Proton Calorimetry: from SuperNEMO to Proton Therapy

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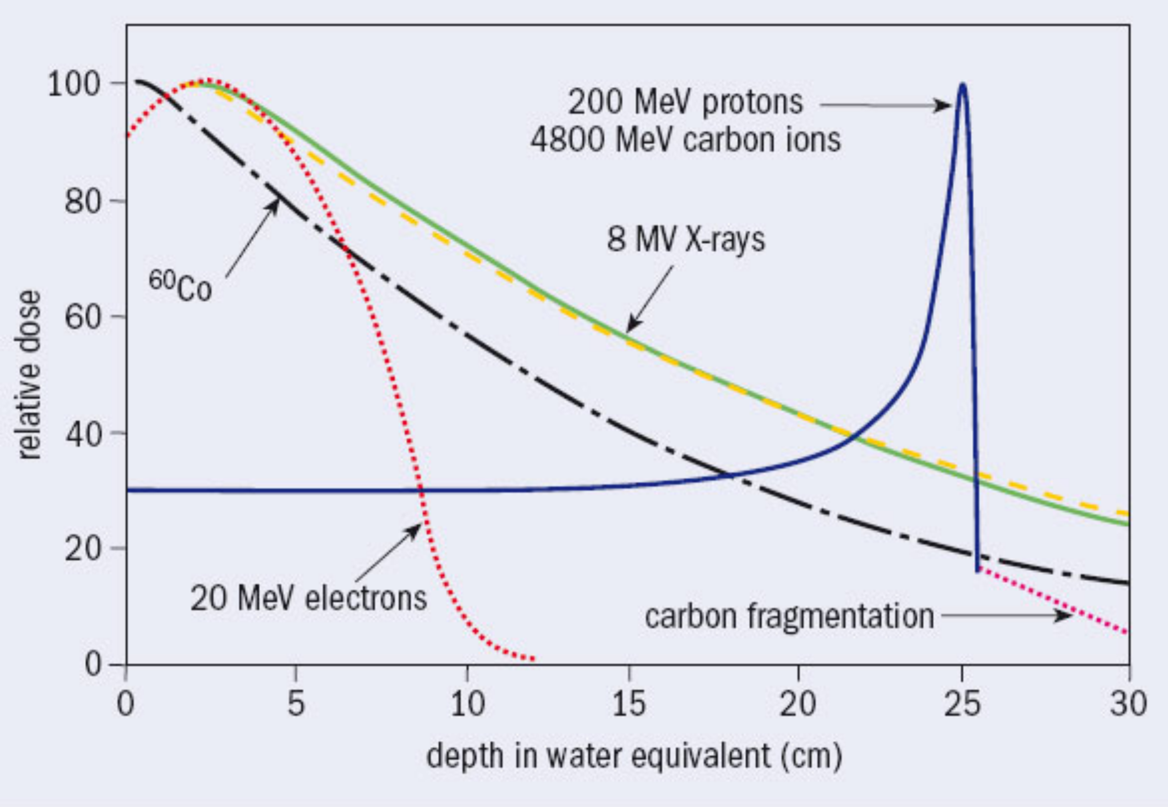
Proton Beam Therapy

- Unlike X-rays, charged particles stop!
- Electrons, being lighter, scatter and spread out.
- Protons deposit most dose at the *end* of their path: the *Bragg Peak*.



- This property is both the advantage and the disadvantage of proton therapy.
- Protons stop, but you need to know where…

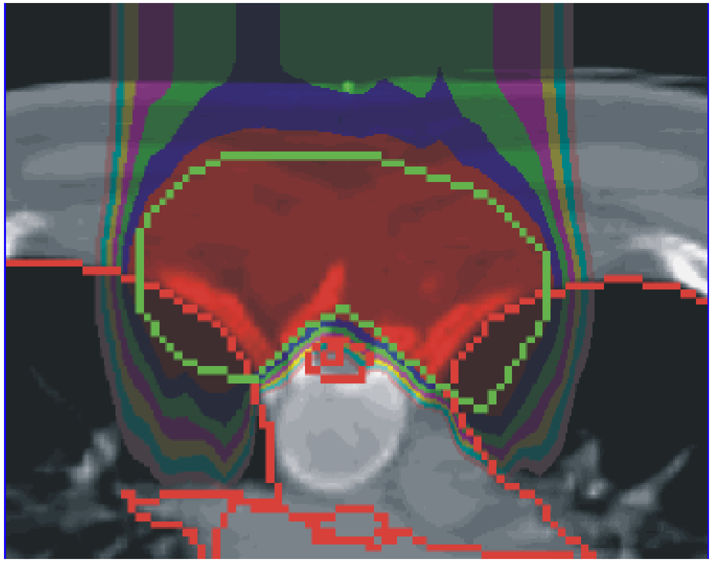
Proton Beam Therapy QA

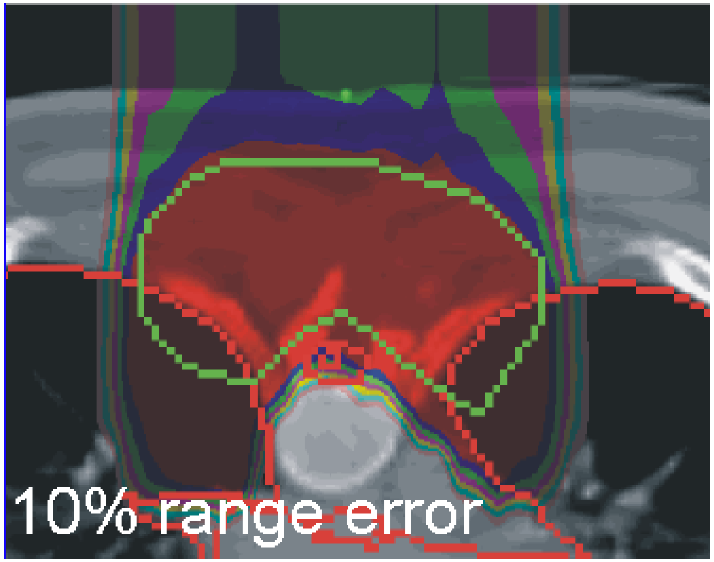
- A range of QA checks are necessary for safe PBT treatment:
  - Daily.
  - Weekly.
  - Monthly.
- Daily checks carried out before treatment:
  - Most time spent verifying range is correct for given energy.

- These range QA checks can take more than an hour for a few measurements.
- Equipment is bulky and slow (setup or measurement).
- A better detector should make the same measurements more quickly and more accurately…

Range Errors

- Requires an increase in imaging resolution compared to X-ray based systems due to localisation of proton dose delivery
- Currently use a conversion factor to convert from X-Ray to proton therapy treatment plans → imprecision and range uncertainty
- Currently, the patient is imaged away from the treatment – any movement of the patient's anatomy introduces further imprecision



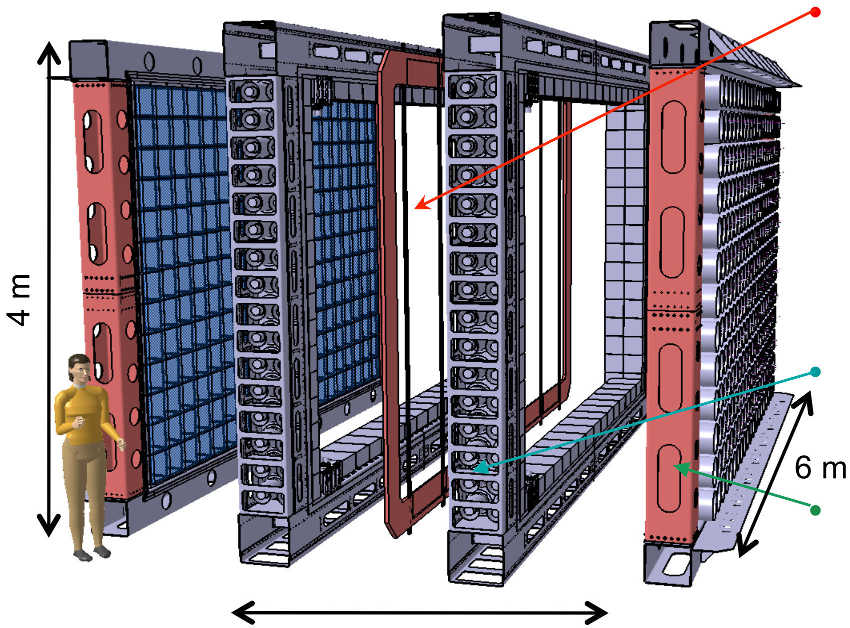


Proton Calorimetry

- Calorimetry approach for measuring range for QA:
  - Measure energy and convert to range using a single scintillator + PMT
  - Measure range directly using a segmented scintillator with a readout on every slice
  - Both methods aim to reduce QA times to 2-3 minutes, are affordable and can have short setup times
- Proton imaging:
  - Image with > 300 MeV proton beam, which will emerge from the body without significant energy deposition
  - Tomography approach:
    - A series of tracking layers upstream and downstream of the patient
    - Accurate calorimeter for energy measurements
    - Target energy resolution: ~1% σ for 300 MeV imaging protons

SuperNEMO

supernemo
collaboration



2 m (assembled, ~0.5 m between source and calorimeter)

- 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

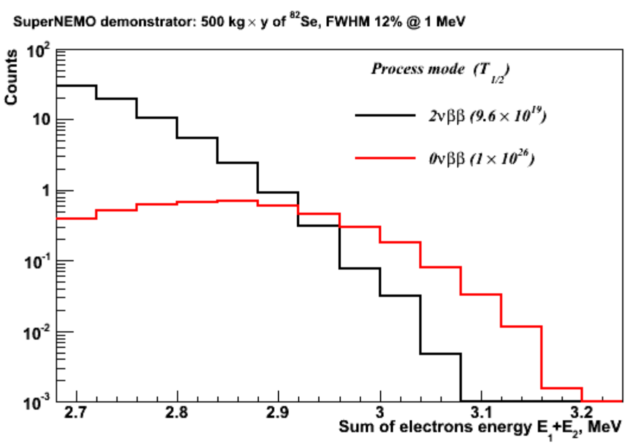
From NEMO3 to SuperNEMO

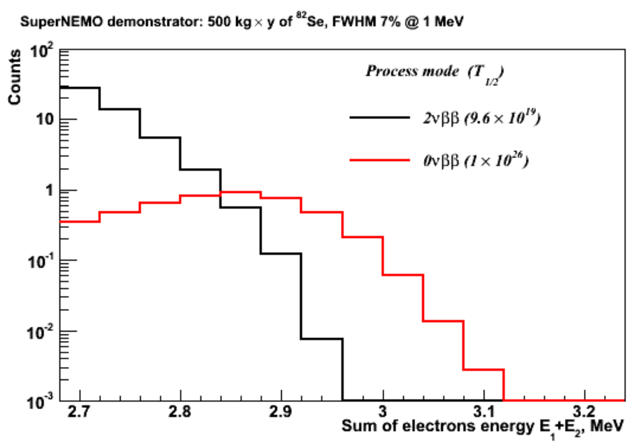
- Energy resolution is one of the main challenges (factor of 2 improvement):

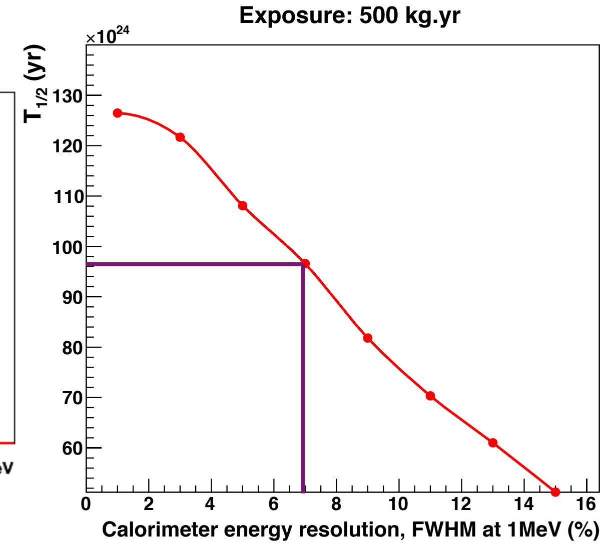
NEMO3: $\frac{6-7\%}{\sqrt{E(MeV)}}$ → SuperNEMO: $\frac{3\%}{\sqrt{E(MeV)}}$

- SuperNEMO scintillator has to be organic plastic scintillator
(high light yield, low electron back-scattering, high radiopurity, fast timing)
→ Can 3% σ at 1 MeV be reached for organic solid plastic scintillator?

- First step in SuperNEMO R&D: secured STFC funding for energy resolution R&D







Energy Resolution

$$\frac{\Delta E}{E} = \frac{2.35\sigma}{E} = \frac{2.35}{\sqrt{N_{pe}}}$$

σ	sigma of distribution
E	mean of distribution
N_{pe}	number of photo-electrons
$N_{ph}/E_{e.}$	number of photons per unit energy
ε^{light}	light collection efficiency
QE^{PMT}	quantum efficiency of the photo-cathode
ε^{PMT}	PMT collection efficiency

Three experimental objectives:

$$\frac{N_{ph}}{E_e} \cdot \epsilon^{light}_{col} \cdot \left(QE^{PMT} \cdot \epsilon^{PMT}_{col}\right) = N_{pe}$$

scintillator light output

Physically translates to:

- Scintillator: material, surface treatment, geometry
- Reflector: material, reflectivity coefficient, specular/diffusive
- Optical coupling quality: material, geometry, light guides
- Photomultiplier Tubes (PMTs): quantum efficiency (QE), collection efficiency, gain of the first dynode

Combined in an "optical module":

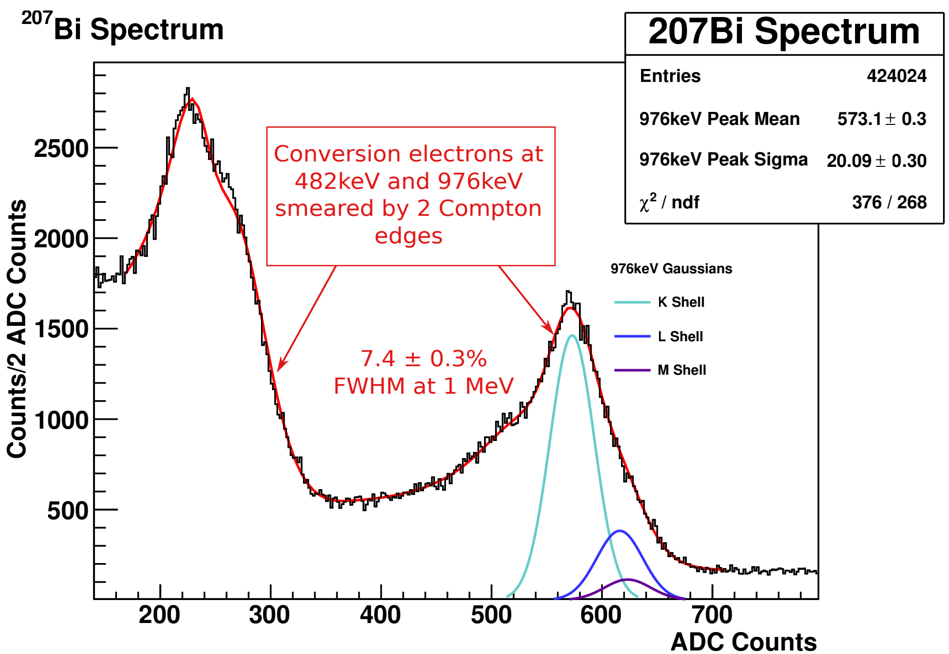
scintillator wrapped in reflective material coupled to a PMT

SuperNEMO Calorimeter Test Bench

Excite scintillator with a monochromatic electron source (approximates the delta function) → any smearing of distribution is due to detector properties

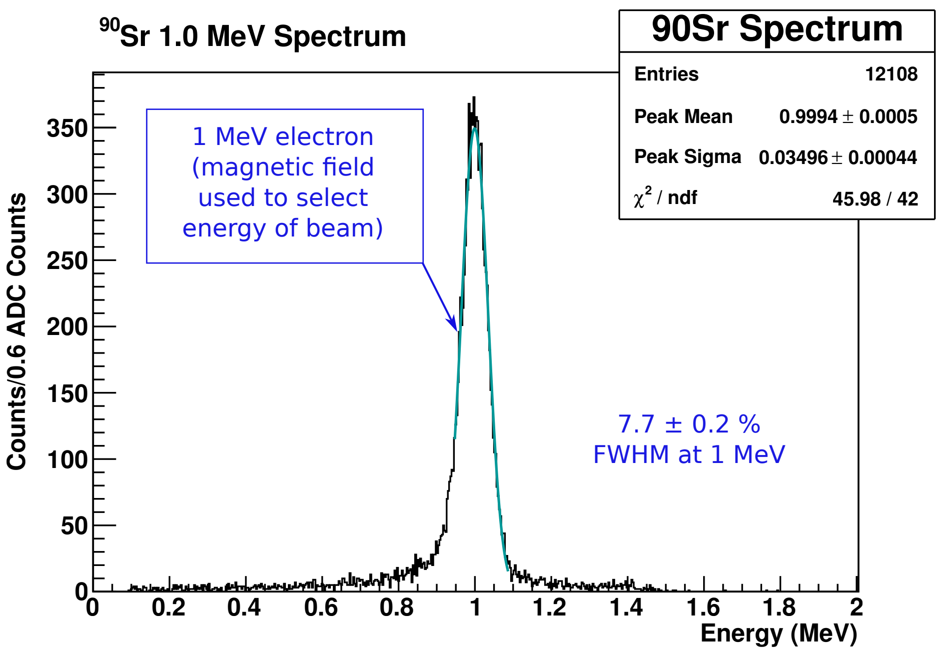
UCL:

- ^{207}Bi source: 976 keV and 482 keV K-shell conversion electrons
- Fit: deconvolution of X-rays, γs, L-shell and M-shell conversion electrons



Bordeaux:

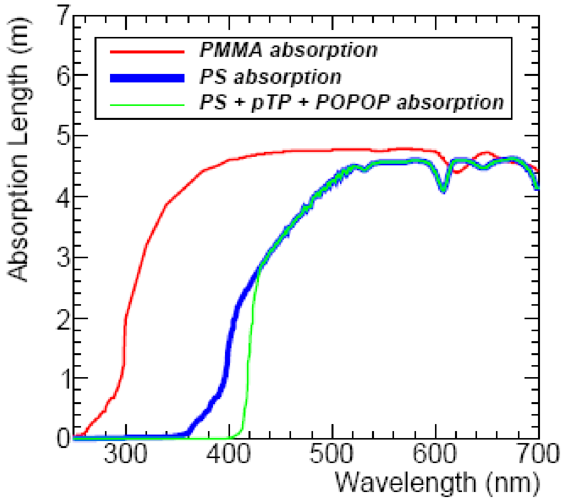
- ^{90}Sr spectrometer: ^{90}Sr beam passed through a magnetic field to select monochromatic electrons of known energy
- Fit: Gaussian

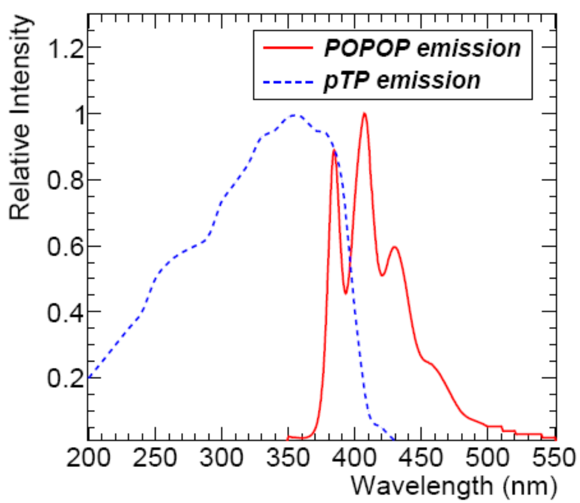


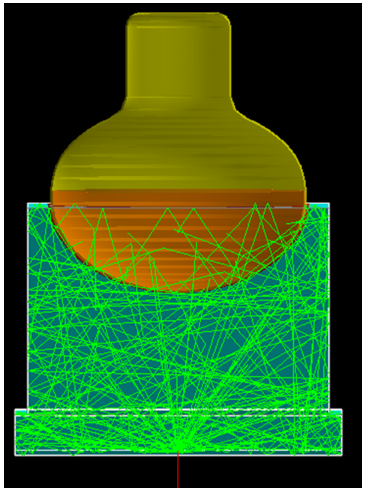
Calorimeter R&D: Simulations

- Full calorimeter simulations:
  - GENBB event generator
  - Physics simulations with GEANT4 (optical photon transport in scintillator detectors)

- The model accounts for wavelength dependence of optical properties, all of which have been experimentally measured, of the:
  - scintillators (self absorption and re-emission)
  - reflective wrappings
  - photomultipliers (QE)
  - optical coupling materials
  - refractive index of optical materials



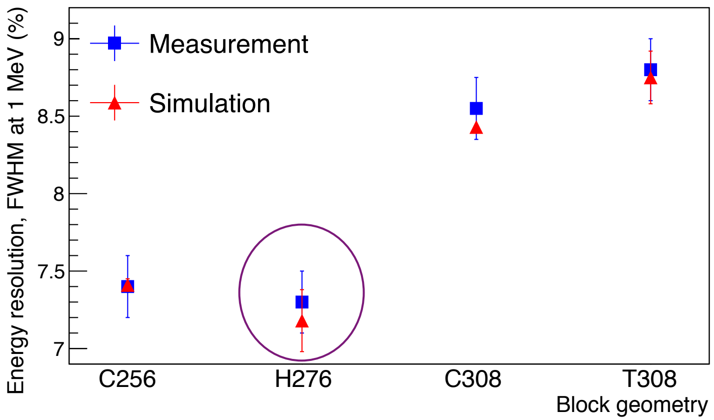




- For further details see: "Spectral modeling of scintillator for the NEMO-3 and SuperNEMO detectors" https://doi.org/10.1016/j.nima.2010.09.027

Calorimeter R&D: Scintillators

- Block shape studies:



C256: cubic 256^2 x 190 mm^2
H276: hexagonal 276 mm diameter with 12 mm minimum depth
C308: cubic 308^2 x 190mm^2
T308: cubic 308^2 x 190mm^2 with tapered sides

- Material: polystyrene (PST) vs. polyvinyl toluene (PVT)

Material	$\Delta E/E(\%)$	f_{FWHM}
JINR NEMO-3 PS	8.9 ± 0.2	1
Eljen-200 PVT	8.3 ± 0.2	1.07 ± 0.03
Eljen-204 PVT	7.8 ± 0.2	1.14 ± 0.03

Material	$\Delta E/E(\%)$	f_{FWHM}
NUVIA PS	7.9 ± 0.2	1
Enhanced NUVIA PS	7.6 ± 0.2	1.04 ± 0.03

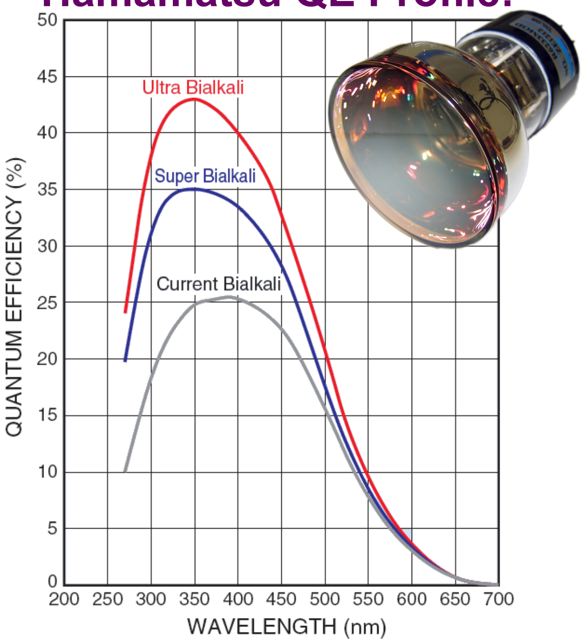
- Close collaboration with manufacturers (JINR Dubna, ISM Kharkiv, NUVIA, ELJEN) for contents of:
  - PPO scintillating agent
  - POPOP wavelength shifter

- Surface finishing: polished vs. depolished
  - All surfaces depolished (machine finish), with the face with the hemispherical cutout polished

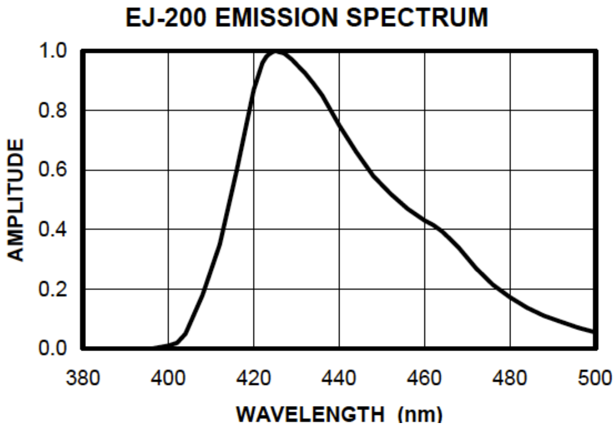
Calorimeter R&D: PMTs (1)

- Photocathode QE:

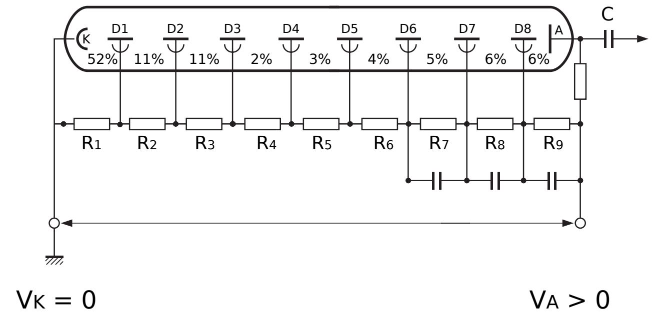
Hamamatsu QE Profile:



  - Bi-alkali alloy development for photocathode material has achieved QE > 40%
  - Selection of PMT to optimise QE to the emission spectra of the scintillator

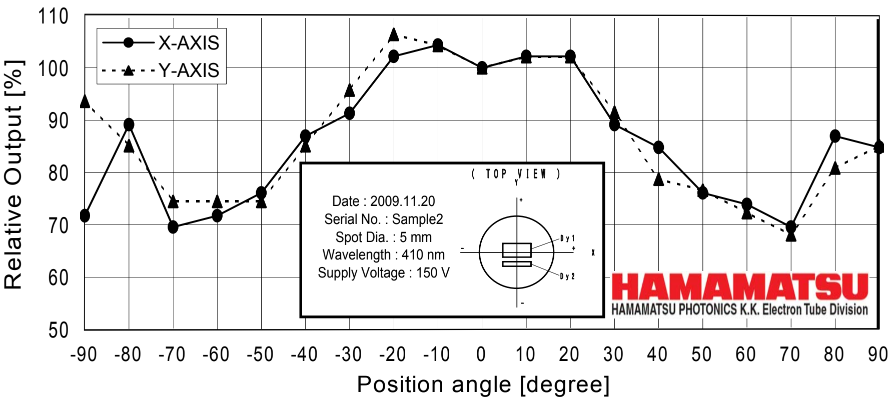


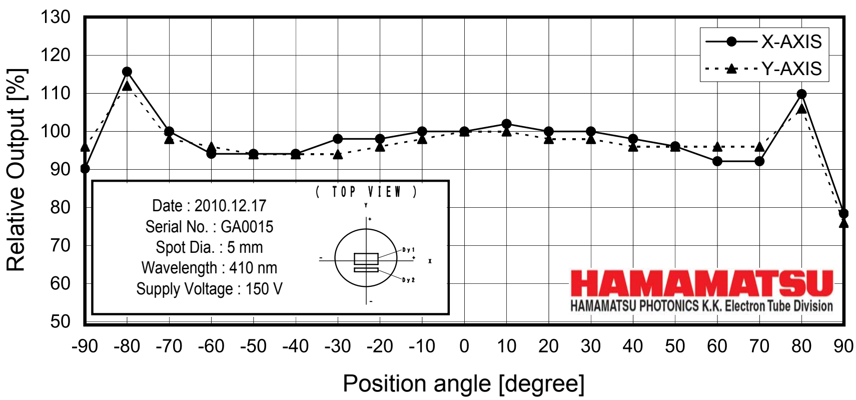
- Collection efficiency (close collaboration with Hamamatsu on 8” R5912-MOD tube):
  - Number of dynode stages reduced from 10 to 8
  - Voltage divider optimisation
  - Improved from <70% to ~80%



Calorimeter R&D: PMTs (2)

- Photocathode uniformity:
  - Close collaboration with Hamamatsu to improve photocathode uniformity across the entire surface of the R5912-MOD PMT

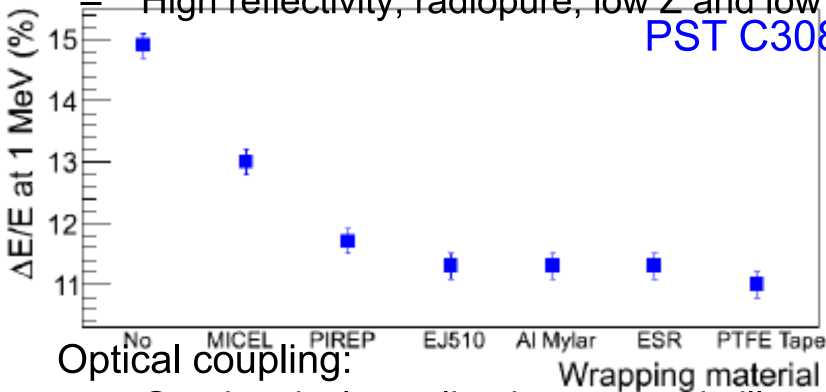


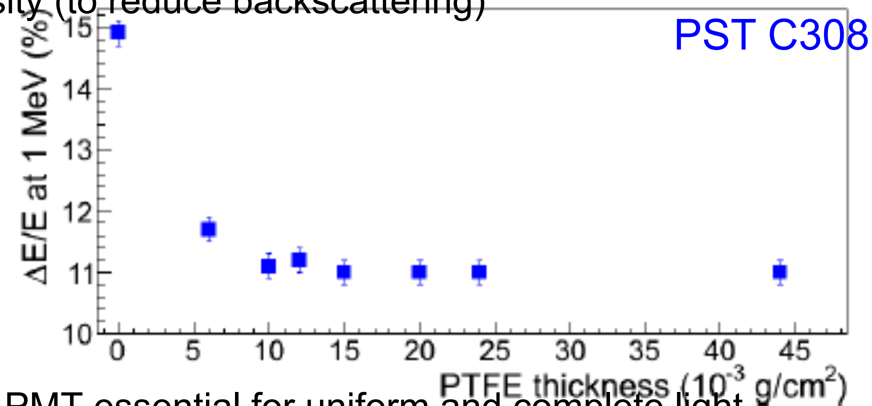


- Timing:
  - Reducing the number of dynode stages improves the timing of the PMT by reducing the time transition spread (TTS)
- Gain and Linearity (a big achievement!):
  - Reducing the number of dynode stages and optimising the voltage divider decreases the gain: ~1 x 10^5
    → Good linearity (< 2% for very high light levels – 50 mA peak current) whilst good gain of the 1^{st} dynode and therefore high collection efficiency

Reflective Material & Coupling

- Reflective material:
  - High reflectivity, radiopure, low Z and low density (to reduce backscattering)





- Optical coupling:
  - Good optical coupling between scintillator and PMT essential for uniform and complete light collection
  - Direct co… in energy resolutio…

Optical Material	Refractive Index	$\Delta E/E(\%)$	f_{FWHM}
Isopropanol alcohol	1.37	9.4 ± 0.2	1
Cargille gel	1.46	8.6 ± 0.2	1.09 ± 0.04
Cargille gel	1.52	8.4 ± 0.2	1.12 ± 0.04
RTV 615	1.41	9.4 ± 0.2	1.00 ± 0.03

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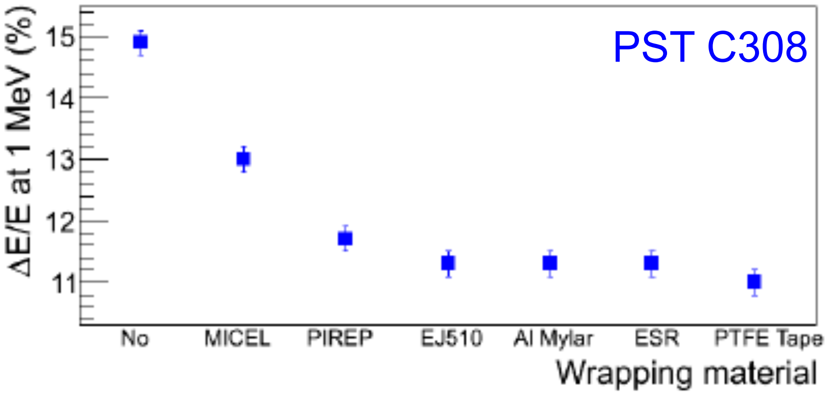

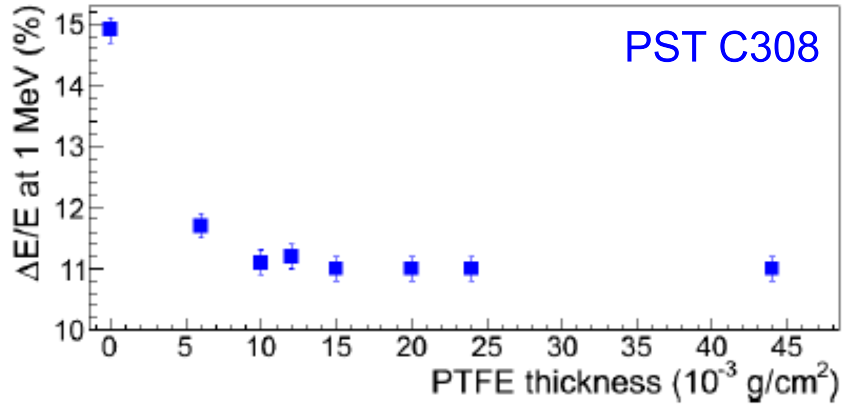

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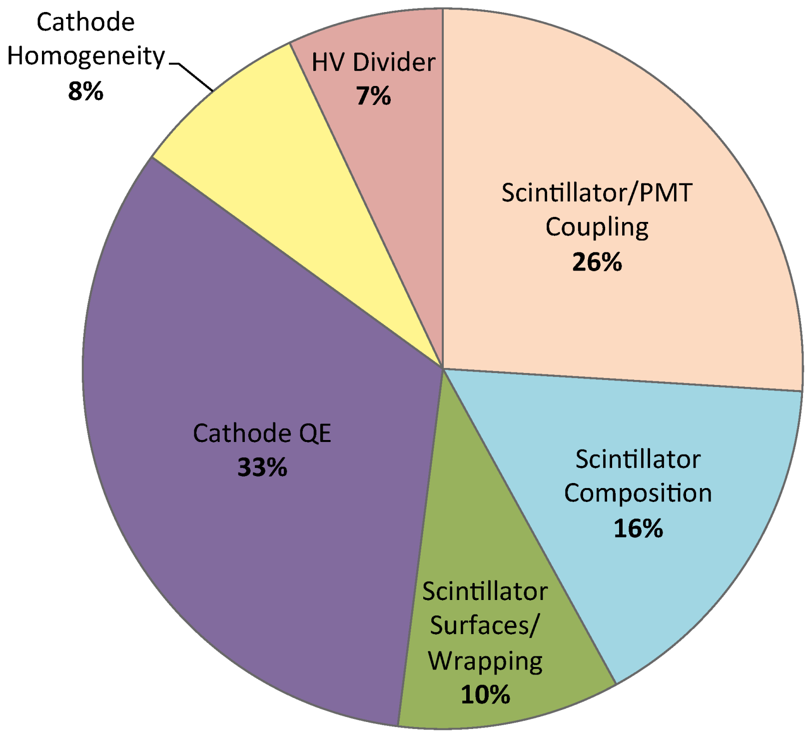
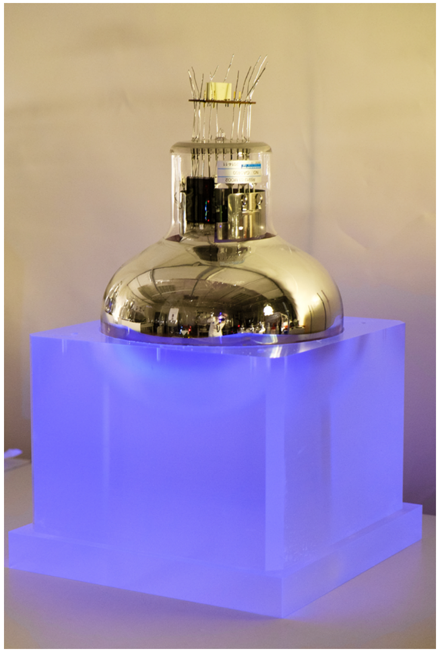
  - Direct coupling of PMT to hemispherical cutout in scintillator gave the biggest impact in energy resolution improvement.

Calorimeter R&D: Summary

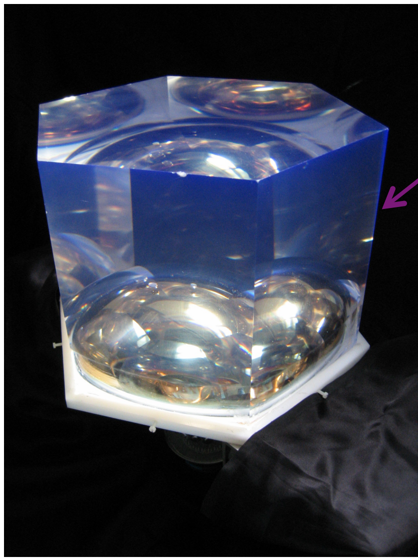




- For further details, see:

"Calorimeter development for the SuperNEMO double beta decay experiment"
https://doi.org/10.1016/j.nima.2017.06.044

Optimised Optical Module Design



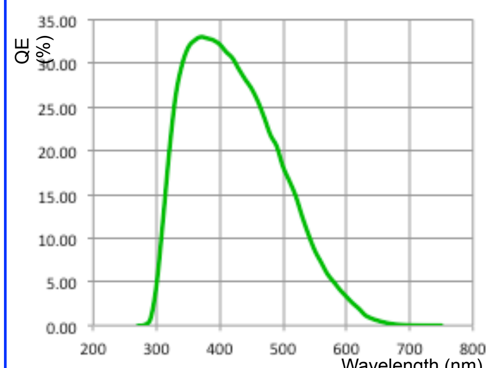
$$\frac{3.2\%(\sigma)}{\sqrt{E(MeV)}}$$

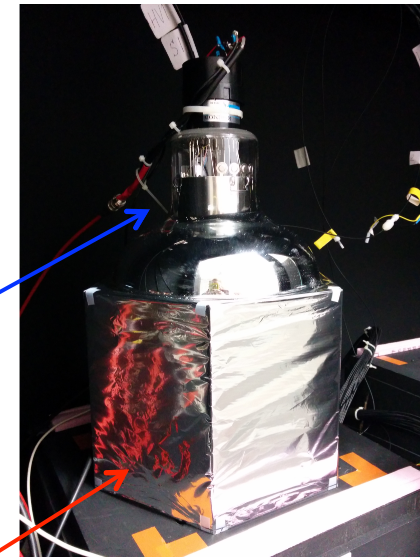
EJ-200 hexagonal PVT block:

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

What About Proton Therapy…?

- With this fantastic energy resolution of 3.2% σ at 1 MeV can we apply the SuperNEMO optical module technology to proton therapy beam monitoring and proton imaging?

  - **Challenges**: from SuperNEMO (electrons) to a proton beam

- Very high intensity of events at a proton beam (~10 GHz):
  - Random number of protons per bucket from beam, we require 1 proton per bucket
  - Pile up!

- 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

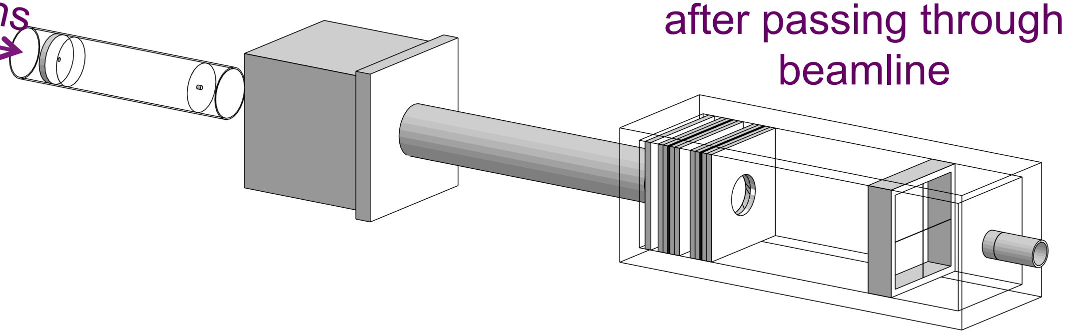
- Energy range:
  - SuperNEMO optimised for electrons from 0.5 – 4 MeV for double beta decay
  - For proton therapy we require ~O(100 MeV)

Step 1: Geant4 Simulations

- A 60 MeV proton beam simulated, positioned 30 cm before the entrance face of the scintillator block
  - Proton beam has been run through the Clatterbridge beamline
- Scintillator geometry and 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 3.2% σ at 1MeV).

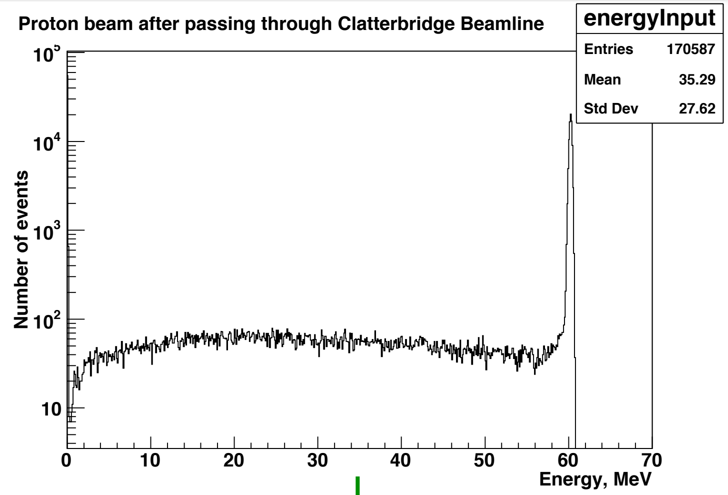
Step 1: Geant4 Simulations

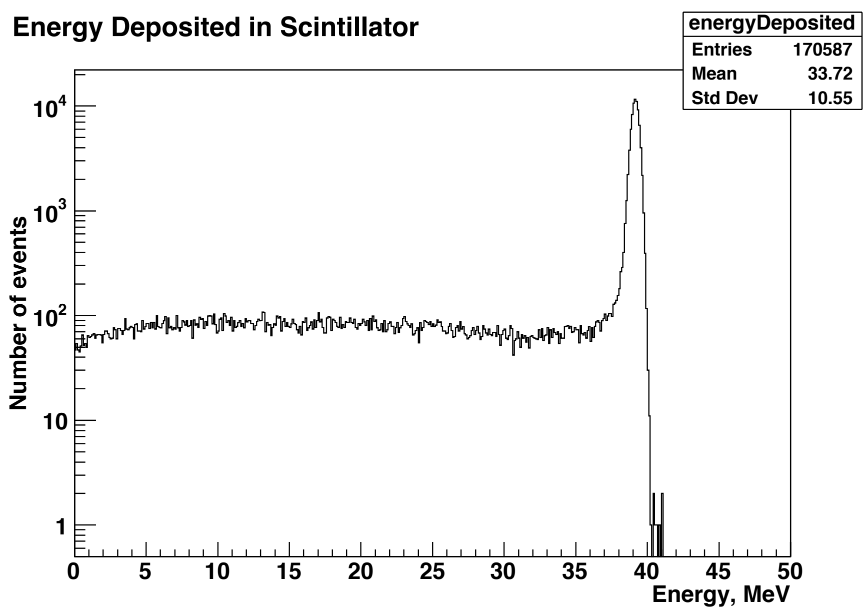
protons



resulting proton beam

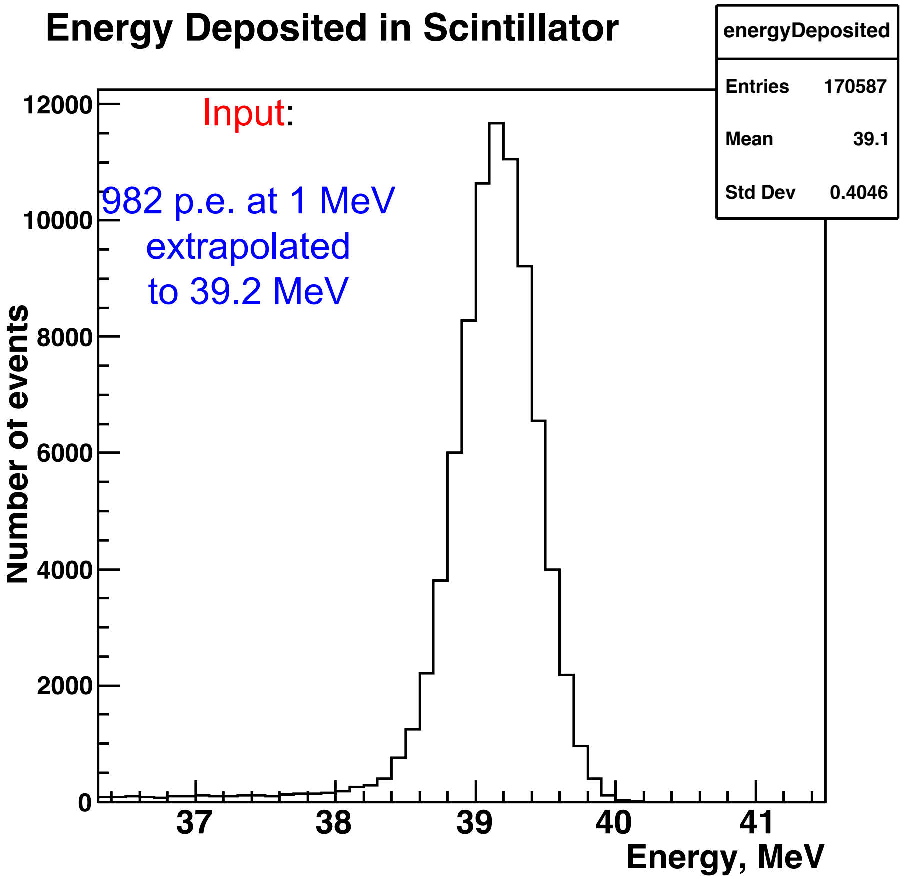
after passing through beamline

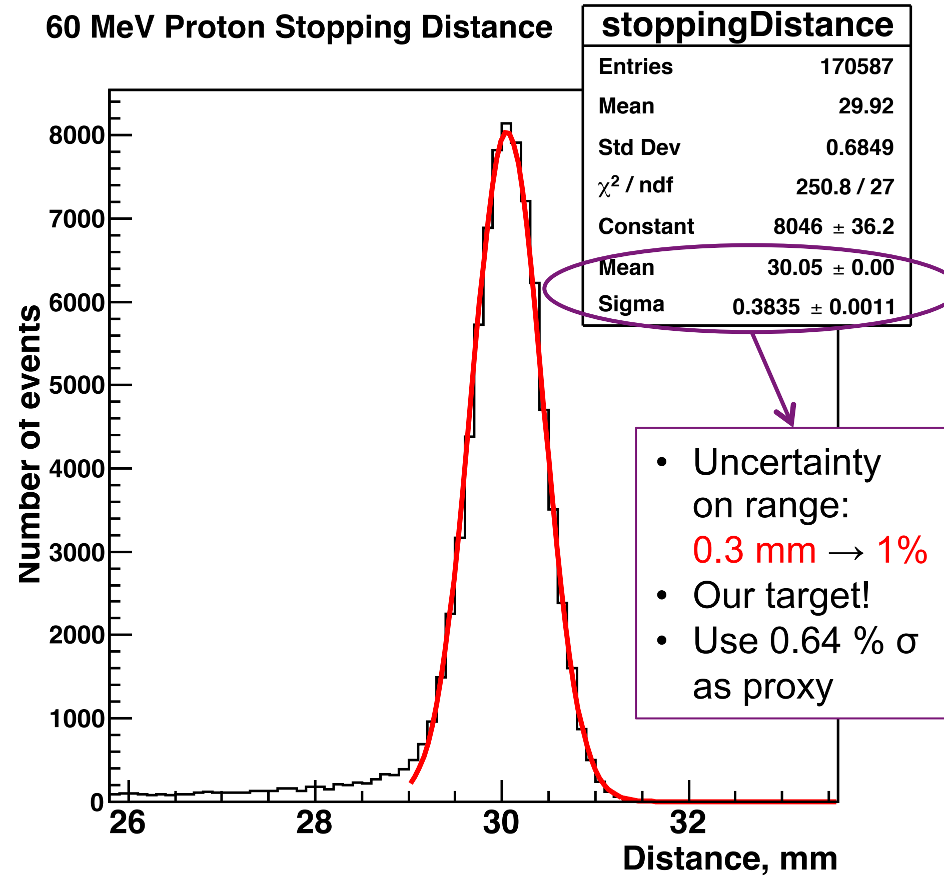




Energy deposited in scintillator after beam passes through detector

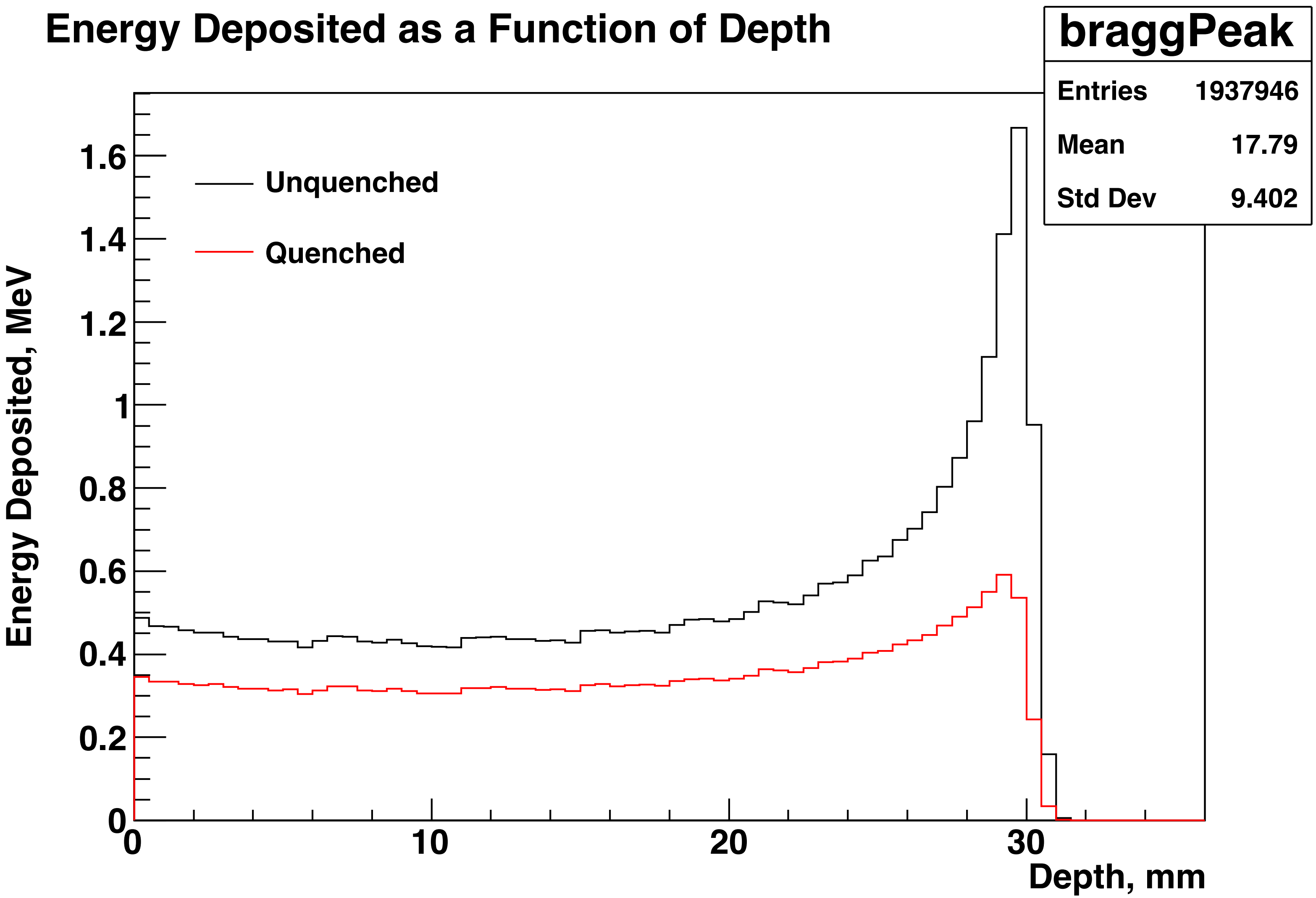
Step 1: Geant4 Simulations





- Quenching from simulations:
  - Simulated mean: 39.2 MeV
  - Quenching: 35% for 60 MeV protons
- Energy resolution from simulations:
  - σ: 0.252, μ: 39.21
  - **σ/E: 0.64 % σ**

Step 1: Geant4 Simulations



60 MeV protons range out at 30 mm in the scintillator

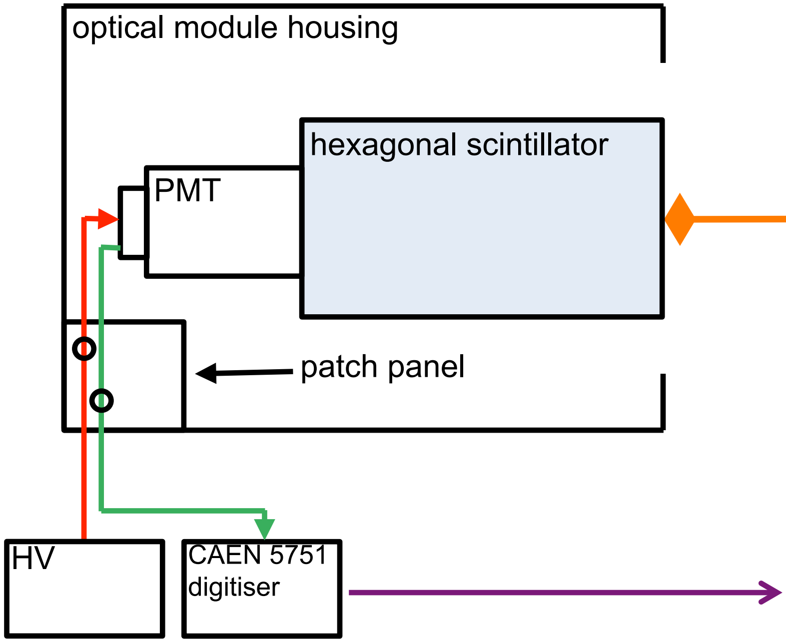
Simulated Stopping Distance

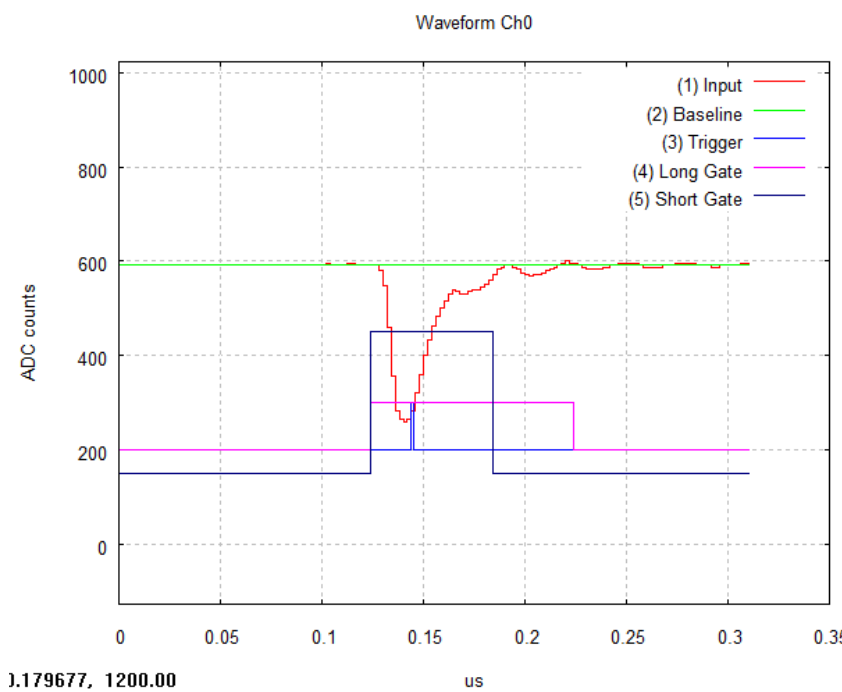
- Simulations of SuperNEMO scintillator vs Water Equivalent:

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

- PolyVinyl Toluene is "water equivalent" for stopping distance and spread, as is Polystyrene.
- One to one conversion for water phantoms.
- We can take advantage of this for range QA measurements: water equivalent + high light output + excellent energy resolution

Step 2: Equipment Setup



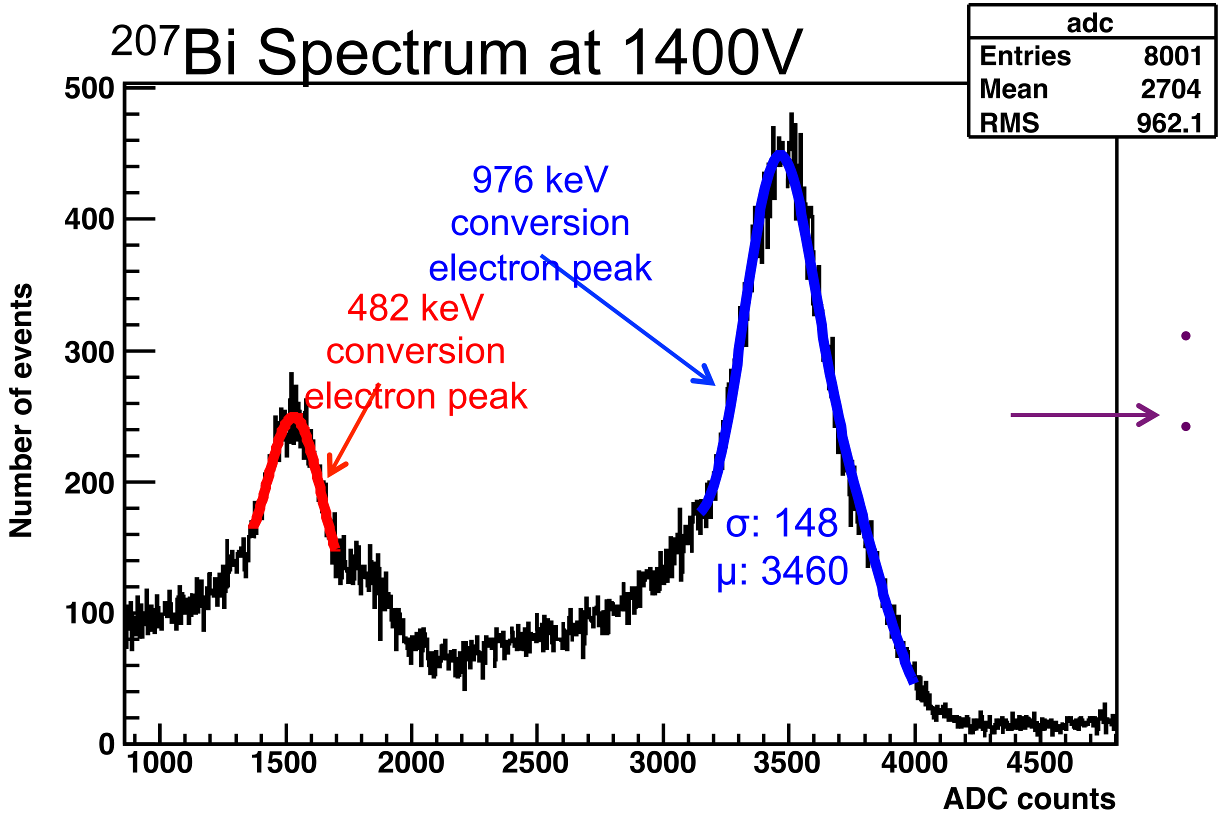


CAEN DT5751 Digitiser:

Dual-gate signal integration
→ Pulse shape analysis
→ Neutron/gamma discrimination

Step 3: ^{207}Bi Test at UCL

- Optical module resurrected after some years: re-measure energy resolution!
  - New test bench at UCL: a thin scintillator introduced into set up, which triggers DAQ only when an electron passes through it
  - → Gammas removed, fit simplified to triple Gaussian of 976 keV and 482 keV peaks



After:
- correction for energy lost in thin scintillator
- conversion to MeV

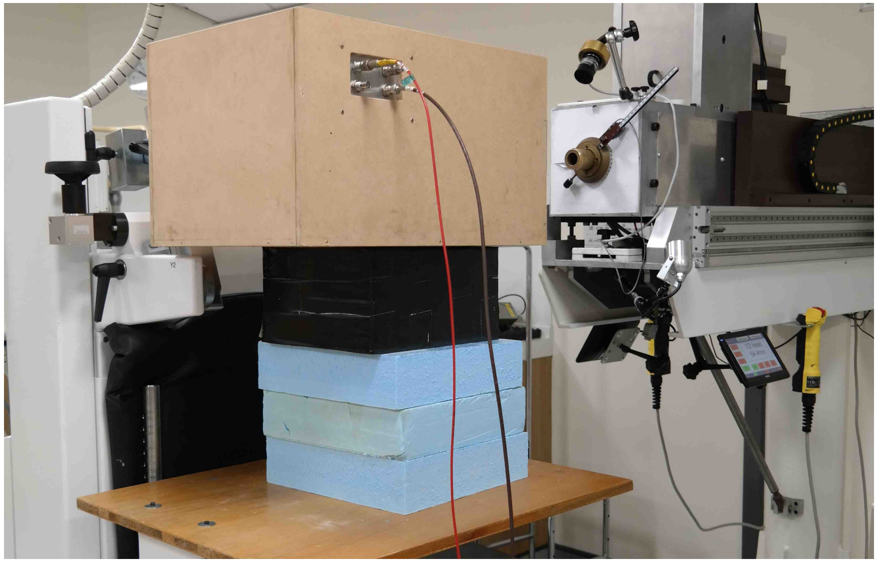
σ/E: **3.6 ± 0.2 % σ** at 1 MeV

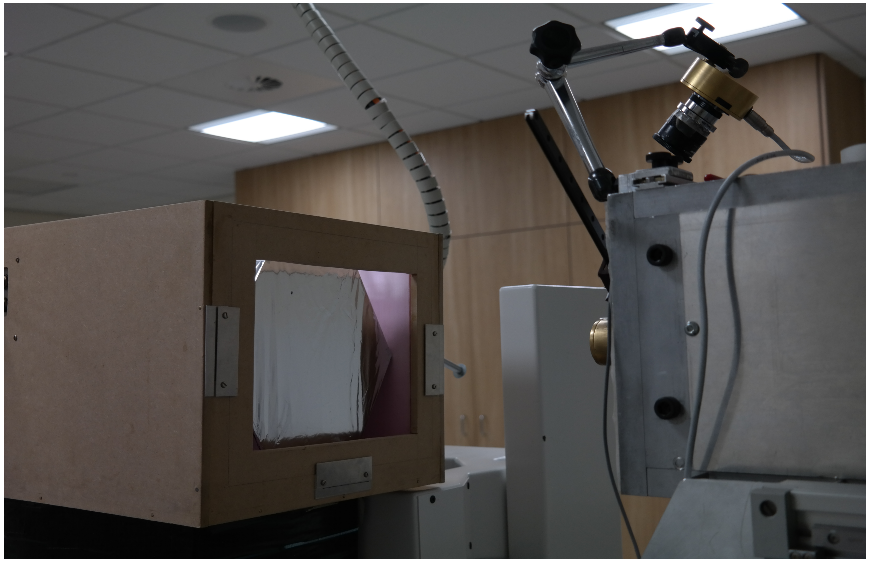
Step 4: Clatterbridge Cancer Centre

- 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…).

Step 4: Clatterbridge Cancer Centre

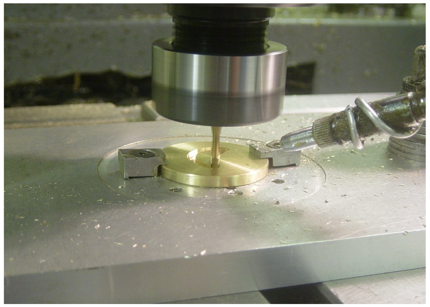




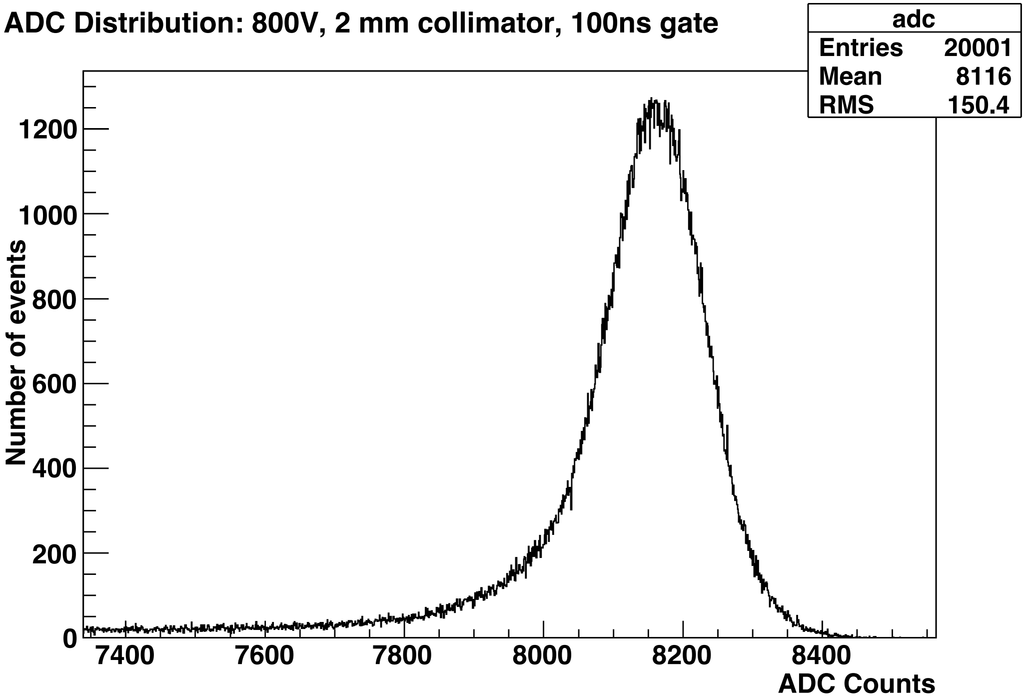
Step 4: Clatterbridge Cancer Centre

Step 4: Clatterbridge Cancer Centre

- The proton rate from the beam was carefully controlled by
  - Inserting brass collimators with varying diameters (0.5 mm – 10 mm) into the beam nozzle (~30 cm upstream of the optical module)
  - Adjustment of the ion source gas supply
  - Adjustment of the ion source discharge current

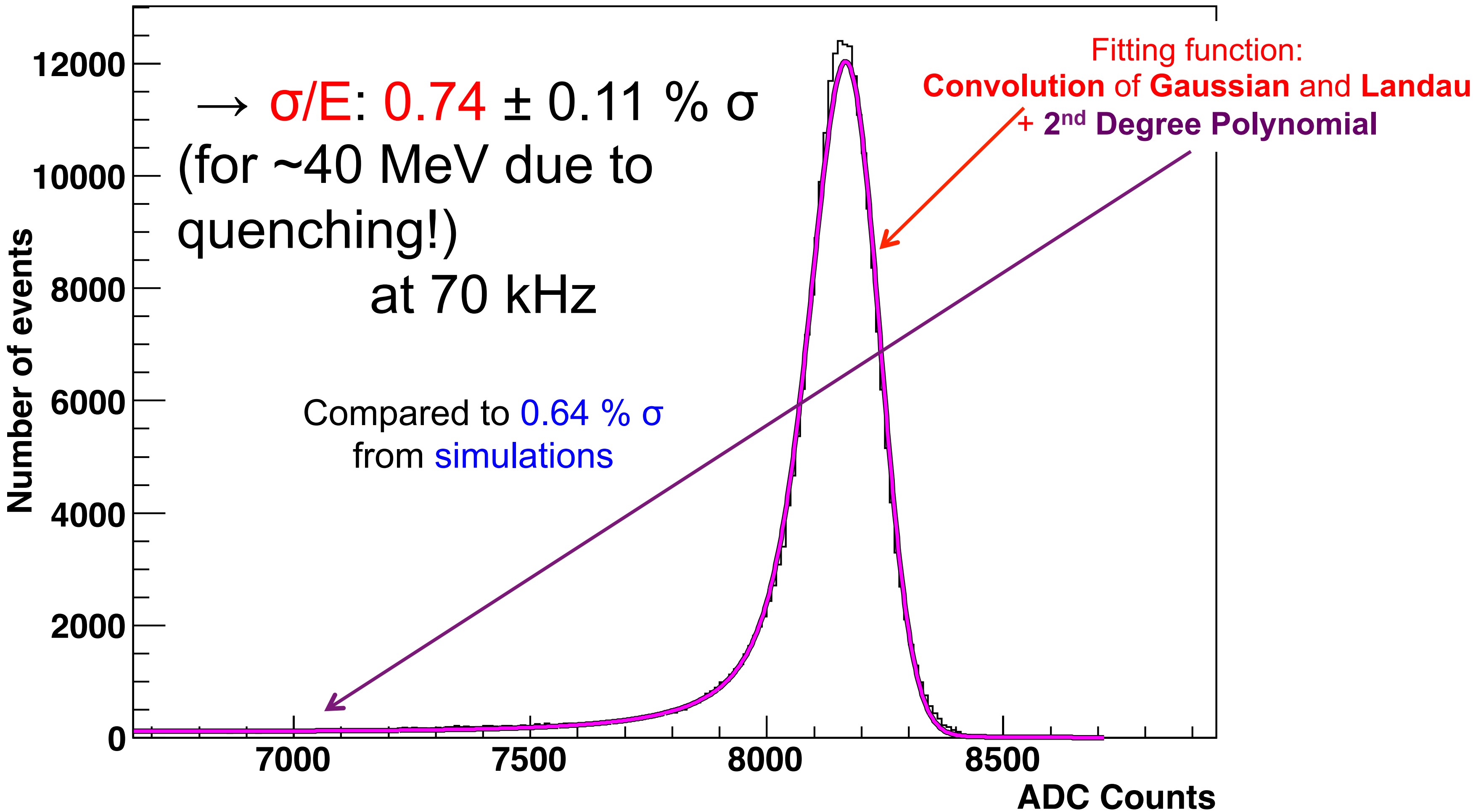


- Resulting distribution:

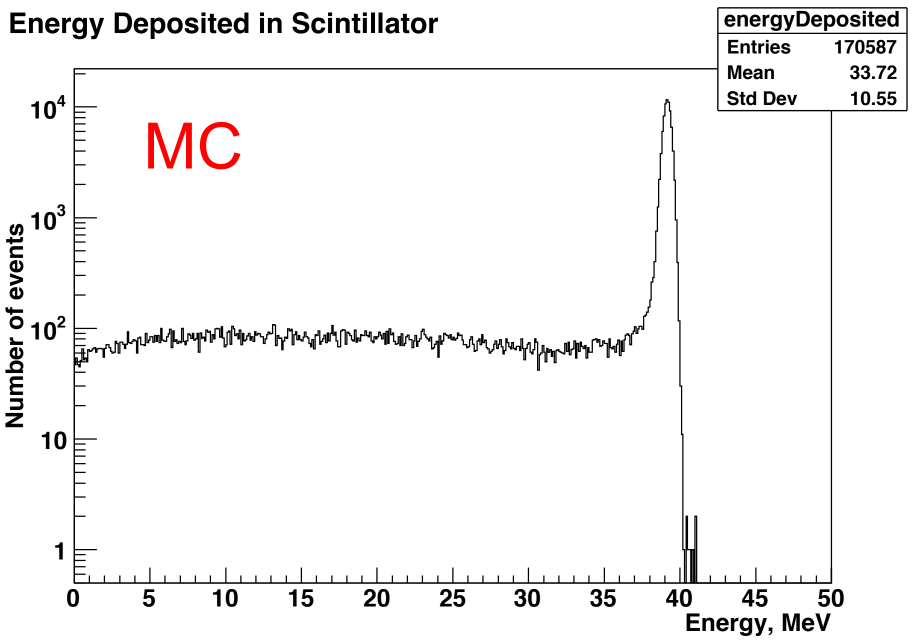


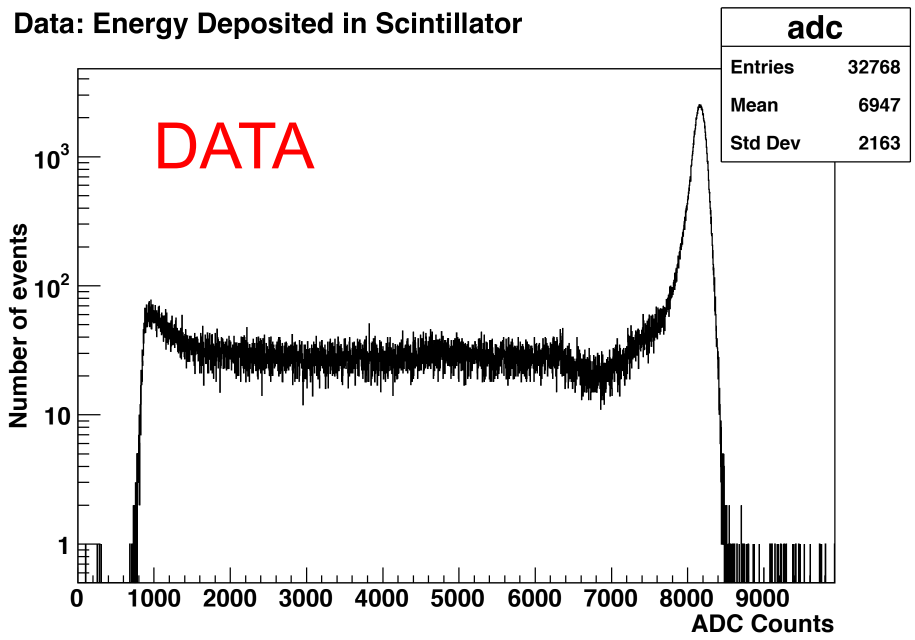
Step 4: Clatterbridge Cancer Centre

ADC Distribution: 800 V, 2 mm collimator, 100 ns gate



Step 4: Clatterbridge Cancer Centre





- Our simulations accurately represent our data!

Step 5: Smaller and Faster

- We have already achieved the target energy resolution: 0.7 % σ
- But, at rates > 250 kHz we start to see pile up

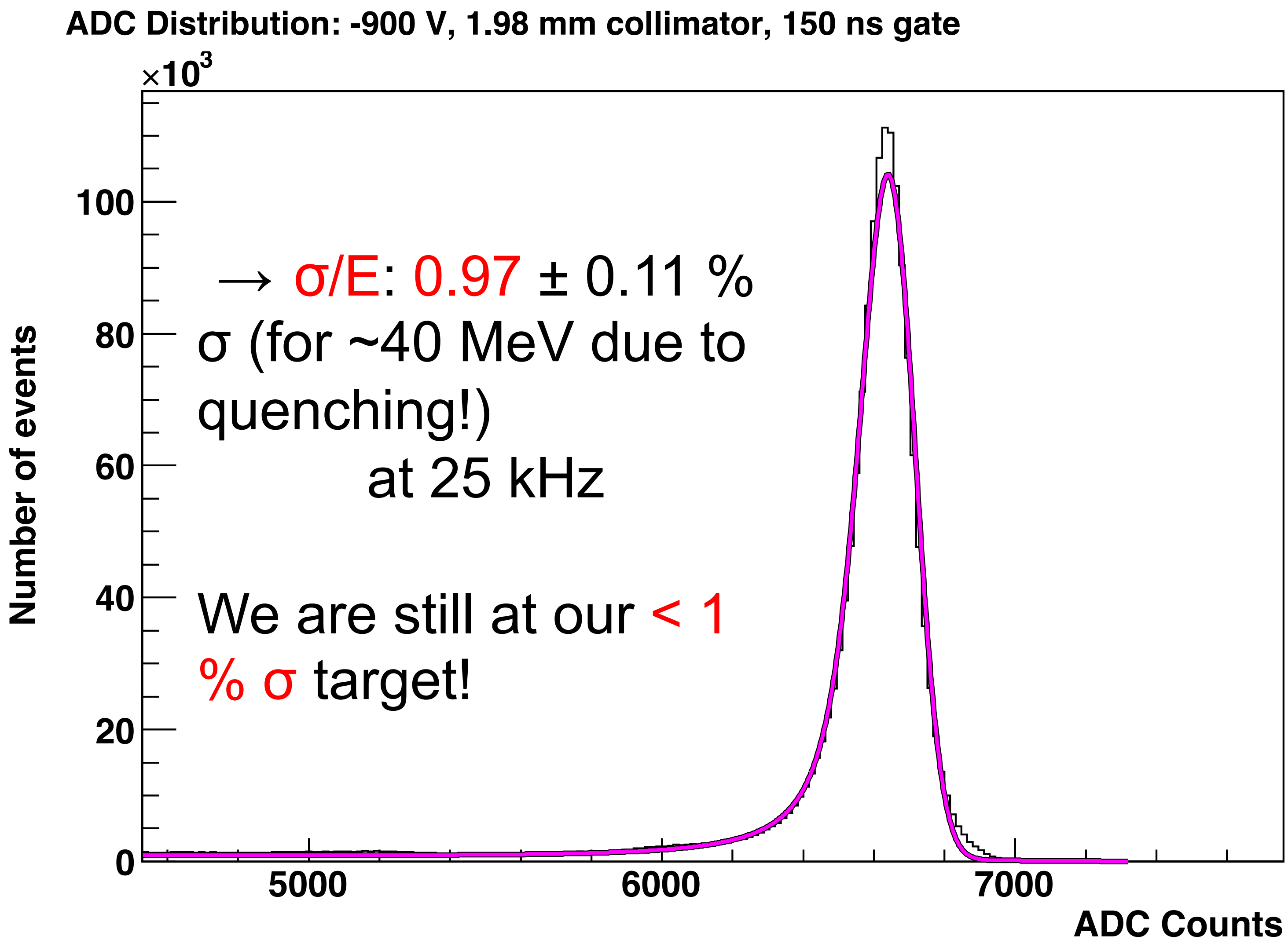
- The next step is to do this for very high rates of 1–10 MHz with a compact design:
  - Reduce the size of the PMT and the scintillator to improve timing and make the design nozzle-mountable
  - -VE HV PMT base to remove decoupling capacitor (not fast enough discharge)

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

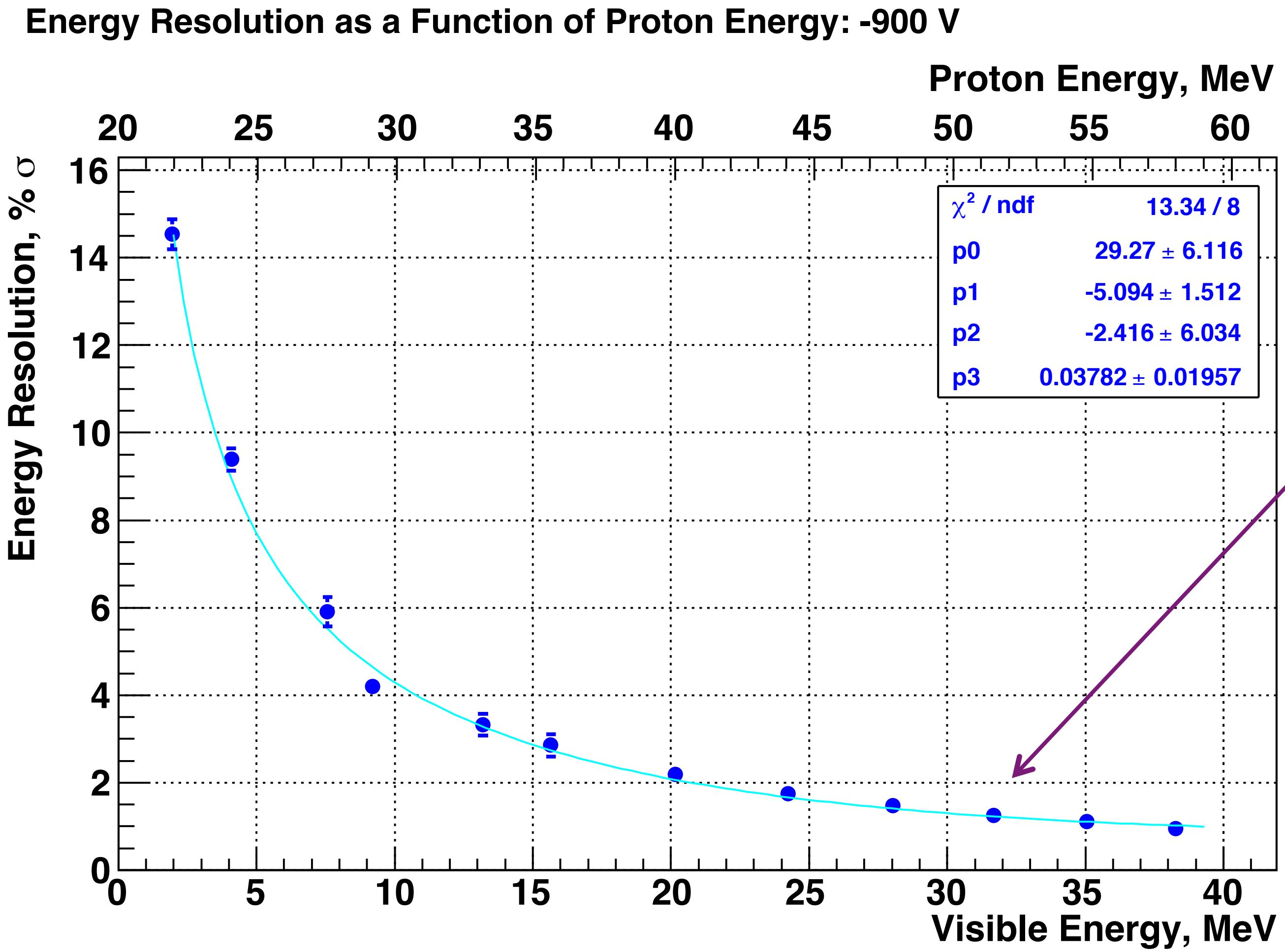
- Coupled with BC-630 Saint Gobain silicone optical gel
- Wrapped in 75 μm of PTFE (Teflon) ribbon on the sides and 12 μm of Mylar on the sides and entrance face

Step 5: Smaller and Faster



Resolution Dependence on Energy

- 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!

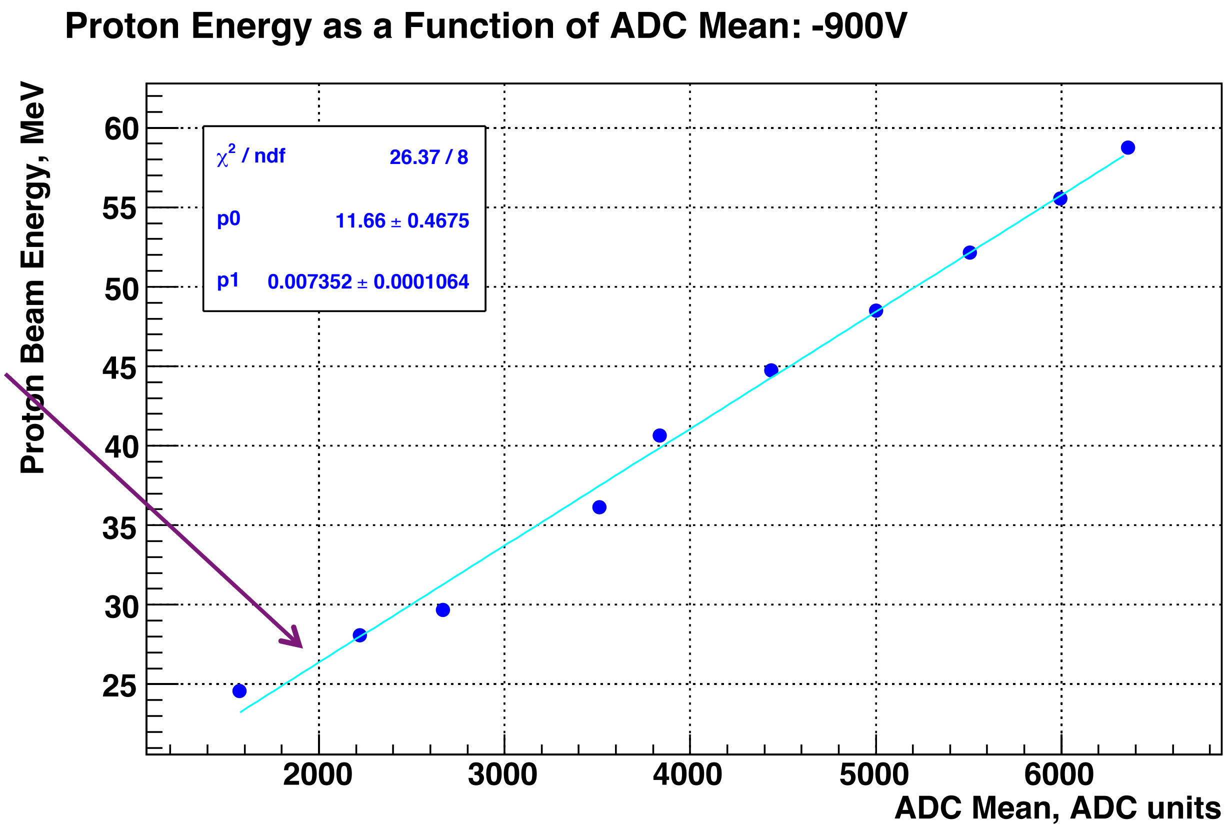
Linearity (-900 V)

- 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

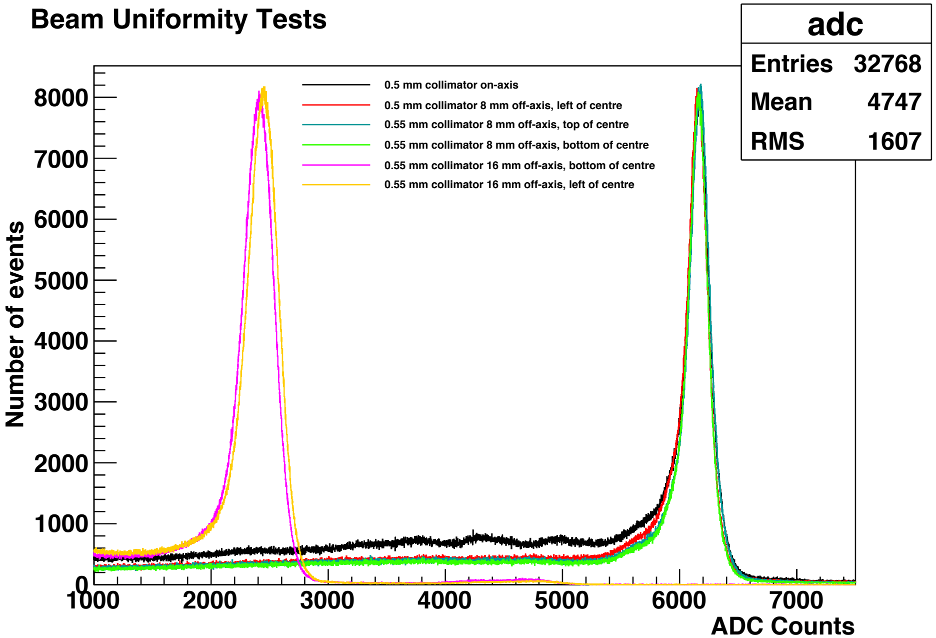
$$y = p0 + (p1 \cdot x)$$

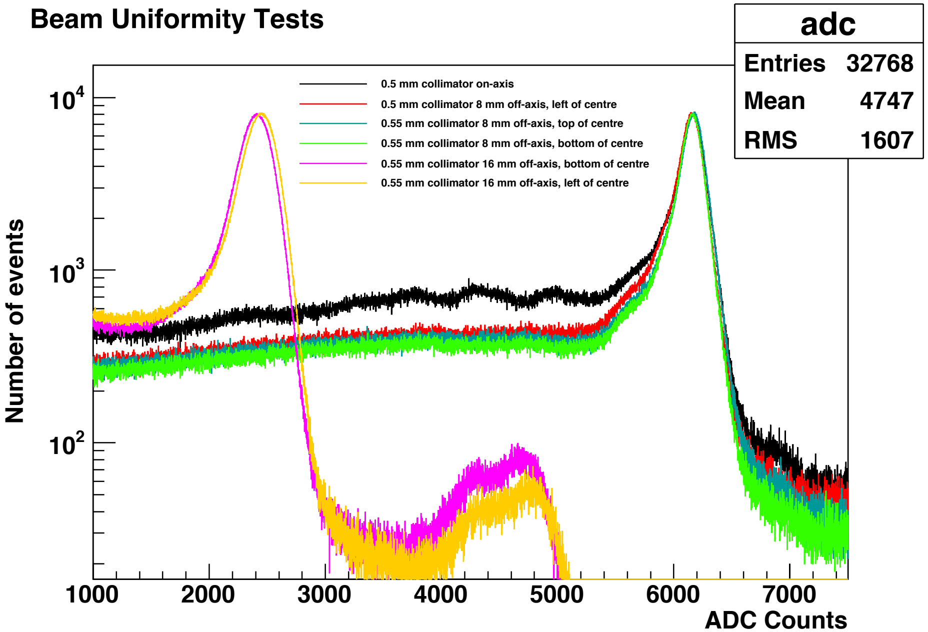
For - 900V: Deviation from linearity < 2%!



Clatterbridge Beam Uniformity

- 0.5 mm Ø collimator

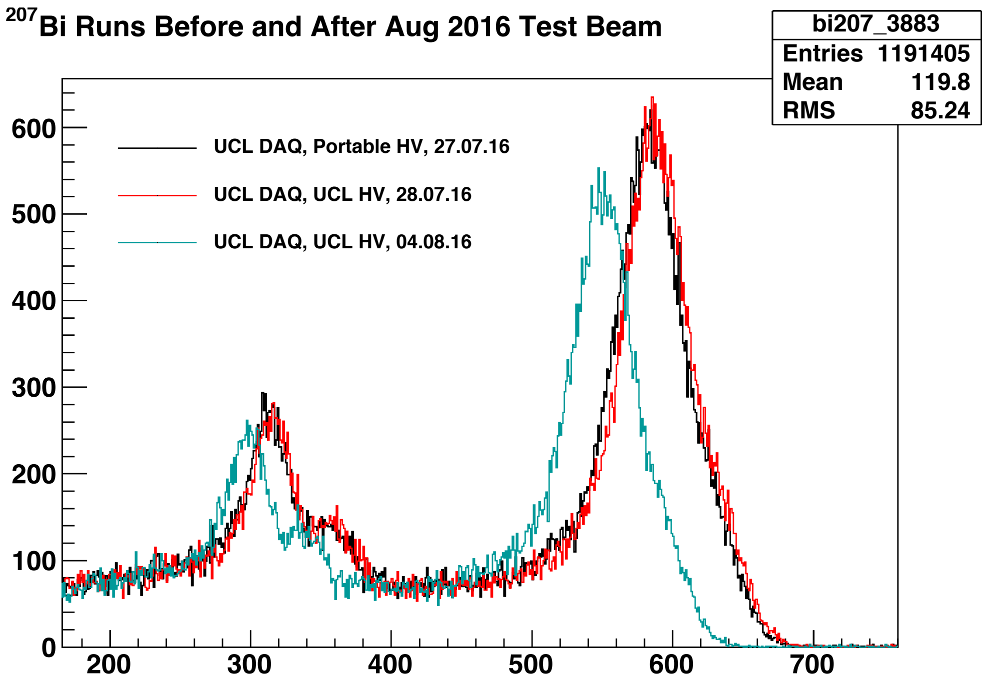




- Uniform 8 mm away from the centre
- 16 mm away from the centre is 1mm away from the beam edge
  - Currently trying to understand these edge effects
- Okay to use collimators to reduce rates!

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.

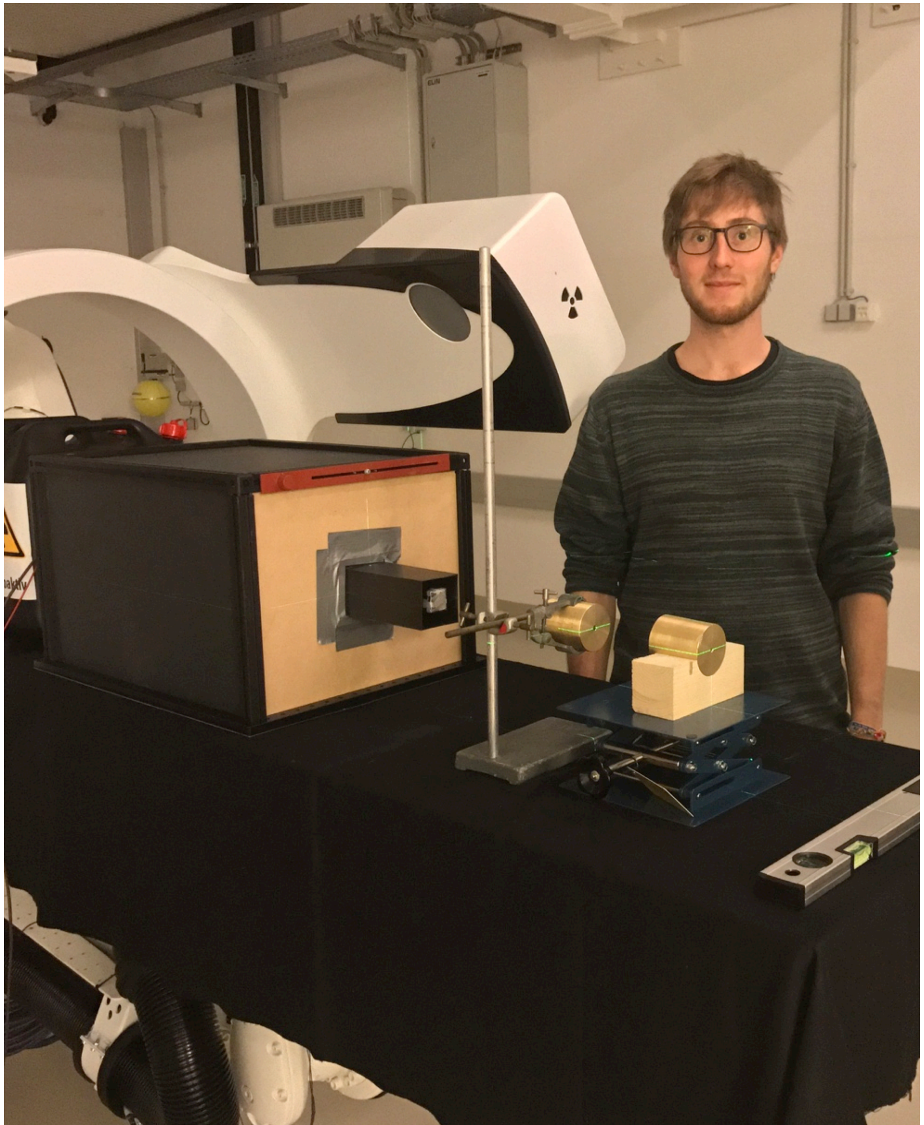
MedAustron 250 MeV Tests

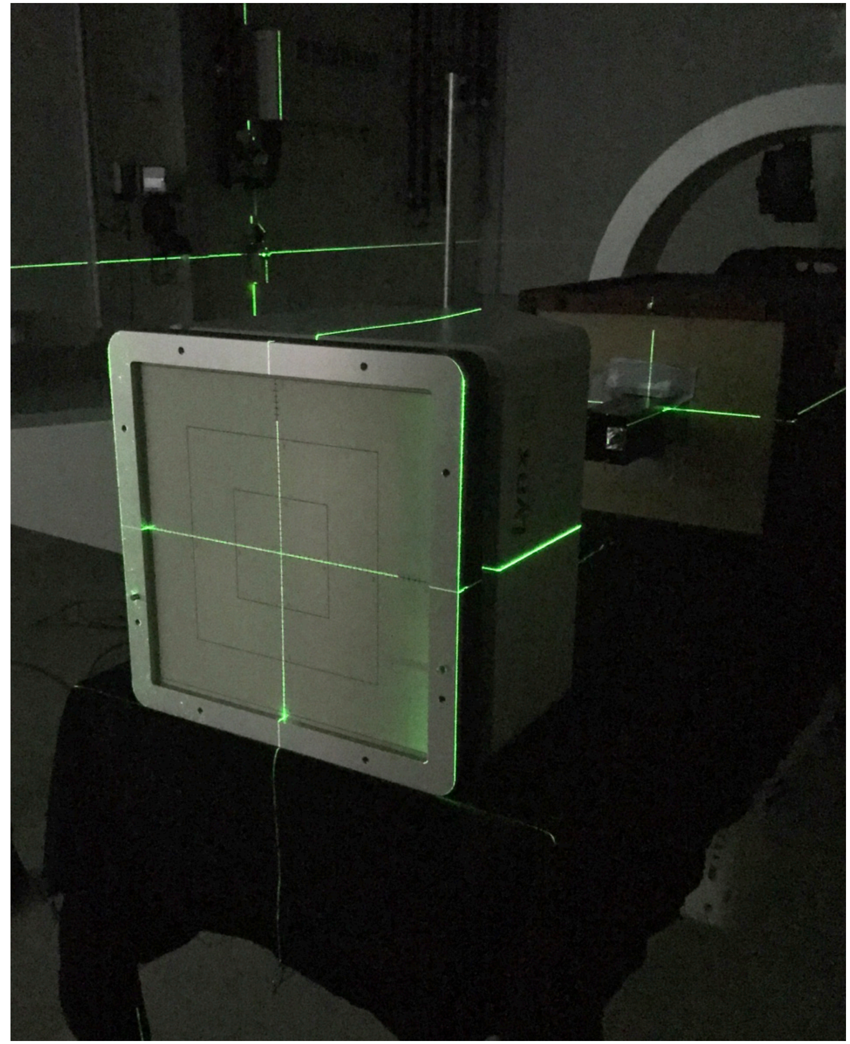
- Having tested detector at 60 MeV, needed to make high energy test to examine performance and test linearity:
  - Longer, 40 cm scintillator block to absorb 250 MeV protons.

  - Same PMT and readout.

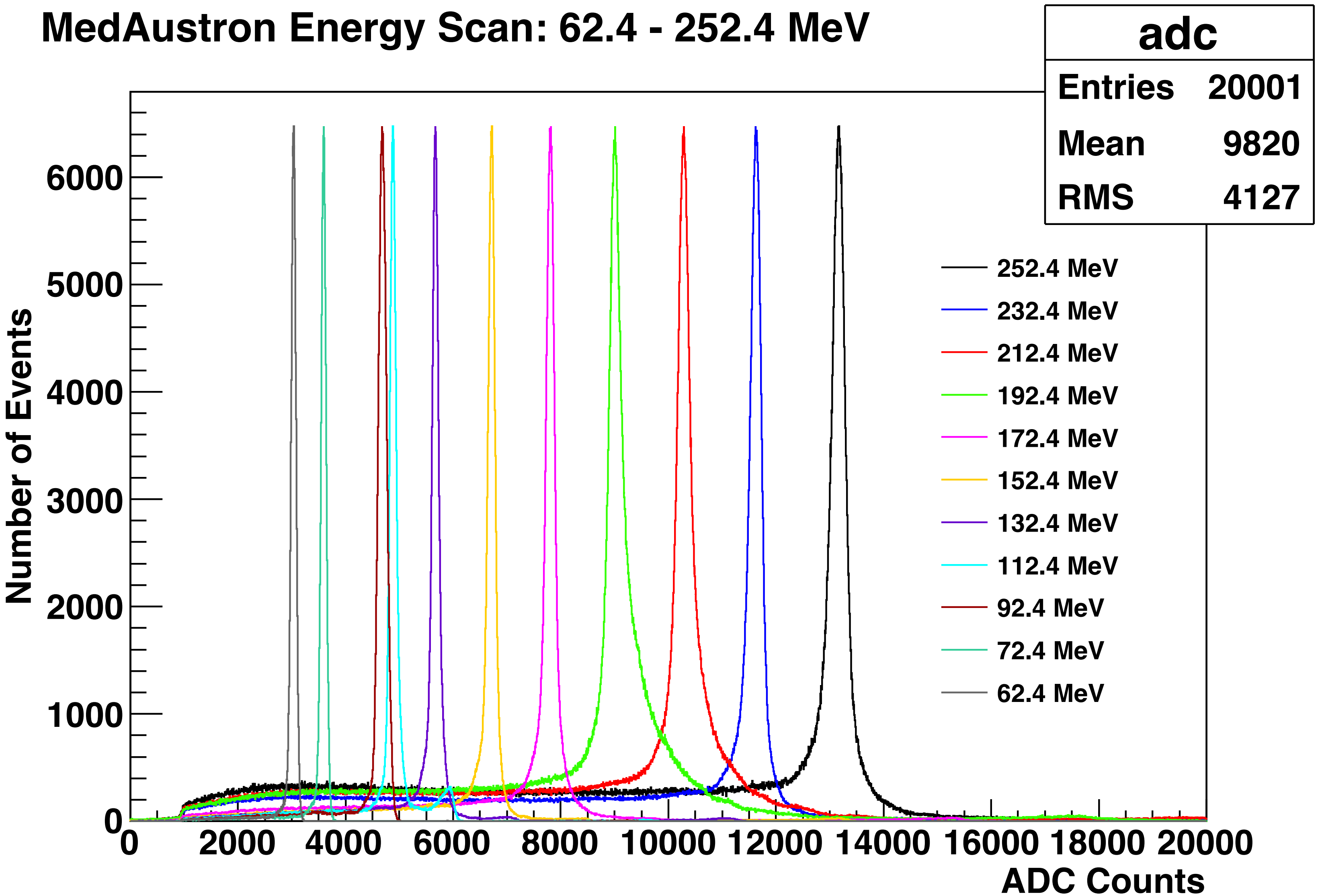
- Through OMA, MedAustron offered us 2 nights of beam tests:
  - 62 MeV up to 252 MeV.
  - Able to drop rate down with chopper adjustment: ran 1 kHz–1 MHz.
  - Custom collimators to reduce intensity and beam size.

MedAustron Setup

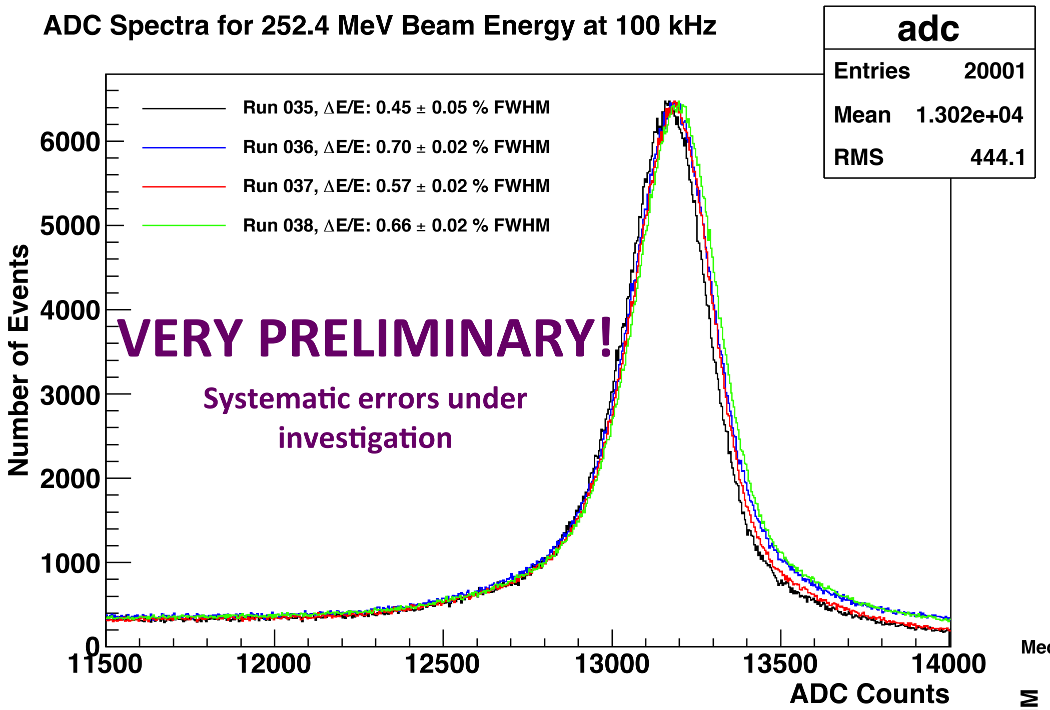




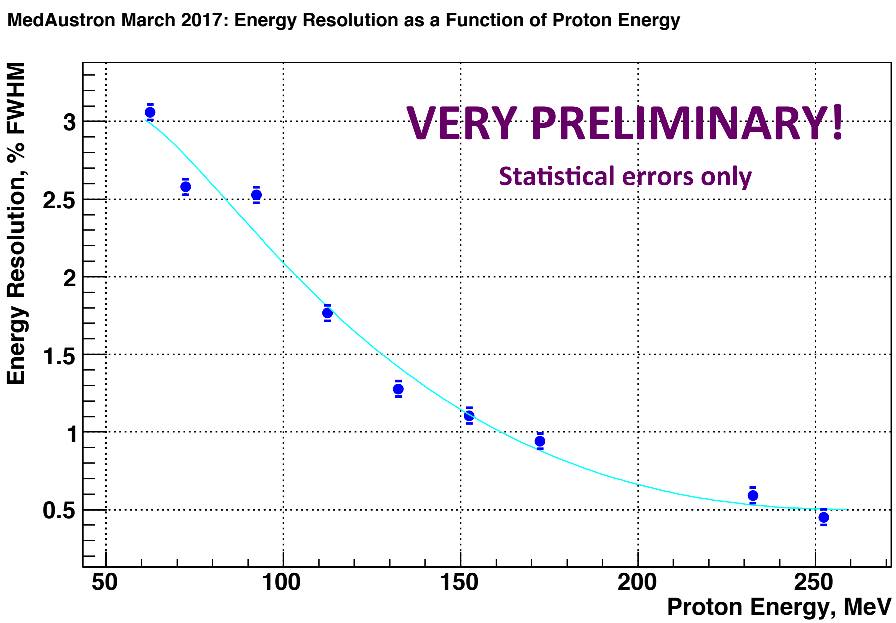
MedAustron Results



MedAustron Results



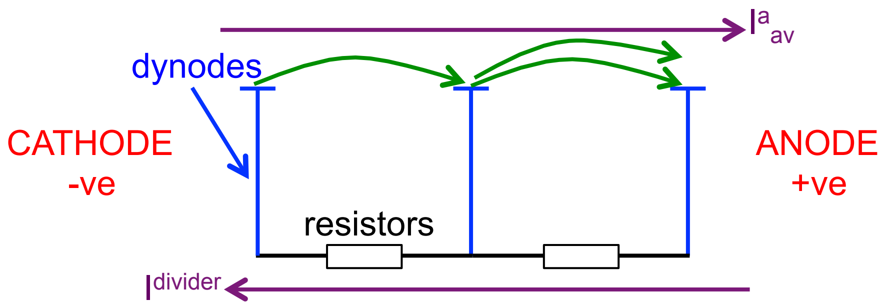
- Still seeing excellent energy resolution up to 252 MeV.
- Best resolution 0.2% σ.
- But also still seeing rate issues:
  - PMT current limit from too much light!
  - Detector not fast enough for 10^{10} p/s clinical rate.



- In close collaboration with Hamamatsu to develop a new kind of light detector:
  - High QE (photocathode) of PMT
  - Lower gain of 10^3.
  - Low noise.
  - Have carried out experiments with a range of bases.

PMT Currents

- When considering a PMT, there are two main currents to consider:
  - The DC current running through the resistor chain, $I^{divider}$ (also know as the "bleeder" current).
- The average anode current, I^{a}_{av}, which is the current caused by the avalanche of electrons and travels in the opposite direction to I^{div}.



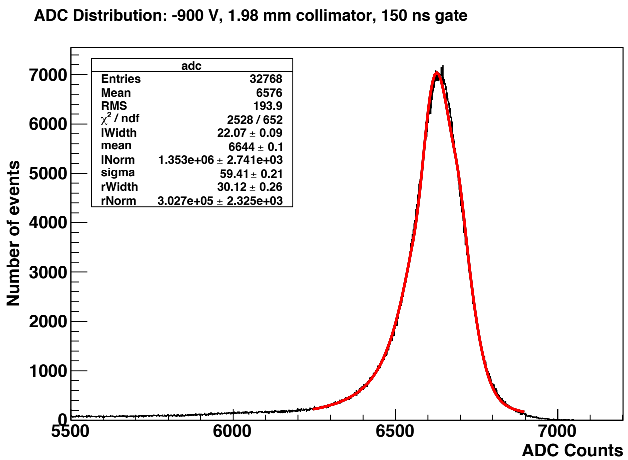
- In order for the PMT to function correctly $I^{a}_{av} << I^{div}$!
- For the R13089-100-11 PMT with the negative Hamamatsu active divider base to function correctly: $I^{a}_{av} < 100\ \mu A$, according to Hamamatsu specifications.
- We are exceeding this as the rate increases, leading to peak current limit: average pulse height drops with rate increase.

Single Module Summary

- An optical module inspired by the SuperNEMO experiment has measured the 60 MeV proton beam at Clatterbridge with an energy resolution of:

0.97 ± 0.11 % σ
(for 40 MeV "visible" energy)

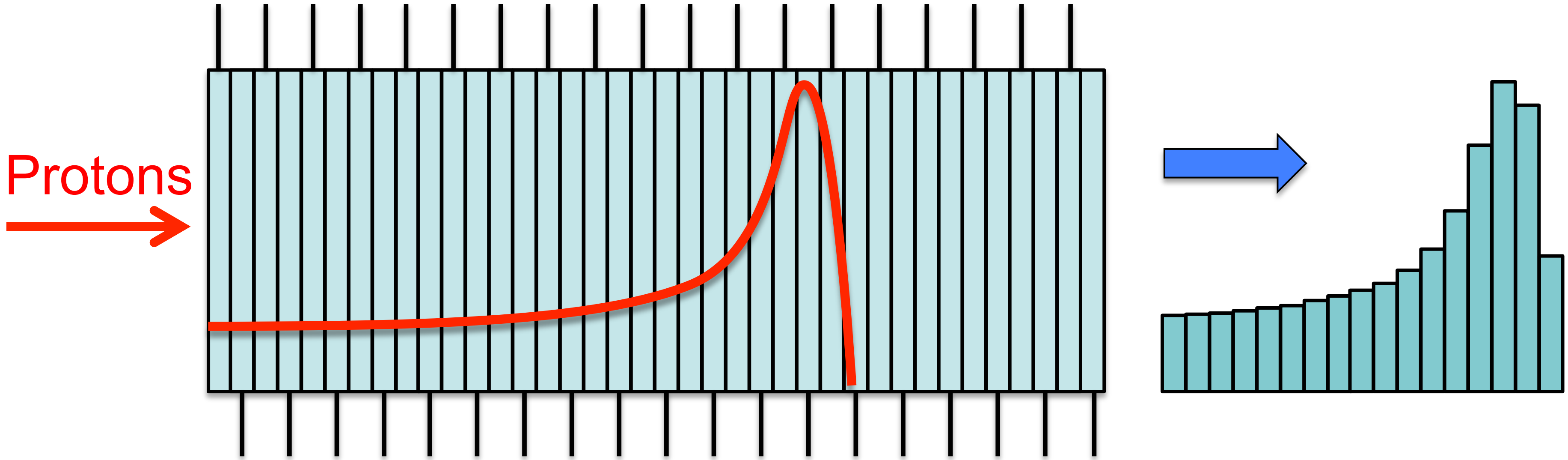
This has reached the target energy resolution of < 1 % σ



- And a 250 MeV proton beam at MedAustron with an energy resolution of 0.2 % σ
- A great result for protonCT
- But this single module isn't fast enough to handle clinical proton rates and therefore is not currently suitable for QA range verification
- Ongoing work to improve timing in collaboration with Hamamatsu
- Goal to reach 10 MHz

⟶ Design a segmented calorimeter to be used as a range telescope!

Segmented Calorimeter



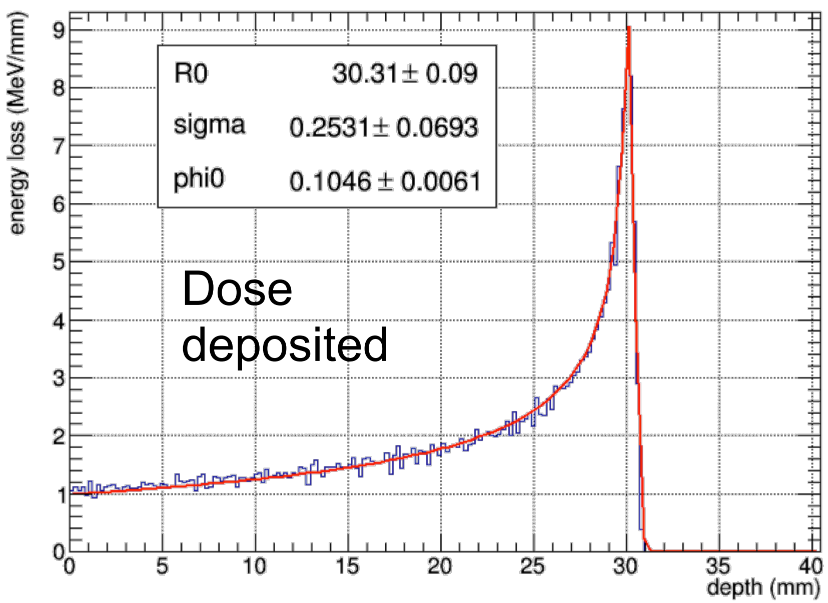
- Segment block into slices and read out light from each slice individually.
- Integrate signal from many protons: very large output from 10^{10}/s.
- Minimum slice width will depend on manufacture: aiming for < 3 mm.
- Use simple, stable light detection: photodiodes/pixel sensors.
- Resolution set by slice width and variation in scintillator light output.
- Light enough to be nozzle-mounted: measurements from multiple gantry angles.

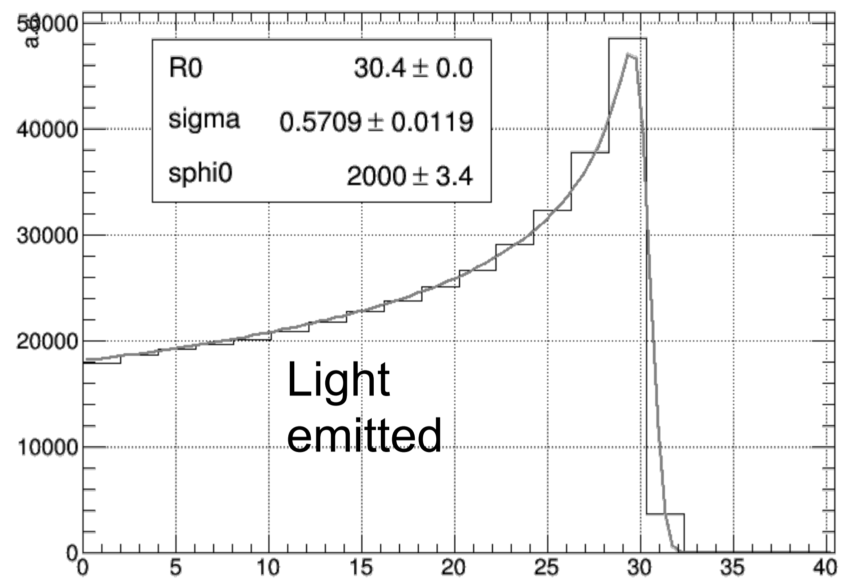
Segmented Calorimeter Design

- Laurent Kelleter has built preliminary model in Geant4:
  - 2 mm slices of plastic scintillator with mylar wrapping.
  - Included quenching in Bortfeld formula: fit to light output.
- STFC IPS grant application 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 with estimate of spread.

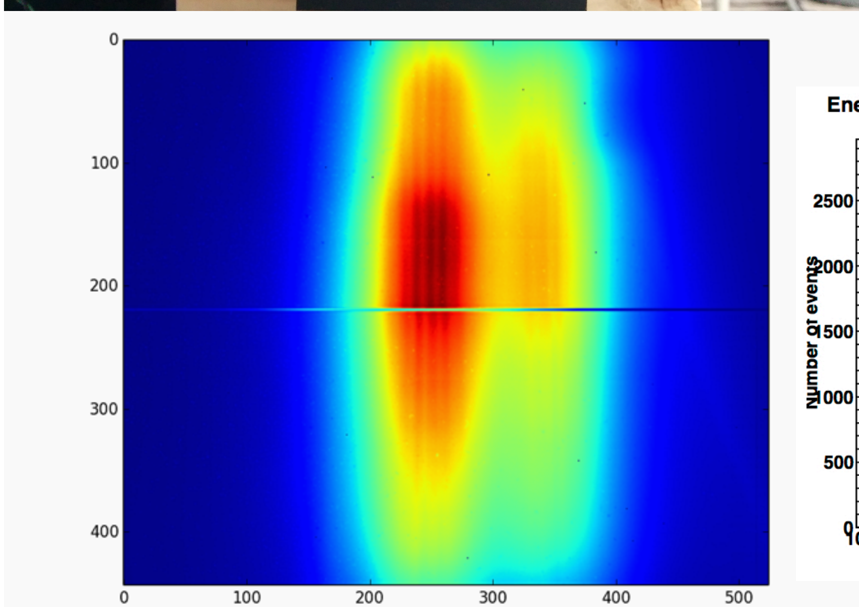
$$\frac{dY}{dx} = \frac{S}{1 + kB(dE/dx)} \times \frac{dE}{dx}$$

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

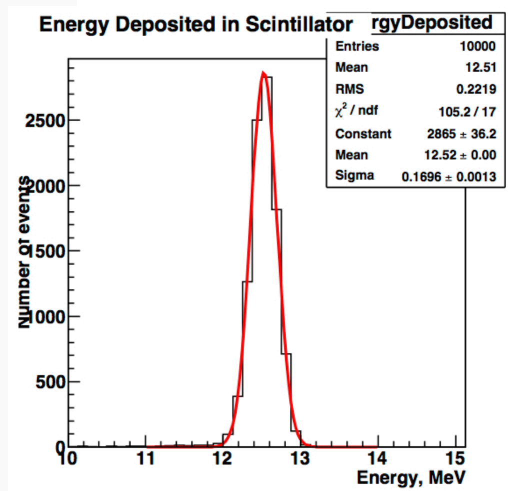


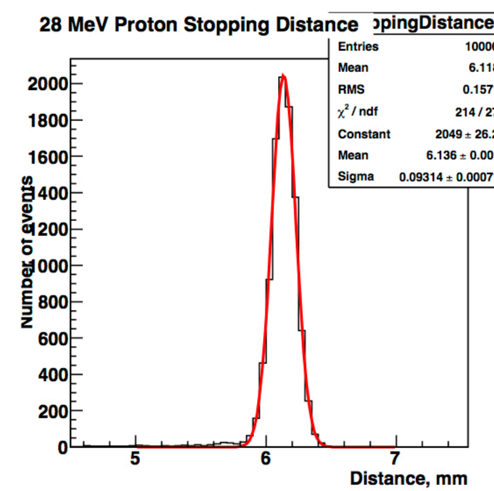


Segmented Calorimeter Tests



- Carried out beam tests of 2 sheet prototype of segmented calorimeter:
  - 3 mm and 4 mm Nuvia plastic scintillator sheets.
  - PRaVDA Priapus MAPS pixel sensor (10 cm x 5 cm).
- Birmingham cyclotron provided 28 MeV proton beam with clinical fluence.





Future Plans

- Currently constructing 60 MeV prototype using:
  - 20 x 3 mm and 30 x 2 mm scintillator sheets obtained from NUVIA.

  - Tests ongoing to determine the best method to isolate sheets from each other and reduce light output (we have too much light!).
  - Clinical beamline tests lined up for the near future:
    - Birmingham (36 MeV), Clatterbridge (60 MeV) and MedAustron (100 MeV).
  - Look at overall performance, radiation hardness and quenching at high rates