Proton tracking for medical imaging and dosimetry

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For the PRaVDA Consortium

Talk Overview

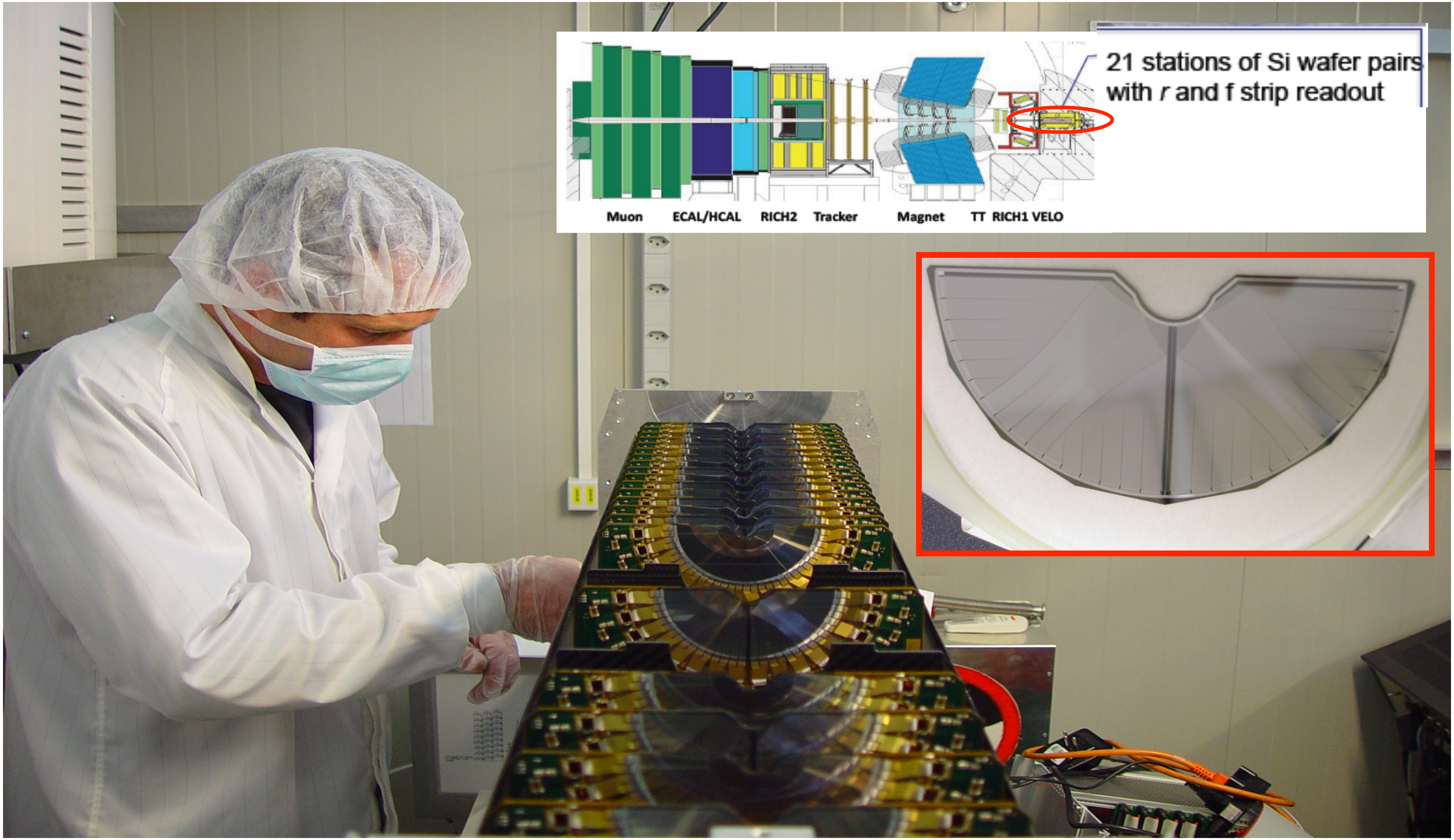
Background
- **Silicon detectors at Liverpool University Physics Dept.**
- **PRaVDA setup and microstrip tracker**

Detector design and testing
- **Sensor & ASIC design**
- **Preliminary results with charged particles**

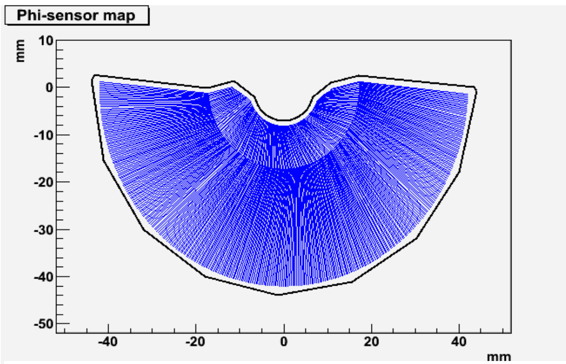
Simulation work
- **Simulating efficiency**
- **GEANT4 simulation and tracking**

Summary and further work

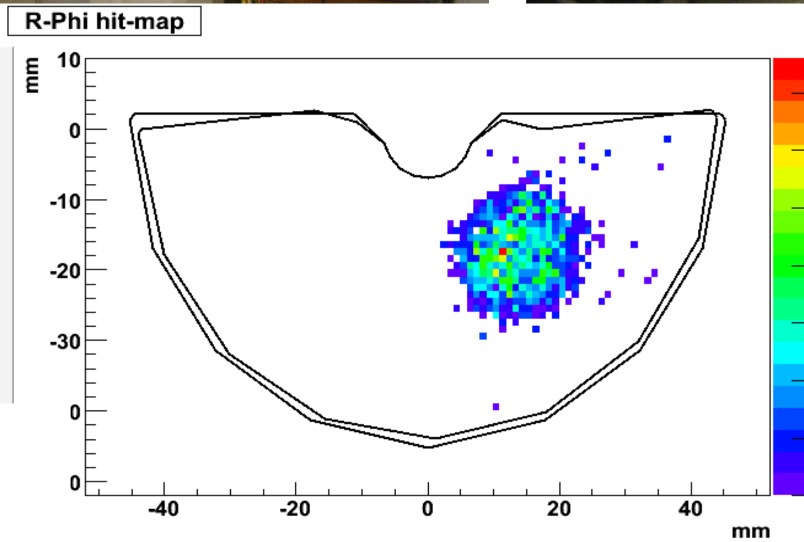
The LHCb VErtex LOcator

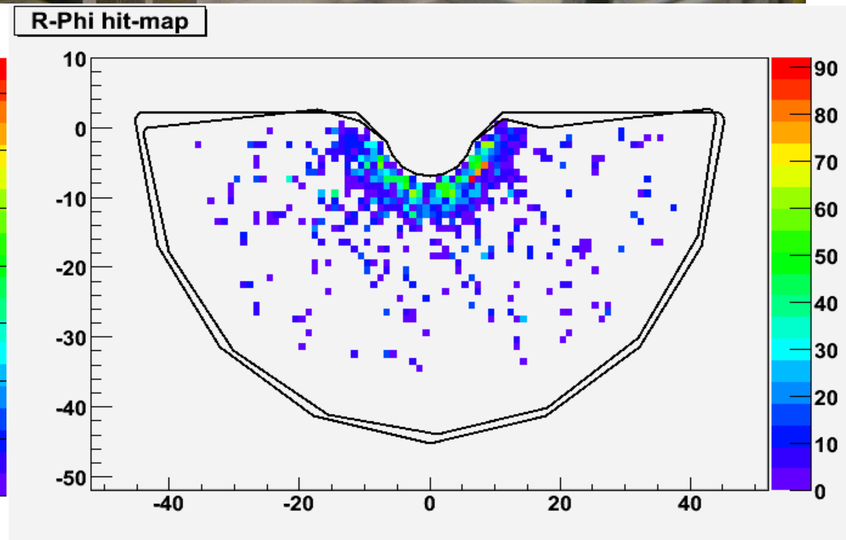


LHCb VELO Module as Beam Halo Monitor

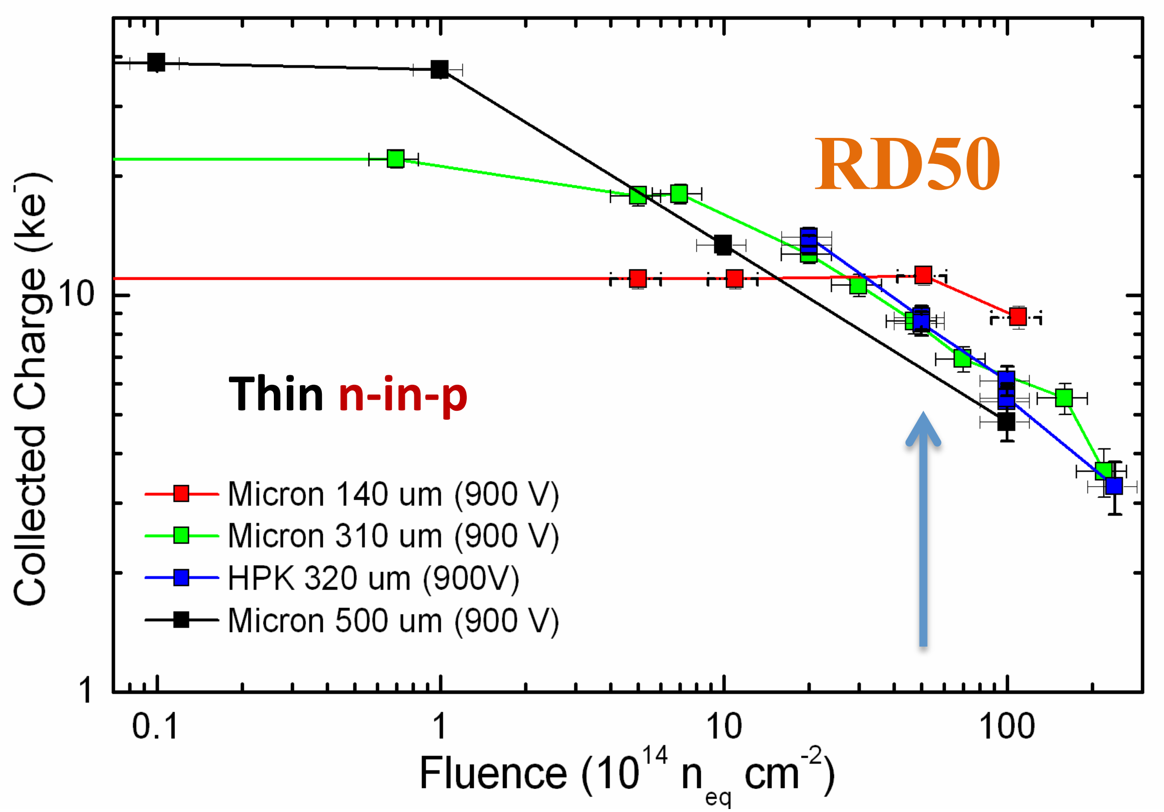


LHCb Back-to-Back Sensor Module





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.

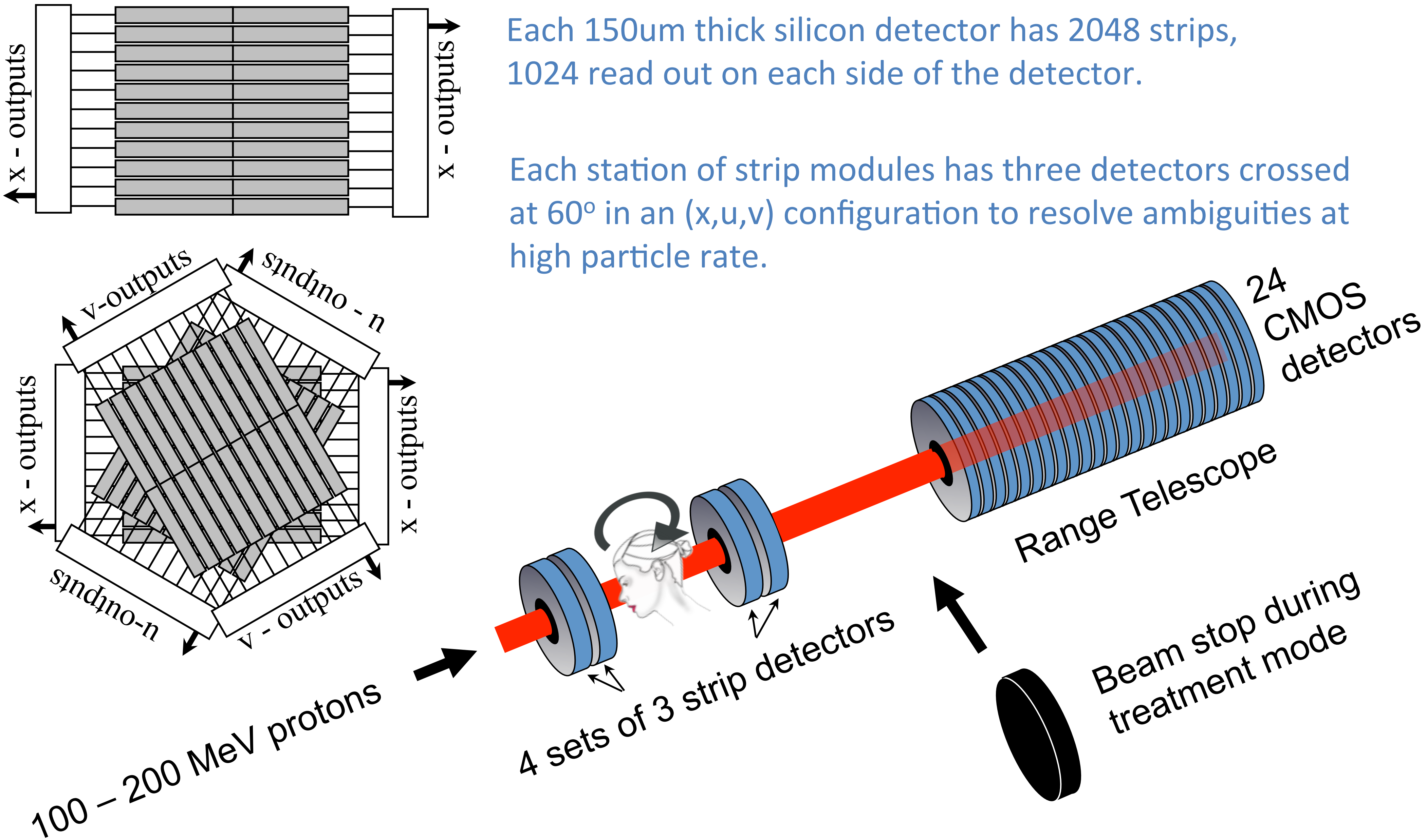
This allows design of detectors that are very rad hard for applications with clinical beams.

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

Each station of strip modules has three detectors crossed at 60° in an (x,u,v) configuration to resolve ambiguities at high particle rate.



Operating Modes

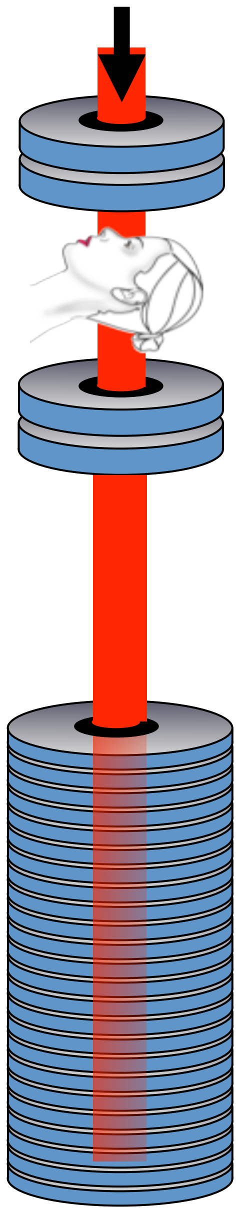
Treatment Mode

(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: 10cm (max.)
Energy: 191 MeV
Flux: ~10^5 protons/cm^2/s

Use Strip Tracker to..

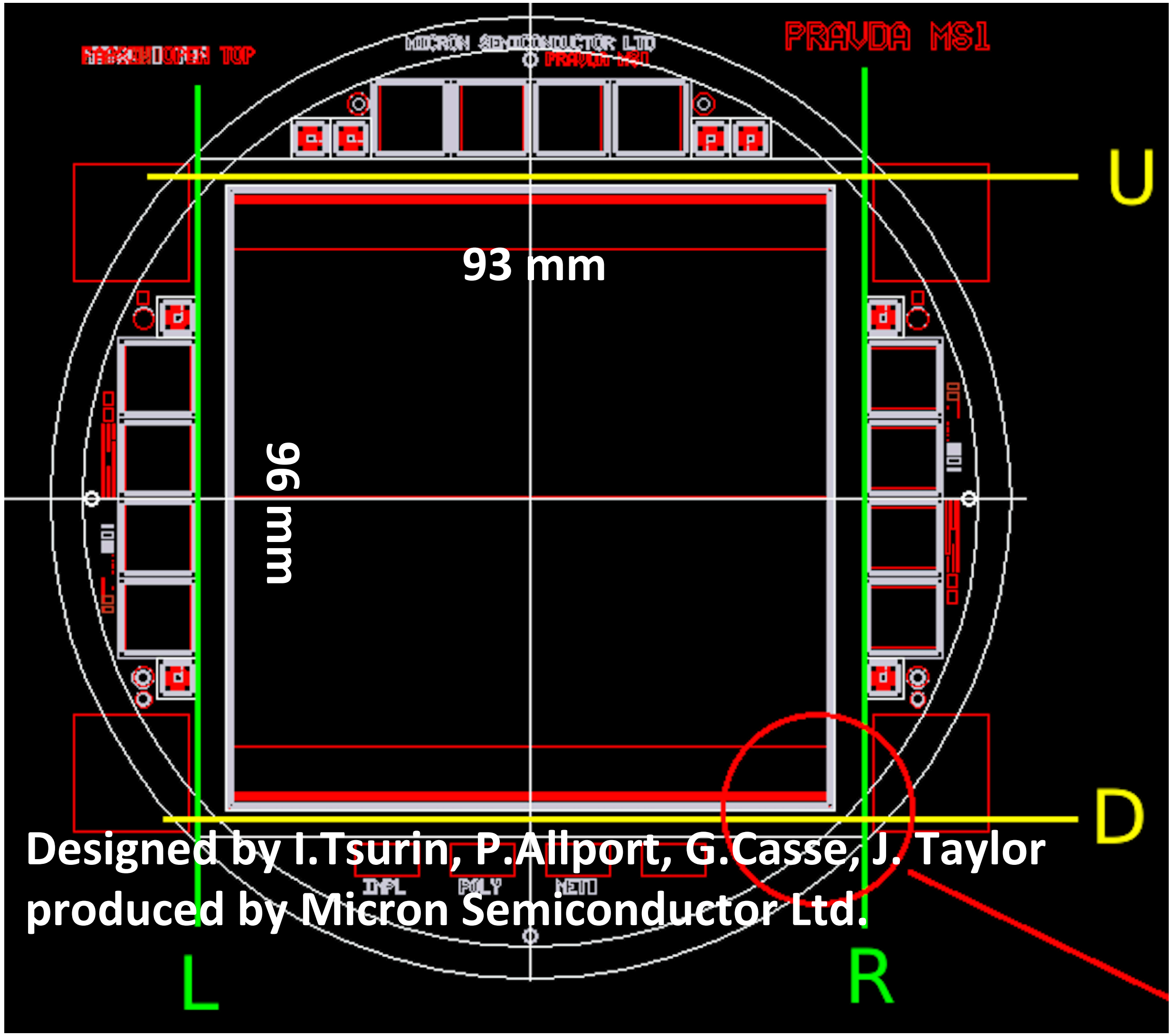
- Track individual protons in (x,u,v) layers

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

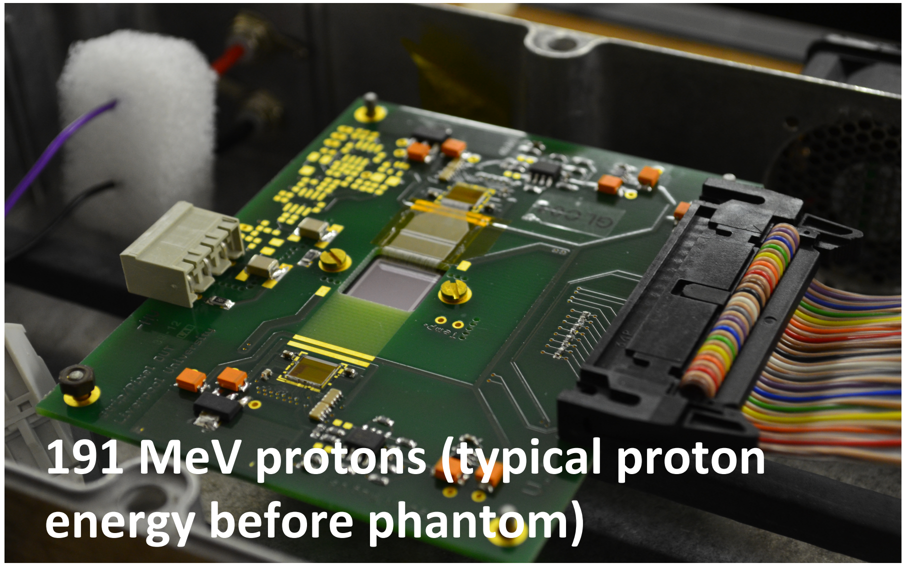
Two thresholds per channel allow for high occupancy

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, testing now underway

Hybrid design by N.A. Smith at Liverpool

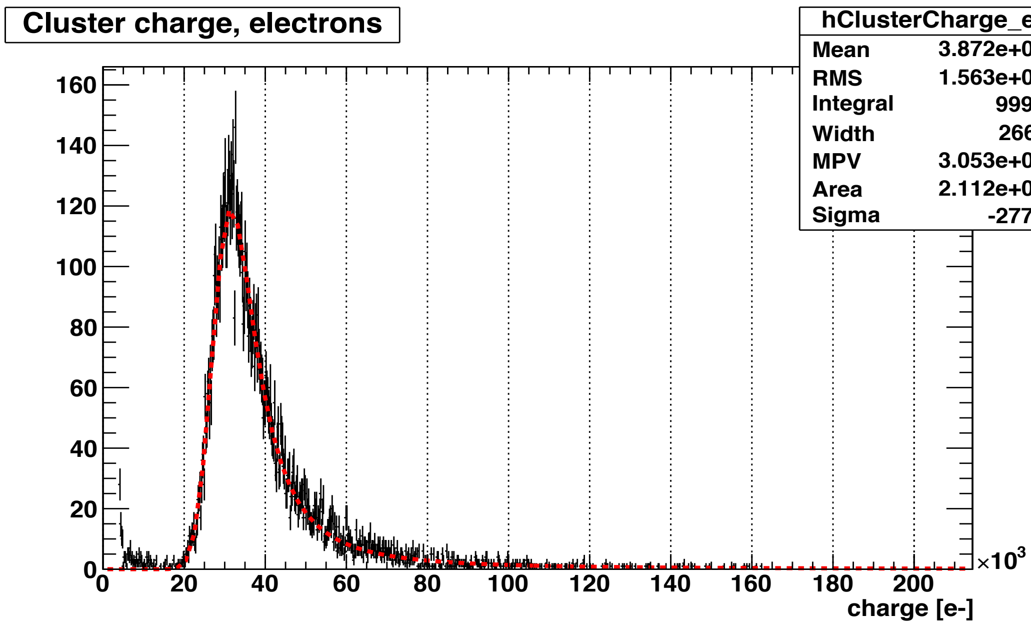
Sensor & ASIC Design

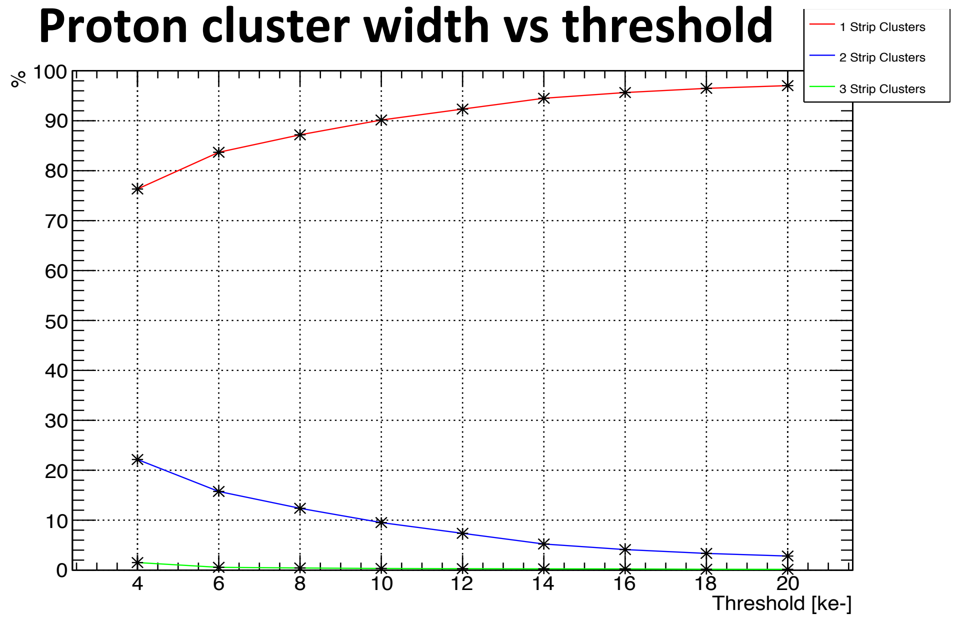


1cm x 1cm x 150um silicon strip detector with 128 channels and 80um strip pitch

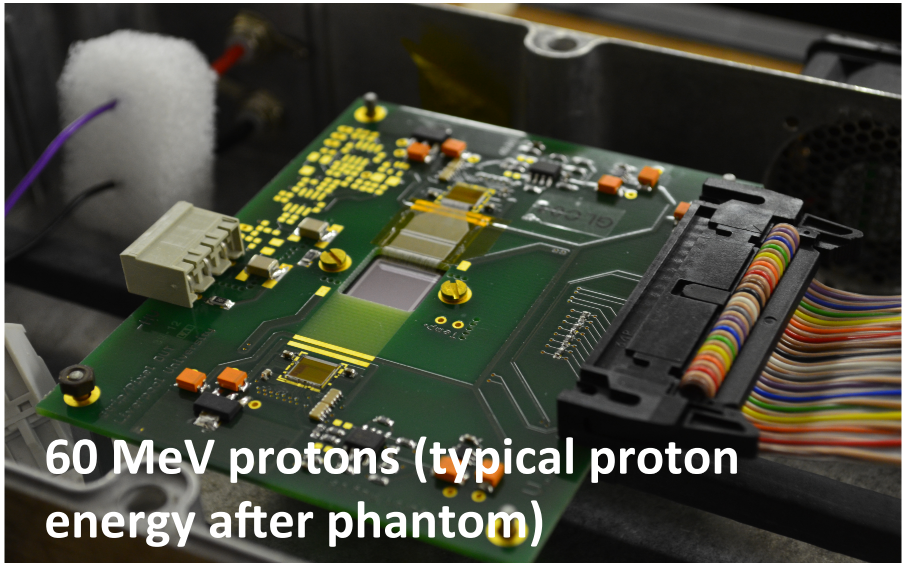
Sensor wire bonded to rad-hard BEETLE ASIC (LHCb experiment) with 40 MHz clock

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





Sensor & ASIC Design



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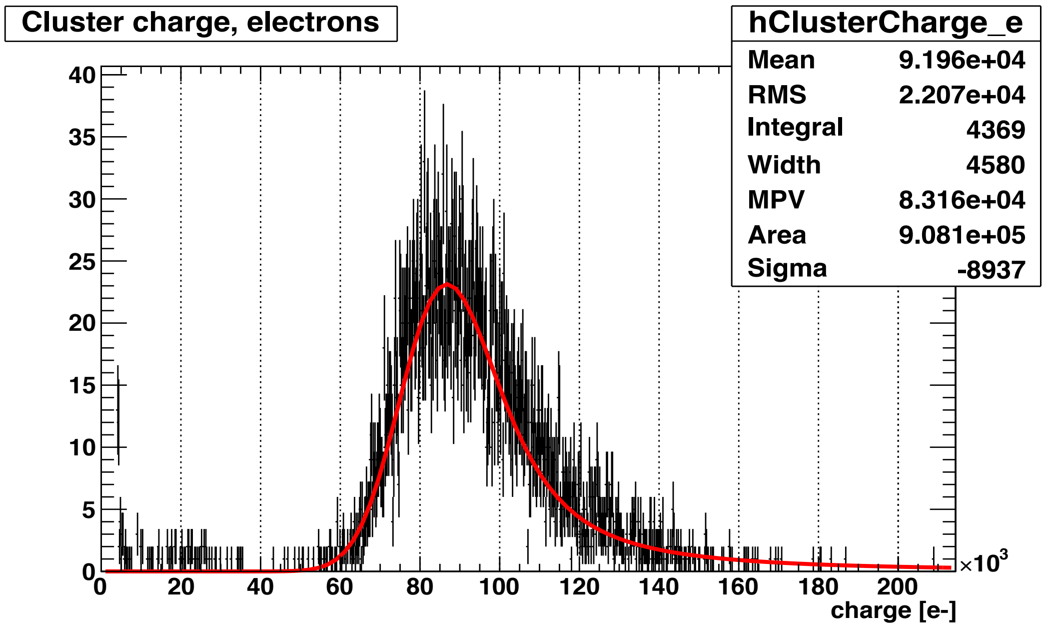
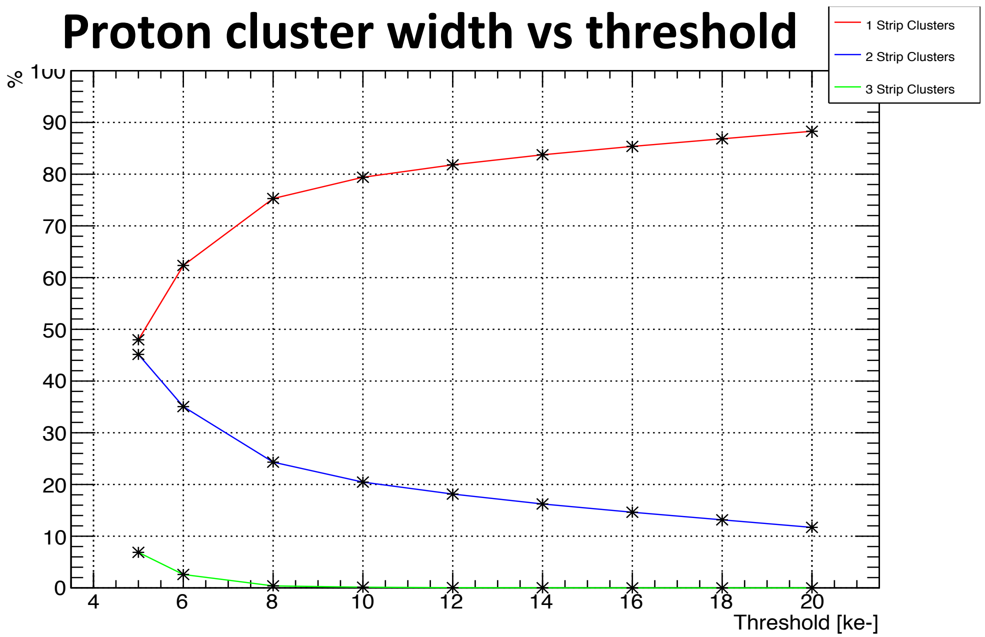




RHEA ASIC

- Rapid high-speed extended ASIC (RHEA)
- Commercially designed ASIC from ISDI Ltd.

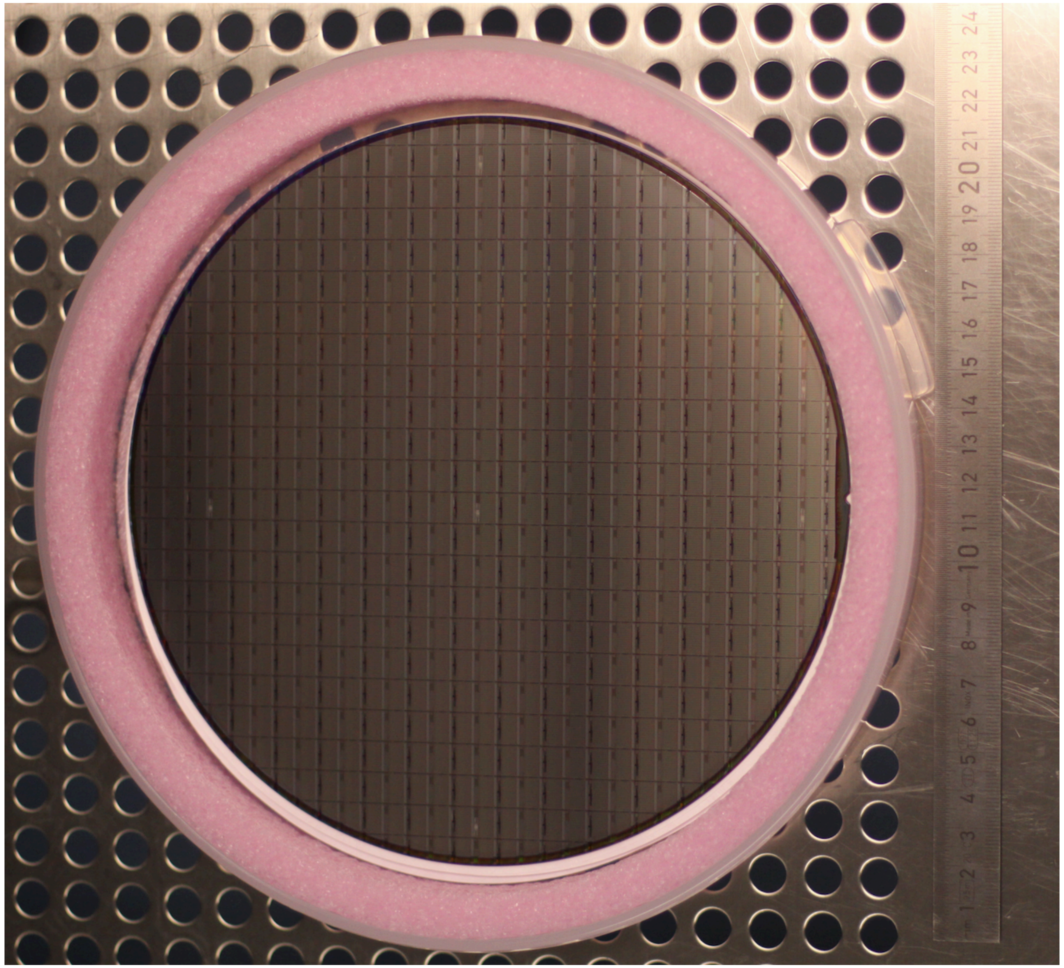
- Binary chip with two tunable thresholds:

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

- Expected equivalent noise charge 700e-

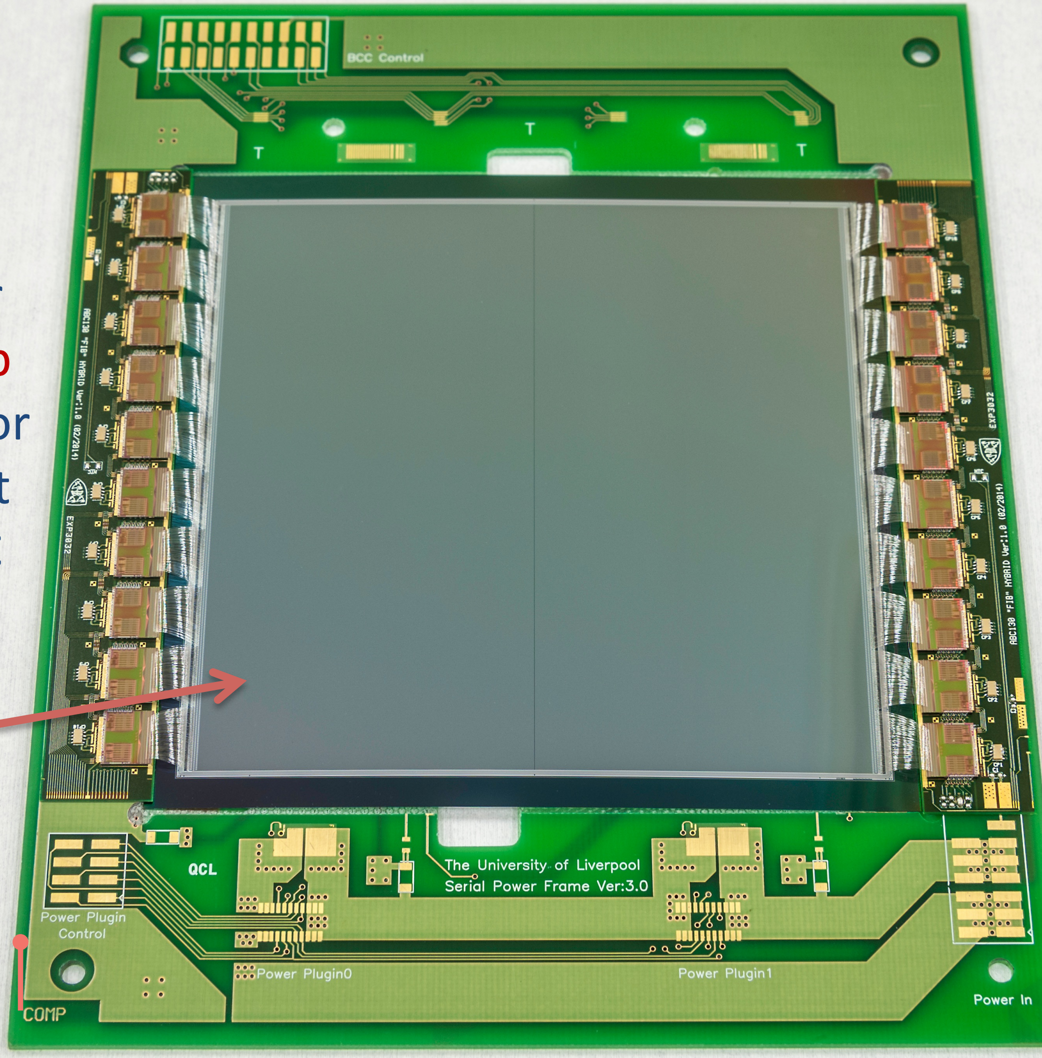
- 128 channels with a bonding pitch of 60um

- Diced chips will be ready this month for testing and wire bonding to the PRaVDA sensors (18 currently available)



PRaVDA Sensor

PRaVDA module mock-up for bonding trials and RS exhibit



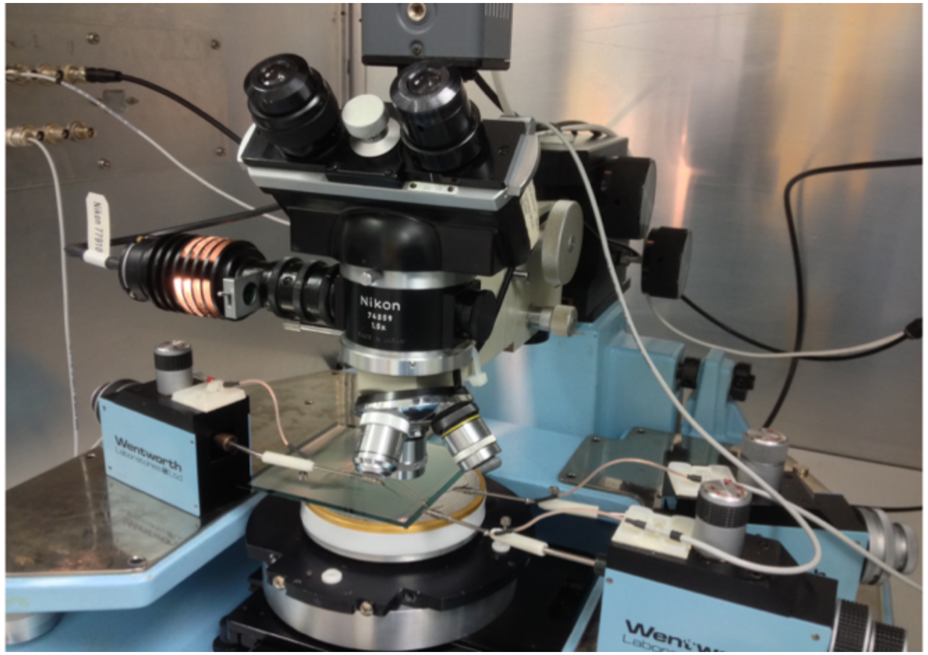
Silicon microstrip sensor using 150µm thick n-in-p technology developed for the ATLAS Experiment at the High Luminosity LHC

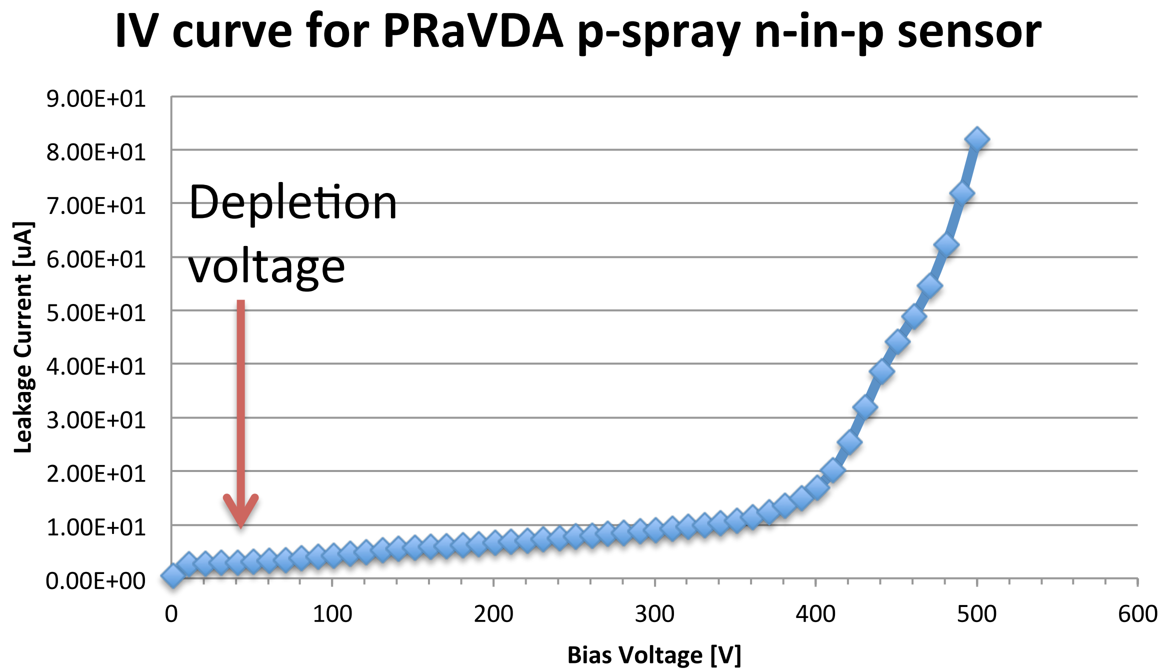
MICRON SEMICONDUCTOR

Left and right sides each contain 1024 strips with a pitch of 90.8um. Each station of strip modules will have three planes crossed at 60^{o} in an (x,u,v) configuration to allow high particle rate.

12 strip modules will be used to make 4 tracking stations, 2 before and 2 after the patient

Sensor QA

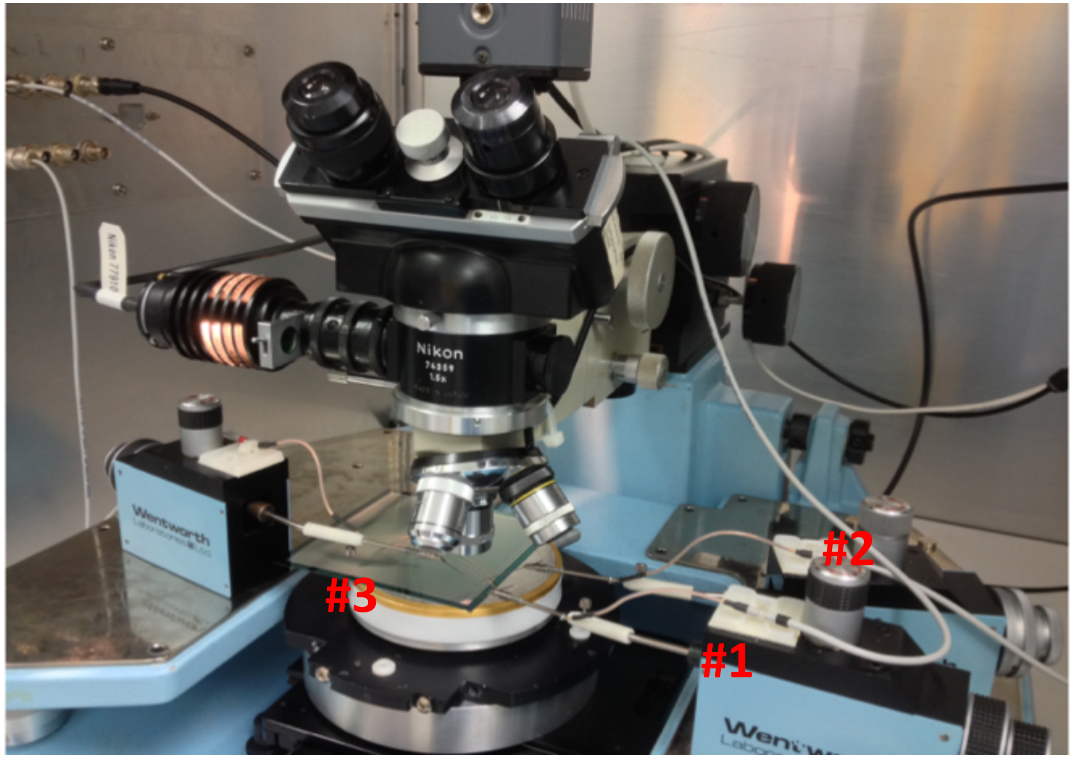


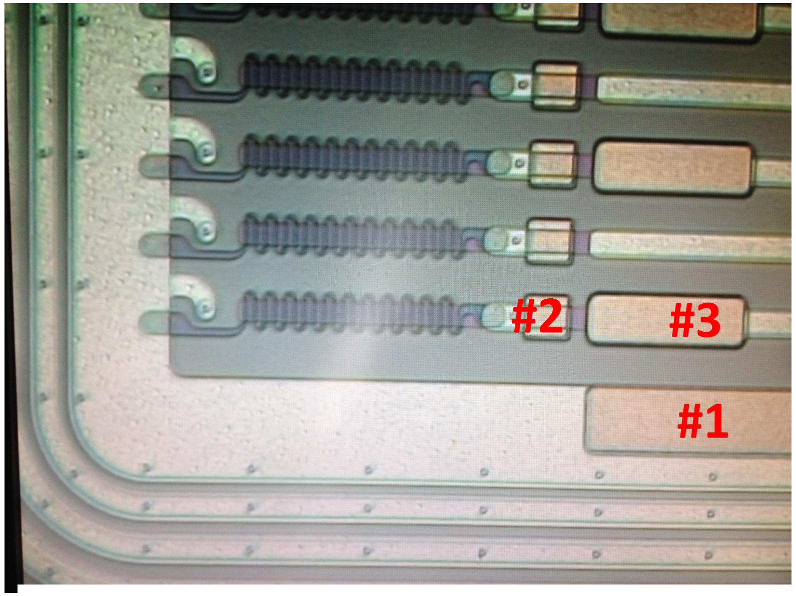


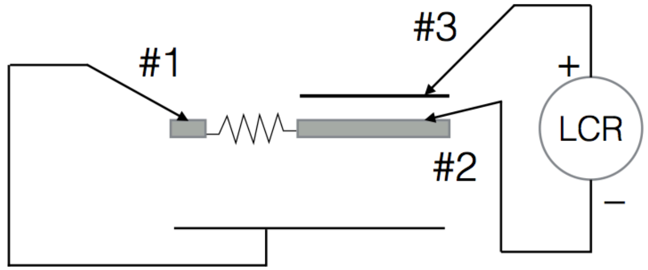
QA on detectors carried out using manual and automatic probe stations to measure global IV and then to measure individual strip characteristics.

Leakage currents for sensors are typically a few uA even at several times depletion voltage.

Sensor QA





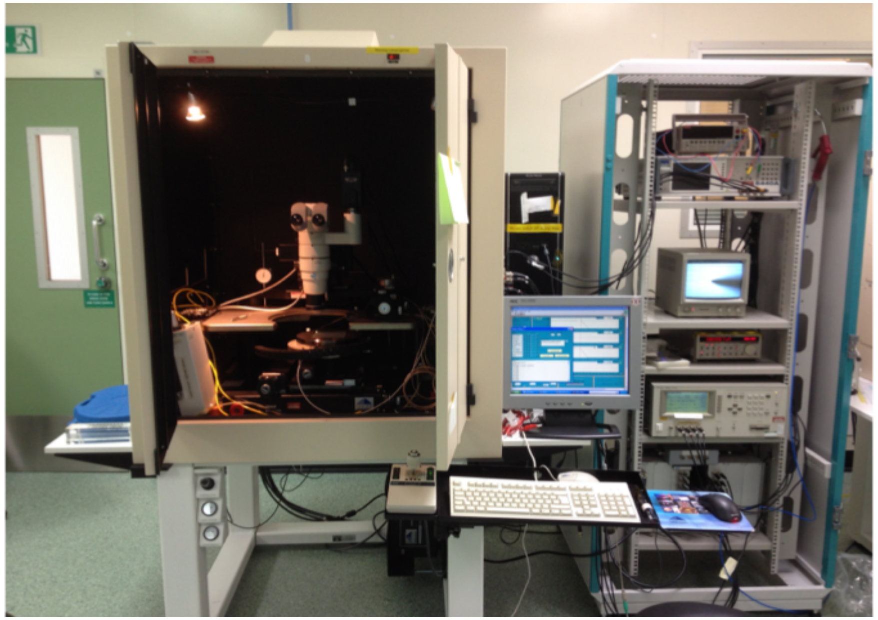


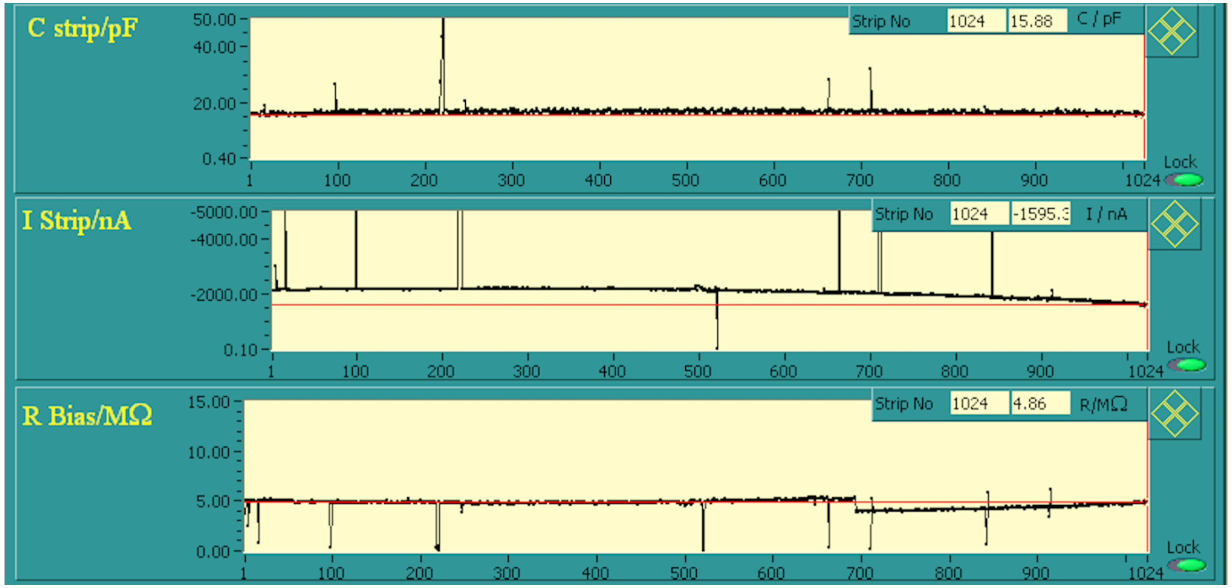
#1 Bias rail
#2 Implant
#3 Strip metal

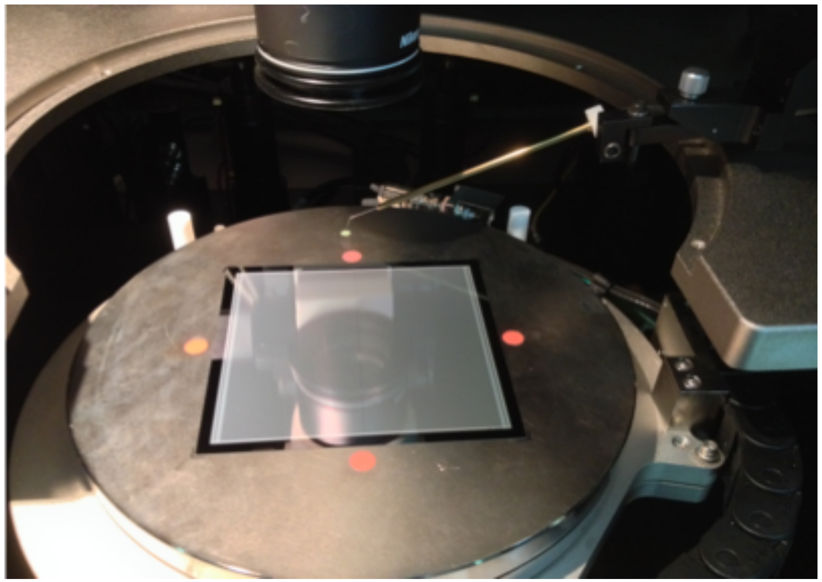
Measurements with probes:

Parameter	Measured value	Spec. value
Polysilicon bias resistor	6 MΩ	>2 MΩ
Coupling capacitance	122 pF	125 pF

Sensor QA



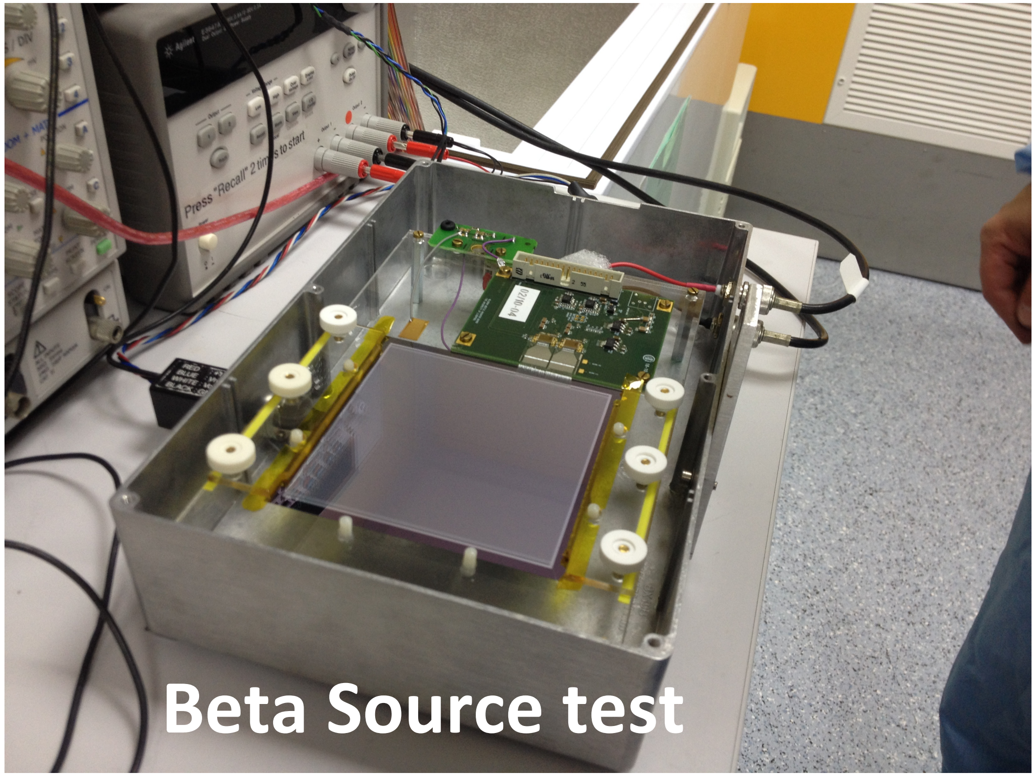




Using an LCR meter and an automatic probe station we can probe the complex impedance for all strips on both sides of a detector

Detectors show at least 99% good strips per side.

Test setup for charged particles

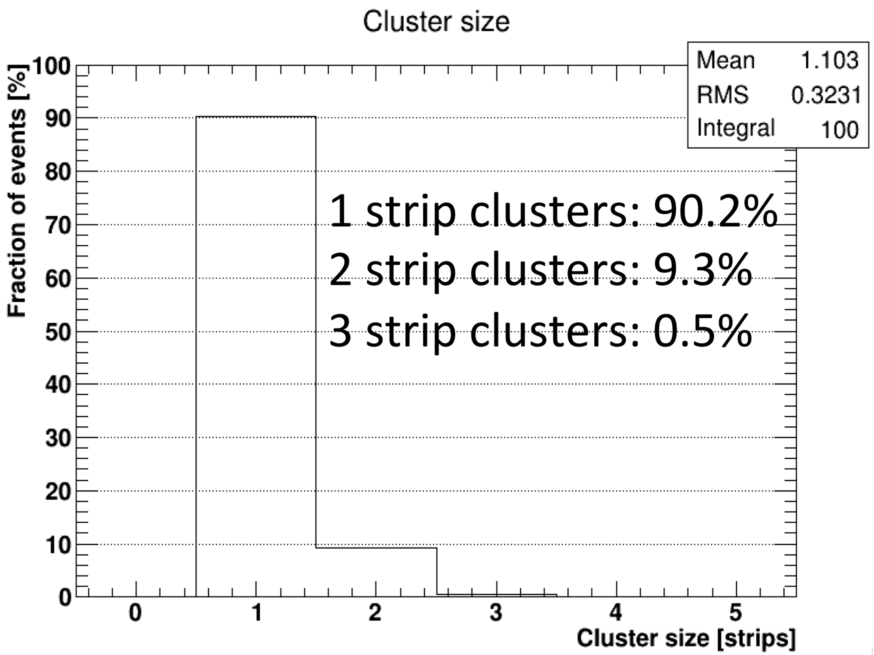


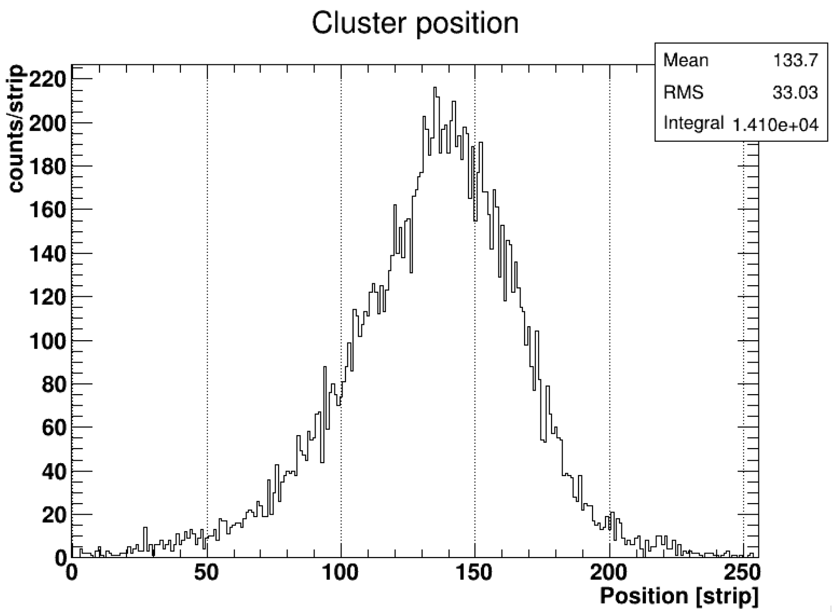
Wire-bonded 256 strips (12.5% of total detector) which allows a beam size of up to ~20 mm to be studied (and laboratory source measurements)

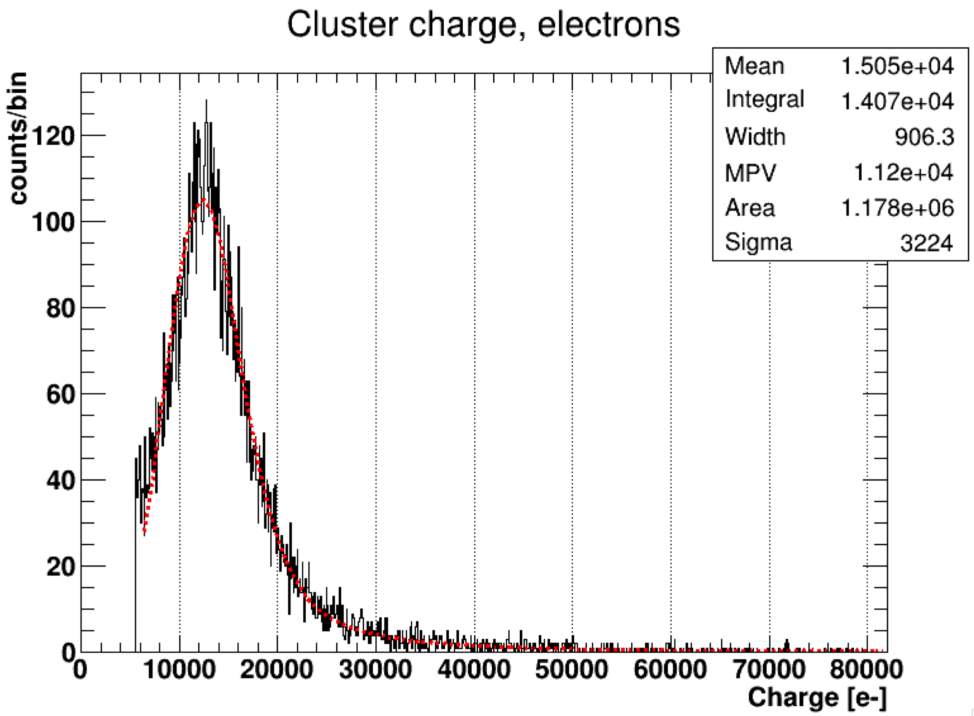
Readout using BEETLE ASIC (LHCb) and ALiBaVa DAQ

Thin beam entrance and exit windows to prevent degrading of energy before detector and backscatter after it

Testing the sensor with MIPs







Threshold on all strips set to 5.5ke-

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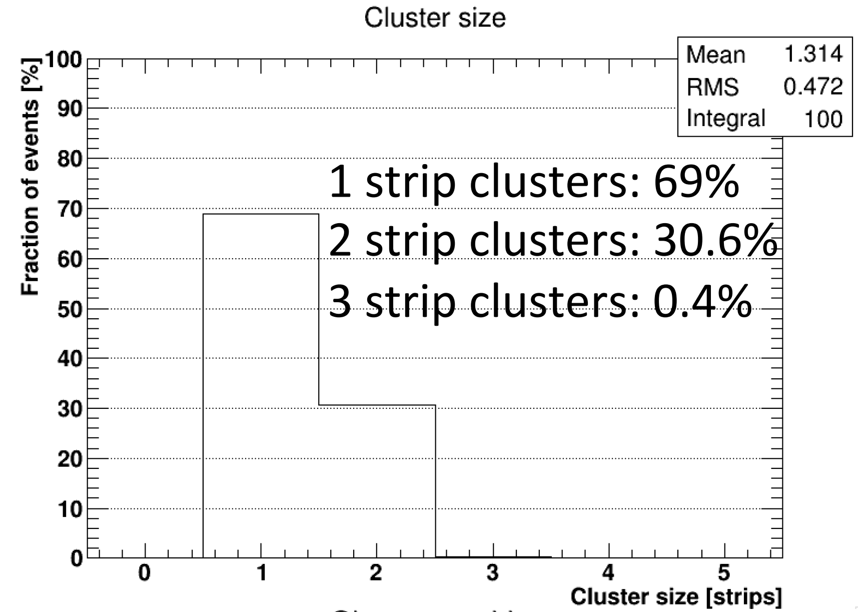
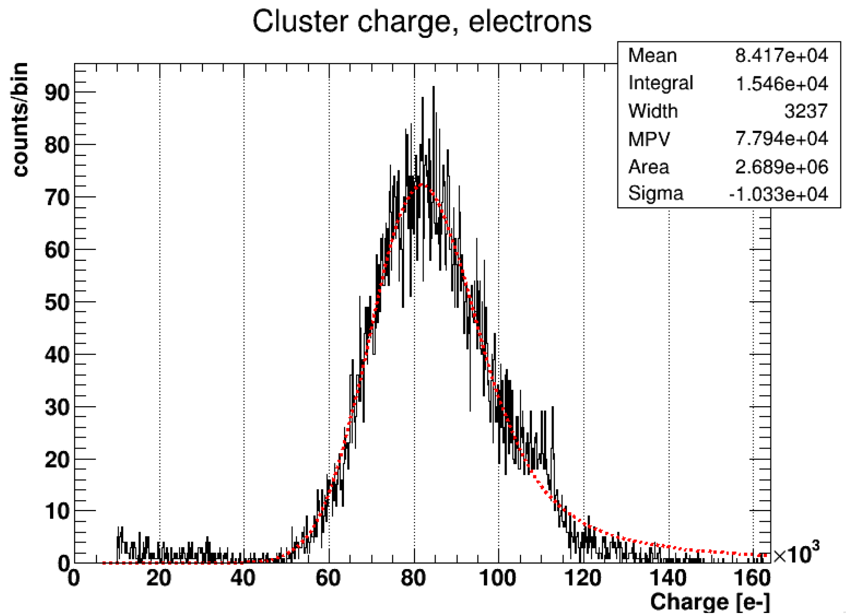
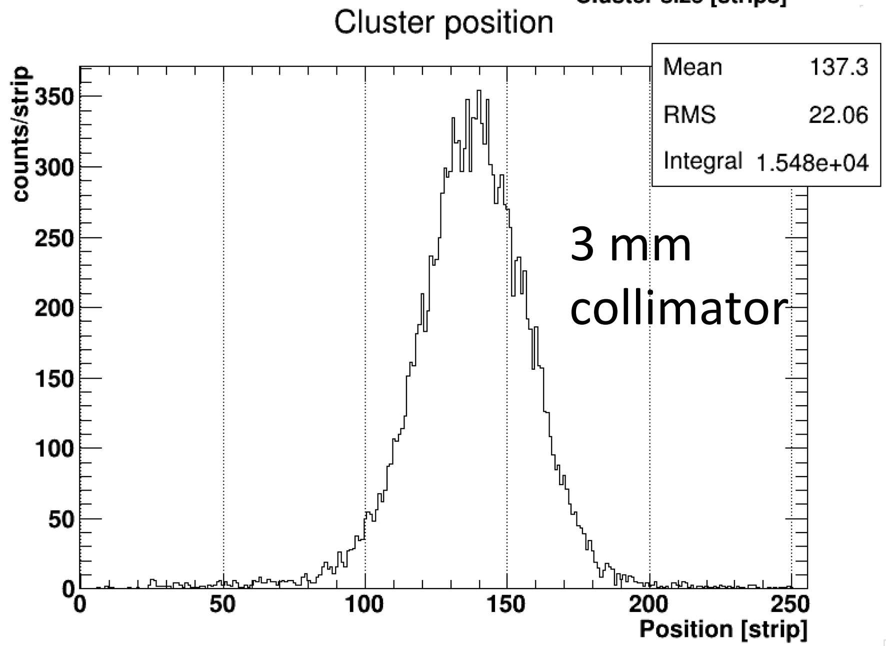
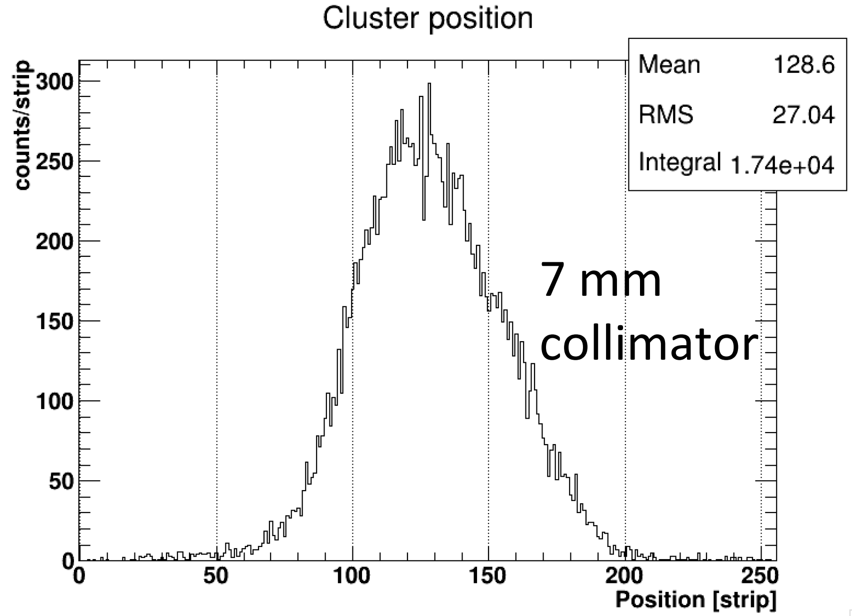
Testing the sensor with 60 MeV protons





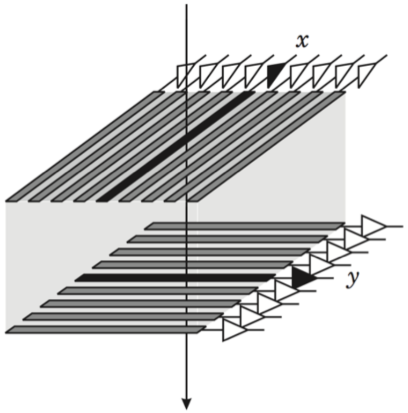


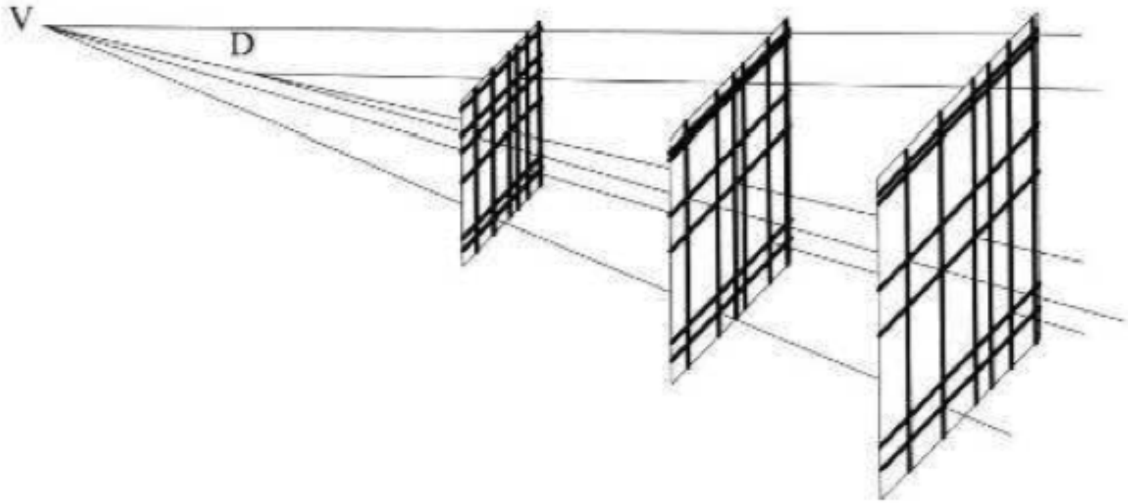


Threshold on all strips of 10 ke-

Simulating the Efficiency of the (x,u,v) configuration

How efficient is the tracker at distinguishing hits in a multi-hit environment in both Treatment and Patient Imaging mode?

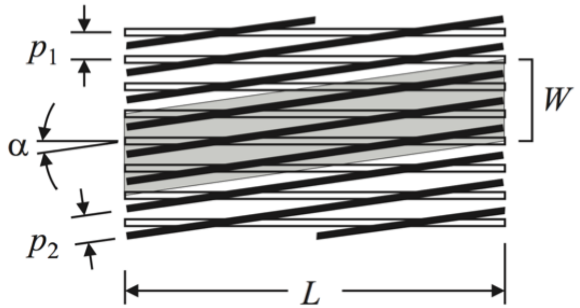


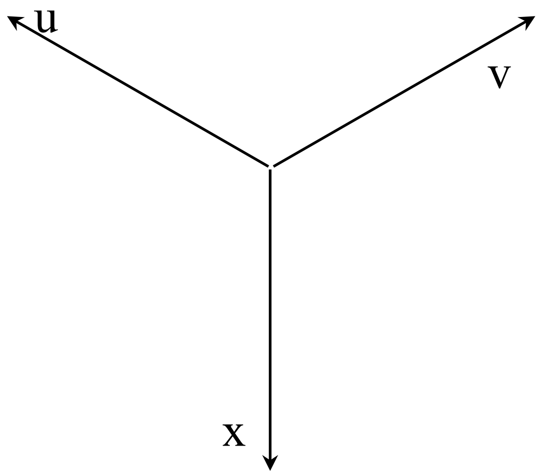


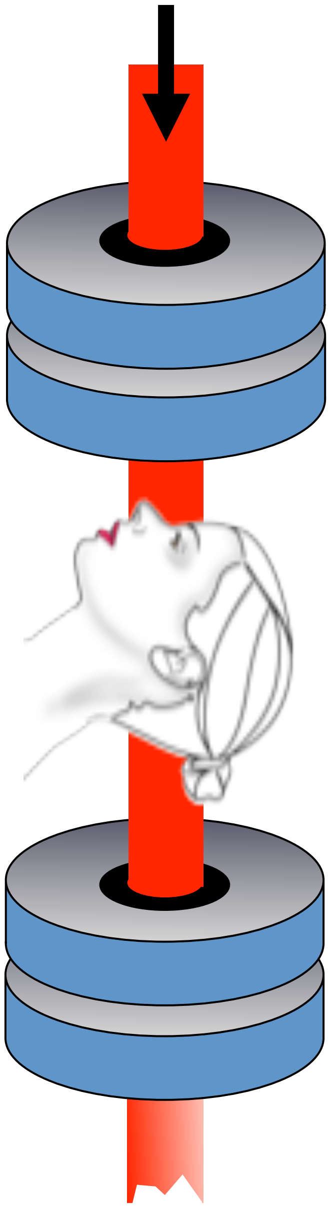
For a strip detector with orthogonal strips and N hits, there are: $N^2 - N$ 'Ghost-hits' or ambiguities generated

Simulating the Efficiency of the (x,u,v) configuration

Tilt planes of strips at a (stereo) angle w.r.t other planes to prevent strip from one plane crossing all strips in the next plane.

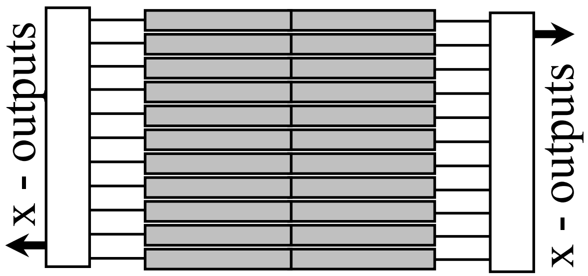


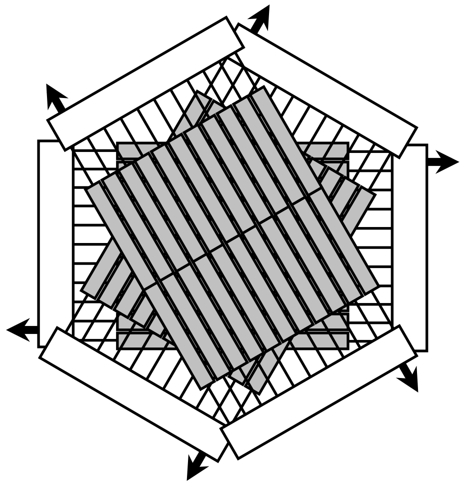




Tracker module design

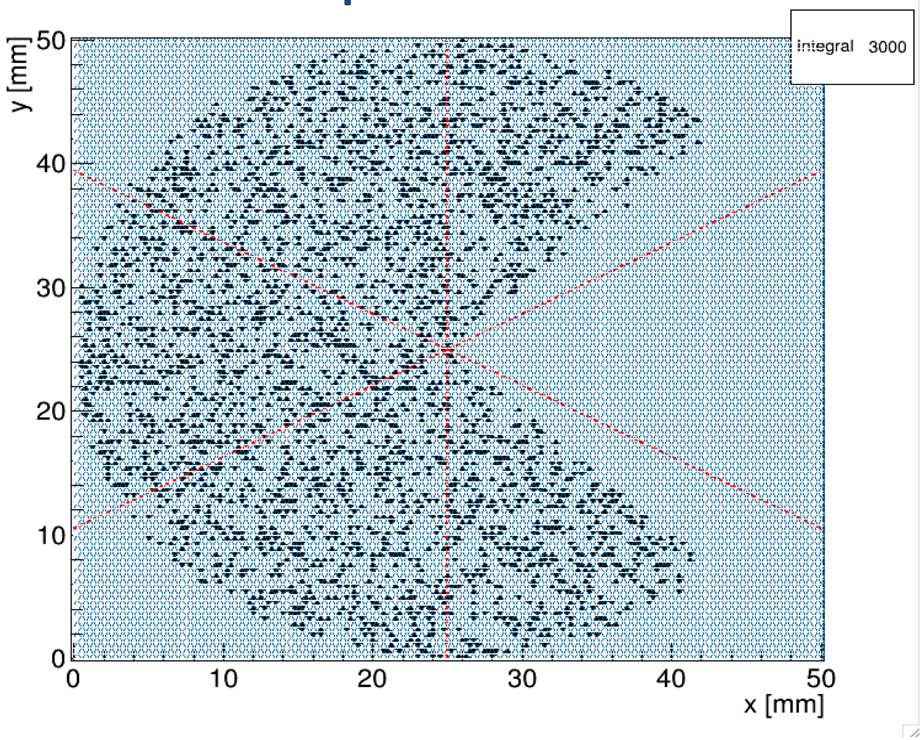
Each station has strips crossed at 60º to one another in (x,u,v) configuration allowing higher particle rate.





Simulated Efficiency in Treatment Mode

Pacman Input Distribution



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

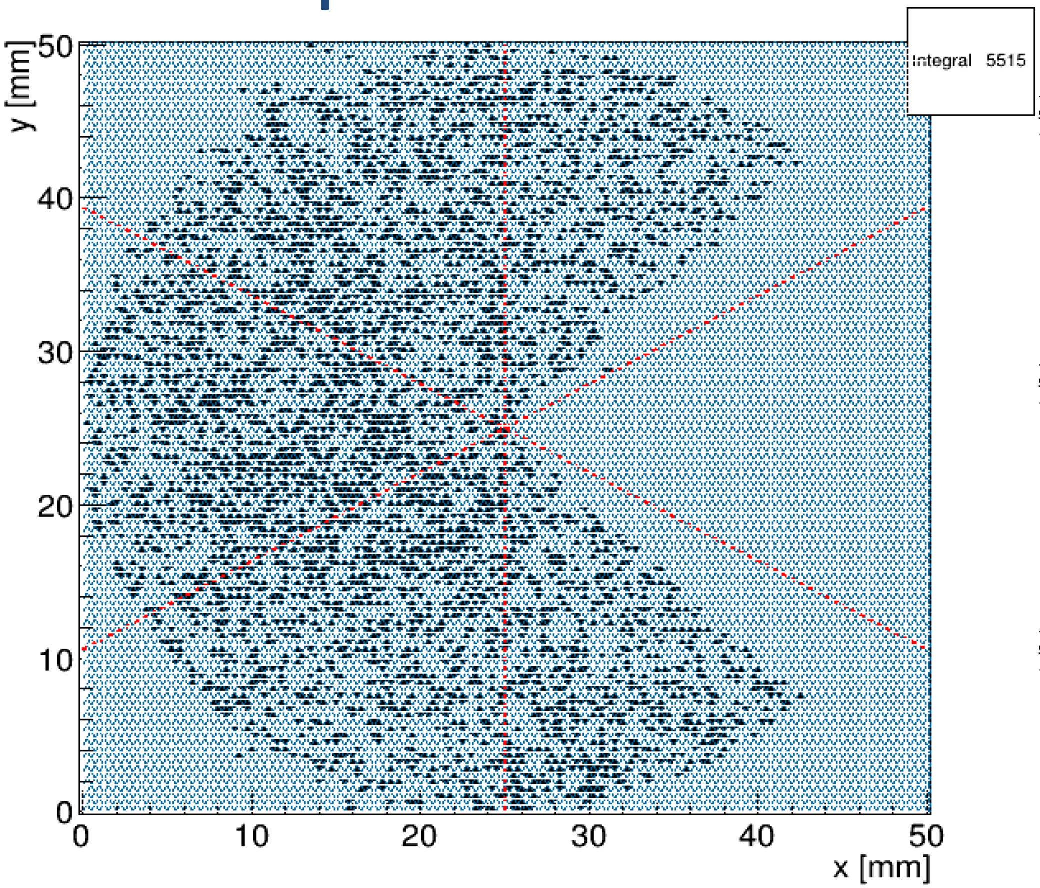
A concave distribution is a good test of how well we can reconstruct the beam profile without introducing artifacts

Events/Frame	Ambiguity Rate	>1 hit per strip	>2 hits per strip
30	8.1%	4.7%	0.0%
60	62.1%	10.5%	0.3%
120	811.1%	18.1%	1.2%

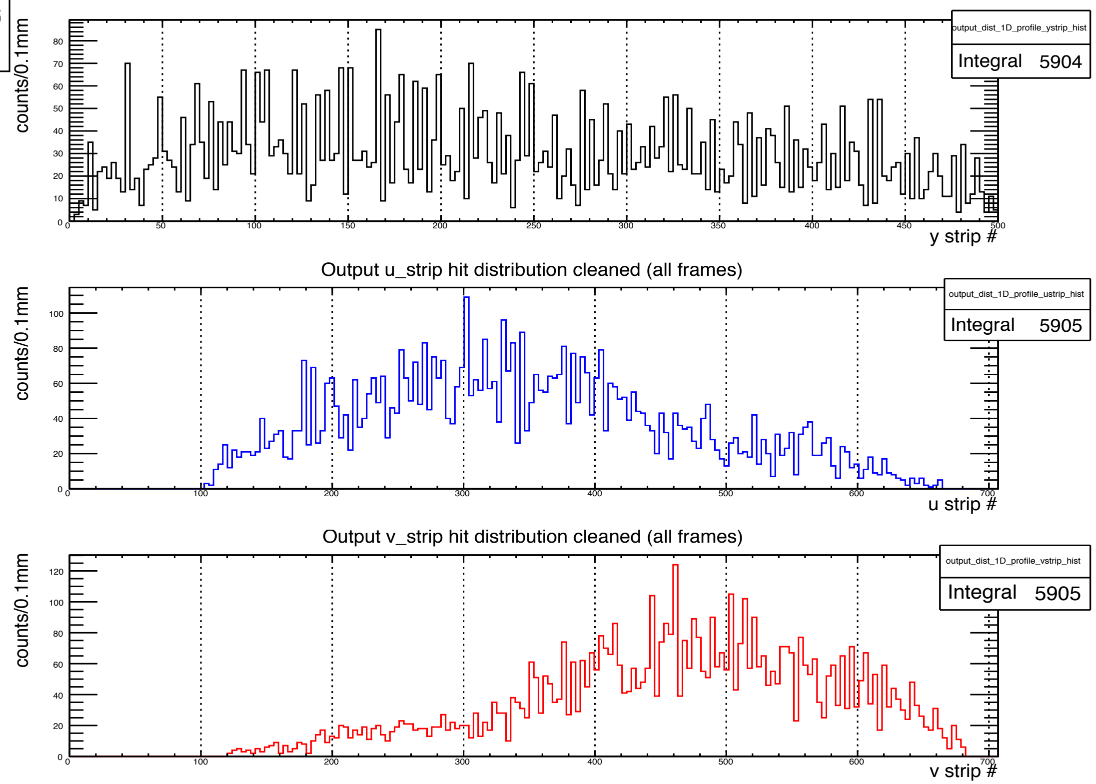
Ambiguity rate = total ambiguous hits/ total real hits

Simulated Efficiency in Treatment Mode

Output Distribution



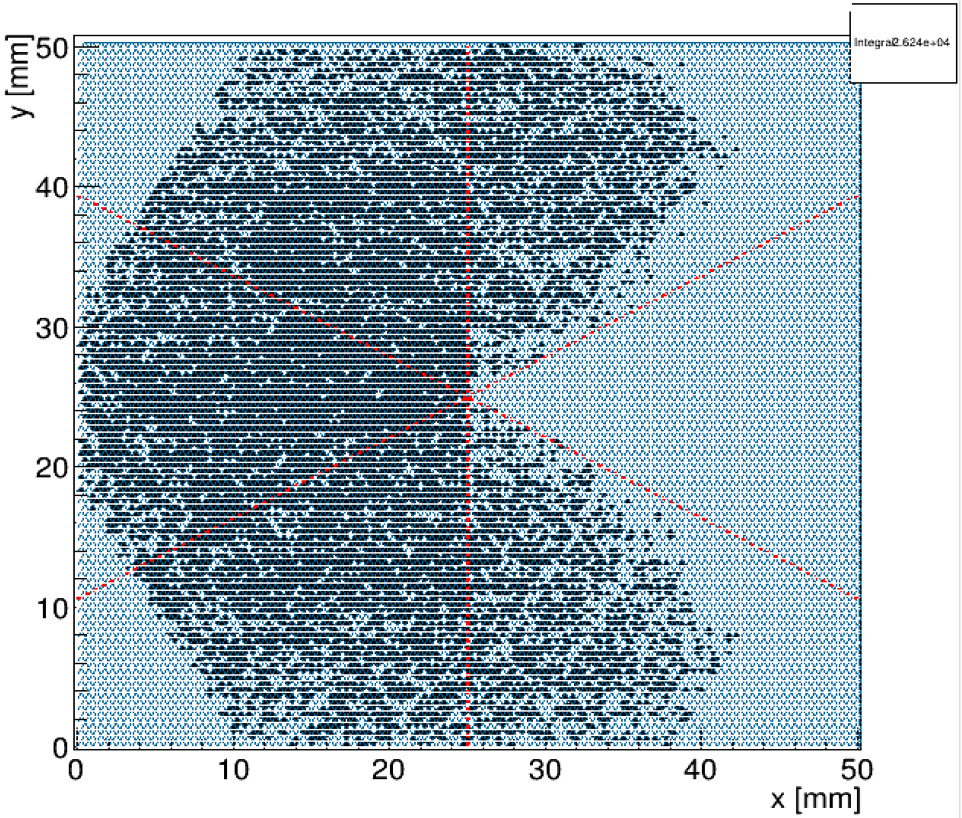
(x,u,v) Output Distributions



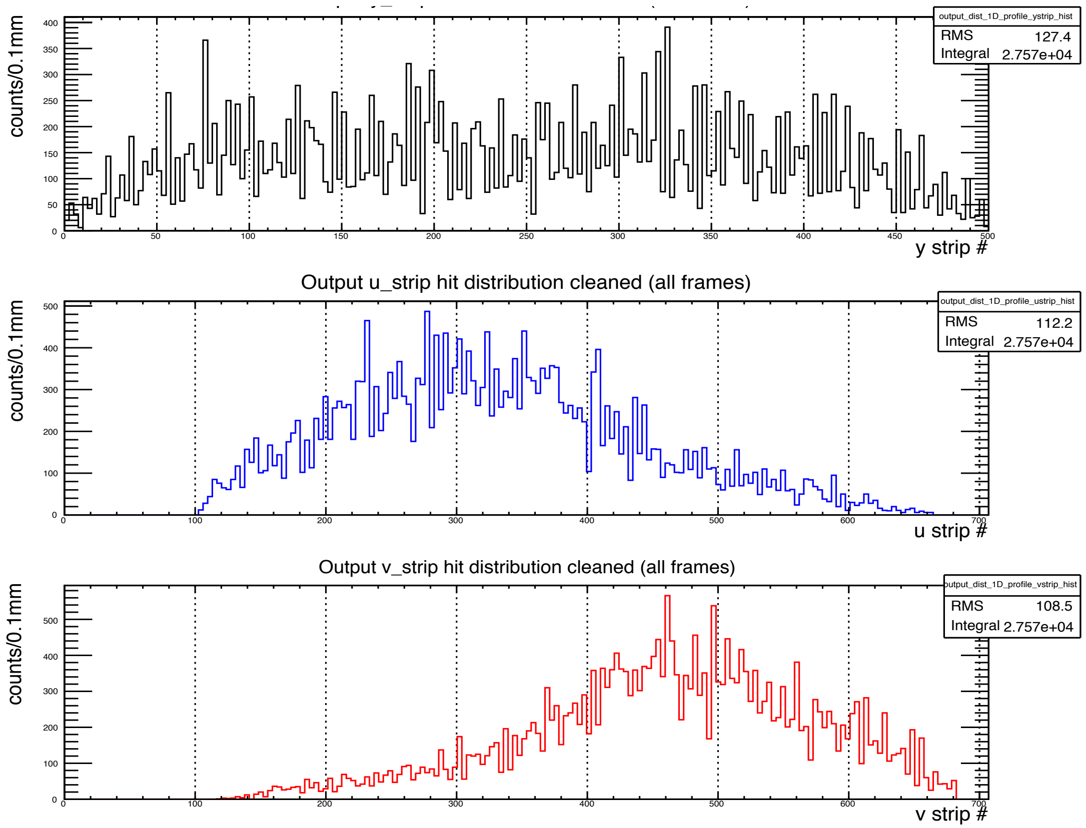
60 protons/frame 1D & 2D output distributions

Simulated Efficiency in Treatment Mode

Output Distribution



(x,u,v) Output Distributions



120 protons/frame 1D & 2D output distributions

Proton counting and 1D histogramming – Possible up 120 protons/frame with only small error in calculated dose since 2 thresholds and only 1.2 % > 2 hits per strip.

2D proton beam profile – Large distortions in a concave beam profile appear at 120 protons/frame

Simulated Efficiency in Patient Imaging Mode

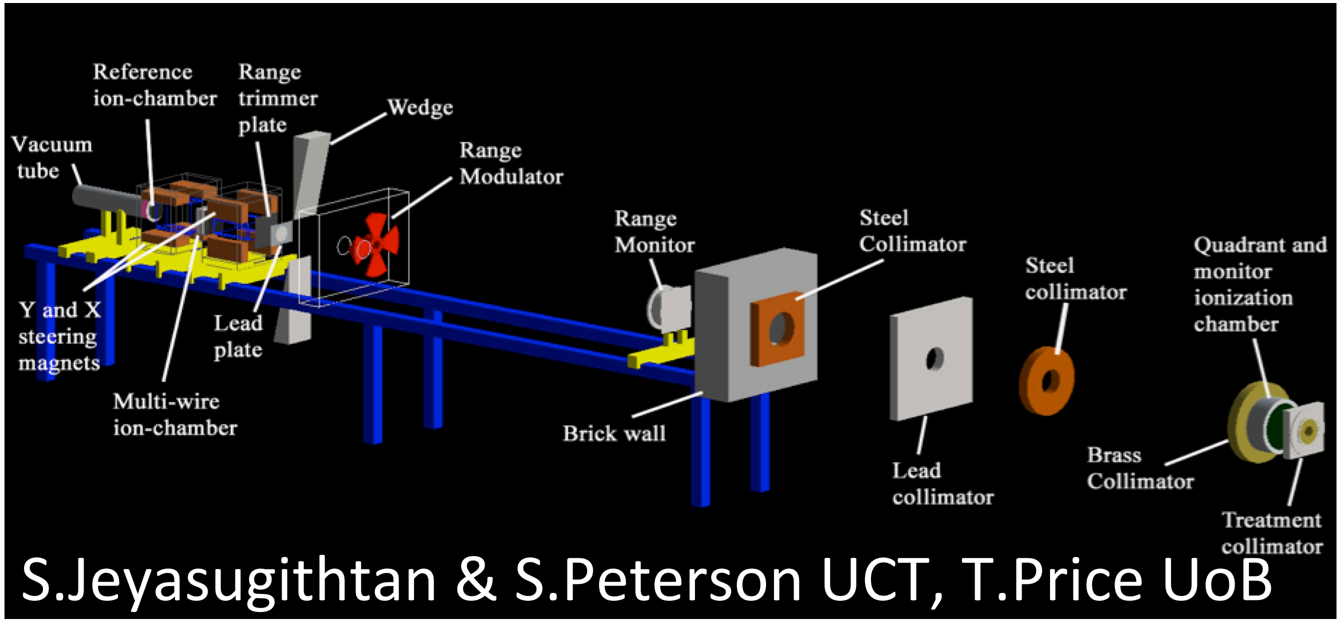
Flux in patient imaging (pCT) mode is 100 times less than treatment mode therefore ambiguity rates are very low (at iThemba only expect 0.04 events/frame)

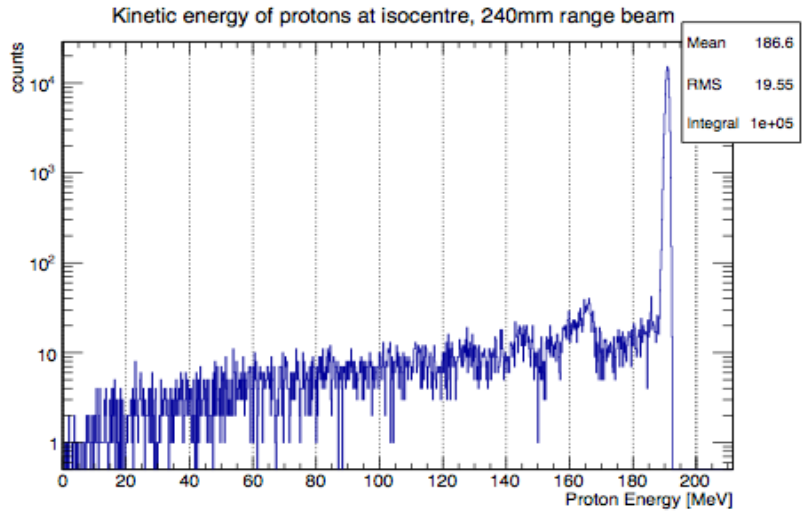
Events/Frame	Ambiguity Rate	>1 hit per strip	>2 hits per strip
5	0.6%	0.8%	<0.1%
10	1.6%	1.4%	<0.1%

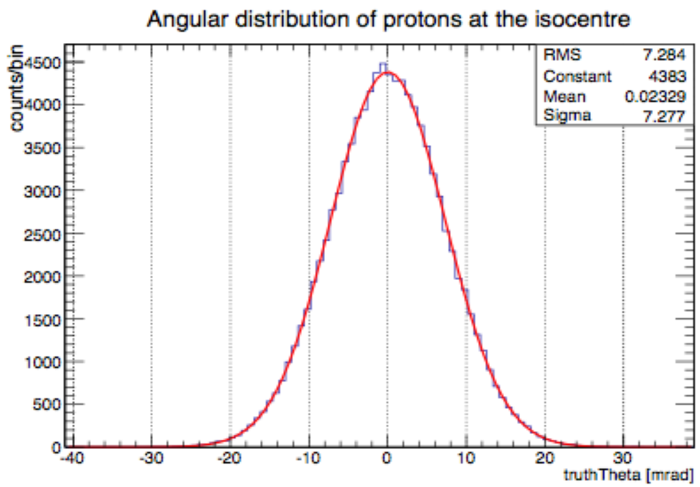
Ambiguity rate = total ambiguous hits/ total real hits

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

iThemba GEANT4 Simulation

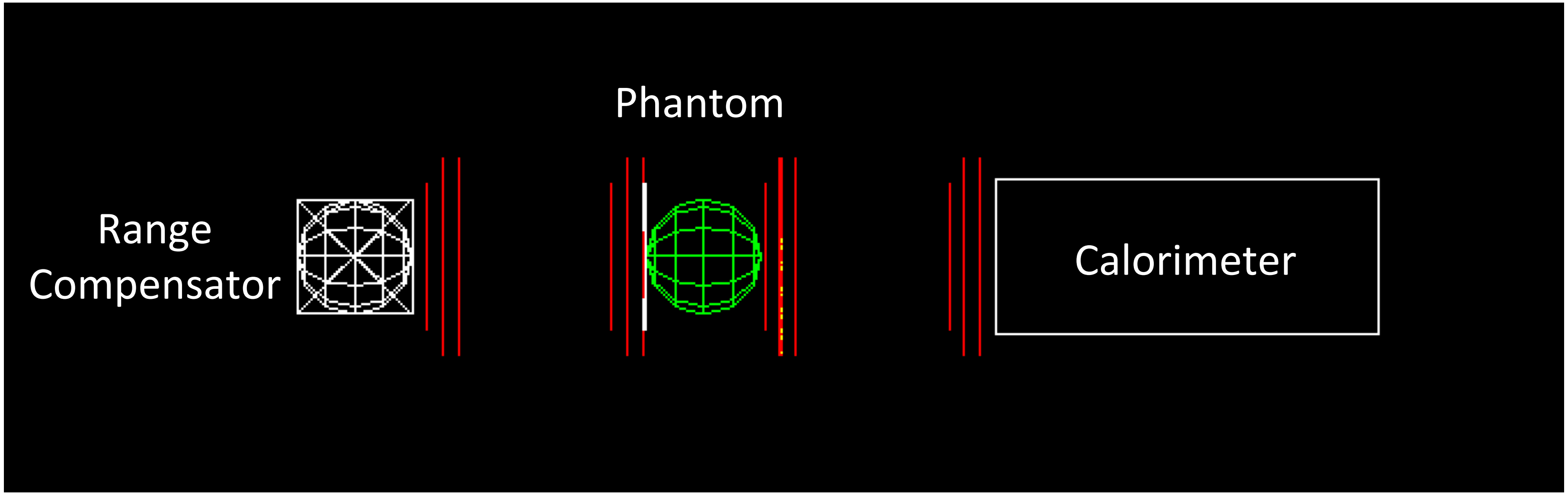






- **iThemba beamline code used as input for GEANT4 simulations of silicon strip tracker**
- **(x,u,v) triplets of 150um Si with 90.8um strip pitch simulated**
- **Simulation provided output for detector/ASIC design and (soon) output for CT reconstruction codes written by University of Surrey**

GEANT4 Simulation of tracker



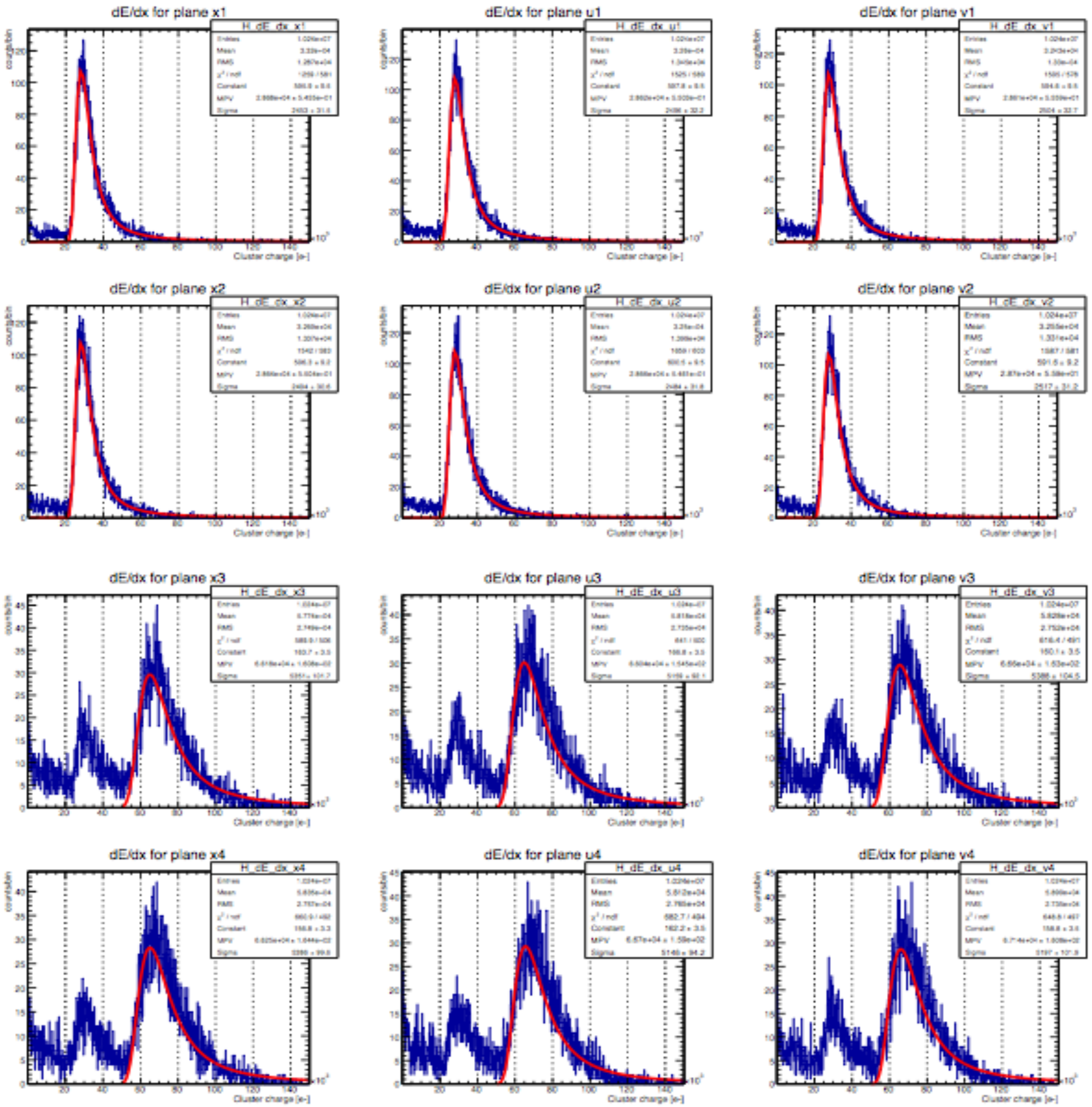
GEANT4 Simulation of the tracker uses the iThemba beamline simulation on the previous slide as an input. The tracker simulation consists of:

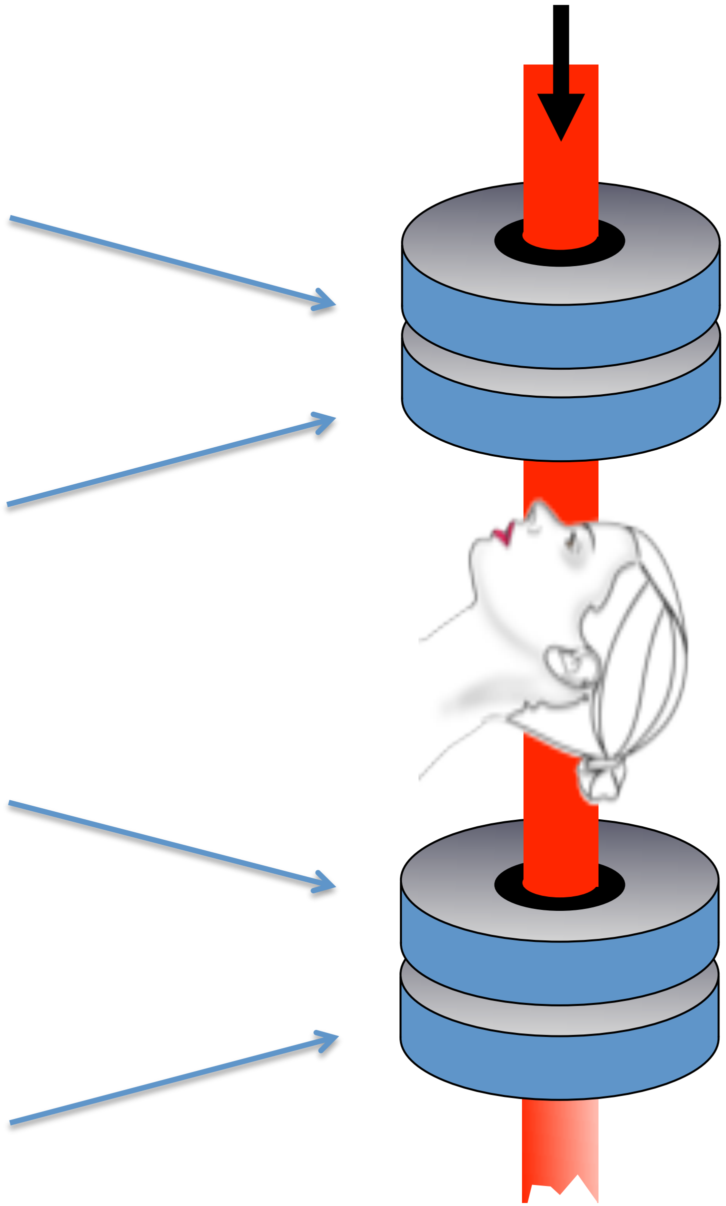
There are 8 planes before and after the phantom:
- 6 silicon planes arranged into two (x,u,v) modules
- 2 air planes used to provide truth information

Each plane uses G4VDigitizerModule to store sensitive detector information into strips

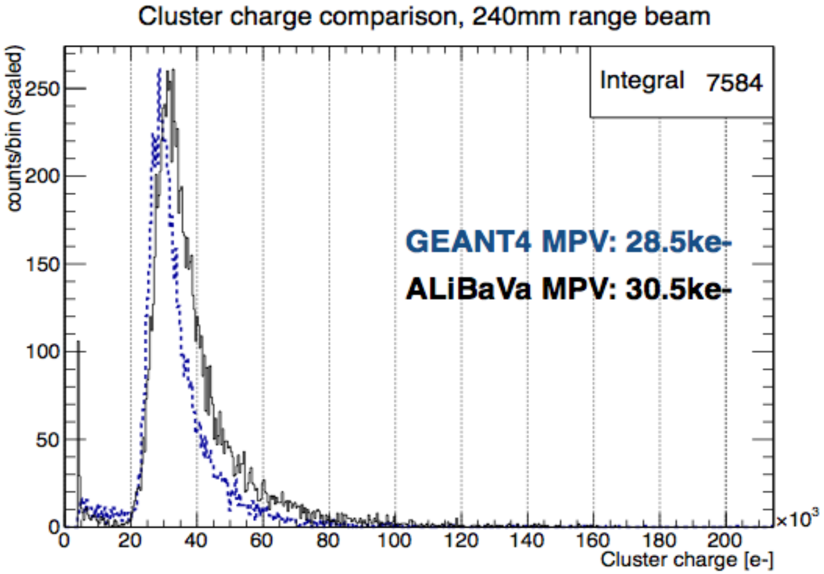
Charge sharing is implemented to provide realistic cluster width distributions for comparison with measured distributions and input to tracking algorithm

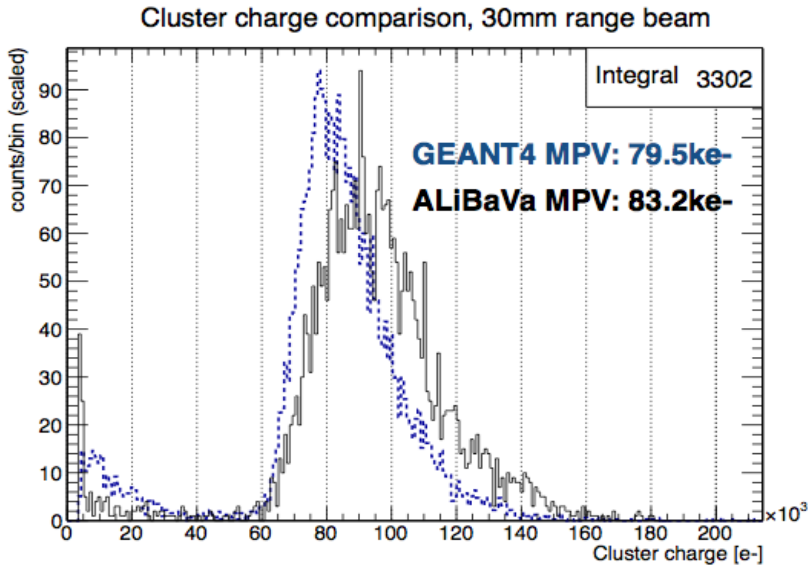
Simulated dE/dx distributions

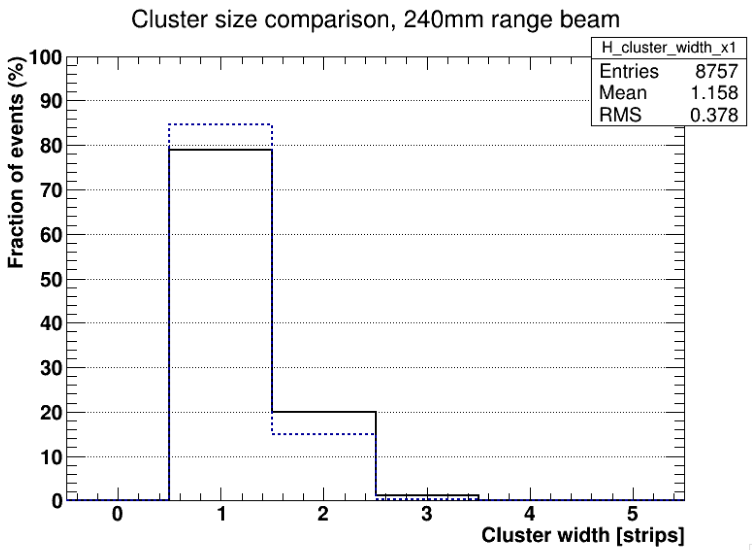


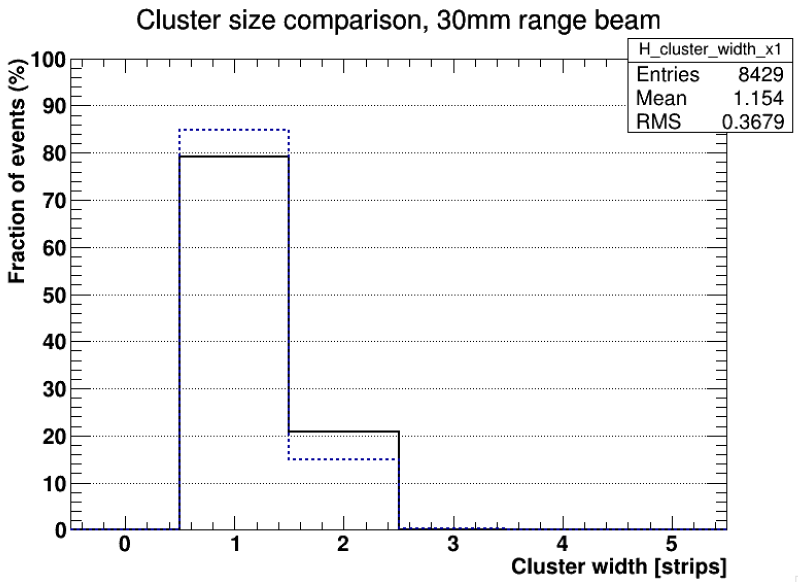


GEANT4 validation



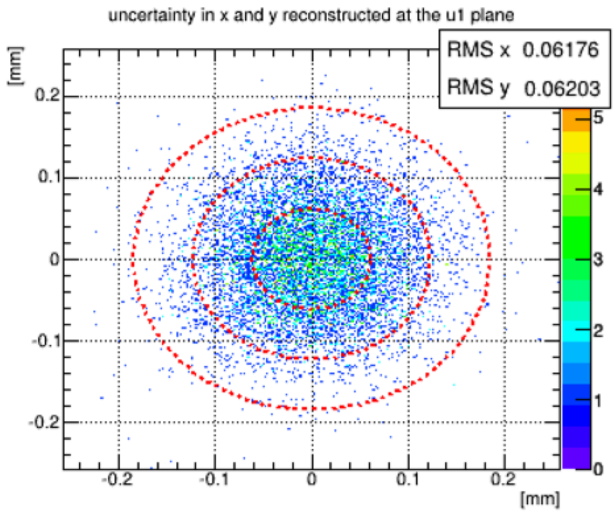


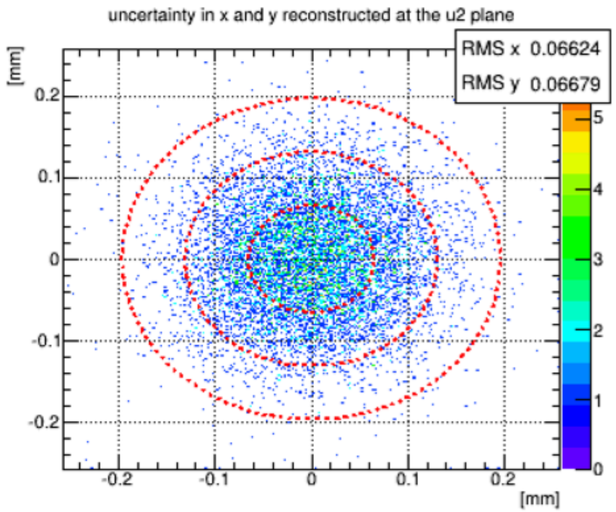




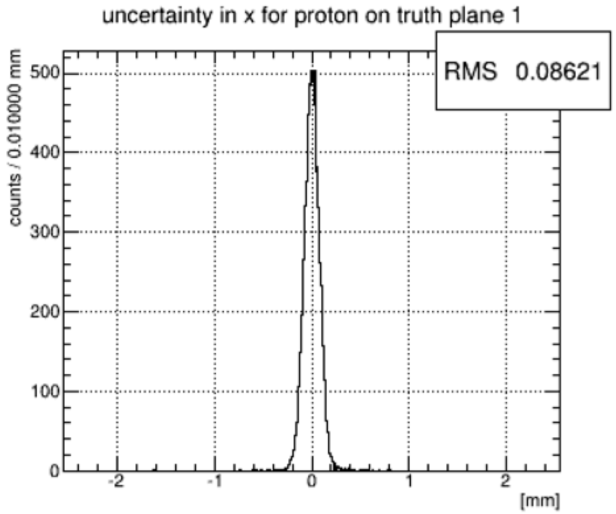
Measured data agrees with GEANT4 simulation to within <10%

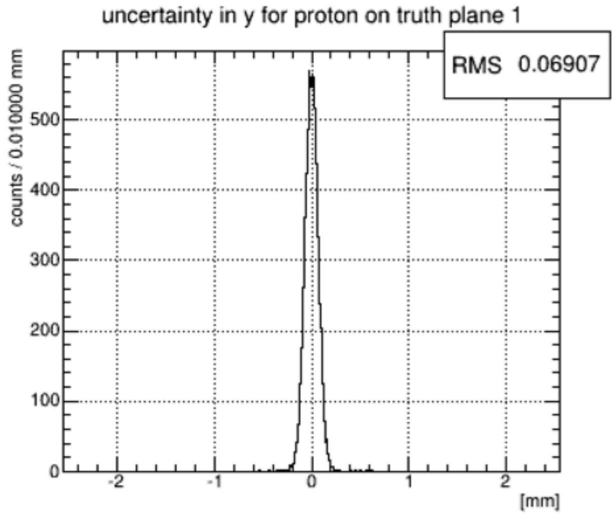
Tracking algorithm

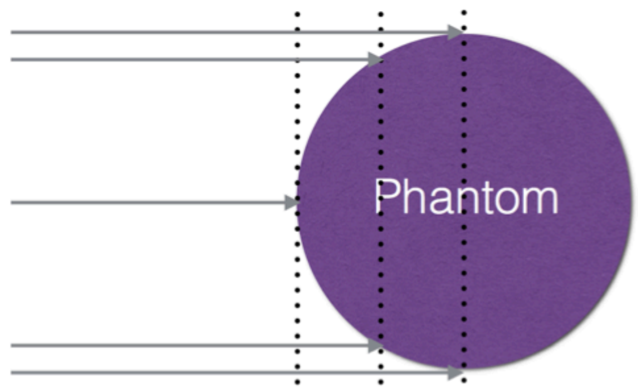




Ellipses indicate 1,2 & 3 sigma values for reconstructed position – truth position







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

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Summary

- The PRaVDA system will enable 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
- The tracker is capable of fast and precise proton tracking for Patient Imaging and accurate dosimetry up to the high beam currents used during Patient Treatment
- Preliminary data has been taken with 150um silicon strip strip detectors and charged particles of varying energies
- Simulation together with preliminary measurements has been used to inform design of a new silicon sensor, ASIC, hybrid and DAQ
- Tracking software and analysis algorithms are currently under development using simulated data from GEANT4 which has been validated with measurments
- Full system to be assembled early next year for beam tests at iThemba LABS, South Africa

Thanks for Listening!

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and..

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UNIVERSITY OF LINCOLN

UNIVERSITY OF SURREY

NRF National Research Foundation

iThemba LABS Laboratory for Accelerator Based Sciences

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