) 158 MeV, f/11.2, **(b)** 158 MeV, f/12.3, and **(c)** 201 MeV, f/18.2

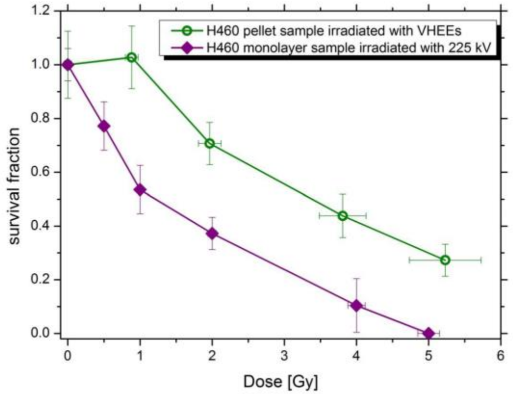
Solid red curves MC simulated depth dose profiles for beams focused only in the horizontal plane.
Dashed green lines MC simulated dose profiles obtained for symmetric focussing,
Dashed blue lines represent collimated beams. Depth-dose curves - collimated and symmetrically focused beams normalised to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

Laser-plasma accelerator beam: Clonogenic capacity of cells following irradiation: 0 – 10 Gy









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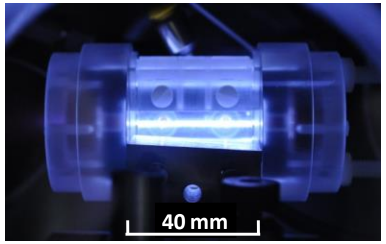
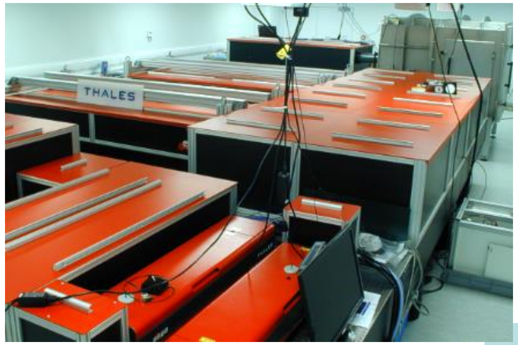




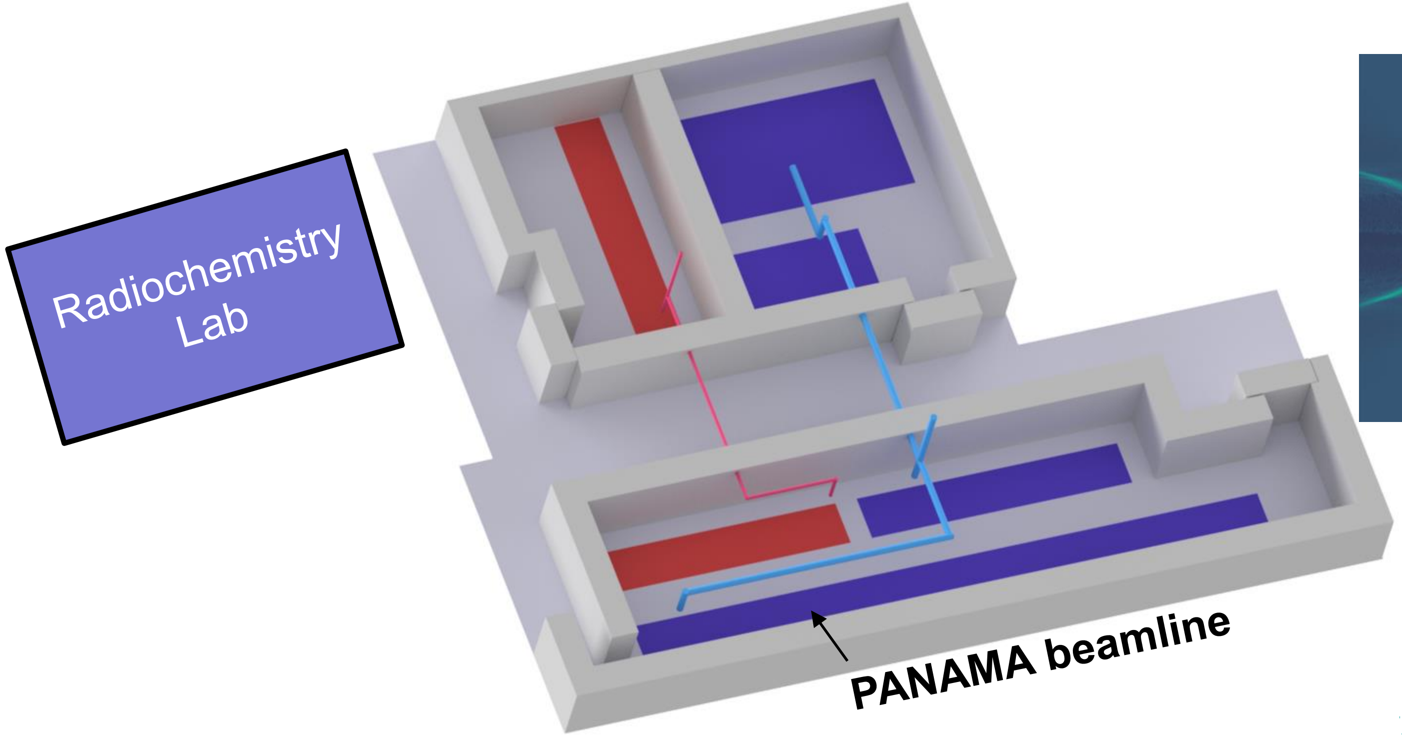
APPLICATIONS

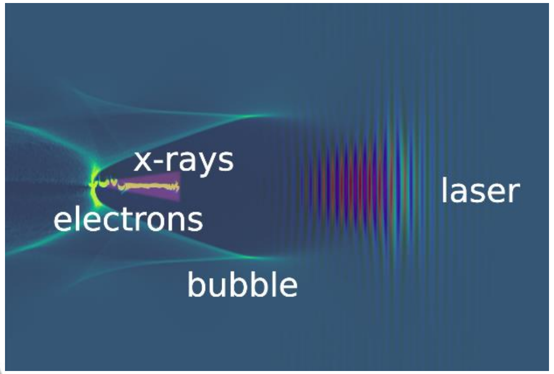
- Radiobiology
- Ultrafast Probing
- High-Resolution Imaging
- Radioisotope Production
- Detector Development
- Radiation Damage Testing
- Dense matter

PANAMA

Plasma Accelerator for Nuclear Applications and Material Analysis

- £3.2M project for EPSRC National Nuclear Users Facility (NNUF), 11.2019 - 03.2023
- PI is Dr. Joanna Renshaw from Civil and Environmental Engineering (Strathclyde)
- Expand SCAPA capabilities - advanced materials testing and characterization
- Develop specialist beamline and associated lab for handling radioactive samples



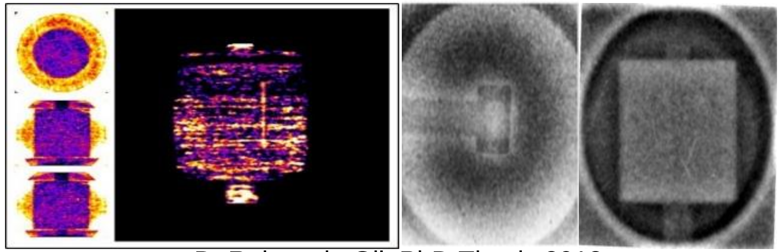


Plasma Accelerator for Nuclear Applications and Material Analysis

PANAMA will enable research on:

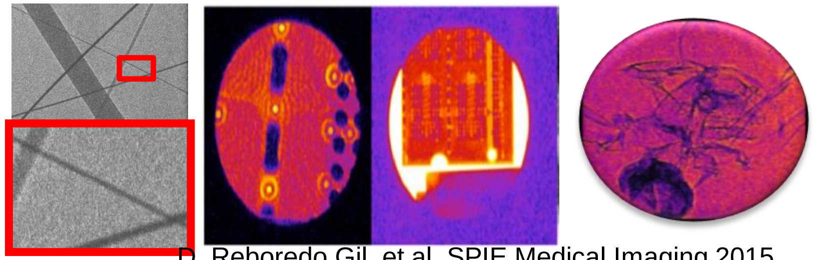
- studies on impact of high radiative environment on structural materials
- X-ray and gamma ray tomographic imaging of nuclear materials
- X-ray beam transport for ultrafast X-ray diffraction (XRD) and energy dispersive X-ray absorption spectroscopy analyses (ED-XAS).
- ultrafast pump-probe configurations
- time-resolved in-situ imaging and analysis of radiation damage

Nuclear Waste barrel imaging (X-rays)



D. Reboredo Gil, PhD Thesis 2018

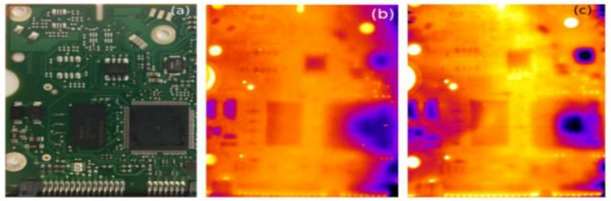
10 & 25 mm Cu (2 mm resolution) (X-rays)



D. Reboredo Gil, et al. SPIE Medical Imaging 2015

Imaging electronic components (electrons)

Hard disk controller 20 shots 1 shot



X. Yang, E Brunetti et al., Scientific Reports 2017

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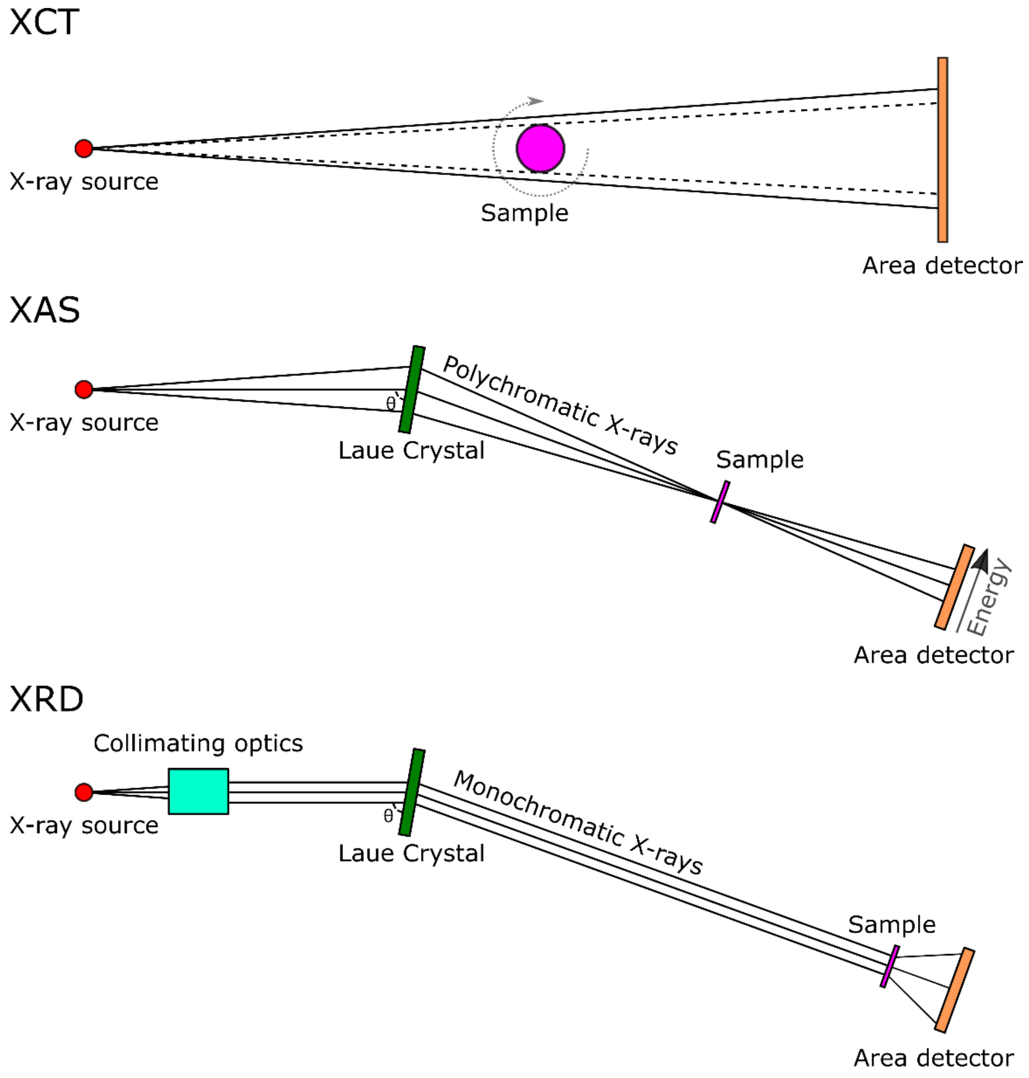
Analytical techniques

With the same X-ray source and minimal changes in setups we are developing 3 different types of analytical techniques:

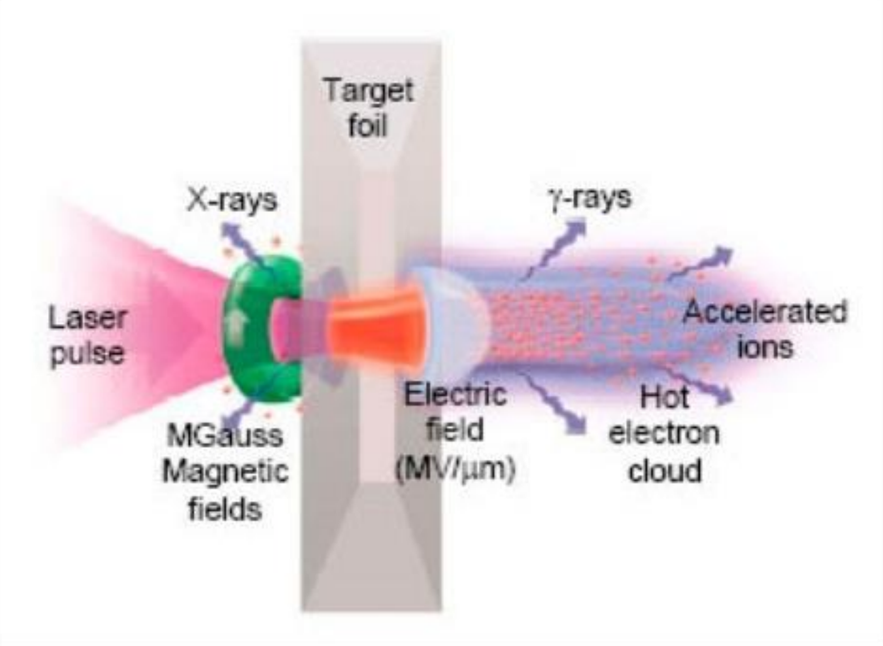
1. X-ray Imaging and X-ray computed tomography (XCT)
2. X-ray absorption spectroscopy (XAS)
3. X-ray diffraction (XRD)



Particles for irradiation experiments

Laser solid interactions can produce a wide range of particles and light ions for irradiation of materials of importance to the nuclear energy sector:

- Protons
- Light ions



Ion acceleration from a laser-solid interaction

https://www.scapa.ac.uk/?page_id=53

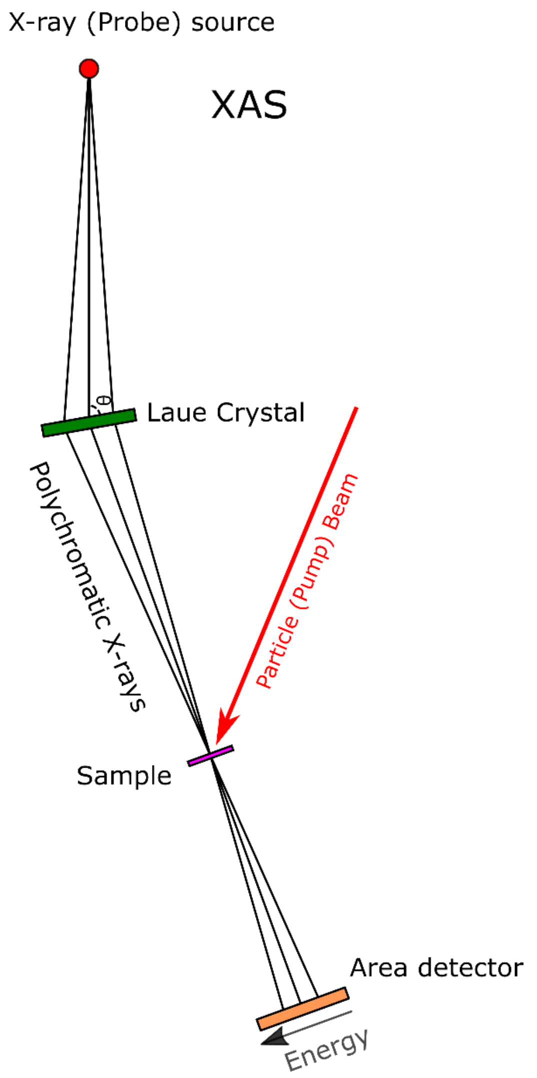
Time resolved in-situ experiments

- Combining laser generated particle and X-ray beams for:

Pump-probe

- Femtosecond (fs) time resolution on beam damage and subsequent relaxation.

- Long duration (fs time-resolution not needed)
  - With (continuous) external 160 keV W X-ray tube: probe damage occurrence over longer times scales



Thank You and Our Team

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

Strathclyde Collaborators: Joanna Renshaw, Pieter Bots, 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 ....

Support: Strathclyde University, SFC, EPSRC, CSO, Laserlab-Europe, STFC, SE

FIN

Thank you