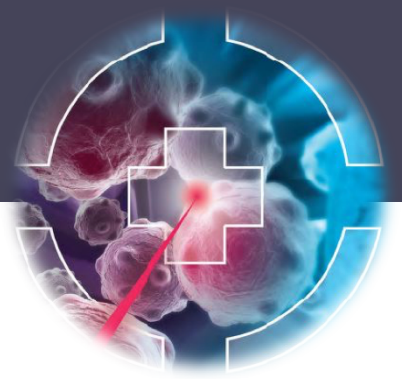
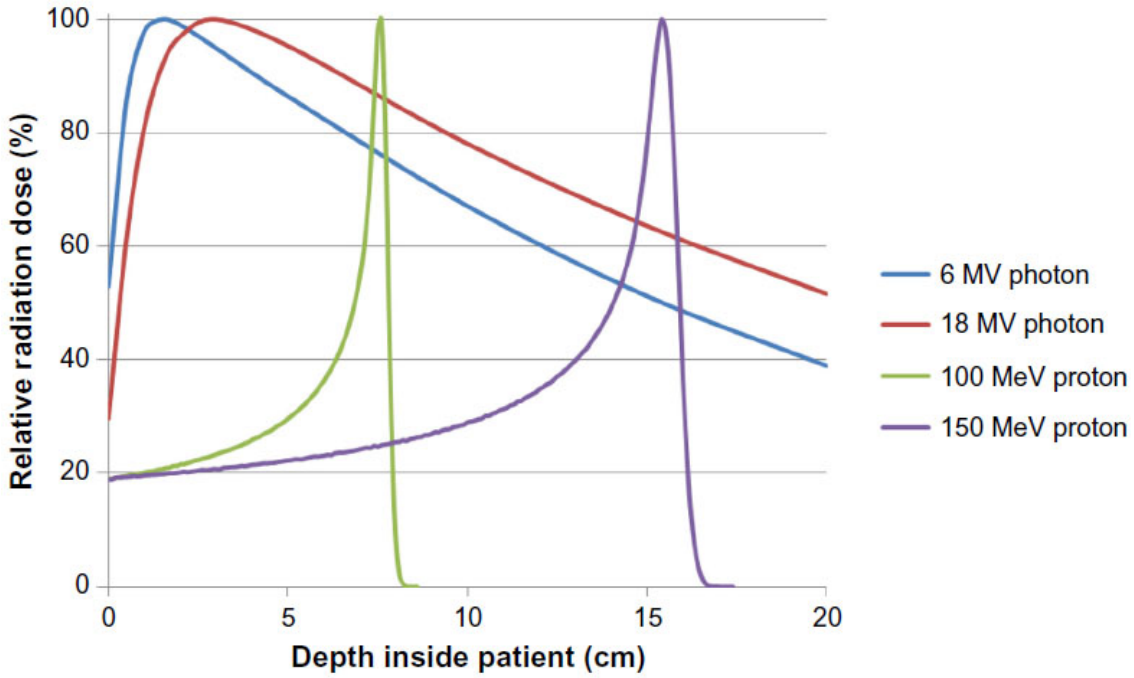
A Calorimeter for Proton Therapy

Laurent Kelleter
Transfer Talk
29/09/2017

Proton Therapy

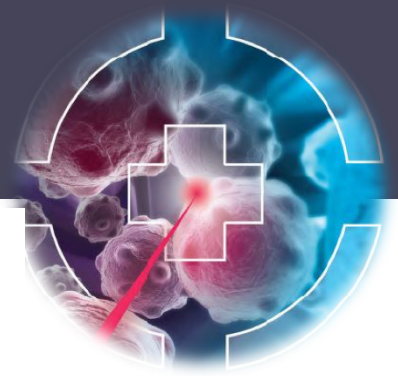


- Cancer is the world's predominant cause of death (WHO)
- Well established treatment method: Radiotherapy
- Conventional radiotherapy: exponential energy deposition curve
- Proton therapy: Bragg peak: Spare healthy tissue

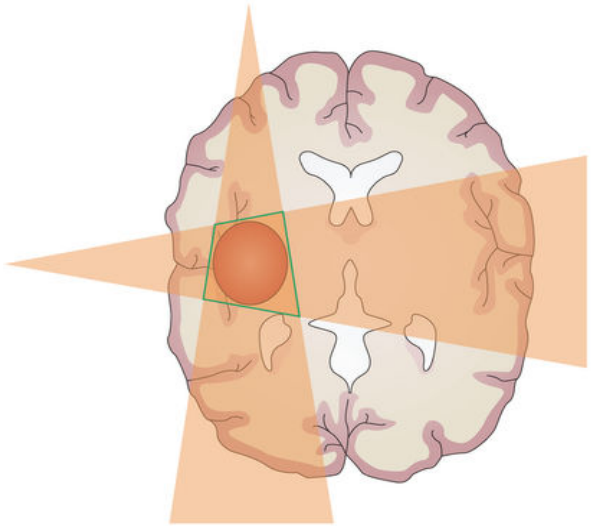


https://doi.org/10.2147/MDER.S65594

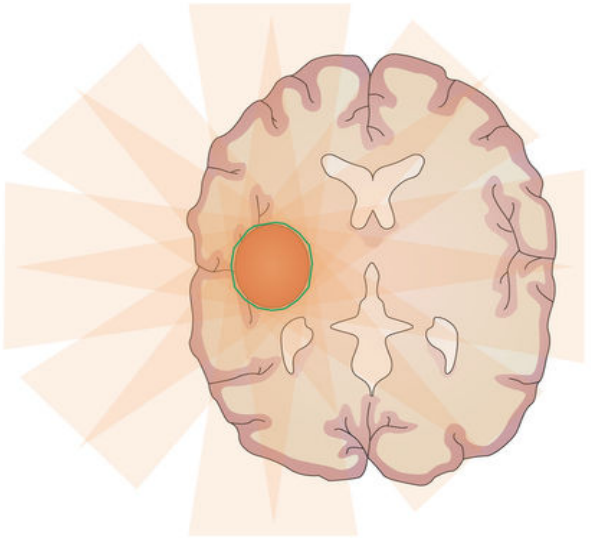
Compare Radiotherapy



X-rays

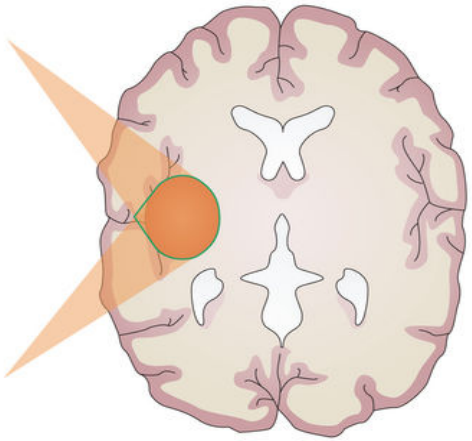


Conventional photon radiotherapy

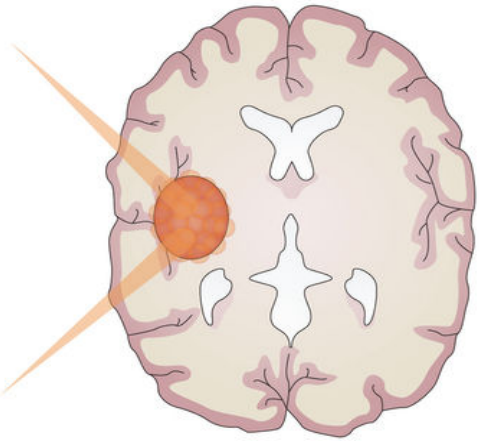


Intensity modulated radiotherapy

Protons



Proton beam therapy

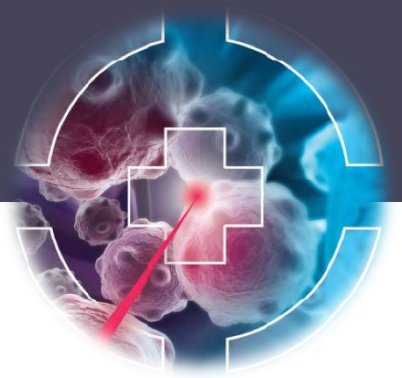


Pencil beam scanning proton therapy

doi:10.1038/nrneurol.2016.70

Nature Reviews | Neurology

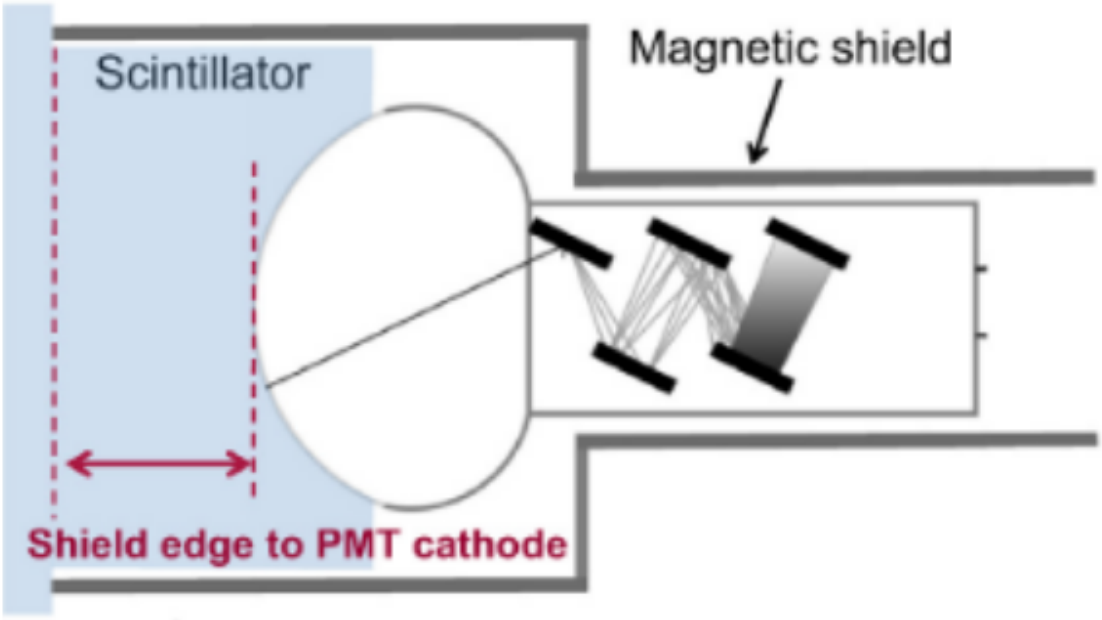
Quality Assurance in Proton Therapy



- Sharp distal edge of Bragg curve makes treatment susceptible to range uncertainties
- Quality Assurance (QA) crucial for assurance of a safe treatment
- QA measurements performed daily/weekly/monthly
- Morning QA: Verify a few proton energies at known depth
- Detector requirements:
  - Energy resolution <1%sigma (2.4% FWHM) at all energies (50 - 250 MeV)
  - Proton rates of ~10^9 per second
  - Fast data acquisition and read-out
  - Cheap
- Can HEP provide the technology?

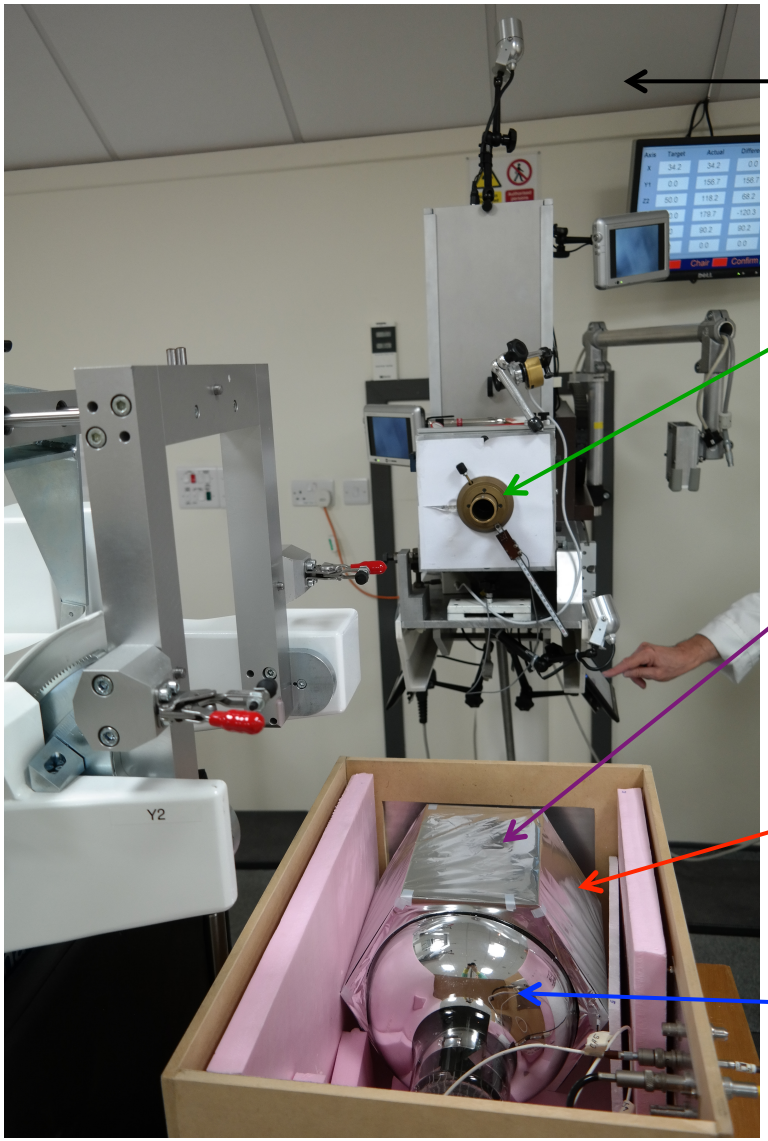
SuperNEMO Calorimeter

- SuperNEMO aims to measure a hypothetical neutrinoless double-beta decay
- SuperNEMO calorimeter developed at UCL
- PMT + plastic scintillator
- Energy resolution of 7% FWHM for 1 MeV electrons
- Fast timing
- Nearly water equivalent scintillator



https://arxiv.org/pdf/1707.06823.pdf

Beam Test #1: Setup



Courtesy Simon Jolly & Anastasia Basharina-Freshville

Clatterbridge Cancer Centre

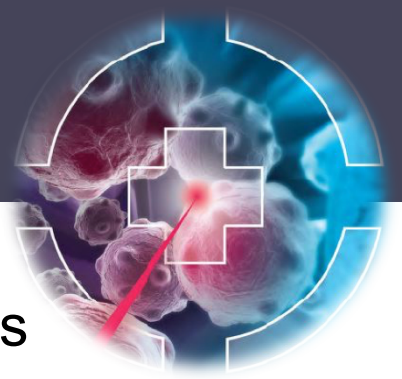
60 MeV Proton beam nozzle

EJ-200 hexagonal PVT block:
276 mm diameter
193 mm deep, minimum thickness between PMT and scintillator: 100 mm

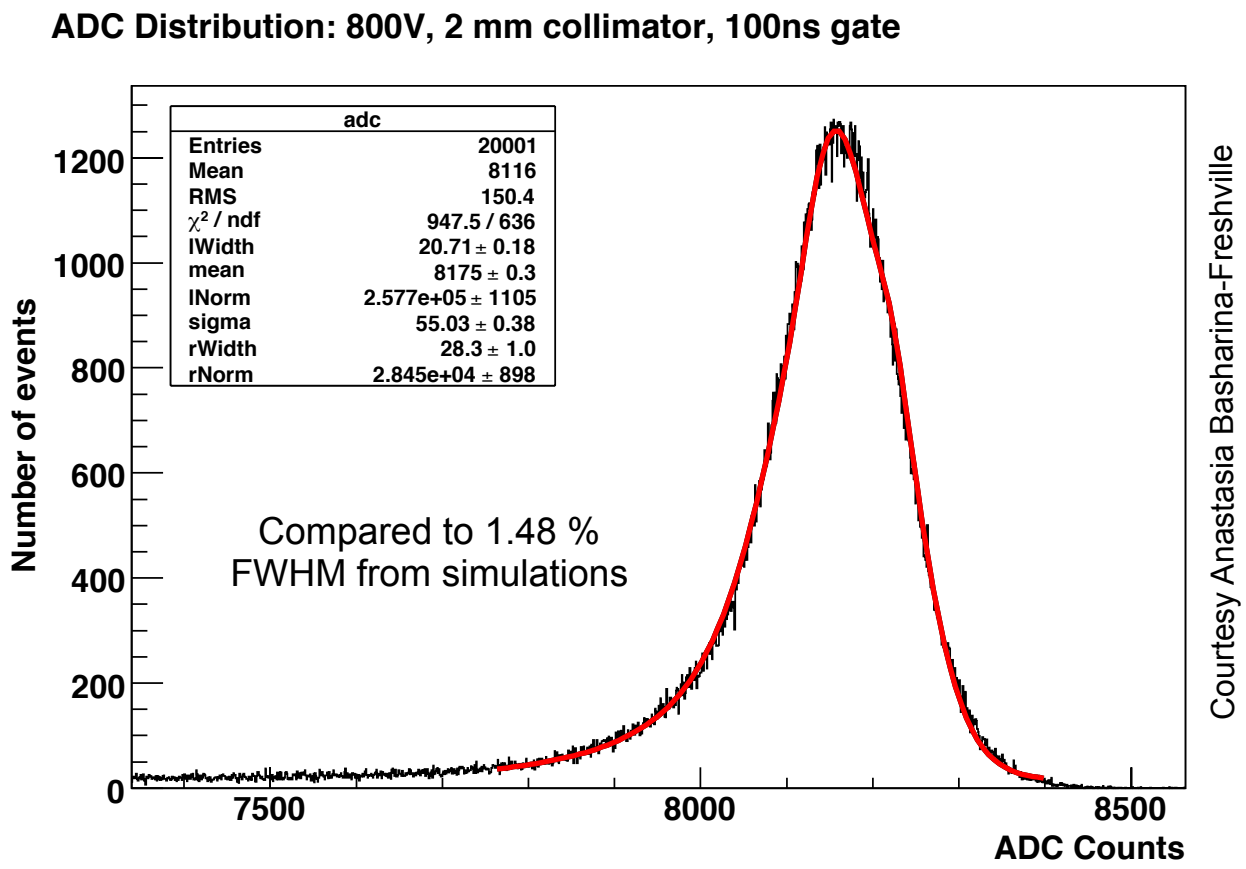
Wrapping:
Sides: 75 μm of PTFE (Teflon) ribbon
Sides and entrance face: 12 μm of Mylar

R5912-MOD Hamamatsu 8" PMT

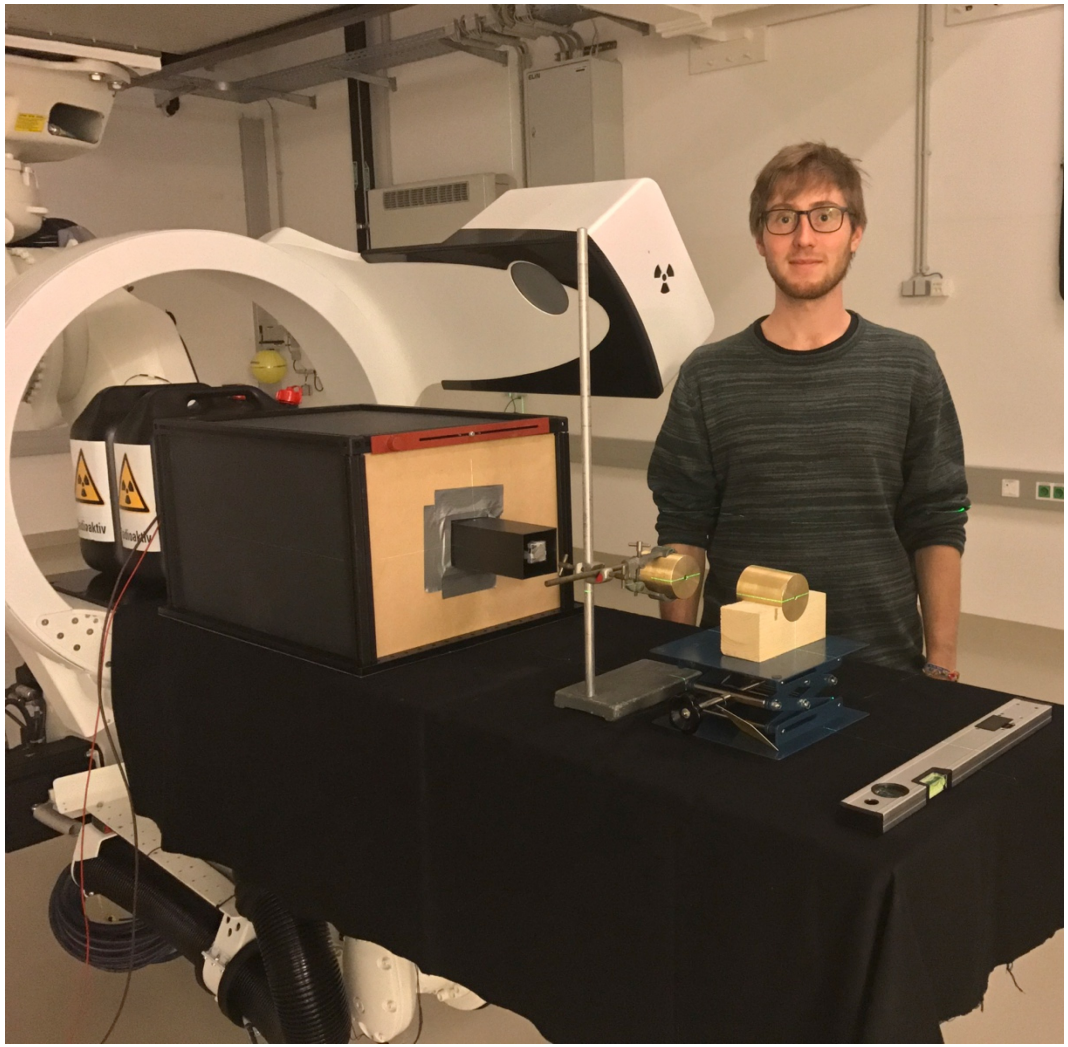
Beam Test #1: Results

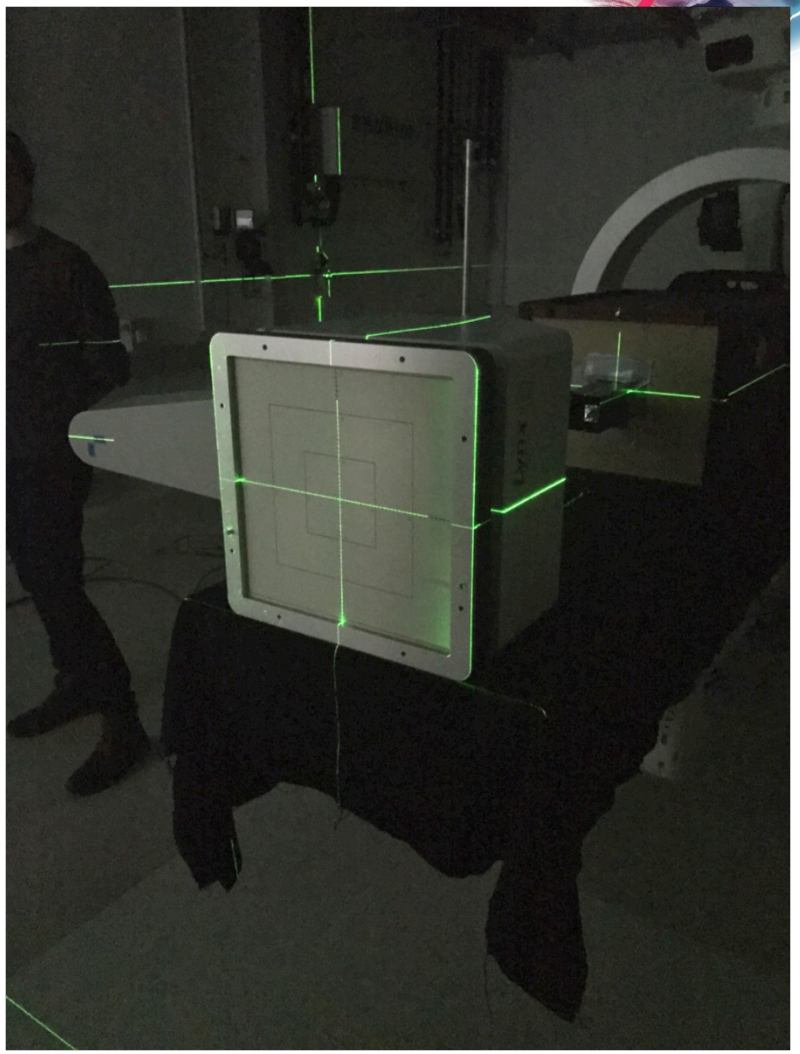


- Energy resolution: 1.57 ± 0.26 % FWHM for 60 MeV protons
- Only for proton rates up to 1 kHz



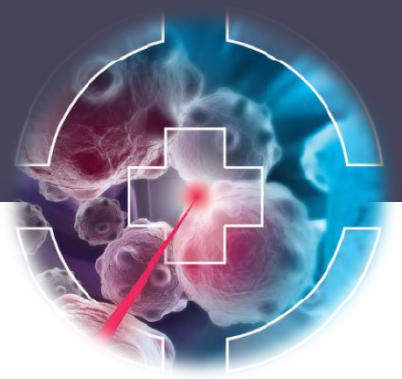
MedAustron Beam Test: Setup





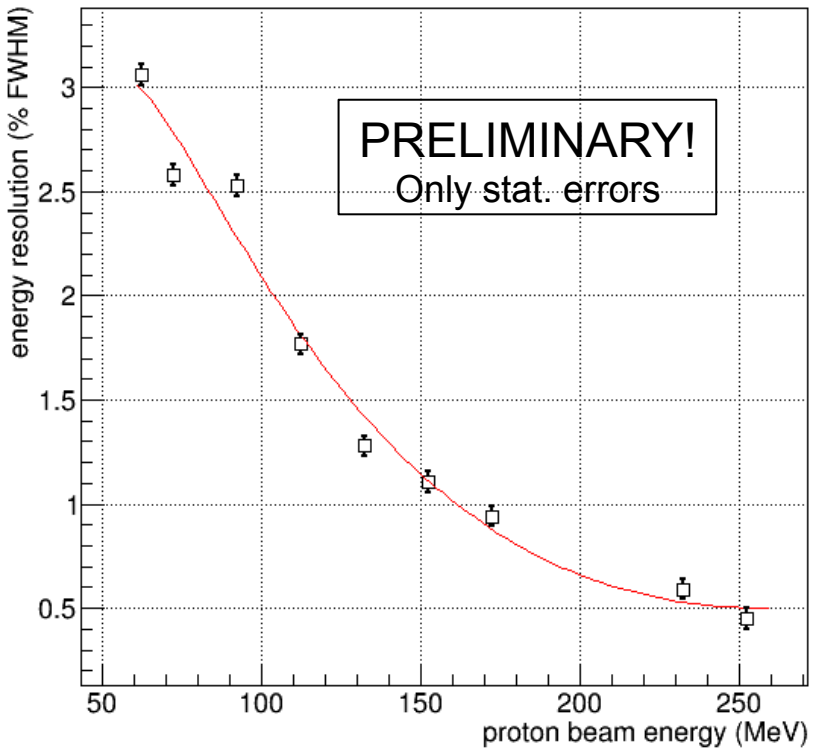
Courtesy Simon Jolly

MedAustron Beam Test: Results

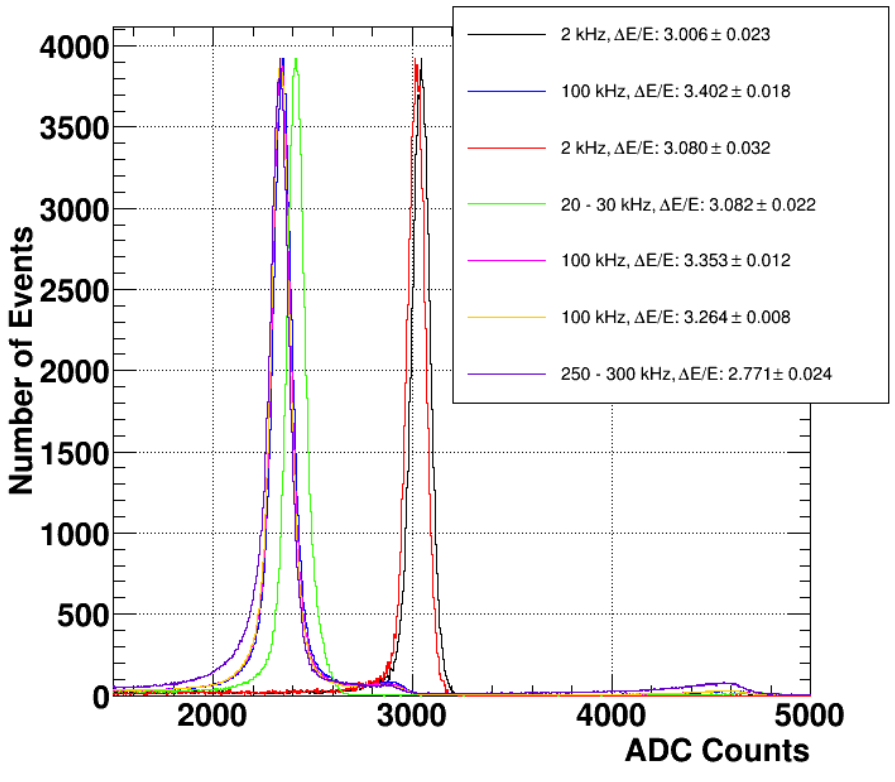


- Measurements at clinical energy range (62 - 252 MeV)
- Energy resolution is still good, but only for proton rates <1 MHz
- We see a strong rate dependence of the ADC counts for proton rates (anode current)
- At proton rates ~1 MHz, pile-up makes single-proton measurement impossible

Energy resolution at ~100 kHz

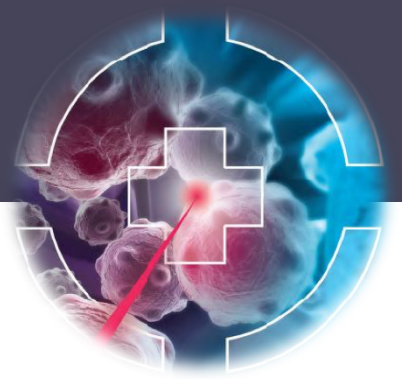


Rate Tests at 62.4 MeV

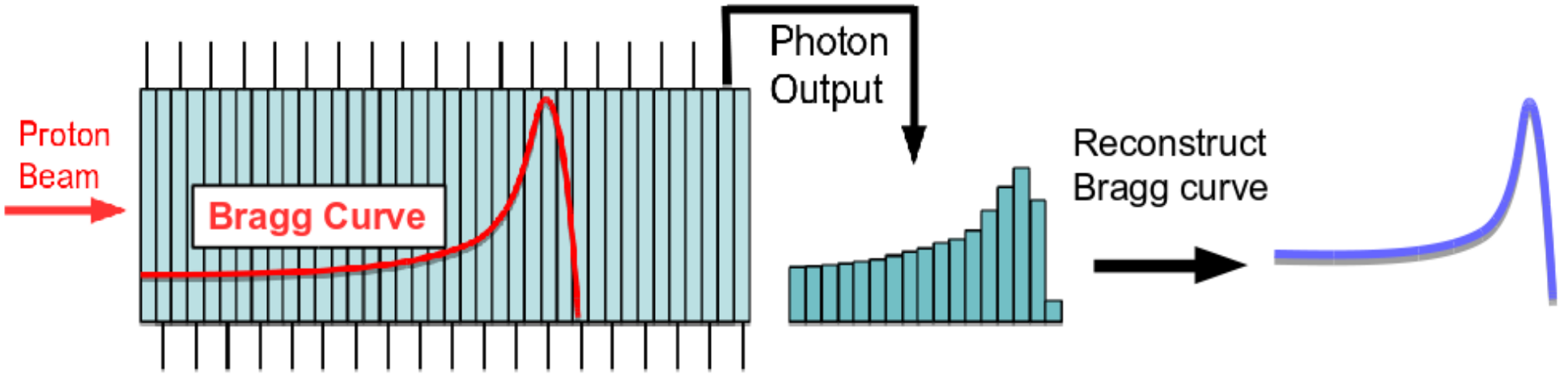


Courtesy Anastasia Basharina-Freshville

New Concept: Range Telescope

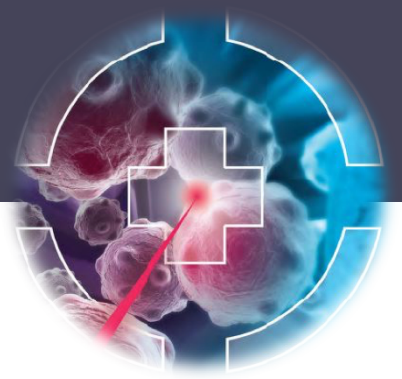


- Cut scintillator in segments (sheets)
- Read out each sheet individually
- Integrate signal from many protons in each sheet
- Reconstruct Bragg curve from photon output
- Measure Range instead of energy: “Range telescope”

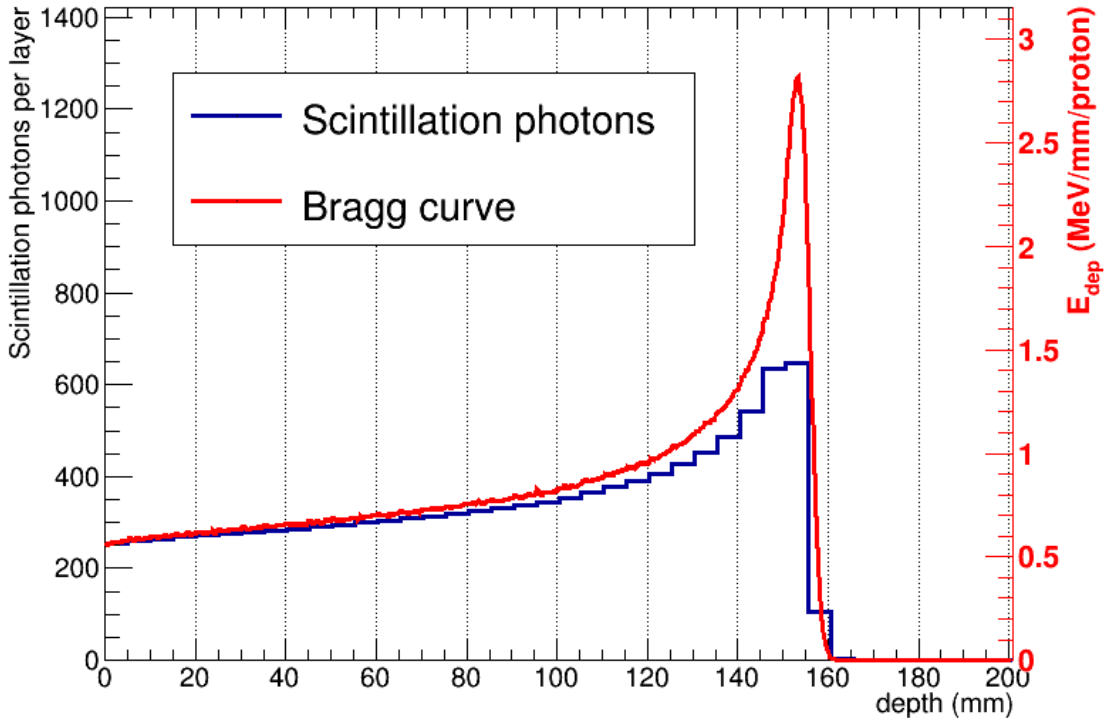


Courtesy Simon Jolly

Quenching

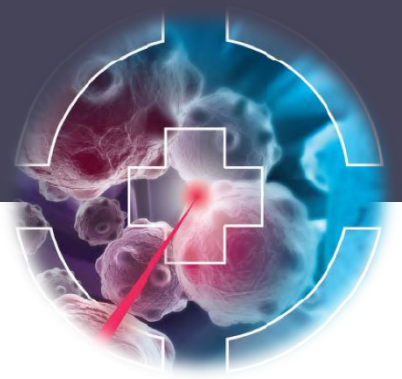


- Challenge in plastic scintillators: Quenching
- Photon production not linear to energy deposition for high energy deposition density
- It can be described by Birk's law: $\frac{dL}{dx} = \frac{S}{\left(\frac{dE}{dx}\right)^{-1} + b}$



GEANT4 simulation

Reconstruction of a Bragg Curve



- Developed an analytical description of a “quenched Bragg curve”
- Combination of a Bragg curve and Birk's law
- 6 material-dependent parameters
- 3 beam-dependent parameters: Range, range straggling and intensity

Bragg curve (Bortfeld 1997)

$$D(x) = \Phi_0 \frac{e^{-\zeta^2/4}\sigma^{1/p}\Gamma(1/p)}{\sqrt{2\pi}\rho p \alpha^{1/p}(1+\beta R_0)} \times \left[\frac{1}{\sigma}\mathfrak{D}_{-1/p}(-\zeta) + \left(\frac{\beta}{p} + \gamma\beta + \frac{\epsilon}{R_0}\right)\mathfrak{D}_{-1/p-1}(-\zeta)\right]$$

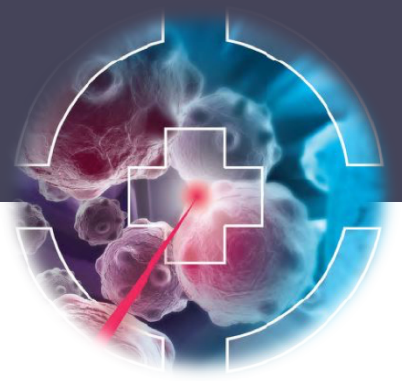
Birk’s law (Birk 1951)

$$\frac{dL}{dx} = \frac{S}{\left(\frac{dE}{dx}\right)^{-1} + b}$$

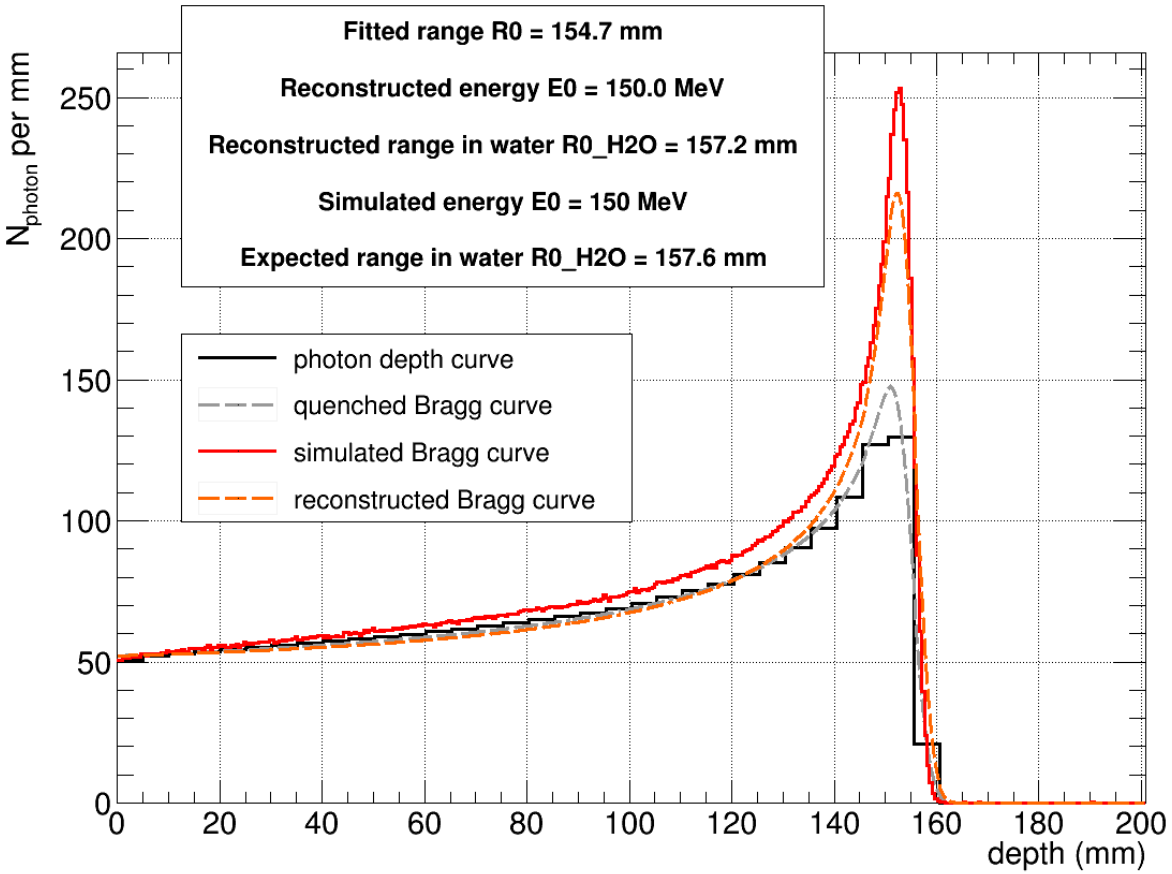
Quenched Bragg curve (Kelleter 2017)

$$Y(x) = \frac{\tilde{\Phi}_0}{\rho}\int_0^{R_0}\left[\frac{1+\beta(R_0-x')}{1+\beta R_0}\frac{1}{\left(\frac{1}{p\alpha^{1/p}}(R_0-x')^{1/p-1}\right)^{-1}+b} + \gamma\frac{\beta}{1+\beta R_0}\times \int_{x'}^{R_0}\frac{1}{\left(\frac{1}{p\alpha^{1/p}}(R_0-\tilde{x})^{1/p-1}\right)^{-1}+b}d\tilde{x}\right]\frac{1}{\sqrt{2\pi}\sigma}\exp\left(-(x-x')^2/2\sigma^2\right)dx'$$

Reconstruction of a Bragg Curve



- Quenched Bragg curve fitted to photon depth curve
- Material-dependent parameters are fixed
- Reconstructed Bragg-curve formula is plotted using fitted beam parameters
- Compare reconstructed Bragg curve to simulated Bragg curve



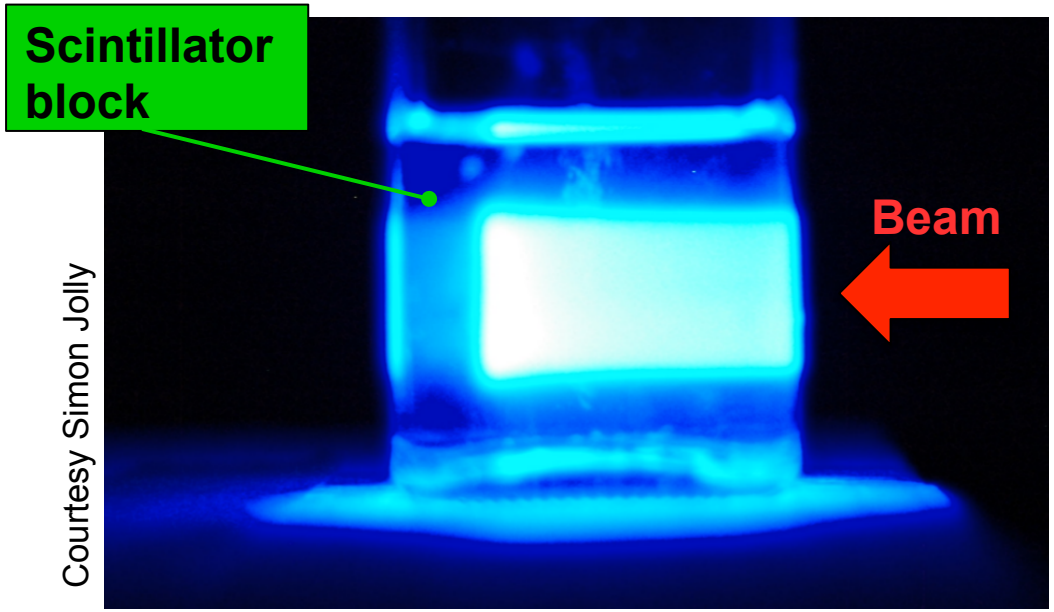
GEANT4 simulation

Results:

- Very good reconstruction of proton range/energy (<0.5% deviation)
- Overestimates range straggling because of coarse resolution (sheet thickness)

Building a Range Telescope

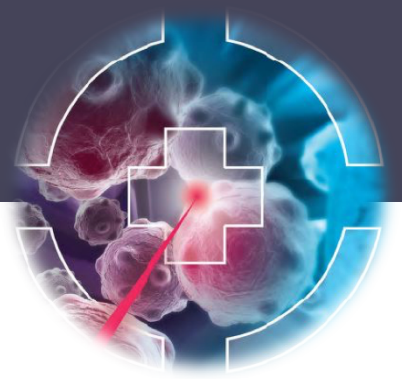
- The scintillator sheets will be produced in collaboration with Nuvia Ltd.
- We will aim for ~2 mm sheet thickness for a good spatial resolution
- Challenge: Read-out because of high number of channels:
  40cm / 2mm = 200 channels
- Solution: Use a “Monolithic Active Pixel Sensor” (MAPS)
- CMOS sensor like in digital cameras
- Take “picture” of scintillation photon depth curve



Courtesy Simon Jolly

http://eprints.lincoln.ac.uk/13879/

Birmingham Beam Test



- 28 MeV proton beam, 7.8 mm range in water
- Measurement with two scintillator sheets: 3 mm and 4 mm
- Two PRaVDA Priapus MAPS (10 cm x 5 cm)

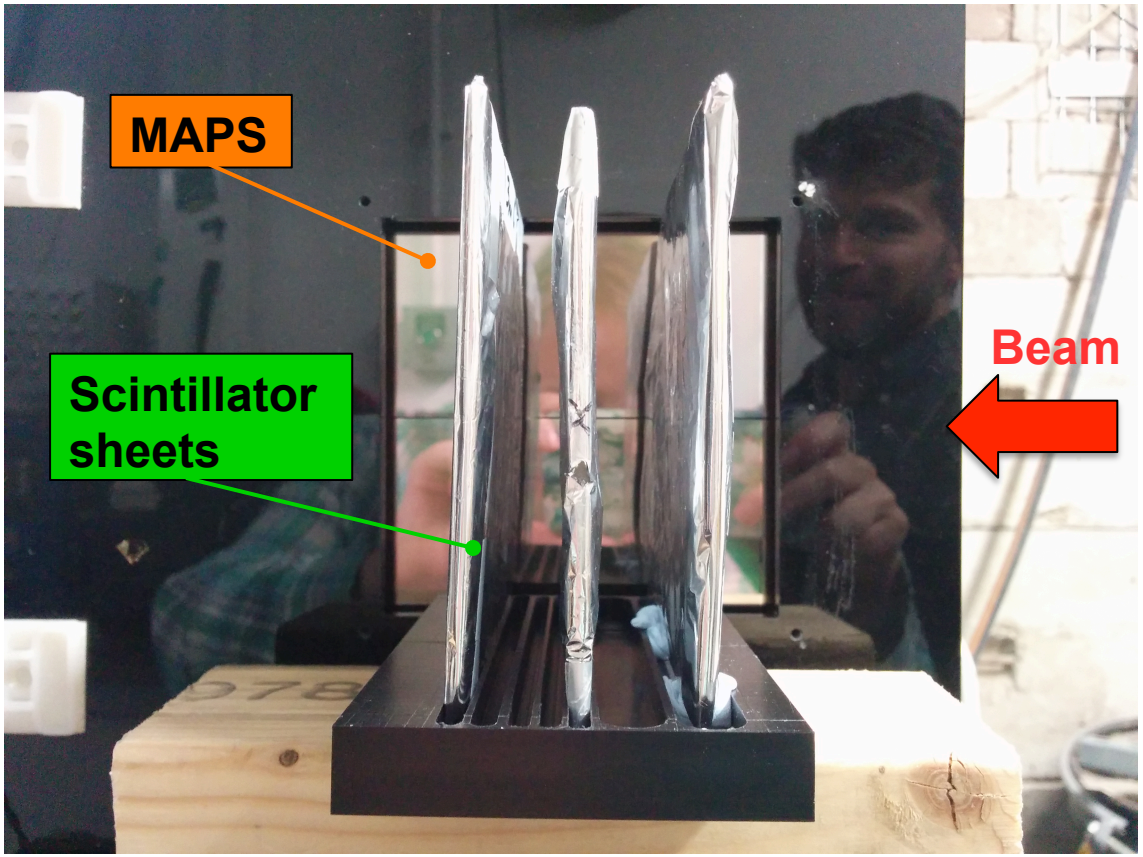
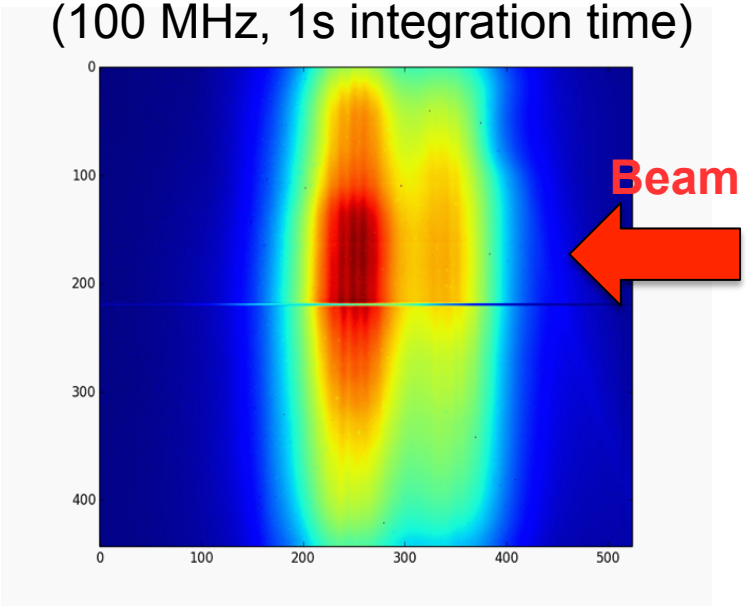
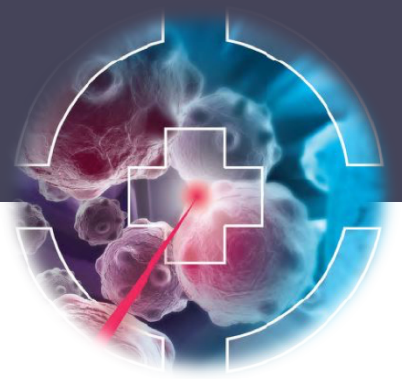


Image taken by MAPS
(100 MHz, 1s integration time)

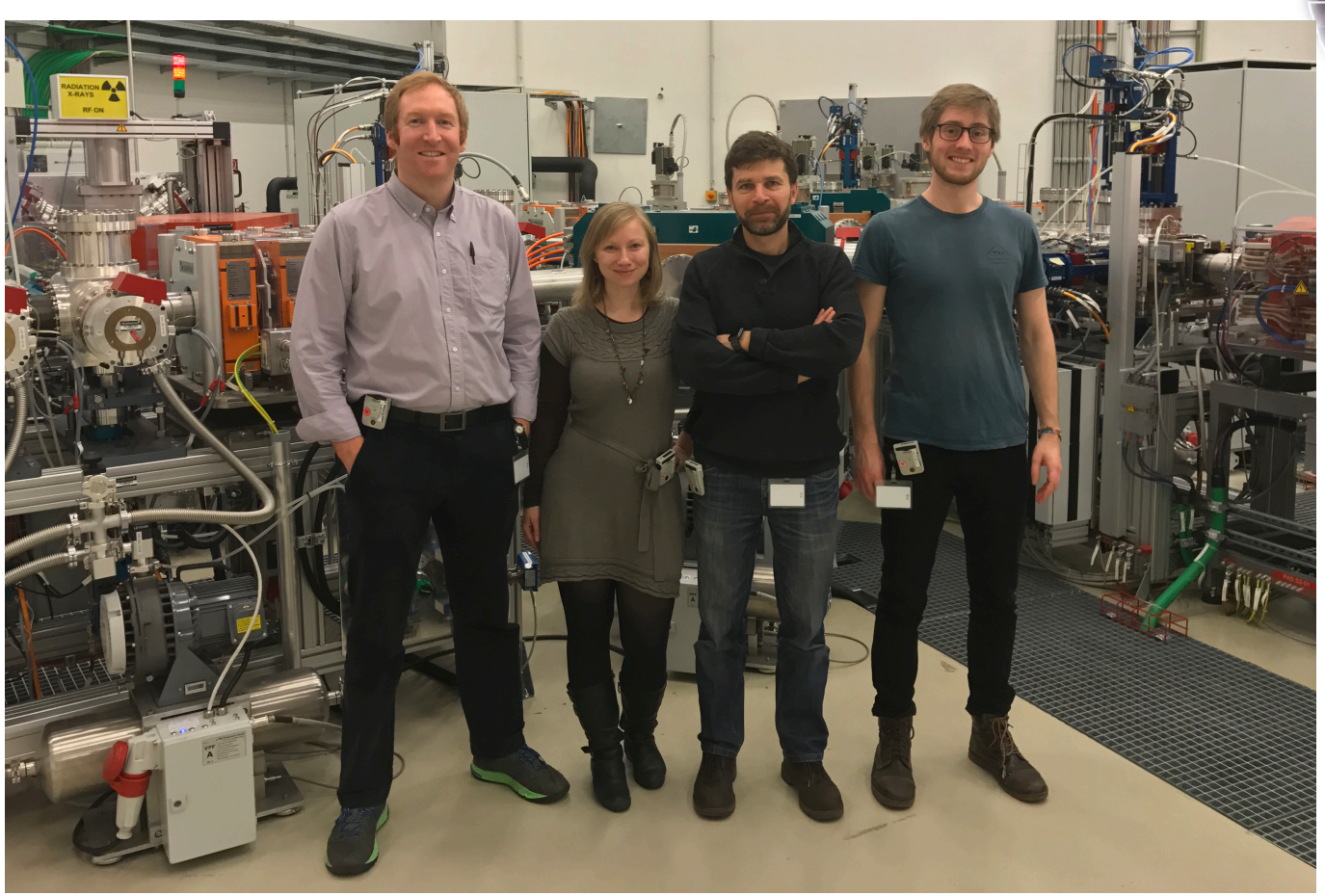


Conclusion and Outlook

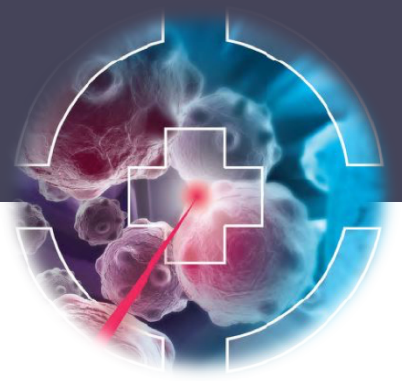


- **Single-Module-Detector:**
  - Beam tests with the single-module-detector show the potential and limitations of the setup
  - We are in contact with Hamamatsu to deal with the rate dependence
- **Range Telescope:**
  - An analytical model for the photon depth curve has been developed
  - Beam test with a MAPS are VERY PROMISING
  - Develop a read-out concept for the range telescope with MAPS

Thank you for your attention!

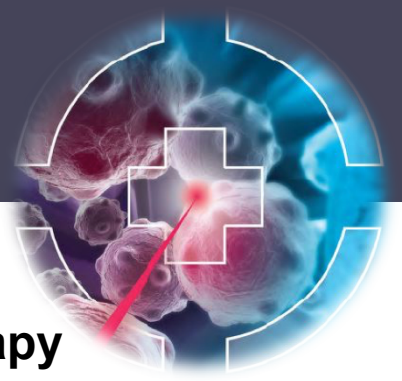


This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 675265, OMA – Optimization of Medical Accelerators.



Backup

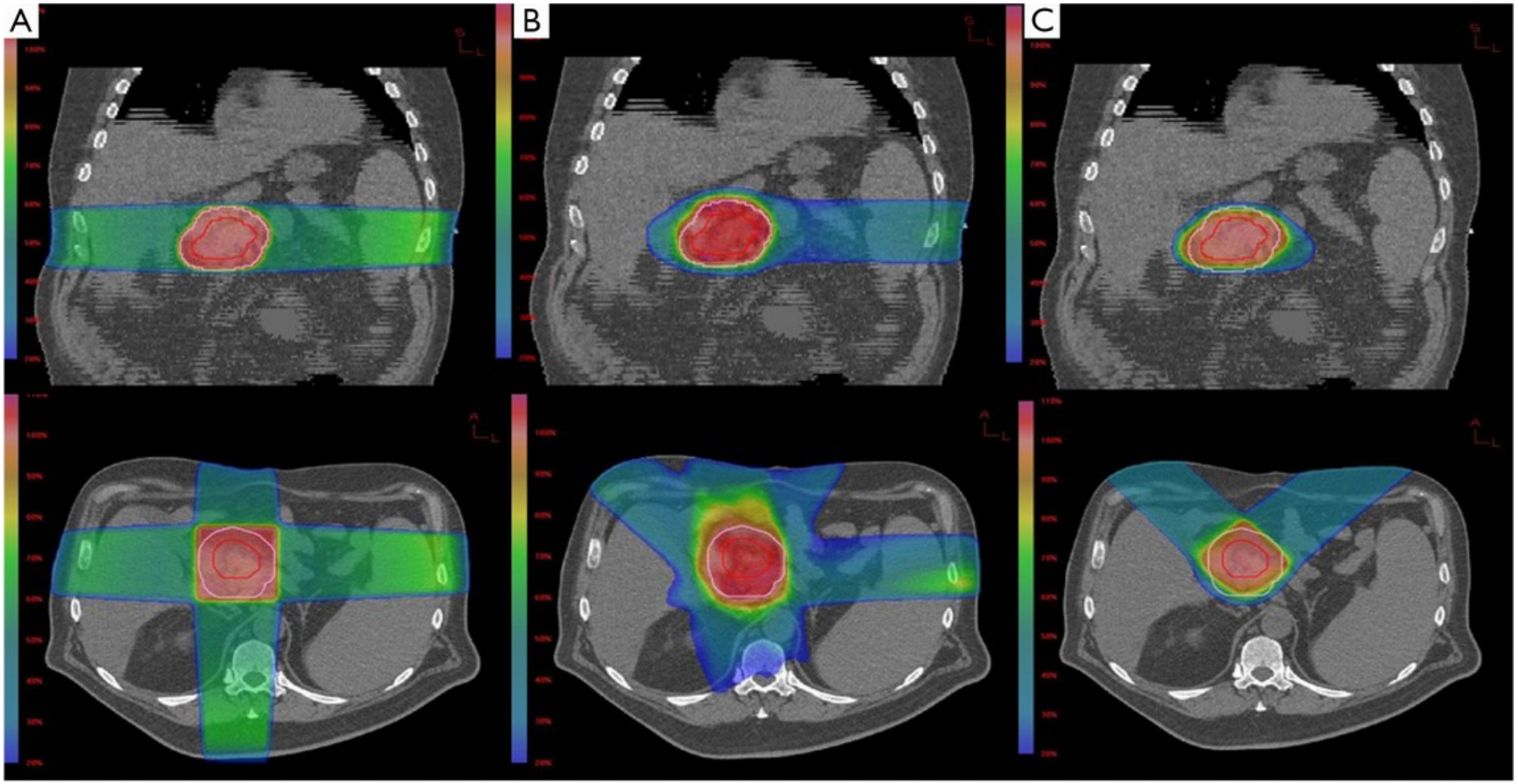
Proton Therapy - Example



A) Conventional radiotherapy (X-rays)

B) Intensity modulated radiotherapy (X-rays)

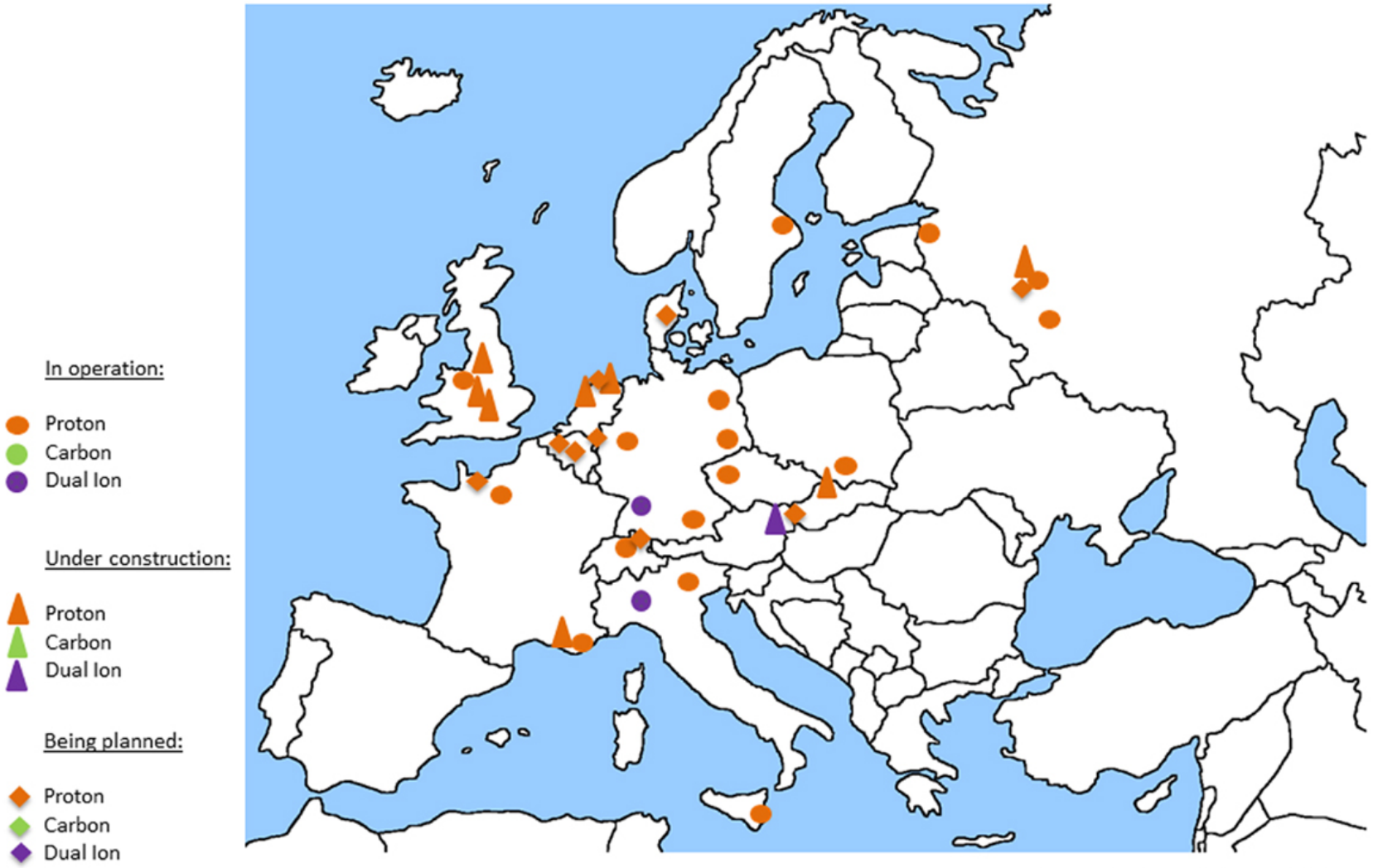
C) Proton therapy



http://jgo.amegroups.com/article/view/3448

Proton Therapy Centres

Particle therapy centres in Europe - 2015



Source: PTCOG, October 2015

Beam Test #2

2” Hamamatsu R13089-100-11 **PMT** with negative HV active divider base

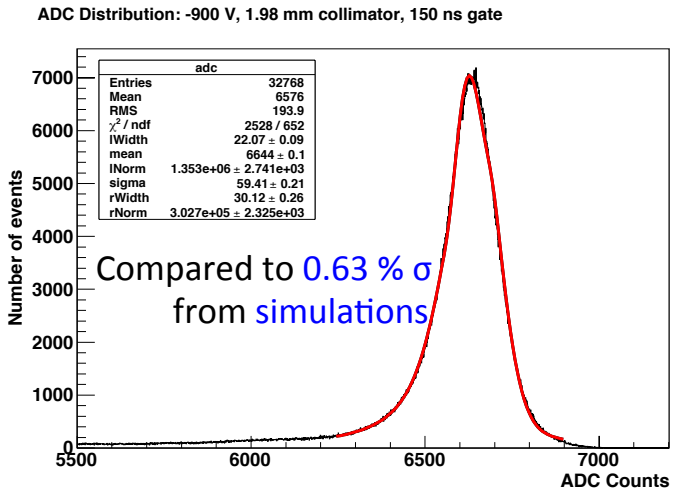
3 cm x 3 cm x 5 cm cuboid ENVINET/NUVIA **PS** standard **scintillator**

Wrapping:

Sides: 75 µm of PTFE (Teflon) ribbon
Sides and entrance face: 12 µm of Mylar

Results:

- Energy resolution: 0.89 ± 0.11 % σ



- Good linearity!
- Reaching rates of up to 250 kHz!
- We suspect a potential problem with the PMT base – next try to use one with no active components.

MedAustron Proton Therapy Centre

http://eps-hep2015.eu