Proton Calorimetry for Range Quality Assurance

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Abstract

In 2011 the UK government announced funding for 2 full-sized proton therapy centres, to be based at University College Hospital in London and The Christie in Manchester. Procurement for these centres began in 2013, with doors expected to open some time after 2018. Each of these centres will be home to a single cyclotron and at least 3 treatment rooms: each of these treatment rooms will house a full 360 degree gantry.

In order to ensure that treatment with such complex machinery is carried out safely, a range of quality assurance (QA) procedures are carried out each day before treatment starts. The majority of this time is spent verifying the Bragg Peak and depth dose curve of several proton beam energies. These energy QA measurements take significant time to set up and adjust for different energies: the full can take more than an hour.

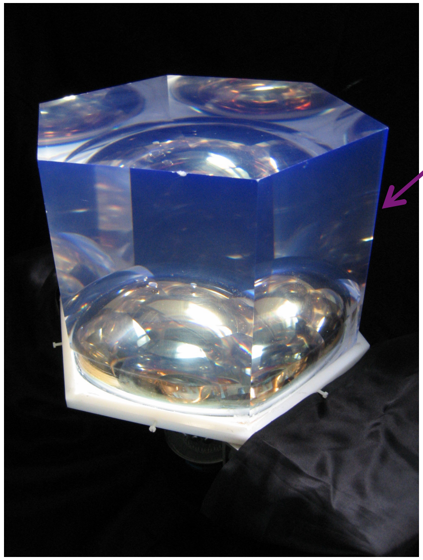
We present the current status of a project that is looking to develop a detector that will make more accurate and more rapid measurements of the proton energy than existing systems. A calorimeter module that was developed for the SuperNEMO high energy physics experiment has been modified to record the energy of a proton therapy treatment beam. This system makes use of a high quality, water equivalent plastic scintillator with superior response time — on the order of a nanosecond — and light output.

Preliminary measurements at the Clatterbridge ocular proton beam therapy centre demonstrated a resolution of well below 1%. The detector design has since been modified to improve the high rate performance: recent measurements were made above 1 MHz with similar energy resolutions. We also describe the design of the detector system currently under development that utilisies a multi-layer calorimeter to make direct measurements of the Water Equivalent Path Length (WEPL) with high resolution at clinical rates.

The SuperNEMO Calorimeter

- For the past 3 years the UCL High Energy Physics group has been looking into proton energy measurement.
- Will some of our detector technology for high energy particle energy measurement also cut the mustard for clinical proton beams?
- SuperNEMO experiment trying to measure neutrinoless double beta decay: very precise measurements of electron/positron energy.
- SuperNEMO calorimeter consists of 550 Optical Modules (wrapped scintillator block + PMT):
  - 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.
  - High light yield, fast timing, excellent energy resolution (3% σ/ 7% FWHM for 1 MeV electrons).
  - VERY well characterised in Geant4 simulations.
- Not quite a solution looking for a problem…

Optimised Optical Module



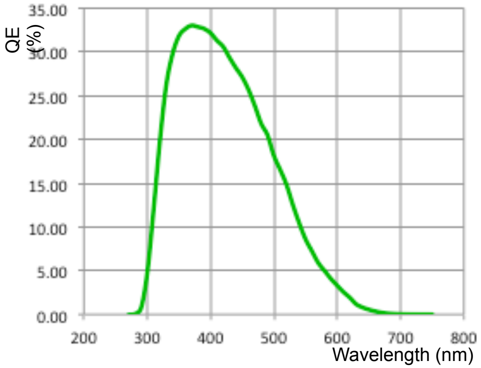
$$\frac{7.5\%}{\sqrt{E(MeV)}}$$

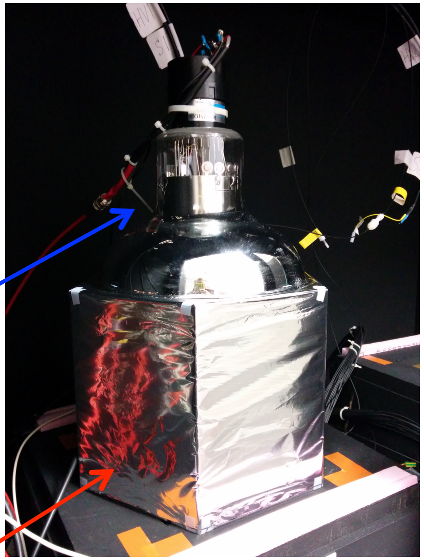
EJ-200 hexagonal PVT block:

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

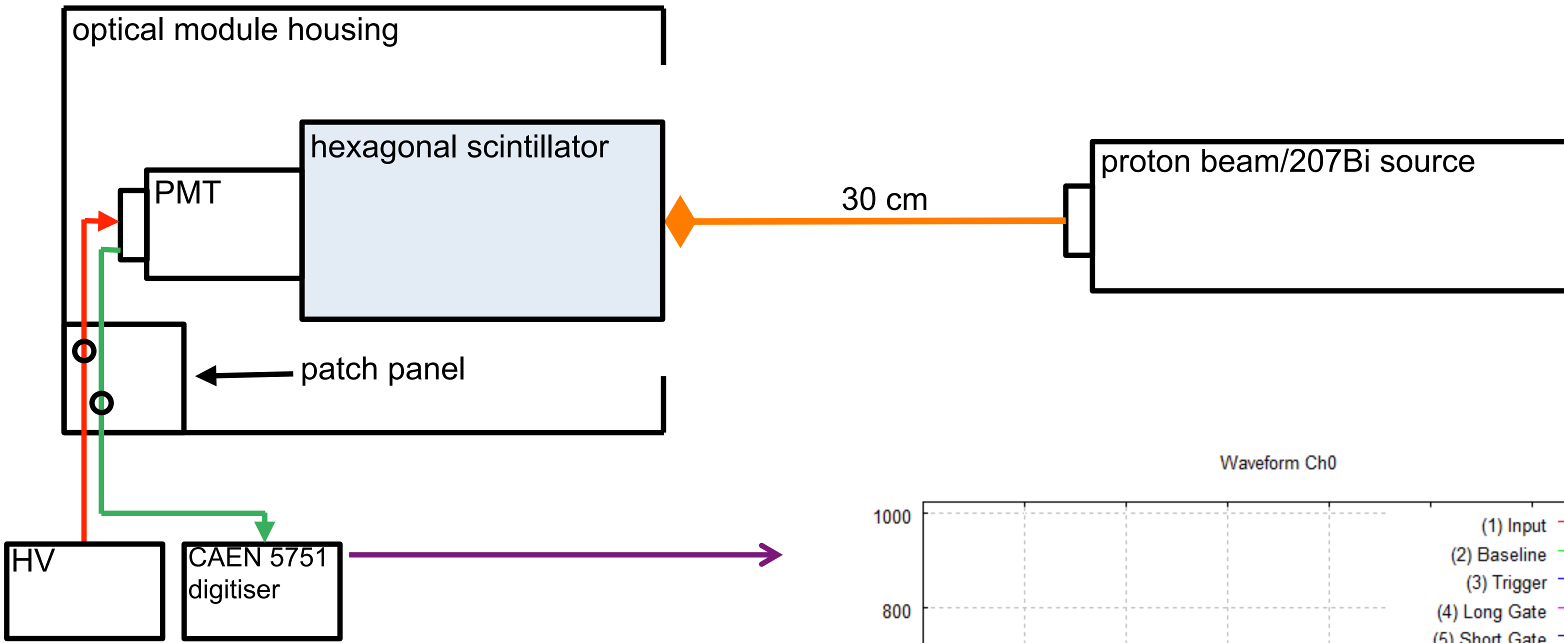


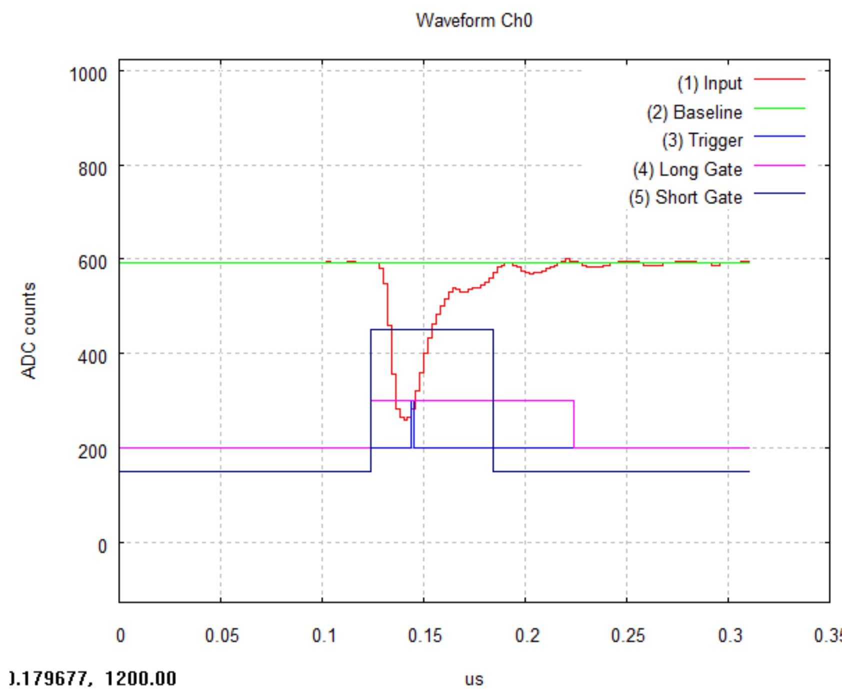


Wrapping:

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

Equipment Setup





CAEN DT5751 Digitiser:

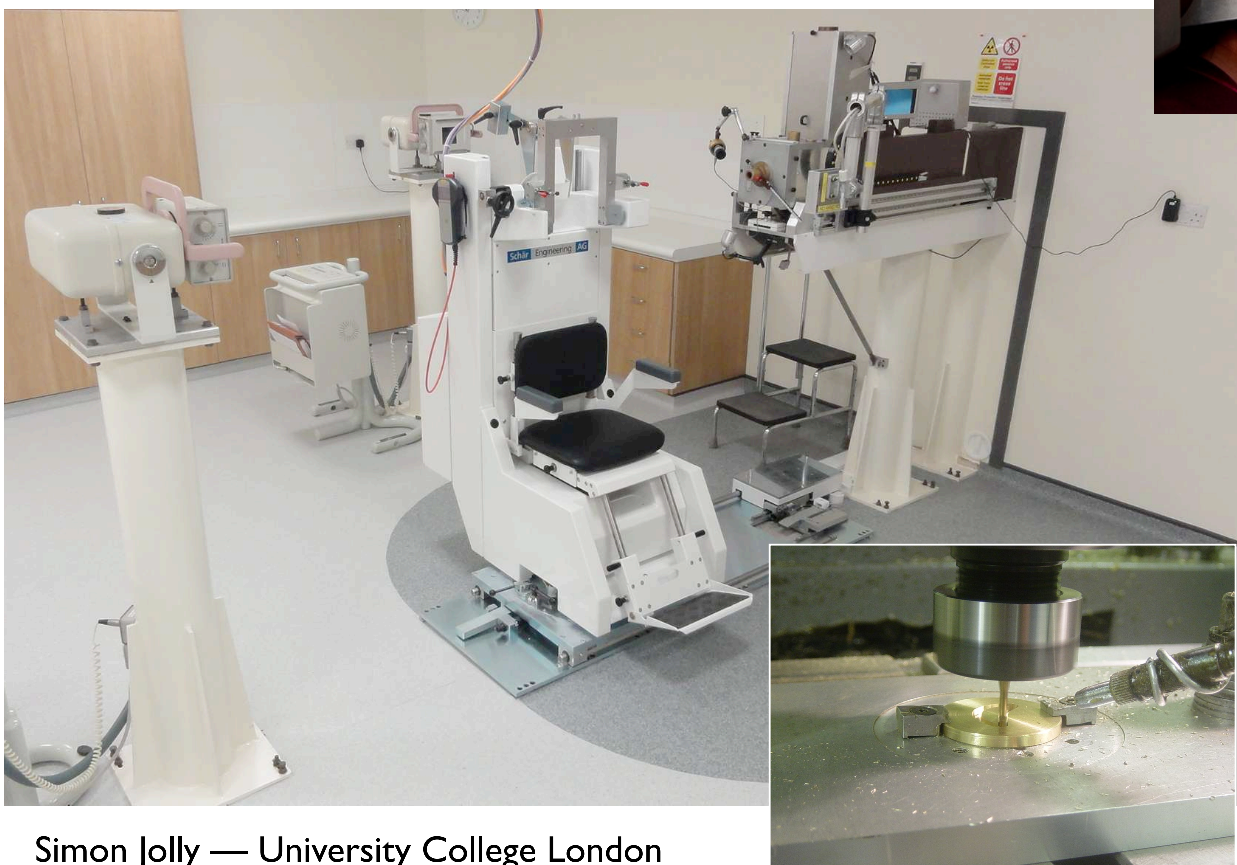
Dual-gate signal integration

→ On-the-fly pulse shape analysis

→ Neutron/gamma discrimination

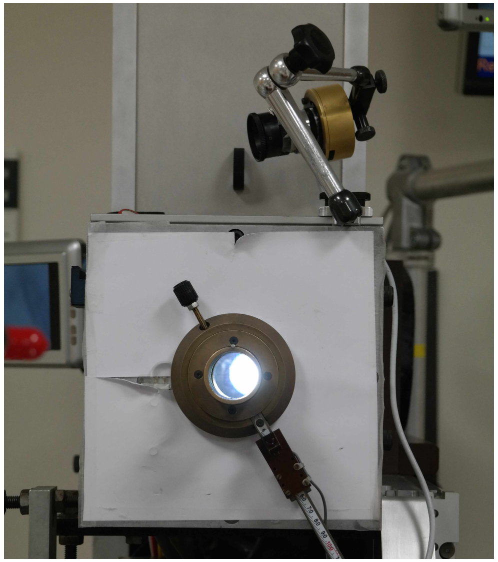
Clatterbridge Cancer Centre

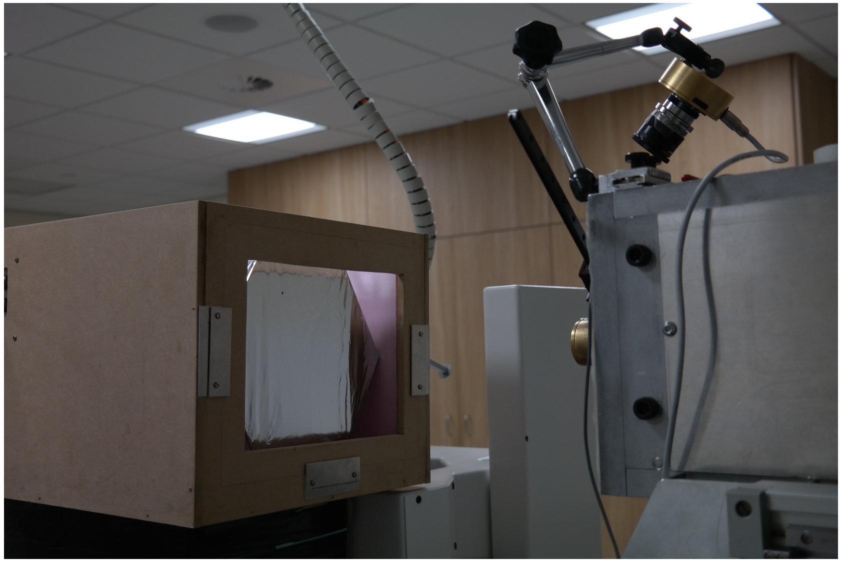
- 62 MeV Scanditronix cyclotron provides 60 MeV protons (31 mm in water) to treatment room through double scattering.
- Beam time provided for research.
- We've had 2-day shifts every few months.
- Already made interesting observations with our equipment about the treatment beam…



- 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…).

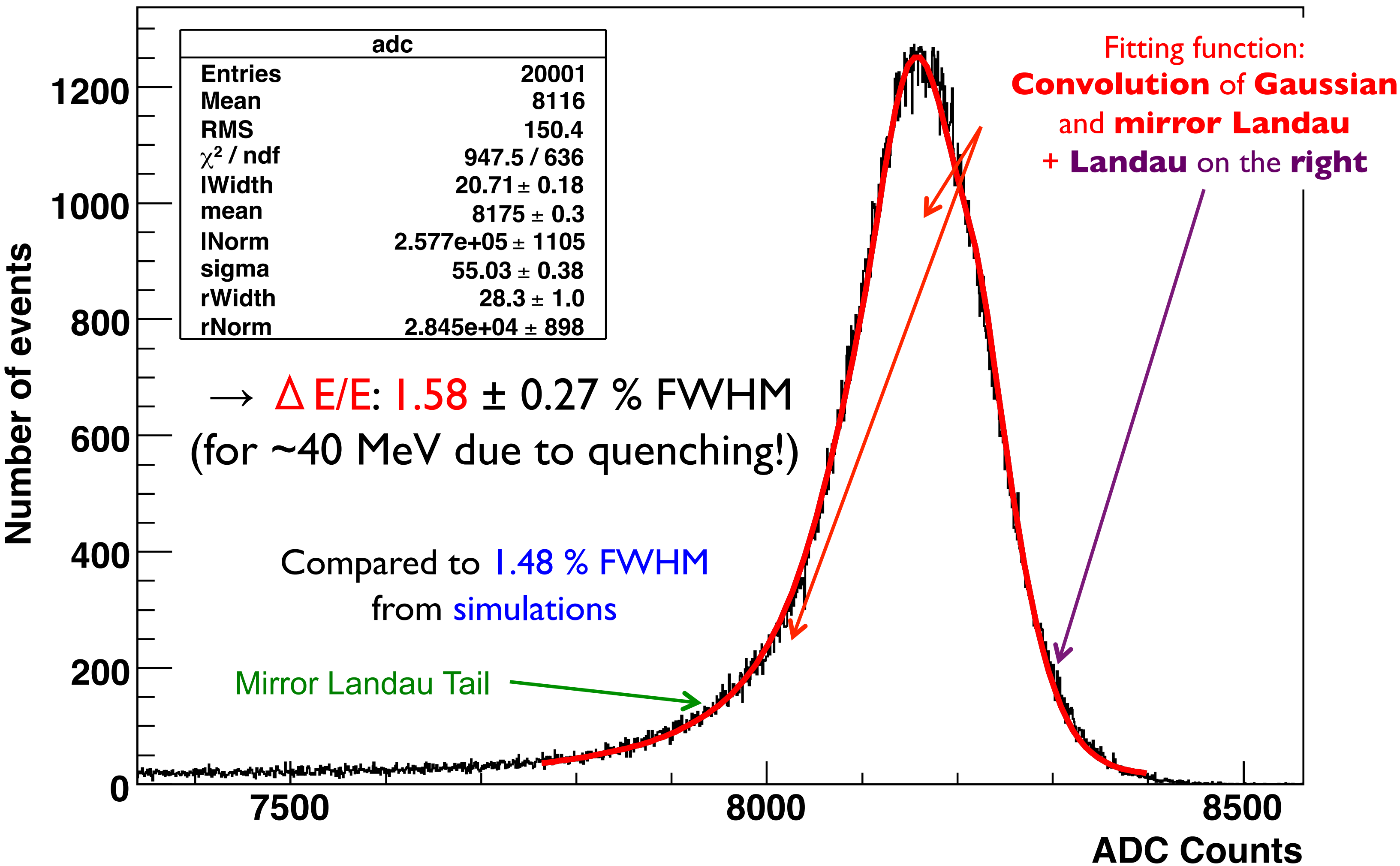
Experimental Tests



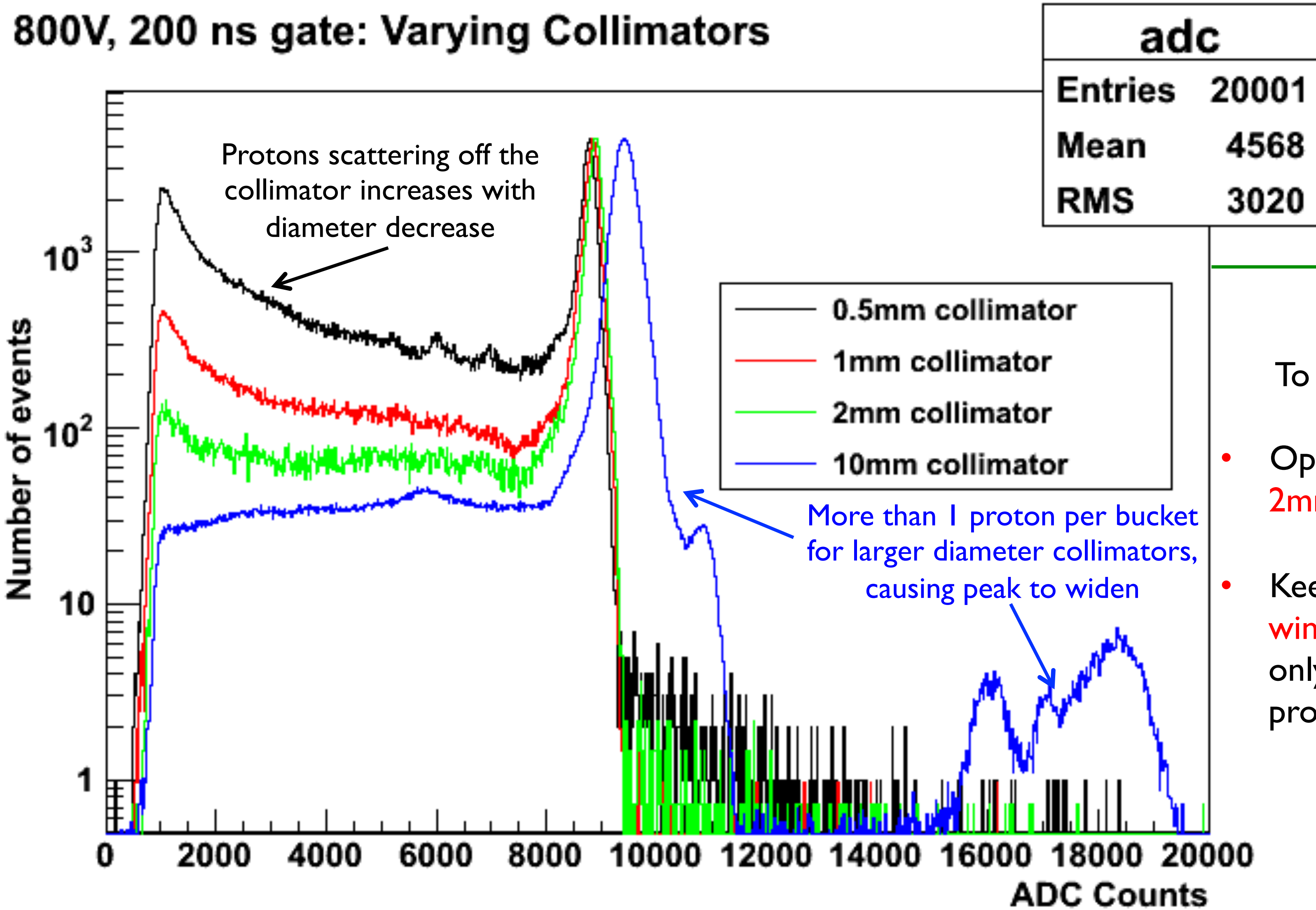


Results: Fitted Data

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



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

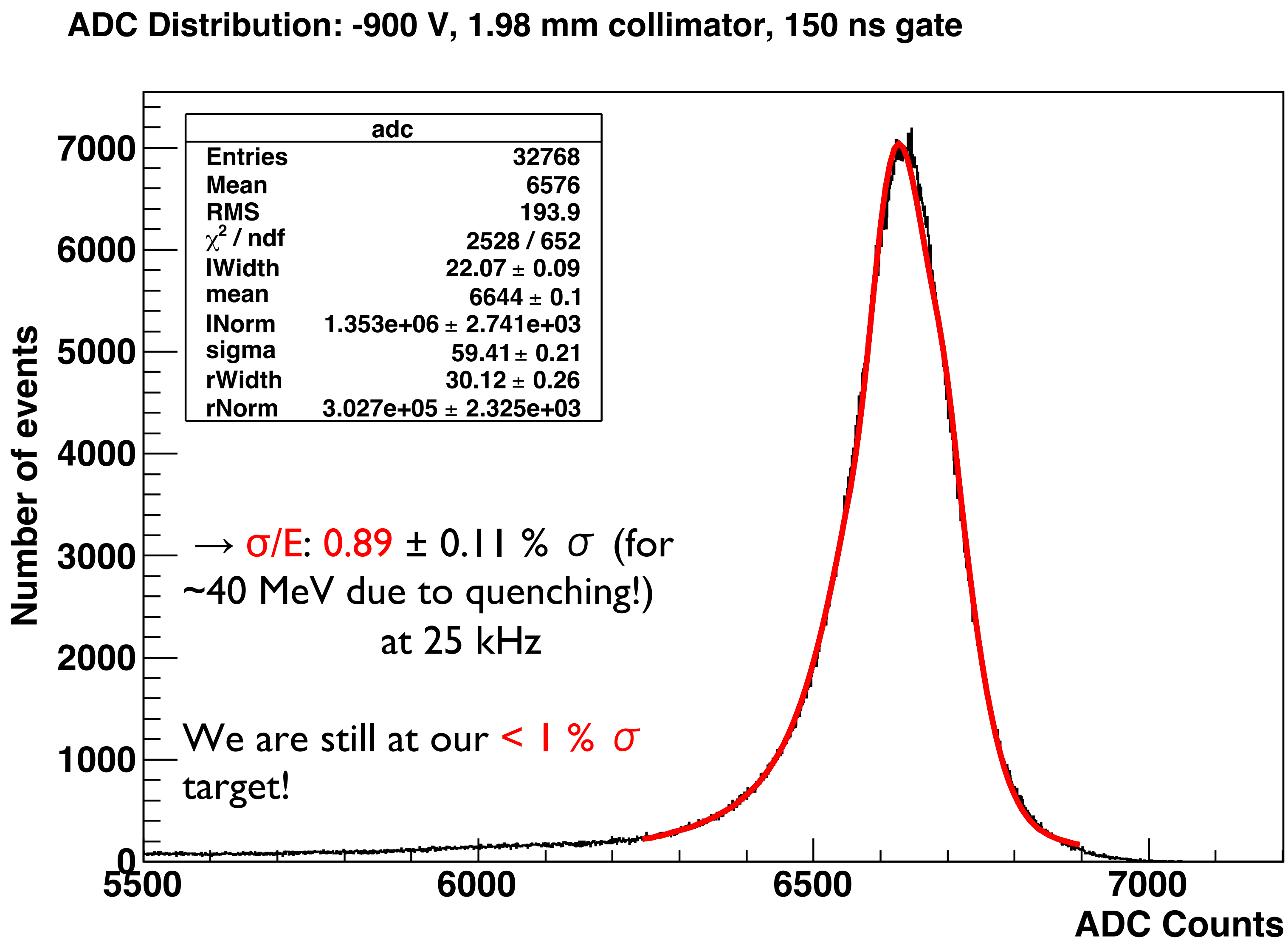
- We have already achieved the target energy resolution: 0.7% σ with
- The next step is to do this for very high rates of 1–10 MHz with a compact design:
- Reduce the size of the PMT and the scintillator to improve timing and make the design nozzle-mountable.
- Negative HV PMT base to remove decoupling 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

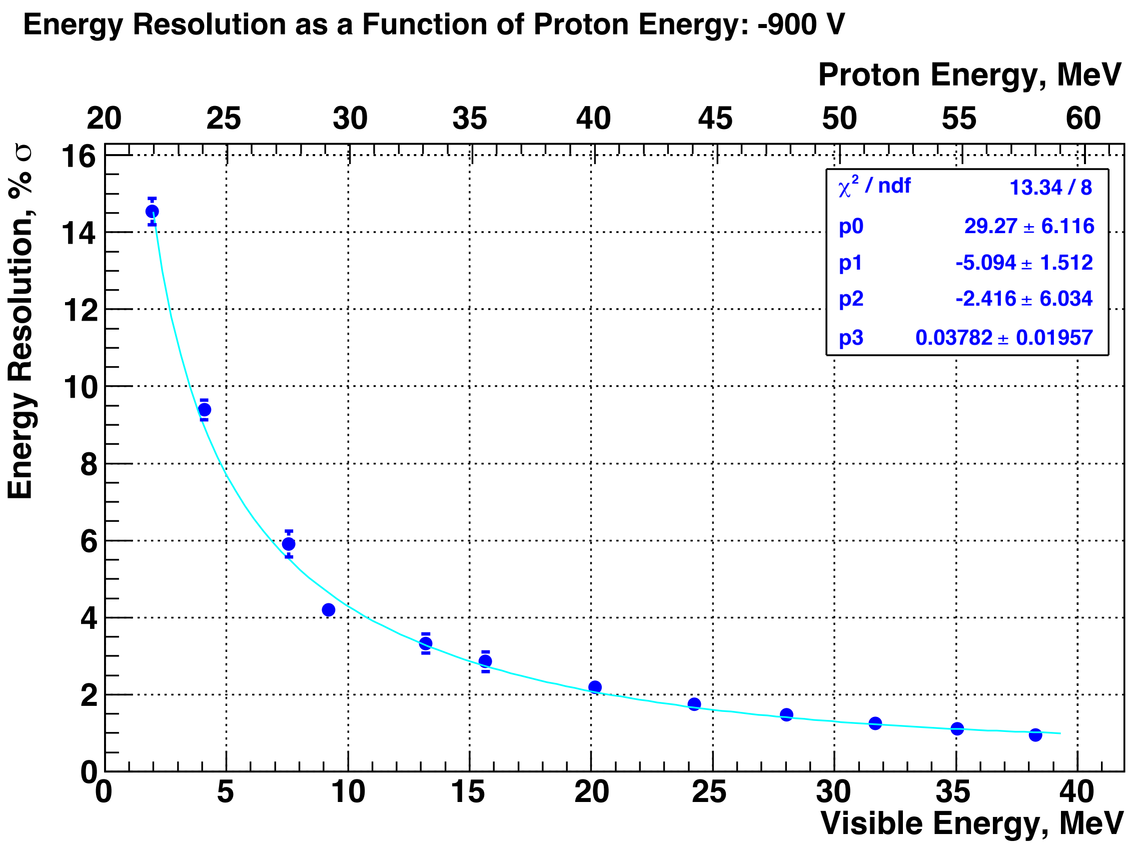


→ σ/E: 0.89 ± 0.11 % σ (for ~40 MeV due to quenching!) at 25 kHz

We are still at our < 1 % σ target!

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.



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

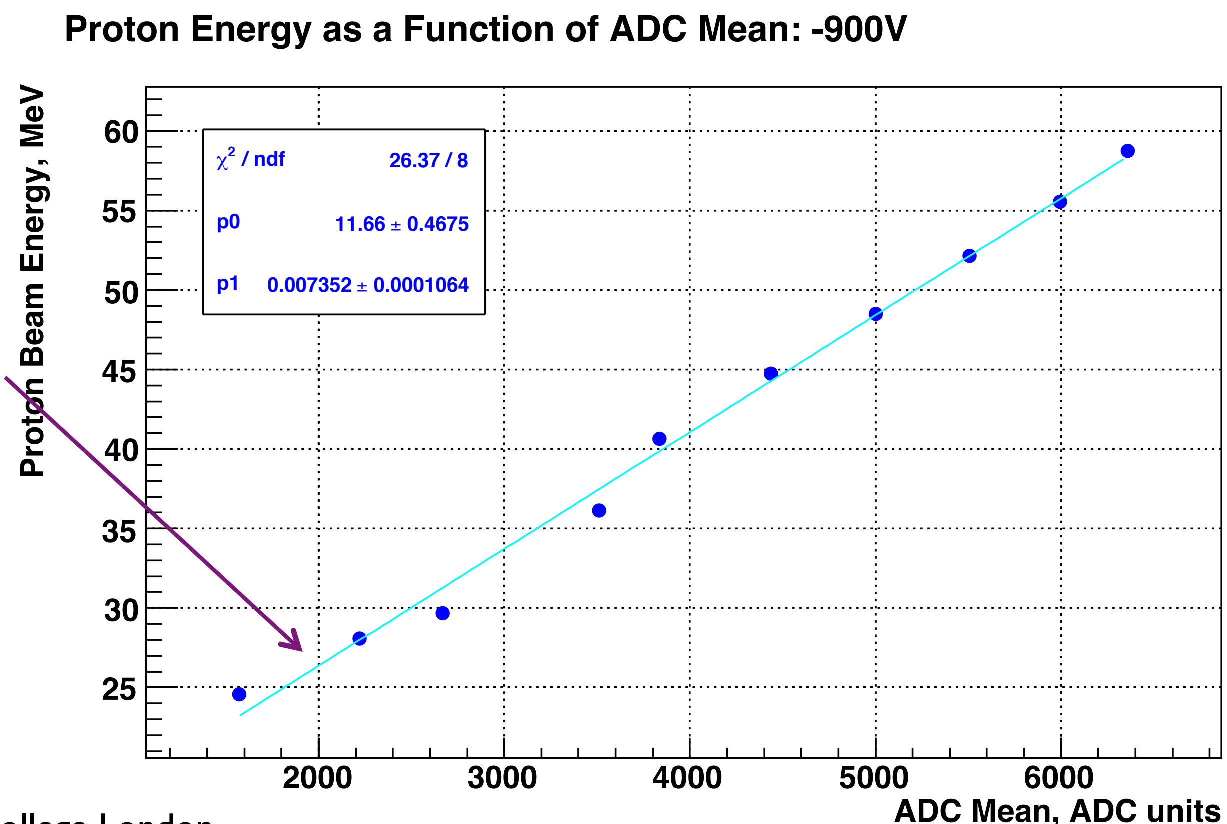
$\sqrt{E}$ dependence!

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:

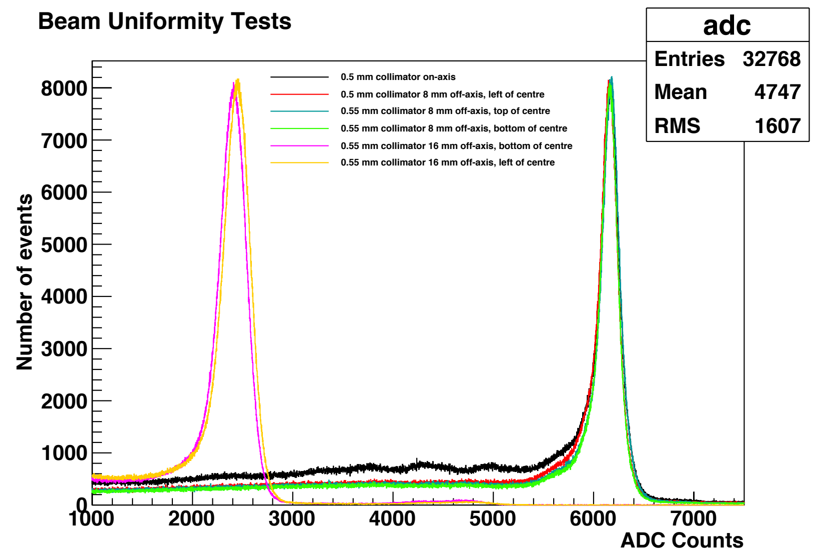
$$y = p0 + (p1 \cdot x)$$

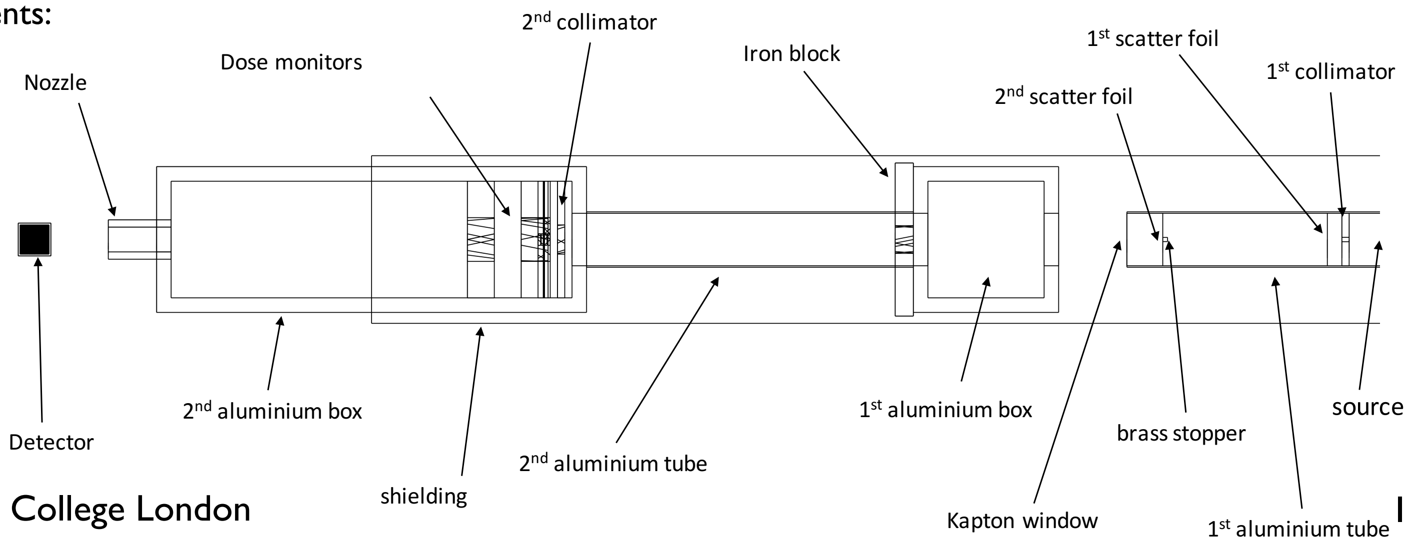
For -900V: Deviation from linearity < 2%!



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:

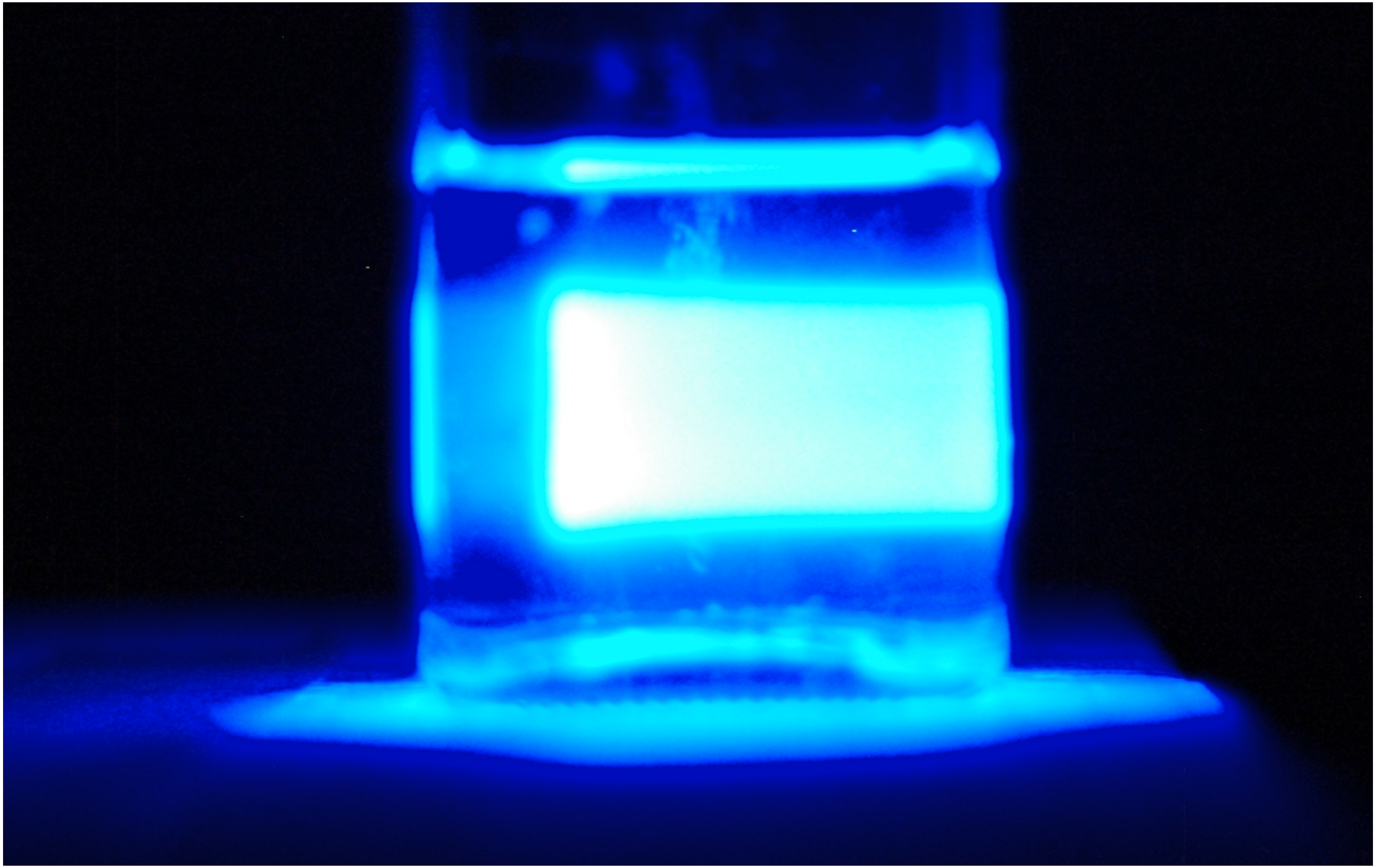




So What…?

- 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. Switch to SiPMs?
- 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



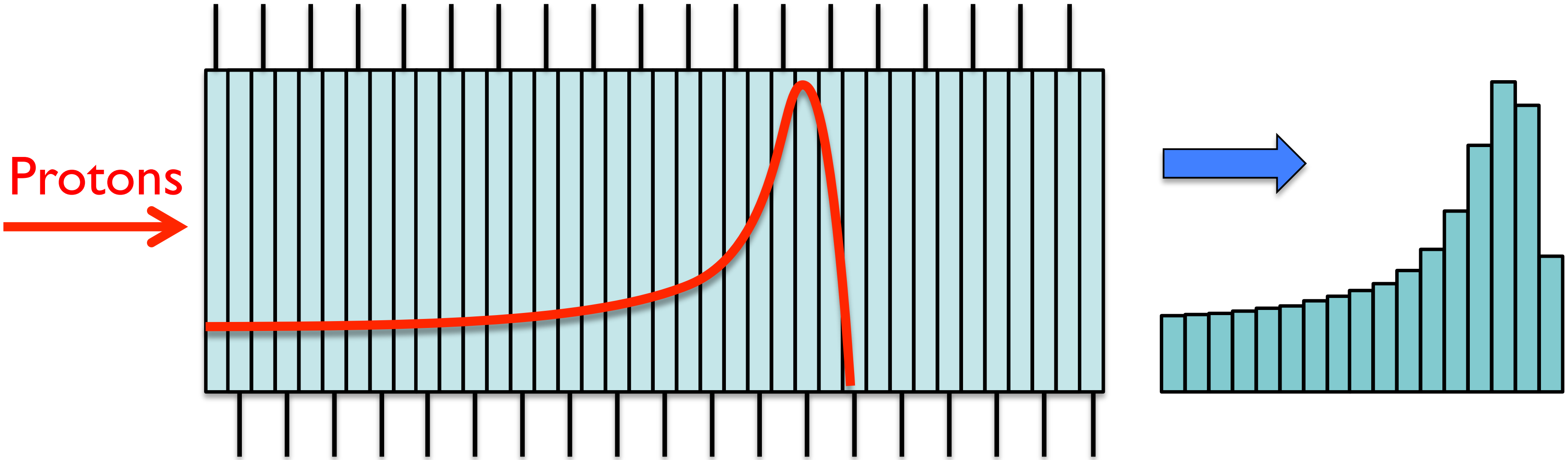
Simulated Stopping Distance

- 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…?

Segmented Calorimeter



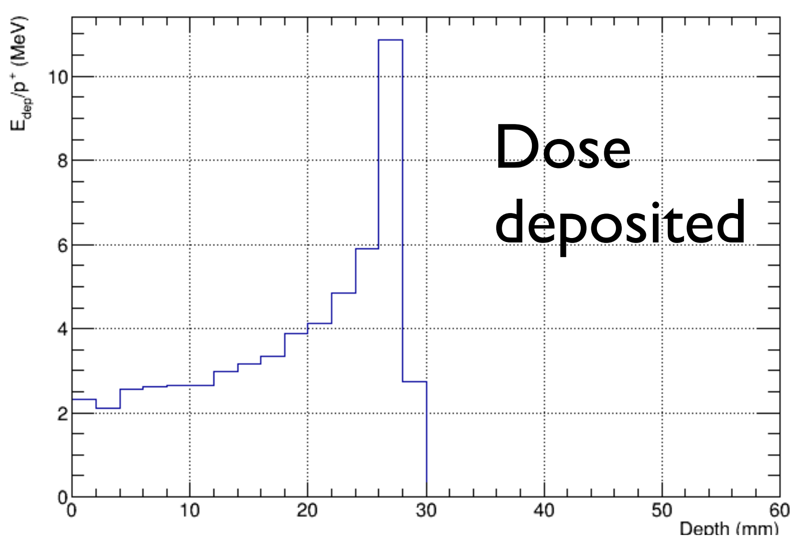
- PVT and PS are both helpfully water equivalent.
- Segment block into slices and read out light from each slice individually.
- Integrate signal from many protons: very large output from 10^{10}/s.
- Minimum slice width will depend on manufacture: aiming for < 2 mm.
- Use photodiodes for readout: poor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

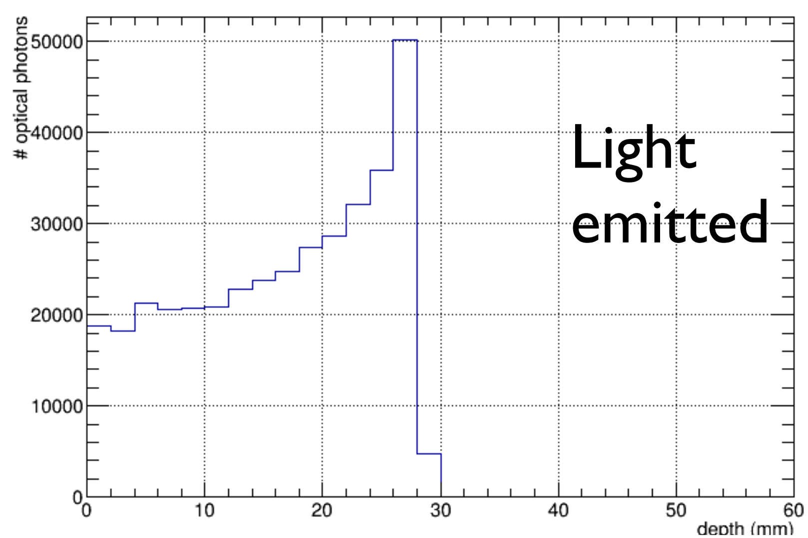
Segmented Calorimeter Design

- 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…?

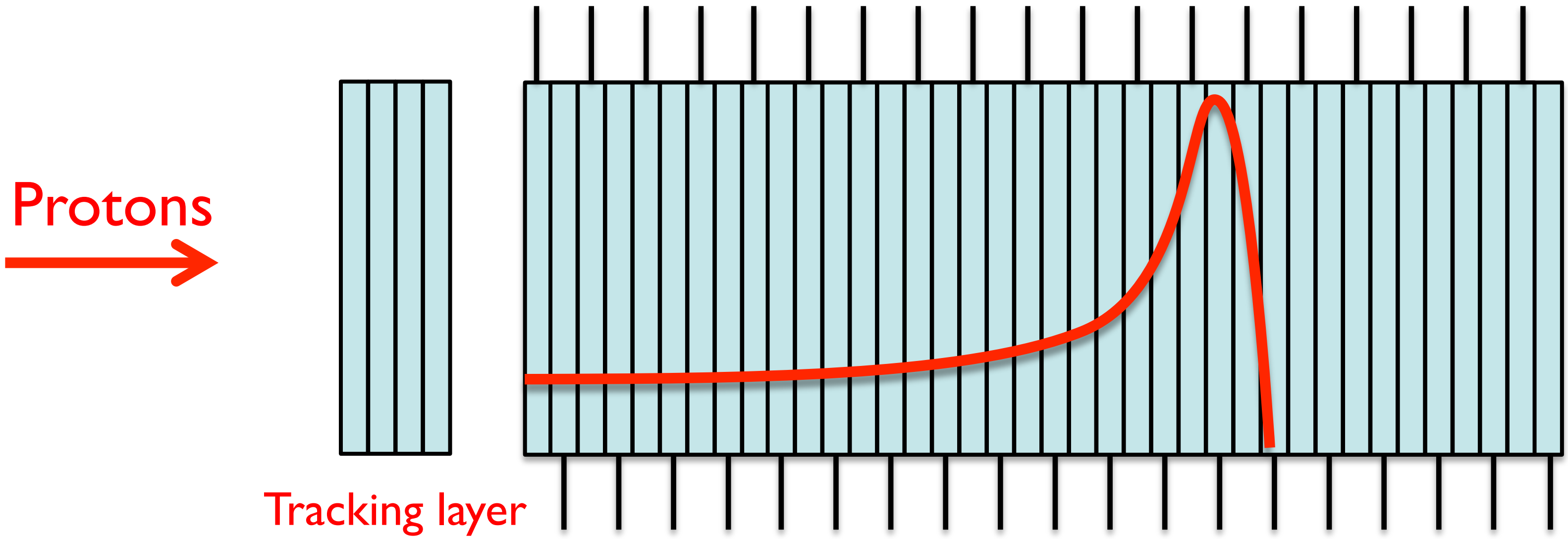
$$\frac{dY}{dx} = \frac{S}{1 + kB(dE/dx)} \times \frac{dE}{dx}$$

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





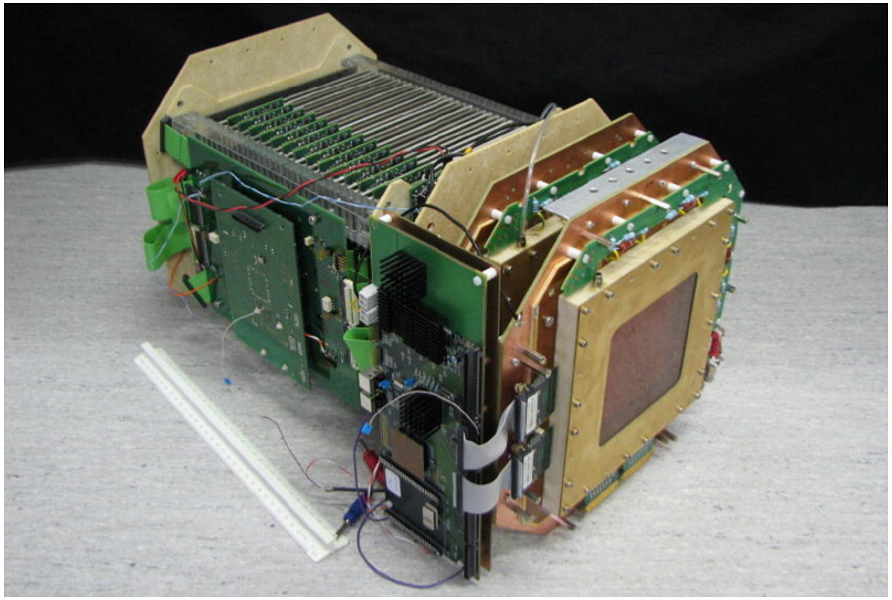
Fast Treatment Plan Verification

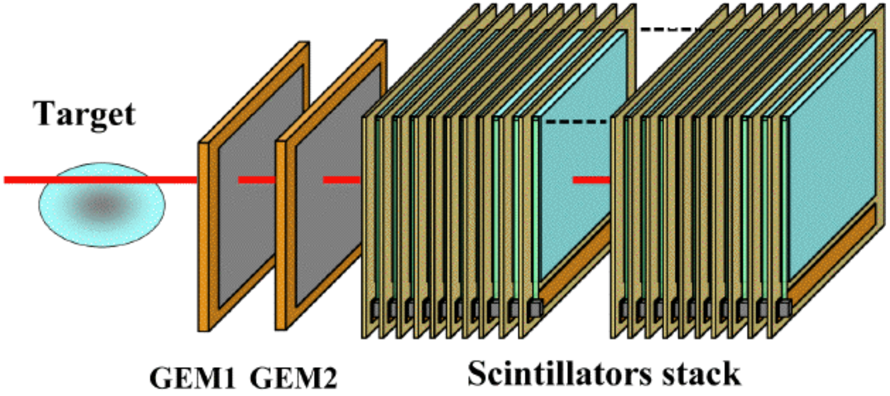


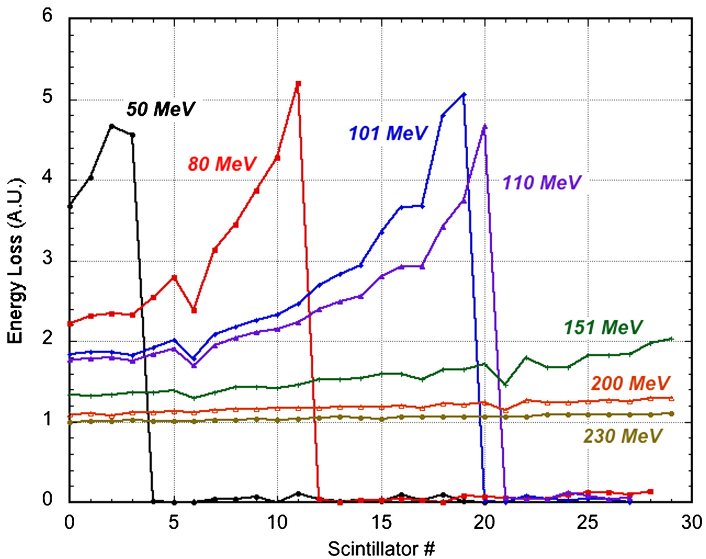
- Take segmented calorimeter: add 2D tracking to front face.
- Still nozzle-mounted and self-contained.
- Read out X/Y profile and integrated range of individual pencil beams.
- Detector read out fast enough to match minimum spot dwell time (3–20 ms).
- Fast reconstruction of water-equivalent treatment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

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