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Proton Calorimetry for Proton Therapy

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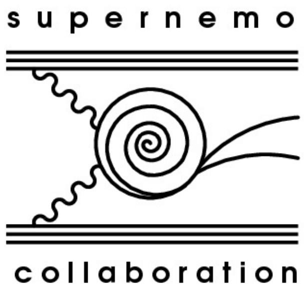
University College London

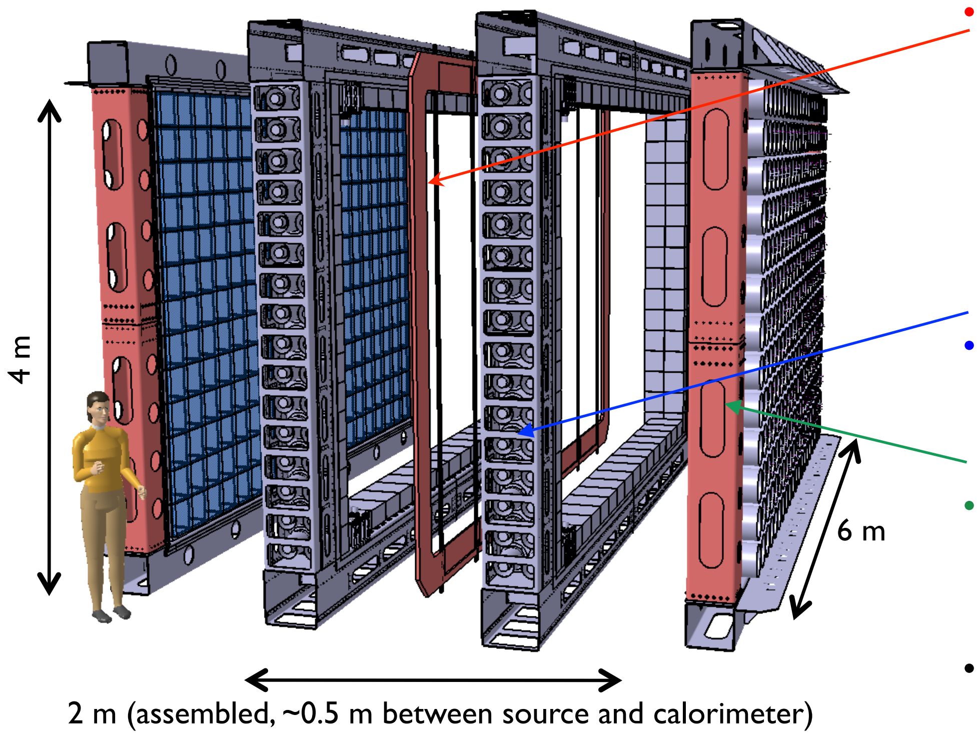
HEP at UCL

- The High Energy Physics Group at University College London is one of the largest in the UK:
  - 19 academic staff.
  - 27 research and technical staff.
  - 32 PhD students.
- Research covers a wide range of experiment and theory.

- ATLAS experiment at the LHC.
- Neutrinos:
  - SuperNEMO.
  - MINOS.
  - NOvA.
  - CHIPS.
  - Ultra-High Energy Neutrino experiments.
- Dark Matter:
  - LUX.
  - LZ.
- Accelerators:
  - Proton therapy.
  - Linear collider.
  - XFEL.
- Muon experiments:
  - Muon g-2.
  - Mu2e.
- Generic detector R&D.

SuperNEMO





- Neutrinoless double beta decay detector using NEMO3's tracker-calorimeter technique
  Target sensitivity: $T_{½} > 10^{26}$ years → $<m_\nu> <0.04 – 0.1$ eV
- Modular detector with a planar geometry

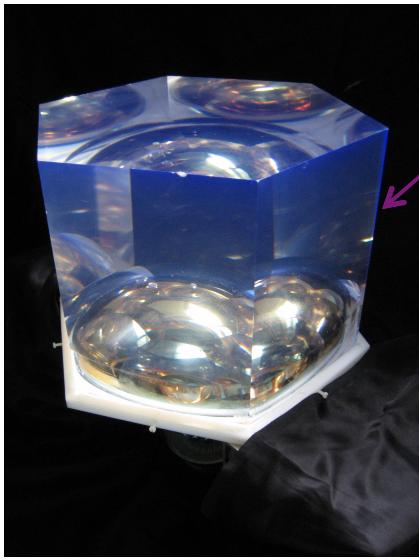
1 module (of 20) consists of:

- Source foil:
  - 5 kg (total of 100 kg) of 40 mg/cm^2 (4 x 2.7 m^2)
  - ^{82}Se (high $Q_{\beta\beta}$, long $T_{1/2}^{2\nu\beta\beta}$, proven enrichment technology): starting baseline
  - ^{150}Nd and ^{48}Ca being considered depending on enrichment possibilities
- Tracker: ~2000 drift cells in Geiger mode → particle identification (for background suppression)
- Calorimeter: ~550 scintillator blocks + PMTs → energy and time of flight measurements of particles
- Passive shielding surrounding each module

SuperNEMO Calorimeter Development

- SuperNEMO calorimeter consists of 550 Optical Modules (wrapped scintillator block + PMT).
- Needed to achieve improved resolution: $\frac{7\%}{\sqrt{E(MeV)}}$
- Scintillator needed to be organic plastic:
  - High light yield.
  - Low electron back-scattering.
  - High radiopurity.
  - Fast timing.
- Extensive R&D programme resulted in final design:
  - ElJen EJ-200 polyvinyltoluene (PVT) scintillator.
  - Hamamatsu 8" PMT (32% QE at 400 nm).
  - Hexagonal scintillator block directly coupled to hemispherical PMT face.
  - Teflon + Mylar wrapping.

Optimised Optical Module



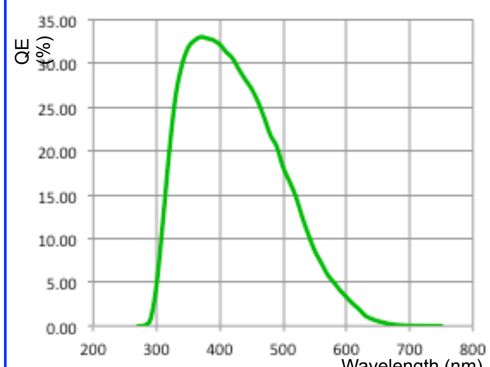
$$\frac{7.5\%}{\sqrt{E(MeV)}}$$

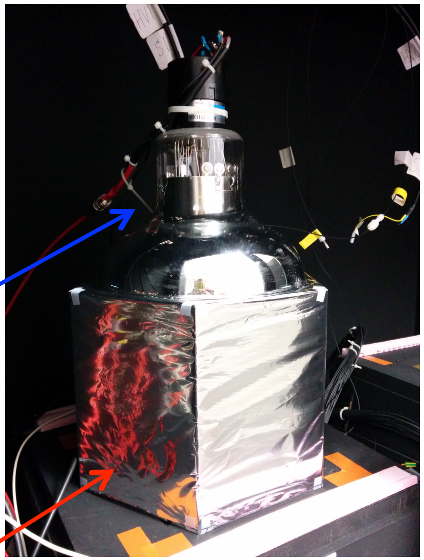
EJ-200 hexagonal PVT block:

276 mm diameter
193 mm deep, minimum thickness between PMT and scintillator: 100 mm

R5912-MOD Hamamatsu 8” PMT:

Maximum quoted QE: 33%
32% QE at 400 nm





Wrapping:

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

So What…?

UCL

- With this fantastic energy resolution of 7.5% FWHM at 1 MeV can we use a SuperNEMO Optical Module for PBT energy measurement?
- Very high intensity of events at a proton beam (10's MHz):
  - A proton beam delivers a random number of protons per bucket, which will worsen the energy resolution measured.
  - We require 1 proton per bucket for a good detector response.
  - But time constant of scintillator (1 ns) makes this possible.
- Scintillator quenching for protons:
  - For a plastic scintillator, the scintillator response is nonlinear with the amount of energy deposited in it.
  - Amount of deviation → "quenching".
  - Characterised by Birk's law:

$$\frac{dY}{dx} = \frac{S}{1 + kB(dE/dx)} \times \frac{dE}{dx}$$

dY/dx	light yield per unit path length
dE/dx	energy lost by particle per unit path length
kB	relates density of ionisation to energy loss = 0.207 mm/MeV
S	absolute scintillation efficiency

  - Becomes important for large dE/dx and ionisation density → important for protons, which have a large dE/dx when they slow down.
- Energy range:
  - SuperNEMO optimised for electrons from 0.5 – 4 MeV for double beta decay.
  - For proton therapy we require ~O(100 MeV).

Simulated Stopping Distance

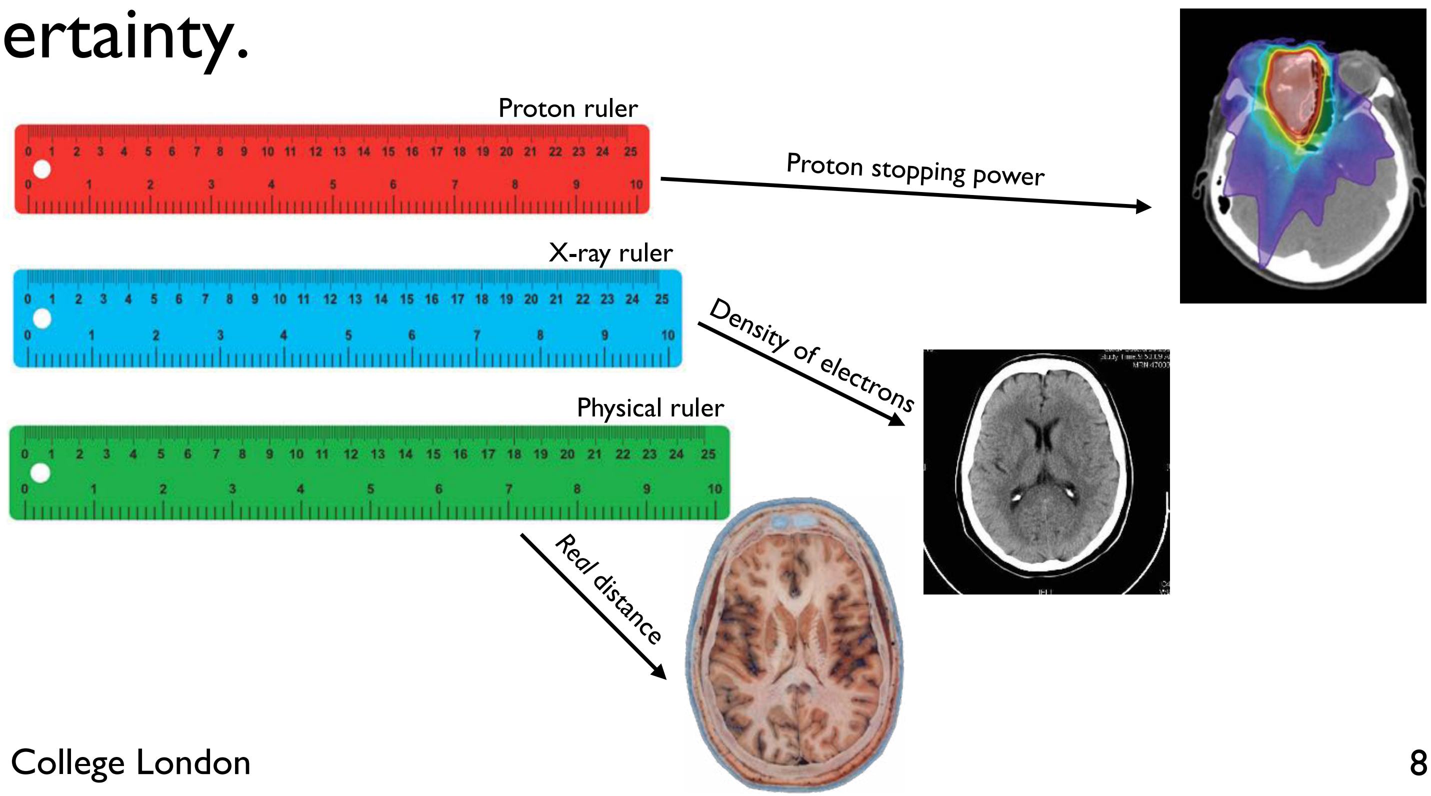
- Simulations of SuperNEMO scintillator vs Water Equivalent:

Proton Beam Energy, MeV	Mean stopping distance, SCINT (mm)	Mean stopping distance, WATER (mm)	σ stopping distance, SCINT (mm)	σ stopping distance, WATER (mm)
60	30.21	30.54	0.33	0.33
200	255.4	257.1	2.48	2.44
300	505.9	509.9	4.64	4.78

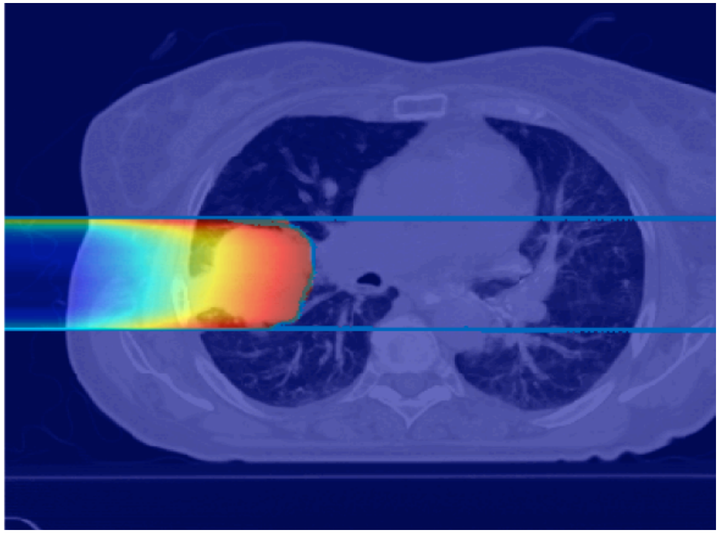
- PVT is "water equivalent" for stopping distance and spread, as is PS.
- One to one conversion for water phantoms.
- Is this important to radiotherapy physics…?

Proton Stopping Power

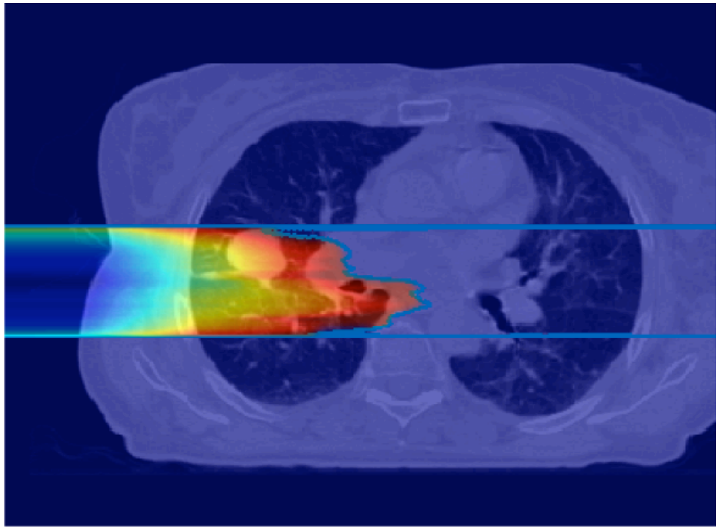
- Treatment plans constructed using X-ray CT.
- Electron density is NOT the same as proton stopping power.
- Hounsfield unit conversion factor introduces range uncertainty.

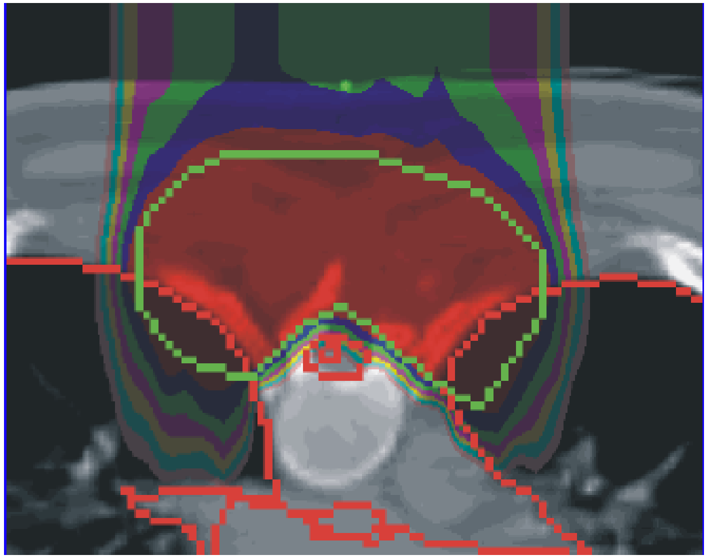


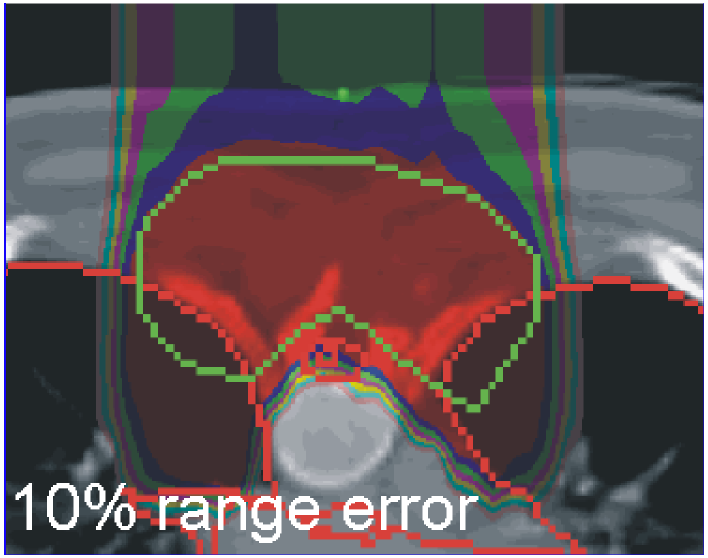
Range Uncertainty (T. Lomax)



Tumour shrinkage after 5 weeks

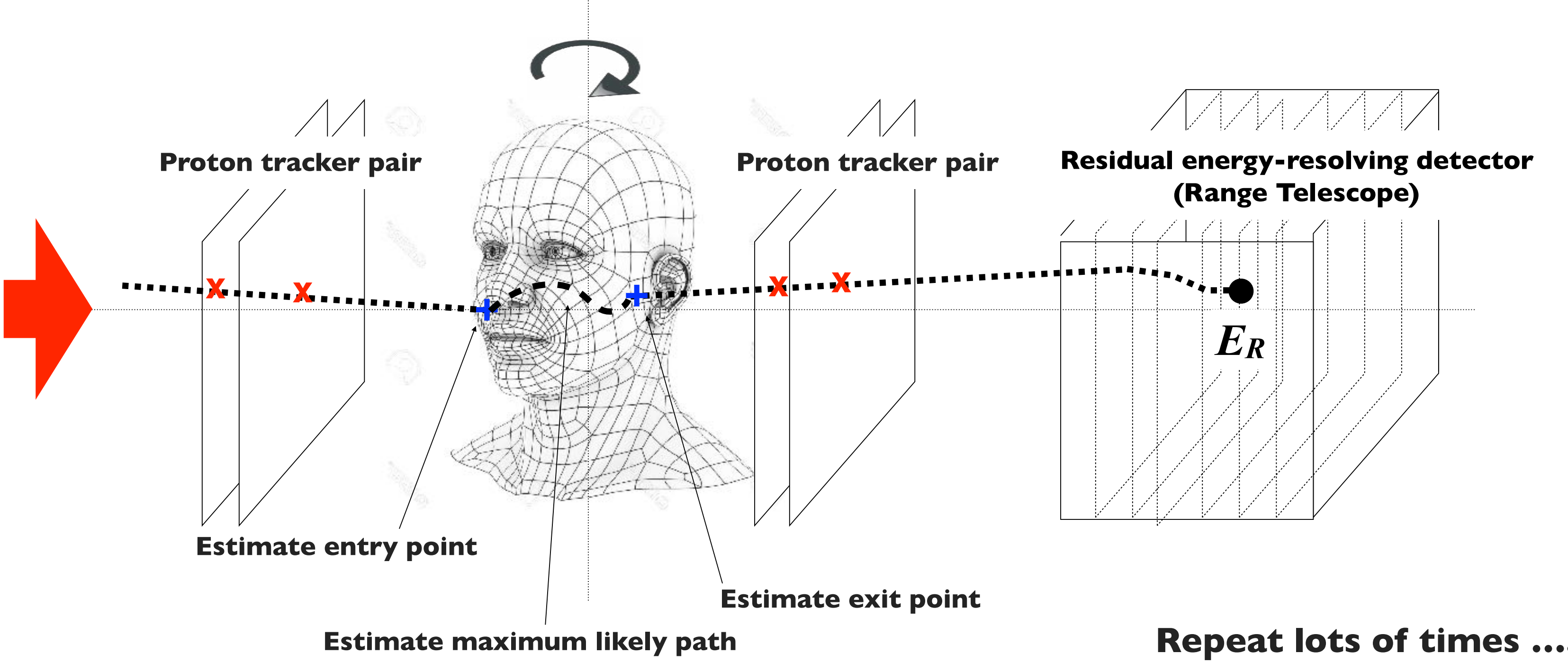




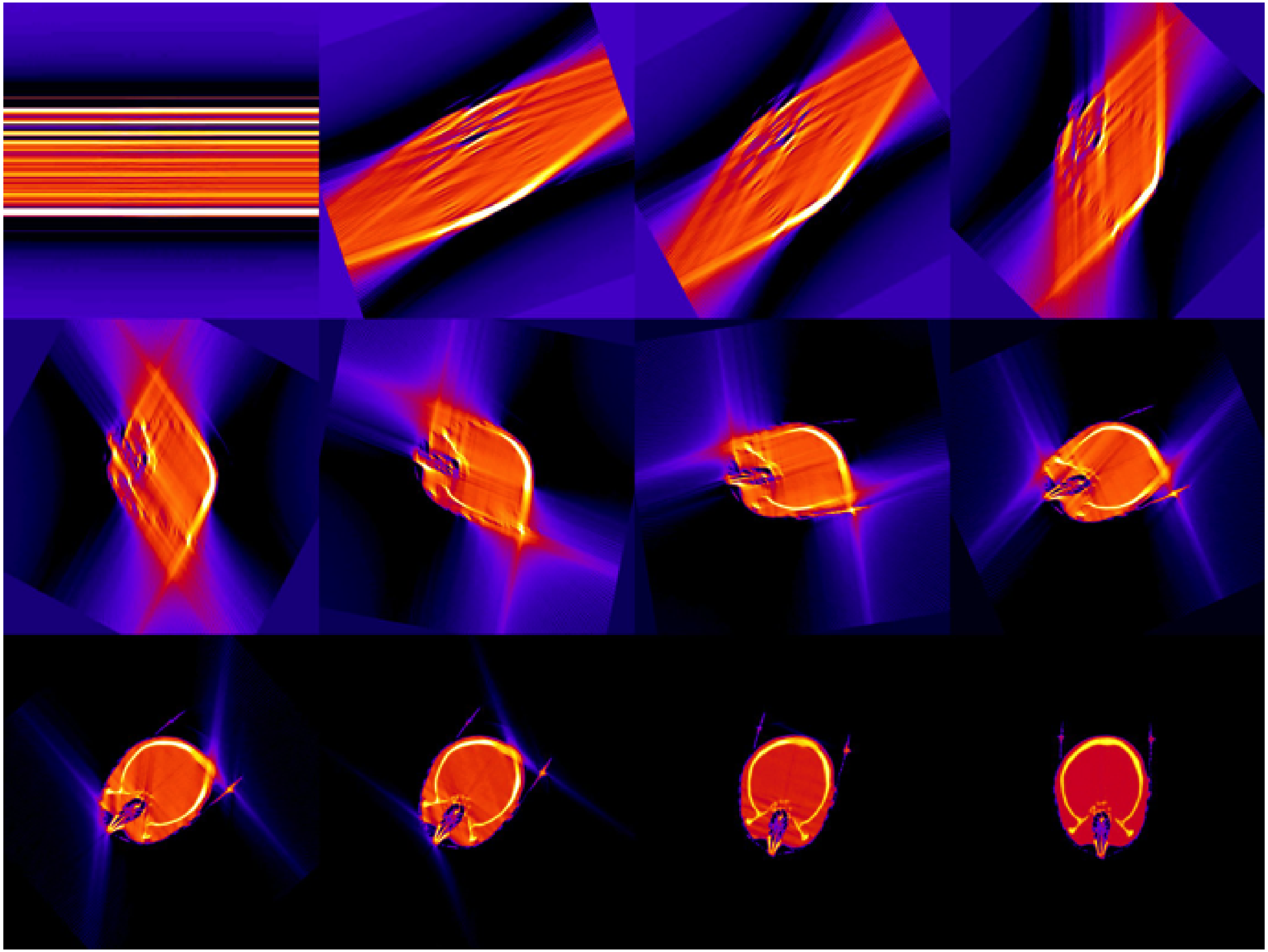


Proton CT (N. Allinson, PRaVDA)

- Use proton imaging to reduce range uncertainties in treatment planning:
  - Measure proton entry and exit positions and trajectories with trackers.
  - Measure energy with Residual Energy Resolving Detector (range telescope or calorimeter).
  - Calculate proton most likely path to reconstruct image.



Proton CT Image Reconstruction

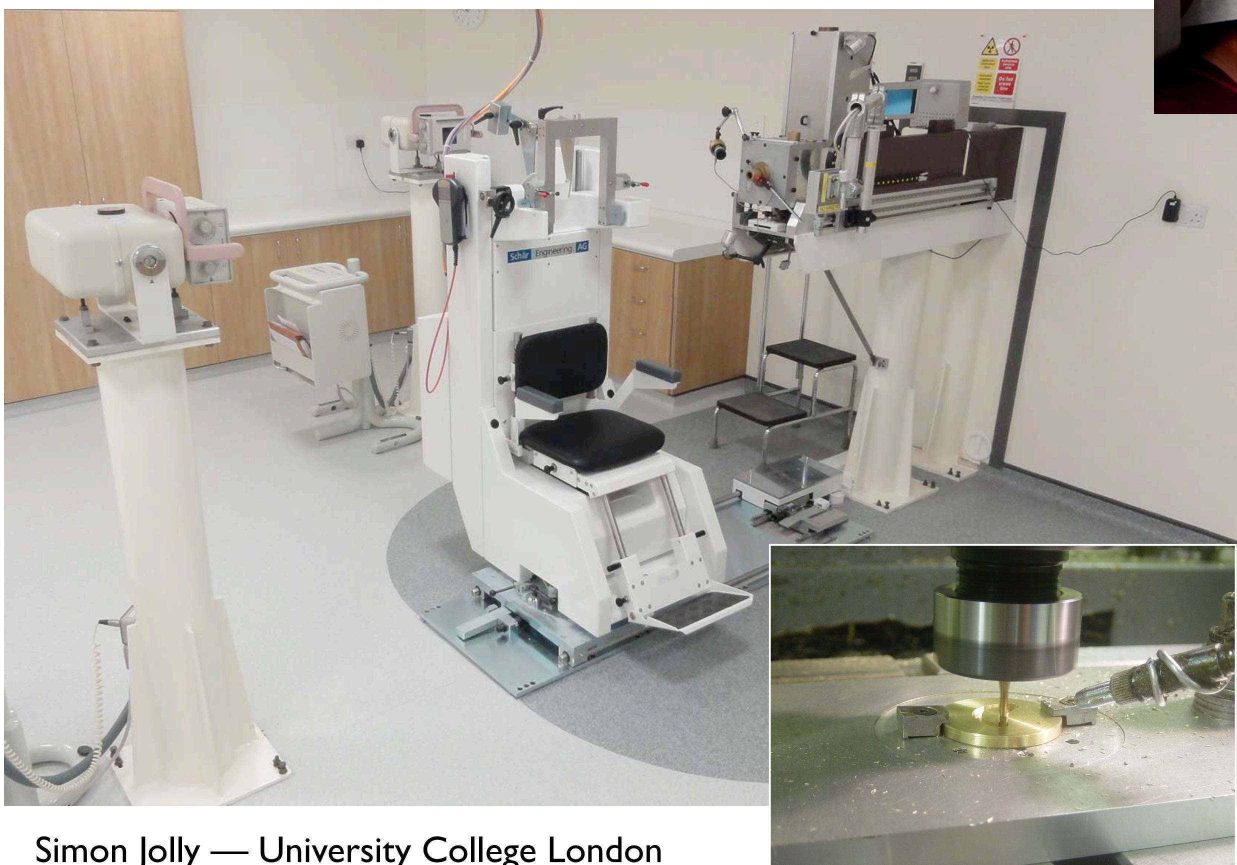


Proton Calorimetry

- For Proton CT, need to read out proton energy quickly and accurately:
  - Energy resolution <1% σ.
  - Rate 1–10 MHz for reasonable imaging time.
- Detector requirements overlap with range QA:
  - Daily measurements are faster but less comprehensive: really just want to verify that the energy of the beam specified by the control system has the correct range in water (Water Equivalent Path Length).
  - Morning range QA normally verifies a few energies at known depths:
    - Proton counting in water-equivalent phantom.
    - Setup and measurement can be time consuming…
  - Requirements for improved QA system:
    - Better than 1% σ resolution across all energies.
    - Easier system setup and faster data acquisition and readout.
- See if SuperNEMO calorimeter works for protons…

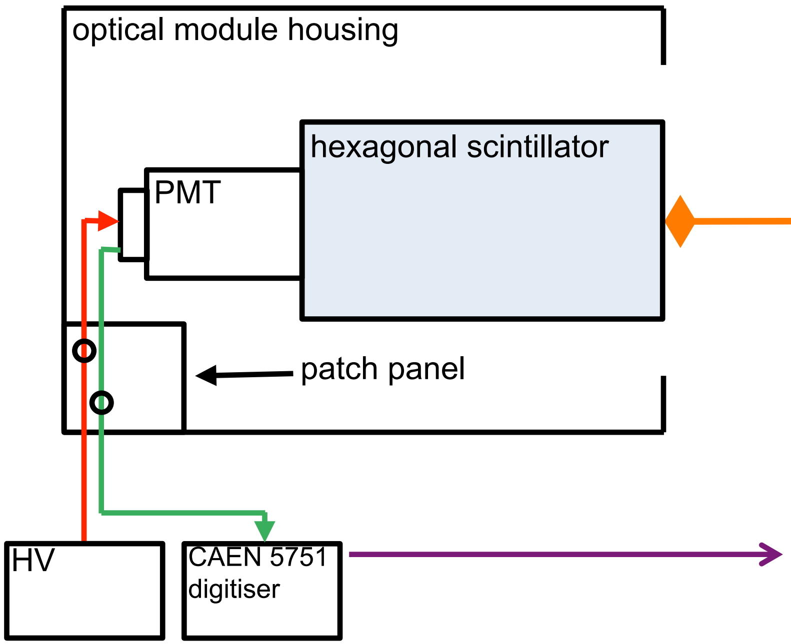
Clatterbridge Cancer Centre

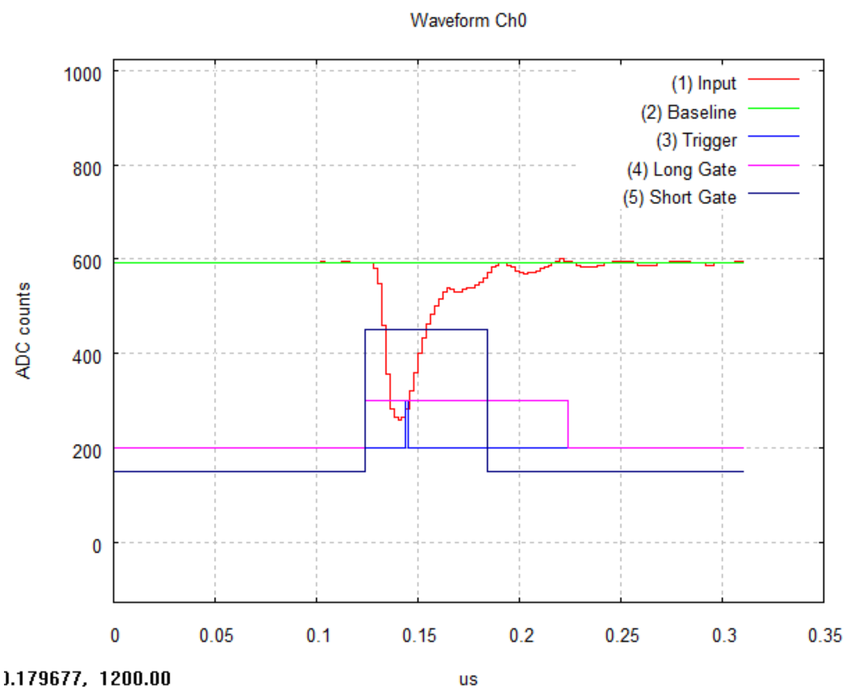
- 62 MeV Scanditronix cyclotron provides 60 MeV protons (31 mm in water) to treatment room through double scattering.
- Beam time provided for research.
- We've had 2-day shifts every few months.
- Already made interesting observations with our equipment about the treatment beam…



- Need much lower proton fluence for our measurements than clinical settings.
- Rate reduction achieved through:
  - Various collimators (0.5–10 mm)
  - Ion source gas supply.
  - Ion source discharge current.
  - Cyclotron sector focussing.
  - RF phasing (wouldn't recommend it…).

Equipment Setup





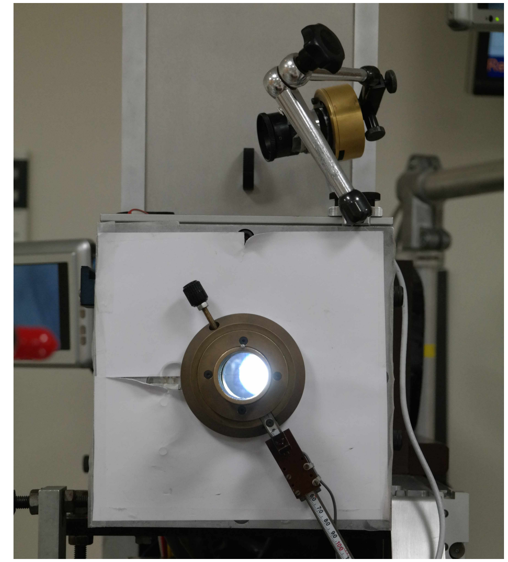
CAEN DT5751 Digitiser:

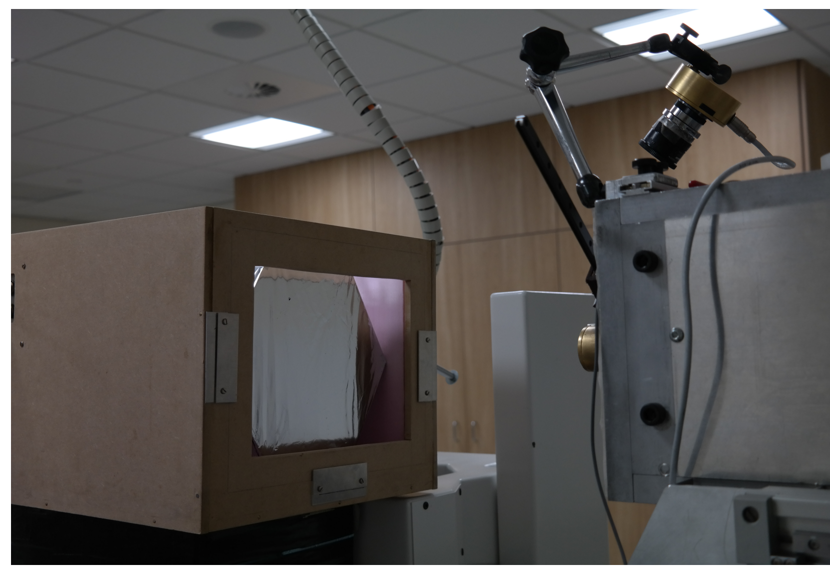
Dual-gate signal integration

→ On-the-fly pulse shape analysis

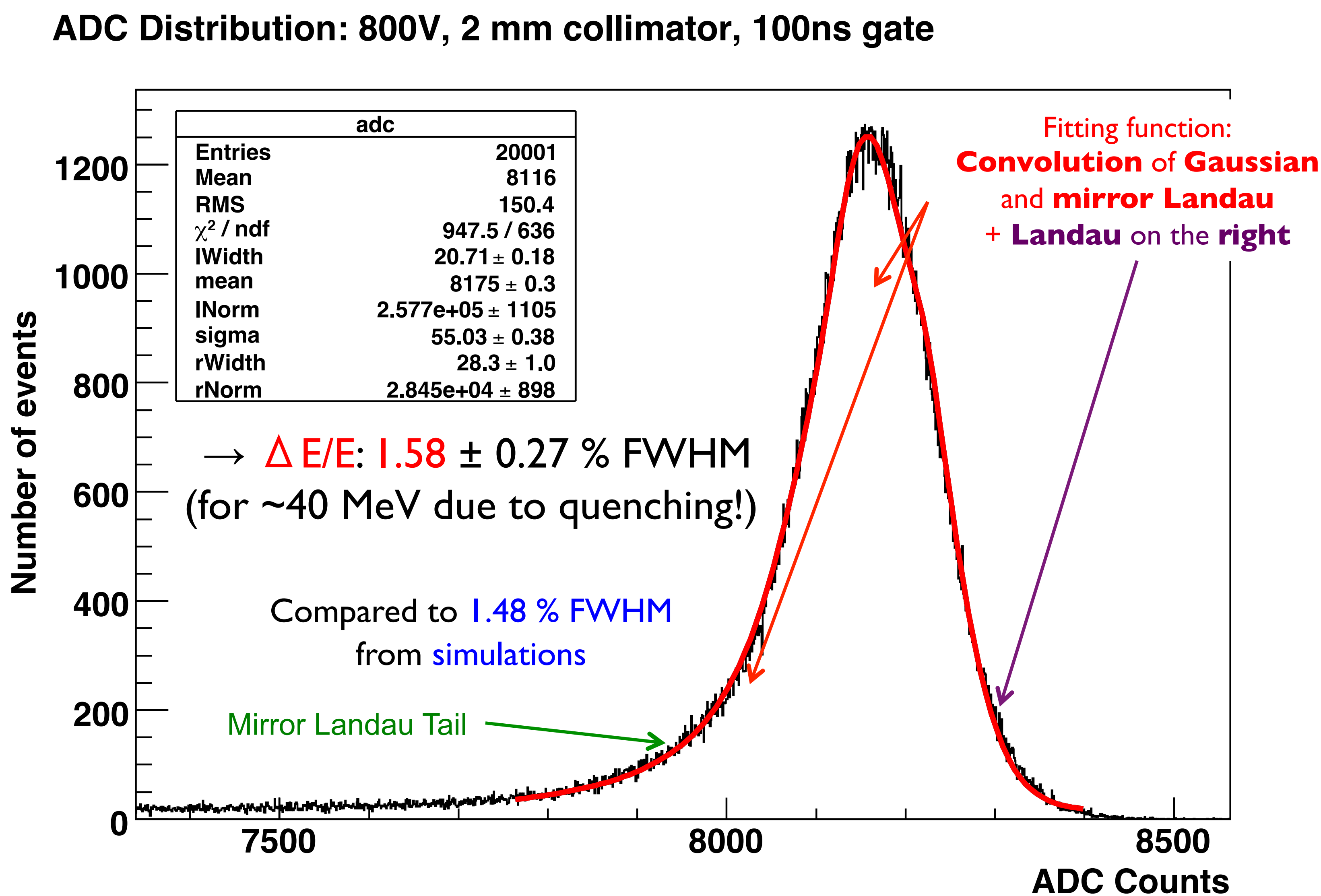
→ Neutron/gamma discrimination

Experimental Tests

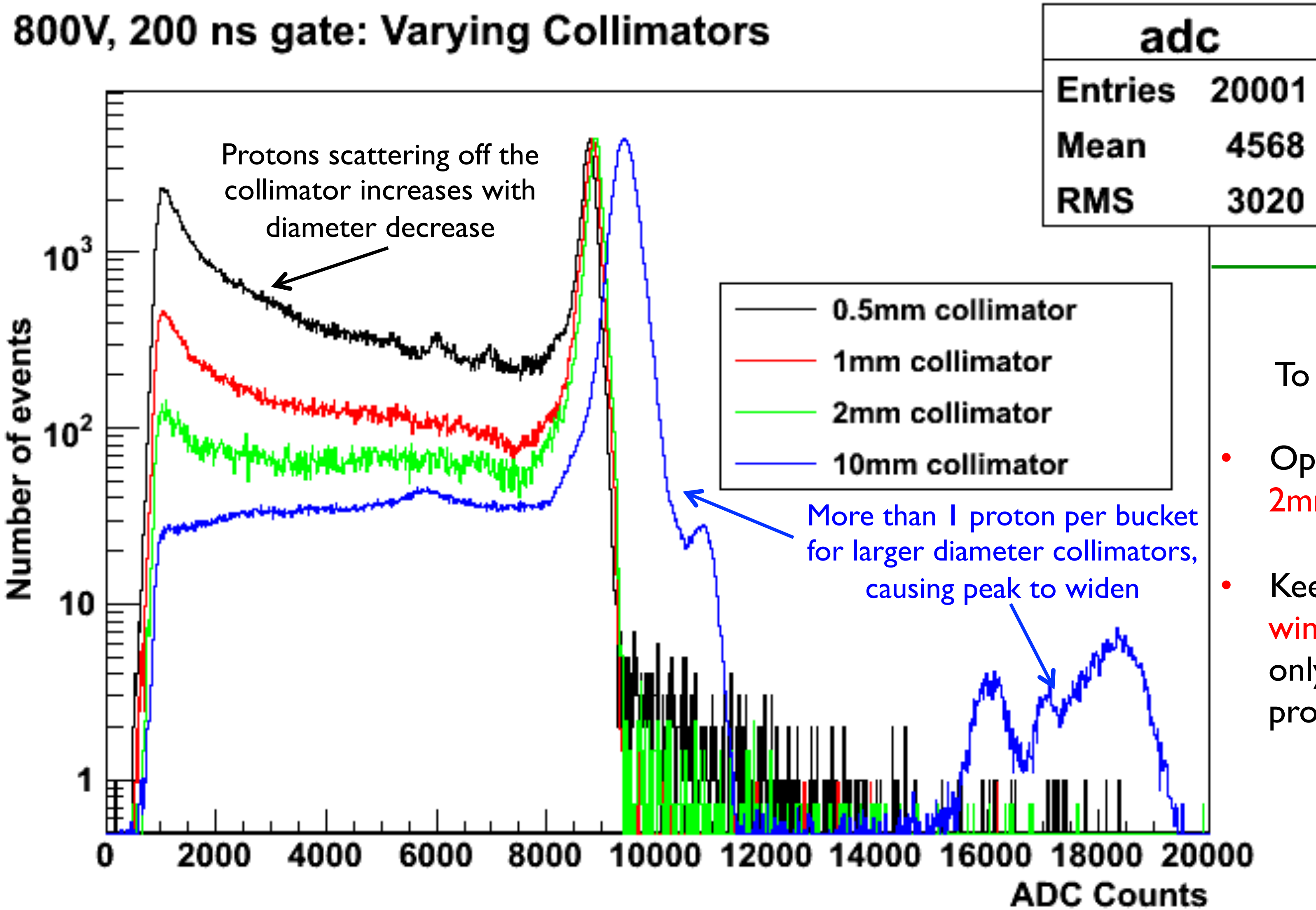




Results: Fitted Data



High Rate Tests: Pulse Pile-Up



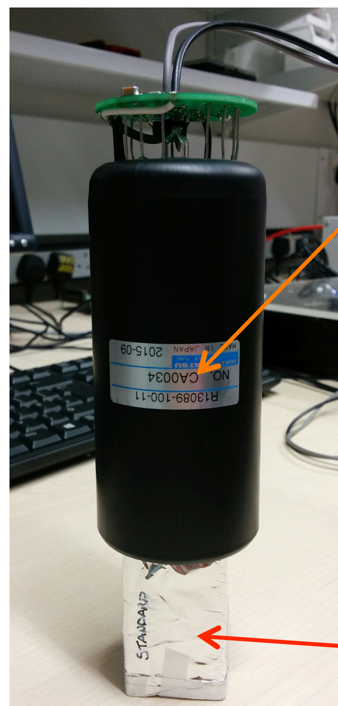
To avoid pile up:

- Optimal collimator: 2mm diameter
- Keep integrating window small to only collect single proton pulse

A Smaller, Faster Detector

- We have already achieved the target energy resolution: 0.7% σ with
- The next step is to do this for very high rates of 1–10 MHz with a compact design:

- Reduce the size of the PMT and the scintillator to improve timing and make the design nozzle-mountable.
- Negative HV PMT base to remove decoupling capacitor (not fast enough discharge).

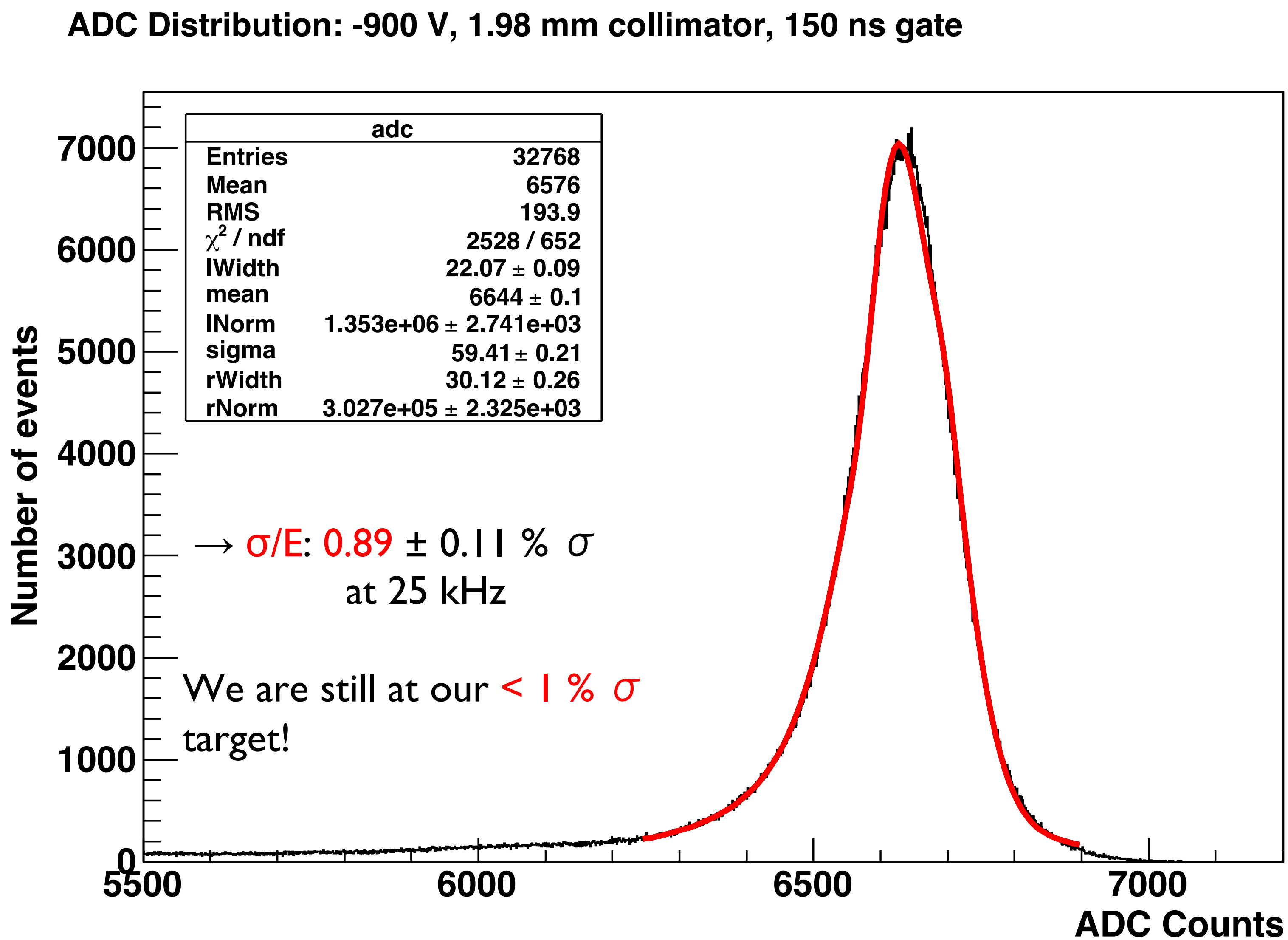


2” Hamamatsu R13089-100-11 PMT with negative HV active divider base

3 cm x 3 cm x 5 cm cuboid ENVINET/NUVIA PolyStyrene standard scintillator

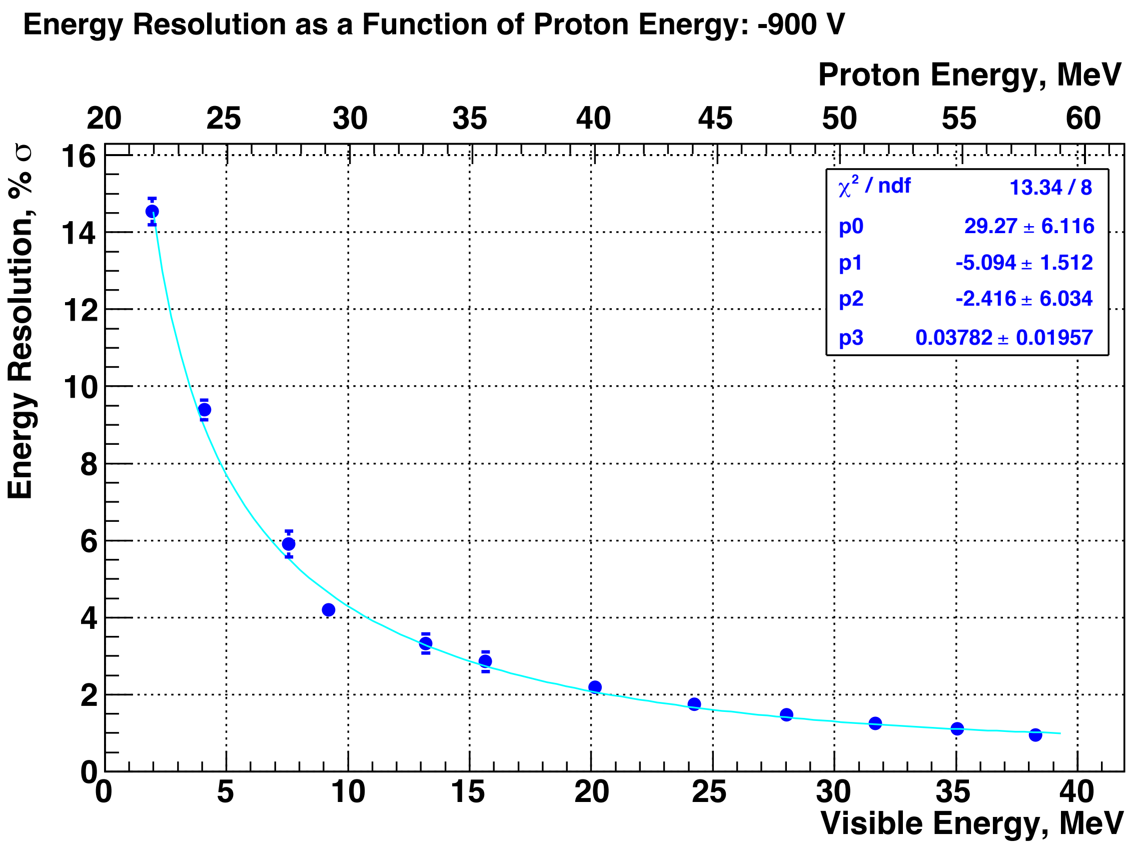
- Coupled with BC-630 Saint Gobain silicone optical gel
- Wrapped in 75 µm of PTFE (Teflon) ribbon on the sides and 12 µm of Mylar on the sides and entrance face

Small Module Results



Resolution: Energy Dependence

- Energy of protons incident on scintillator varied by placing absorbers (PMMA plates and calibration wheel) of known thickness ~1.8 m upstream of the optical module.



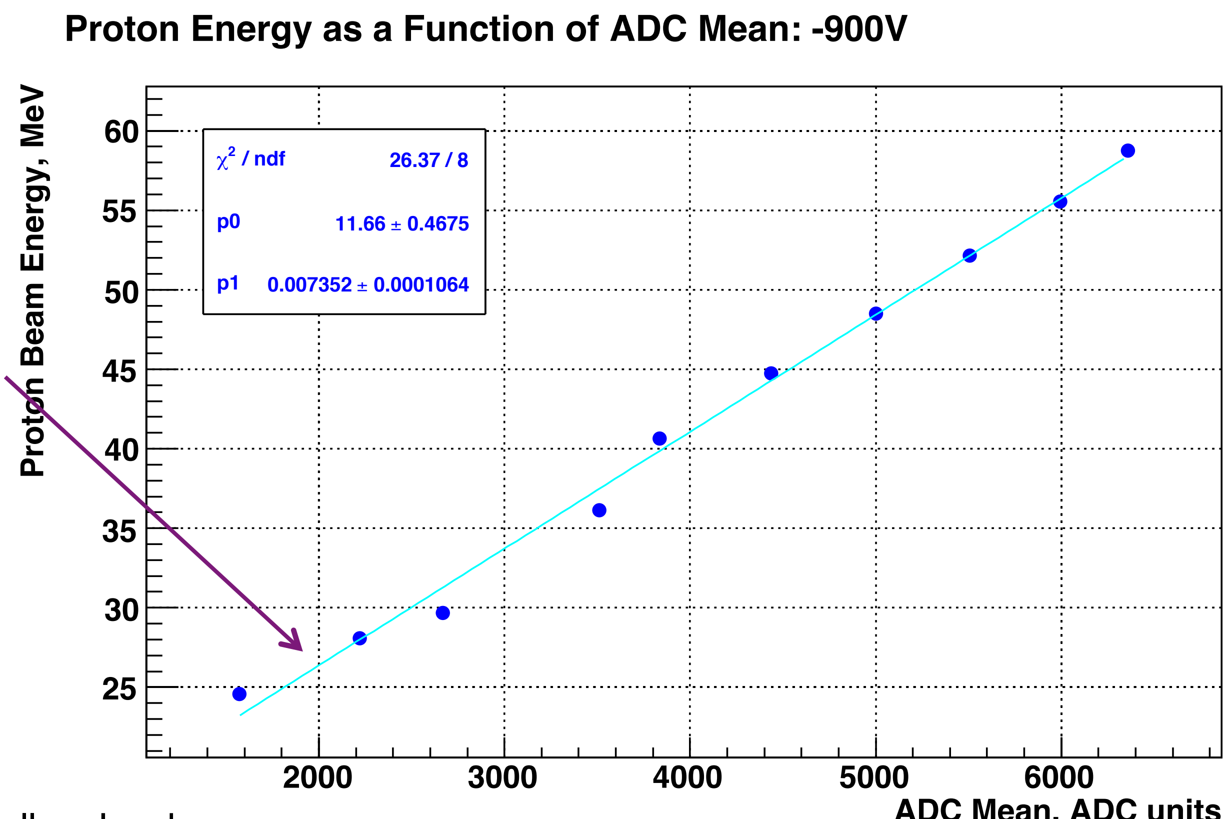
$$y = p0 + \frac{p1}{\sqrt{x}} + \frac{p2}{x} + p3 \cdot x$$

$\sqrt{E}$ dependence!

Resolution: Linearity

- We want to run the PMT at higher voltages (can run at up to -1500V) as this will increase the PMT's collection efficiency and will improve the energy resolution.
- BUT we have a LOT of light (tens of thousands of photo-electrons) so we need to make sure we are not saturating the PMT.
- Look at linearity:

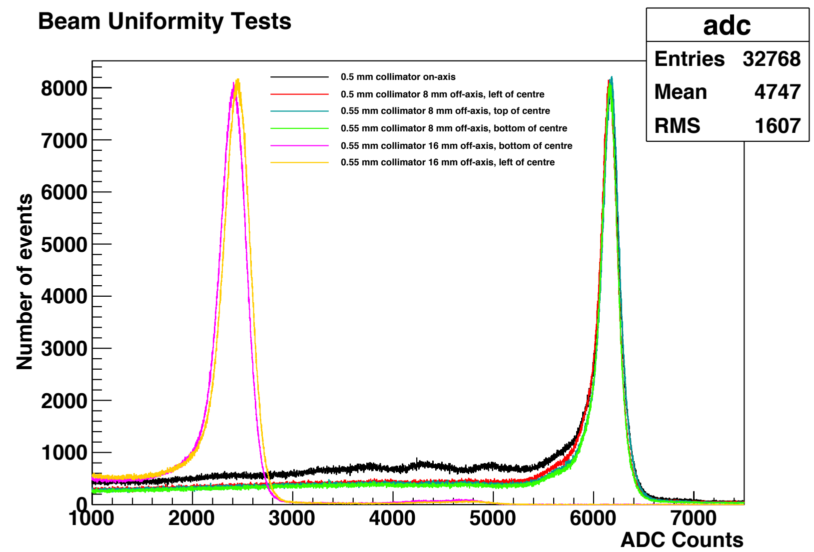
$$y = p0 + (p1 \cdot x)$$

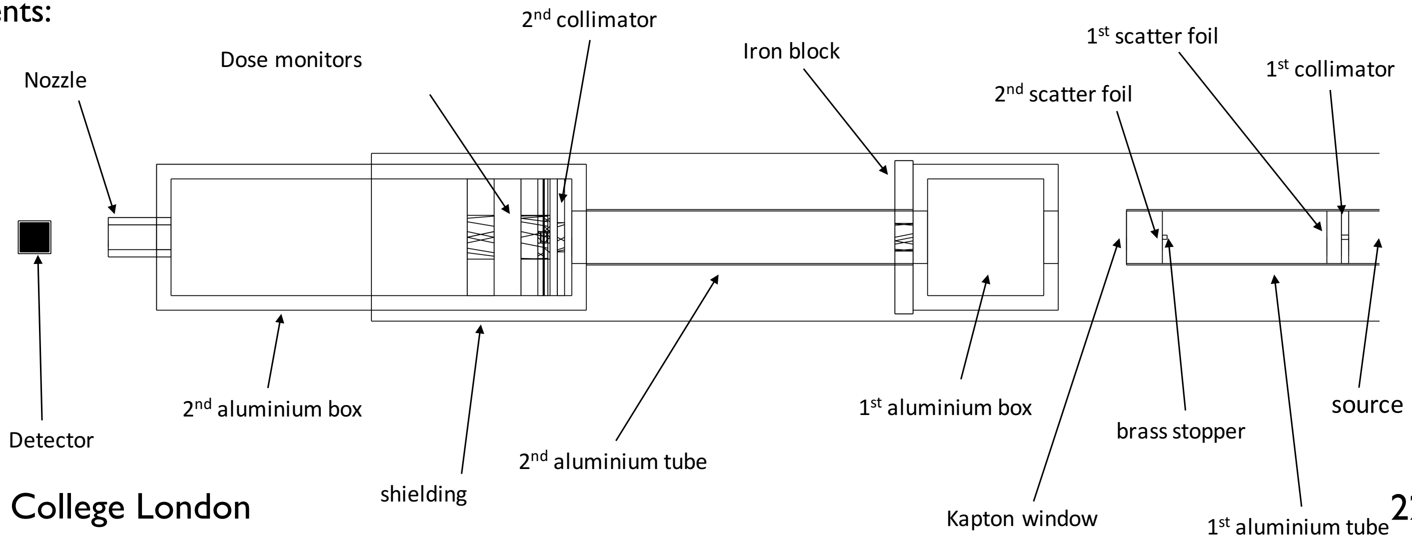


For -900V:
Deviation from linearity < 2%!

Beam Test Conclusions

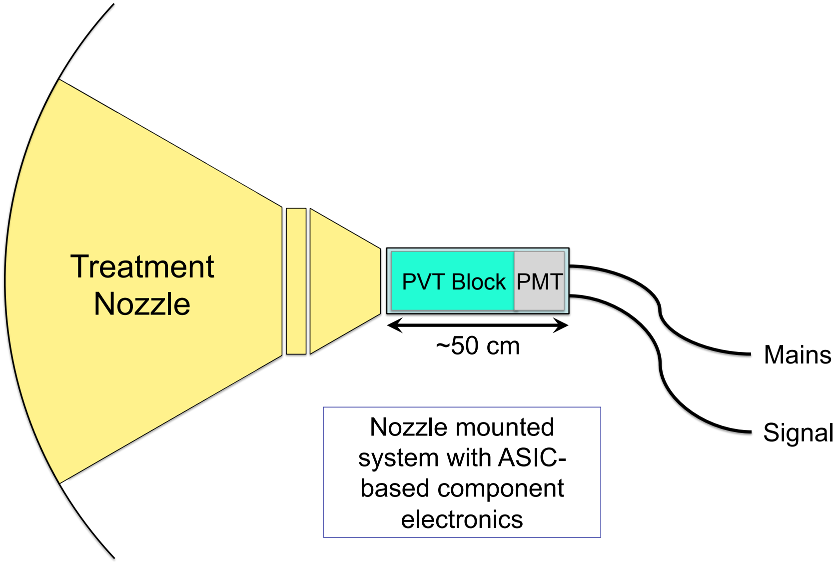
- What have we learned?
- The scintillator performs just as well for single protons as it does for electrons!
- Making the module smaller does what it's supposed to:
  - Improves timing (good measurements up to around 300kHz, compared to 1 kHz for original 8" module),
  - No detrimental effect on resolution.
- But…
  - We still can't handle rates approaching 1 MHz.
  - Despite Hamamatsu's promises to the contrary, we think the PMTs have a frequency-dependent gain.
- Interesting discoveries about Clatterbridge beam:
  - Nonlinear time distribution of protons (bunches of bunches...).
  - Close to nozzle edge, energy falls off.
  - Building complete simulation to compare to Clatterbridge/UCL measurements:



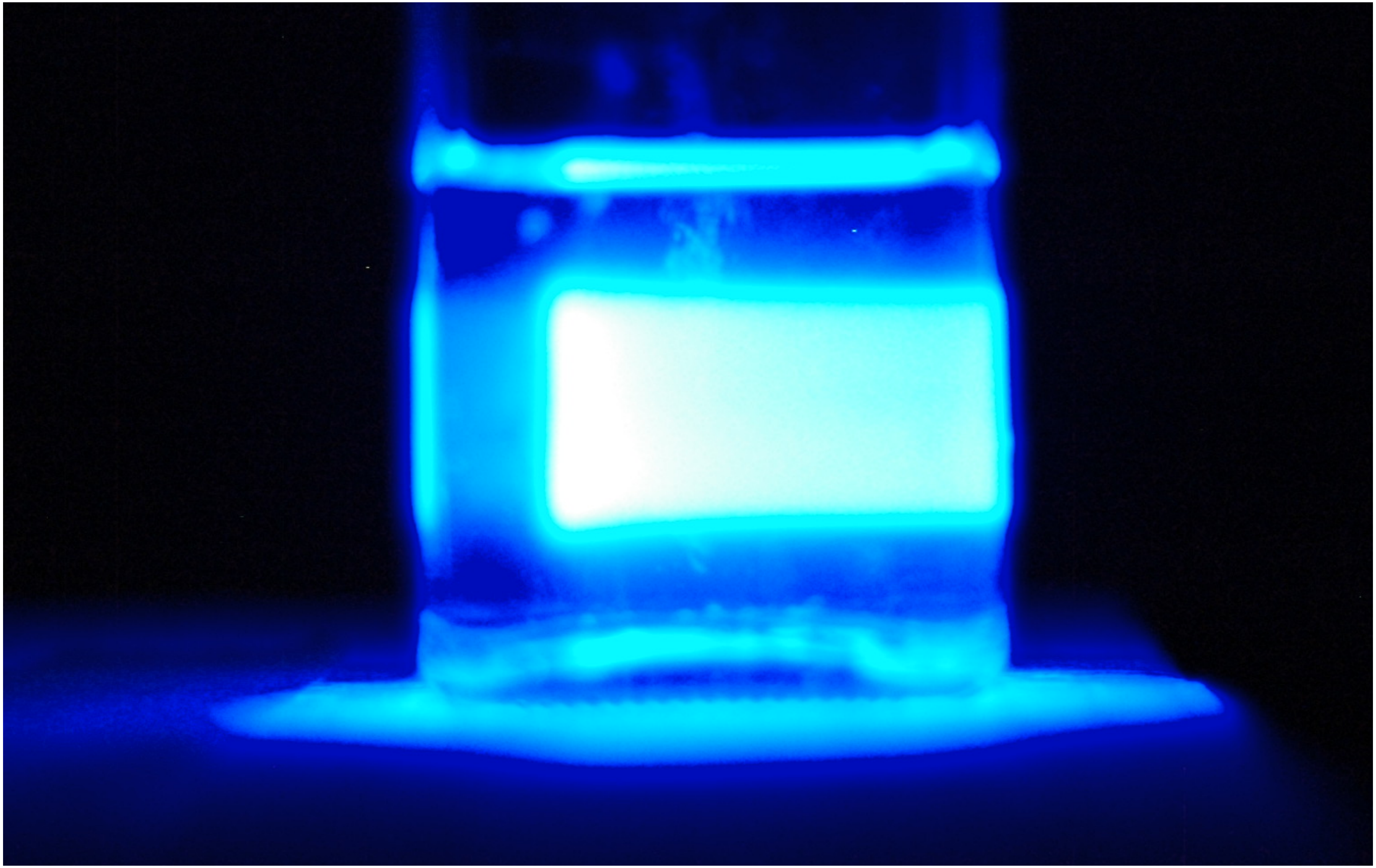


So What…?

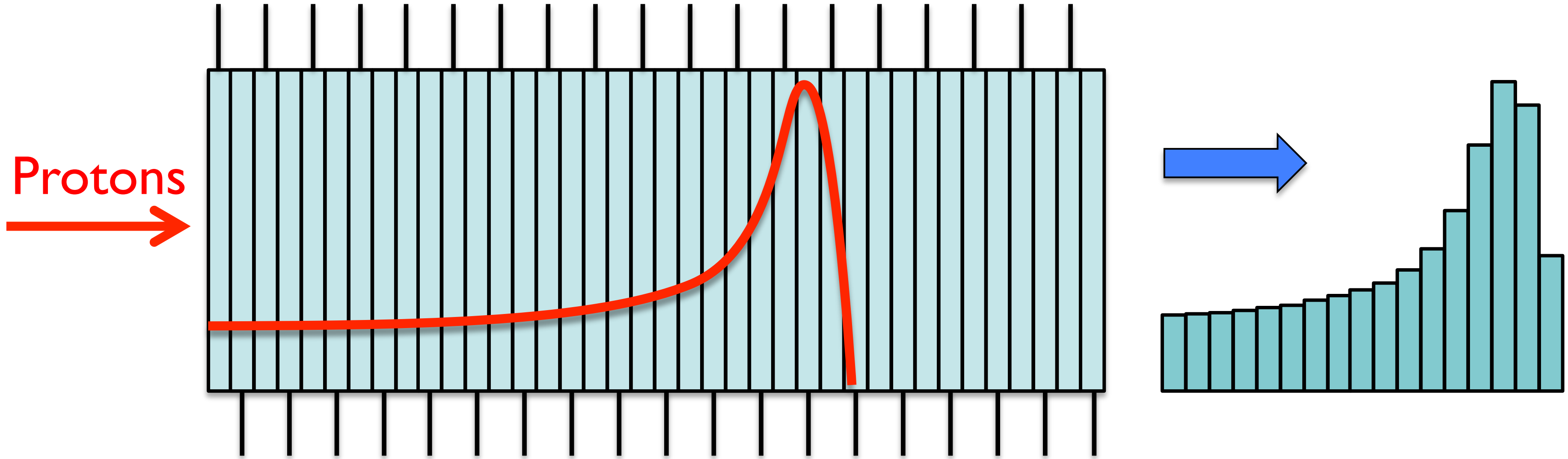
- Our goal was originally to develop a calorimeter to act as the energy measurement stage for a proton CT system:
  - Needed better than 1% resolution and rates in the region of 1–10 MHz.
  - Managed to achieve the resolution; rates limited by electronics.
  - Work will continue: discussions with PRaVDA and Loma Linde.
- Clinical steer to provide fast energy/range QA tool to work at clinical rate.
- Needs a change in design philosophy: also take advantage of water equivalence of plastic scintillator.



A Real Bragg Peak In Liquid Scintillator



Segmented Calorimeter



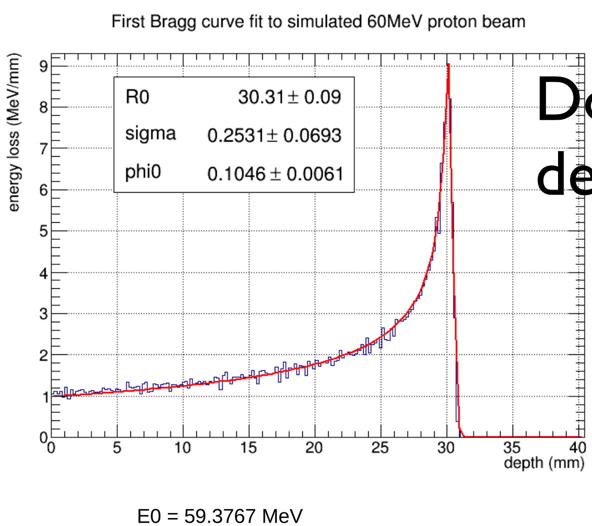
- PVT and PS are both helpfully water equivalent.
- Segment block into slices and read out light from each slice individually.
- Integrate signal from many protons: very large output from 10^{10}/s.
- Minimum slice width will depend on manufacture: aiming for < 2 mm.
- Use photodiodes for readout: poor light detectors but stable and cheap with large dynamic range.
- Resolution set by slice width and variation in scintillator light output.

Segmented Calorimeter Design

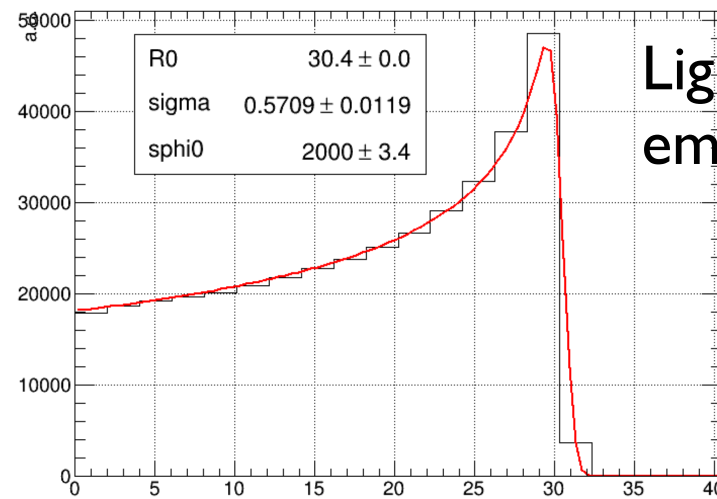
- Laurent Kelleter has built preliminary model in Geant4:
  - 2 mm slices of plastic scintillator with mylar wrapping.
  - Currently integrating photodiode readout.
- STFC IPS grant application currently pending approval: working with NUVIA a.s. in Czech Republic to produce our scintillator sheets: manufacturing challenging!
- Need to characterise light quenching to reconstruct Bragg curve: **pencil beams only**.
- Fit to measured curve drastically improves mean range measurement: do you need range or range spread…?

$$\frac{dY}{dx} = \frac{S}{1 + kB(dE/dx)} \times \frac{dE}{dx}$$

dY/dx	light yield per unit path length
dE/dx	energy lost by particle per unit path length
kB	relates density of ionisation to energy loss = 0.207 mm/MeV
S	absolute scintillation efficiency

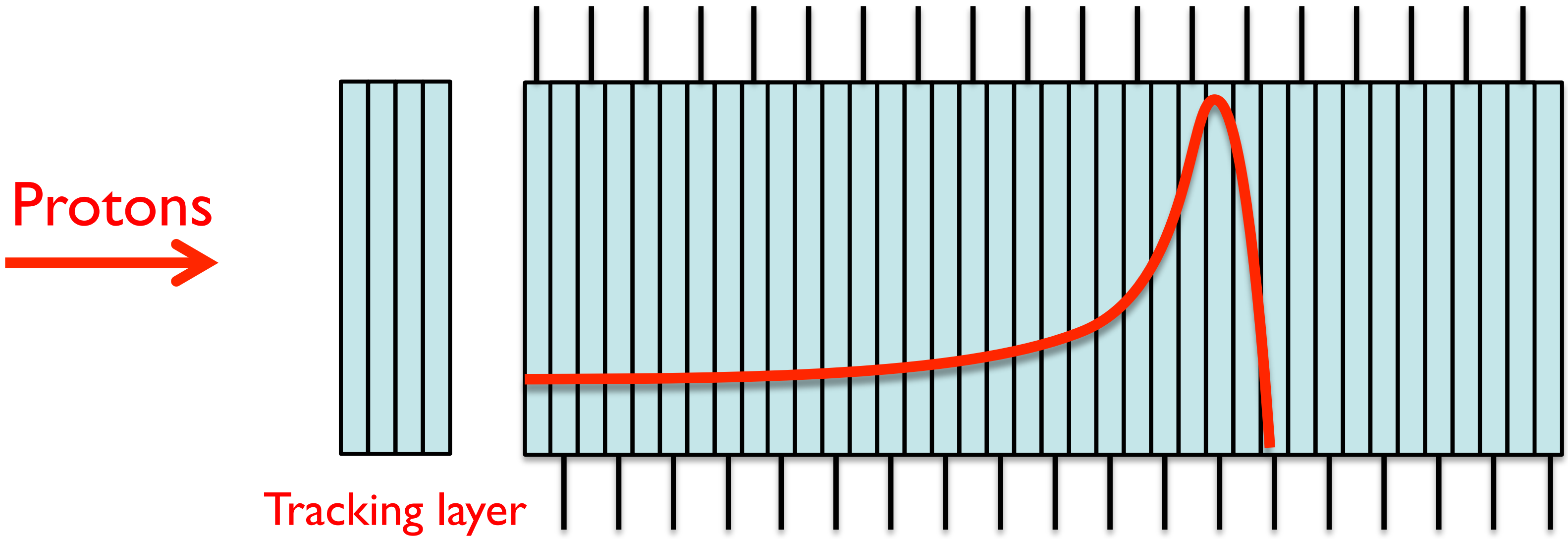


Dose deposited



Light emitted

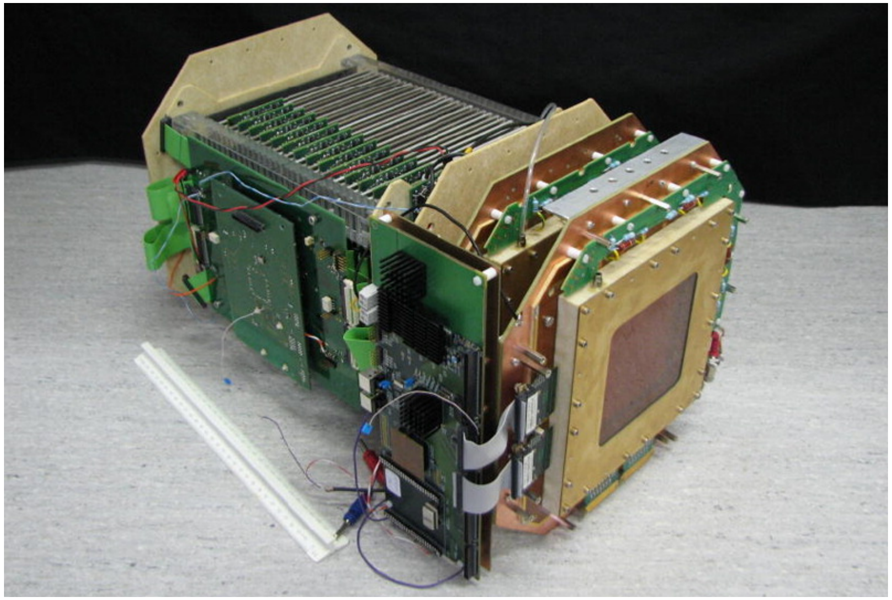
Fast Treatment Plan Verification

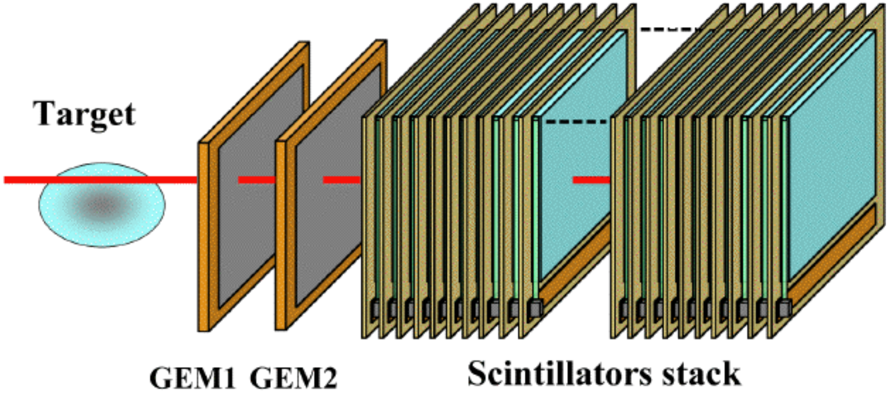


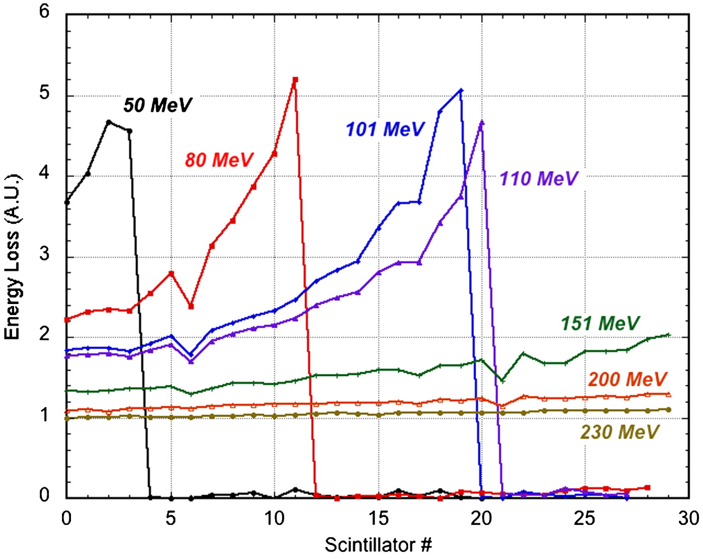
- Take segmented calorimeter: add 2D tracking to front face.
- Still nozzle-mounted and self-contained.
- Read out X/Y profile and integrated range of individual pencil beams.
- Detector read out fast enough to match minimum spot dwell time (3–20 ms).
- Fast reconstruction of water-equivalent treatment plan.

TERA: Proton Range Radiography

- Don't need to prove the principle using scintillator sheets: TERA have done it for us!
- Proton Range Radiography:
  - Gas Electron Multiplier (GEM) tracking.
  - 2 mm PVT scintillator sheets fibre coupled to Silicon PhotoMultipliers.
- Can't use this exact setup:
  - Designed for single protons for pCT.
  - They get "good enough" proton range by looking at end-of-range only.
  - SiPMs expensive, high gain devices: not appropriate for high light output with full beam intensity.







Future Plans

- Continue development of single calorimeter module for proton CT and lower rate applications:
  - Well characterised.
  - The fewer channels the better: single block also means more light per proton per detector.
- Work on segmented calorimeter design to produce water equivalent path length detector:
  - Resolution better than 2 mm: much better with appropriate fit.
  - "Immediate" readout (a few seconds).
  - Need >150 sheets for 32 cm: start with 20 sheets and do fast measurement at Clatterbridge.
- Full design aims to be gantry mounted: can characterise multiple fields.
- Fast treatment plan verification very promising, but needs work to get segmented calorimeter working before adding tracking:
  - Tracking and range measurement need to be fast enough to read out data with suitable resolution within spot dwell time.
  - Needs electronics to synchronise.

Acknowledgements

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  - Brian Marsland

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  - Hywel Owen
  - Karen Kirkby

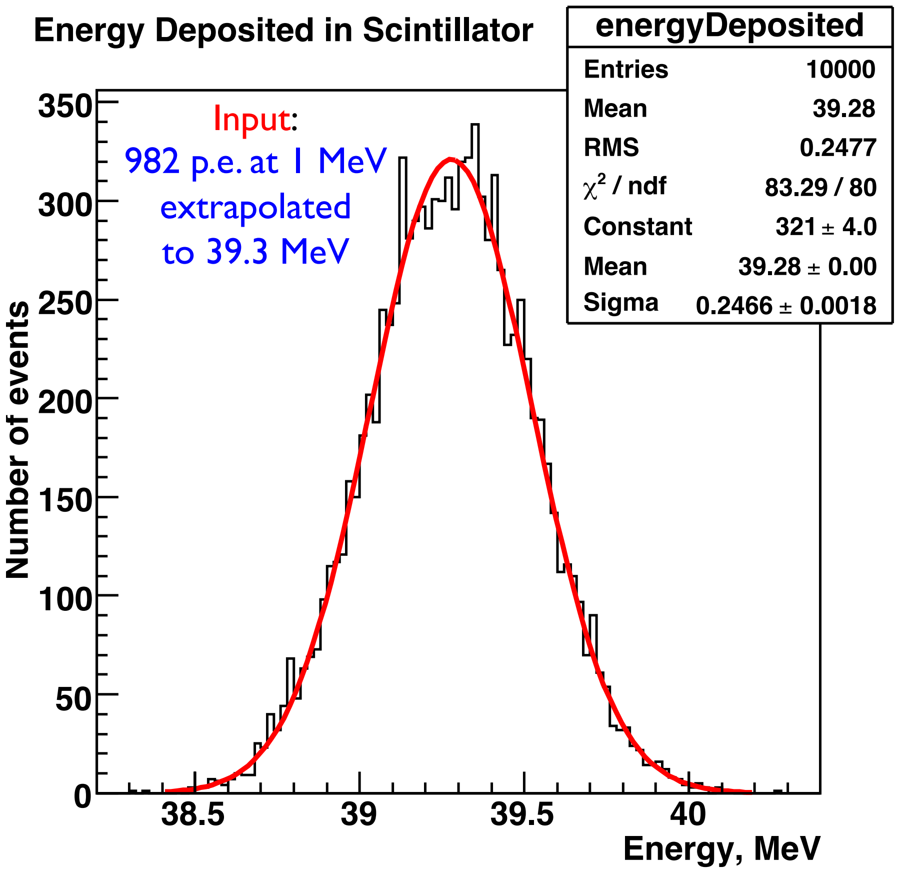
- PSI
  - Tony Lomax
  - Marco Schippers

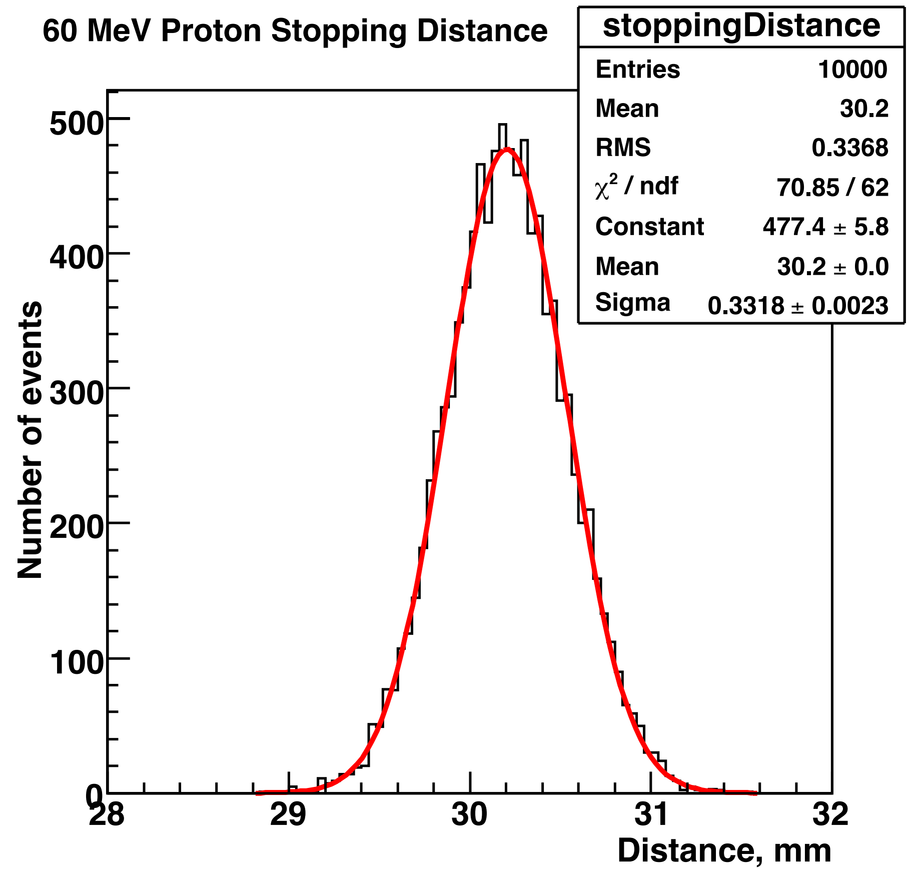
Spare Slides

Geant4 Simulations

- A pencil proton beam (60 MeV) simulated, positioned 70 cm from the entrance face of the scintillator block.
- Scintillator modeled as a square block (256 mm x 256 mm x 120 mm) with scintillator composition fully described.
- Quenching of scintillation light in plastic scintillator for protons.
- Energy deposited smeared according to Poissonian fluctuations in the number of generated photo-electrons.
- The number of photo-electrons per MeV taken from test bench data (SuperNEMO calorimeter R&D): 982 photo-electrons per MeV (for an energy resolution of 7.5% FWHM at 1 MeV).

Simulation Results

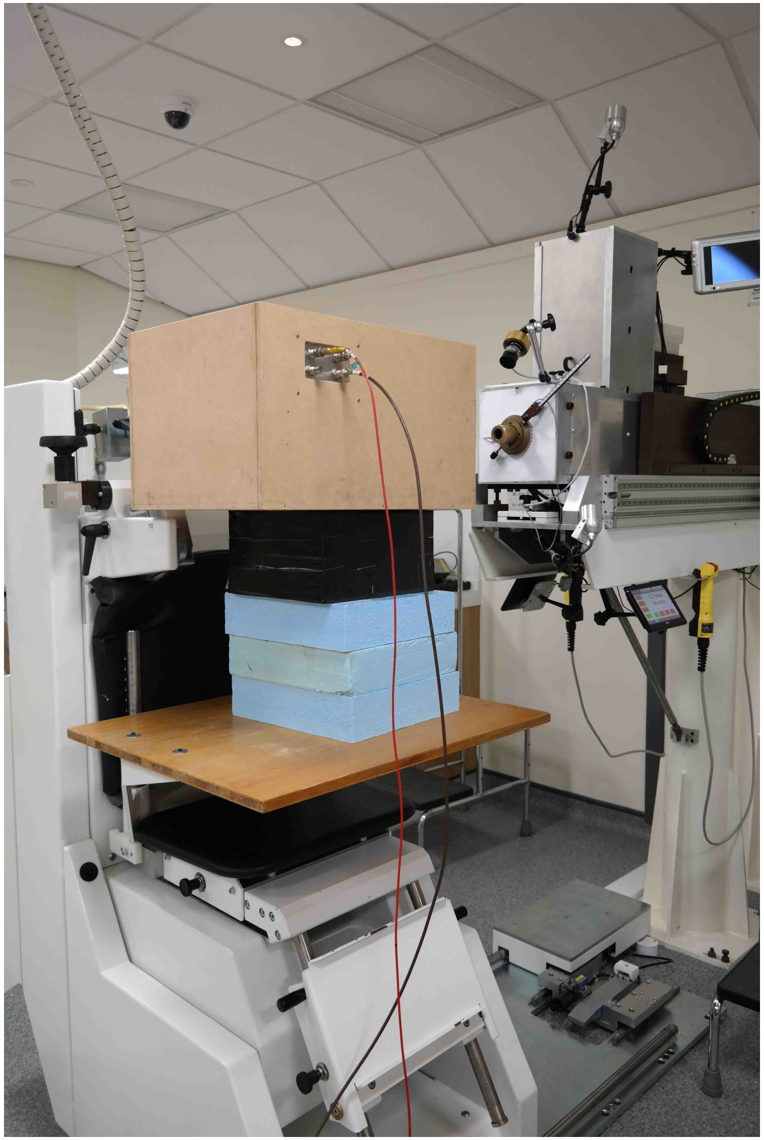




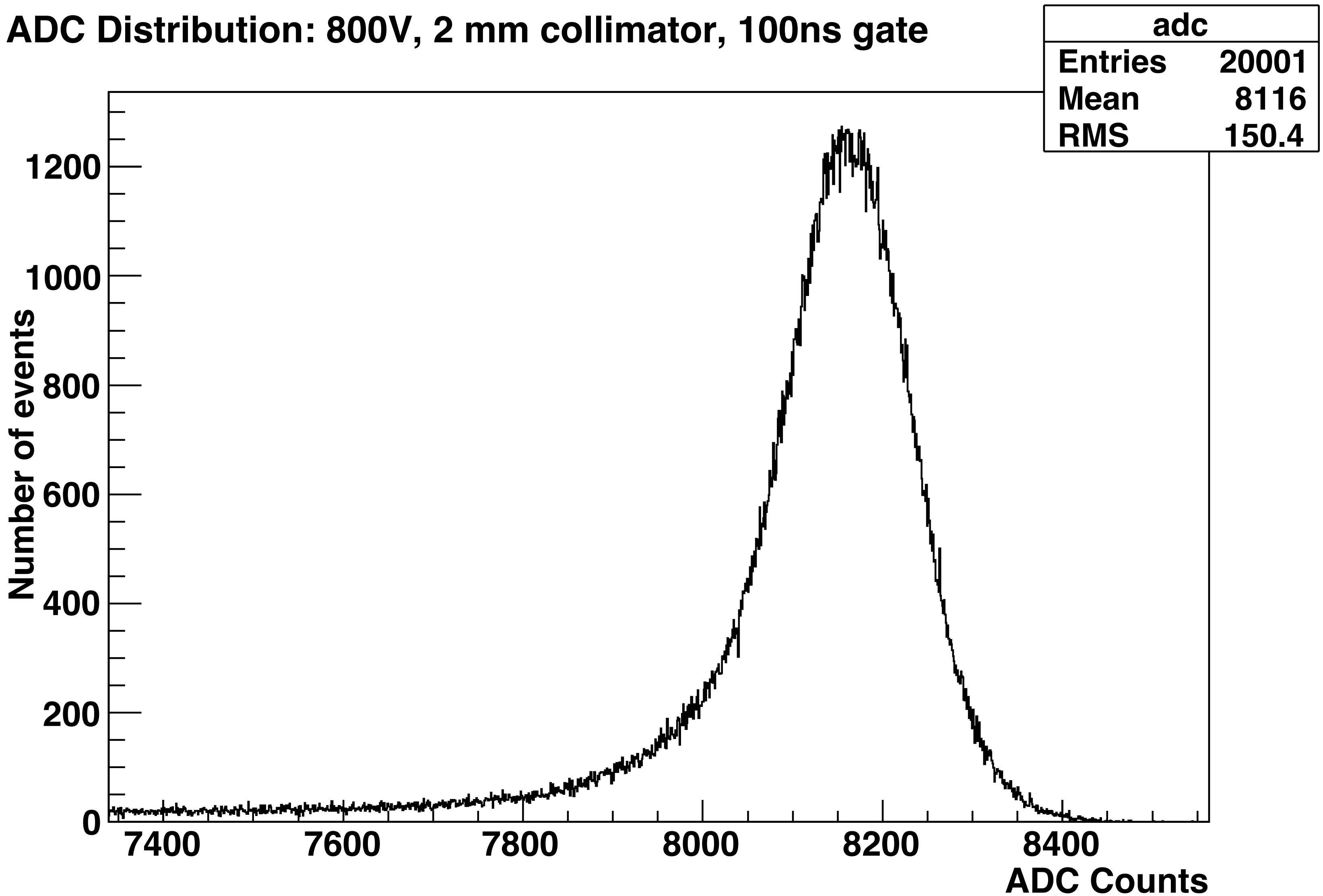
- Quenching from simulations:
  - Simulated mean: 39.3 MeV
  - Quenching: 35% for 60 MeV protons
- Energy resolution from simulations:
  - $\sigma: 0.247,\ \mu: 39.28$
  - Δ E/E: 1.48 % FWHM

$$\boxed{\frac{\Delta E}{E} = \frac{2.35\sigma}{E}}$$

Experimental Tests



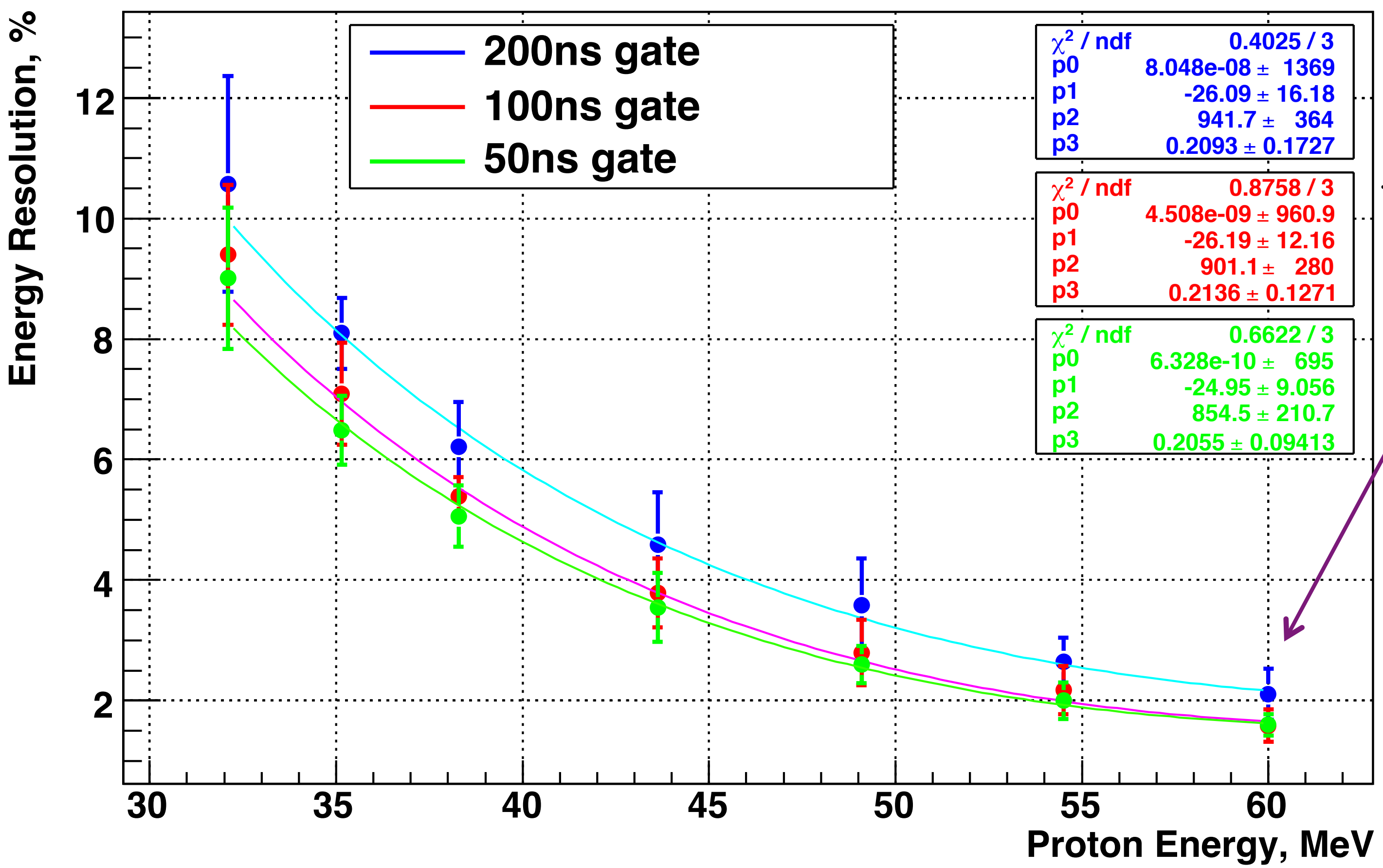
Results: Raw Data



Resolution: Energy Dependence

- Energy of protons incident on scintillator varied by placing absorbers (PMMA plates) of known thickness ~1.8 m upstream of the optical module

Energy Resolution as a Function of Proton Energy: 800V

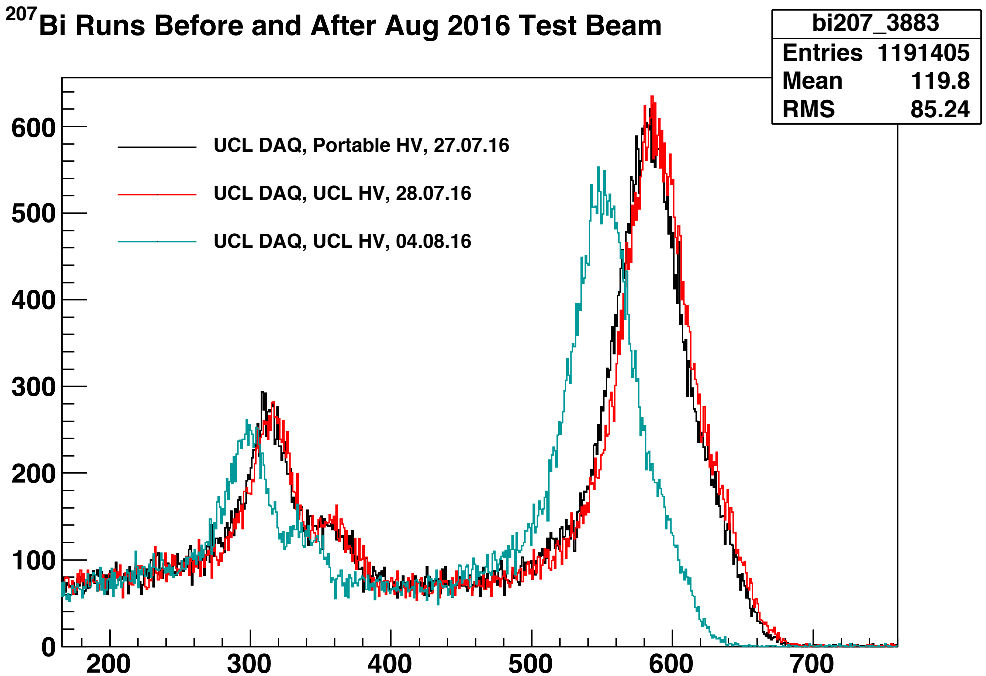


$$y = p0 + \frac{p1}{\sqrt{x}} + \frac{p2}{x} + p3 \cdot x$$

$\sqrt{E}$ dependence!

Radiation Damage

- Total estimated radiation dose received by 2" OM: 0.25 Gy.



Date	HV Supply	DAQ	σ /E (%)
27/07/16	Portable	UCL	3.16 ± 0.03
28/07/16	UCL	UCL	3.14 ± 0.03
Clatterbridge Test Beam: 02-03/08/16			
04/08/16	UCL	UCL	3.08 ± 0.03

- No noticeable difference in resulting energy resolution so far.