By pCT standards, not LhARAs!!

# Proton Computed Tomography in "High" Proton Flux Environments

~~Nigel Allinson~~ ~~Alasdair Winter~~ Tony Price, on behalf of the OPTIma consortium

IoP: Advancing Radiobiology Technology

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UNIVERSITY OF BIRMINGHAM

NHS University Hospitals Birmingham NHS Foundation Trust

UNIVERSITY OF LINCOLN

OPTIma Optimising Proton Therapy through Imaging

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The Christie NHS Foundation Trust

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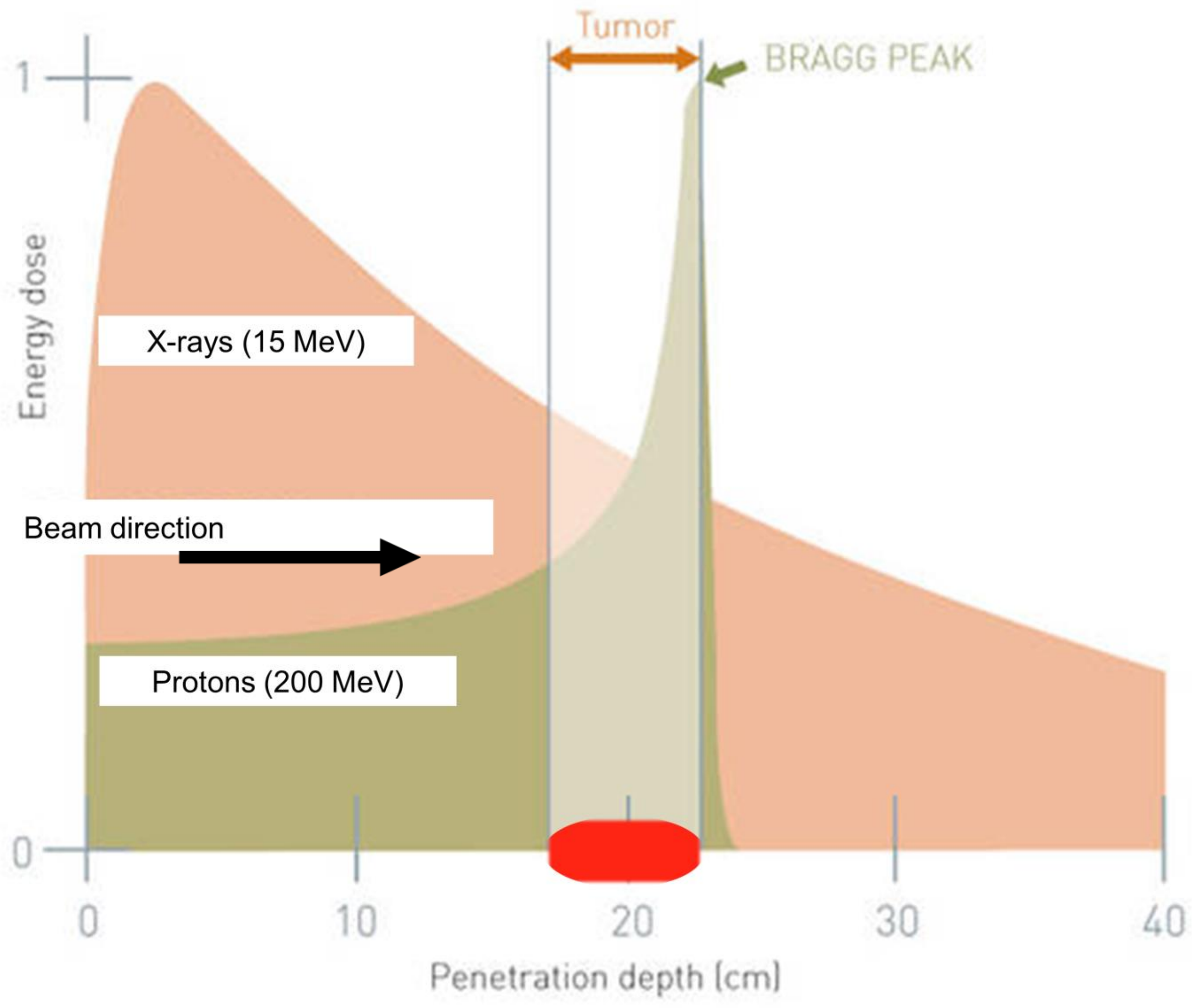
# Why Proton CT?

- Hadron therapy uses the Bragg peak to improve the target to healthy tissue dose ratio

- But, this relies on knowing exactly where your peaks will be
  - ➢ Sharp edge mean small range errors cause larger local variations in dose

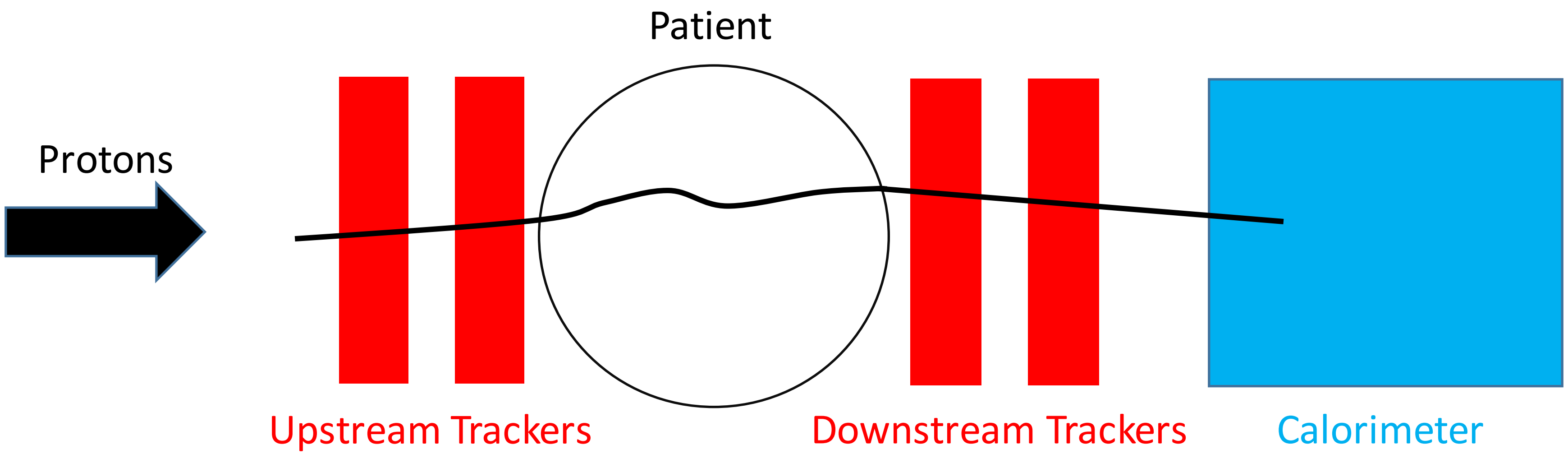
- Treatment planning currently based on X-ray imaging:
  - **DECT range uncertainties ~1-3%**
  - **Partly limited by conversion from X-ray attenuation to proton stopping powers**
  - **pCT avoids this limitation by imaging directly with protons**



# Basics of pCT Design

Information required from the system:

- Path taken by each proton through the patient (challenging due to MCS!)
- Energy lost by the proton along that path




Patient is imaged with high energy protons from multiple directions

Image reconstruction produces 3D map of relative stopping power (RSP)

# Design Considerations

- Image quality
  - Requires good tracking (~100 µm) and energy resolution (~1%)
  - **Low noise** detectors
  - **Thin detectors** to avoid disturbing the proton path

- Clinical beam conditions
  - Global shift from broad passively scattered beams to pencil beam scanning systems
  - High currents ~200 pA and pencil beams (~10 mm)
  - Bunch frequency ~100 MHz
  - High flux density (not by LhARA standards!) → **multiple protons per bunch (20 protons per ~10 ns)**

- Practicalities
  - **Scan time** → patient can't be expected to remain still >30min
  - Needs to be **mountable** on a gantry
  - **Affordable**
  - **Reliable** → the simpler the system the better
  - Radiation **hard**
  - **Highly efficient** to minimise wasted dose

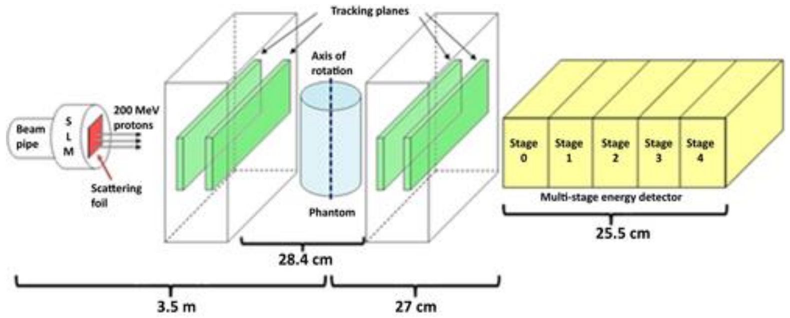
**This is where most devices struggle!**

**Too many protons or very complicated systems**

**Arguments to be made for defocussing the beam or dialling current down, but requires operating outside vendors standard windows**

# Existing Approaches

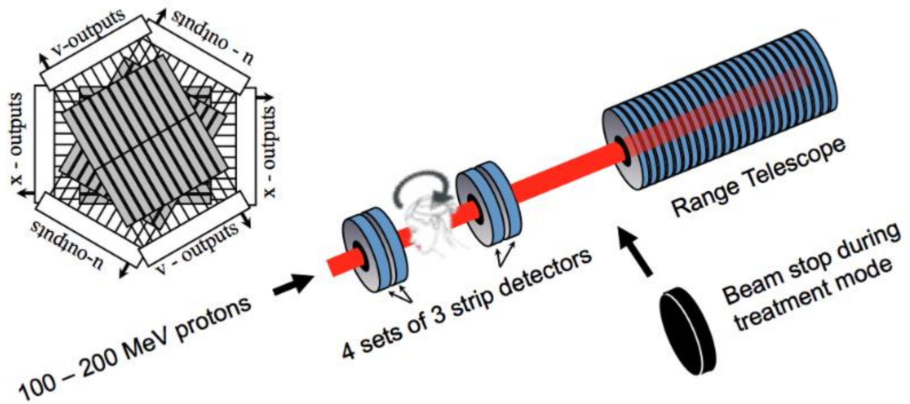
A non-exhaustive list….




*Loma Linda Preclinical Head Scanner*

| Tracker Technology | Challenges |
|---|---|
| Silicon strips/scintillating fibres | Multiple layers required per module to resolve hit locations in bunches with more than 1 proton |
| CMOS pixels | Challenging to produce large area, radiation hard, fast readout sensors |

| Energy Measurement Technology | Challenges |
|---|---|
| Range telescope | System becomes impractically large for high energies and requires substantial instrumentation |
| Calorimeter | Requires fine segmentation to cope with multiple protons per bunch→ challenging readout structure |
| Time of flight | Promising approach but requires very fast timing sensors (ps) to achieve desired energy resolution for the flight distances available in treatment rooms |
| Spectroscopy | Hard to imagine mounting an appropriate magnet system on a gantry |

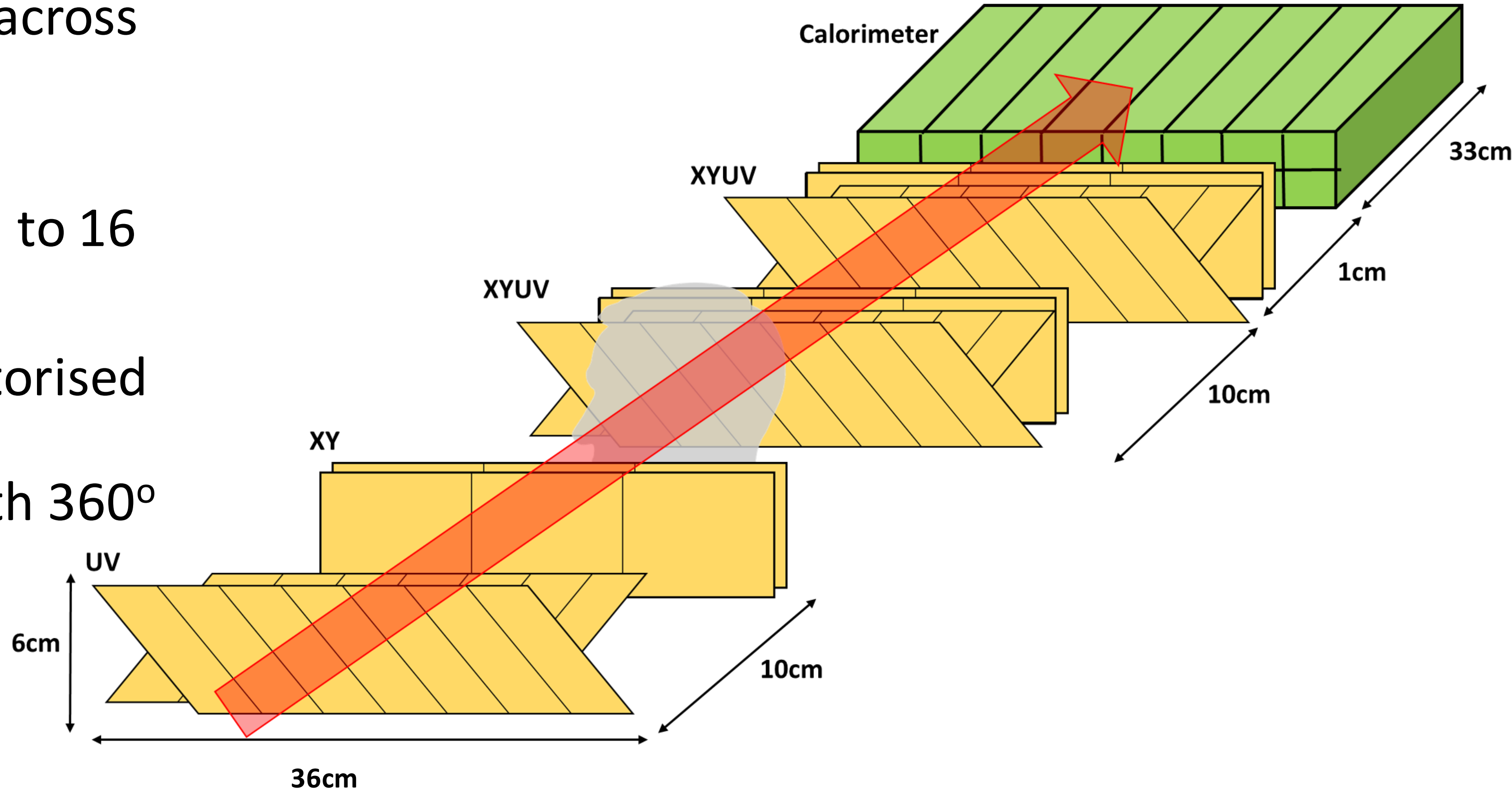



*PRaVDA pCT system*

….+ hybrids of these

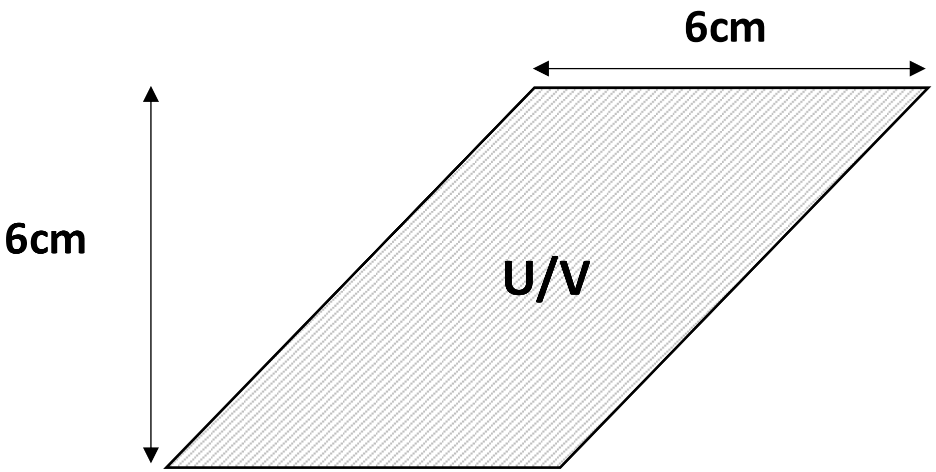
# OPTIma: System Overview

- Tracking: 12 layers of tiled silicon strips spread asymmetrically across four modules
- Calorimeter: 8x2 array of scintillating plastic connected to 16 SiPM
- Used in conjunction with motorised phantom stage to allow total imaging area of 36x36cm$^2$ with 360$^o$ coverage
- Designed with The Christie beamline (Varian) in mind

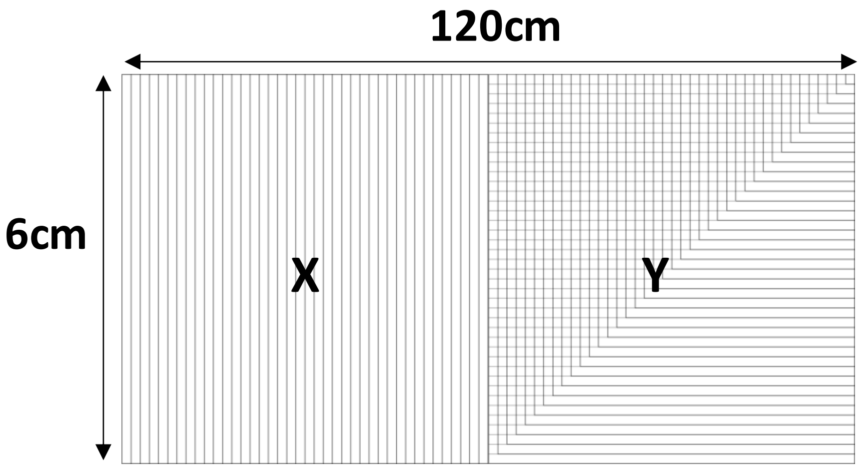


# OPTIma: Tracking

- Ideally would use CMOS MAPS, but strips are a ready technology, relatively cheap, radiation hard, have good S/N, and can be easily readout at 100 MHz
- Design based on 150 µm thick ATLAS ITK n-on-p silicon strips produced by Hamamatsu Photonics
- Four layers required per module to handle ambiguities in hit locations for high flux densities
  - Reduced to 2 layers for upstream modules where beam optics help resolve ambiguities (not possible in rear trackers due to scattering)
- Two sensor types were required to provide segmentation in up to four directions




*UV Sensor*

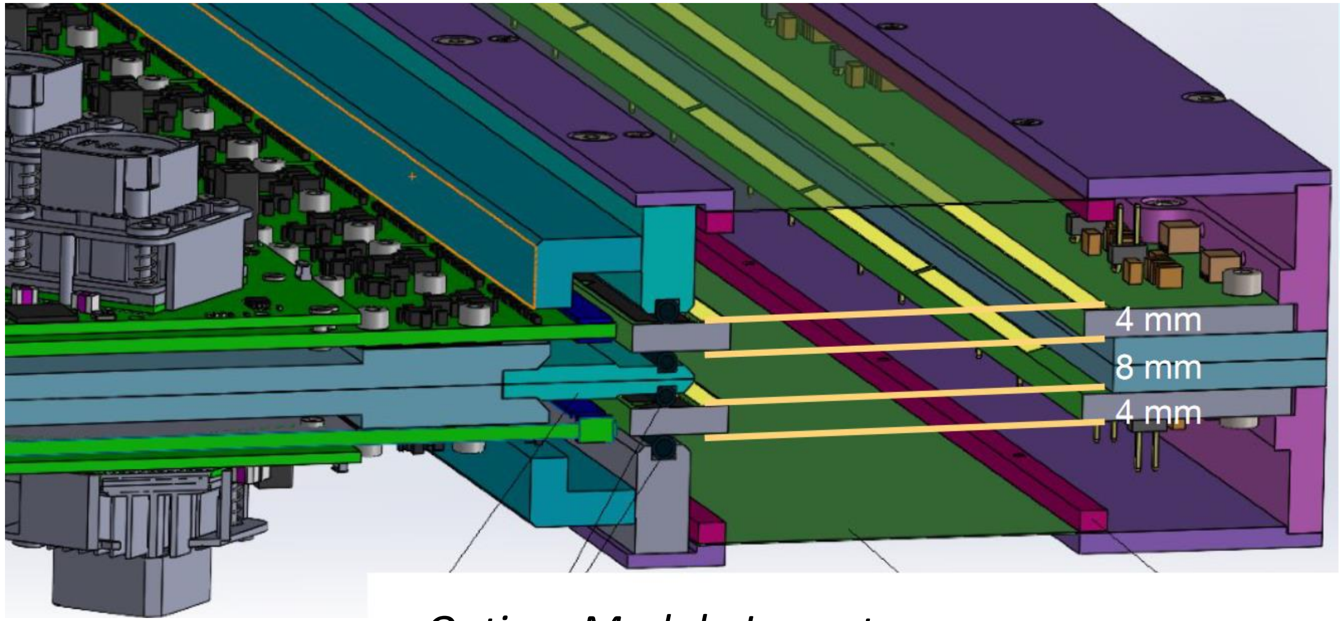



*XY Sensor: right hand side uses a double metal structure to redirect signal to long edge*

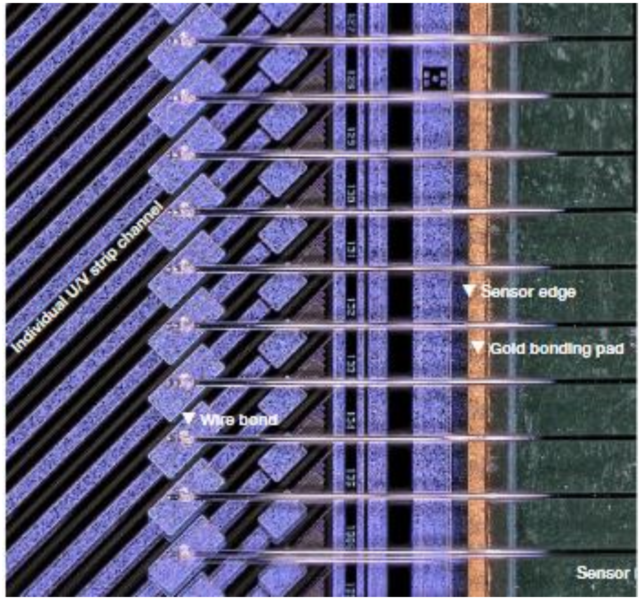
# OPTIma: Tracking

Module design is focused on keeping layers as close together as possible

- Minimises uncertainty on hit location
- Achieved by using two sensor boards and gluing sensors to both sides of each board

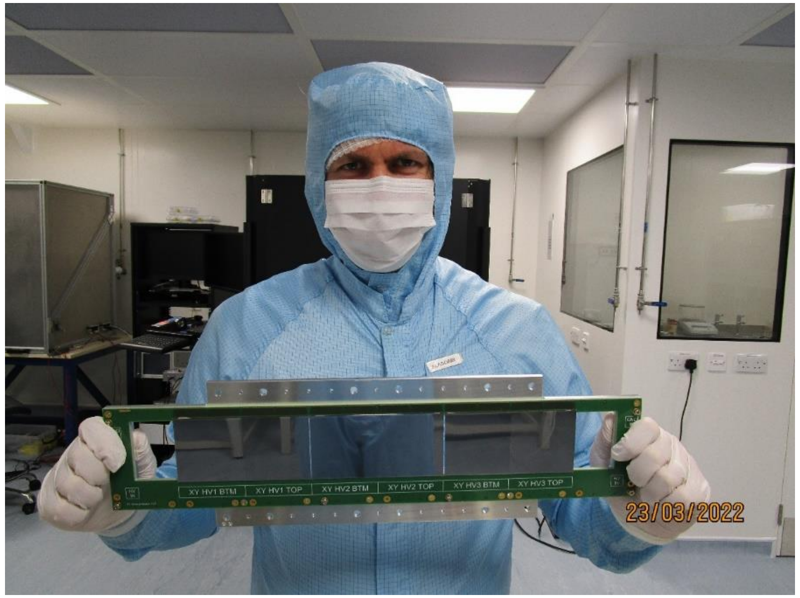



*Optima Module Layout*




Sensor testing completed- no issues encountered!

Assembly underway at Birmingham, aiming to test complete system in 2024



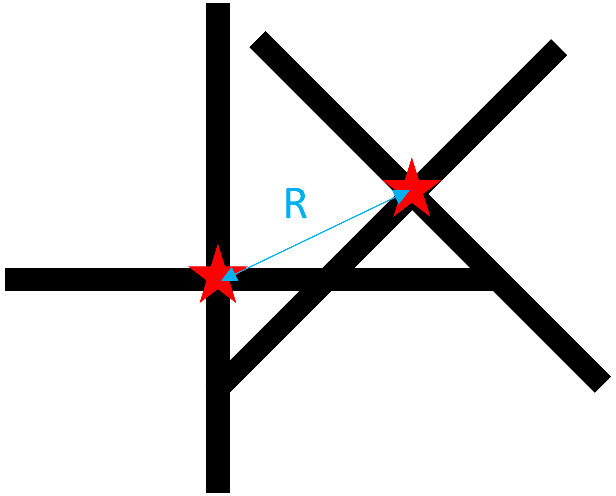

*Optima XY sensor board*

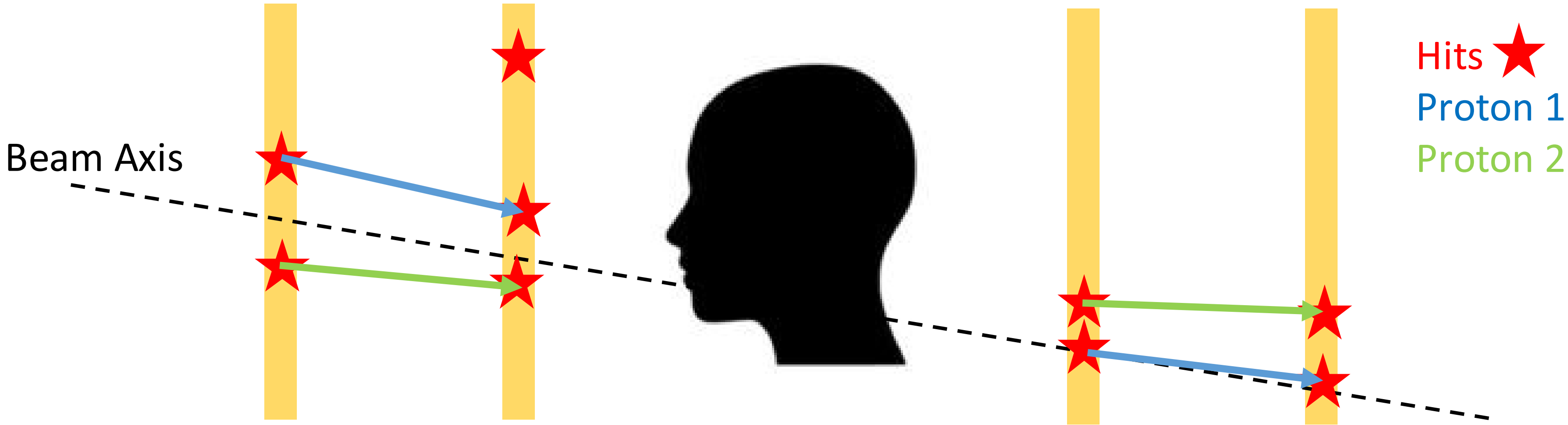
# Track Reconstruction

Three stages:

1. Find hits in each module
2. Form upstream tracks → can assume protons travel parallel to beam axis, no protons lost to hard interactions
3. Match upstream tracks to downstream hits

- Multiple approaches tried but ultimately simple cut based methods based on track straightness proved best
  - Maximum allowed deviation from straight line determined from performing a calibration of scattering vs residual energy for water blocks
- Pixel sensors remove step 1 but steps 2 & 3 are still necessary



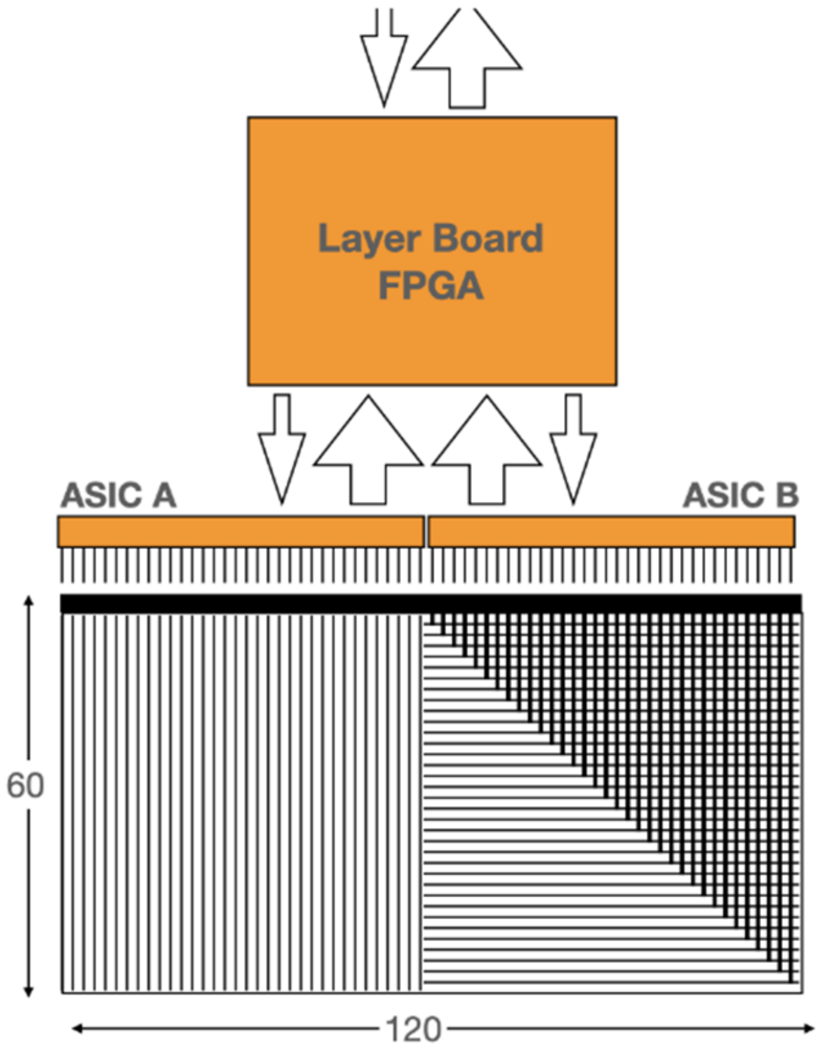




Step 1) Find combinations of strips in each module that minimise ‘R’

Step 2) Pair up hits between upstream modules to form tracks ~parallel with beam axis

Step 3) Match downstream hits to the upstream tracks. **This is the hardest step due to scattering in the phantom**

# Readout




Limits system to currents of <50pA at the Christie
Requires beam collimator to reduce current by x5

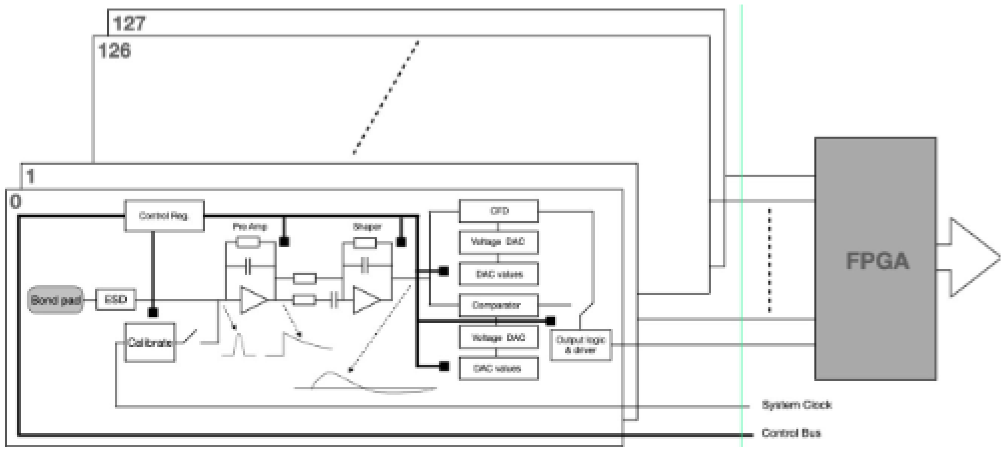
**Layer Board FPGA**

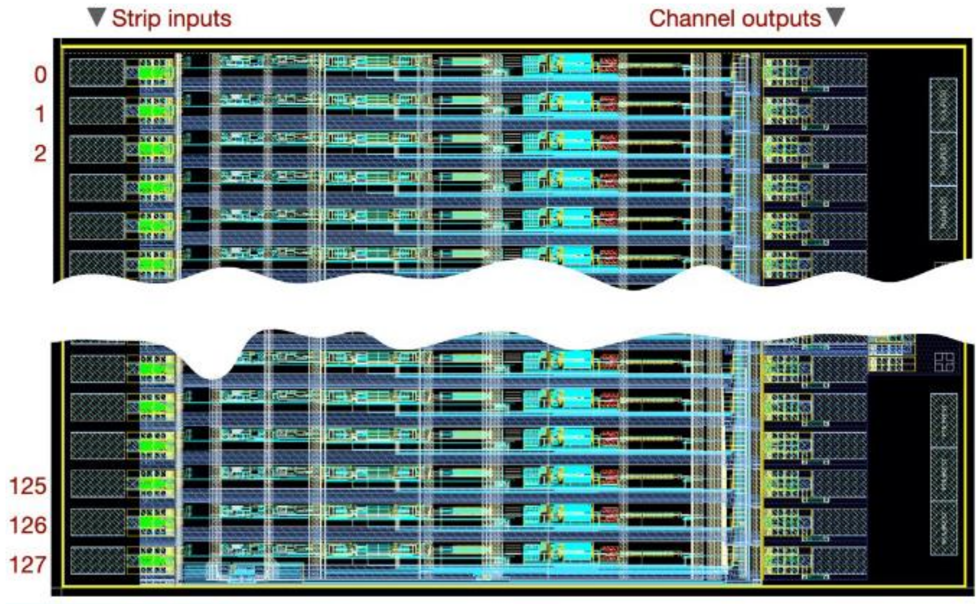
- Xilinx Kintex-7
- Record **maximum of 8 events** per clock cycle due to bandwidth limitations
- Manages faulty channels
- Performs crude clustering
- Transmits data packet on a multi-gigabit transceiver link

**System Layout**

- 1536 channels per tracking layer
- 12 tracking layers in the system
- Each ASIC services 128 channels
- Each layer board FPGA services 2 ASICs
- Total components:
  - 18432 silicon strips
  - 144 ASICs
  - 72 FPGAs
  - + additional FPGAs to aggregate layer data and reject cases with >8 hits in any layer

# ASIC




**Functionality**

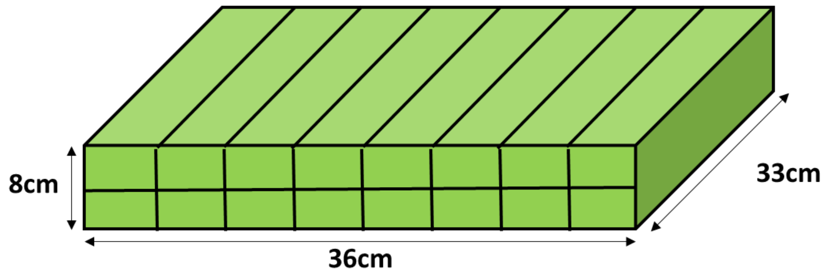
- Converts the input charge pulse (10,000-100,000 $e^-$) from 128 silicon strip channels into a reliable digital signal
- The analogue chain consists of a standard preamplifier and shaper (bandpass filter)
- Simple discriminator + a constant fraction discriminator convert the signal into a digital pulse with minimal time jitter
- Integrated calibration circuitry included to reduce channel by channel variations

**Structure**

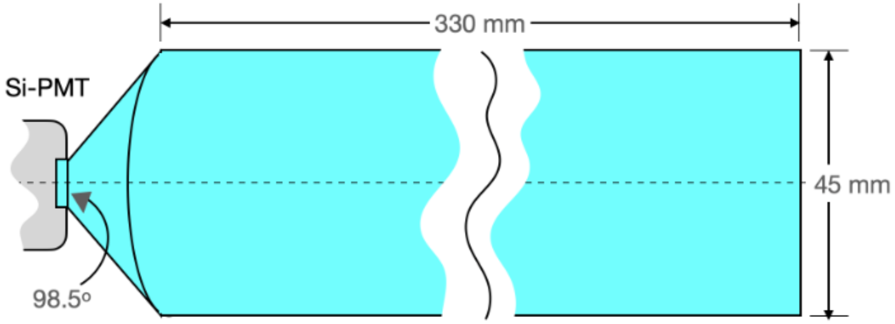
- Die size: 27.22 mm x 5.00 mm
- 350 nm CMOS technology
- 128 strip channel inputs
- 128 digital outputs
- 58 additional control and power pads
- Power dissipation ~0.5W

# OPTIma: Calorimetry

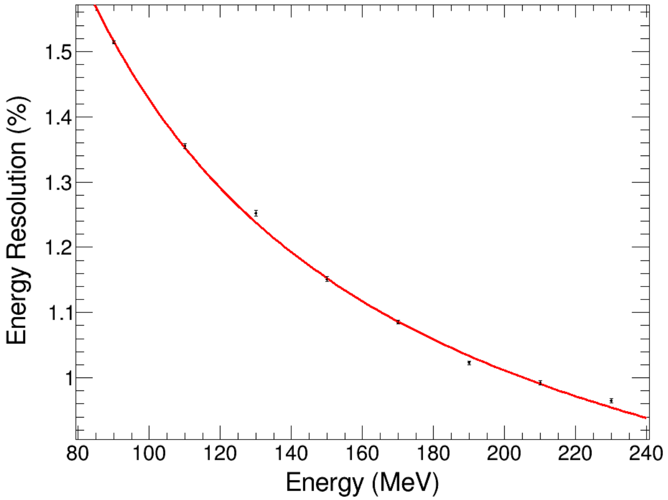
- Typically, the use of a calorimeter in a multi-proton environment requires the use of highly segmented scintillators and complex readout structures
  - Here we have developed a novel approach that requires only that the calorimeter reports the total integrated light output across all channels per bunch (no spatial information!!)
  - By using trajectory information from the trackers and some simple assumptions it is then possible to recover the individual proton energies
- Calorimeter design is based on an 8x2 array of 45x40x330 $mm^3$ BC408 plastic scintillators, each with a H10721 Si-PMT
  - While segmentation is not needed to provide spatial information, it was found that a small amount is required to ensure suitably small path lengths for the resulting light




*Array of scintillating bars*




*Cross section of scintillating bar*




*Single proton resolution*

*Calorimeter setup at Christie PBT research beamline*

# De-Averaging

Example images at 30pA for air, cortical bone and lung tissue embedded in 150 mm of Perspex

- If we simply used the raw output from this calorimeter and assigned each proton the average energy per bunch, the resulting image is very poor

- However, if one makes the assumption that all protons that follow the same the same path should have a similar residual energy one can construct the matrix below, solve for $E_j$, and instead assign each proton an energy determined by it's trajectory

- **<u>With ideal trackers has been shown to work up to low end treatment currents of 250pA</u>**

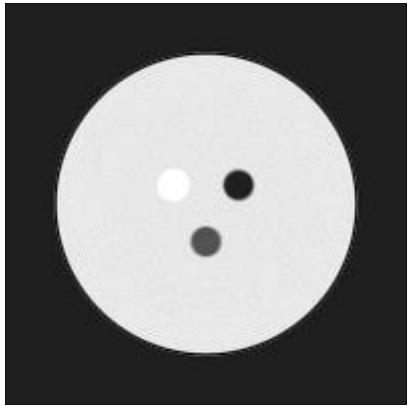
Energy of each trajectory

$$\begin{pmatrix} n_{j=1}(t=1) & n_{j=2}(t=1) & \dots & n_{j=J}(t=1) \\ n_{j=1}(t=2) & n_{j=2}(t=2) & \dots & n_{j=J}(t=2) \\ \vdots & \vdots & & \vdots \\ n_{j=1}(t=T) & n_{j=2}(t=T) & \dots & n_{j=J}(t=T) \end{pmatrix} \begin{pmatrix} E_{j=1} \\ E_{j=2} \\ \vdots \\ E_{j=J} \end{pmatrix} \approx \begin{pmatrix} E_{tot}(t=1) \\ E_{tot}(t=2) \\ \vdots \\ E_{tot}(t=T) \end{pmatrix}$$

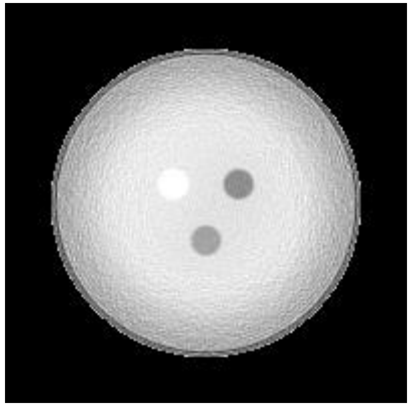
Measured no of protons/trajectory/pulse, n

Energy measured per pulse

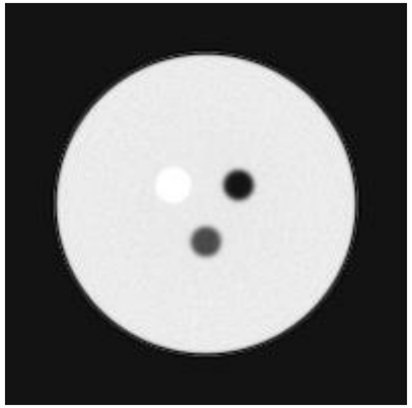
**Resolving Calorimeter**



**Averaged**

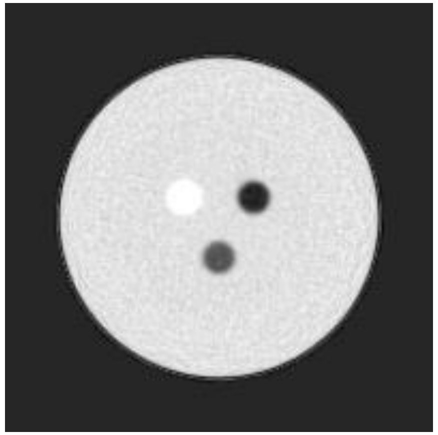


**De-averaged**

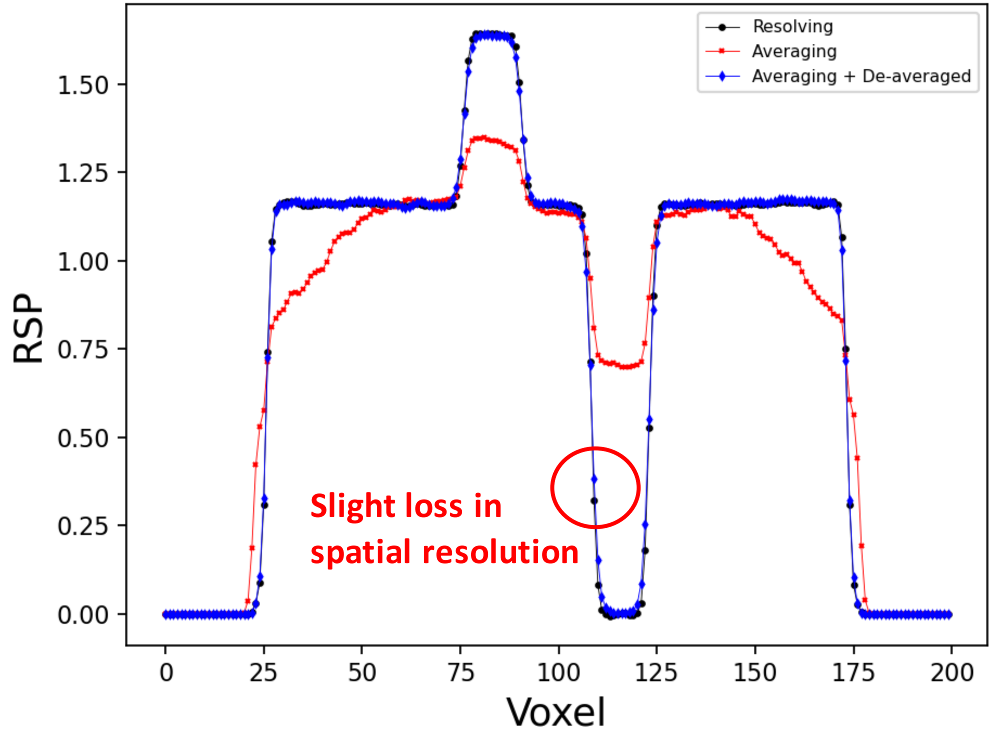


# Results

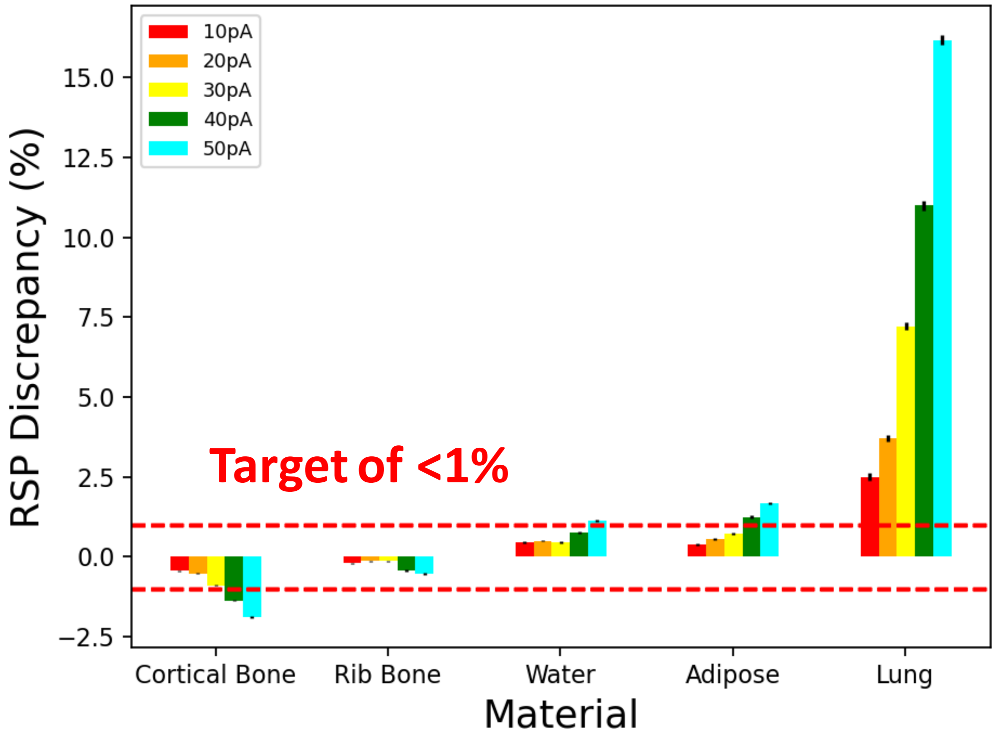
- Simulation studies performed using various tissues embedded in a 150mm Perspex sphere
- Performance evaluated for both ideal and realistic trackers
- De-averaging found to be predominantly limited by the tracking capabilities



*250pA, ideal trackers*




*Line profiles through air and skull bone tissues for images produced with ideal tracking detectors*




*RSP discrepancy in central region of tissues for simulations based on realistic detectors*

# Project Status

- **Trackers**:
  - Bare sensor testing complete
  - Ladder assembly underway at Birmingham
  - Full details of testing and full system simulation published: DOI:10.1088/1748-0221/18/04/P04026
- **Calorimeter**:
  - Full scintillator + PMT stack assembled
  - First beam test performed at Christie earlier this month
  - Patent submitted
  - Paper submitted, under review
- **DAQ**:
  - ASICs fabricated and readout designed
  - System under test by aSpect Systems, Dresden
- Full system to be completed 2024

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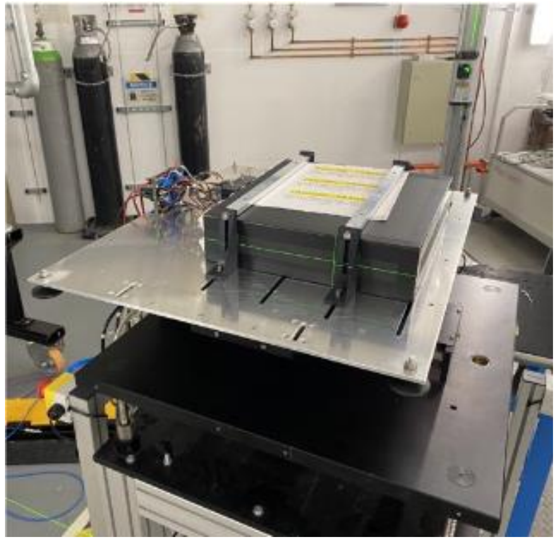
**OPTIma: a tracking solution for proton computed tomography in high proton flux environments**

A. Winter,[a,c,*] A. Aitkenhead,[d,e] N. Allinson,[c] P. Allport,[a] J. Cotterill,[a] M. Esposito,[c] S. Green,[b] K.J. Kirkby,[d,e] R.I. MacKay,[d] S. Manger,[d,e] M.J. Merchant,[d,e] T. Price,[a] S. Pyatt,[a] M.J. Taylor[d,e] and C. Waltham[c]



*Calorimeter setup from recent beam test at The Christie*

MDPI
Article

**OPTIma: Simplifying calorimetry for proton computed tomography in high proton flux environments**

Alasdair Winter[1,2,*], Bart Vorselaars[2], Michela Esposito[2], Amir Badiee[2], Tony Price[1], Philip Allport[1] Nigel Allinson[2],

# Backup

# Conclusions

- Proton CT allows for reduced range uncertainties for treatment planning
- Existing approaches struggle to cope with the high fluxes of modern facilities
- OPTIma have developed a full pCT system that is expected to deliver RSP discrepancies of <1% at multi-proton currents
  - Novel approach to energy reconstruction has greatly simplified the readout requirements for calorimeters
  - Tracking currently limited to 8 protons per bunch
    - Ideally would use CMOS once technology is ready for our beam conditions
- All parts of the OPTIma system are under construction with first tests expected in 2024