Proton tracking for medical imaging and dosimetry

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For the PRaVDA Consortium

Proton Radiotherapy Verification and Dosimetry Applications

10th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors
Xi'an, China

Talk Overview

Background
- Motivation
- PRaVDA setup and microstrip tracker

Detector design and testing
- Sensor & ASIC design
- First results with charged particles
- GEANT4 simulations

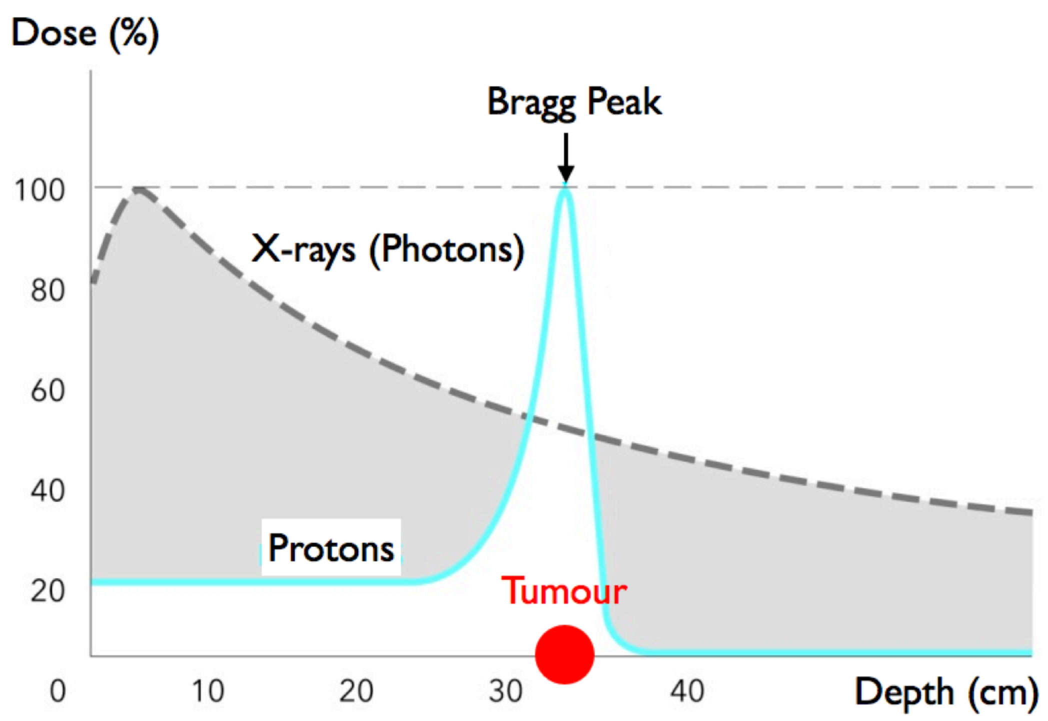
Beam test results
- 1D histograms and dosimetry
- 2D histograms and tracking

Summary and further work

What is particle therapy?

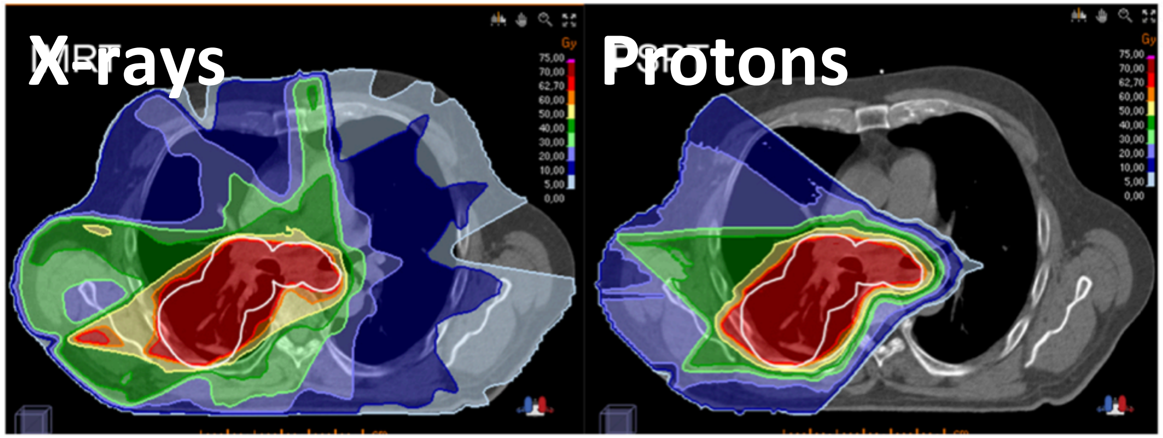
Particle therapy advantages:

- Potential for much improved dose targeting
- Much reduced entrance and exit dose



Treatment sites:

- Paediatrics – reduced occurrence of secondary cancers
- Tumours near critical organs



Wink et al. 2014

Proton Computed Tomography (pCT)

Due to the Bragg Peak, proton therapy is more sensitive to uncertainties in treatment delivery than conventional x-ray treatment

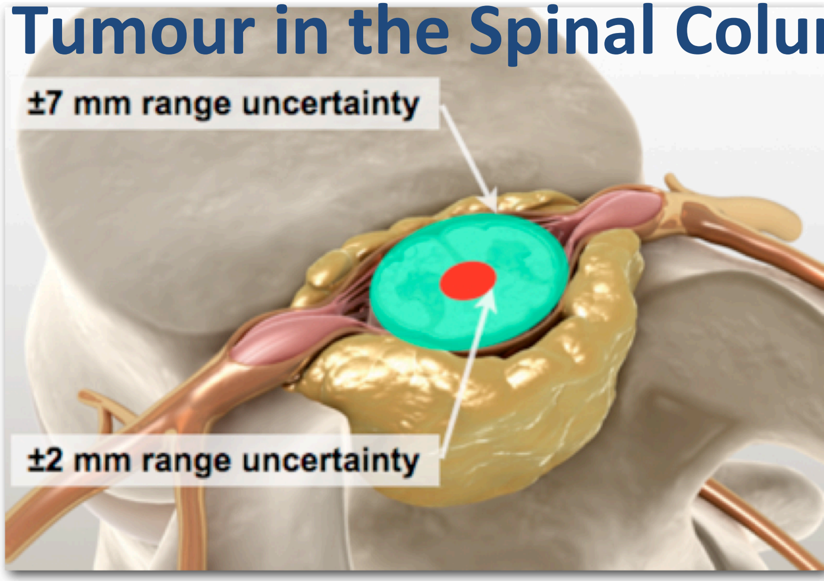
Current uncertainty in proton range is ~3.5% due in part to conversion from x-ray CT to proton dE/dx (shown in green)

Can prohibit treatment of tumours near critical sites e.g. spinal cord

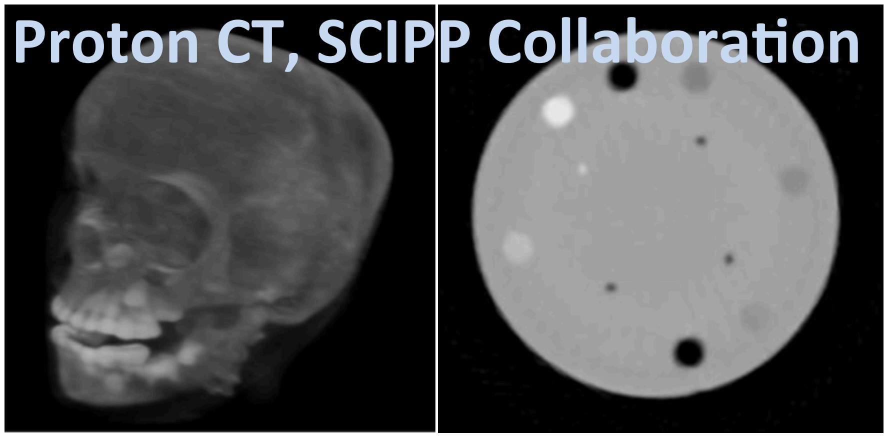
We aim to reduce proton range uncertainties to ~1% (shown in red) and give dose of ~1mGy

See Poster 41 by Hartmut Sadrozinski
And many other papers in the literature by the SCIPP pCT group

Tumour in the Spinal Column

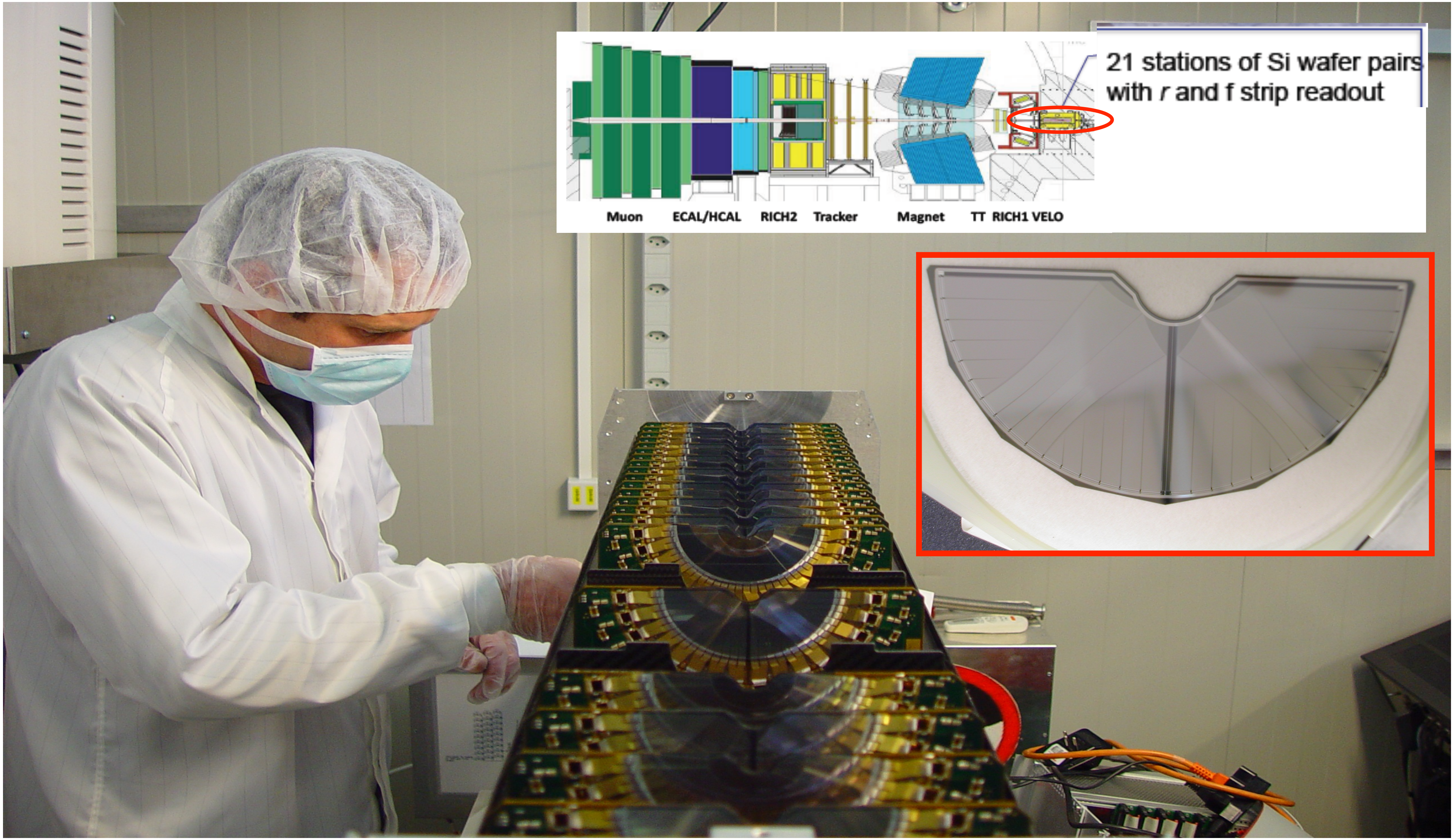


Proton CT, SCIPP Collaboration



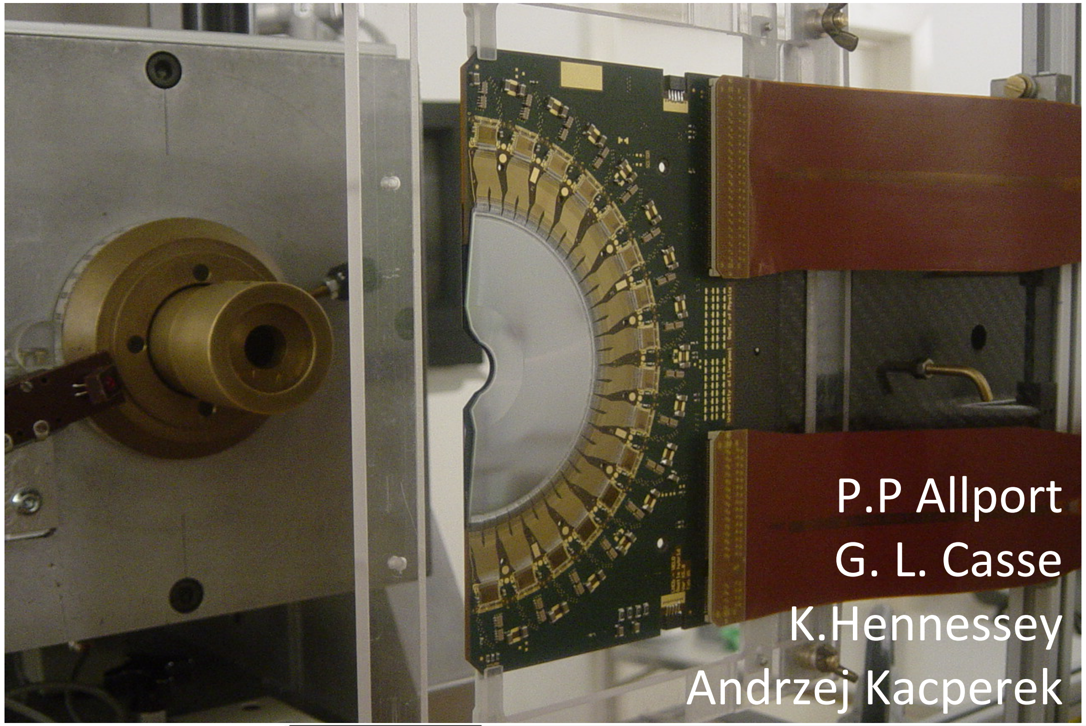
V.A. Bashkirov et al, NIM A (2015)

The LHCb VErtex LOcator

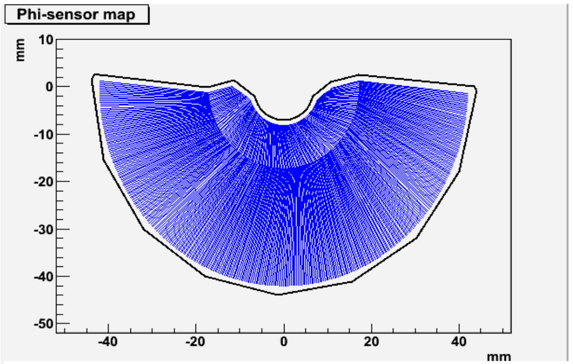


LHCb VELO Module as Beam Halo Monitor

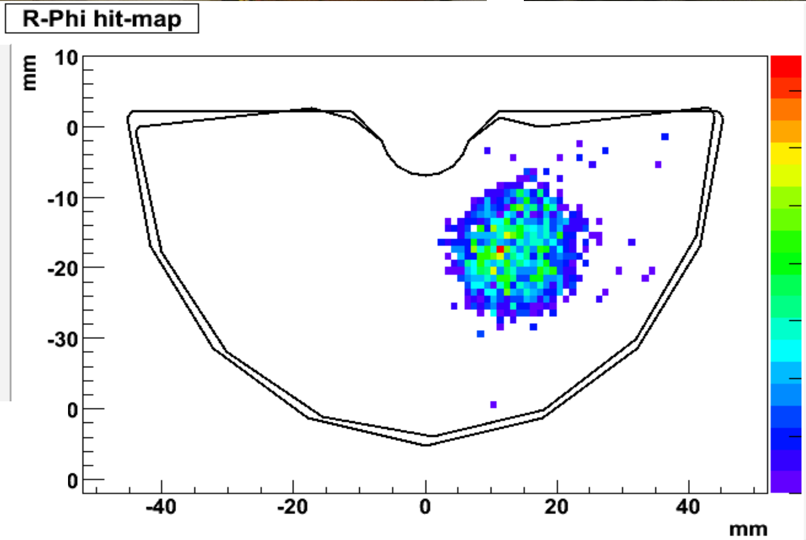
Clatterbridge Centre for Oncology Proton Therapy Facility

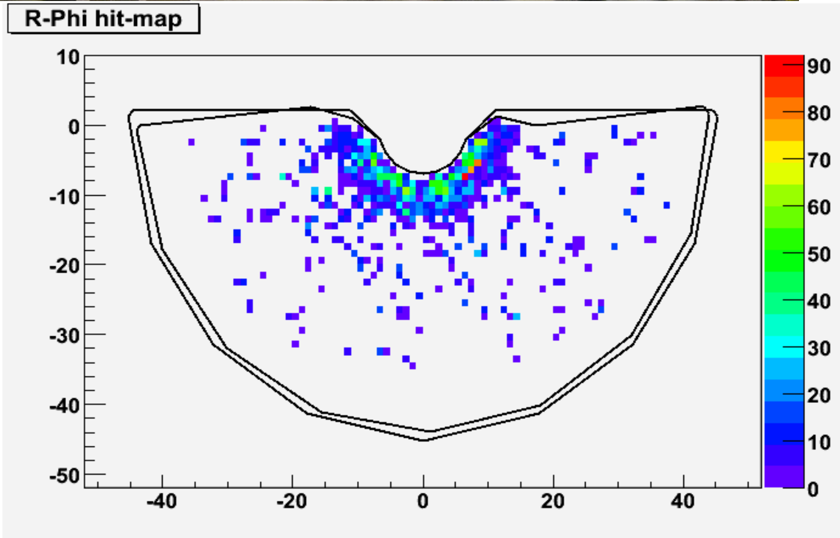


P.P Allport
G. L. Casse
K.Hennessey
Andrzej Kacperek

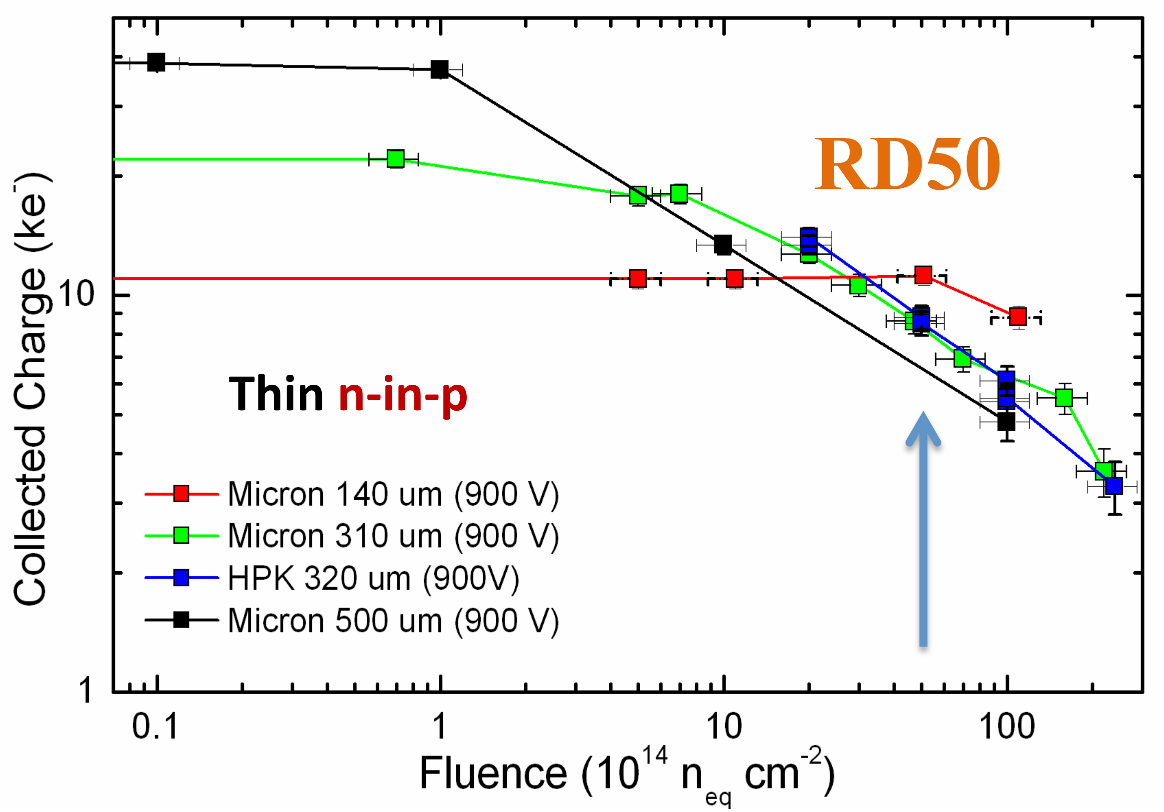


LHCb Back-to-Back Sensor Module





Radiation hardness studies

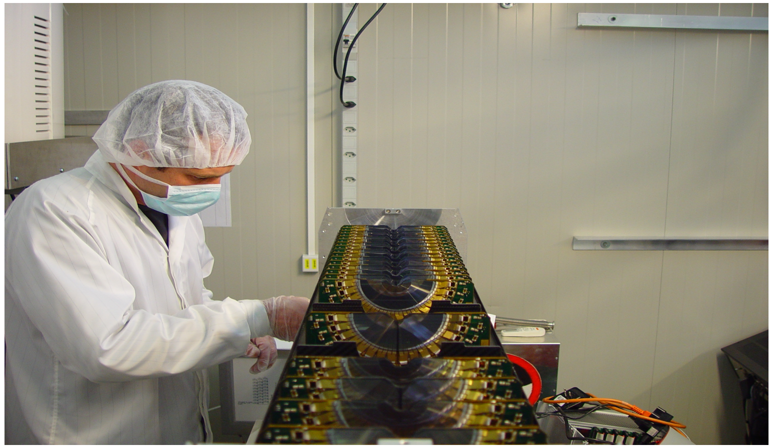


CERN RD50 collaboration has shown radiation hardness of thin n-in-p detectors up to at least 10^{16} n eq/cm^2.

This allows design of detectors that are very rad hard for applications with clinical beams.

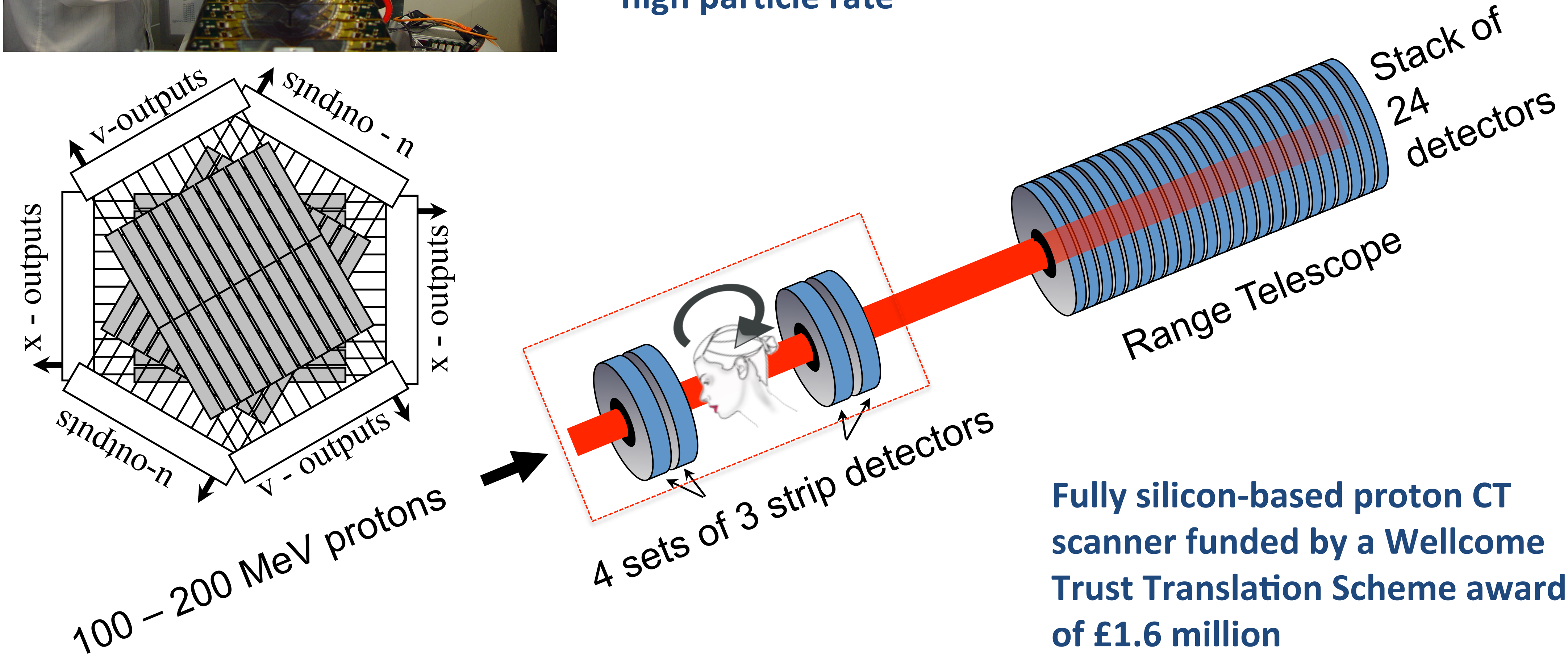
Thin detectors can be present in the beam for doses up to 5 x 10^{15} n eq/cm^2 without requiring re-calibration due to radiation damage effects.

System Overview



Each 150µm thick silicon detector has 2048 strips, 1024 read out on each side of the detector

Each tracking unit has three detector modules crossed at 60º in an (x,u,v) configuration to resolve ambiguities at high particle rate



Fully silicon-based proton CT scanner funded by a Wellcome Trust Translation Scheme award of £1.6 million

Operating Modes

Treatment Mode

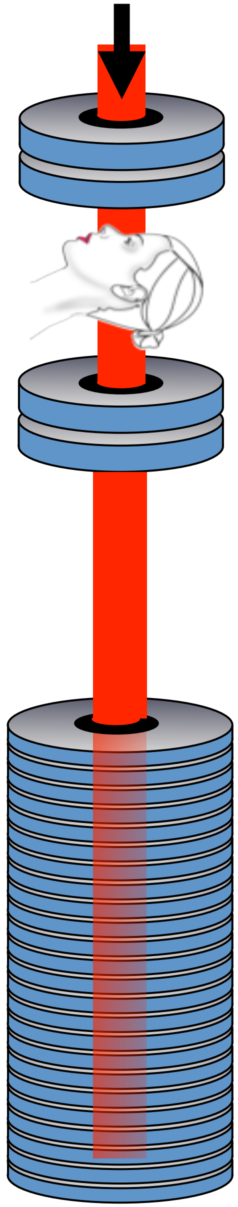
(High Current)
Field size: 5cm collimated treatment beam
Energy: 60 - 191 MeV
Flux: ~10^7 protons/cm^2/s

Use Strip Tracker to..

- Check beam profile – reconstruct 1D & 2D histograms
- Measure dose

Requirements:

- Proton counting
- 1D histograms
- 2D beam profile



Patient Imaging Mode

(Low Current)
Field size: 7-10cm (max. with current design)
Energy: 191 MeV
Flux: ~10^5 protons/cm^2/s

Use Strip Tracker to..

- Track individual protons in (x,u,v) layers

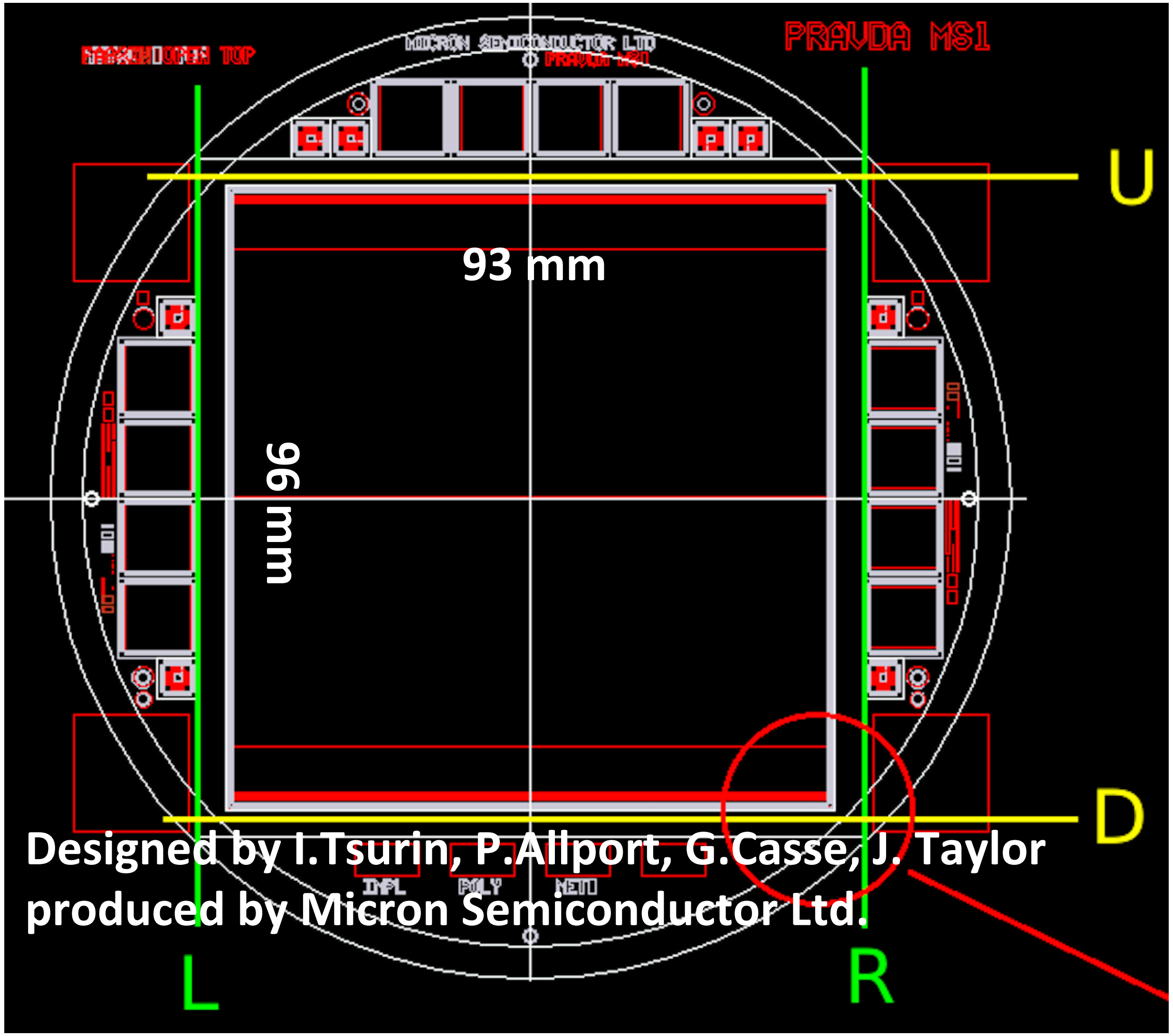
Use Range Telescope to..

- Measure positions and energies of each proton

Requirements:

- Accurate Tracking
- High Efficiency

Sensor & ASIC Design



ASIC design carried out by ISDI CMOS Ltd. Binary chip allowing:

Treatment Mode: Read out all strips every 100us for 1D & 2D beam profile histograms and dosimetry map

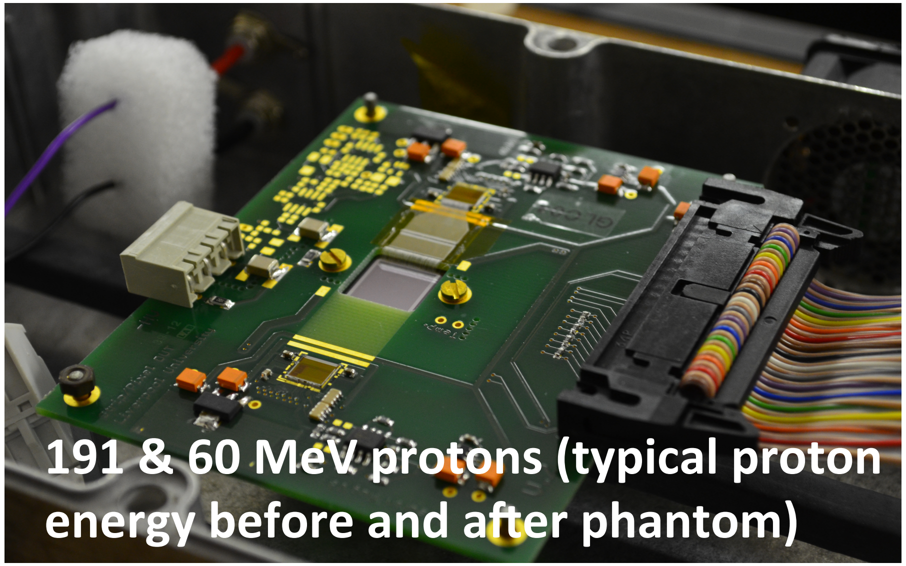
Two thresholds per channel allow for high occupancy

Patient Imaging Mode: Read out up to 4 strips per ASIC with signal over threshold possible at 26MHz (beam spill repetition rate at iThemba)

ASIC was fabricated in August 2014, now wire-bonded to assembled modules

Hybrid design by N.A. Smith at Liverpool

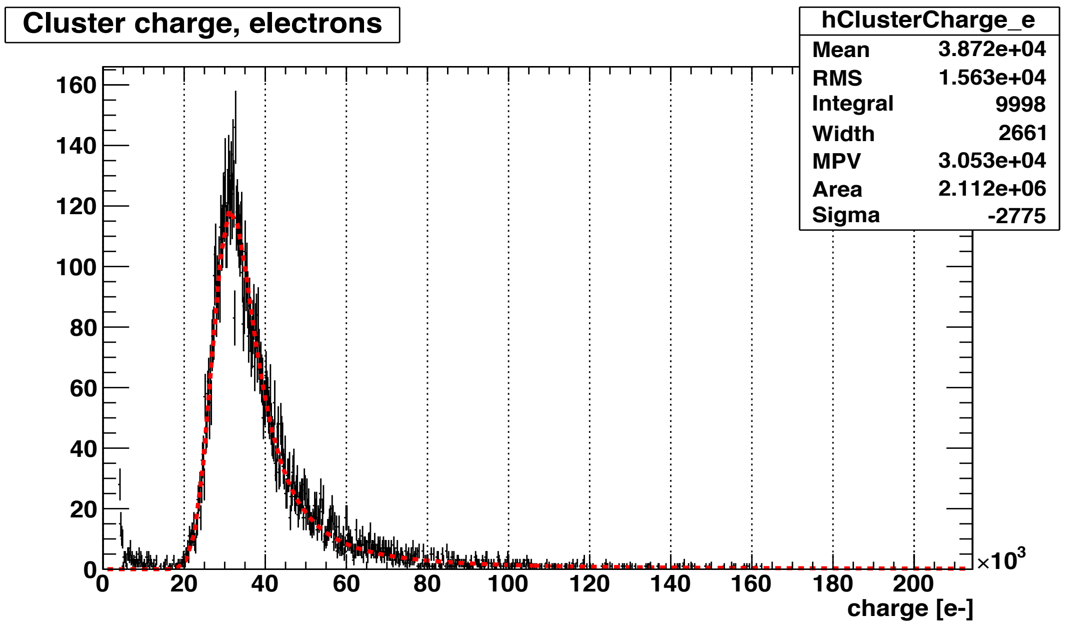
ALiBaVa Measurements for Sensor & ASIC Design

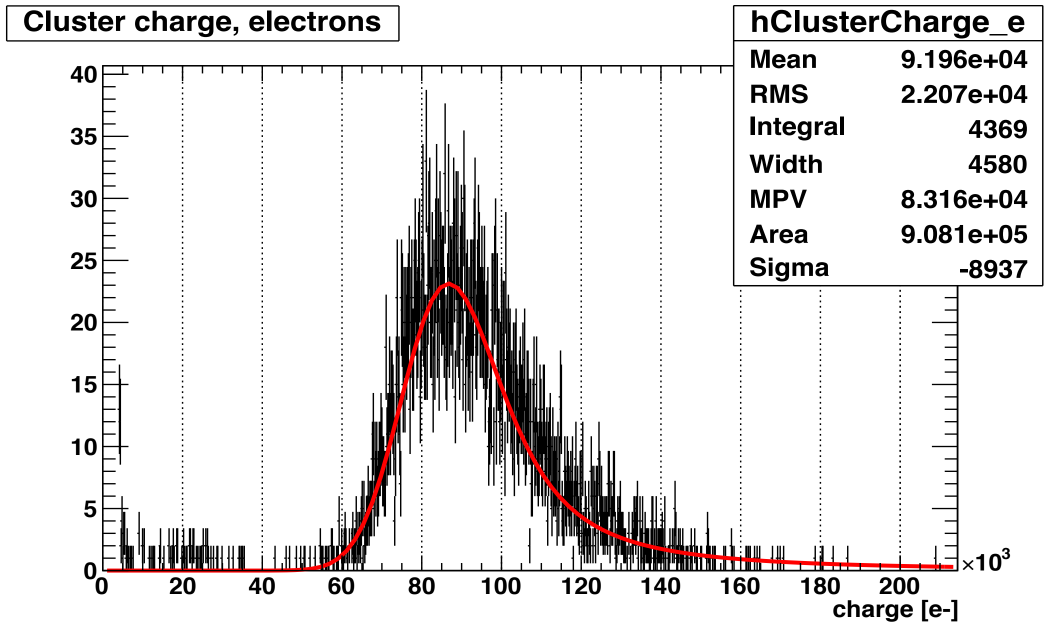


1cm x 1cm x 150µm silicon strip detector with 128 channels and 80µm strip pitch

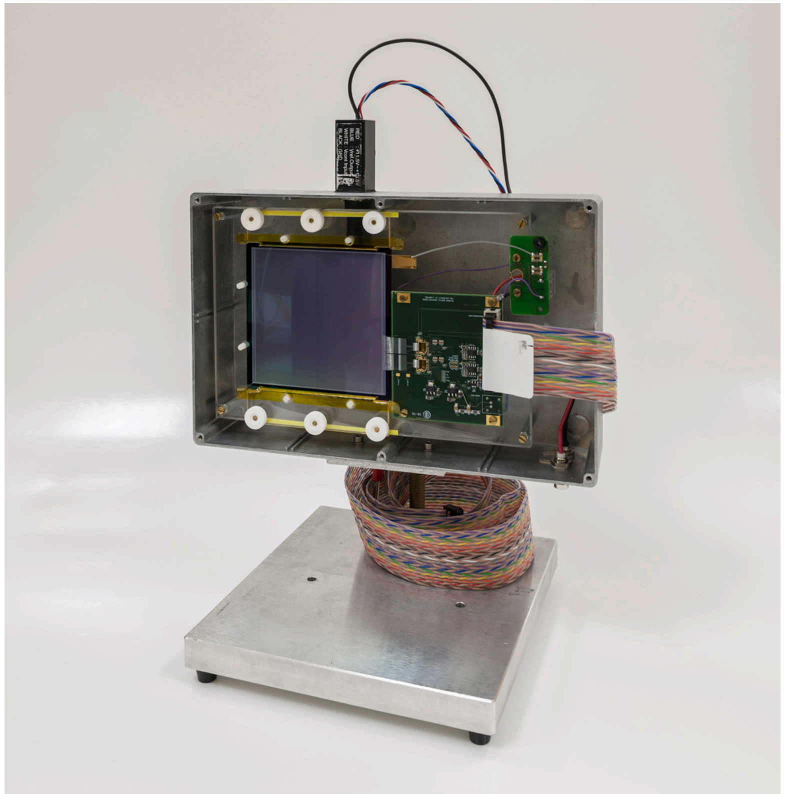
Sensor wire bonded to rad-hard BEETLE ASIC (LHCb experiment) with 40 MHz clock

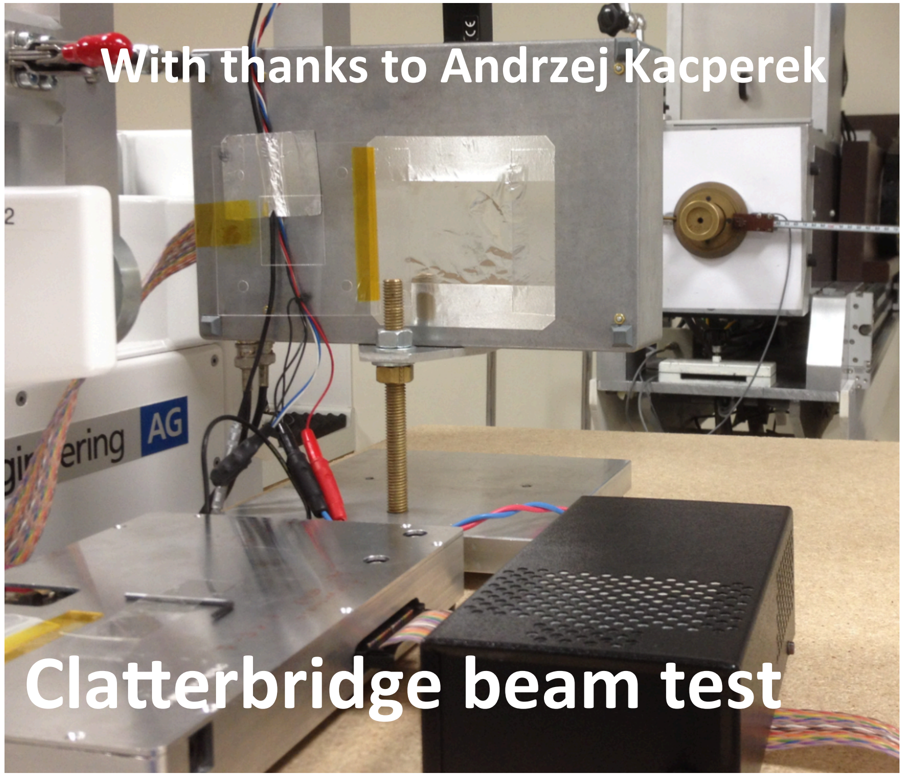
ALiBaVa readout motherboard capable of much slower 300 Hz readout using scintillator trigger behind sensor





ALiBaVa readout for PRaVDA sensor





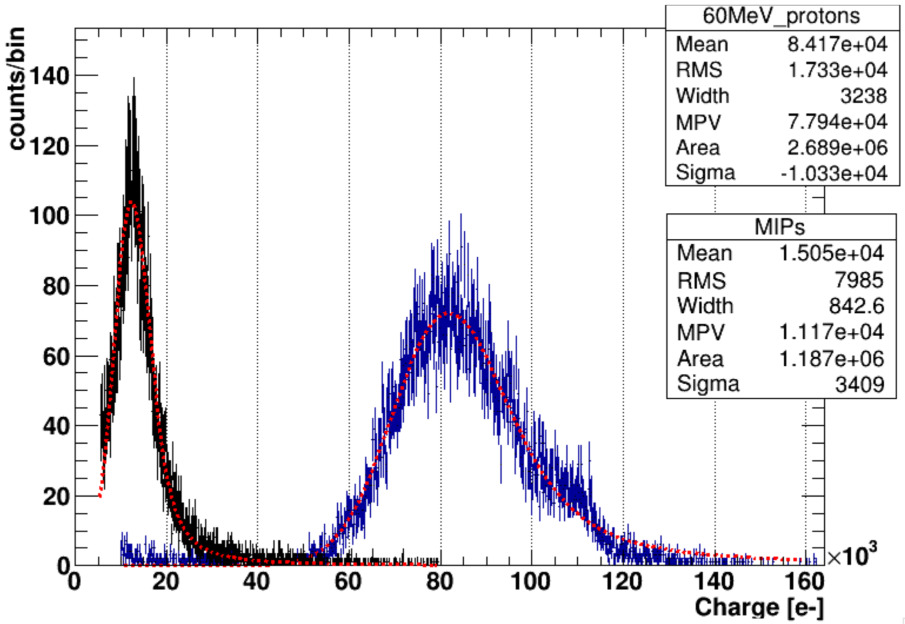
Wire-bonded 256 strips (12.5% of total detector) which allows a beam size of up to ~20 mm to be studied (and laboratory source measurements)

Readout using BEETLE ASIC (LHCb) and ALiBaVa DAQ

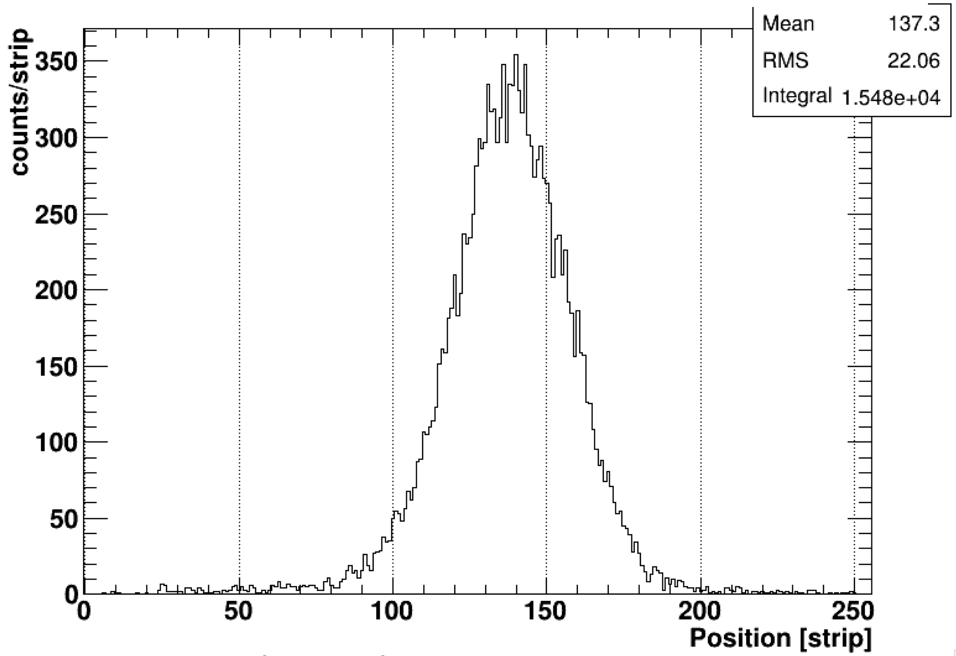
Thin beam entrance (not shown) window to prevent degrading of energy before detector, tests with MIPs (Sr90) and 60 MeV protons at Clatterbridge Cancer Centre.

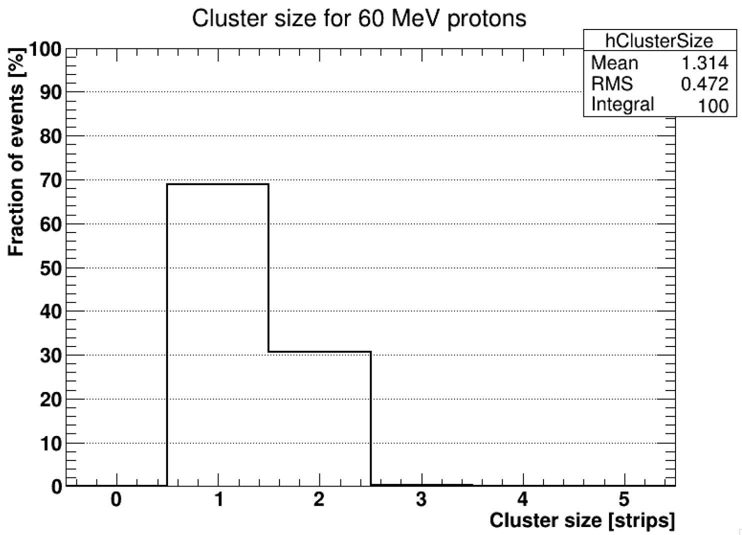
Testing the sensor with 60 MeV protons

dE/dx data for MIPs and 60 MeV protons



Cluster position for 60 MeV protons





J. T. Taylor *et al, JINST (2014)*

PRaVDA Sensor tested with MIPs and 60 MeV protons

Readout using BEETLE ASIC (LHCb) and ALiBaVa DAQ with a threshold of 10 ke- on all strips

RHEA ASIC

- Rapid high-speed extended ASIC (RHEA)
- Commercially designed ASIC from ISDI Ltd. using 0.18μm CMOS.

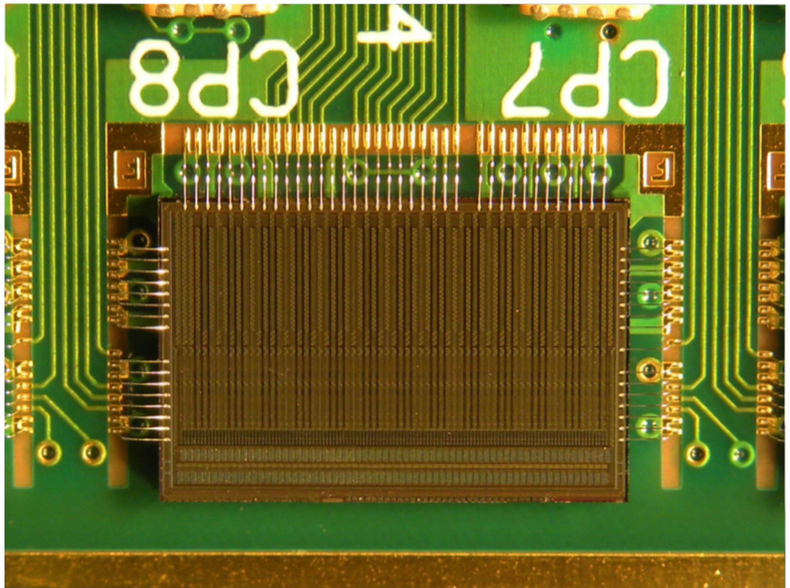
- High fluence application so binary ASIC with two tunable thresholds:

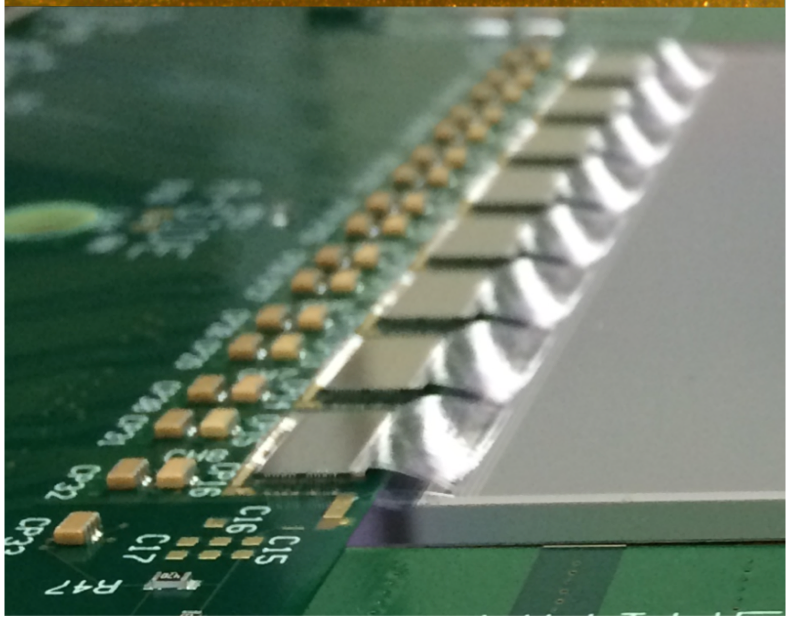
  Threshold range 1: 2,000 – 10,000 e-
  Threshold range 2: 20,000 – 160,000 e-

- 128 channels with a bonding pitch of 60μm

- Read out up to 4 strips per ASIC with signal over threshold at 26MHz

- Radiation damage testing by T.Price and P. Allport at the University of Birmingham cyclotron has shown ASIC to be radiation hard up to 2kGy (2-3 years of clinical use)



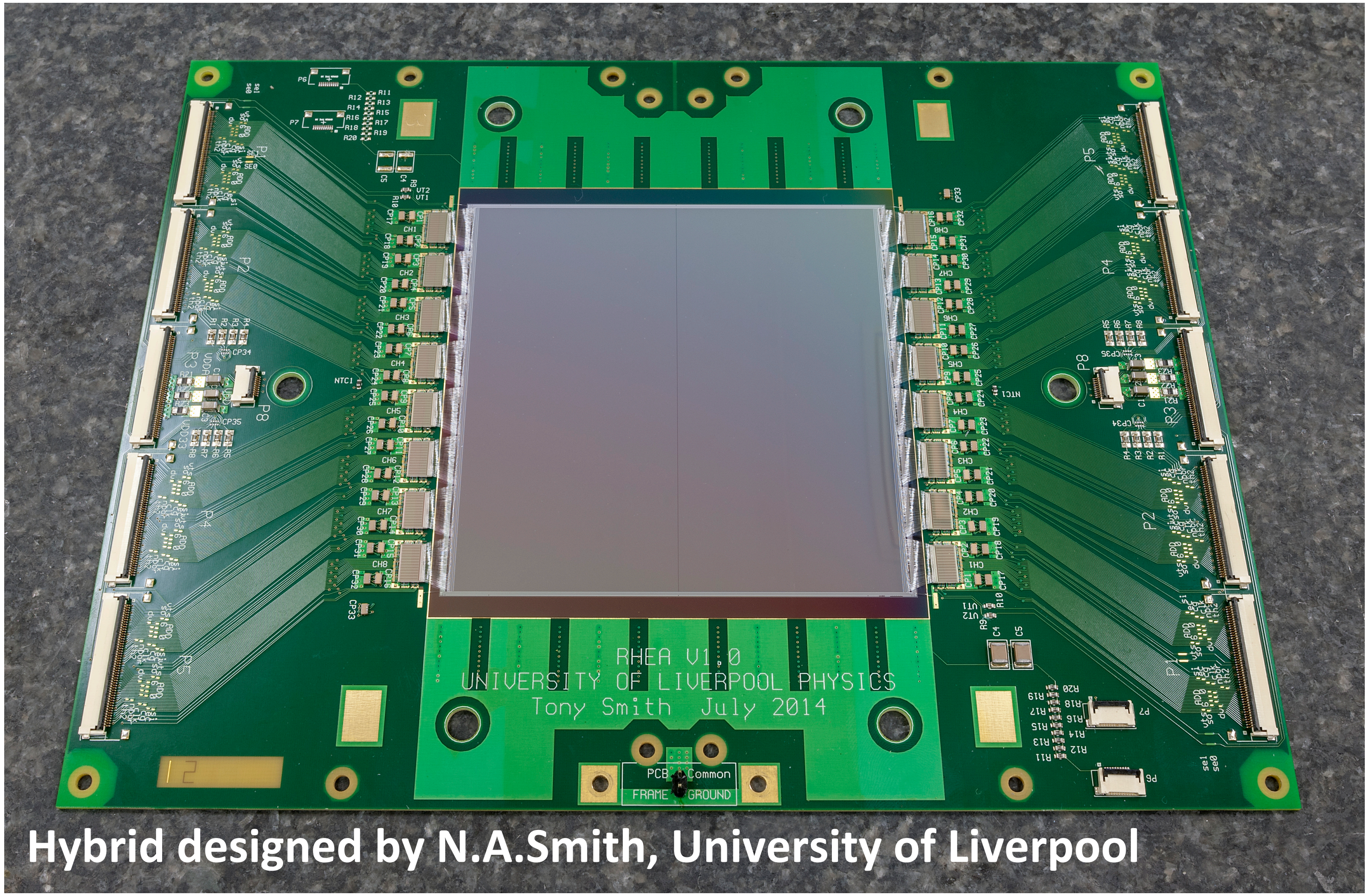


PRaVDA tracker module

Sensor manufactured by Micron Semiconductor Ltd.

Silicon microstrip sensor using **150μm** thick **n-in-p** technology developed for the **ATLAS Experiment** at the High Luminosity LHC

Left and right sides each contain 1024 strips with a pitch of 90.8μm.



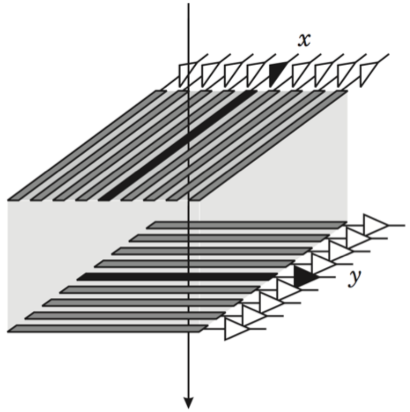
Hybrid designed by N.A.Smith, University of Liverpool

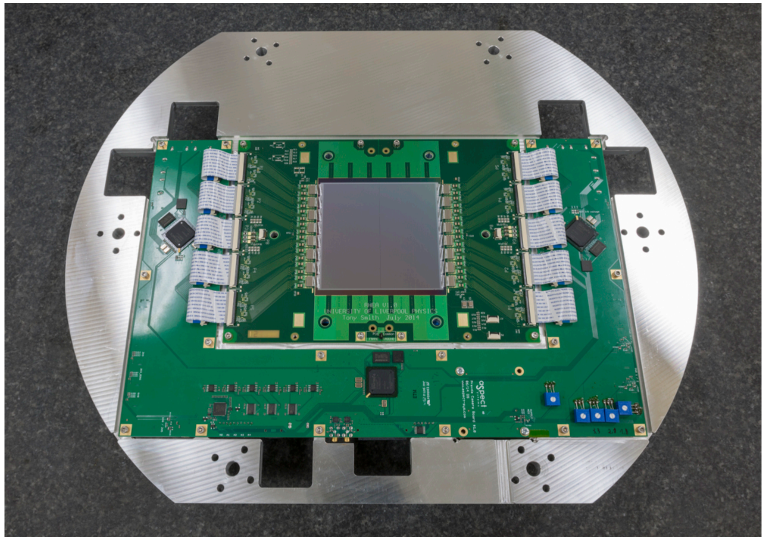
High occupancy achieved with…

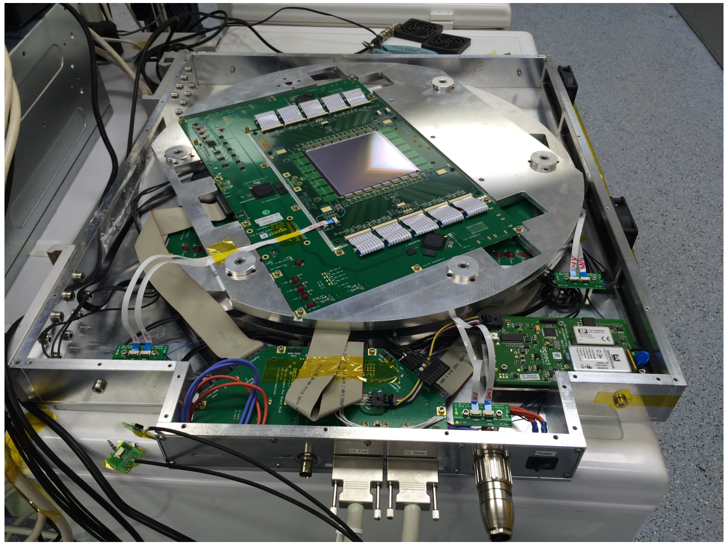
- **Double threshold on each channel (allows for two hits on each channel)**
- **Sensor readout from both sides (4.8cm strips with split in centre of detector)**
- **Tracking unit constructed from 3 detector modules at 60° stereo angle**

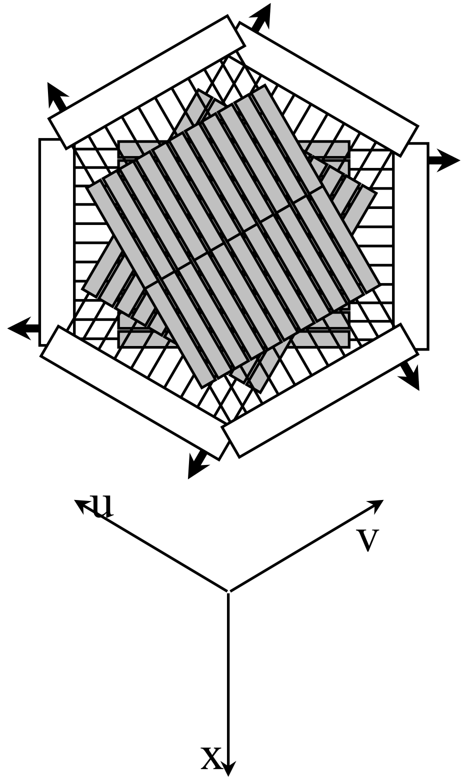
Tracker Geometry

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





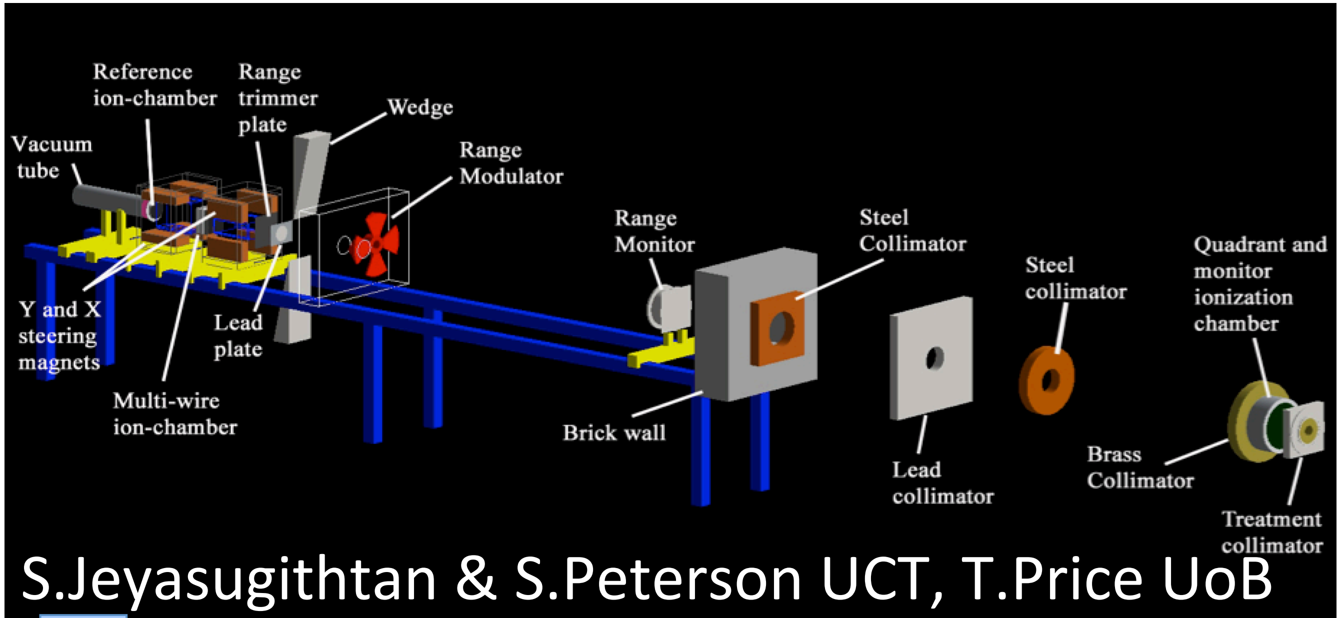




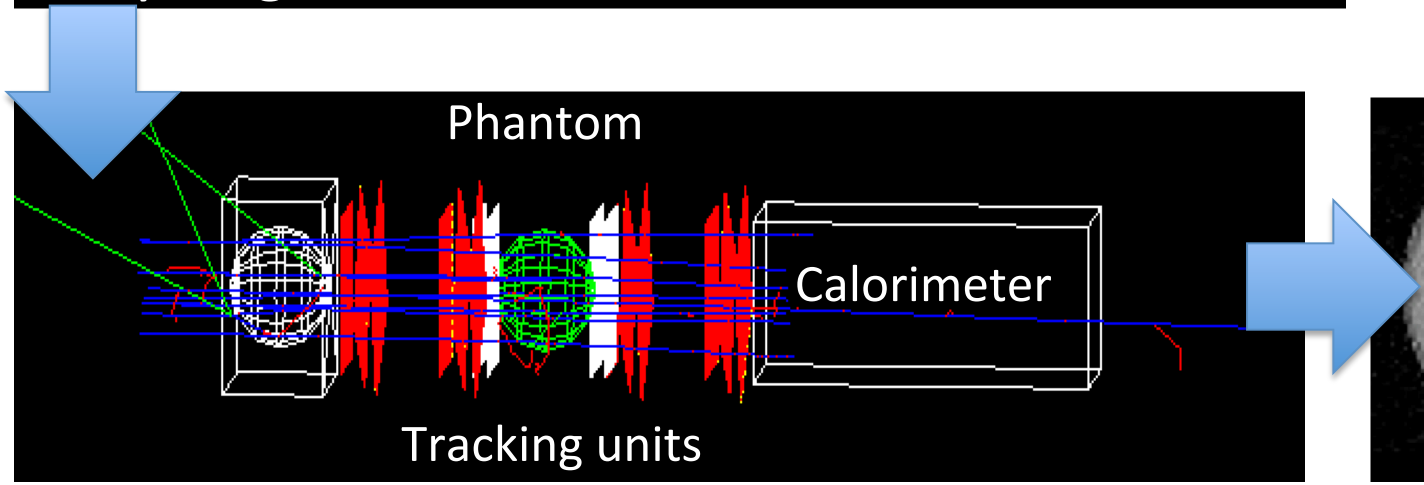
Mechanics designed by C.Waltham, University of Lincoln

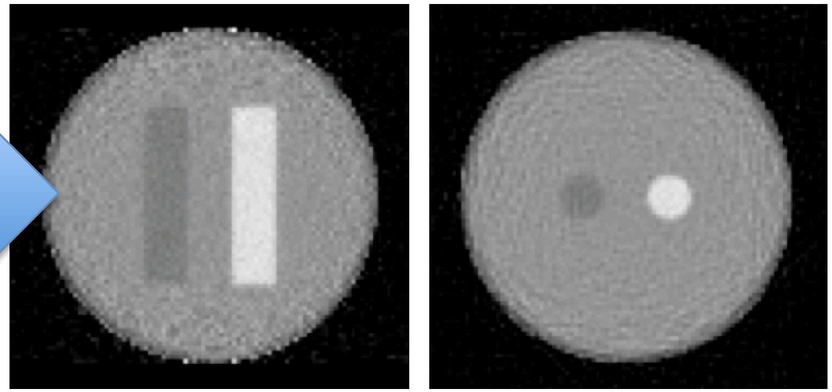
Each tracking unit has three strip modules crossed at 60° to one another in (x,u,v) configuration allowing higher particle rate.

GEANT4 Simulation of tracker



- iThemba beamline code used as input for GEANT4 simulations of silicon strip tracker
- Simulation provided output for detector/ASIC design and output for CT reconstruction algorithm

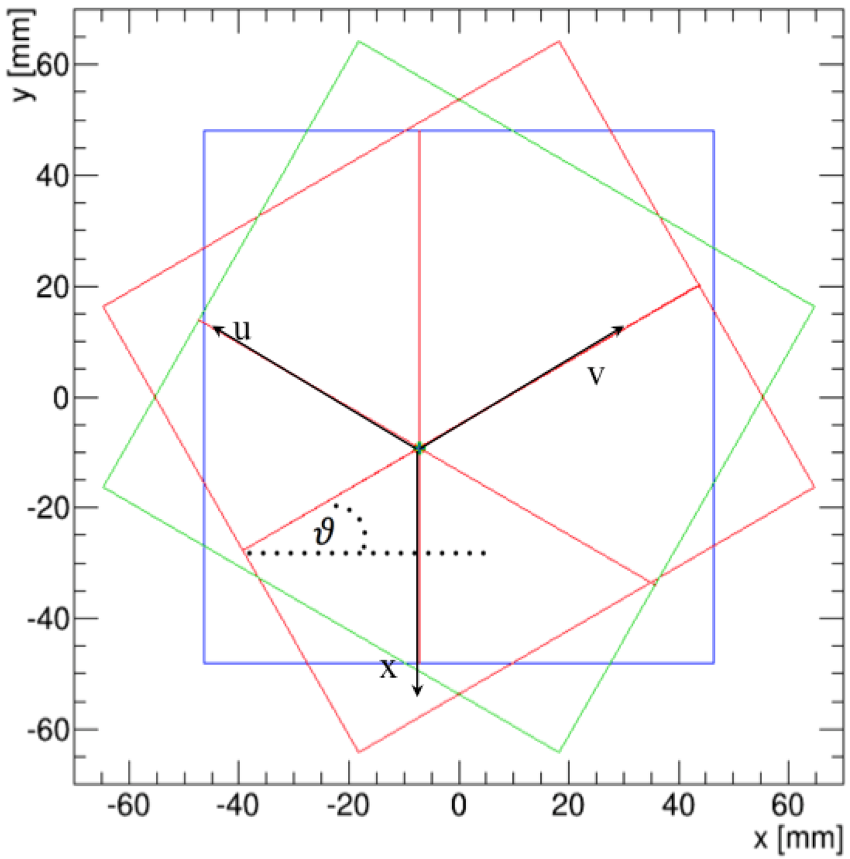


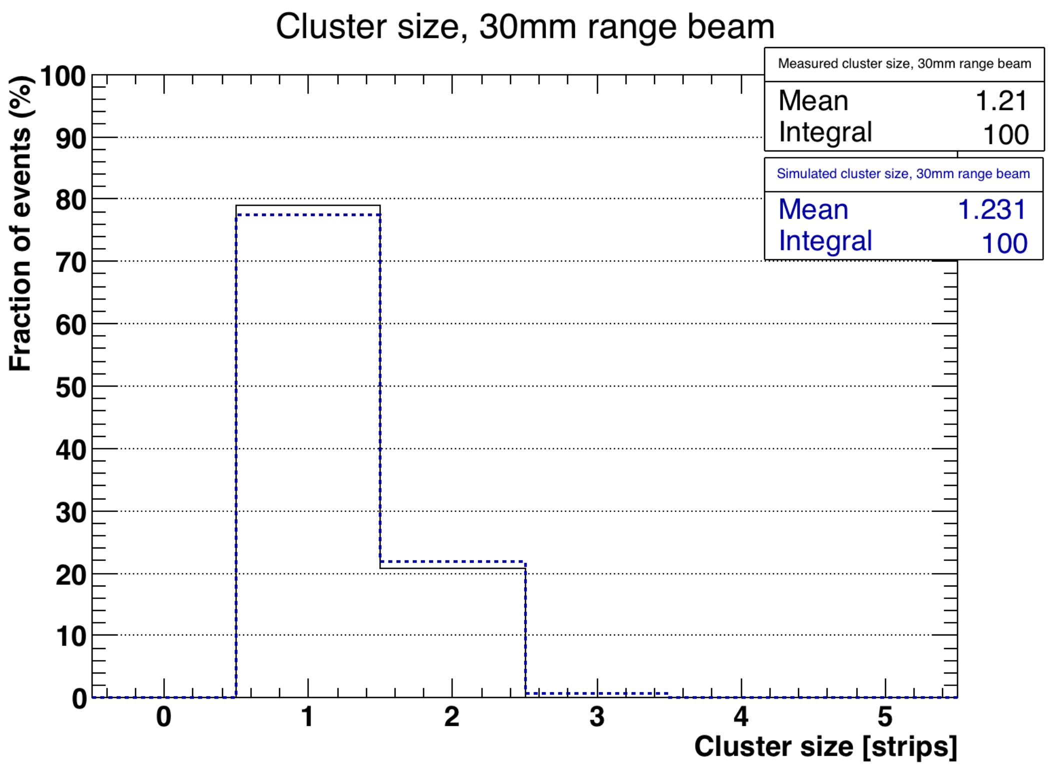


For details of novel CT reconstruction algorithm used see:
G.Poludniowski et al, Phys. Med. Biol. 59 (2014)

G. *Poludniowski, University of Surrey*
T.Price, University of Birmingham
J. T.Taylor, University of Liverpool

Tracking data from GEANT4





Once charge sharing is implemented in GEANT4, measured data agrees with simulation to within a few %

Tracking precision is found to be 300 – 600 µm from GEANT4 simulations depending on iThemba beam energy used

Results from the Birmingham cyclotron

Testing of tracking units using..

Beams of 36 and 29 MeV protons

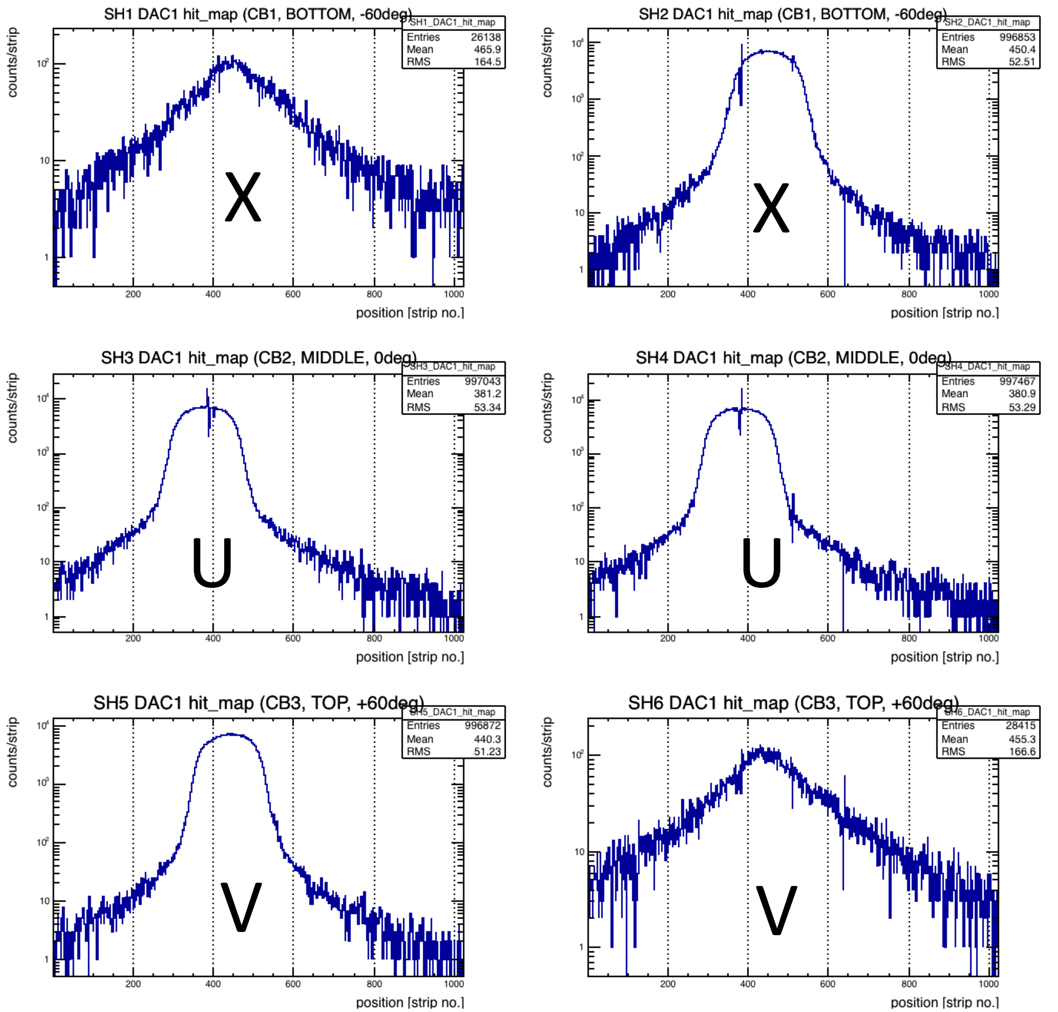
Beams available from 50 – 1 mm in size.

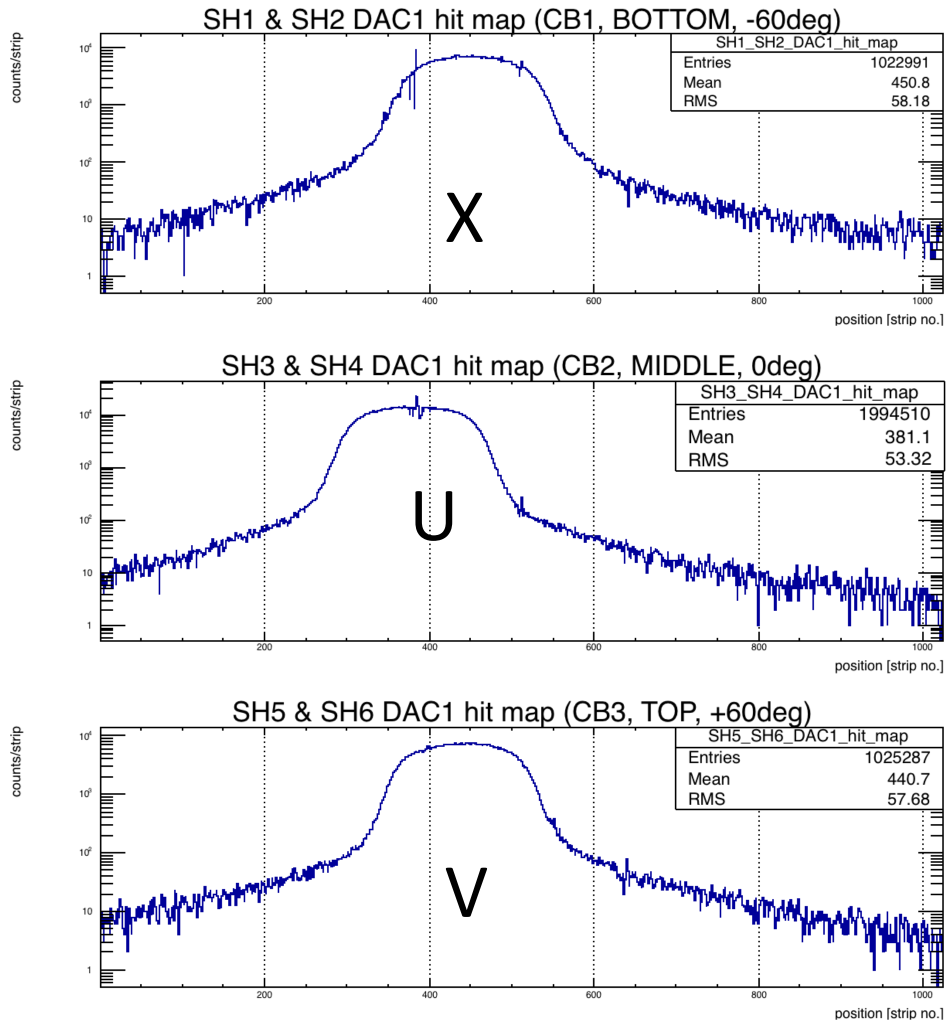
Currents from 10pA – 10nA ($5x10^3$ – $5x10^6$ protons/ cm^2/s when using 50 mm beam)

System can be triggered from RF system of cyclotron (26 MHz @ 36 MeV)

1D Histograms for Dosimetry

1D histograms for 15mm proton beam





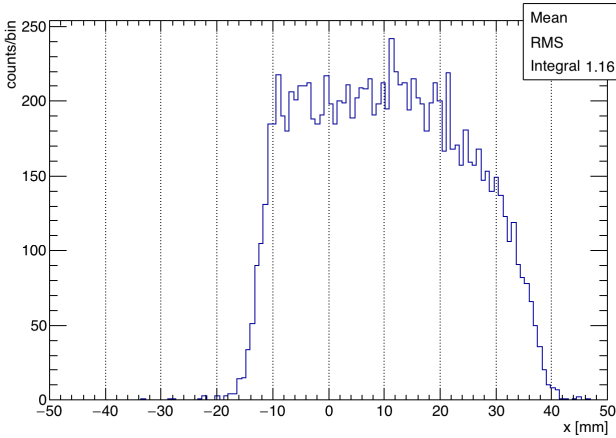
Individual strip halves

Individual layers

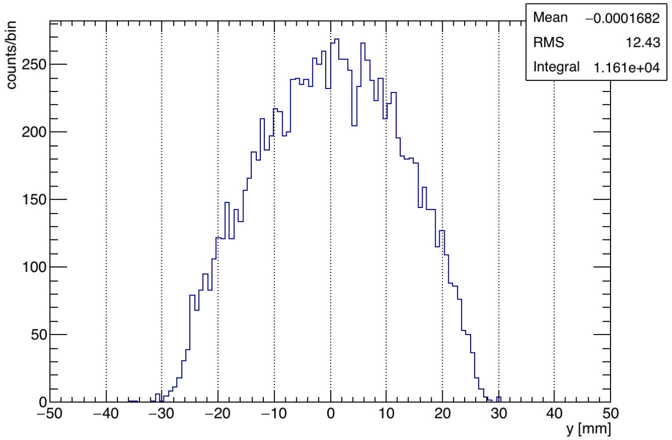
2D histograms for tracking and beam monitoring

50 mm un-collimated beam

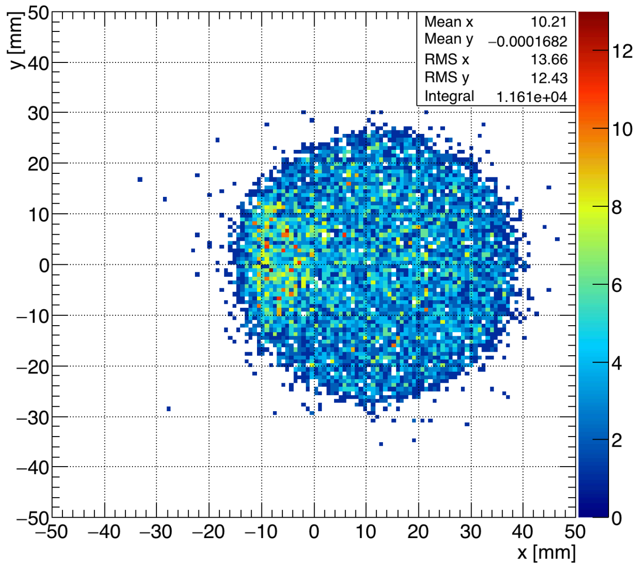
Reconstructed x position of protons for 50mm beam



Reconstructed y position of protons for a 50mm beam

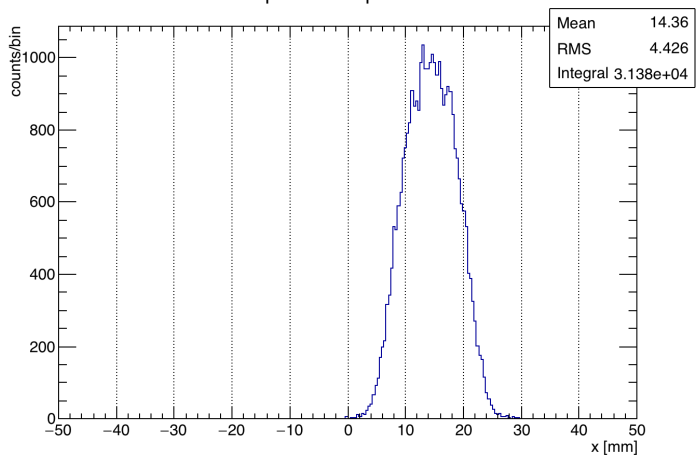


Reconstructed xy positions of protons for a 50mm beam

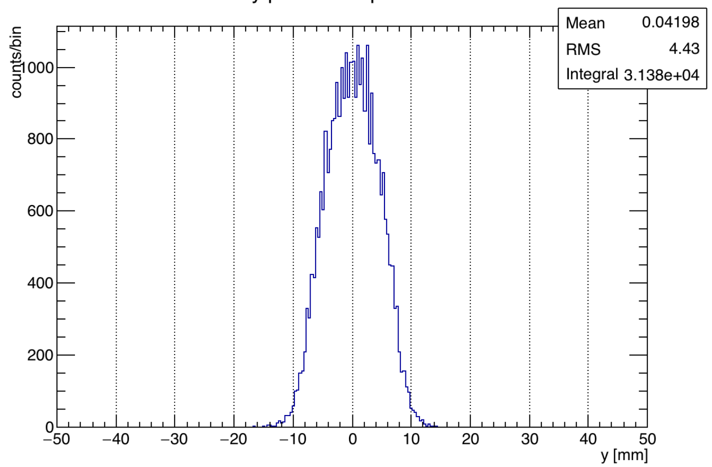


15 mm collimated beam

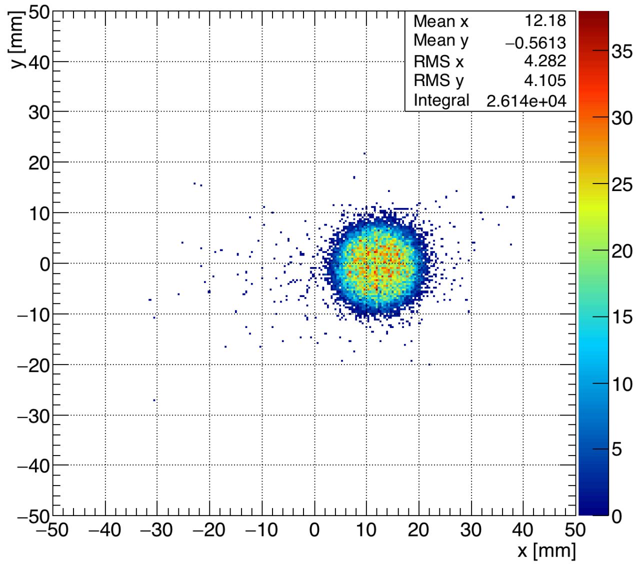
Reconstructed x position of protons for 15mm beam



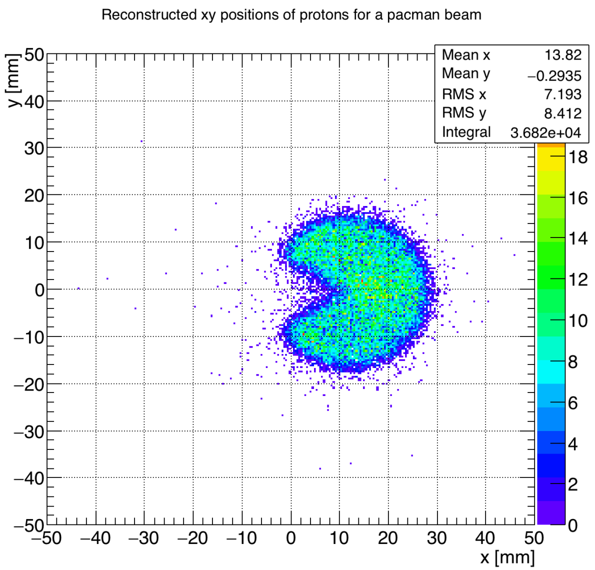
Reconstructed y position of protons for 15mm beam

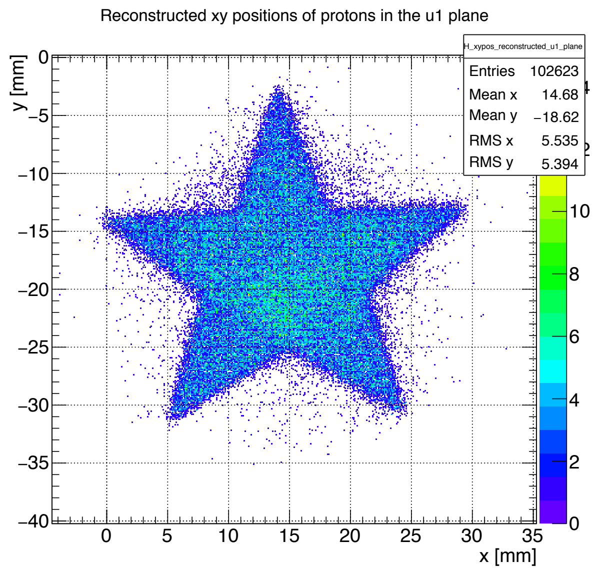


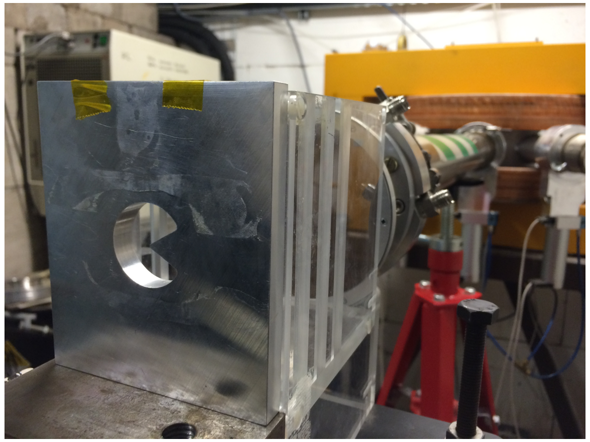
Reconstructed xy positions of protons for a 15mm beam



2D histograms for reconstruction test







Reconstructing concave shapes to test for artifacts/reconstruction problems

Summary

- The PRaVDA system will enable fast and precise proton tracking for proton CT and real-time beam monitoring with dosimetry making proton therapy safer and more accurate

- A tracker has been designed for the PRaVDA system using 150µm thick silicon microstrip sensors with radiation-hard n-in-p technology developed for the ATLAS Experiment at the High Luminosity LHC

- GEANT4 Simulation together with measurements using the LHCb BEETLE ASIC and ALiBaVa DAQ has been used to inform design of a new silicon sensor, ASIC, hybrid, DAQ together with reconstruction algorithms

- Preliminary data has been taken with MIPs and with proton beams of varying energies, beam sizes and beam currents to demonstrate the operation of the tracking detectors, the RHEA ASIC and DAQ

Thank you for Listening!

And many thanks to..

N.Allinson, P.P. Allport, G.L.Casse, T.Price, I. Tsurin, N.A. Smith, C.Waltham

and…

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NRF National Research Foundation

iThemba LABS Laboratory for Accelerator Based Sciences

University Hospitals Coventry and Warwickshire NHS Trust

University of Birmingham

University of Lincoln

The University of Warwick

University of Cape Town · iYunivesithi yaseKapa · Universiteit van Kaapstad

isdi Image Sensor Design & Innovation

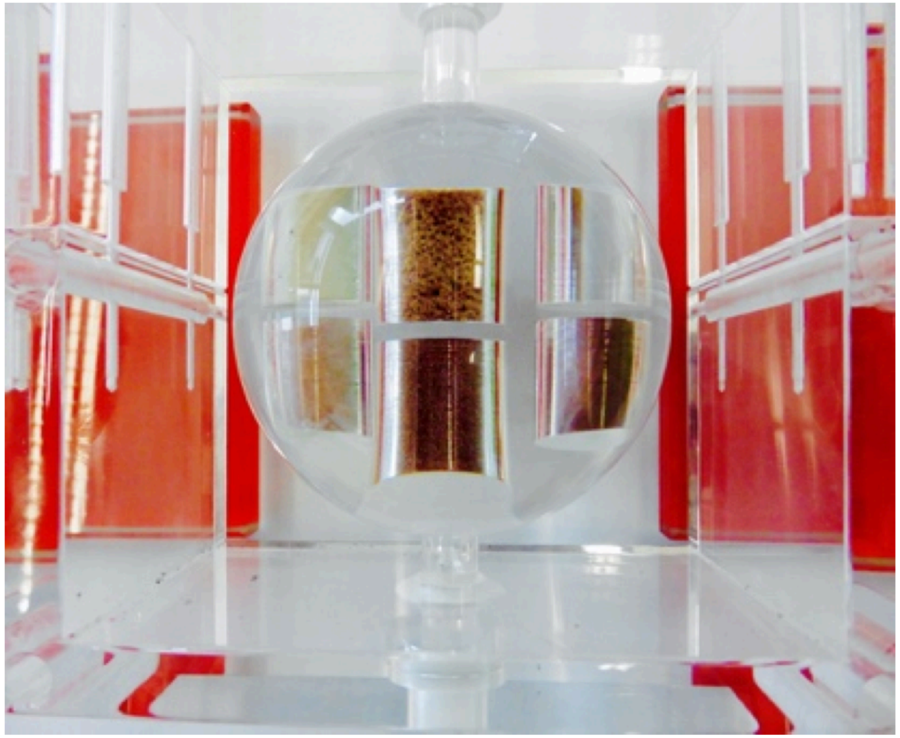
University of Surrey

aspect systems

Backup Slides

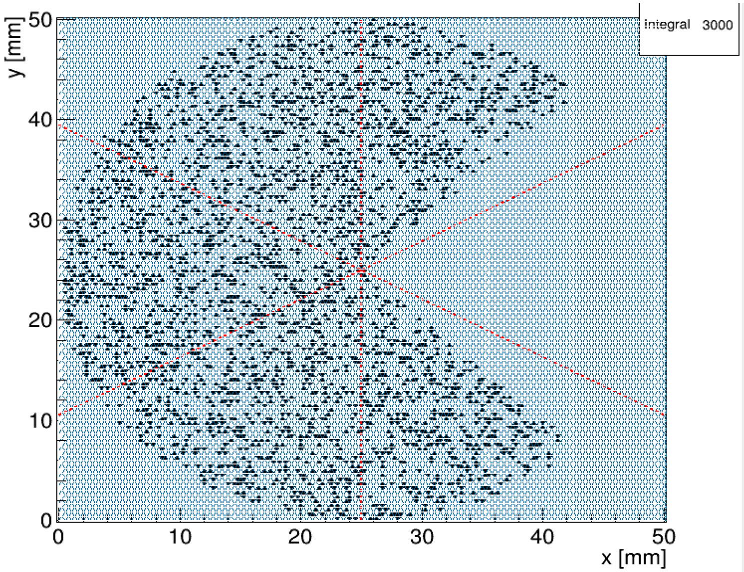
Phantom and compensator design

PHANTOMS

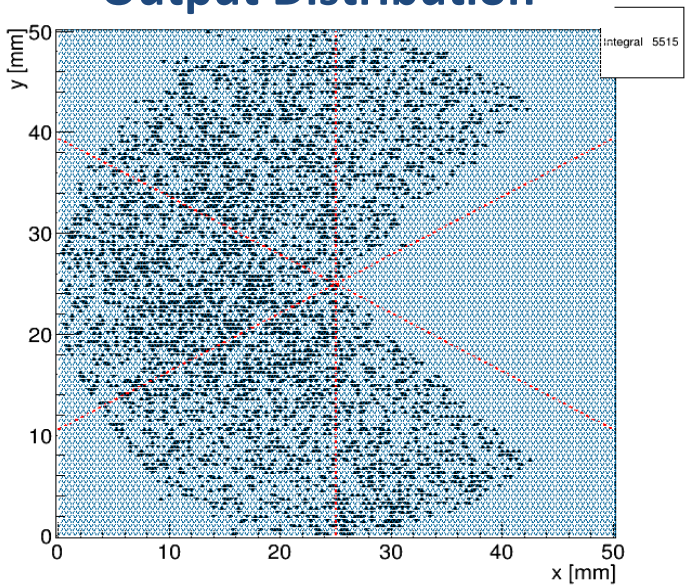


Simulated Efficiency in Treatment Mode

Pacman Input Distribution

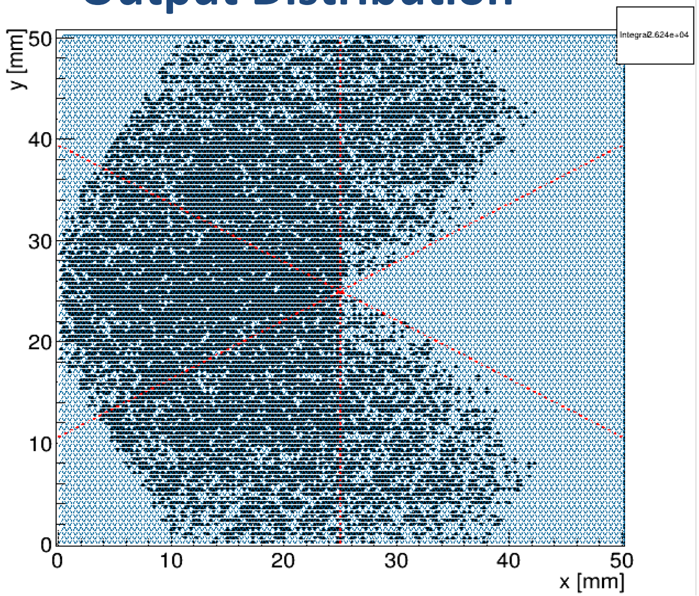


Output Distribution



60 protons/frame

Output Distribution



120 protons/frame

Determine efficiency of (x,u,v) configuration in treatment mode using simple Monte Carlo

A concave distribution is a good test of how well we can reconstruct the beam profile without introducing artifacts

High Efficiency – The detector is highly efficient for patient imaging with >99% hits unambiguous at well over 10 times planned iThemba pCT mode rates

Simulated Efficiency in Patient Imaging Mode

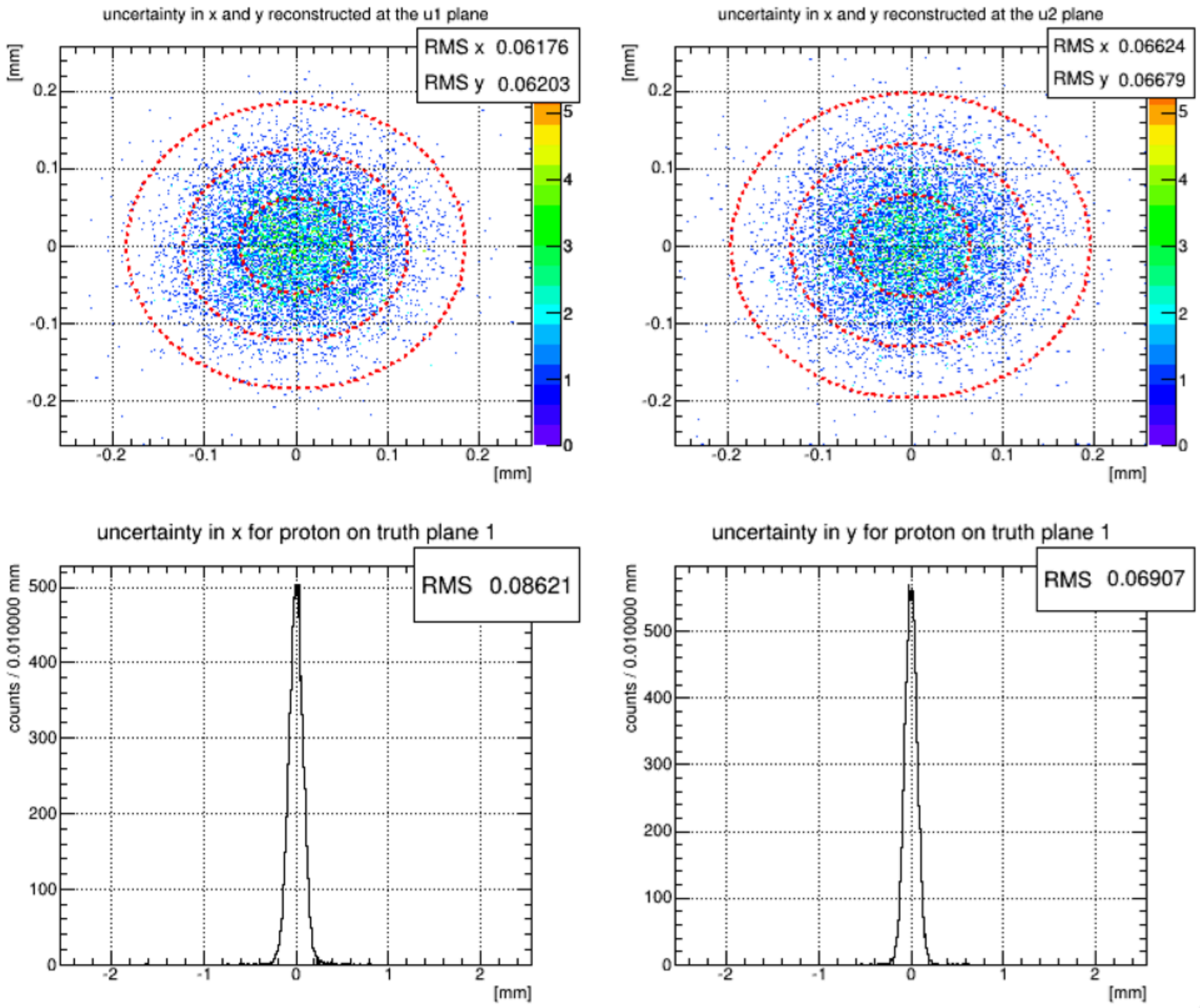
Flux in patient imaging (pCT) mode is 100 times less than treatment mode therefore ambiguity rates are very low (at iThemba only expect 0.04 events/frame)

Events/Frame	Ambiguity Rate	>1 hit per strip	>2 hits per strip
5	0.6%	0.8%	<0.1%
10	1.6%	1.4%	<0.1%

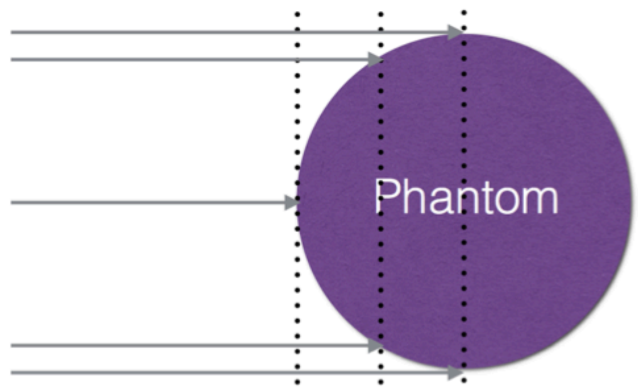
Ambiguity rate = total ambiguous hits/ total real hits

High Efficiency – The detector is highly efficient for patient imaging with >99% hits unambiguous at well over 10 times planned iThemba pCT mode rates

Tracking algorithm



Ellipses indicate 1,2 & 3 sigma values for reconstructed position – truth position



The uncertainty on the projected track depends on its length, ie the distance to the phantom surface.