From Higgs to Healthcare

Particle Physics Detectors for Hadron Therapy Monitoring and Imaging

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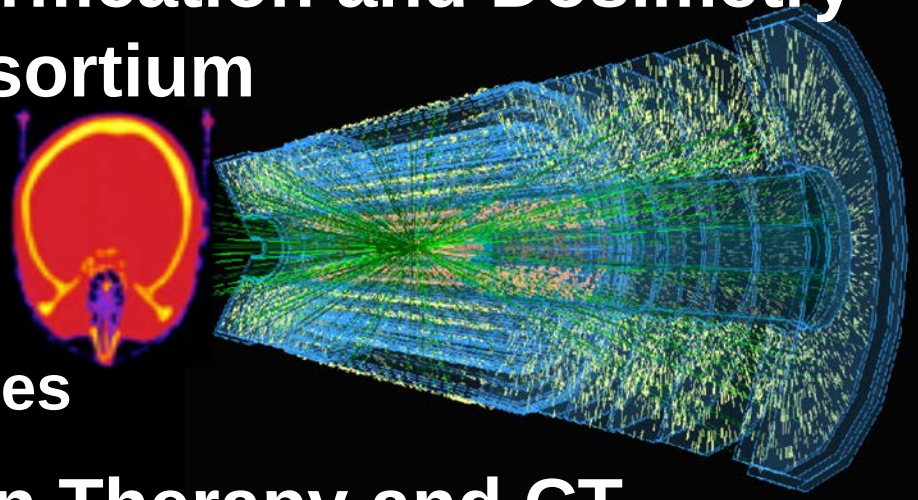
25/10/16

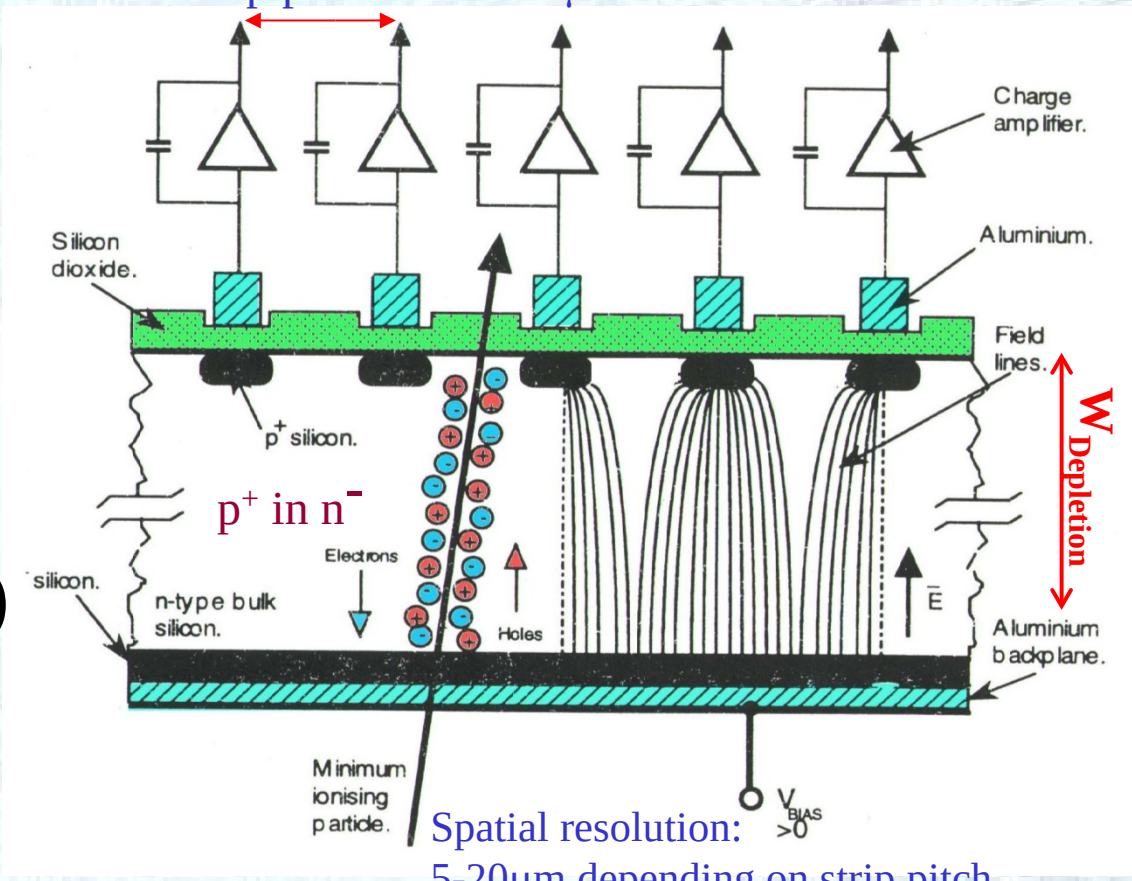
- Introduction to Silicon Detectors in Particle Physics
- The ATLAS SCT and the ATLAS Upgrade ITk
- The Proton Radiotherapy Verification and Dosimetry Applications (PRaVDA) Consortium
  - Concept and Layout
  - Performance and Results
  - SPECTRE and UK Opportunities



- International context: Hadron Therapy and CT
- Conclusions

Silicon Detector Trackers in Particle Physics

- Highly segmented silicon detectors have been used in high energy and nuclear physics experiments for 40 years
- The principle application has been to detect the passage of ionising radiation with high spatial resolution, fast timing and good efficiency.



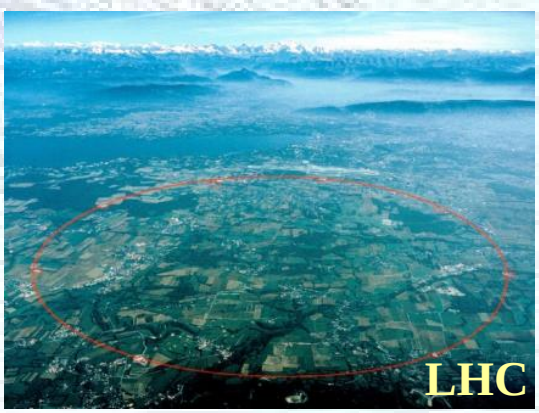
- Segmentation → position
- Depletion depth → efficiency
- ($W_{Depletion} = \{2\rho\mu\varepsilon(V_{ext} + V_{bi})\}^{½}$)

Resistivity Mobility Applied Voltage

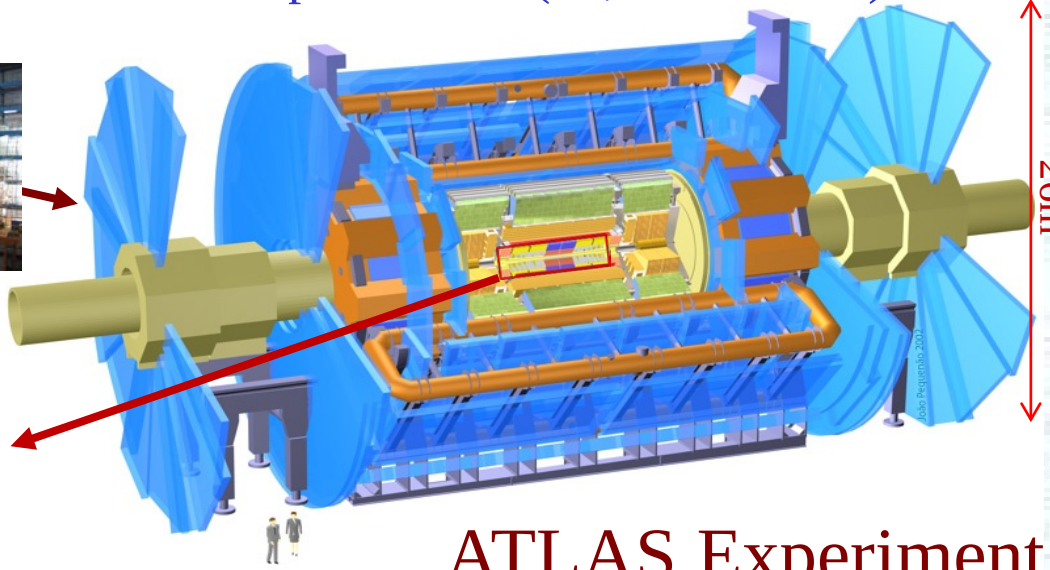
- ~80e/h pairs/μm produced by passage of minimum ionising particle, 'mip' → signal of 1.3fC per 100μm of depleted detector
- Signal collected typically in a few ns (depends on ρ, μ and V)

Silicon Detector Trackers in Particle Physics

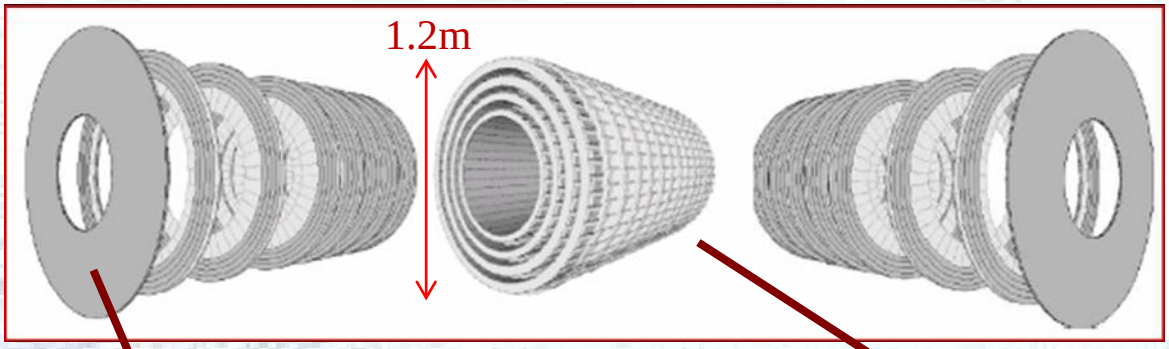
- **Large areas of silicon detectors for high rate, high radiation environments built for the Large Hadron Collider at CERN**

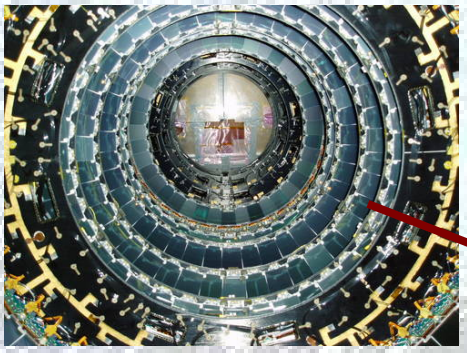


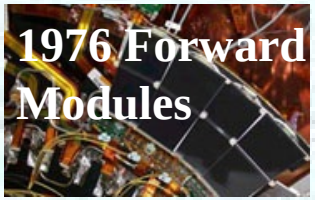
The innermost tracking system has 610,000 cm^2 of silicon micro-strip detectors (17,000 sensors)

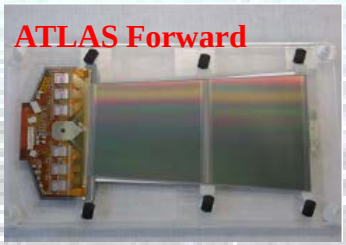


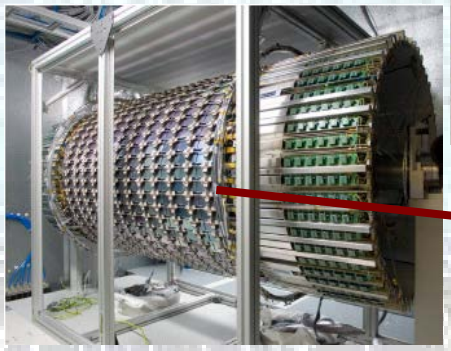
ATLAS Experiment

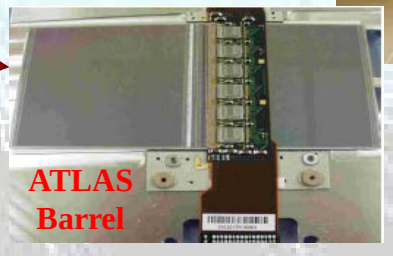










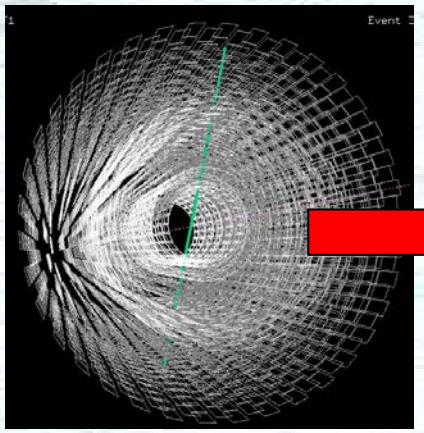


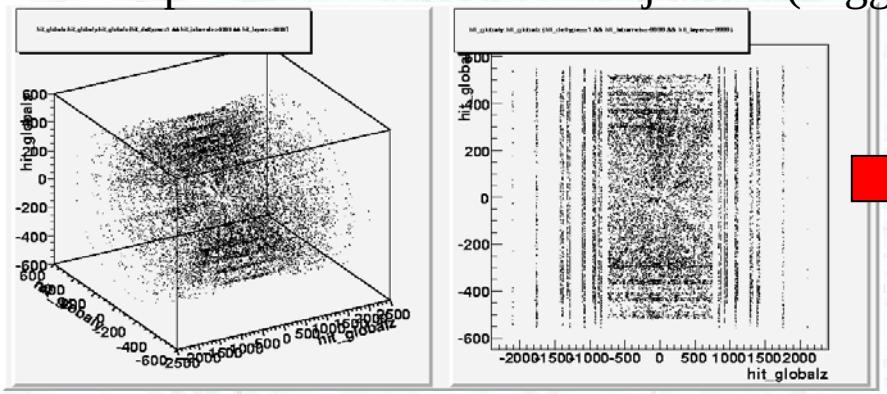
Silicon Detector Trackers in Particle Physics

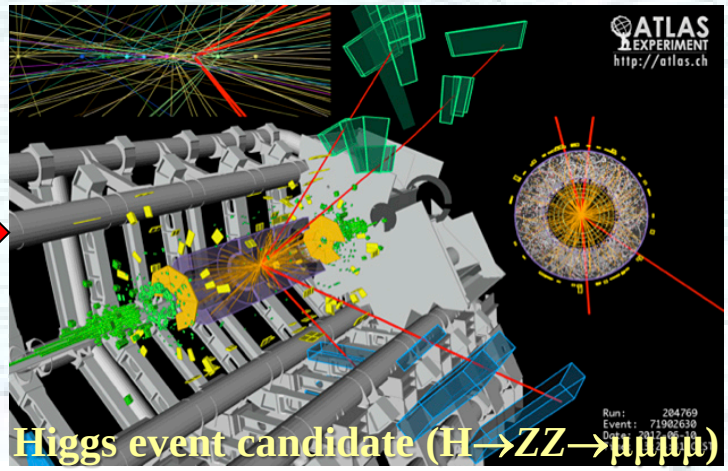
- Large areas of silicon detectors for high rate, high radiation environments built for the Large Hadron Collider at CERN
- Charged particle tracks found from joining hits in the large arrays of finely segmented silicon detectors

New image every 25ns but can only store up to 1000/s

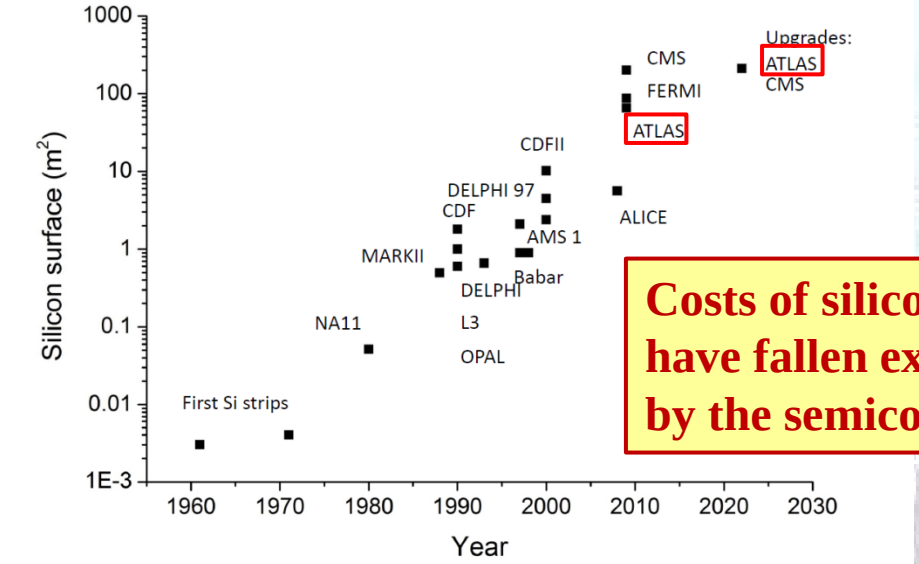
Need complex on-detector event rejection (triggering)





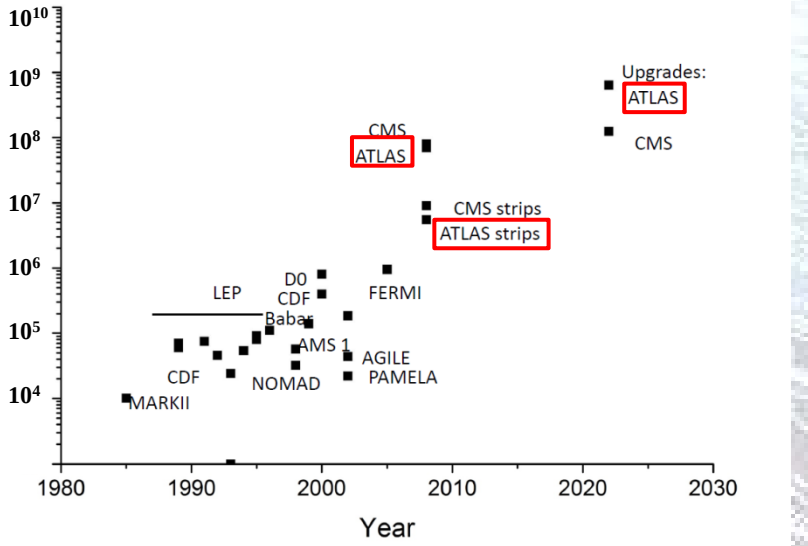


Higgs event candidate (H→ZZ→μμμμ)



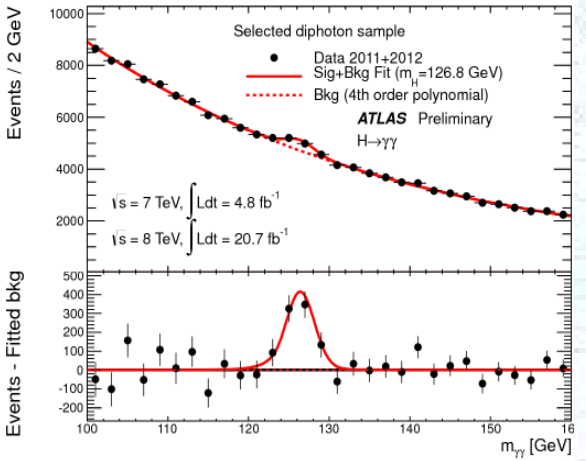
Detector areas and channel numbers grow exponentially

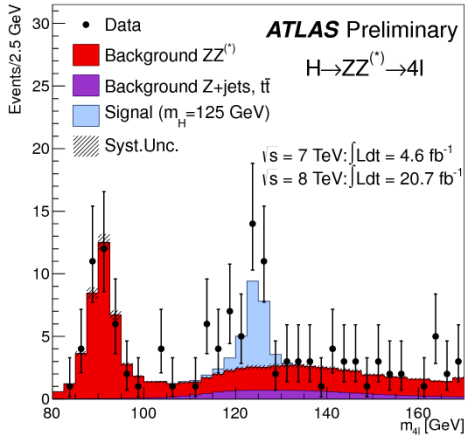
Costs of silicon technologies have fallen exponentially driven by the semiconductor industry

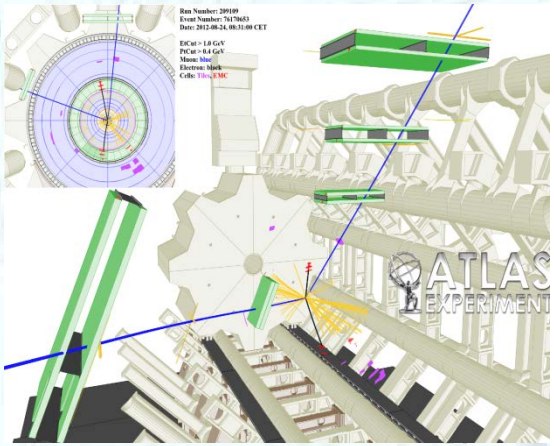


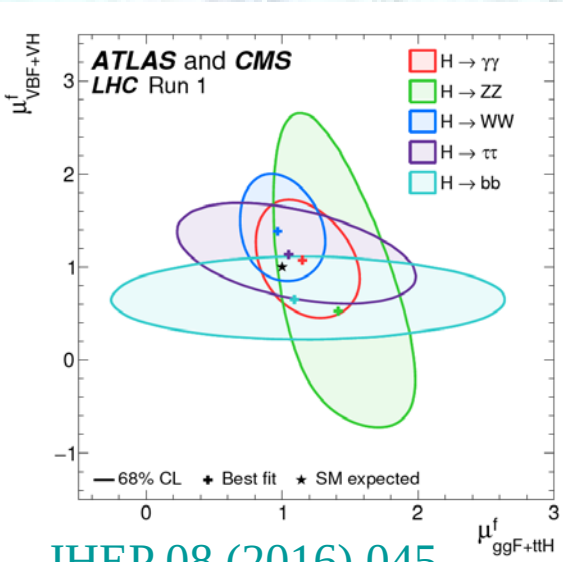
Discovery of the Higgs at the LHC

- Prior to the LHC start-up all we knew: Higgs mass > 114 GeV
- After 2 years of successful LHC operation, in July 2012 ATLAS and CMS announced the discovery of a new Higgs-like boson
- Clearest in γγ, ZZ, but now many channels probed









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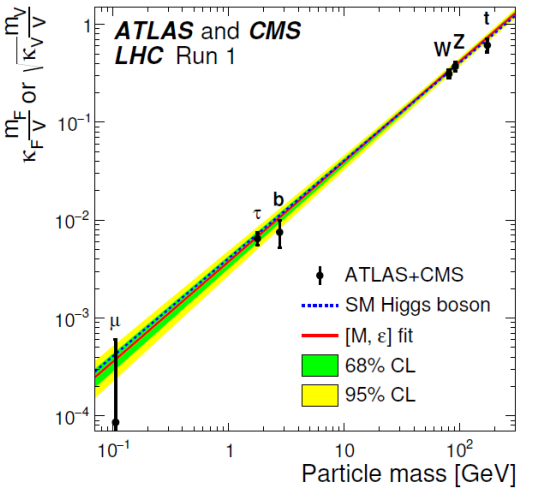
ATLAS+CMS combined fit:

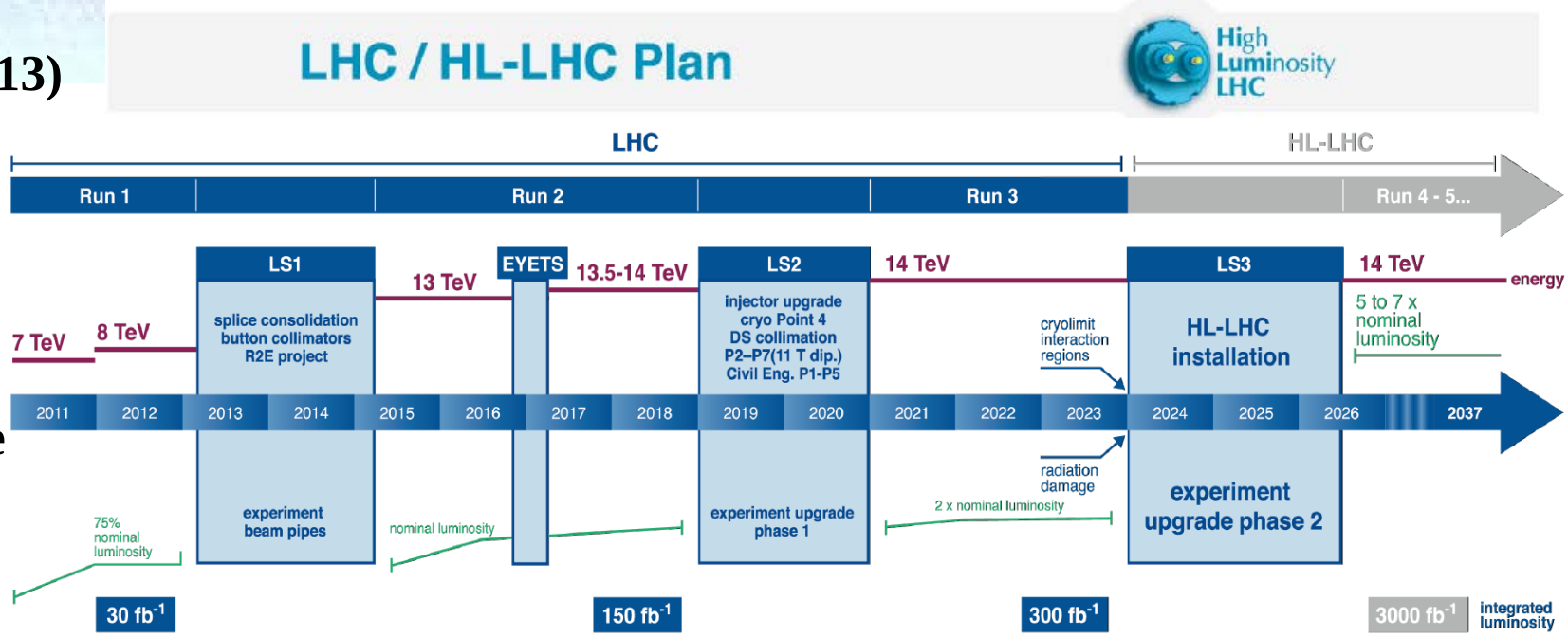
$m_H = 125.09 \pm 0.24\ (0.21\ \text{stat.} \pm 0.11\ \text{syst.})$ GeV

- It is unique amongst the fundamental particles we know (zero spin: so neither a force or matter particle)
- It is key to the way the universe works
- It is stepping stone to a deeper understanding
- Priority is detailed measurements of all its properties



Energy Frontier: Next Steps at the LHC

CERN Council (May 2013)
"The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.

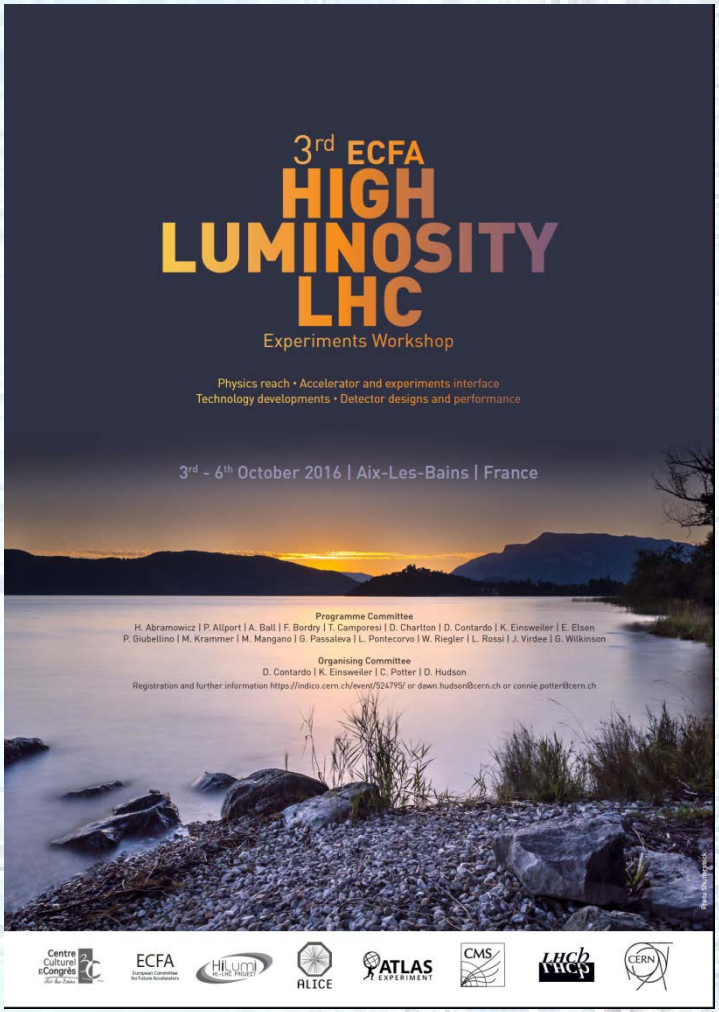


"*Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030*"

HEPAP in the US (May 2014) decided: "*The HL-LHC is strongly supported and is the first high-priority large-category project in our recommended program***"**

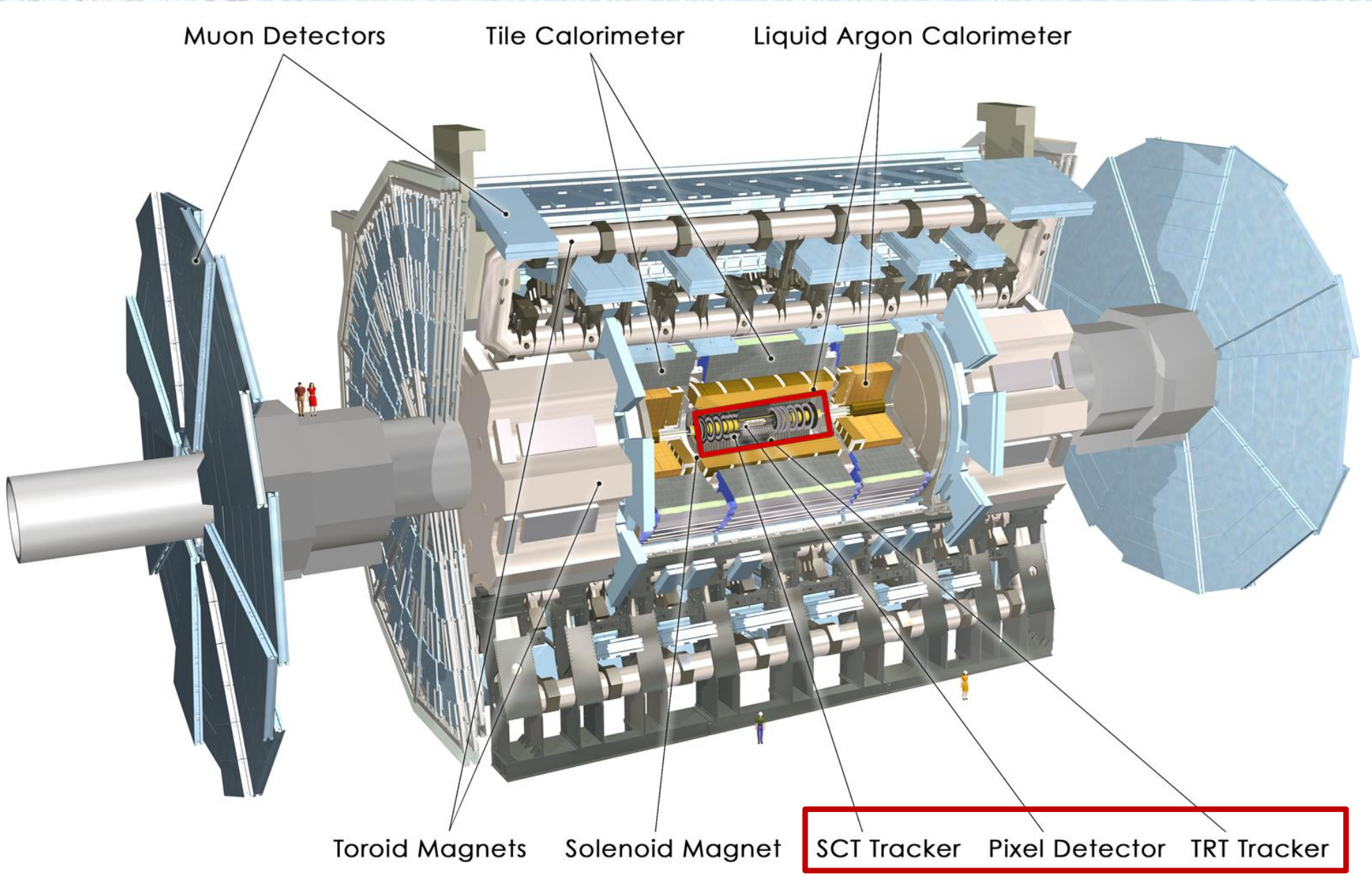
CERN Council (June 2016) Formal approval of the High Luminosity LHC project, HL-LHC

Energy Frontier: Next Steps at the LHC



ATLAS Phase-II Tracker Upgrade (ITk)

Current ATLAS Inner Detector ($60m^2$, 10^8 channels)



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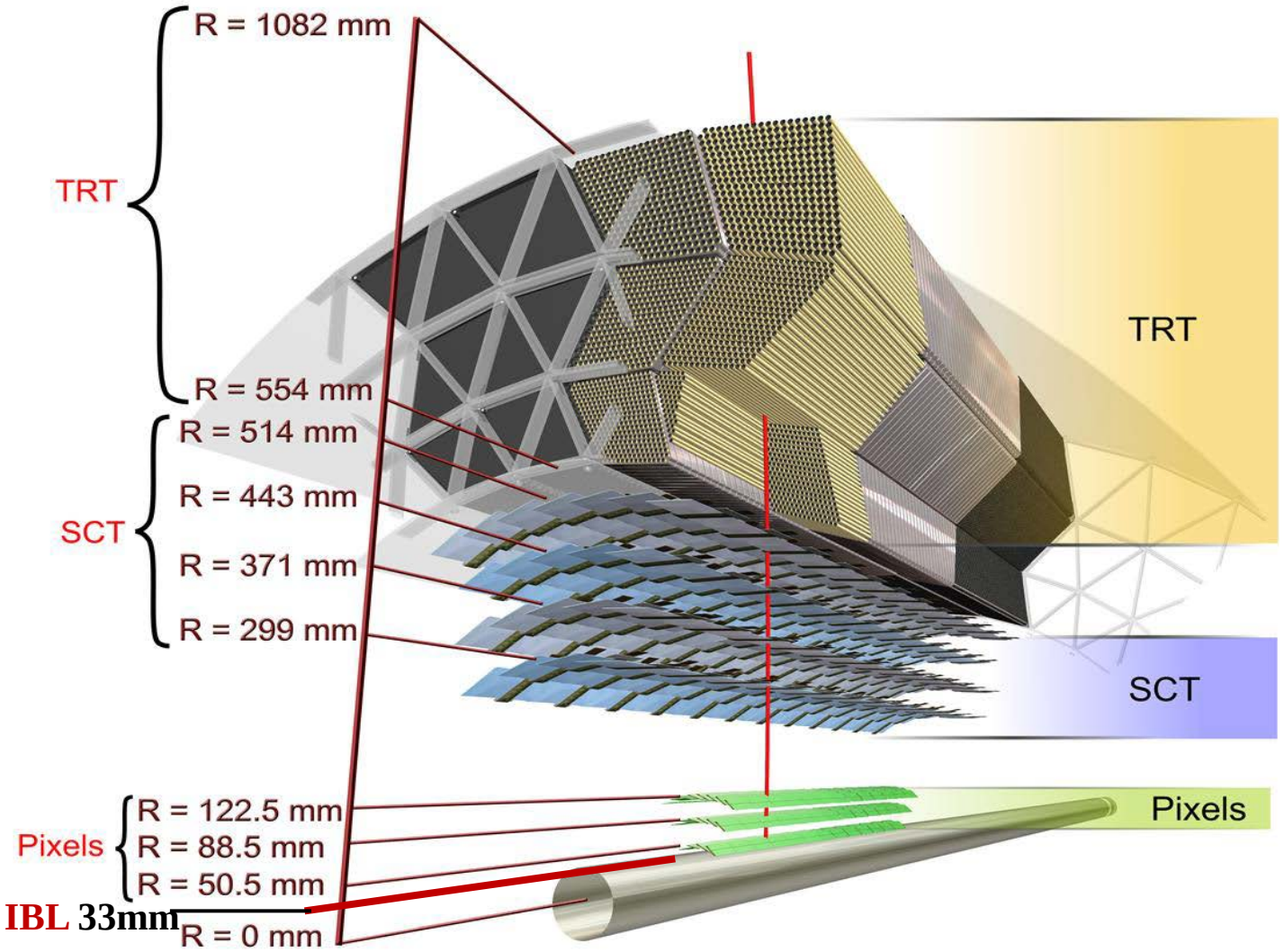


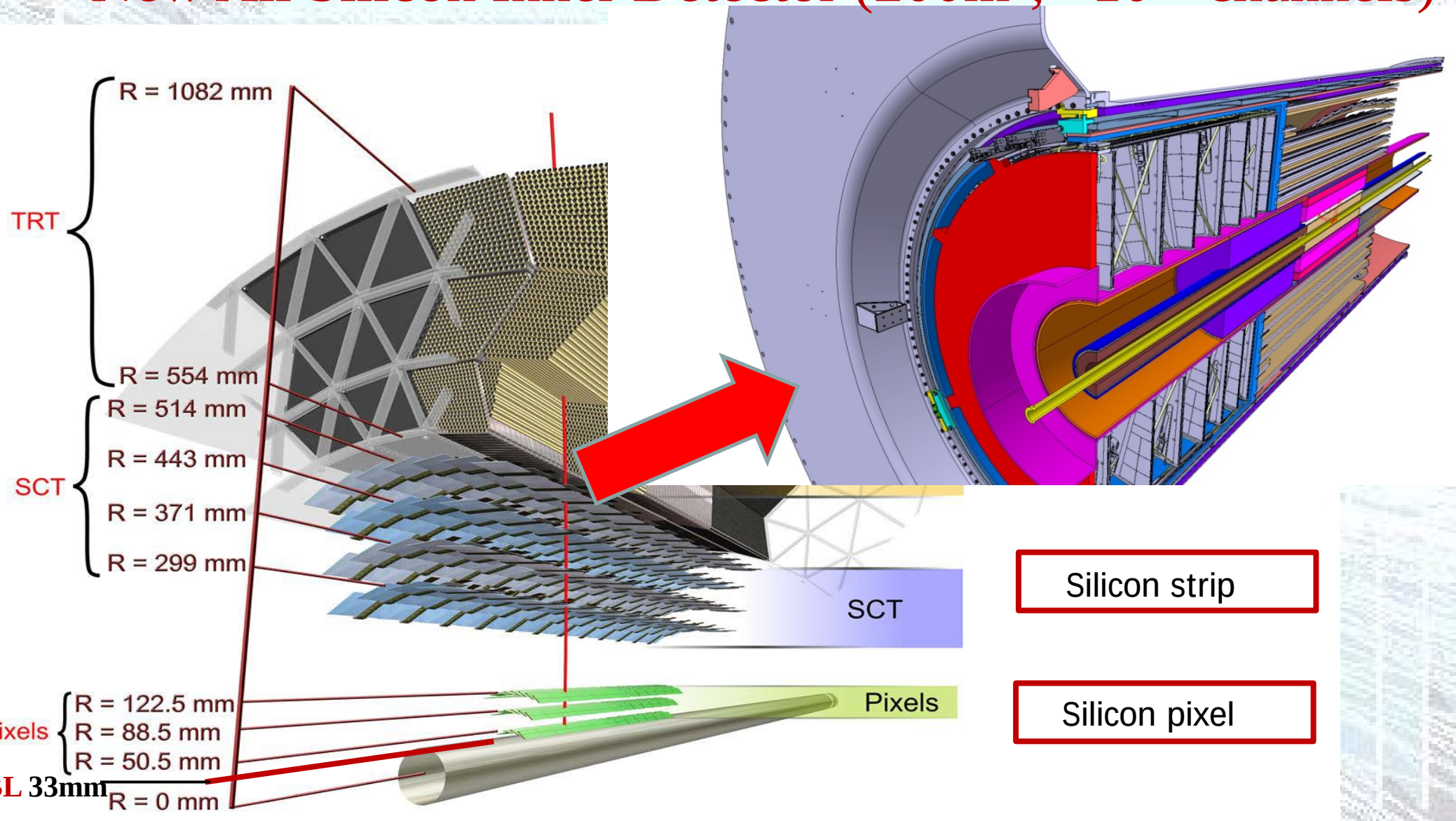
Straw tubes

Silicon strip

Silicon pixel

ATLAS Phase-II Tracker Upgrade (ITk)

New All Silicon Inner Detector (200m^2, ~10^{10} channels)



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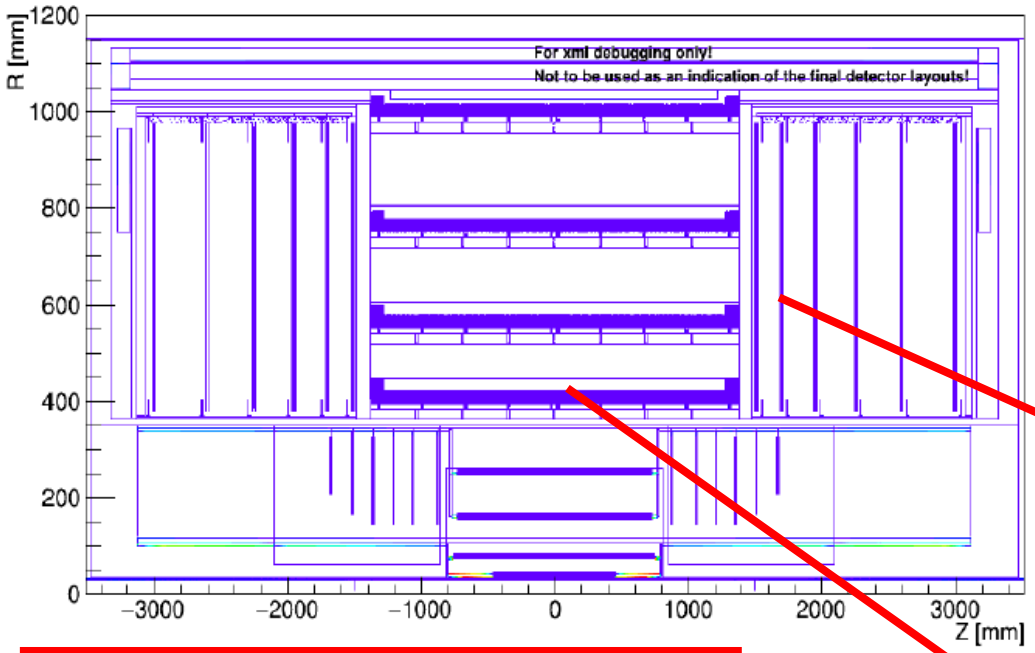

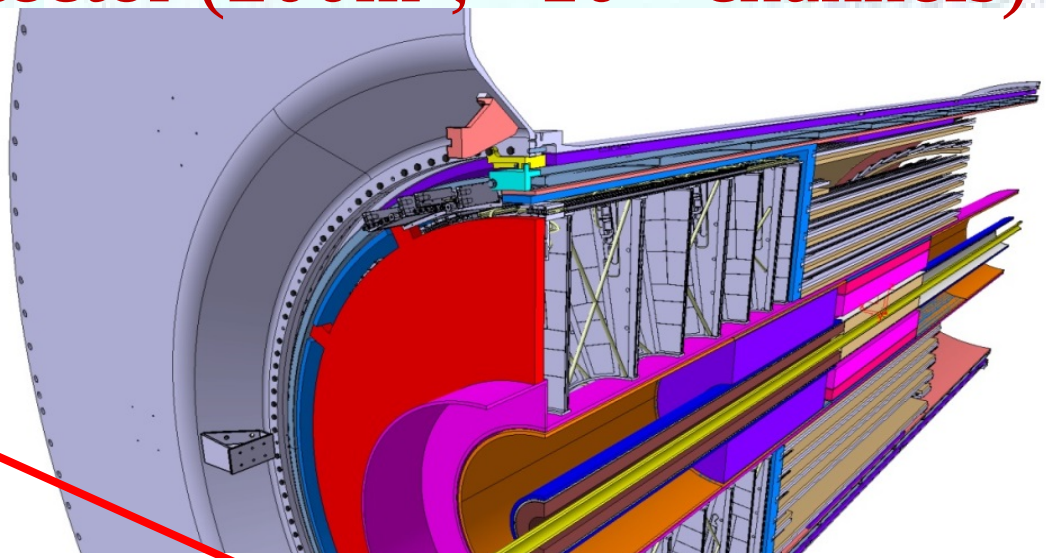

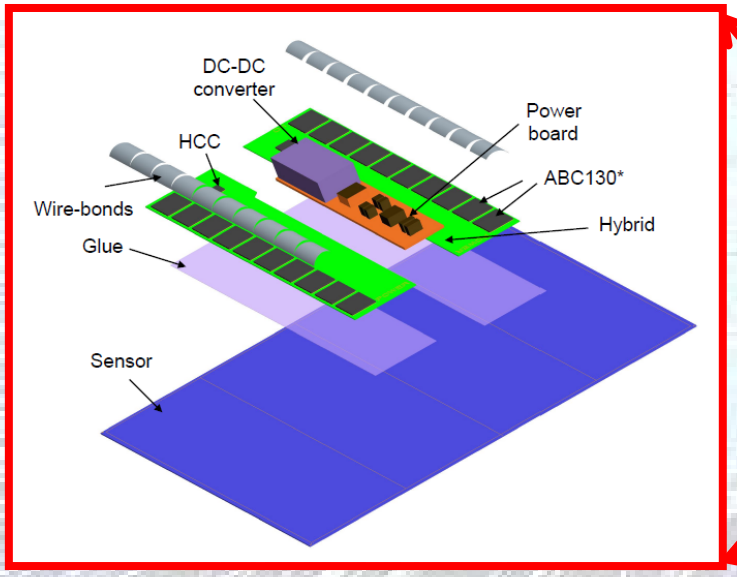

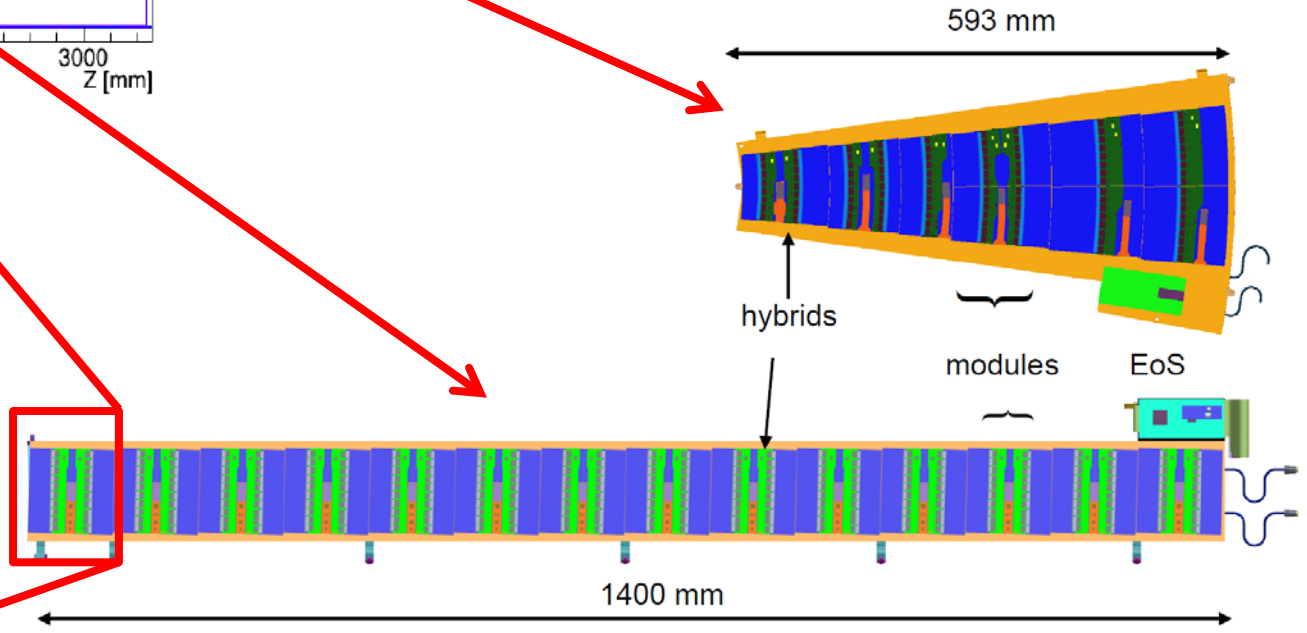

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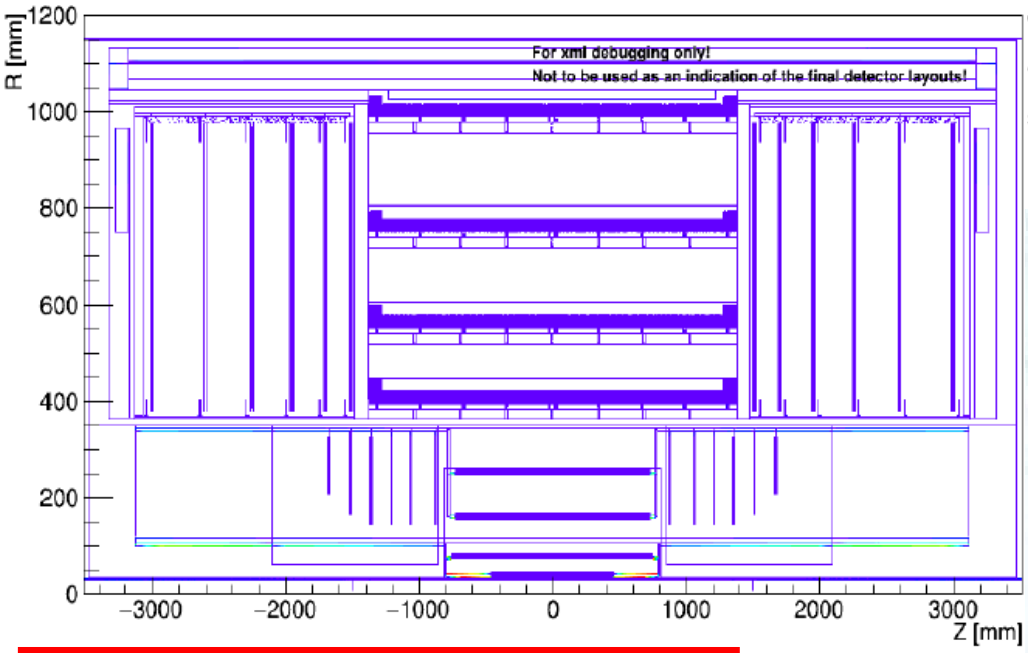
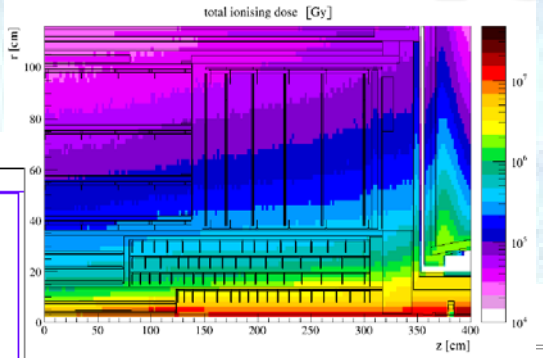
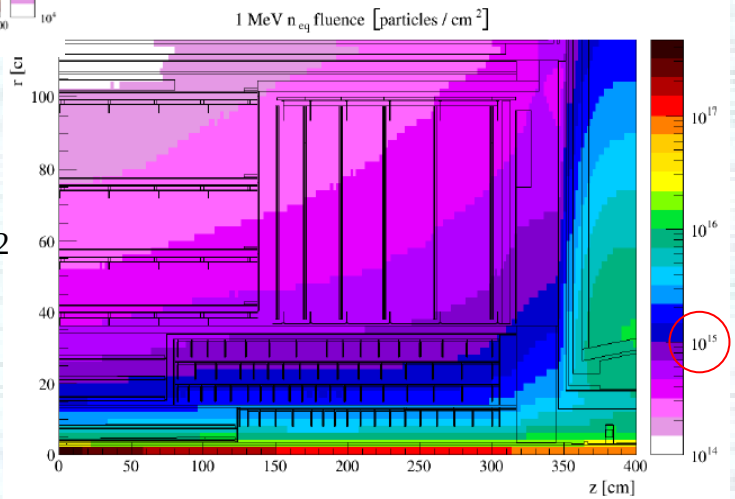
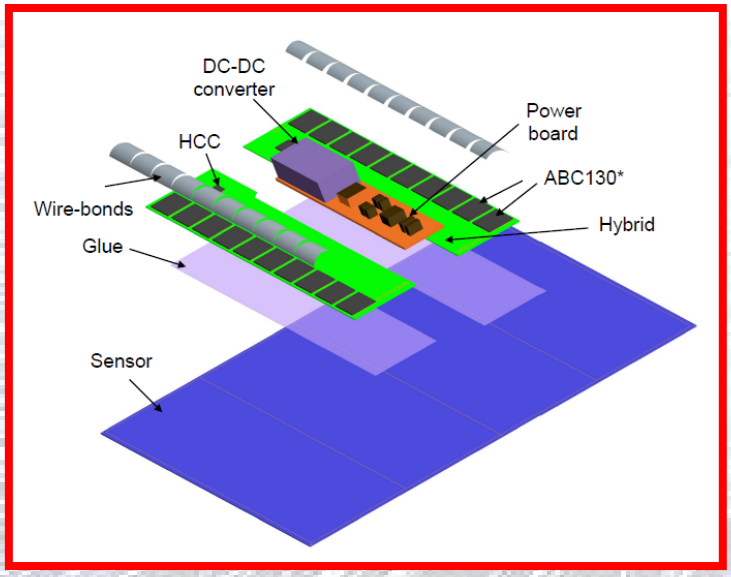


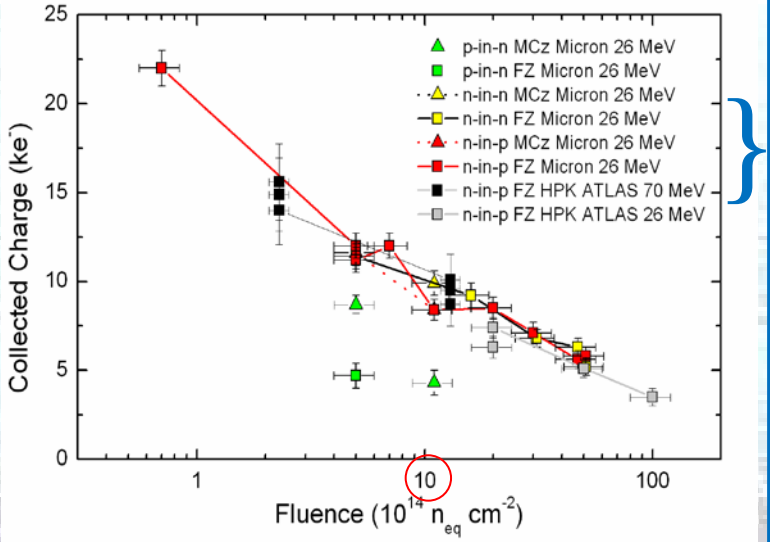


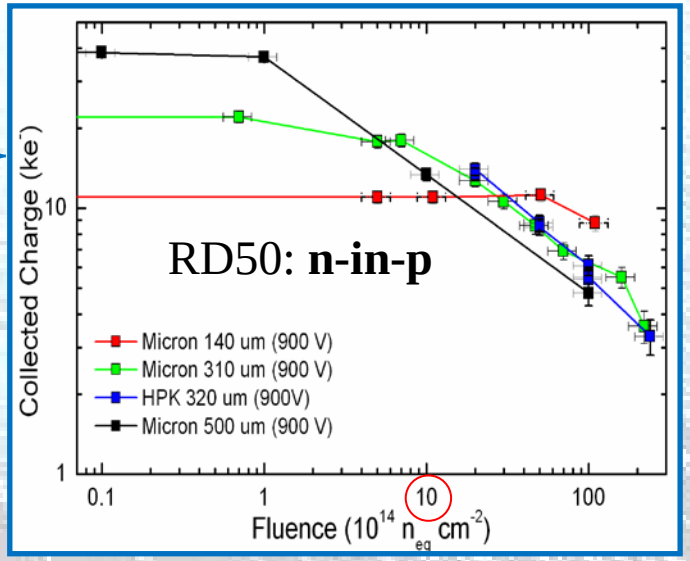
Unprecedented levels of radiation at HL-LHC

Strip detectors must survive damage to lattice equivalent to that from $1.2\times10^{15}/cm^2$ 1 MeV neutrons and 0.5 MGy.
(Pixels > ×10 this)





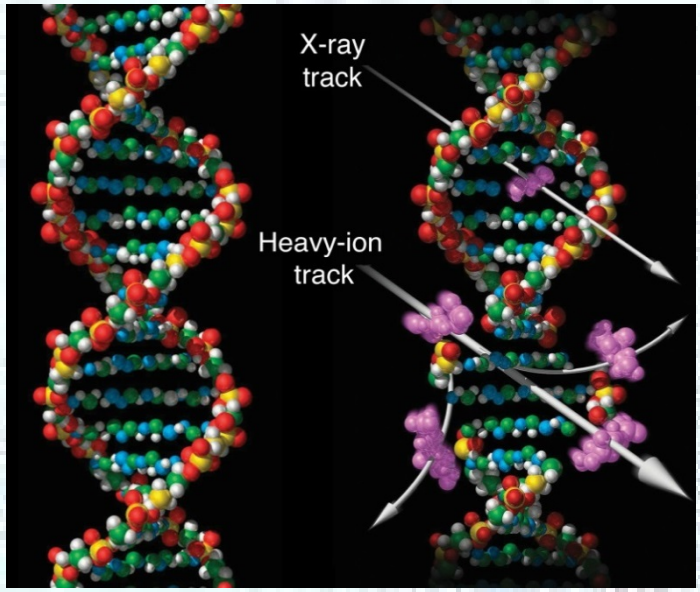




Proton Radiotherapy Verification and Dosimetry Applications

- Cancer is responsible for 1 in 8 deaths worldwide
- In the UK alone there is 350,000 cases per year and 1 in 2 people will be affected by cancer at some point in their lives
- Most common cancers in the UK are Lung (22%), Colorectal (10%), Breast (8%), Prostate (6%)
- Overall survival rate in the UK is above 50%
- Radiotherapy is used in 40% of all cancer treatment in the UK

- Radiotherapy uses radiation to kill the cancer cells
- Energy is deposited in the cells which damages the DNA and stops the cells from replicating
- Surrounding healthy cells are also damaged so need to plan treatment to minimise the dose to the healthy tissue and maximise that to the cancer

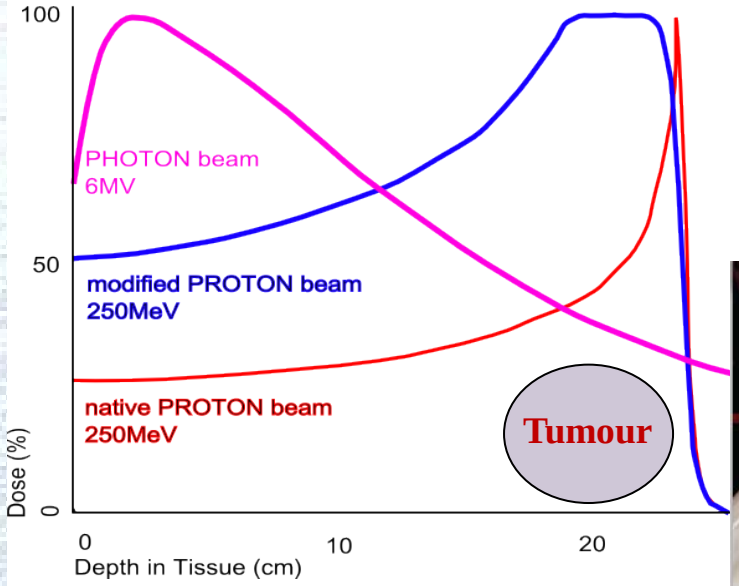


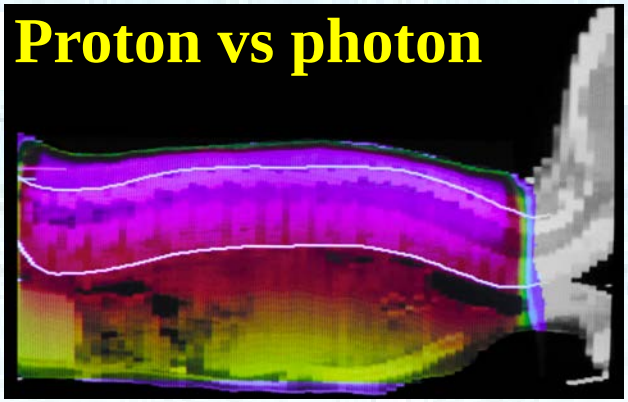
- High energy x-rays from linear accelerators to treat cancer deep inside a patient
- Low energy x-rays and electrons to treat skin cancers
- Protons/Ions used to give highly localised dose distributions using beams mostly from cyclotrons or synchrocyclotrons
- Ions heavier than protons cause even more ionisation and more complex forms of damage, resulting in less repair and a more lethal effect on the tumour
- Recent EuCARD^2 Workshop at Birmingham (https://indico.cern.ch/event/456299/)

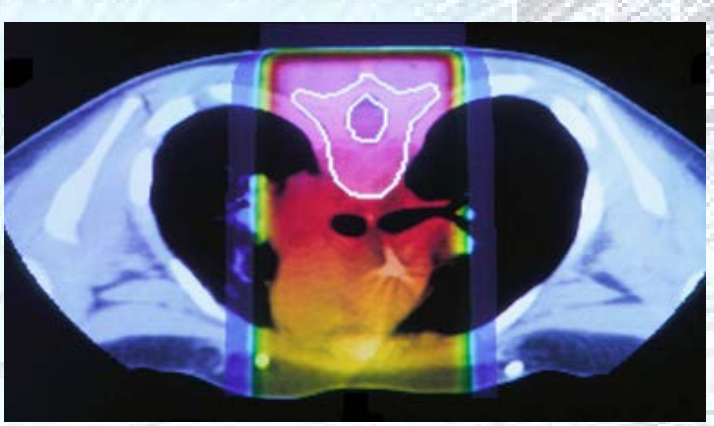
Proton Radiotherapy Verification and Dosimetry Applications

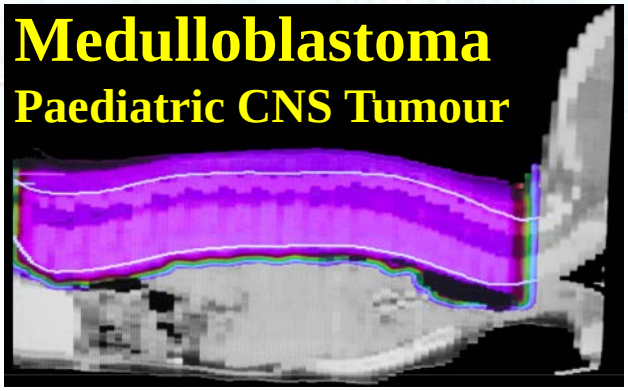
Proton and Ion therapy

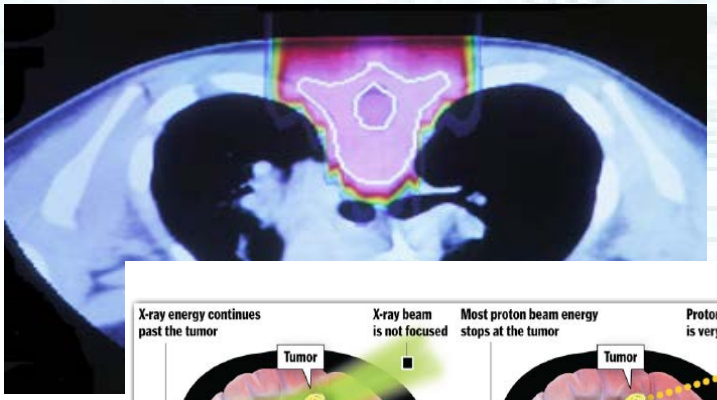
- Tumours in the head and neck region
- Tumours near the spine or other critical organs
- Some types of brain tumours
- Some childhood cancers so the risk of second cancers later in life is greatly reduced
- Shorter treatment lengths
- Less side-effects
- Faster recovery

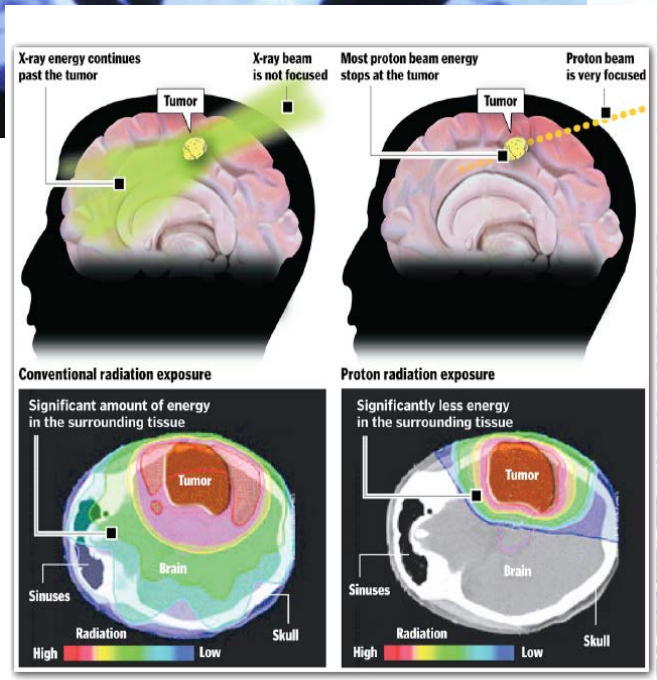








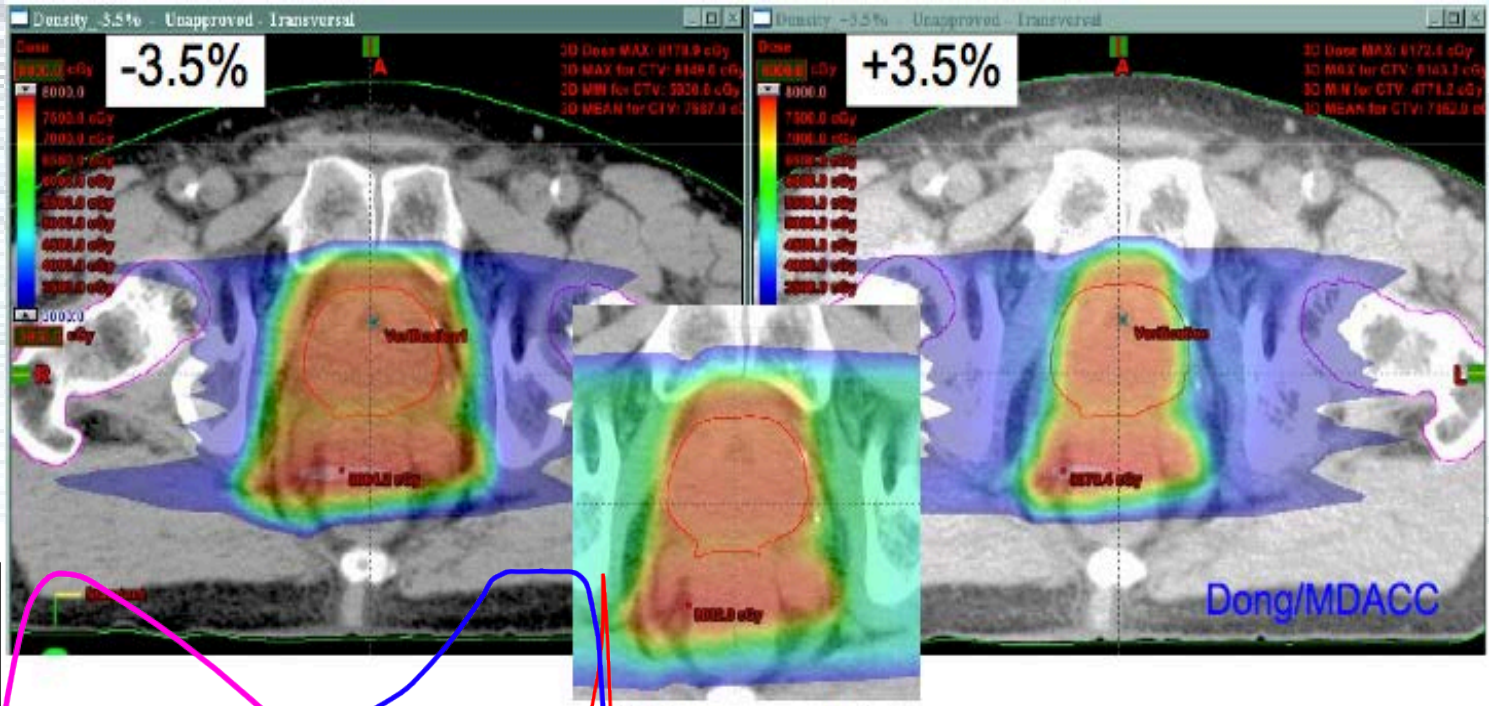


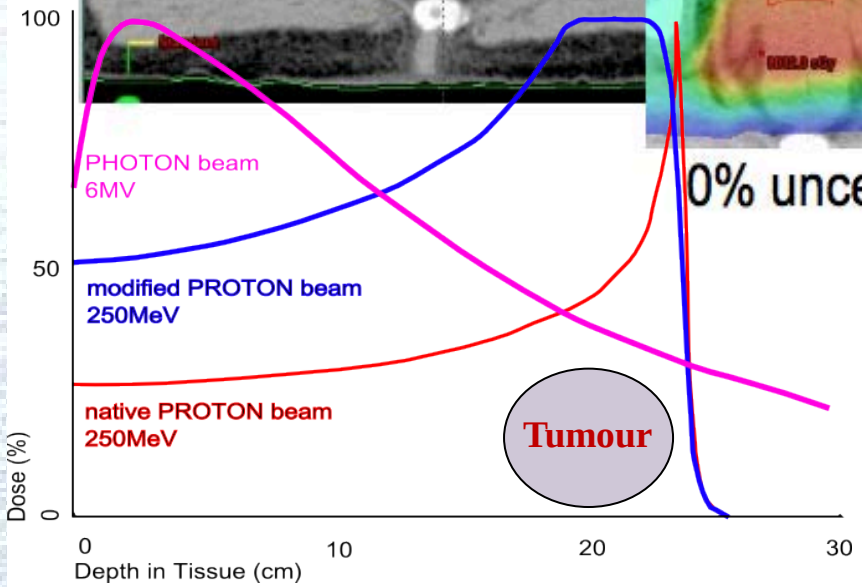


https://www.ptcog.ch/index.php/

Lists 70 facilities in operation, 37 "in construction" and 17 in planning stage

Proton Radiotherapy Verification and Dosimetry Applications





Advantage

Intense dose in small targeted volume

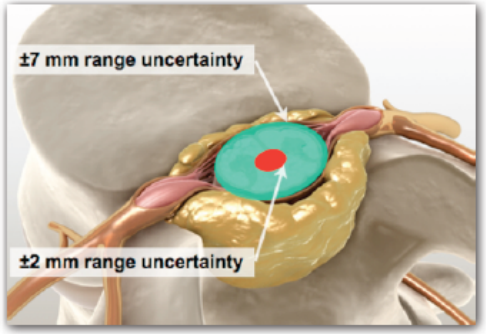
Potential Problem

Intense dose in small healthy volume

Patient planning

- Perform x-ray CT
- Translate from diagnostic x-rays to treatment protons
- Prone to errors - 1 - 2 cm in soft tissue, greater in bone

- **Need to see the patient using the "same" protons as used in treatment**



Proton Computed Tomography (pCT) hoped to be the key

https://www.ptcog.ch/index.php/

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Proton Radiotherapy Verification and Dosimetry Applications

- **Integrated beam monitoring, computed dosimetry and tomography instrumentation for proton therapy**
- **Supported by the Wellcome Trust Translation Award Scheme, grant WT098285.**
- **Members from academia, industry, and the health service.**

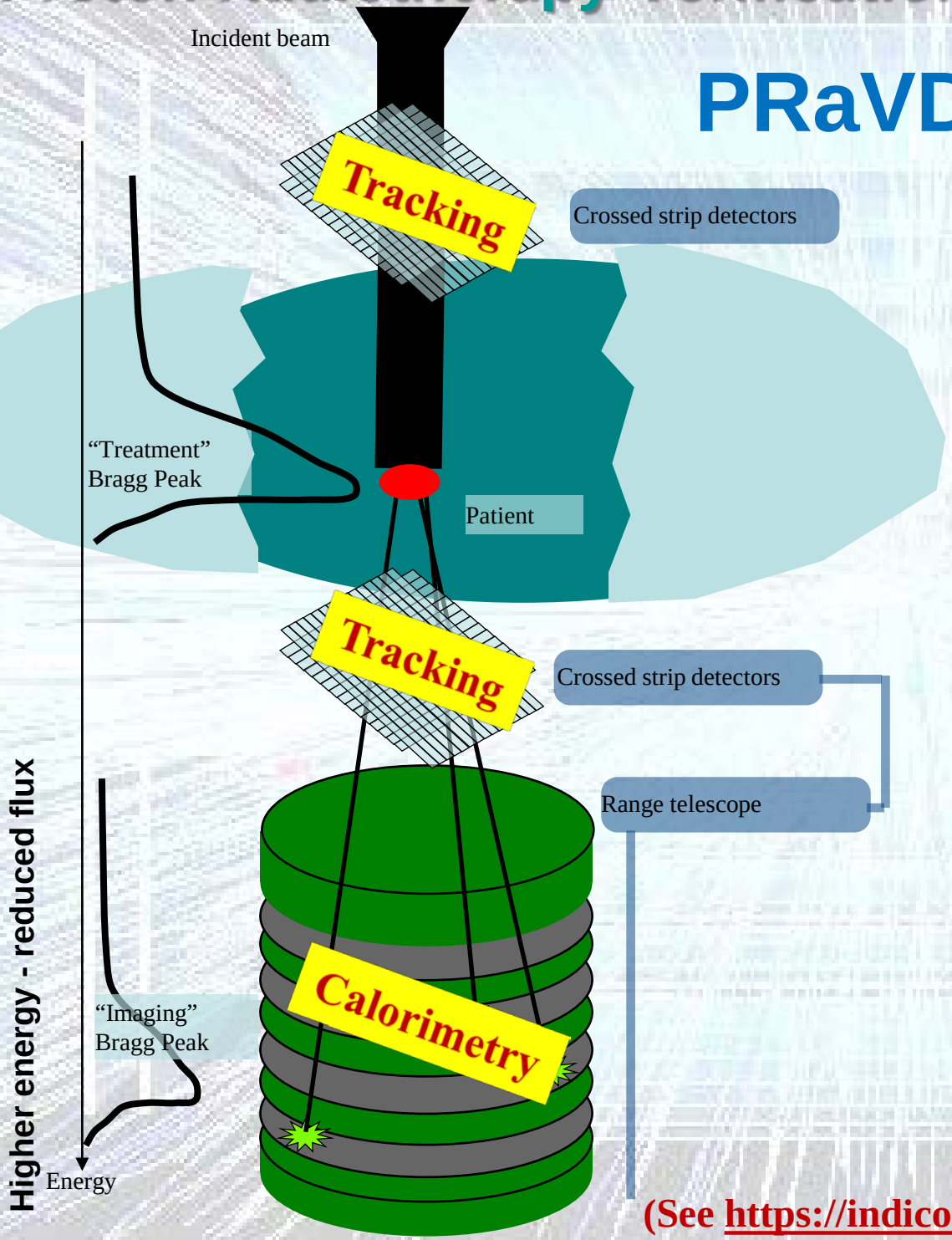
- **One of only 22 projects across all of science and engineering selected for RS Summer Exhibition (http://sse.royalsociety.org/2014/) and winner of 2014 Innovation Award of the IET.**

IET AWARDS The Institution of Engineering and Technology

INNOVATION WINNER 2014

2016 shortlisted: The Engineer 'Collaborate to Innovate' Award

Proton Radiotherapy Verification and Dosimetry Applications



PRaVDA System Overview

Records beam position and profile in real-time to correct beam steering

Beam profile, particle flux for a given current and energy distribution can be routinely determined to cross-check delivery system calibration

With gantry movement permit full proton-Computed Tomography (pCT) scan using same particle type as for treatment.

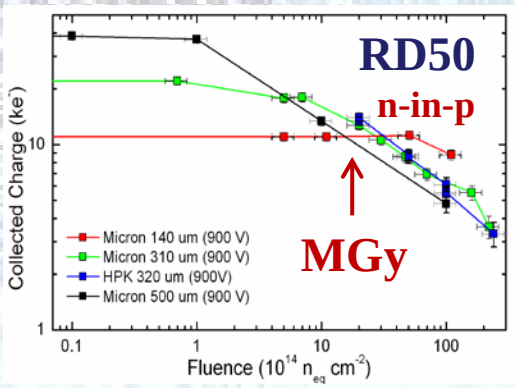
Current uncertainty in proton range is ~3.5%. If beam passes through 20cm of tissue, then Bragg peak could be anywhere within +/- 7 mm

Aim to reduce proton range uncertainties to a ~1% – variation of +/- 2mm.

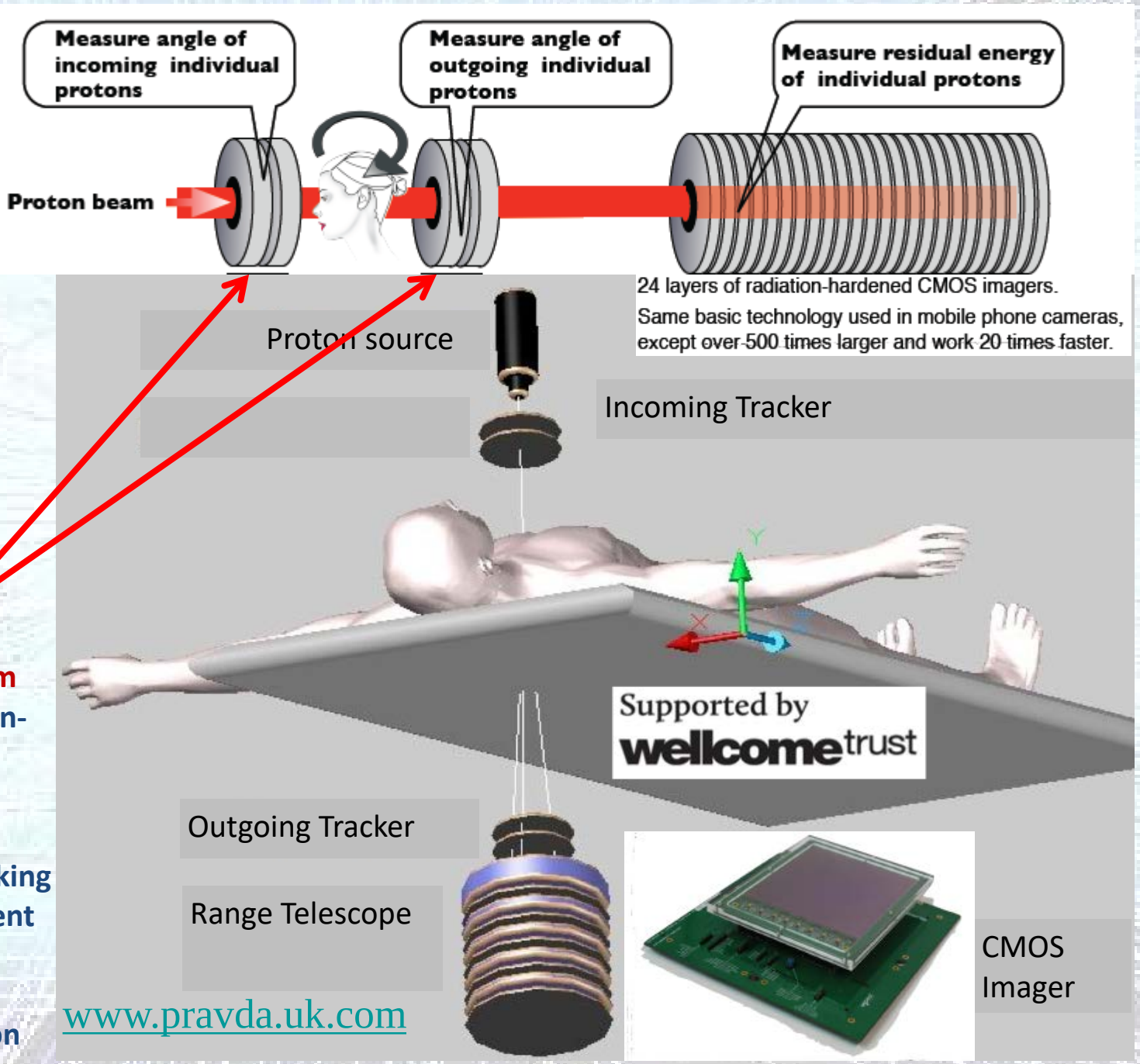
Simplified treatment plans – fewer beams; reduced probability of secondary cancers induced; and treatments will be shorter

(See https://indico.cern.ch/event/340417/session/6/contribution/95)

Proton Radiotherapy Verification and Dosimetry Applications



PRaVDA micro-strip detector

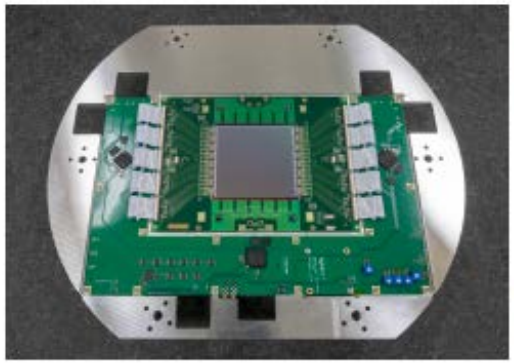


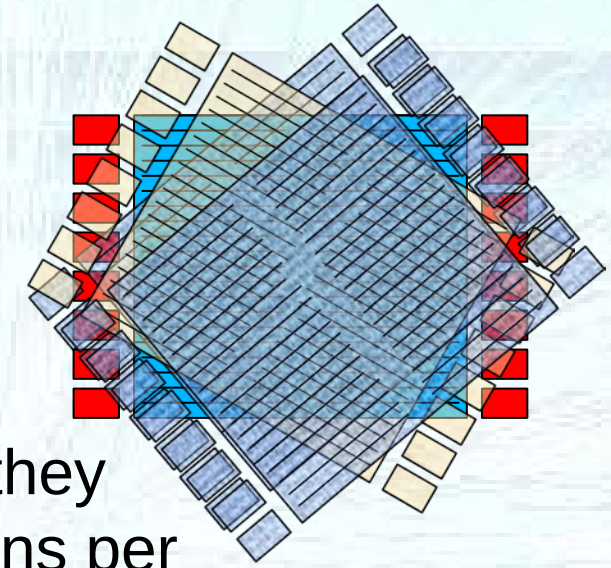
Silicon sensors with 2048 strips at 91µm pitch using 150µm thick n-in-p radiation-hard technology developed for High Luminosity LHC

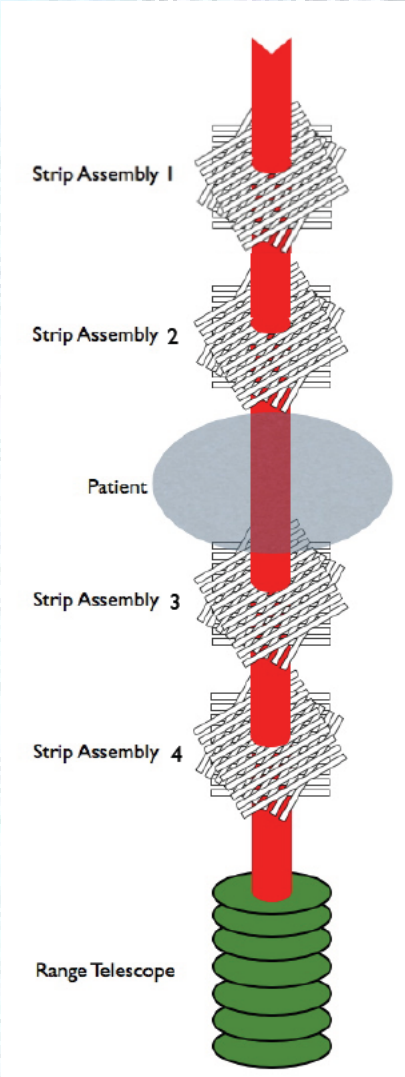
12 planes of strips used to make 4 tracking modules, 2 before and 2 after the patient

Each module of strips has three planes crossed at 60° in an (x,u,v) configuration to allow high particle rate

Proton Radiotherapy Verification and Dosimetry Applications

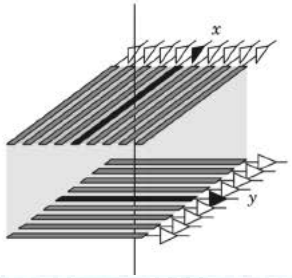


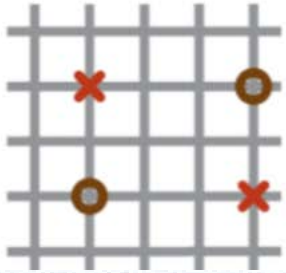




- **x-u-v:** A disadvantage of other systems with crossed strips is that they cannot cope with two or more protons per frame without ambiguities.

For a strip detector with orthogonal strips and N hits, there are: $N^2 - N$ 'Ghost-hits' or ambiguities generated

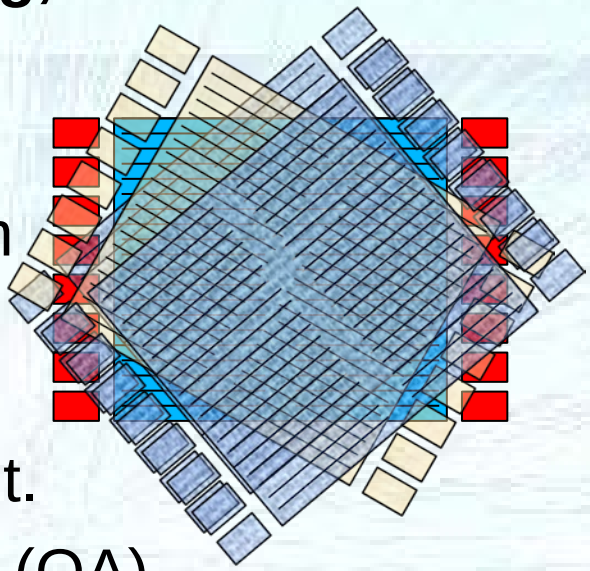


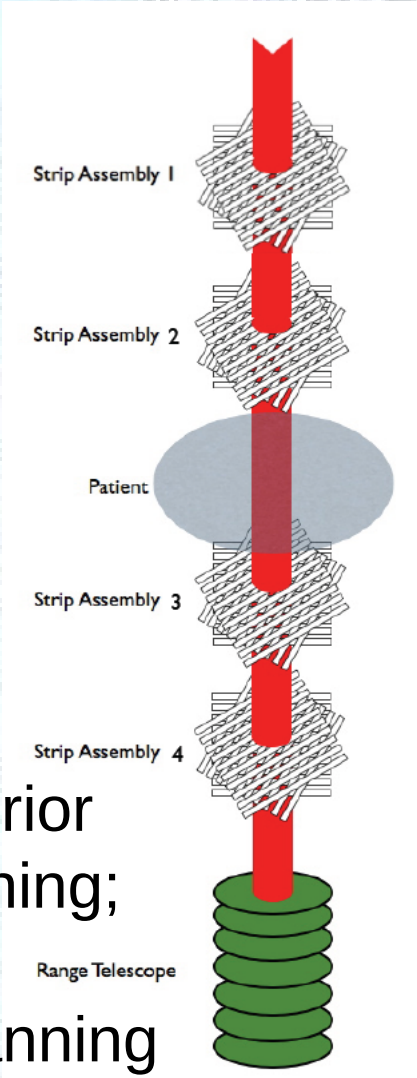


- The usual way round this with strips is to have a third layer **(3N Channels)**
- Depending on strip pitch, still problems above ~100 hits / frame
- Then need truly pixelated sensor, but needs to be fast **(N^2 Channels)**

Proton Radiotherapy Verification and Dosimetry Applications

- **PRaVDA targets beam monitoring, beam diagnostics and pCT**
- **In-treatment Beam monitoring.**
  - This can be employed when beam is being delivered to a patient.
  - Also when the treatment beam is being checked prior to treatment.
  - Useful for basic quality assurance (QA) of the proton beam during commissioning.





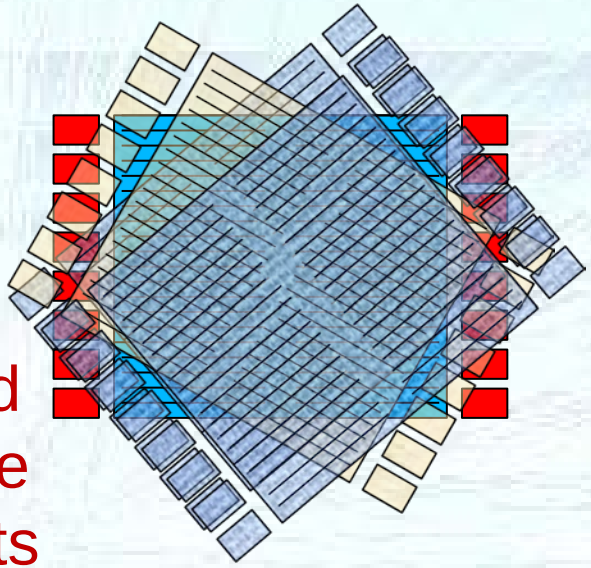
- **Patient Imaging.** This mode could be used several days prior to the first treatment fraction to obtain a CT image for planning; planar and CT imaging may also be used on treatment days for intra-fraction image-guidance or subsequent replanning
- Designed for **~10^5 protons/cm^2/s** and 39ns duty cycle (iThemba)

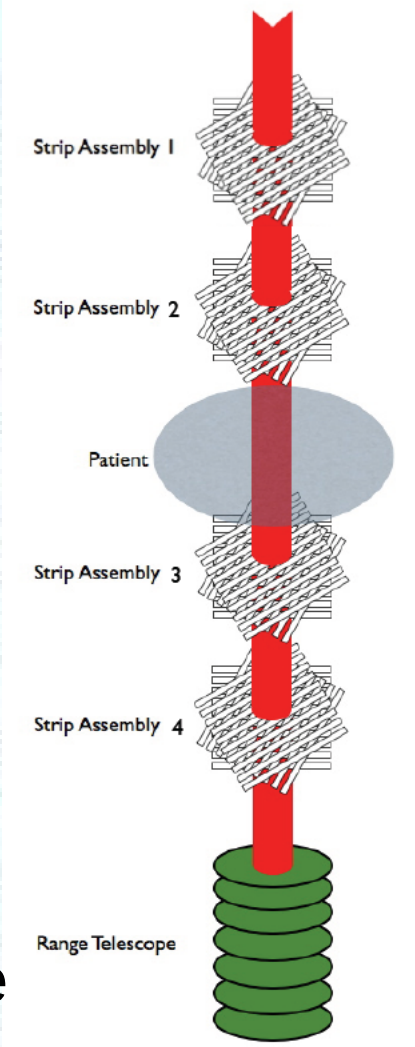
  Energies at IThemba up to **191 MeV**

  Collimation to 8.5cm diameter beam (not spot scanning mode)

Proton Radiotherapy Verification and Dosimetry Applications

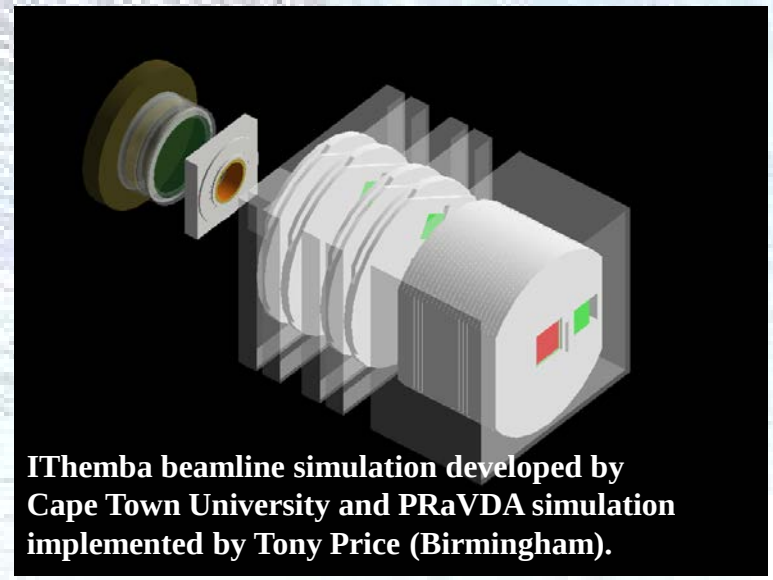
- **In-treatment Beam monitoring:**
- **10^7 protons/cm^2/s** at energies ranging from **60-191 MeV**
- Assuming 50cm^2 and 39ns would expect ~20 protons per frame
- At this rate ambiguities rates should still be negligible and 2D hits can be reconstructed but for higher currents could expect significant ambiguities but can still histogram 1D projections. (Can register double hits on strips as two thresholds can be set.)



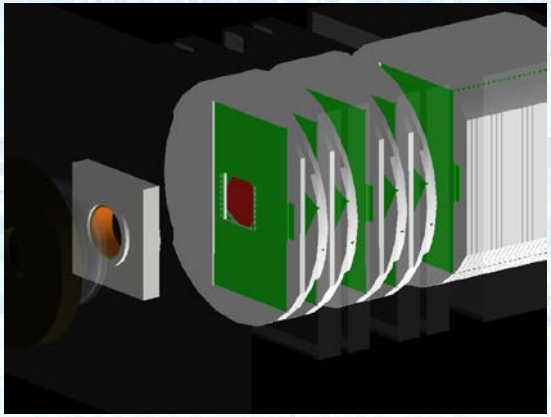


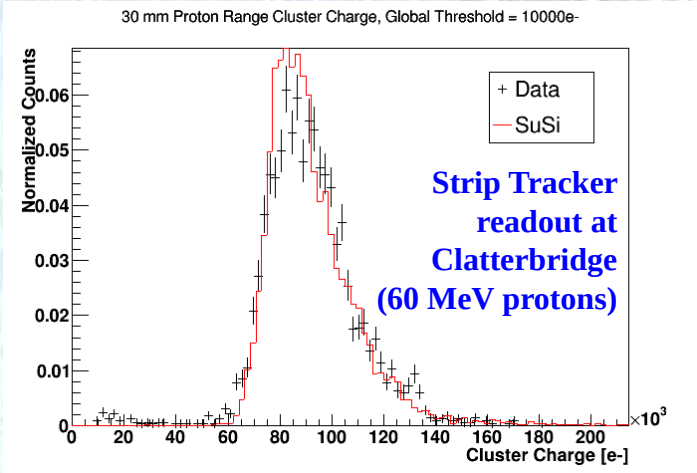
- **Patient Imaging:**
- **10^5 protons/cm^2/s** in 39ns gives < 1 proton per duty cycle
- This is well within what can comfortably handled from an ambiguities perspective.
  The strip system would certainly cope with a higher data rate if there was sufficient read-out bandwidth.

Proton Radiotherapy Verification and Dosimetry Applications



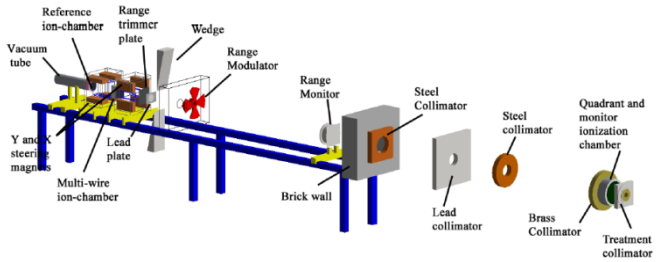
IThemba beamline simulation developed by Cape Town University and PRaVDA simulation implemented by Tony Price (Birmingham).

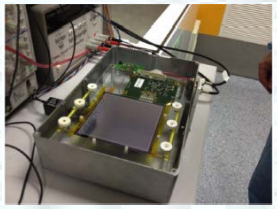




Strip Tracker readout at Clatterbridge (60 MeV protons)

iThemba LABS Proton Therapy Beamline





Proton tracking for medical imaging and dosimetry

J.T. Taylor,[a,1] P.P. Allport,[a] G.L. Casse,[a] N.A. Smith,[a] I. Tsurin,[a] N.M. Allinson,[b] M. Esposito,[b] A. Kacperek,[c] J. Nieto-Camero,[d] T. Price[e] and C. Waltham[b]
[a]Department of Physics, University of Liverpool, Oxford Street, Liverpool, L69 7ZE, U.K.
[b]Laboratory of Vision Engineering, School of Computer Science, University of Lincoln, Lincoln, LN6 7TS, U.K.
[c]Douglas Cyclotron, The Clatterbridge Cancer Centre NHS Foundation Trust, Clatterbridge Road, Bebington, Wirral, CH63 4JY, U.K.
[d]iThemba LABS, PO Box 722, Somerset West, 7129, South Africa
[e]School of Physics and Astronomy, University of Birmingham, Birmingham, B25 2TT, U.K.

2015_JINST_10_C02015

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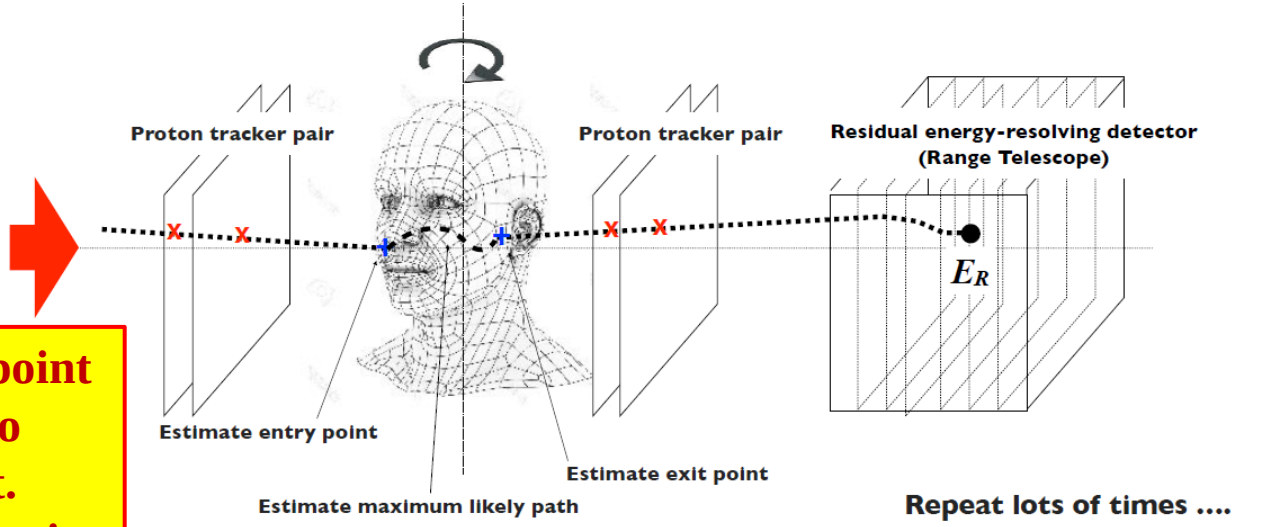
Physics in Medicine & Biology
Phys. Med. Biol. **59** (2014) 7905–7918
doi:10.1088/0031-9155/59/24/7905

Proton computed tomography reconstruction using a backprojection-then-filtering approach

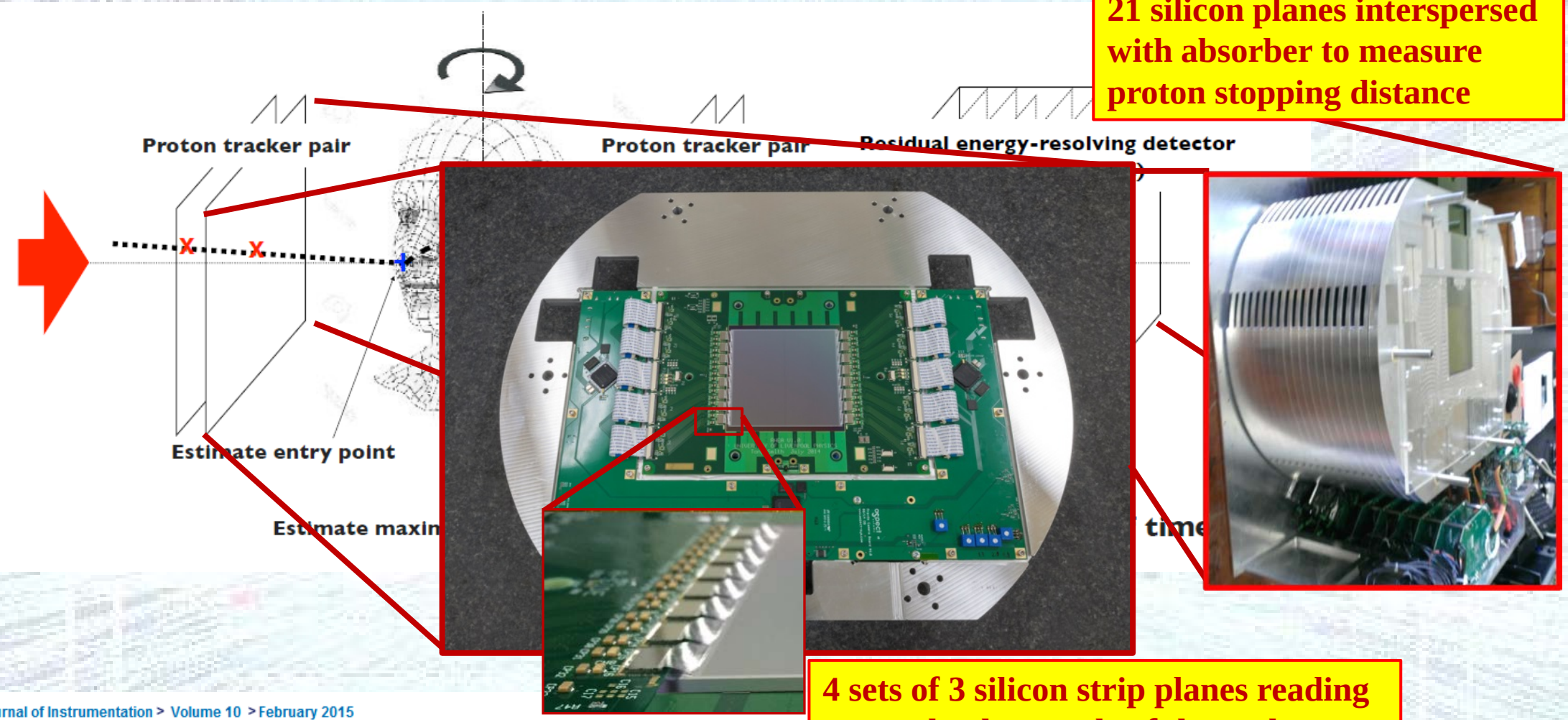
G Poludniowski[1,3], N M Allinson[2] and P M Evans[1]

[1] Centre for Vision Speech and Signal Processing, University of Surrey, Guildford, GU2 7XH, UK
[2] Laboratory of Vision Engineering, School of Computer Science, University of Lincoln, Brayford Pool, Lincoln, LN6 7TS, UK



Need to know momentum vector and entry point of each proton going into the patient and also momentum vector and exit point coming out. Need tracks plus incoming and outgoing energies

Proton Radiotherapy Verification and Dosimetry Applications



21 silicon planes interspersed with absorber to measure proton stopping distance

4 sets of 3 silicon strip planes reading out at the duty cycle of the cyclotron

Journal of Instrumentation > Volume 10 > February 2015
J.T. Taylor *et al* 2015 *JINST* **10** C02015 doi:10.1088/1748-0221/10/02/C02015

Proton tracking for medical imaging and dosimetry

10TH INTERNATIONAL CONFERENCE ON POSITION SENSITIVE DETECTORS

J.T. Taylor[a], P.P. Allport[a], G.L. Casse[a], N.A. Smith[a], I. Tsurin[a], N.M. Allinson[b], M. Esposito[b], A. Kacperek[c], J. Nieto-Camero[d], T. Price[e] and C. Waltham[b]
Show affiliations

Br J Radiol. 2015 Sep;88(1053):20150134. doi: 10.1259/bjr.20150134. Epub 2015 Jun 4.

Proton radiography and tomography with application to proton therapy.

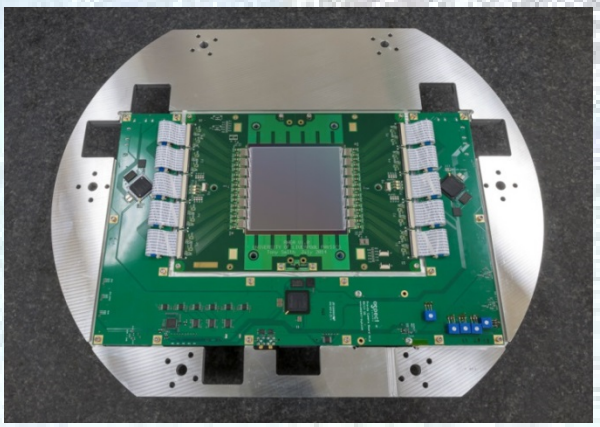
Poludniowski G[1,2], Allinson NM[3], Evans PM[1].

Proton Radiotherapy Verification and Dosimetry Applications

Tracker units tested extensively at Birmingham cyclotron with beams of 29MeV and 36 MeV protons.

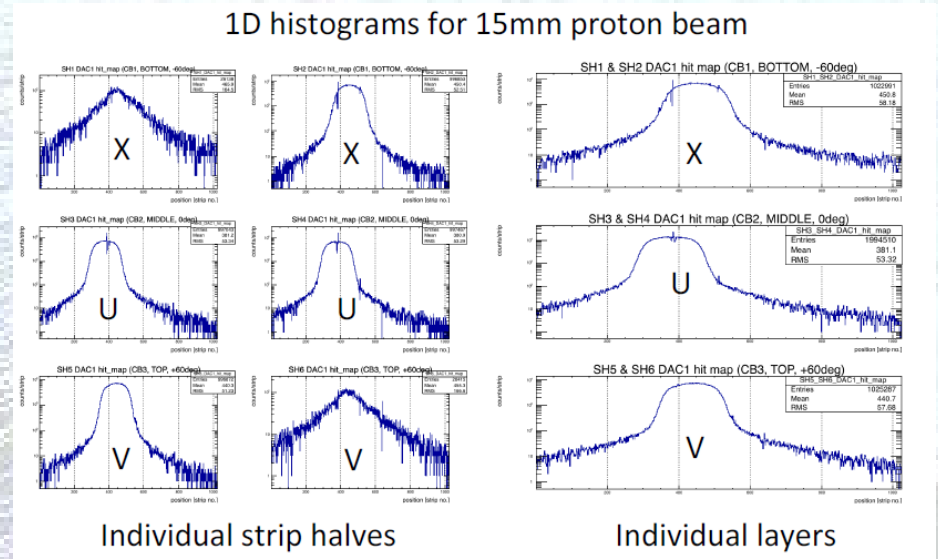
Currents from 10pA-10nA used which for 50mm beam corresponds to 5×10^3 - 5×10^6 protons/cm^2/s

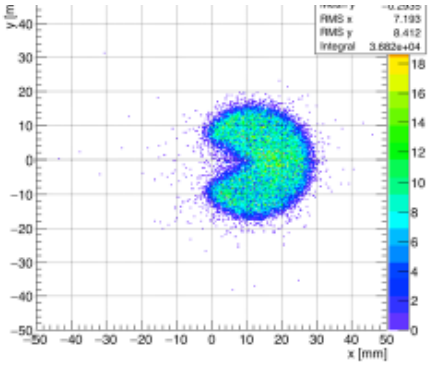
Radiation tested to >2kGy

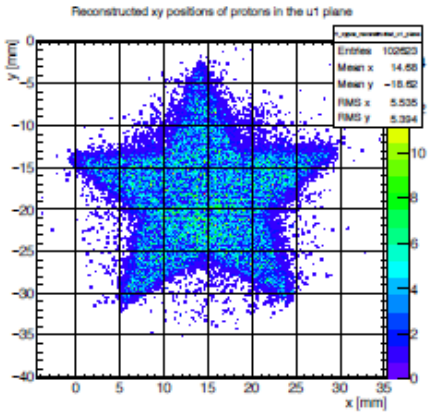


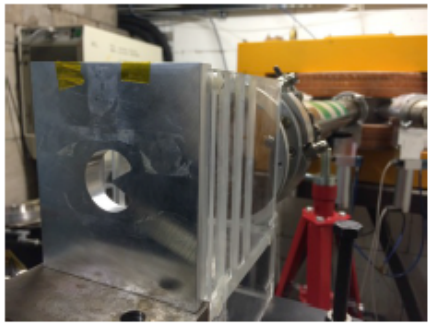
All 12 tracker planes completed and used in beam at IThemba

26MHz RF used for trigger



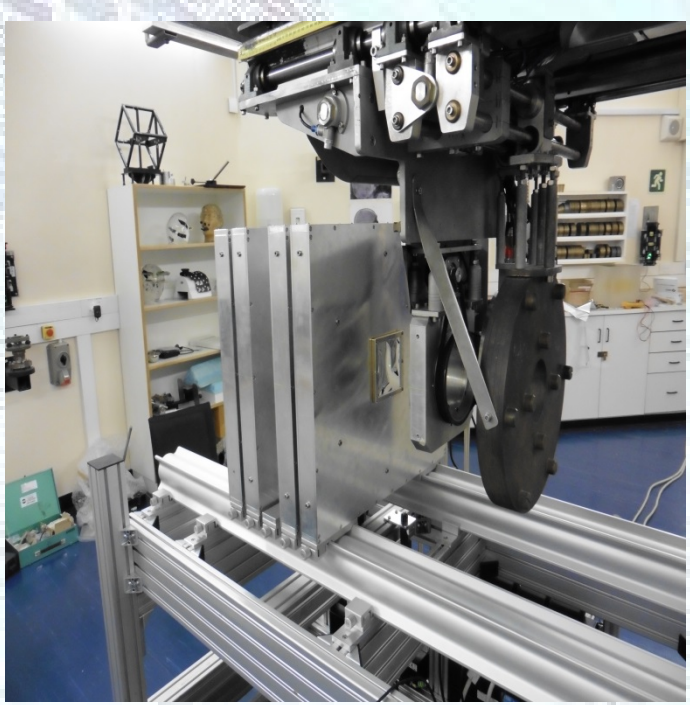


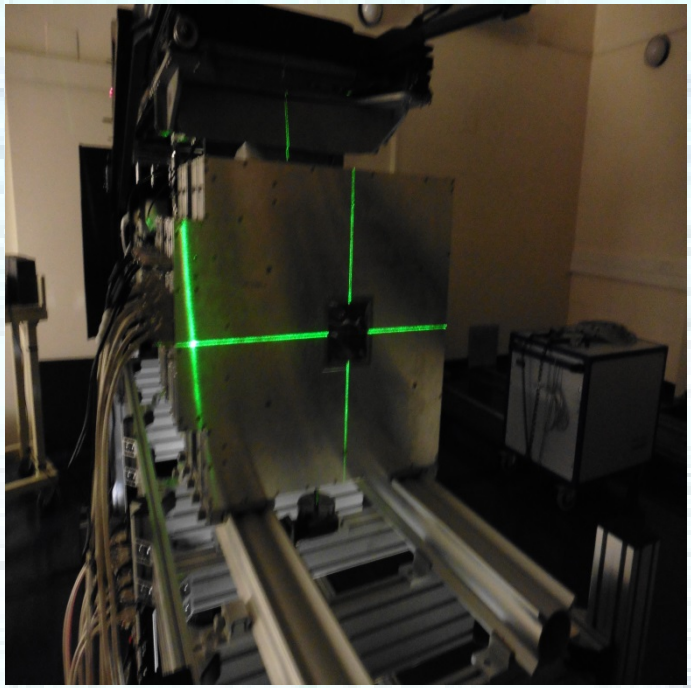


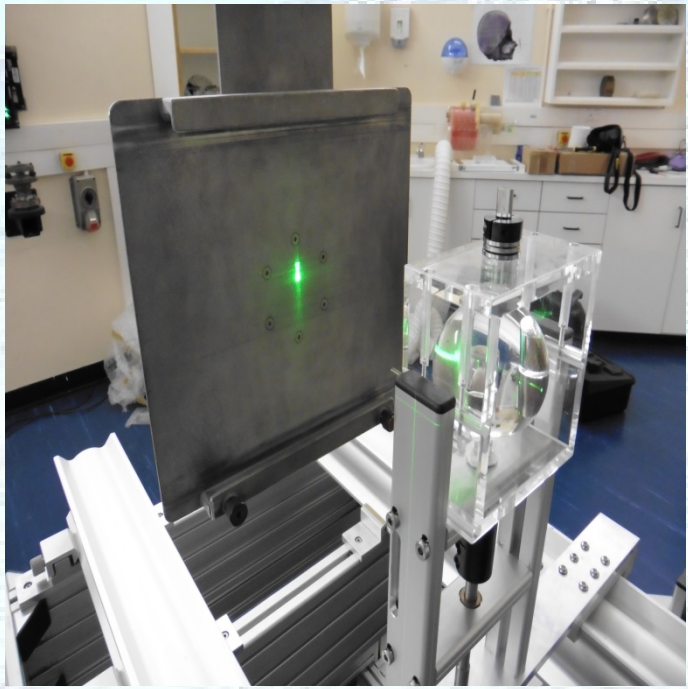


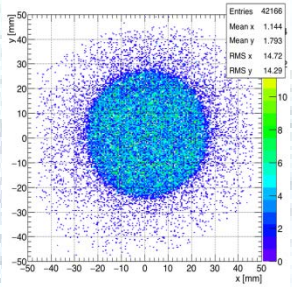
Proton Radiotherapy Verification and Dosimetry Applications

Results at iThemba (see http://www.pravda.uk.com/)

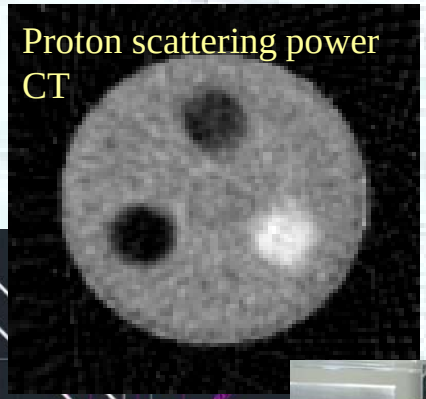


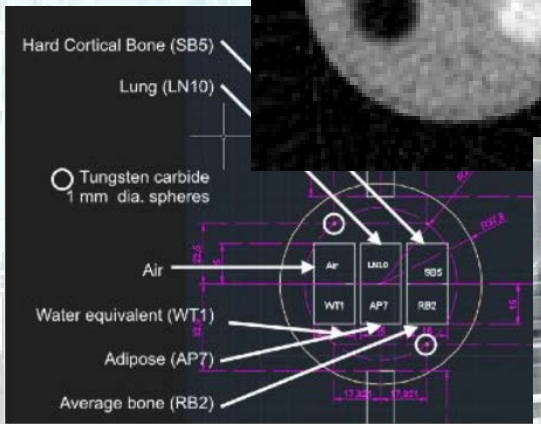






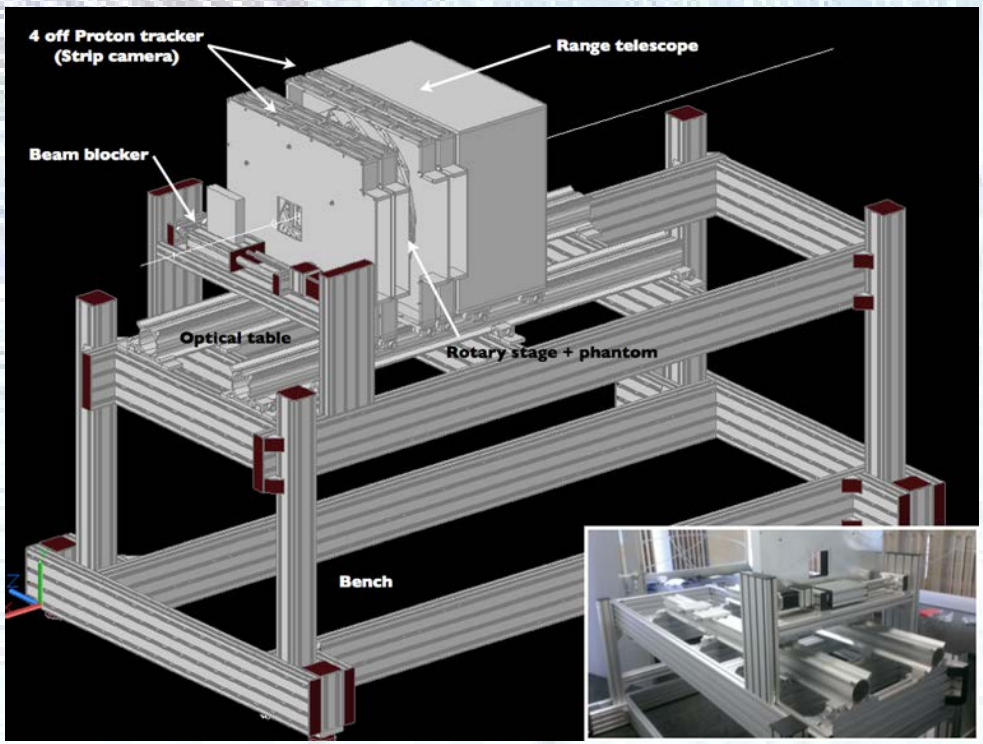
Highly successful run in November 2015 at IThemba for strip tracker.
Measured the mean-square scattering angle of every proton.
Performed a CT reconstruction using novel "back-projection-then-filtering" algorithm developed within PRaVDA.
5 degree angular steps.
125 MeV degraded beam.
15M events / angle
80% tracking efficiency in all layers.

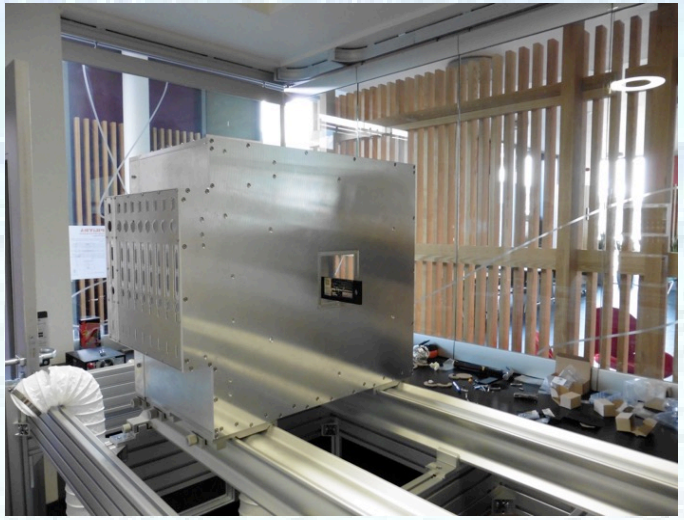


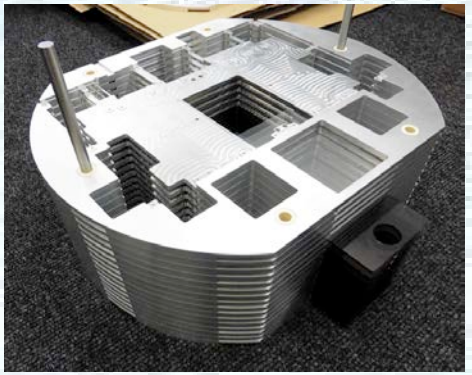


Phantom Images

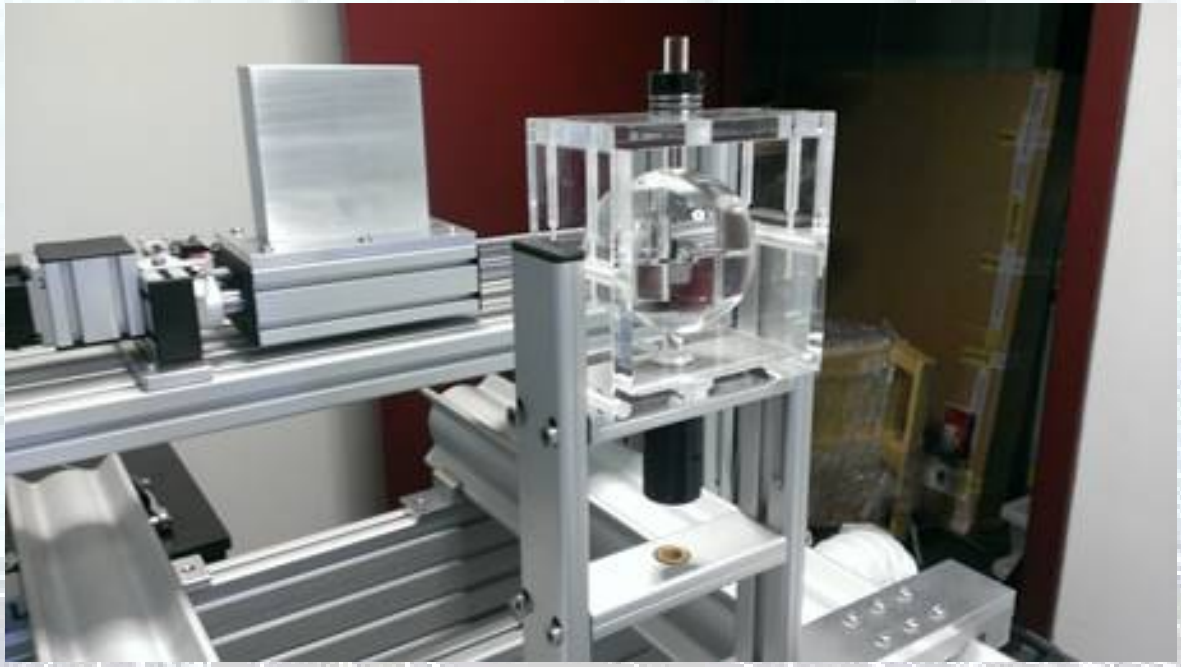
Proton Radiotherapy Verification and Dosimetry Applications





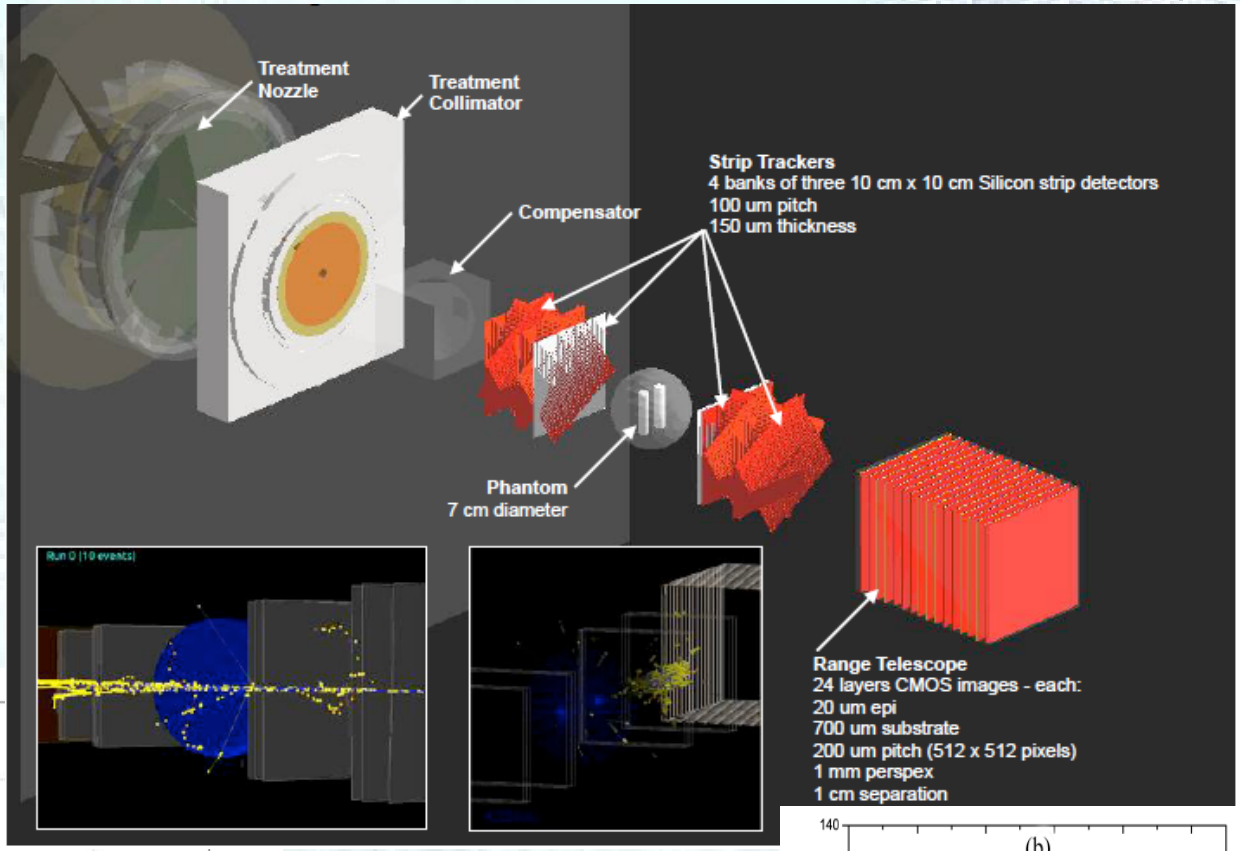


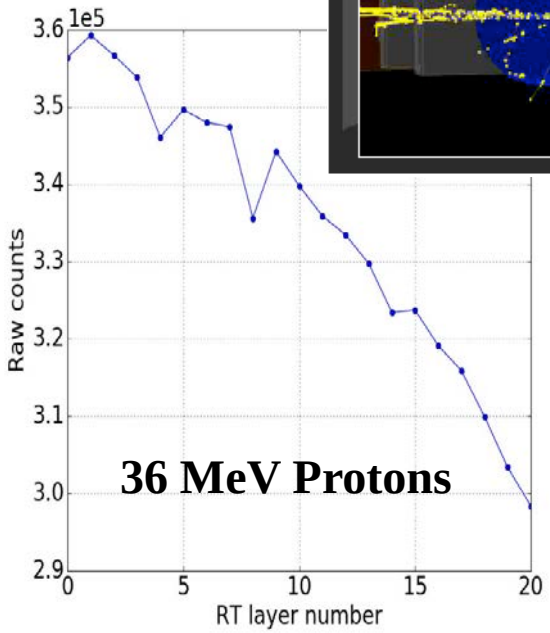
Mechanics, cooling and phantom design and manufacture, University of Lincoln



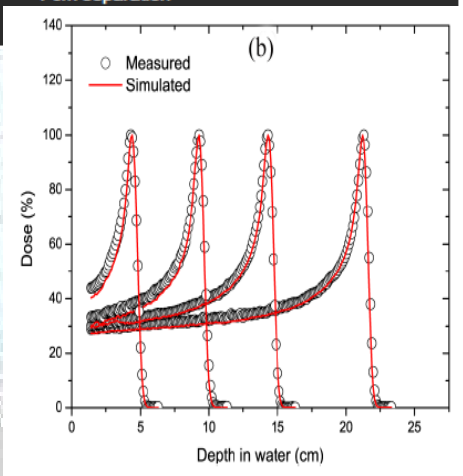
Proton Radiotherapy Verification and Dosimetry Applications

Full system with strip detector based range telescope, commissioning on the Birmingham MC40



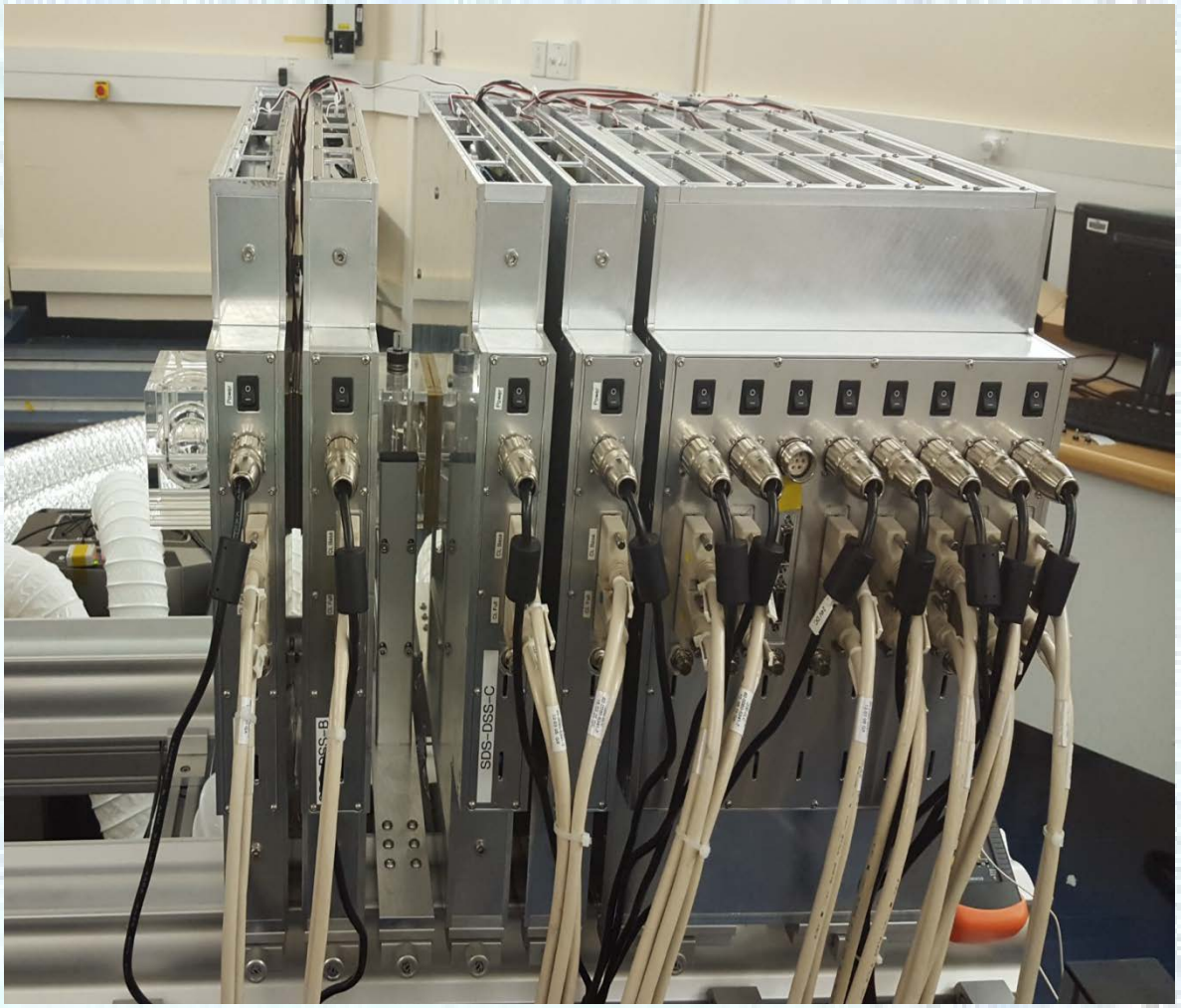


Full system also built and tested in Geant4 simulation as well: SuSi (Tony Price)



Proton Radiotherapy Verification and Dosimetry Applications

- Installed at iThemba for first tests May 2016 (125 MeV degraded beam)
- Compensator in place
- 180 rotations at 1º steps
- ~1M protons / rotation
- All strip systems were talking to each other, albeit timing issues between systems meant only 10% useable data
- Investigations since have fixed this and second pCT run coming in November 2016
- Nevertheless, have pCT results within a project that has only been running for 4 years from conception



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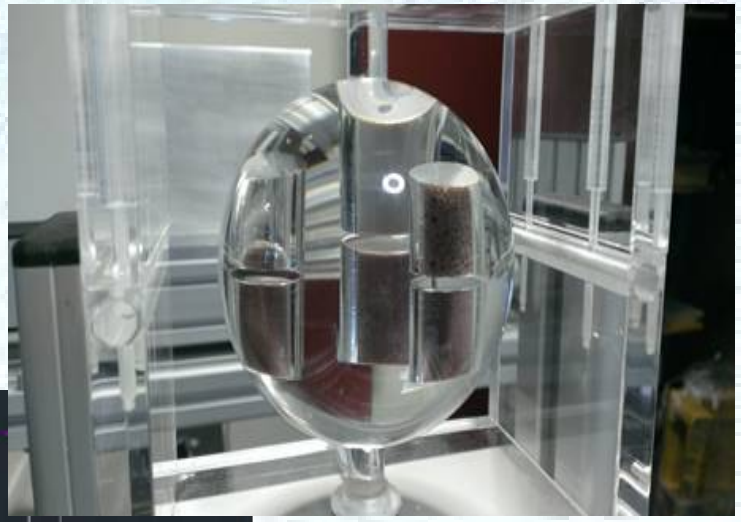

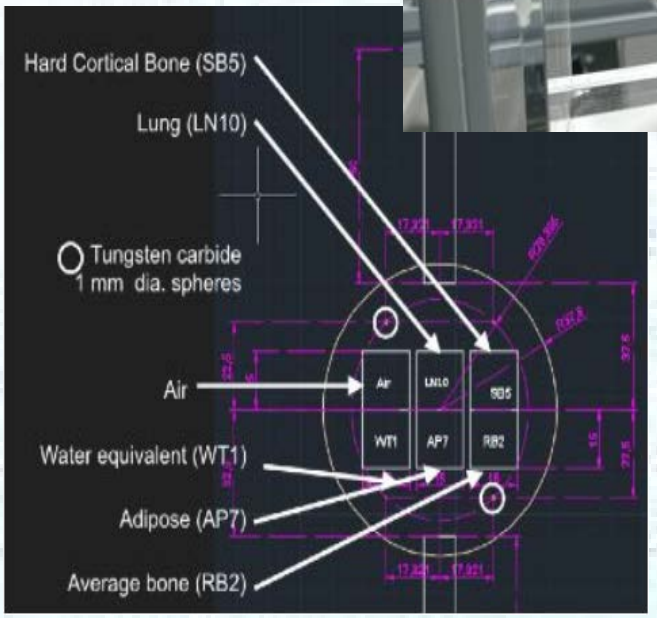

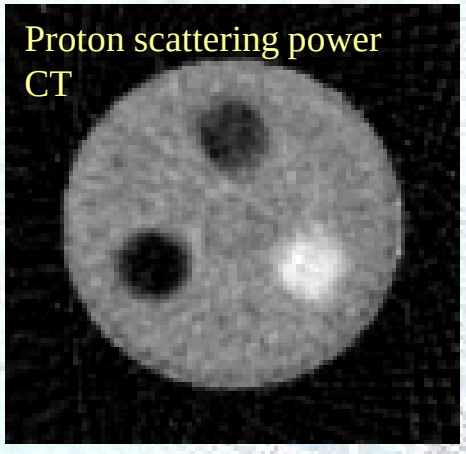

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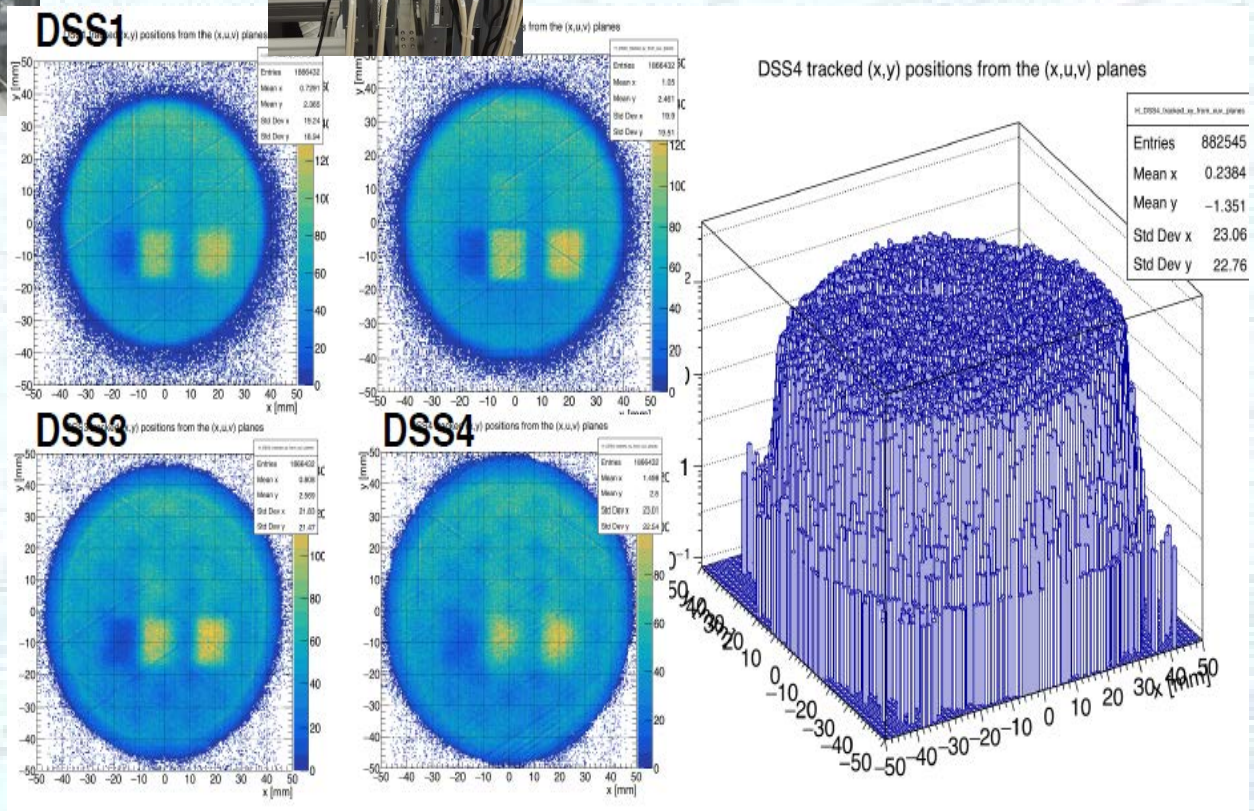
- 180 rotations at 1º steps
- ~1M protons / rotation

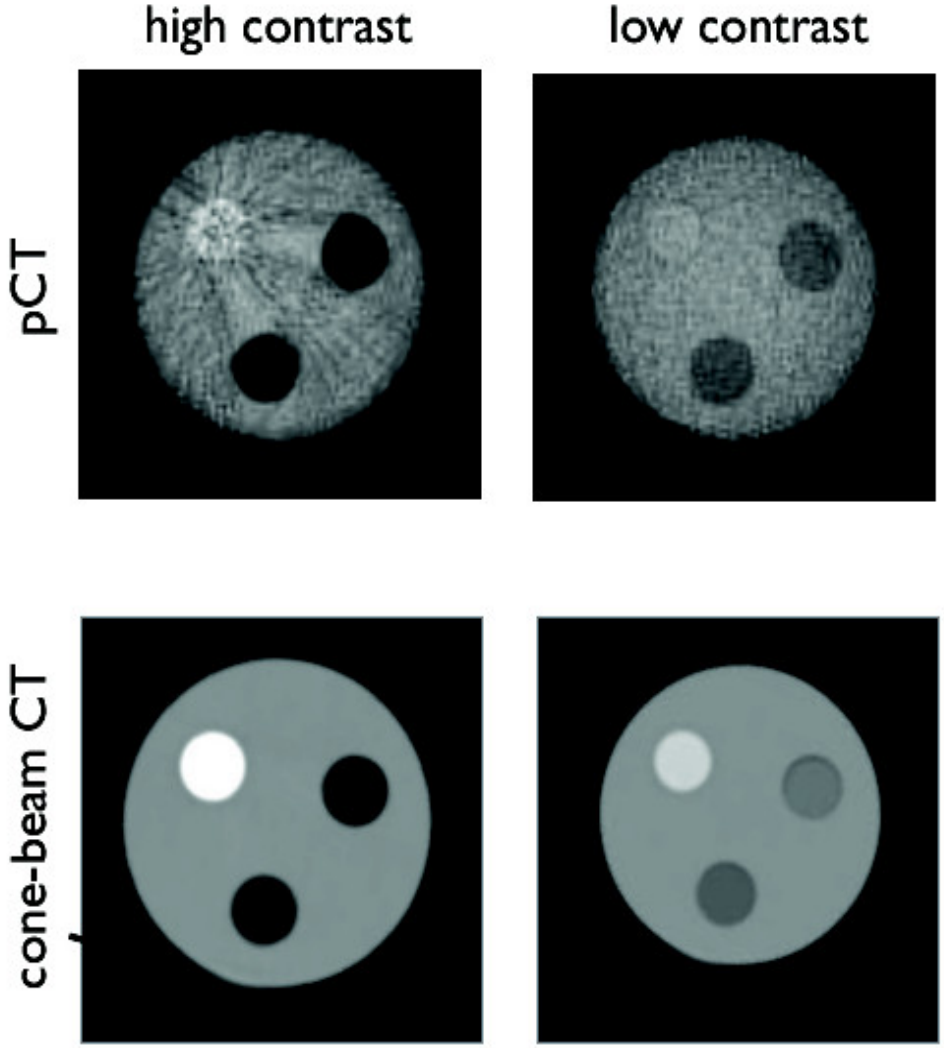


- All systems were talking to each other, albeit timing issues between systems meant only 10% useable data
- Investigations since have fixed this and second pCT run coming in November 2016
- Nevertheless, have pCT results within a project that has only been running for 4 years from conception

Proton Radiotherapy Verification and Dosimetry Applications

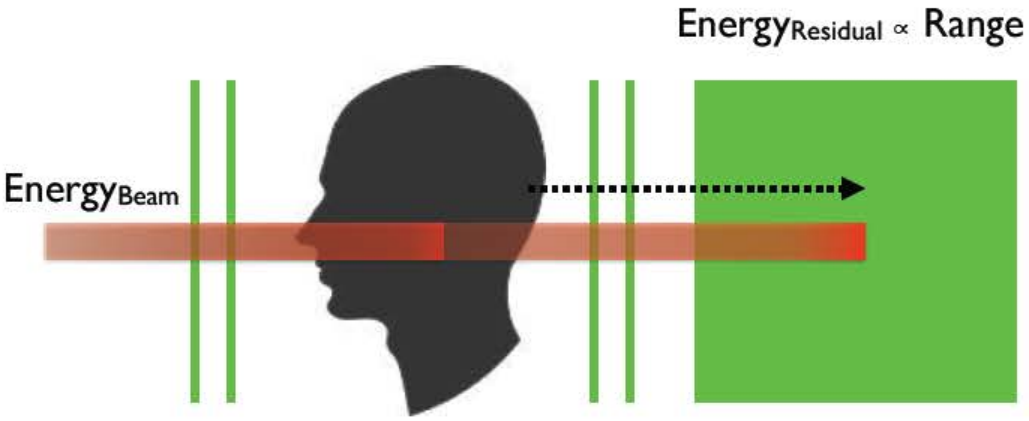
- Installed at iThemba for first tests May 2016 (125 MeV degraded beam)
- Compensator in place
- 180 rotations at 1º steps
- ~1M protons / rotation

- All systems were talking to each other, albeit timing issues between systems meant only 10% useable data
- Investigations since have fixed this and second pCT run coming in November 2016
- Nevertheless, have pCT results within a project that has only been running for 4 years from conception



pCT activities In the US

Alternative tracking and Energy Measuring Technologies



Proton trackers

Multi-Wire Proportional Chambers
Scintillating fibre hodoscopes
X-Y planes of silicon strip detectors
Gas Electron Multiplier detectors

RERD

Calorimeter
Scintillator stack
Etc.

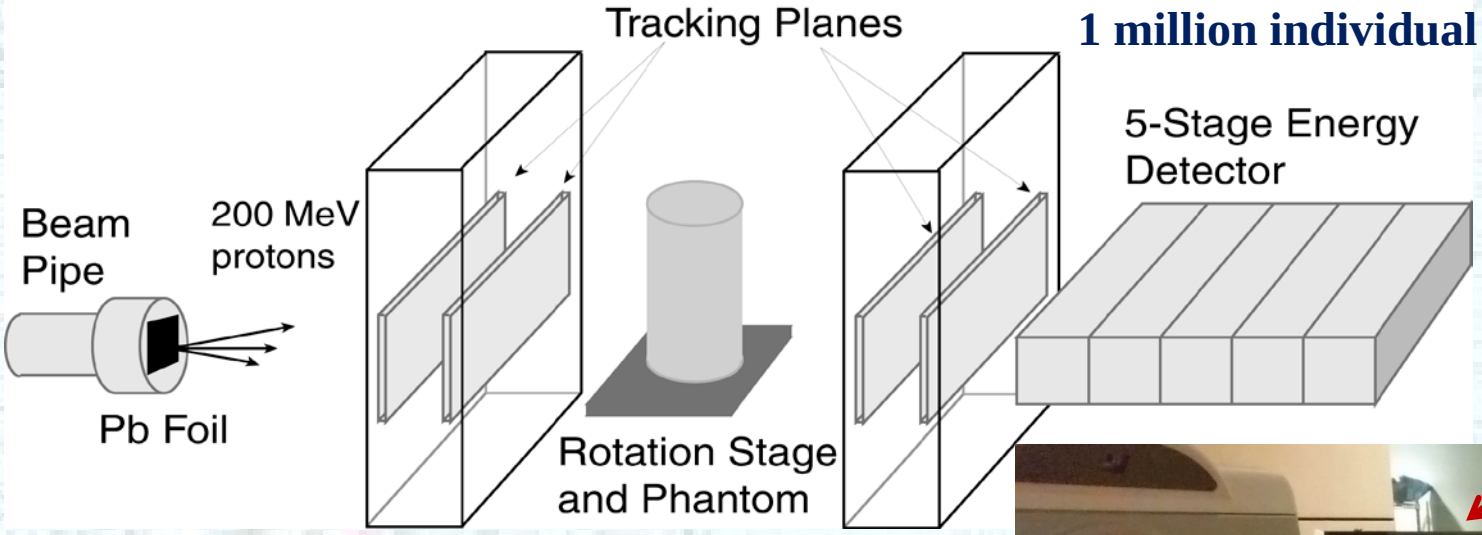
Loma Linda

Fermi Lab

The pCT Collaboration

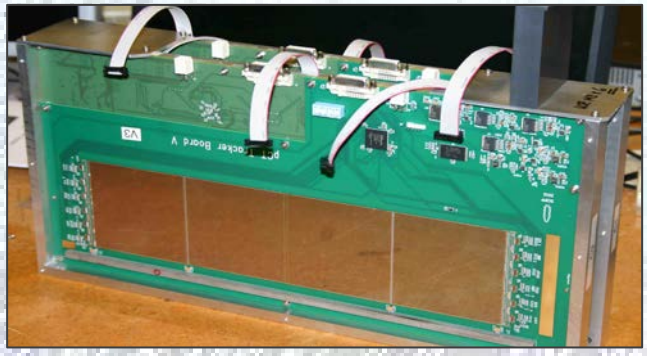
R. P. Johnson, Tia Plautz, Hartmut F.-W. Sadrozinski, A. Zatserklyaniy: *SCIPP, U.C. Santa Cruz, Santa Cruz, CA , USA*
V. Bashkirov, V. Giacometti, F. Hurley, P. Piersimoni, R. Schulte: *Division of Radiation Research, Loma Linda University, CA, USA*
P. Karbasi, K. Schubert, B.Schultze: *Baylor University, Waco, TX, USA*

Loma Linde with SCIPP (UCSC) see presentation by Hartmut Sadrozinski at
https://indico.cern.ch/event/340417/session/16/contribution/4/attachments/1160640/1670929/HSTD10-pCT_Poster-2.pptx

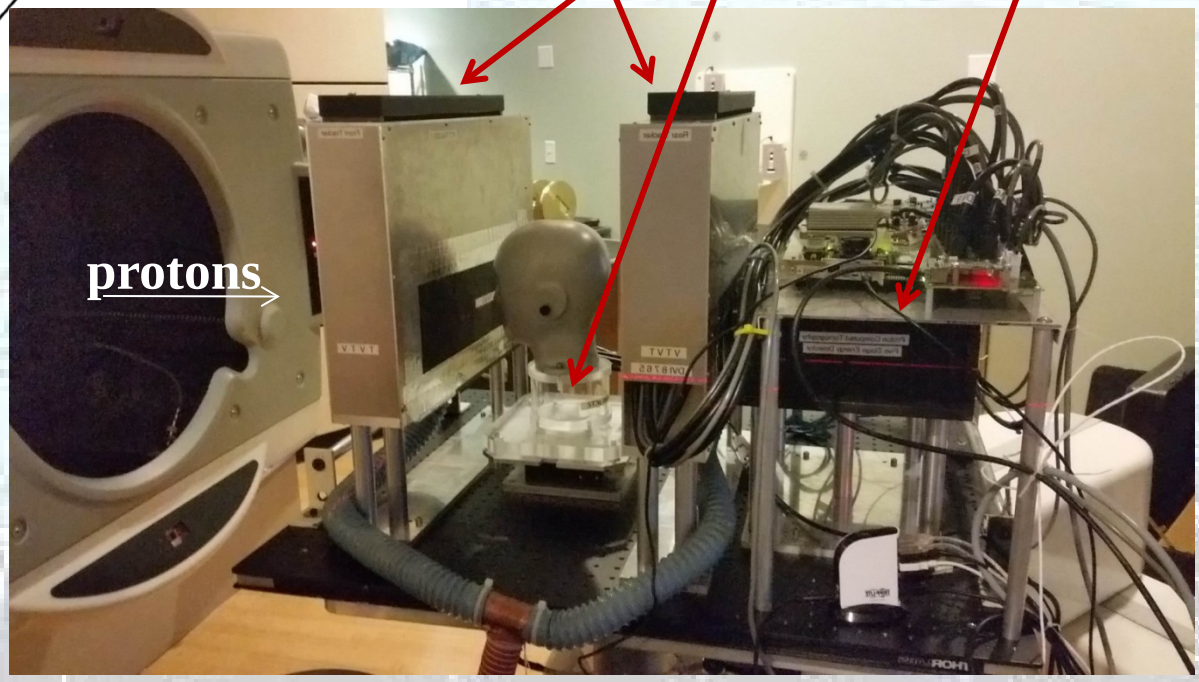


1 million individual protons reconstructed per second

H.F.-W. Sadrozinski, et al, *Development of a Head Scanner for Proton CT*, Nucl. Instr. Meth. A 699 (2013) 205.



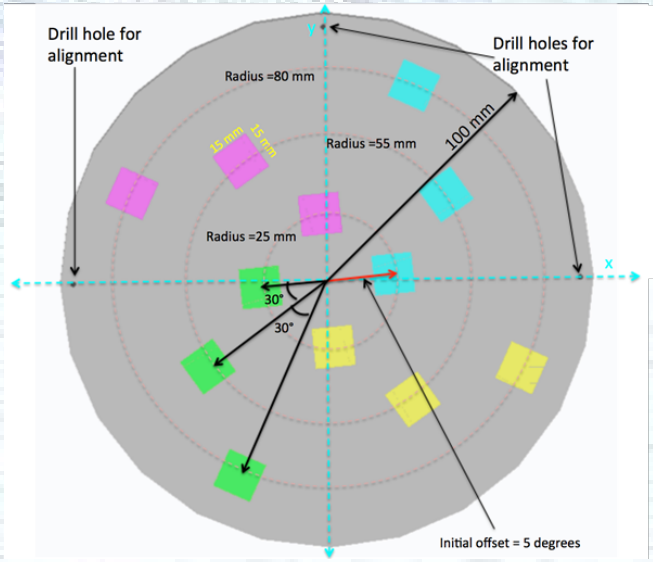
Four 9cm*9cm silicon strip sensors with thin-edge technology in x-y configuration

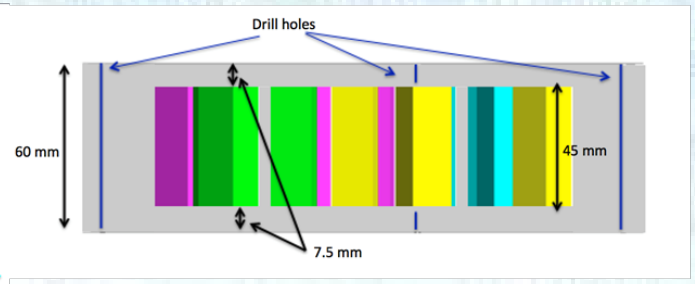


The pCT Collaboration

Spatial Resolution Studies: Edge Phantom

A phantom was designed and fabricated for the purpose of measuring a **modulation transfer function (MTF)**





Left: Top down view of the Edge Phantom.
Right: Side view of the Edge Phantom

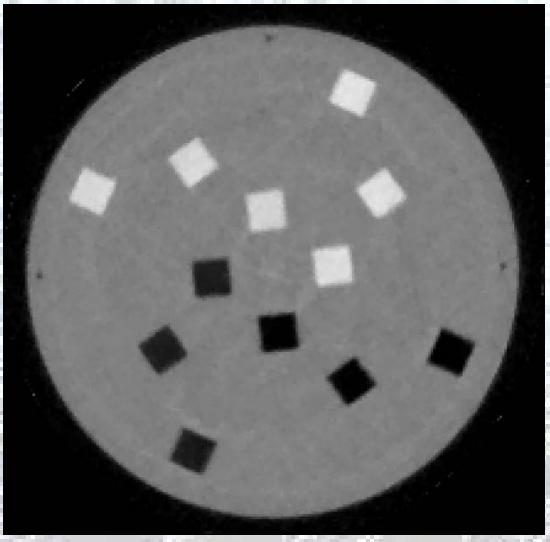
Cyan: Tooth Enamel
$\rho = 2.04\ g/cm^3$; RSP = 1.784
Magenta: Cortical Bone
$\rho \sim 1.91\ g/cm^3$; RSP = 1.699

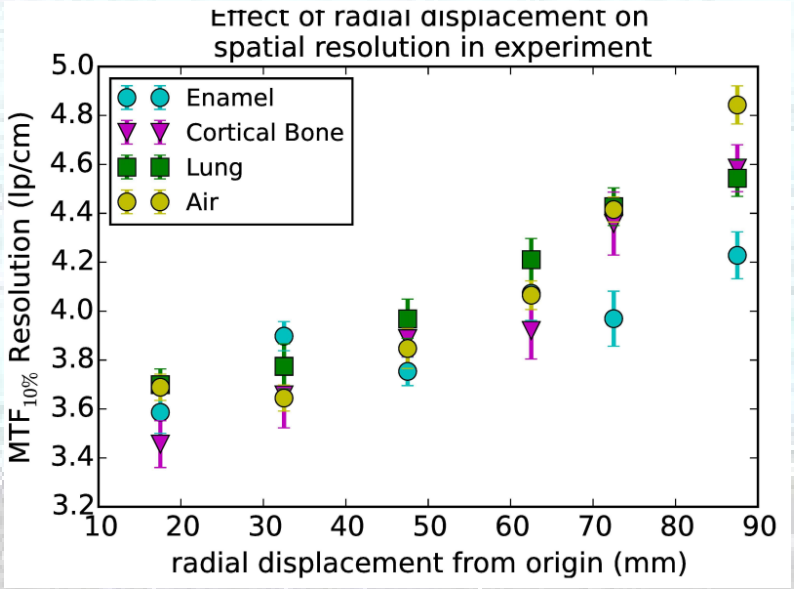
Green: Lung
$\rho \sim 0.205\ g/cm^3$; RSP = 0.203
Yellow: Air
$\rho = 0.0012\ g/cm^3$; RSP = 1.06e-03

MTF is the function of relative modulation with respect to spatial frequency (lp/cm) that characterizes the resolution of an imaging system.

Water Equivalent Path Lengths measured using stepped pyramids of polystyrene blocks show each proton can be reconstructed to an rms precision of ~3 mm

7 min continuous scan (1 rev/min), 150 Million histories, 1 mm x 1 mm x 1 mm voxel size, 1 deg angular bin size.

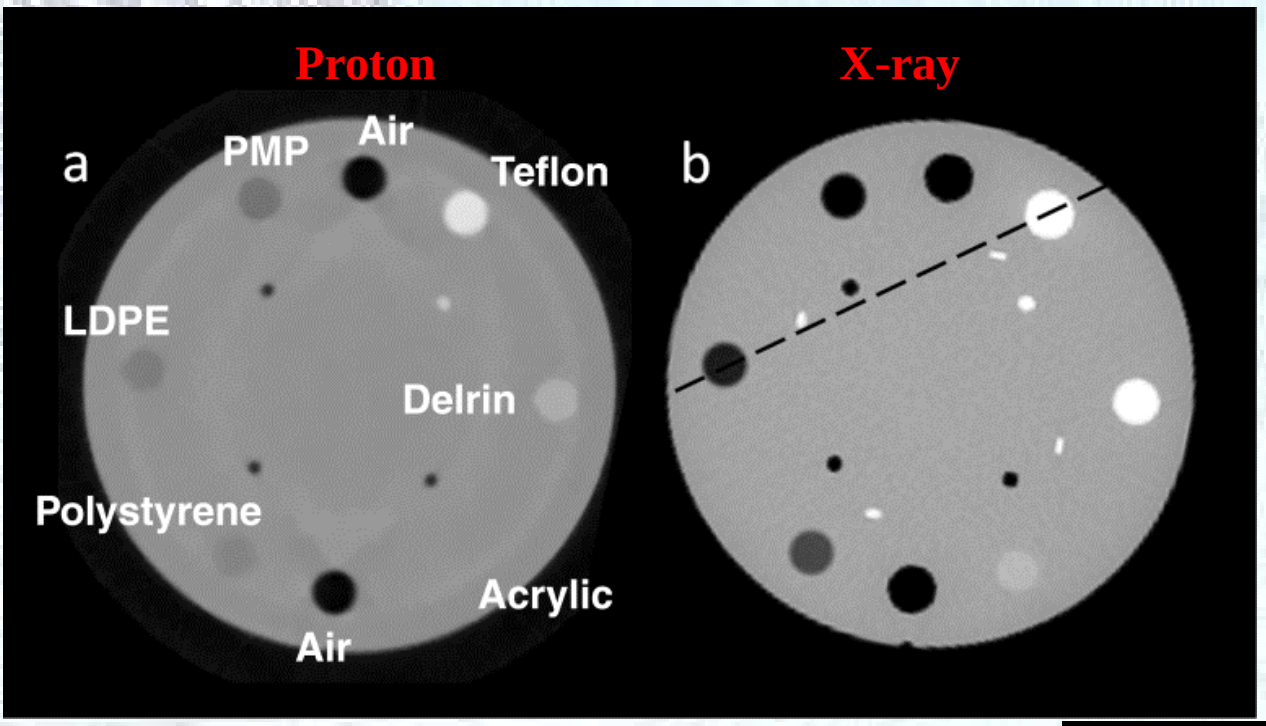


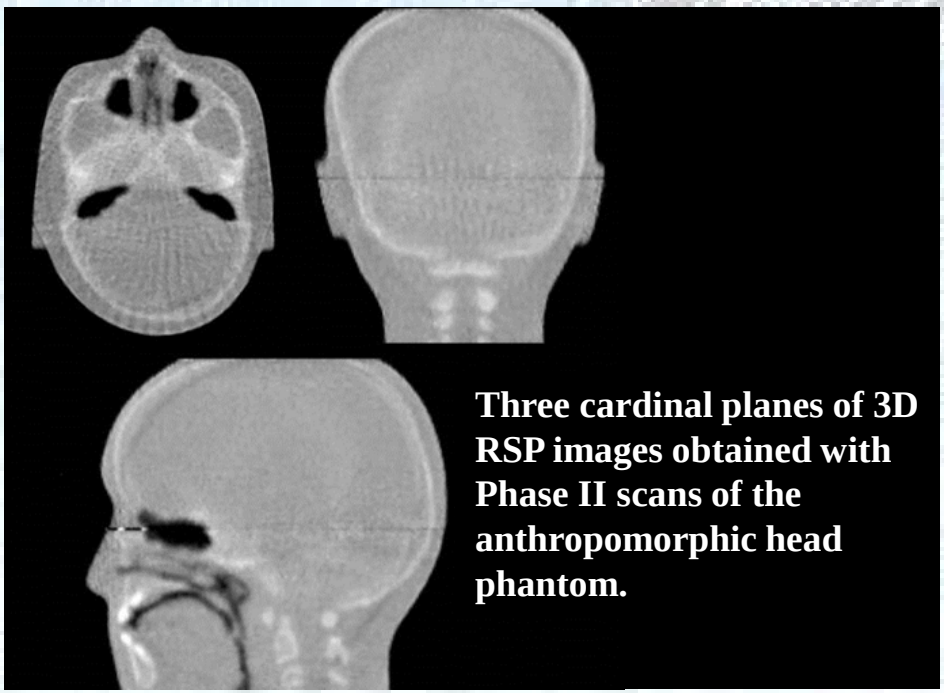


Spatial Resolution is close to maximum (for 1mm pixels the Nyquist frequency is 5 lp/cm).

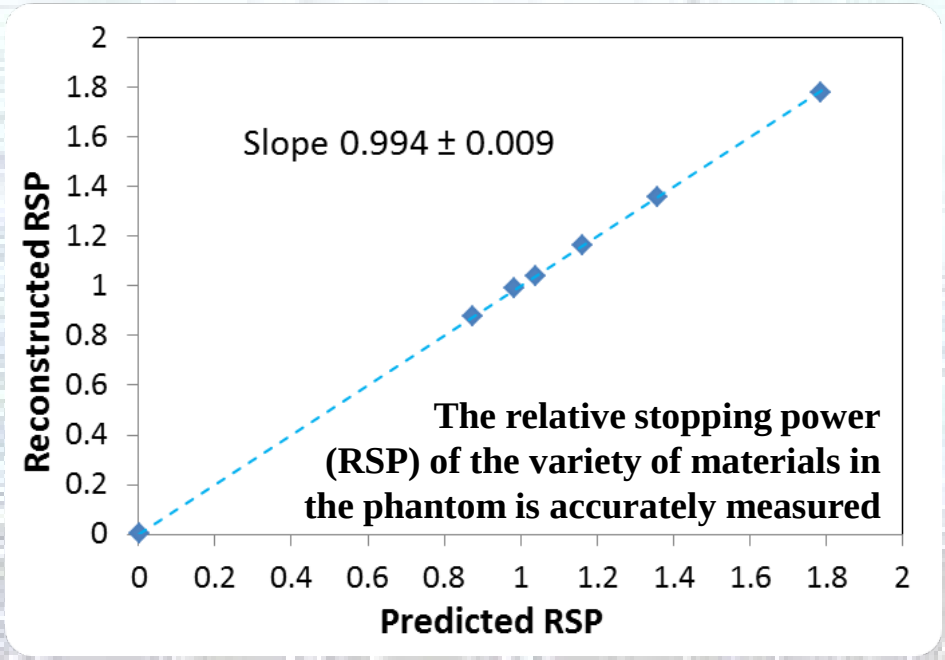
MTF varies as a function of radius by ± 10-20%.

The pCT Collaboration

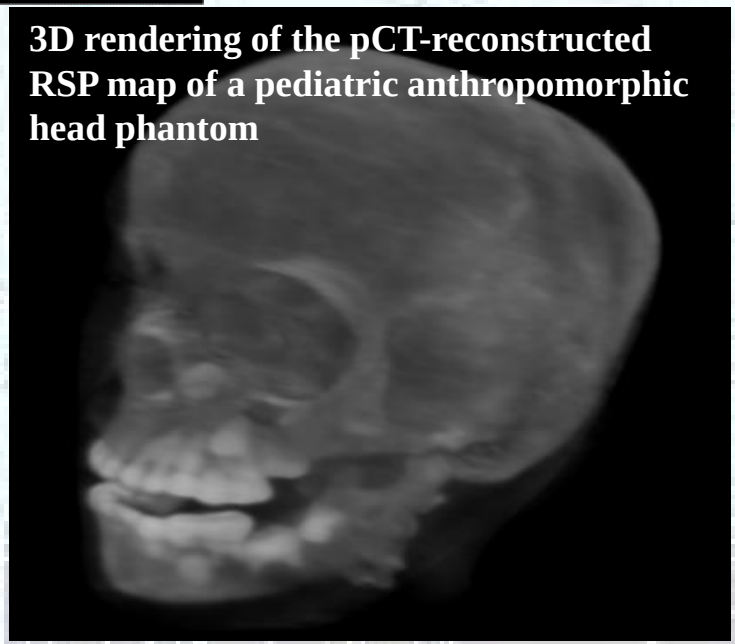




Three cardinal planes of 3D RSP images obtained with Phase II scans of the anthropomorphic head phantom.



The relative stopping power (RSP) of the variety of materials in the phantom is accurately measured



3D rendering of the pCT-reconstructed RSP map of a pediatric anthropomorphic head phantom

P 219

From SuperNEMO to Proton Therapy: Adapting the SuperNEMO Optical Module for Proton Energy QA

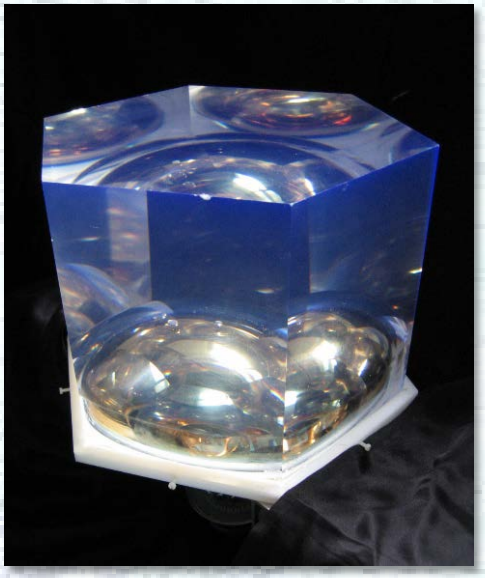
A. Basharina-Freshville[1], S. Jolly[1], R.Saakyan[1], H.F. Wong[1], R. Amos[2], A. Kacperek[3]

[1]University College London, Physics & Astronomy, London, UK

[2]University College London Hospitals, Radiotherapy Physics, London, UK

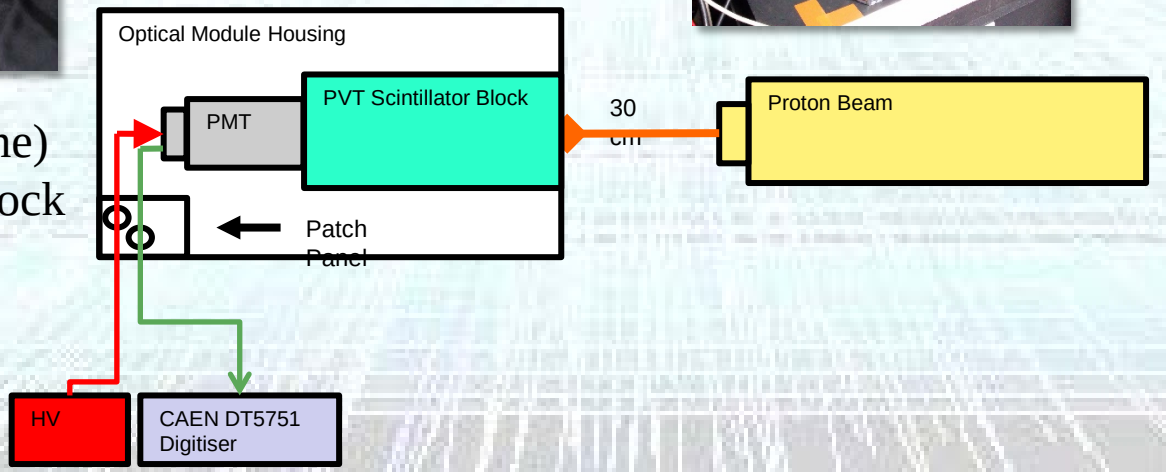
[3]Clatterbridge Cancer Centre, National Eye Proton Therapy Centre, Bebington, UK

UCL



8” PMT (HPK)

PVT (polyvinyl toluene)
EJ-200 Scintillator Block
2ns rise-time



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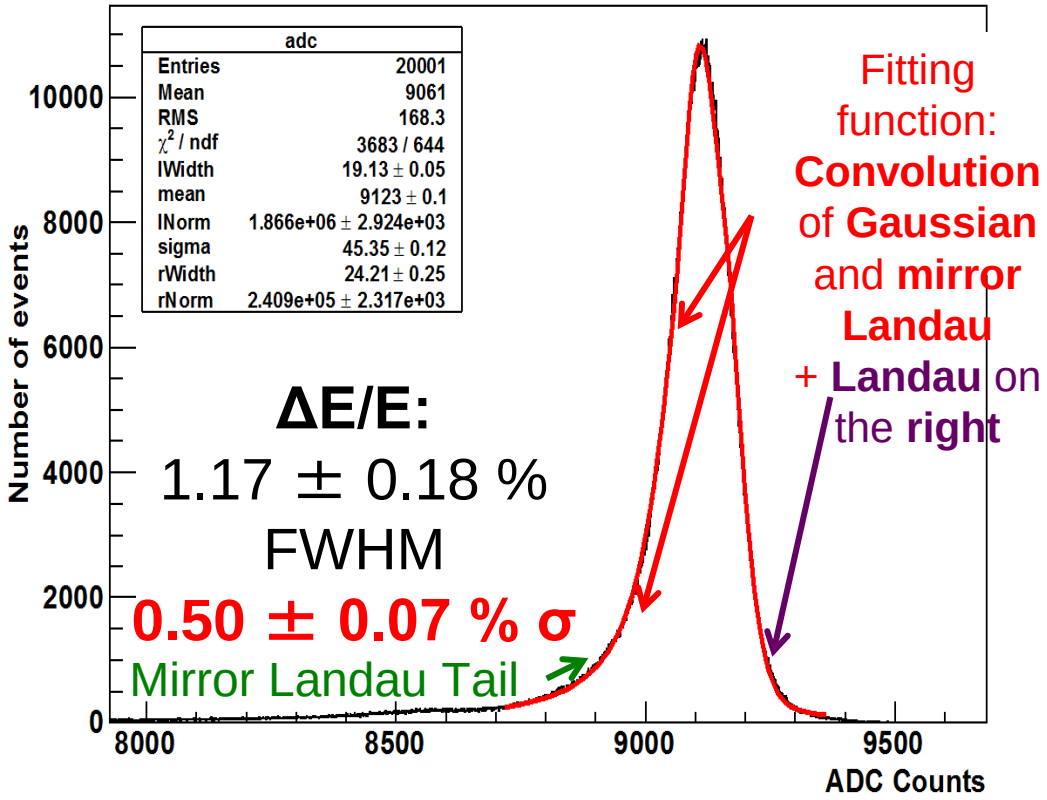
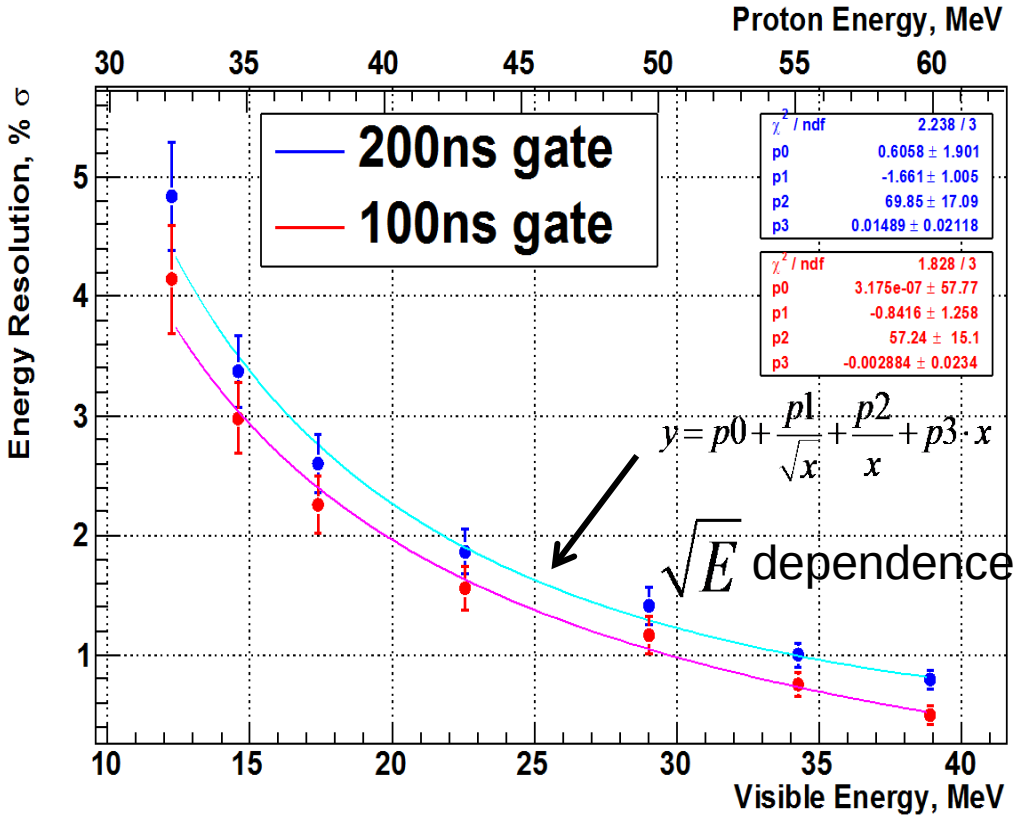
[3]Clatterbridge Cancer Centre, National Eye Proton Therapy Centre, Bebington, UK

60 MeV Clatterbridge Beam Test ADC Spectrum

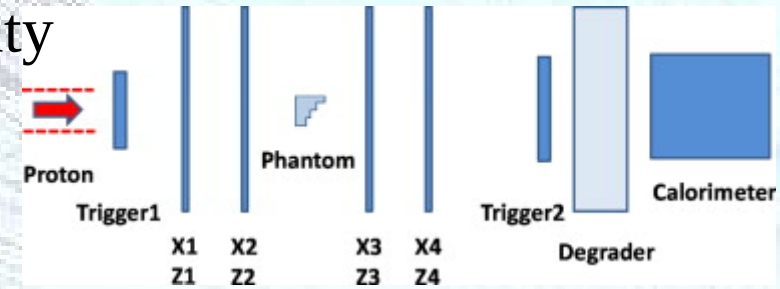


Energy Resolution as a Function of Proton Energy: -950 V

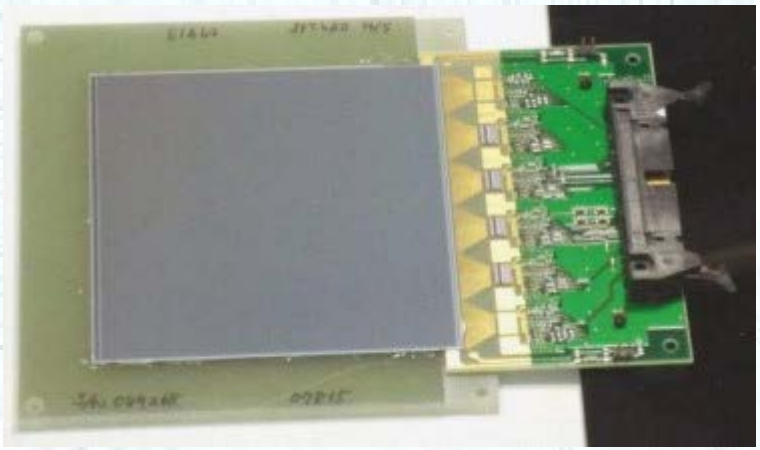


Other Silicon Trackers

- Another group using similar sensors to the pCT Collaboration is based at Niigata University



Item	Specifications
Outer dimensions	89.5×89.5 mm²
Active area	87.6×87.6 mm²
Substrate thickness	410±10μm
Strip pitch	228μm
Readout pitch	456μm
Number of strips	384
Full depletion voltage	<120<120 V



ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 735, 21 January 2014, Pages 485–489

Study of spatial resolution of proton computed tomography using a silicon strip detector

Y. Saraya[a], T. Izumikawa[b], J. Goto[b], T. Kawasaki[a], T. Kimura[a]

Show more

doi:10.1016/j.nima.2013.09.051

JINST

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PIXEL 2014 INTERNATIONAL WORKSHOP
SEPTEMBER 1–5, 2014
NIAGARA FALLS, CANADA

Low power, high resolution MAPS for particle tracking and imaging

P. Giubilato, C. Cavicchioli, P. Chalmet, T. Kugathasan, C. Marin Tobon, S. Mattiazzo, H. Mugnier, D. Pantano, N. Pozzobon, J. Rousset, W. Snoeys and P. Yang

Padova University, via Marzolo 8, 35131, Padova, Italy
INFN Padova, via Marzolo 8, 35131, Padova, Italy
CERN, rue de Meyrin 12, Meyrin, Switzerland

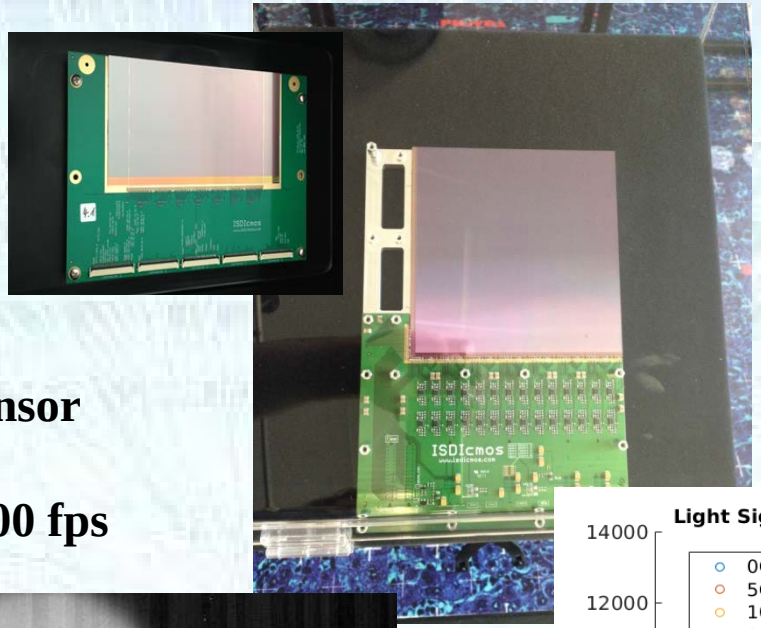
E-mail: piero.giubilato@pd.infn.it

- A very promising approach being followed by Padua with CERN is the use of MAPS technologies for the tracking but with intelligent on-chip data sparsification to deliver faster, low power readout
- There are a number of other initiatives using different tracking technologies, scintillating fibres, multi-wire proportional chambers, … all of which have potential advantages and disadvantages when compared with silicon detectors

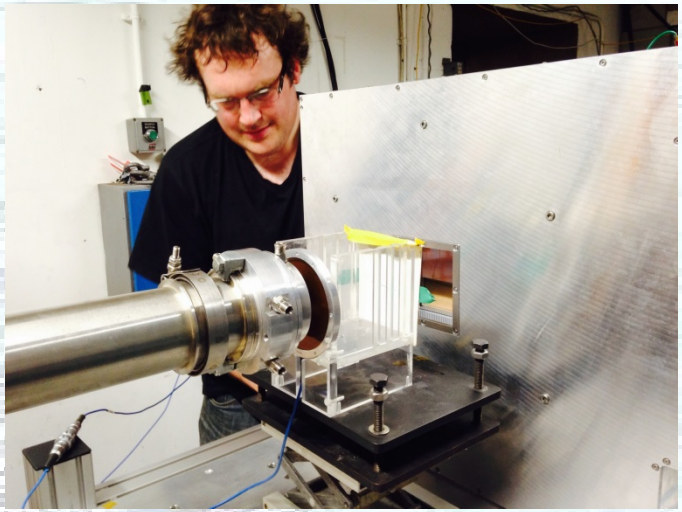
Proton Radiotherapy Verification and Dosimetry Applications

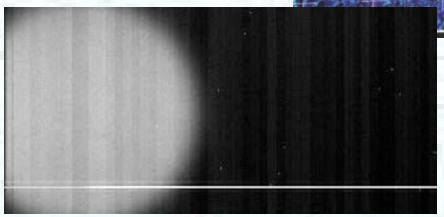
PRaVDA: Monolithic Active Pixel Sensor (MAPS) prototype:

- **Active area of 50 x 100 mm^2**
- **Pixel pitch of 194 x 194 µm^2**
- **Epitaxial layer thickness 18 µm**
- **Total wafer thickness 750 µm**
- **0.35 µm CMOS Active Pixel Sensor**
- **8-14 bit programmable ADC**
- **Rolling shutter read out at > 1000 fps**
- **ROI readout available**
- **3 sides buttable**

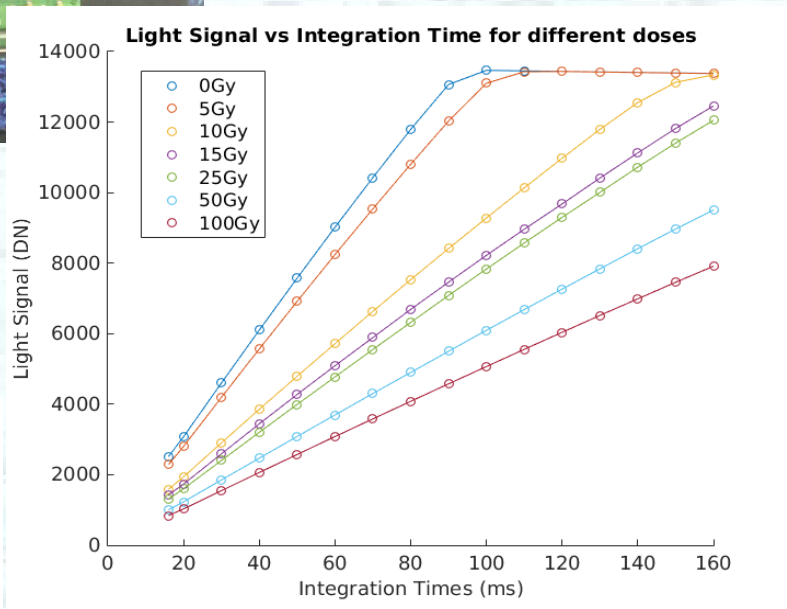


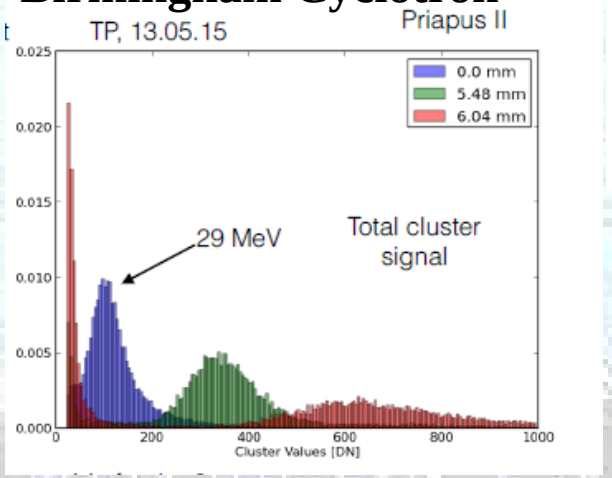
Because slow, was intended for range telescope with 24 planes interspersed with thin absorber to measure stopping distance of each proton extrapolated to the range telescope by the tracking layers



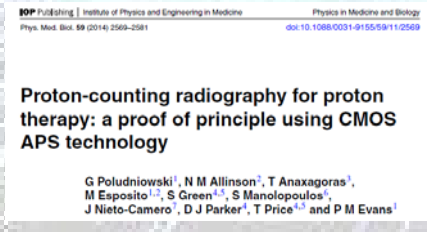


MAPS beam image at Birmingham Cyclotron





Radiation-hardness needs enhancing
Signal/noise OK at lower energies
New devices delivered and currently under evaluation


IOP Publishing | Institute of Physics and Engineering in Medicine — Physics in Medicine and Biology
Phys. Med. Biol. 59 (2014) 2569–2581 — doi:10.1088/0031-9155/59/11/2569

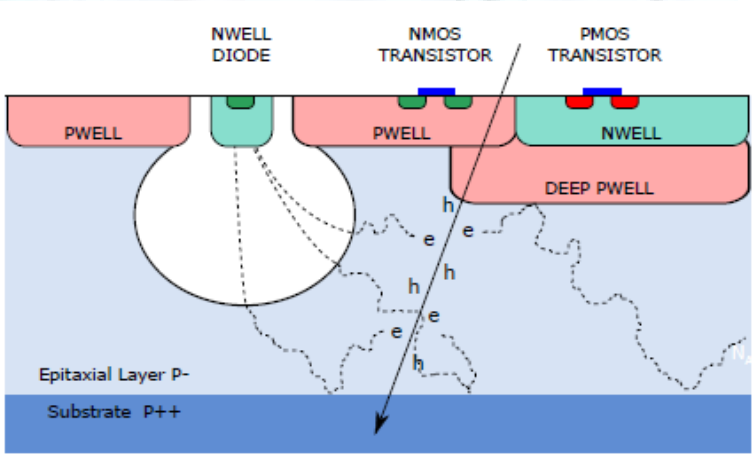
Proton-counting radiography for proton therapy: a proof of principle using CMOS APS technology

G Poludniowski[1], N M Allinson[2], T Anaxagoras[3], M Esposito[1,2], S Green[4,5], S Manolopoulos[6], J Nieto-Camero[7], D J Parker[4], T Price[4,5] and P M Evans[1]

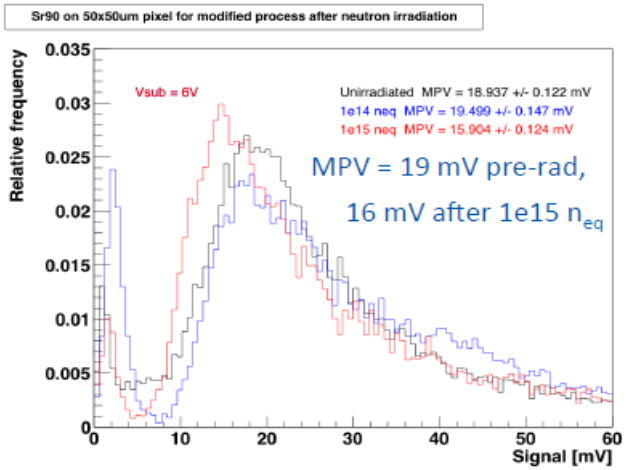
Single Particle Enabled Computed Tomography Radiotherapy Equipment

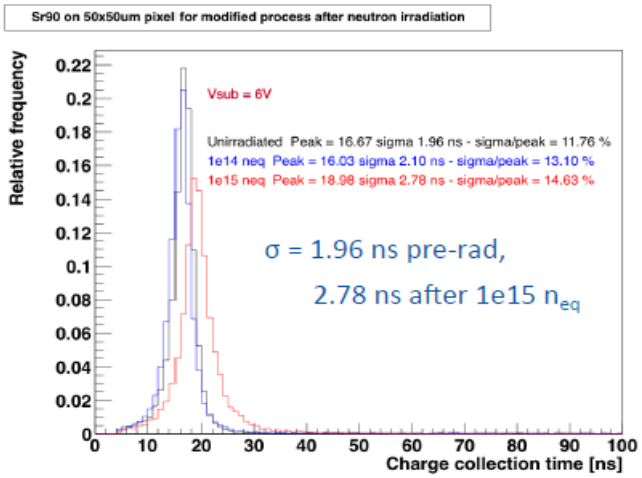
Most modern hadron therapy facilities are mostly scanning spot systems and the time structures depend on whether cyclotron, synchrocyclotron, synchrotron or linear accelerator

- **PRaVDA prototype is anyway too small in area for many tumours**
- **Would need array of “edgeless” sensors (in practice always some boundary)**
- **Alternative for scanned system is smaller detectors that move with the beam**
- **Need high rate pixelated detectors, but current MAPS not sufficiently radiation hard**
- **Depleted Monolithic Active Pixel Sensor (DMAPS) technologies could be the answer**

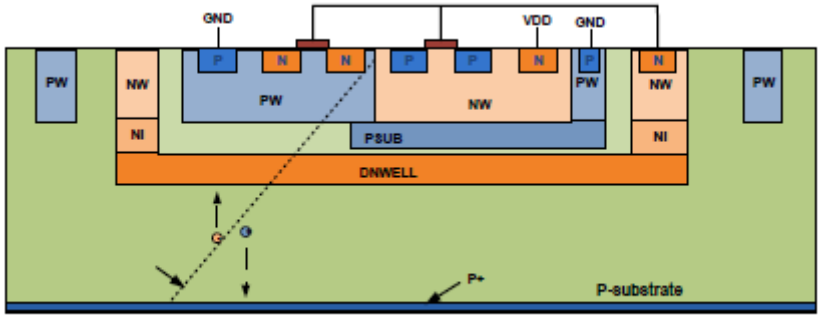


The more the device is depleted, the less charge collected by diffusion



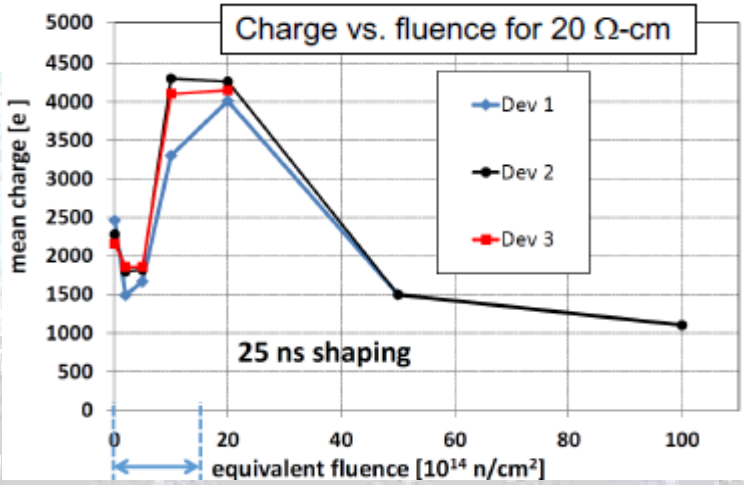


Courtesy of H. Pernegger (ATLAS)



N. Wermes, AIDA2020 1st annual meeting, Hamburg, June 2016

Charge collection by drift not diffusion
→ faster
→ less trapping
→ much more radiation hard



UK Hadron Therapy Status

https://www.ptcog.ch/index.php/

Lists 70 facilities in operation, 37 "in construction" and 17 in planning stage
Of these only the National Centre for Eye Proton Therapy at Clatterbridge (60 MeV protons) is operational in the UK

New NHS centres at Christie (Manchester opening 2018 with 3 rooms and UCLH (London opening 2019 also with 3 rooms)
Private provision for protons

Numerous centres are being developed around the country including the following with varying degrees of certainty / likelihood.

Company	No centres / treatment rooms	Locations	Likelihood	Opening	Links
Proton Partners Intl – wave 1	3 / 3	Newport, Reading, Middlesborough	Certain..	2018/19	https://iba-worldwide.com/content/proton-partners-international-newport-0
Proton Partners Intl – wave 2	2 / 2	Liverpool, Birmingham	Not confirmed	?	http://www.proton-int.com/
Advanced Oncotherapy	2 / 5?	Harley St, Pebble Mill	Confirmed	2018?	http://www.advancedoncotherapy.com/
University of Oxford PTCRi	1/?	Oxford	No obvious updates on current status	?	http://www.ox.ac.uk/news/2014-10-23-%C2%A3110m-research-centre-cancer-medicine-be-established-oxford-university
VPS healthcare ground, Abu Dhadi	?	London – Royal Masonic hospital site, Hammersmith	?	?	http://www.telegraph.co.uk/news/health/11778481/UK-hospital-to-offer-proton-beam-therapy.html
City proton / Imperial	1 / ?	Moorgate, London	Not confirmed - Web-site available	2018/19?	http://www3.imperial.ac.uk/newsandeventspggrp/imperialcollege/newssummary/news_20-5-2016-13-23-37

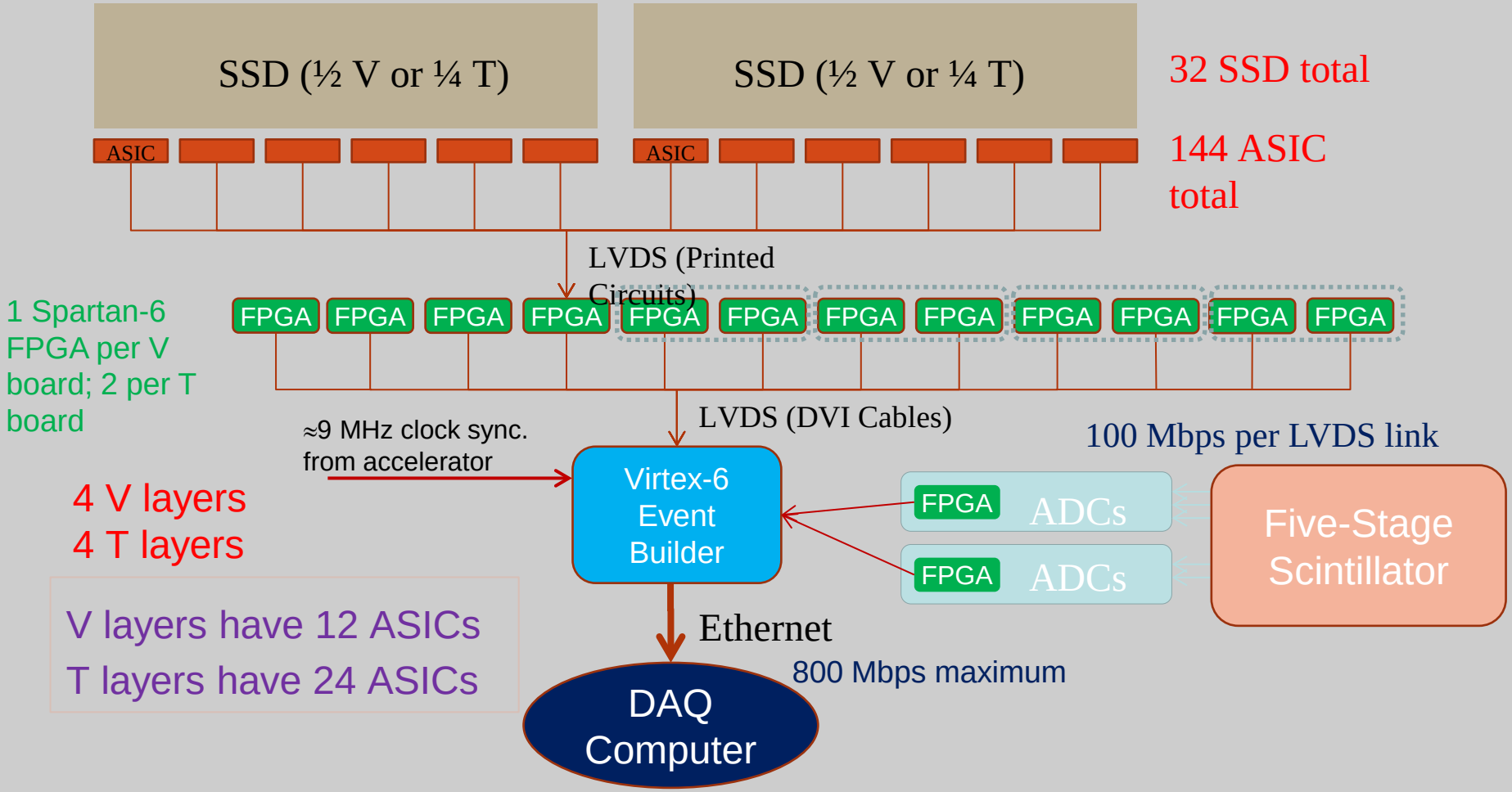
Conclusions

- The particle physics community has 40 years of experience of operating finely segmented silicon sensors for precision tracking of charged particles in high rate, high radiation environments
- In developing these radiation-hard detectors, we have seen a possible application for sensors which would need to sit permanently in a hadron beam for years without any need to recalibrate for change in signal with dose
- Large area Monolithic Active Pixel Sensors have been developed for PRaVDA range telescope but speed and radiation-hardness need improving. (Developments in depleted CMOS sensors (DMAPS) allow common pixel technology throughout)
- A number of consortia are investigating ways to use both tracking and energy measuring technologies from particle physics and other fields in support of hadron therapy facilities. (PRaVDA and pCT discussed here as examples using silicon detectors; but many other international activities not covered here.)
- Accurately tracking the path of protons will be of value to future hadron therapy facilities not only for beam monitoring and diagnostics, but also as providing the exciting possibility of pCT to even better improve accuracy for treatment

Back Up

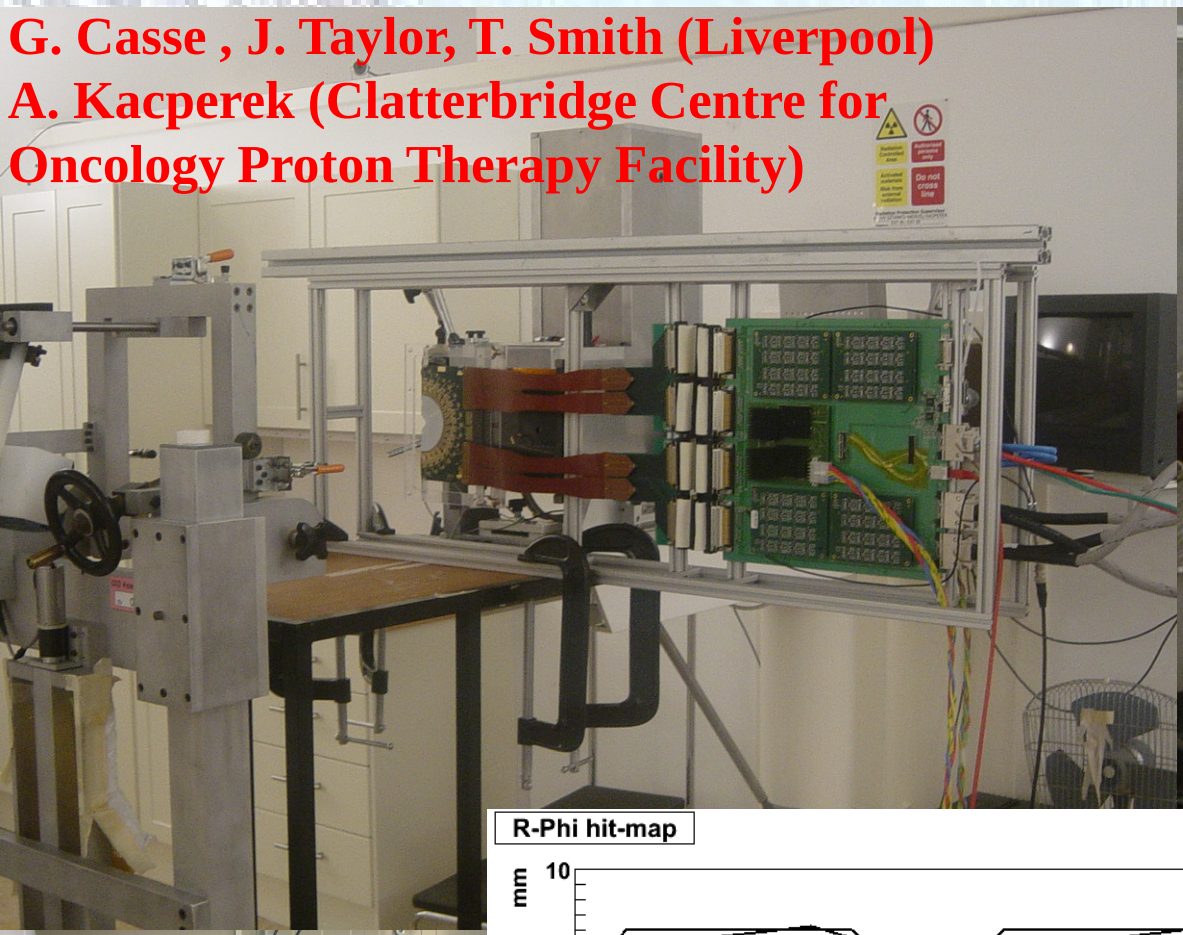
pCT Data Acquisition (DAQ) Flow

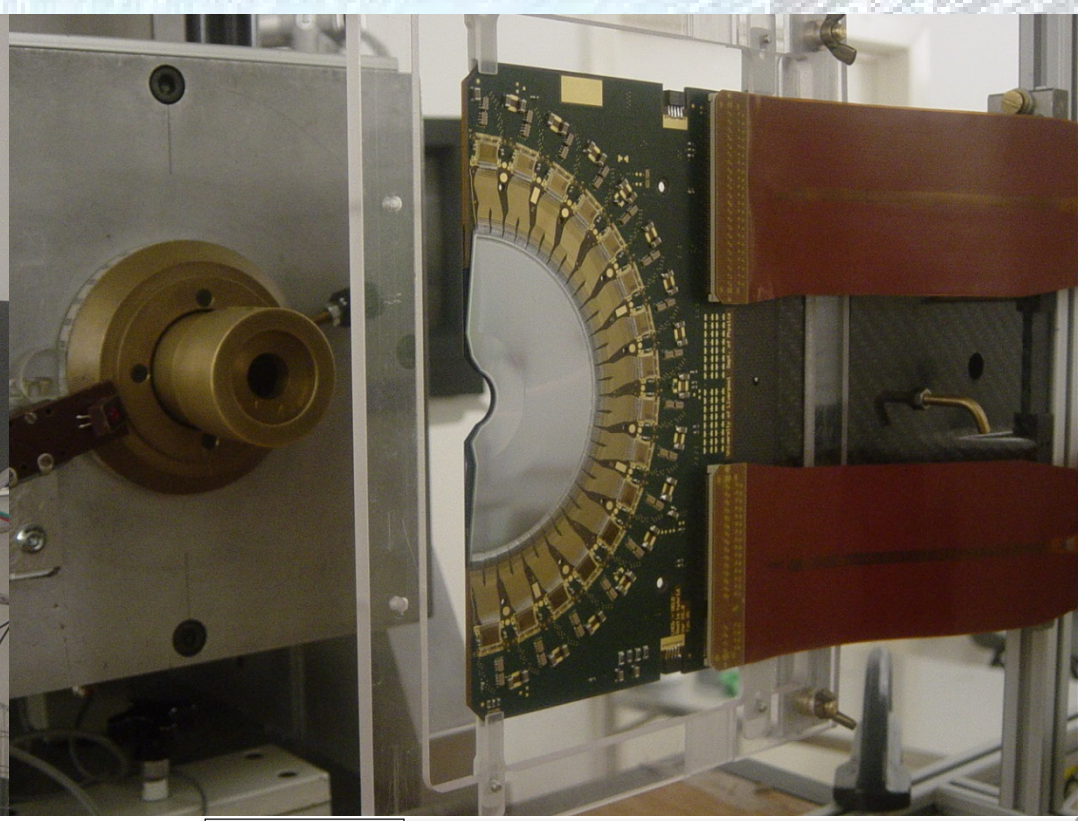
The readout is triggered, for ease of synchronization and event building, with ample buffering at the front end to minimize dead time. Eight layers of silicon strip detectors are read out by 144 64-channel ICs, each with a 100 Mbit/s link to an FPGA on the same board. Similarly, each of the two energy detector boards includes an FPGA. The 14 front-end Spartan-6 FPGAs build the local event data and then send it over dual-link DVI-D cables to the Virtex-6 FPGA, which builds the complete event and then sends it by Ethernet to a computer that is running a custom Python-coded DAQ program.



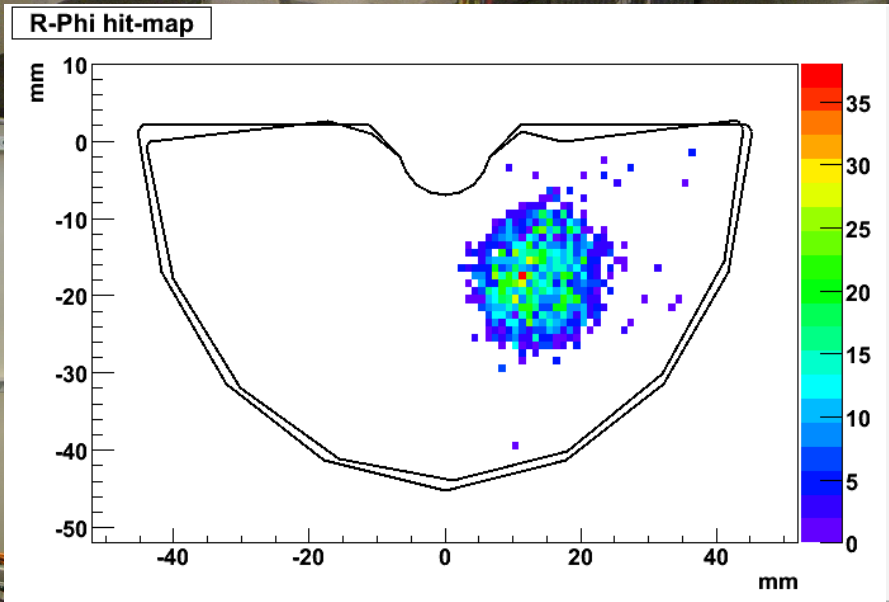
LHCb VeLo Module as Beam Halo Monitor

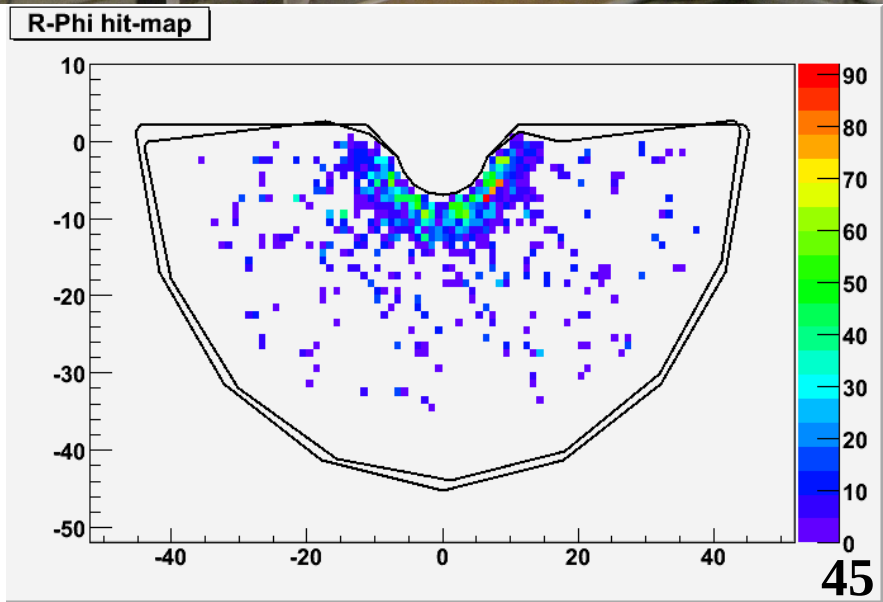
G. Casse , J. Taylor, T. Smith (Liverpool)
A. Kacperek (Clatterbridge Centre for Oncology Proton Therapy Facility)





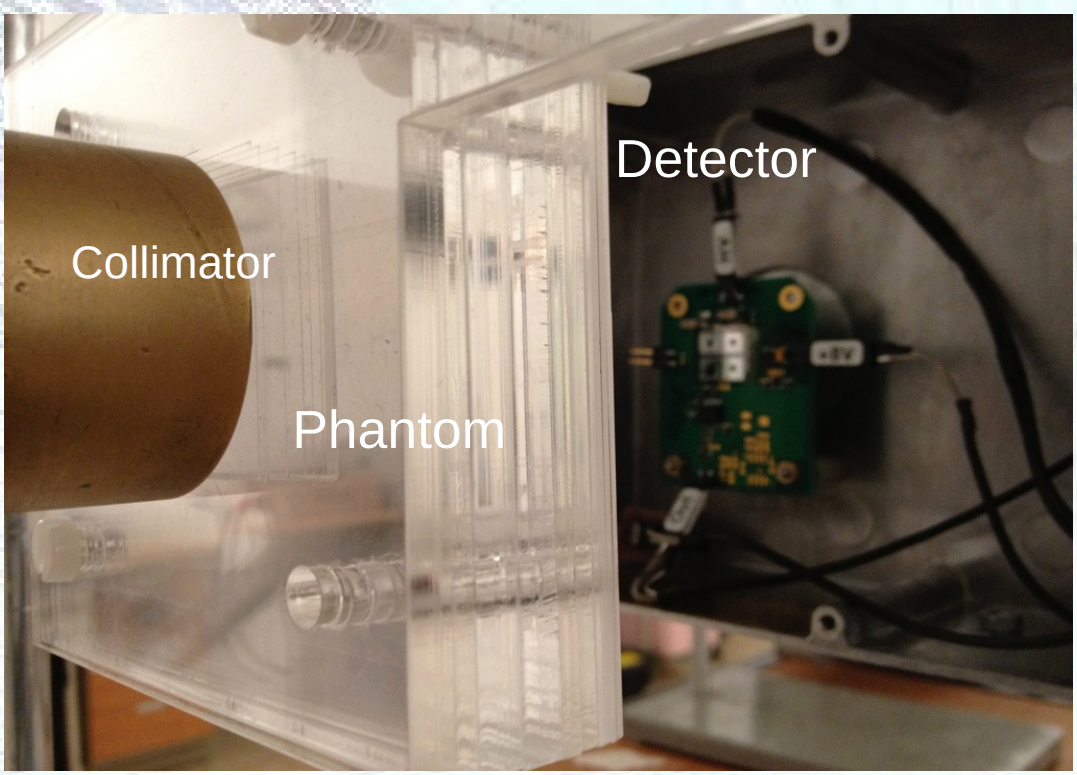
LHCb Vertex Locator (VeLo) assembly at CERN

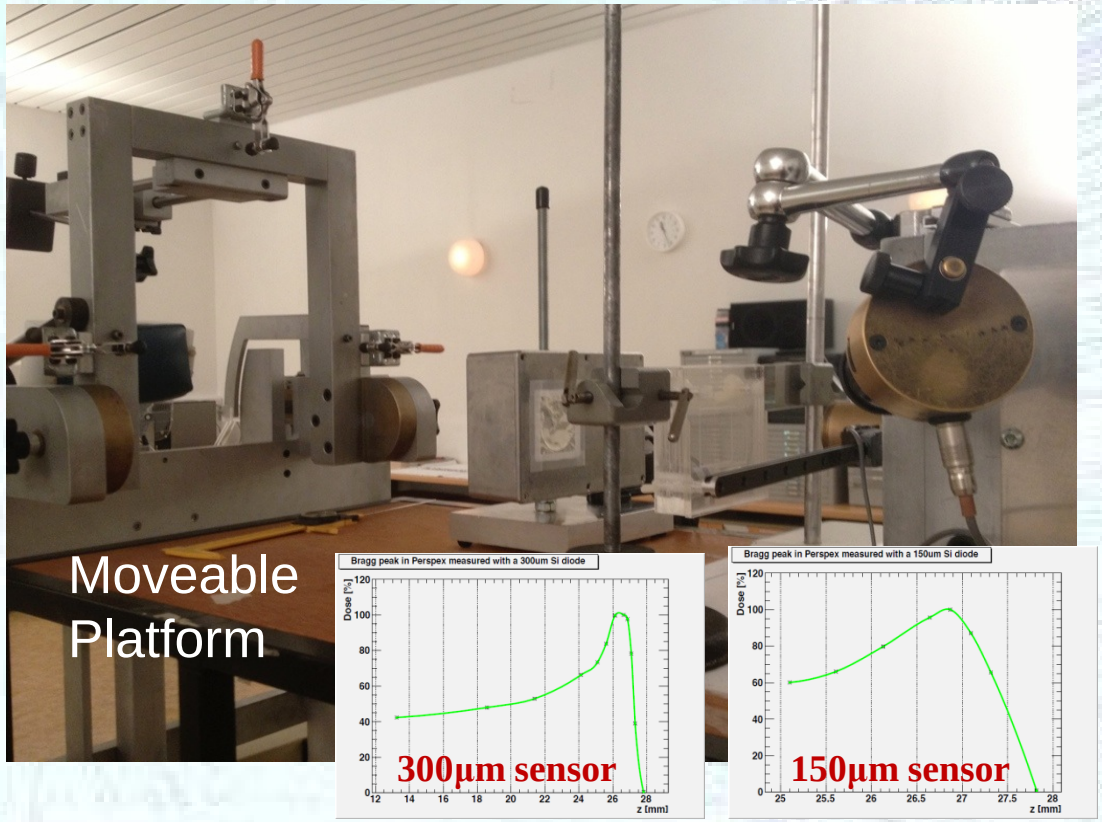




Perspex Phantom Measurement at Clatterbridge

J. Taylor, G. Casse (University of Liverpool); A. Kacperek (Clatterbridge Centre for Oncology)





Initial aim: to reproduce Bragg peak in perspex using n-in-p silicon detectors shown to be radiation hard to MGy doses

Detector system comprised of RD50 n-in-p diode and custom built data acquisition

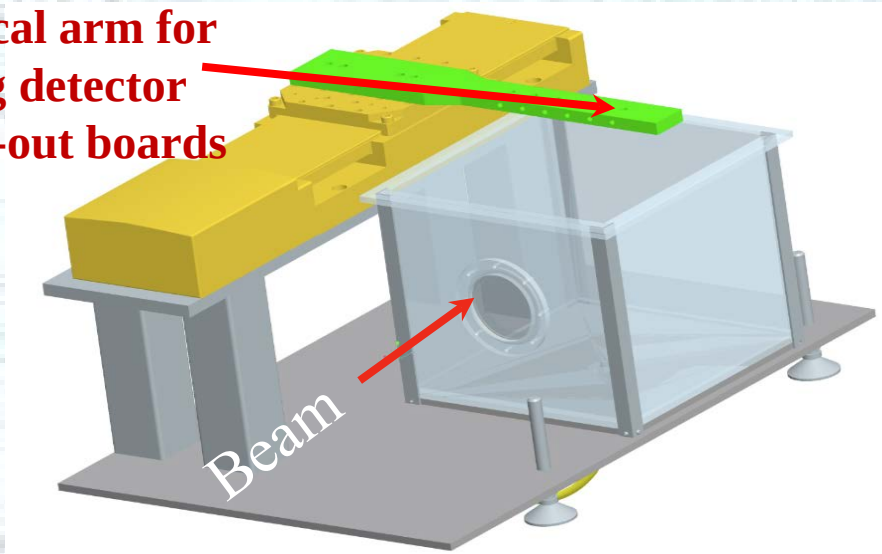
Phantom machined on the laser cutter with sheets of Perspex of varying thickness: 5 - 0.2 mm to allow precise steps to be made

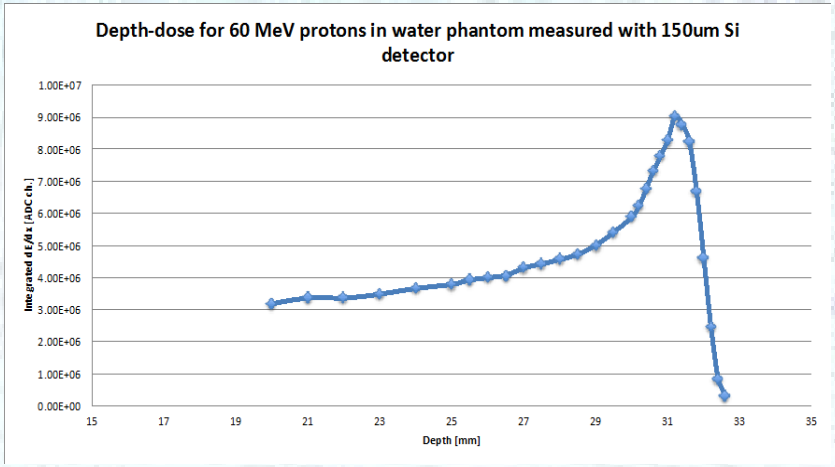
Novel Water Phantom Beam Monitoring System

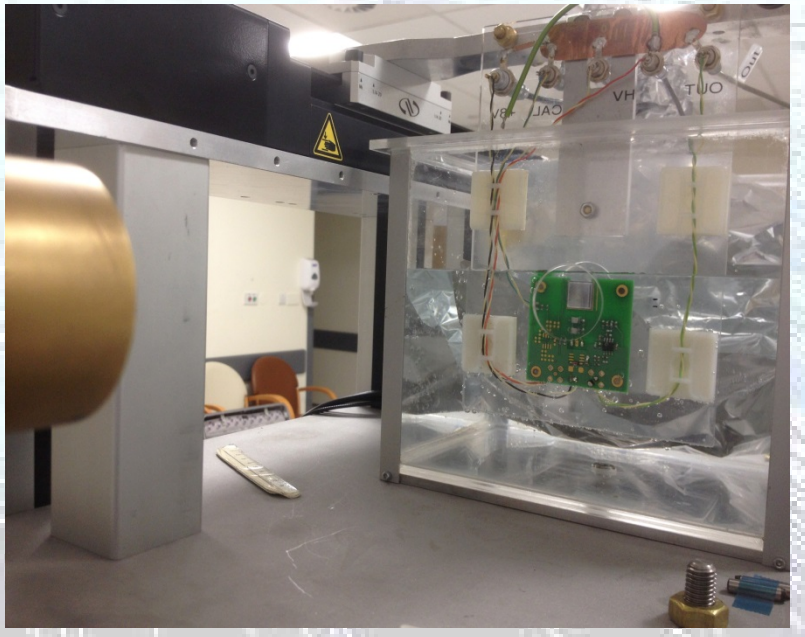
J. Taylor, G. Casse (University of Liverpool); A. Kacperek (Clatterbridge Centre for Oncology)

A silicon sensor is rapidly scanned through a tissue equivalent liquid to give the depth-dE/dx profile with high resolution. Silicon diodes (1D), and micro-strip detectors (2D) currently used. Ideally use a pixel to see full 3D dE/dx distribution for treatment planning and beam quality assurance.

Mechanical arm for mounting detector and read-out boards



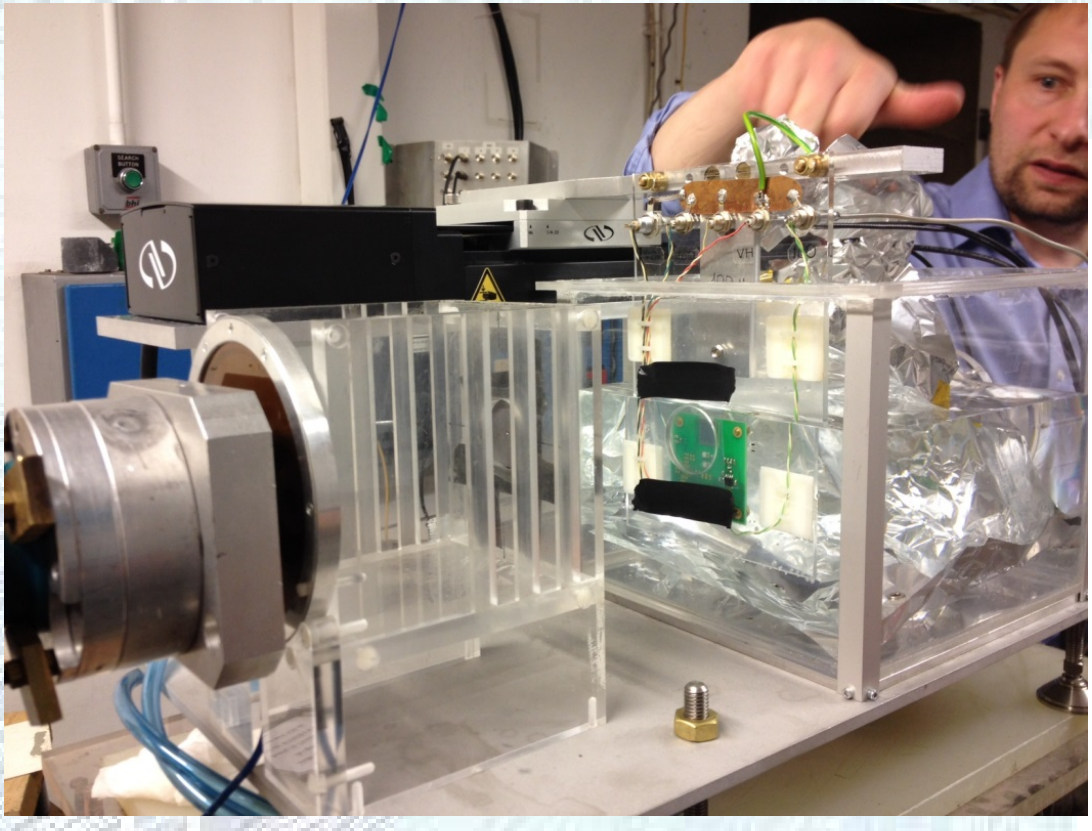




Water Phantom Measurements at Birmingham

Tony Price, David Parker, Stuart Green, Phil Allport (Birmingham)
Jon Taylor, Ilya Tsurin, Gianluigi Casse, Tony Smith (Liverpool)

100μm thick silicon detectors with 50μm parylene coating as a water barrier allowing good calibration with depth



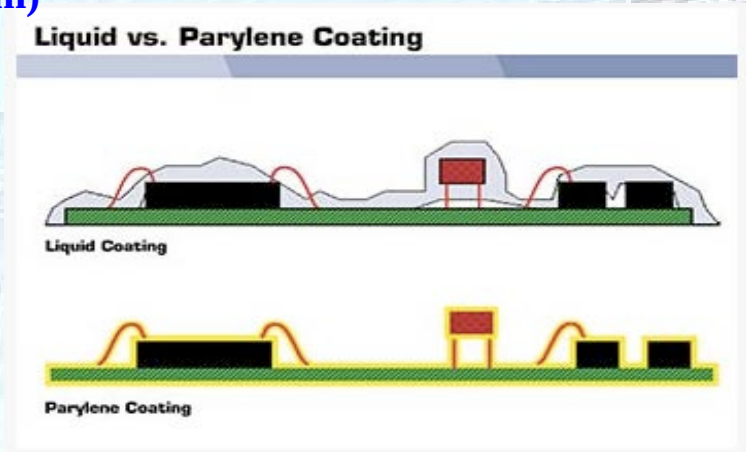
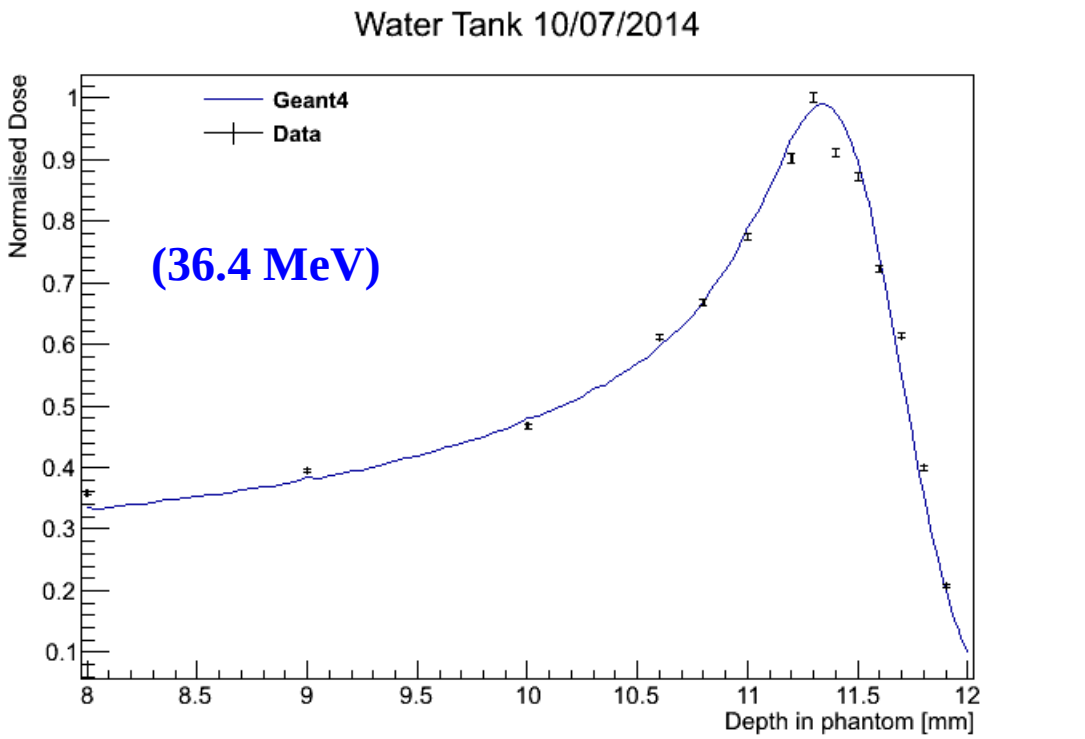


Illustration of liquid coating and Parylene coating



GEANT4 predictions including beam-line modelling

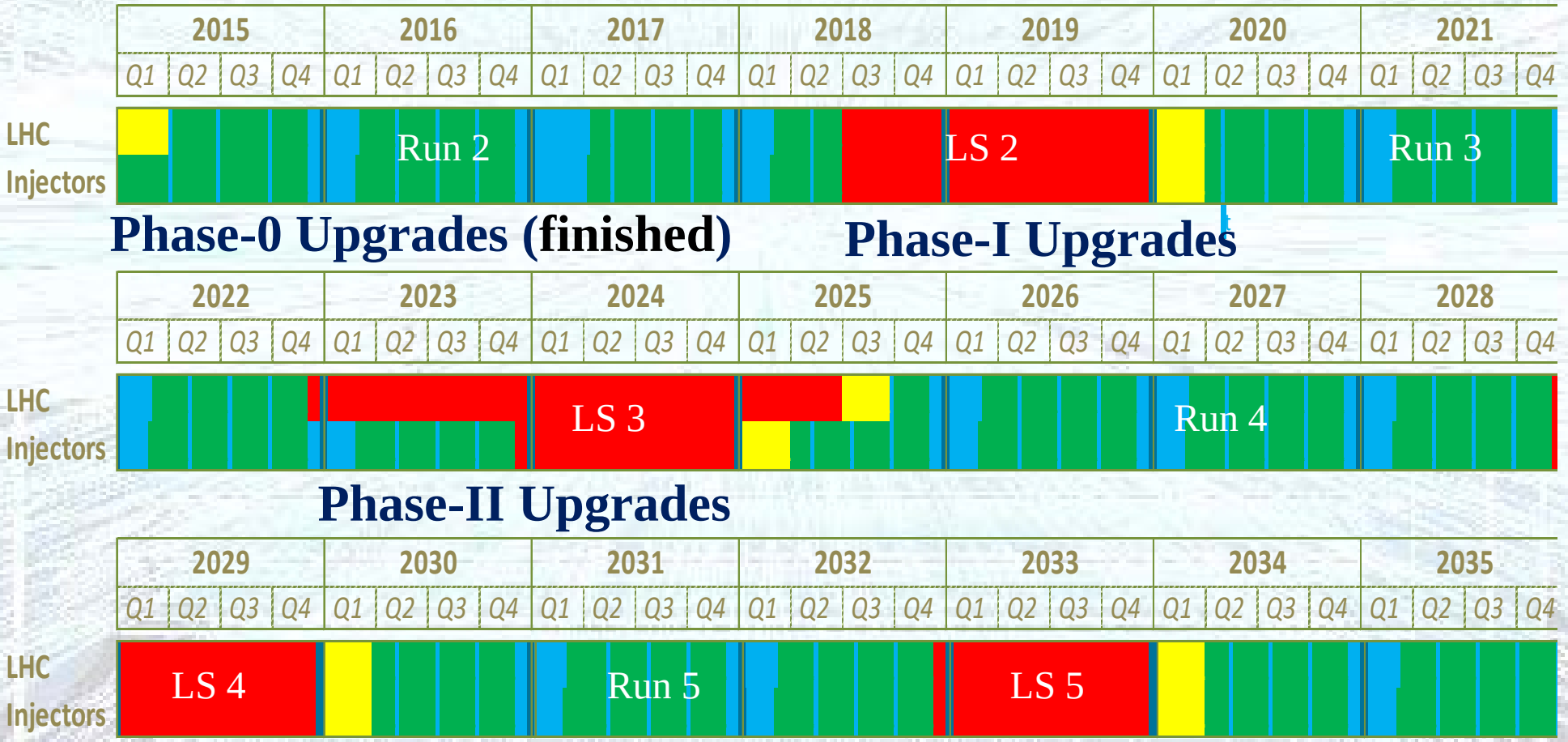
New LHC schedule beyond LS1

Only EYETS (19 weeks) (no Linac4 connection during Run2)

LS2 starting in 2018 (July) 18 months + 3months BC (Beam Commissioning)

LS3 LHC: starting in 2023 => 30 months + 3 BC

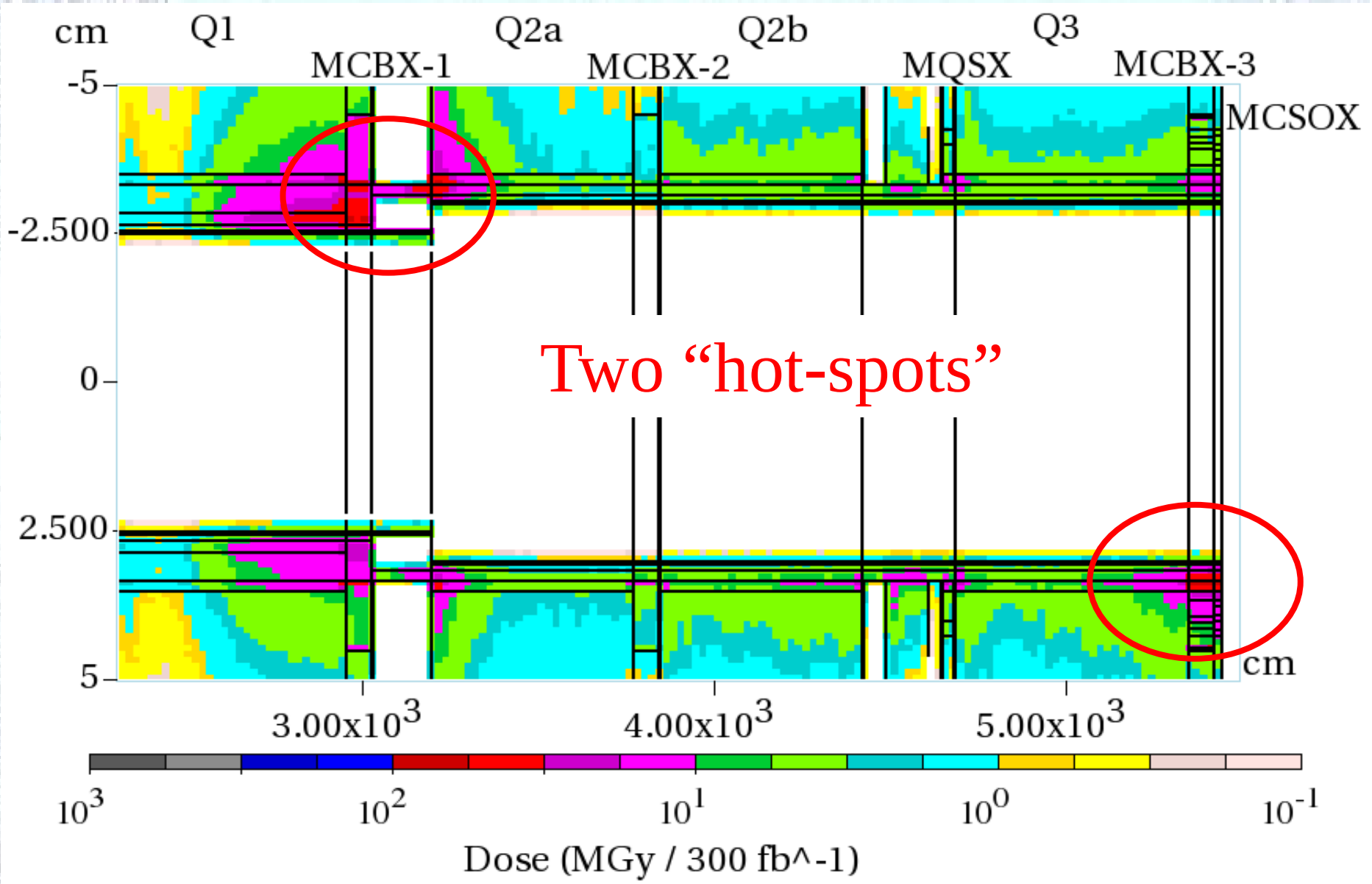
injectors: in 2024 => 13 months + 3 BC



LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators Monday 2nd December 2013

Radiation dose in the present triplet (300 fb^{-1})

L. Bottura

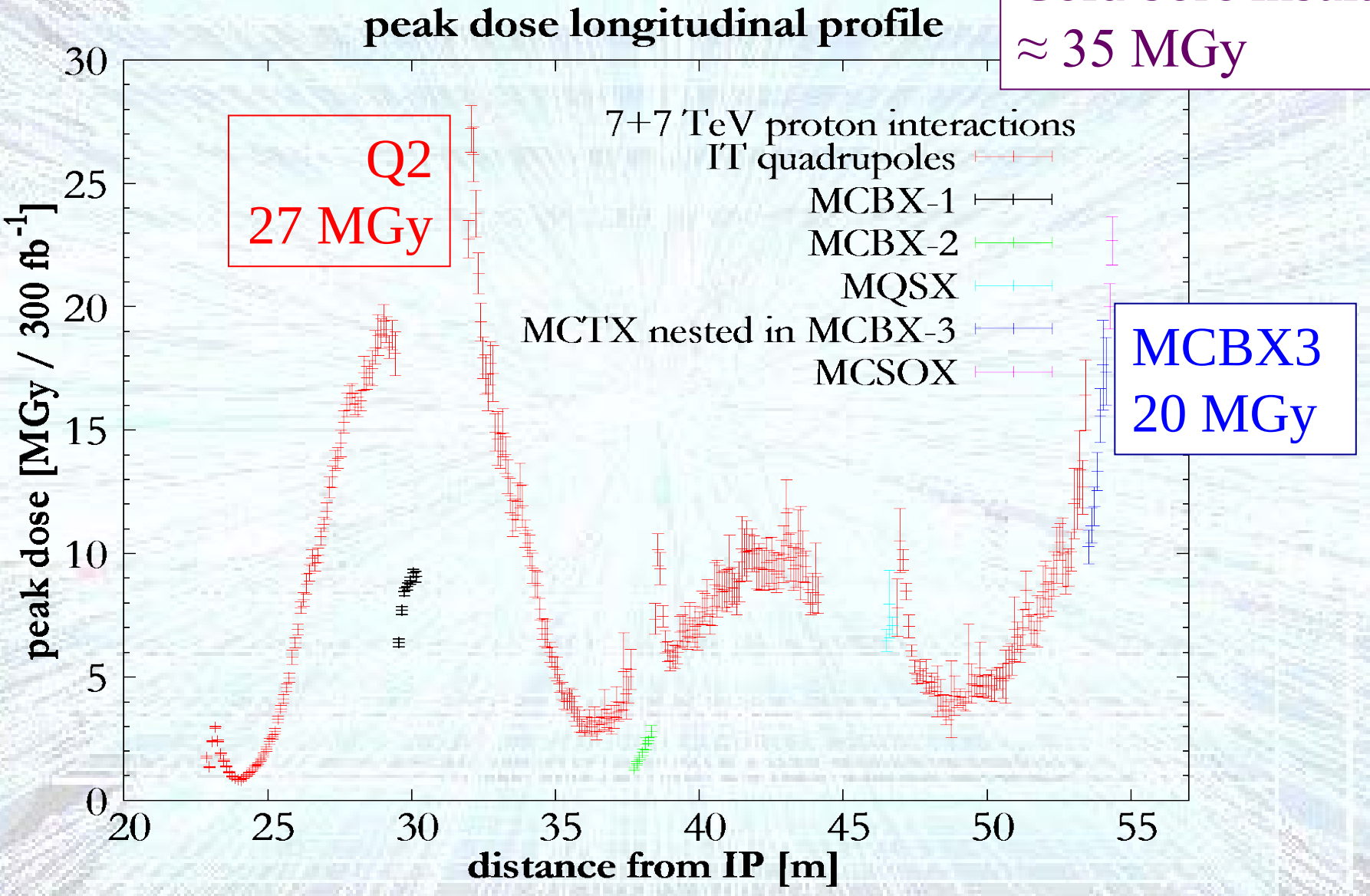


F. Cerutti, et al., WP10: Energy Deposition and Radiation Damage in Triplet Magnets, April 2013
https://indico.fnal.gov/conferenceDisplay.py?confId=6164

Radiation dose in the present triplet (300 fb^{-1})

L. Bottura

Cold bore insulation
≈ 35 MGy



Q2
27 MGy

MCBX3
20 MGy

F. Cerutti, et al., WP10: Energy Deposition and Radiation Damage in Triplet Magnets, April 2013
https://indico.fnal.gov/conferenceDisplay.py?confId=6164

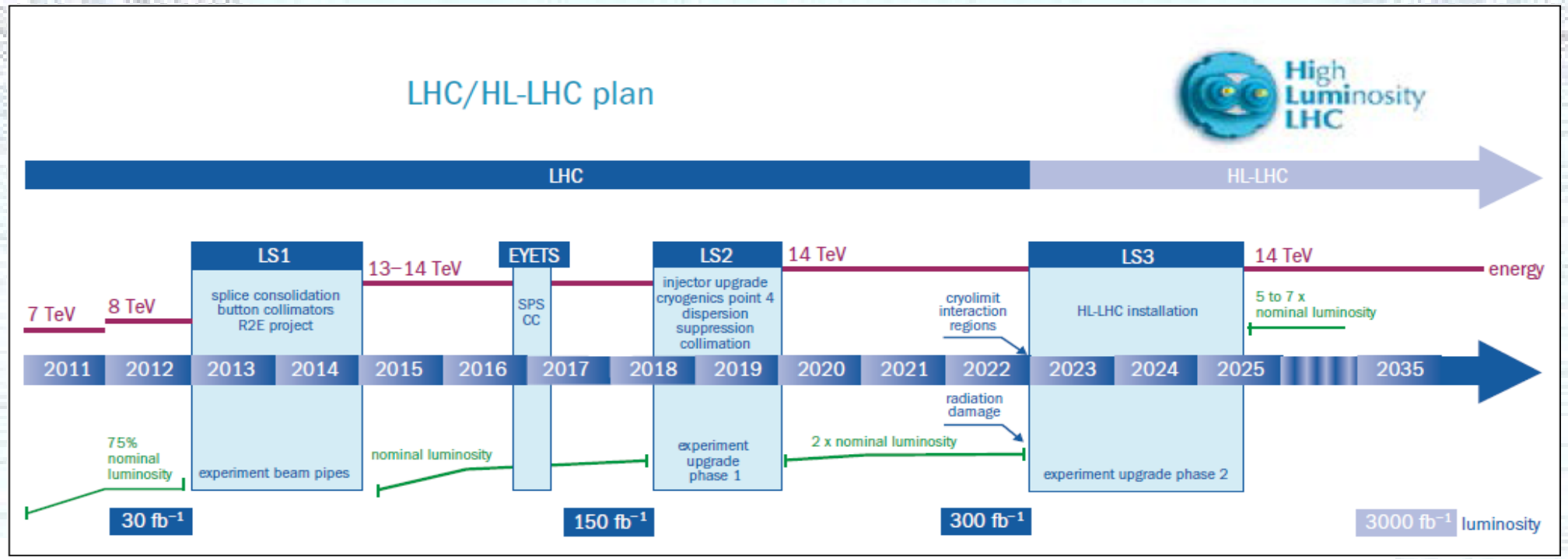
RLIUP Summary on LHC Inner Triplets

L. Bottura https://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=260492

- Expected dose by LS3 (300 fb^{-1}) with 50 % uncertainty(3)
  - Range of 27 [18…40] MGy in the Q2
  - Range of 20 [13…30] MGy in the MCBX
- Bonding strength (shear) of epoxies is strongly degraded (80 %) above 20 MGy
- Fracture strength of insulating materials degrades by about 50 % in the range of 20 MGy (G11) to 50 MGy (epoxies, kapton)
- Insulations (polyimide) become brittle above 50 MGy
- Triplet magnets may experience mechanically-induced insulation failure in the range of 300 fb^{-1} (LS3 ± 1 year)
  - Premature quenches (cracks in end spacers)
  - Insulation degradation (monitor on line(4))
  - Mechanical failure (nested coils in MCBX)

RLIUP Summary on LHC Inner Triplets

L. Bottura https://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=260492



induced insulation failure in the range of 300 fb^{-1} (LS3 ± 1 year)

- Premature quenches (cracks in end spacers)
- Insulation degradation (monitor on line(4))
- Mechanical failure (nested coils in MCBX)