Silicon Detectors in 3D-Technology

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4) CNM Barcelona
5) Universita di Trento

8th International Conference on Position Sensitive Detectors (PSD), Glasgow, Scotland

-Part of this work is performed in the framework of the CERN RD50 Collaboration-

Introduction

- 3D Detectors started 1996
- Harvesting 12 years later
  - 3D Projects in ATLAS, RD50,...
  - At PSD08, six 3D-related talks and posters

3D Detector Idea: Parker, Kenny, Segal, *NIM* **A395**, (1997) 328

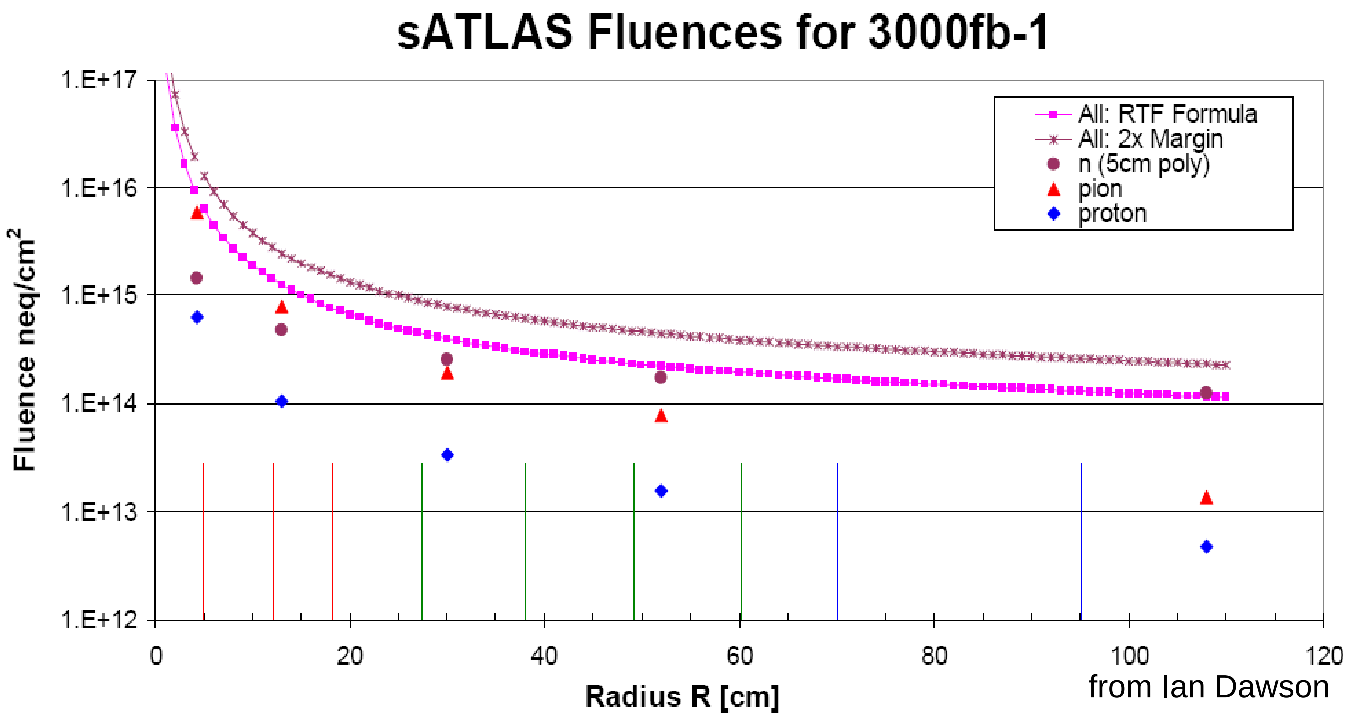
Disclaimer:

At VERTEX 2008, Chris Parkes presented an overview of 3D detectors, see:
http://indico.cern.ch/conferenceDisplay.py?confId=30356

Chris extensively covered 3D pixel detectors and processing. I will concentrate on 3D strips, especially STC.

Motivation: The SLHC

- LHC Upgrade to Super-LHC (SLHC) planned for 2016:
  - Increase luminosity by factor ten compared to LHC
  - Massive increase of radiation dose for silicon detectors, making radiation damage the major concern
  - ATLAS will need to replace Inner Tracking system to cope with SLHC
  - Not clear if radiation hardness of planar Silicon pixel or strip detectors is sufficient



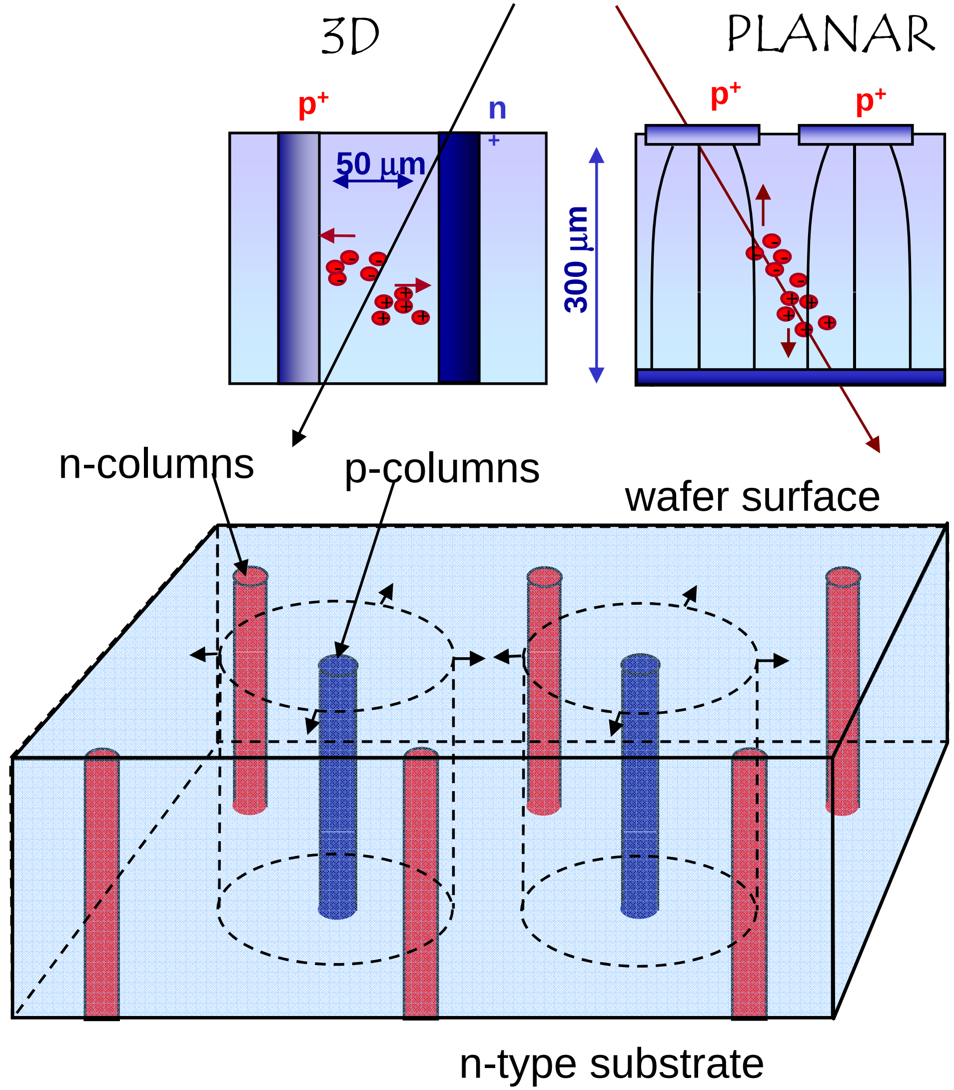
from Ian Dawson

→ 3D designs investigated for SLHC pixel detectors

→ Study 3D short strip detectors (~2-3cm strip length)

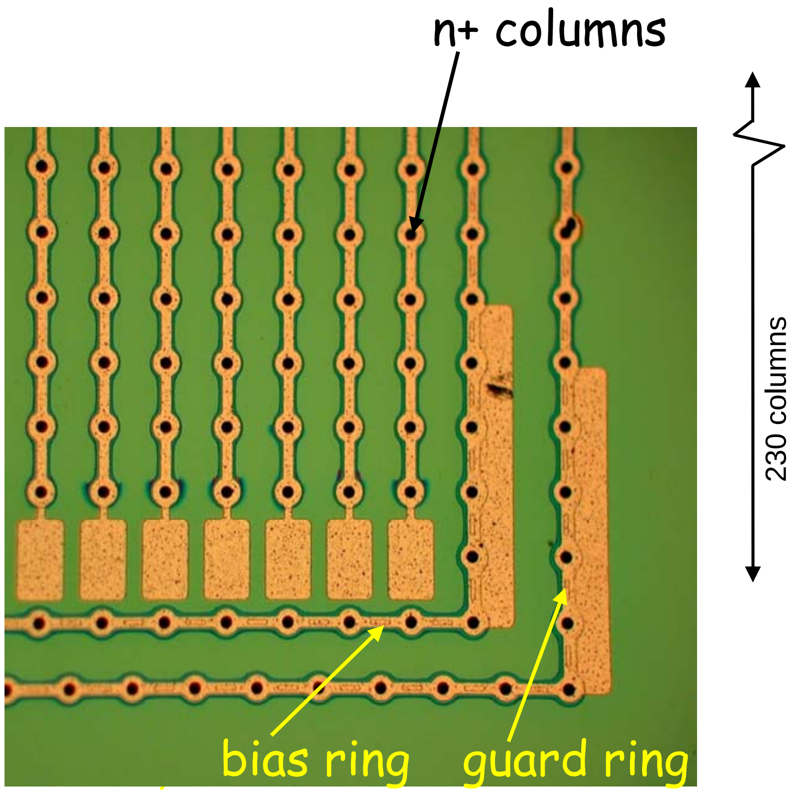
Reminder: The 3D Principle

- 3D detectors decouple thickness (=signal) and depletion voltage
- Depletion and charge collection is sideways
- Superior radiation hardness "by design"
  - less trapping (as collection distances are short)
  - Full depletion voltage less affected by growing acceptor concentration (V_{dep} ~ distance^2)
- Original 3D designs
  - Brilliant but complex
  - conceived as pixel devices
  - can connect rows of columns to form strips



3D Designs

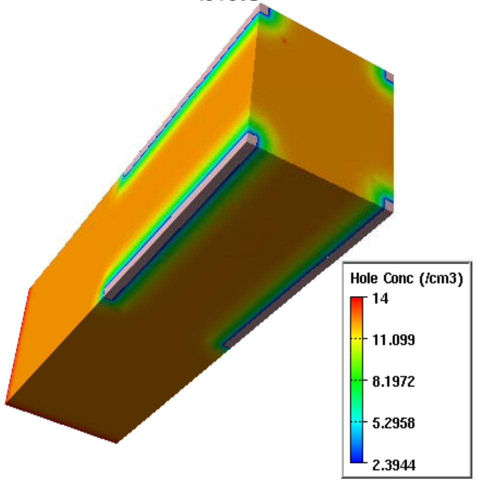
- Original 3D
  - Good performance but costly and complex to manufacture
  - Mainly made for pixel applications
- Single Type Column (STC) 3D
  - Much simpler: columns on one side only
  - Produced successfully: Pixel and strip detectors exist
  - STCs tested extensively
- Double Type Column (DTC) 3D
  - Better than STC, yet simpler than classic 3D
  - The next step in “simpler 3Ds”



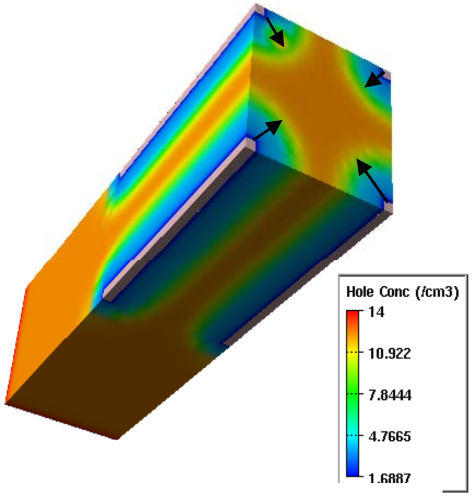
3D STC strip detector

3D STC Simulations – Depletion

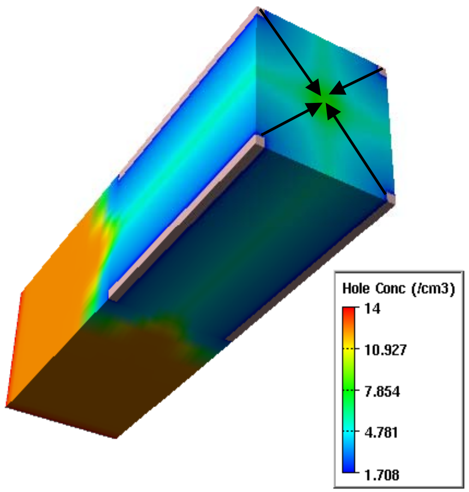
1) U_{bias}=0V



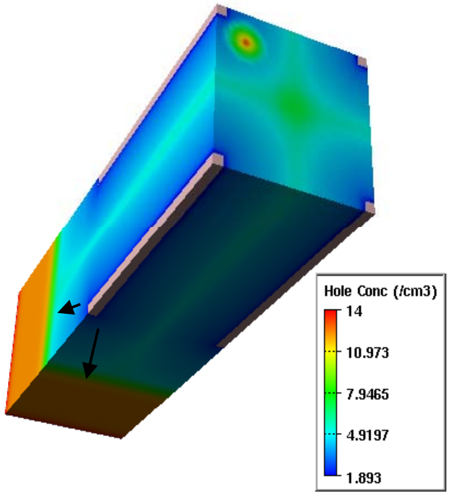
2) U_{bias}=2V



3) U_{bias}=5V

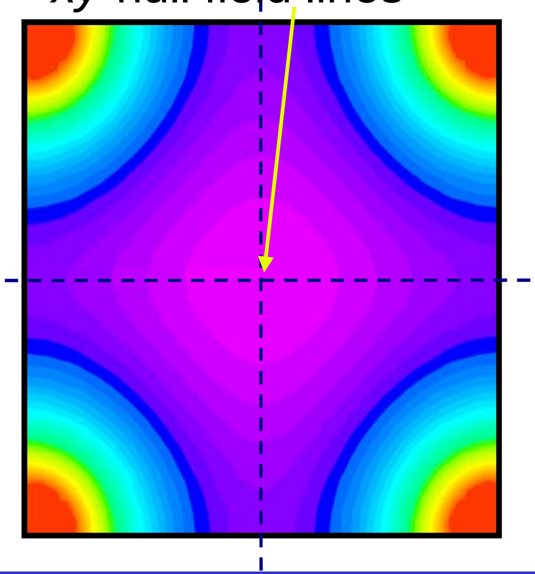


4) U_{bias}=20V

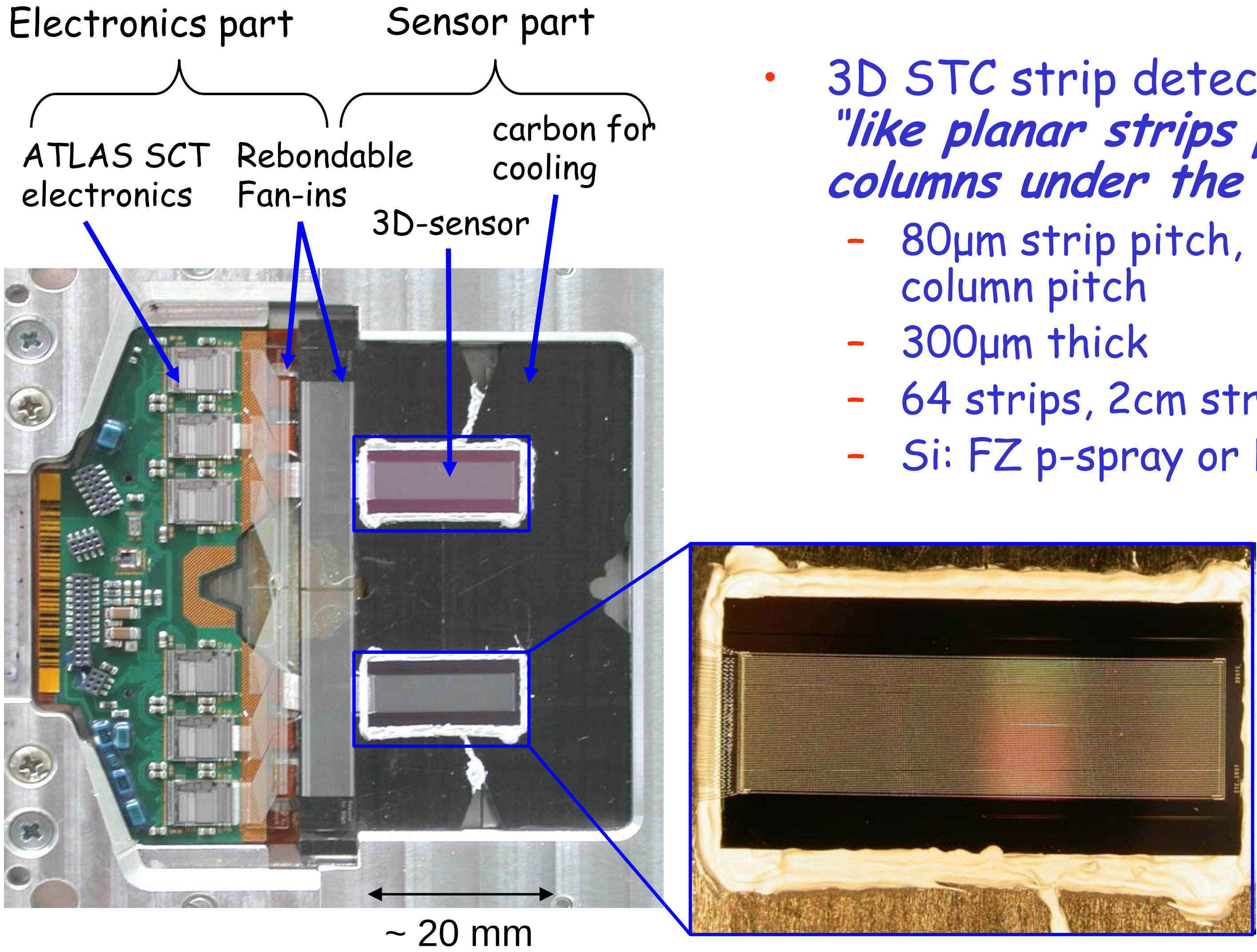


- STC sensors made by FBK-irst (Trento)
- Initial fast lateral depletion at 5V for FZ Si
- Then depleting like a planar detector
- Low field in central region remains
  - indep. of bias voltage
  - bias affects only field under columns towards back side

xy-null field lines

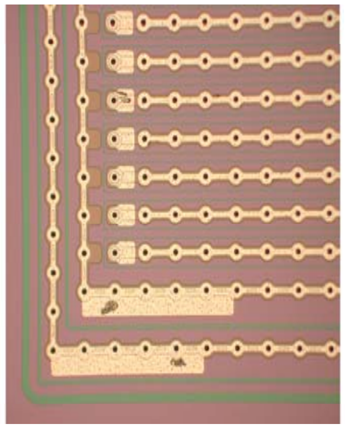


3D STC Module with FZ sensors

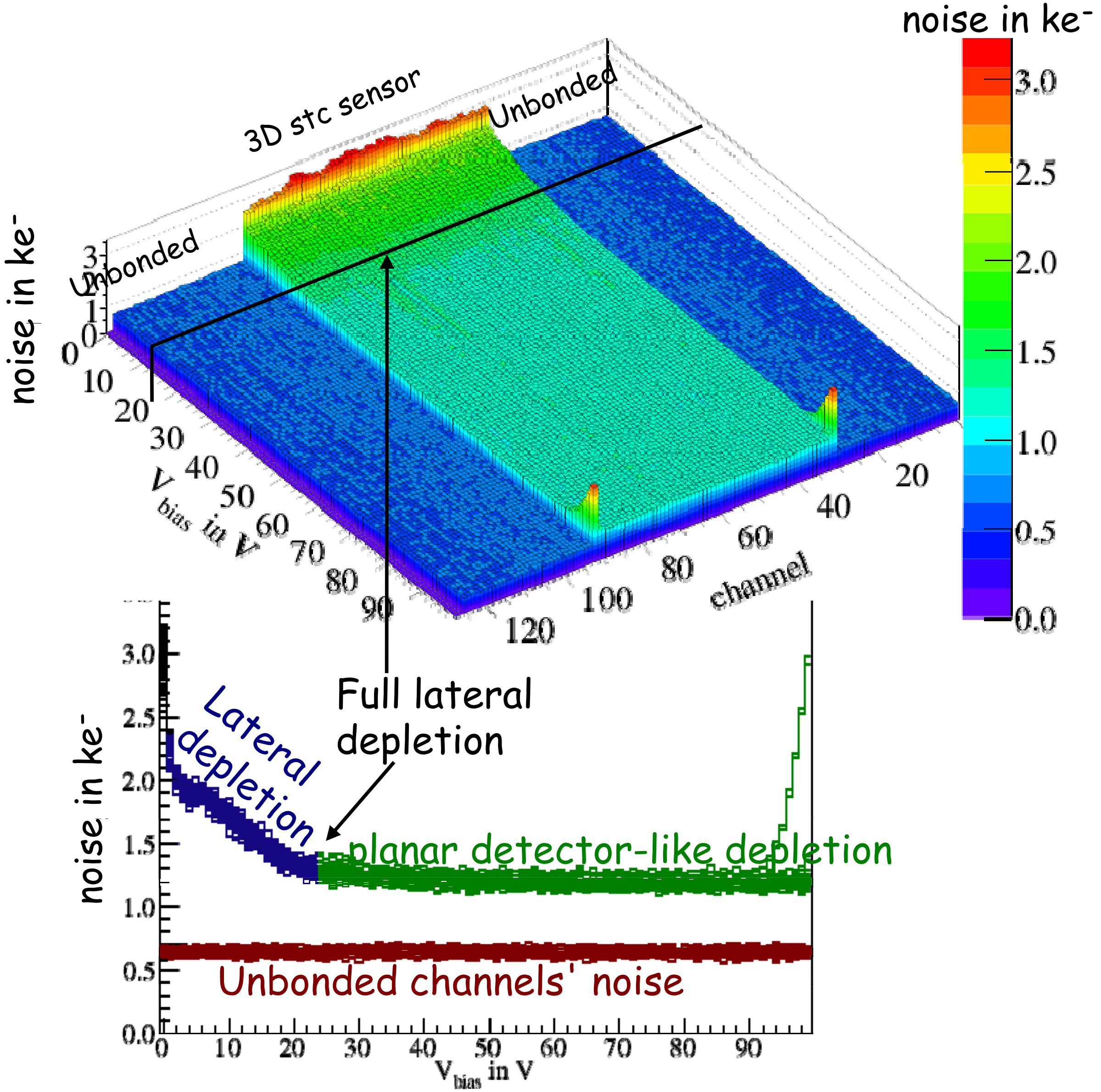


- 3D STC strip detectors are ***"like planar strips plus columns under the strips"***
  - 80µm strip pitch, 80µm or 100µm column pitch
  - 300µm thick
  - 64 strips, 2cm strip length
  - Si: FZ p-spray or FZ p-stop

FZ p-stop sensor



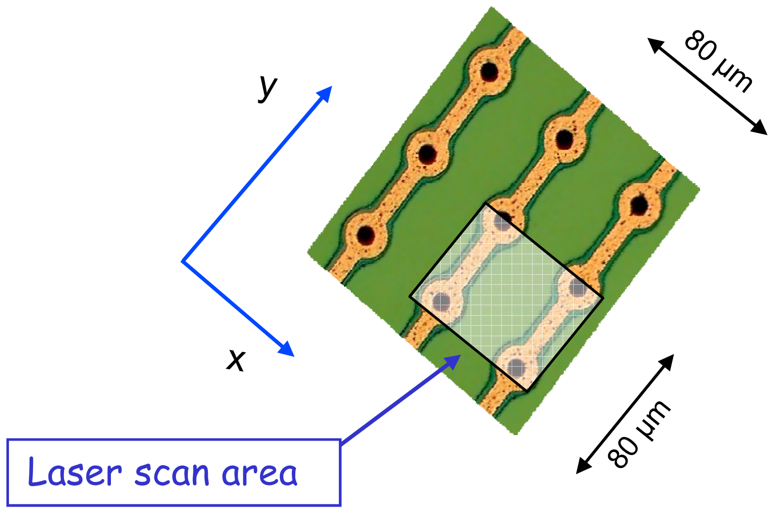
Noise Behaviour

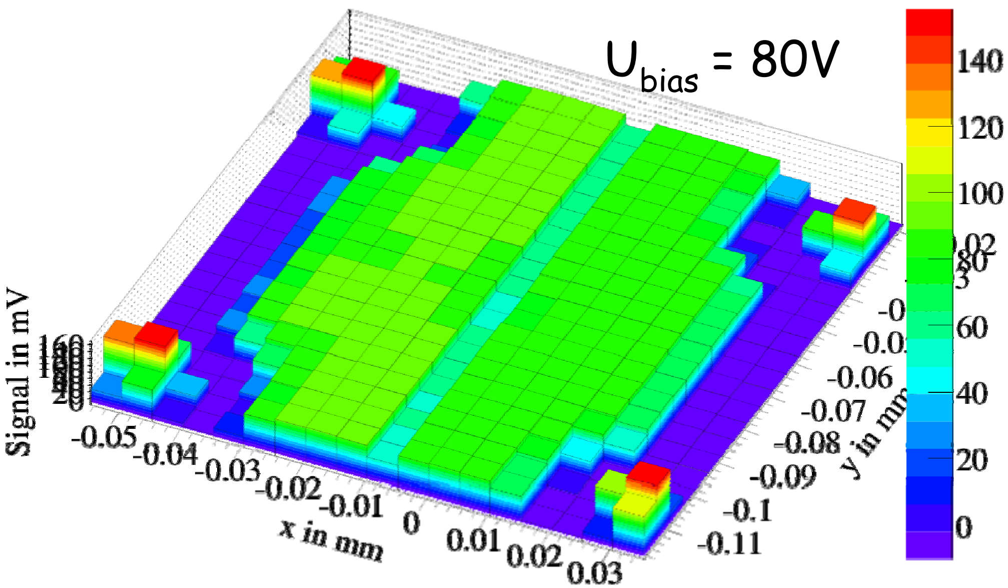


- 3D devices will have higher capacitance (and noise!) than planar designs
- Measure noise at LHC readout speed (40MHz)
- Noise is
  - Uniform across sensor
  - Rapidly decreasing with bias voltage until lateral full depletion at ≈ 25V
  - Then slowly decreasing as sensor continues to deplete towards backside
  - Typical noise 1200 ENC (corresponds to 6-7cm strips in planar design)
- Micro-discharge starting at 95V (before sensor is fully depleted)

Signal: IR Laser Measurements

- Three methods available to generate charge in Si:
  - Laser
  - Radioactive source
  - High-energy particles (MIP)
- Example: pulsed IR Laser
  - Focused to 5µm spot size
  - Coupled into fiber
  - Scan detector surface to study uniformity of charge collection efficiency
  - Scan area is unit cell
- Narrow region of lower CCE (≈5µm) on p-spray sensor
- Likely cause is central low field region
- Signal drops by ≈25% - 30%

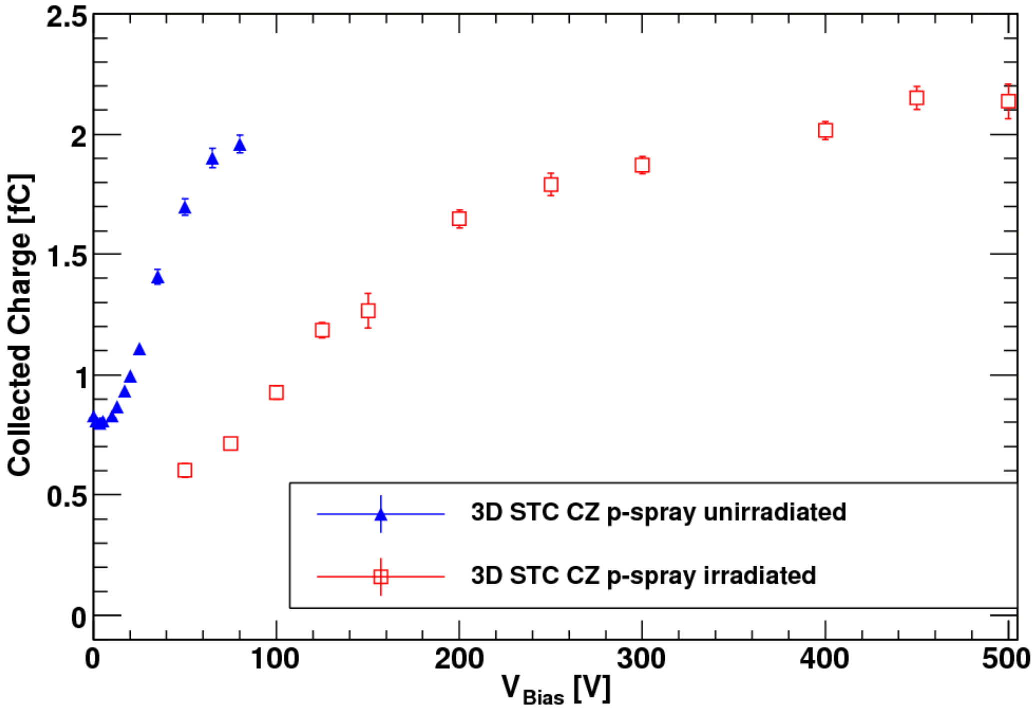




Signal: Source

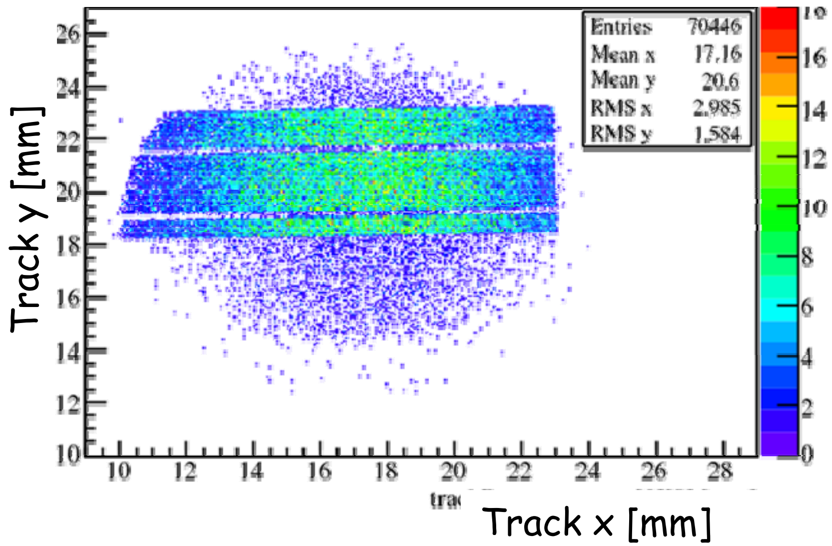
- 3D-STC modules tested with e- from Sr90 beta source
- Test before and after irradiation to $10^{15} N_{eq}/cm^2$
- Charge collection is reduced by irradiation
- Given sufficient HV stability, the irradiated detector collects the same charge as prior to irradiation
- V_{FD} ~ 230V as predicted for CZ p-type

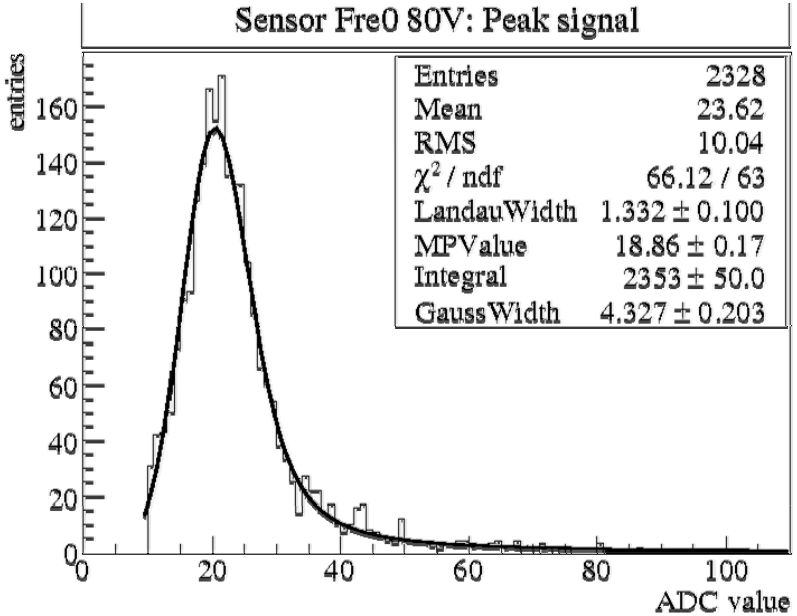
3D STC on CZ p-type Si



2007 Beam Test

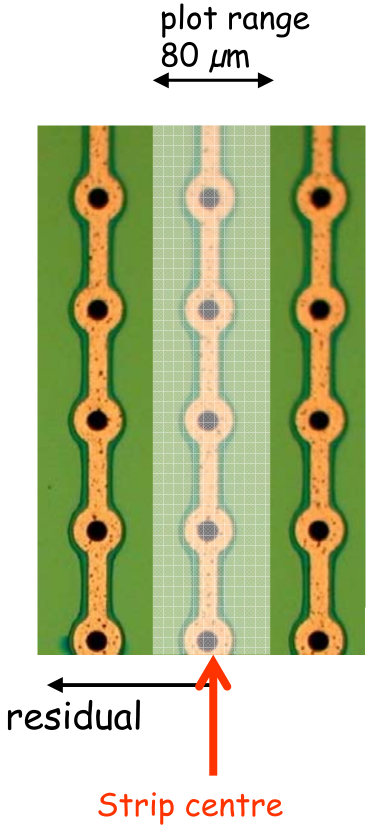
- Two 3D STC detectors were tested with 180GeV SPS Pions in Autumn 2007
- Main aim: position-resolved study of CCE, signal and signal shape
- Signal measurement with ADC Calibration: Landau MPV at 2.4 fC (70% of 3.5 fC)
- Note: Entire Test Beam analysis still **preliminary**
  - work on tracking & alignment ongoing





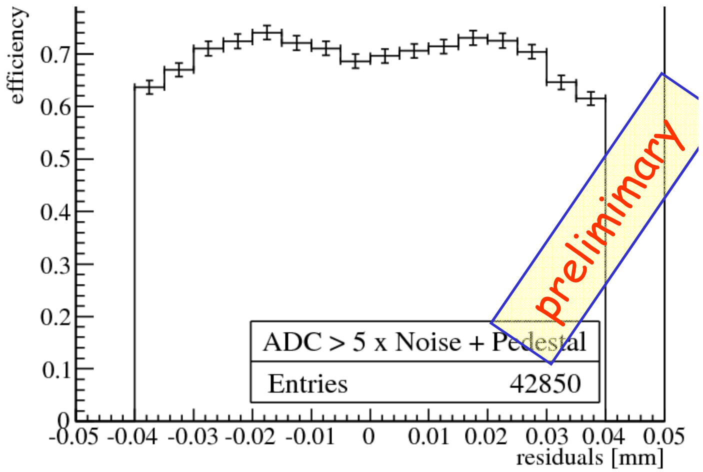
Efficiency in Beam Test

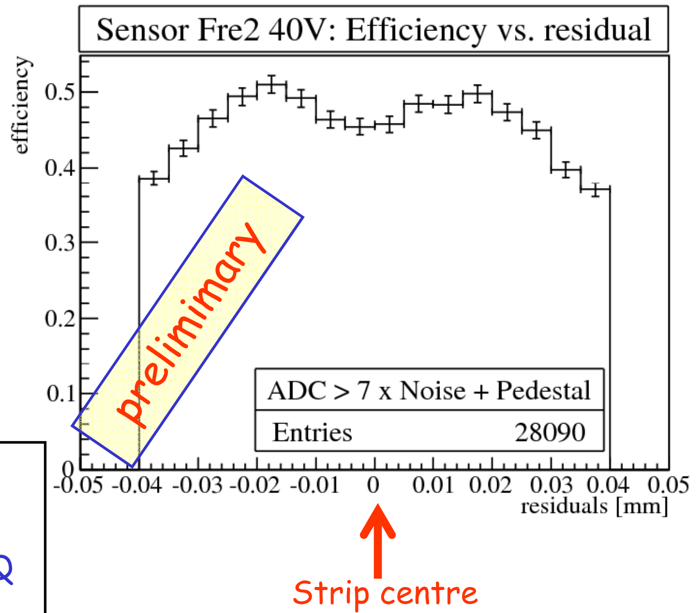
- Alignment much better orthogonal to strips due to small beam shape
- Study 1-D efficiency orthogonal to strip
  - number of hits on 3D matched to tracks as a function of distance to strip „residual“
  - map entire detector onto one strip
- Low efficiency at
  - large distance to strip: **low field region**
  - strip center: **no charge deposition in hollow columns**



Note: only relative efficiency is measured!

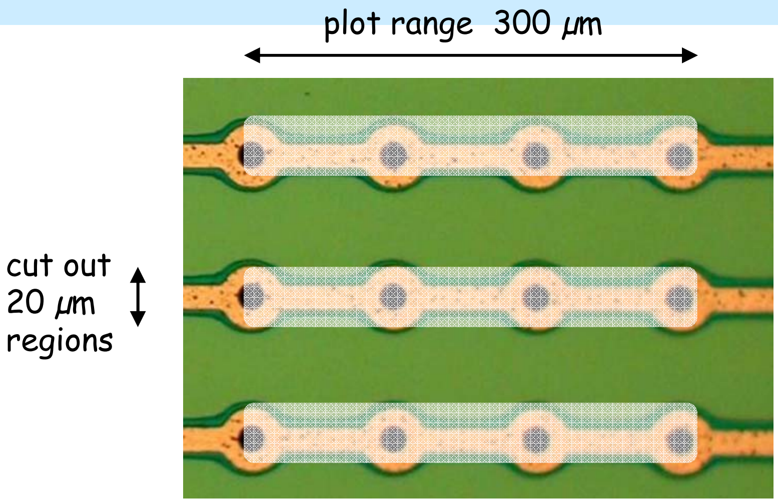
Absolute eff. higher due to DAQ desynchronisation, dead strips

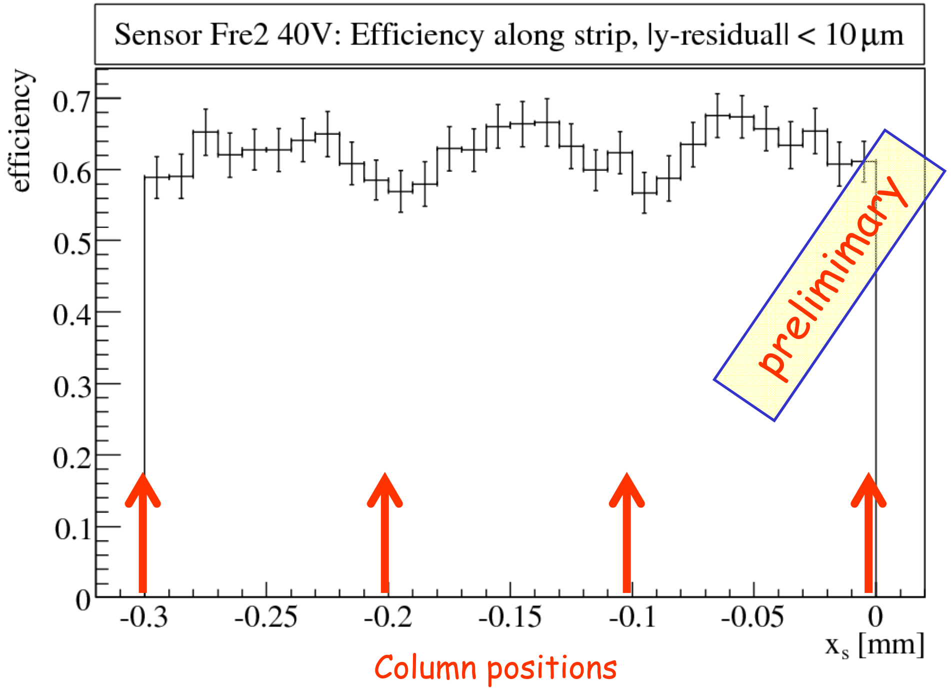




Efficiency in Beam Test

- Can also study 1-D efficiency parallel to strip
  - "Looking for columns"
  - Restrict to hits 10µm each side of strip centre
  - Map 20µm wide bands from entire detector onto 300µm long cell
  - Structure with 100µm spacing is visible, but washed out due to
    - Track Resolution
    - 2.5°Tilt angle and angle uncertainty
  - **Columns have lower efficiency**
  - Detailed analysis still ongoing

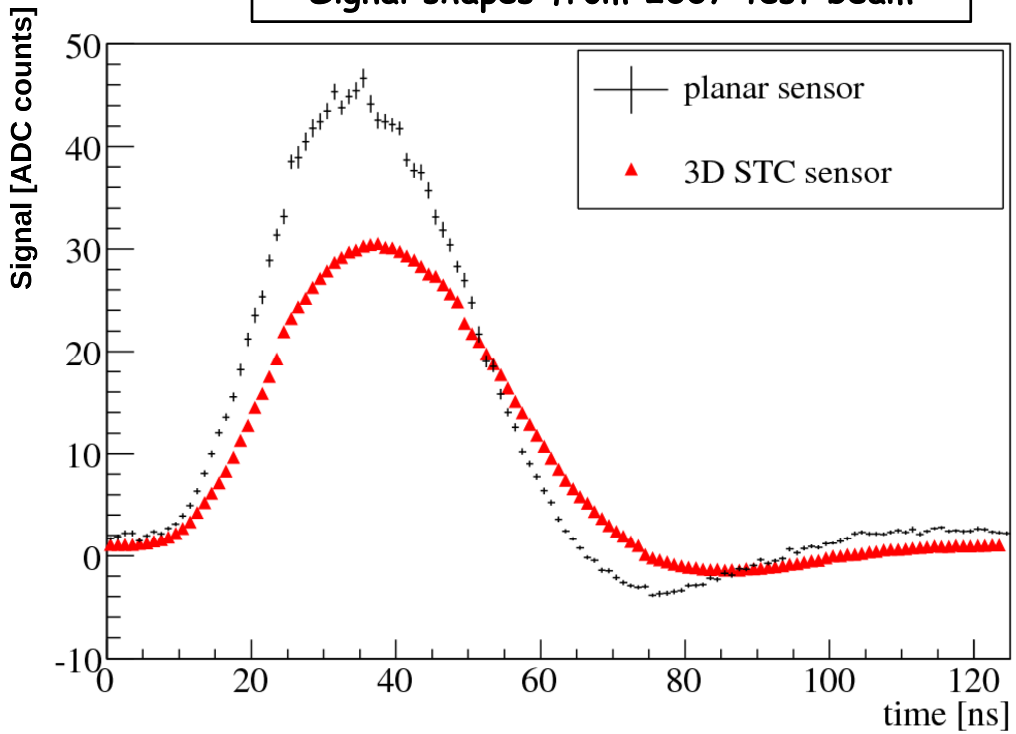




Comments on 3D-STCs

- **Overall charge level low (~2.3fC)** due to ballistic deficit arising from 3D-STC field configuration
- 3D-STC after irradiation to $10^{15} N_{eq}/cm^2$ are still operational
- Same CCE as unirradiated device, but at much higher bias voltage
- 3D STC designs are first steps towards simple cost-effective 3Ds

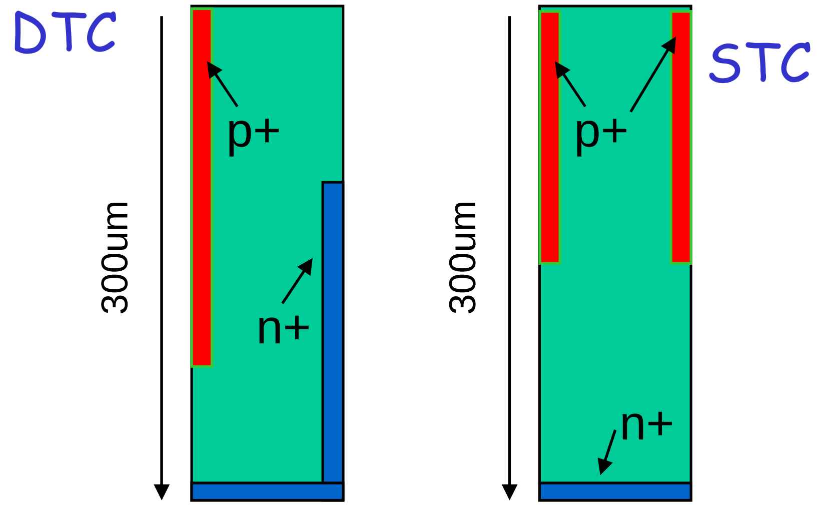
Signal shapes from 2007 test beam

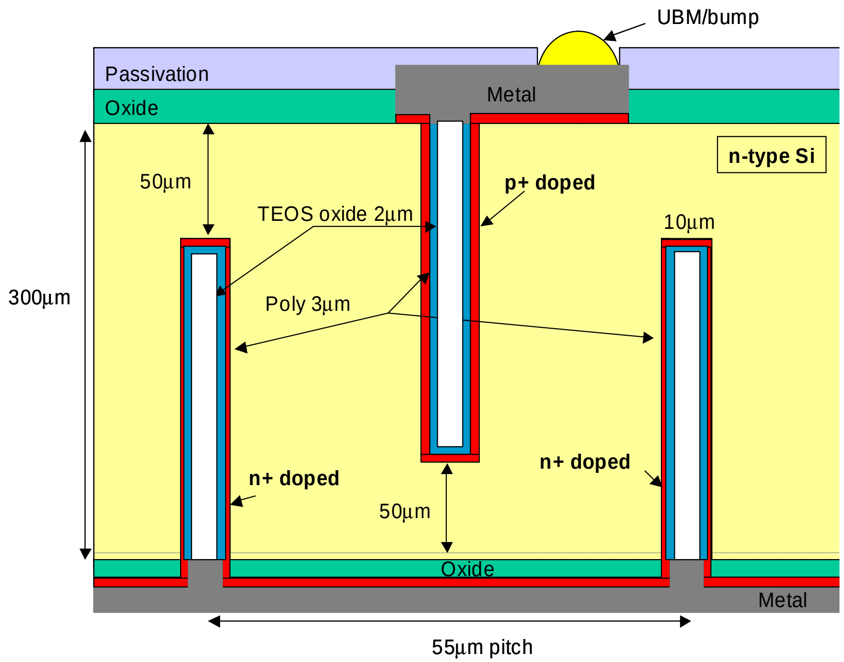


Need to move from STC to DTC!

Double-sided 3D detectors

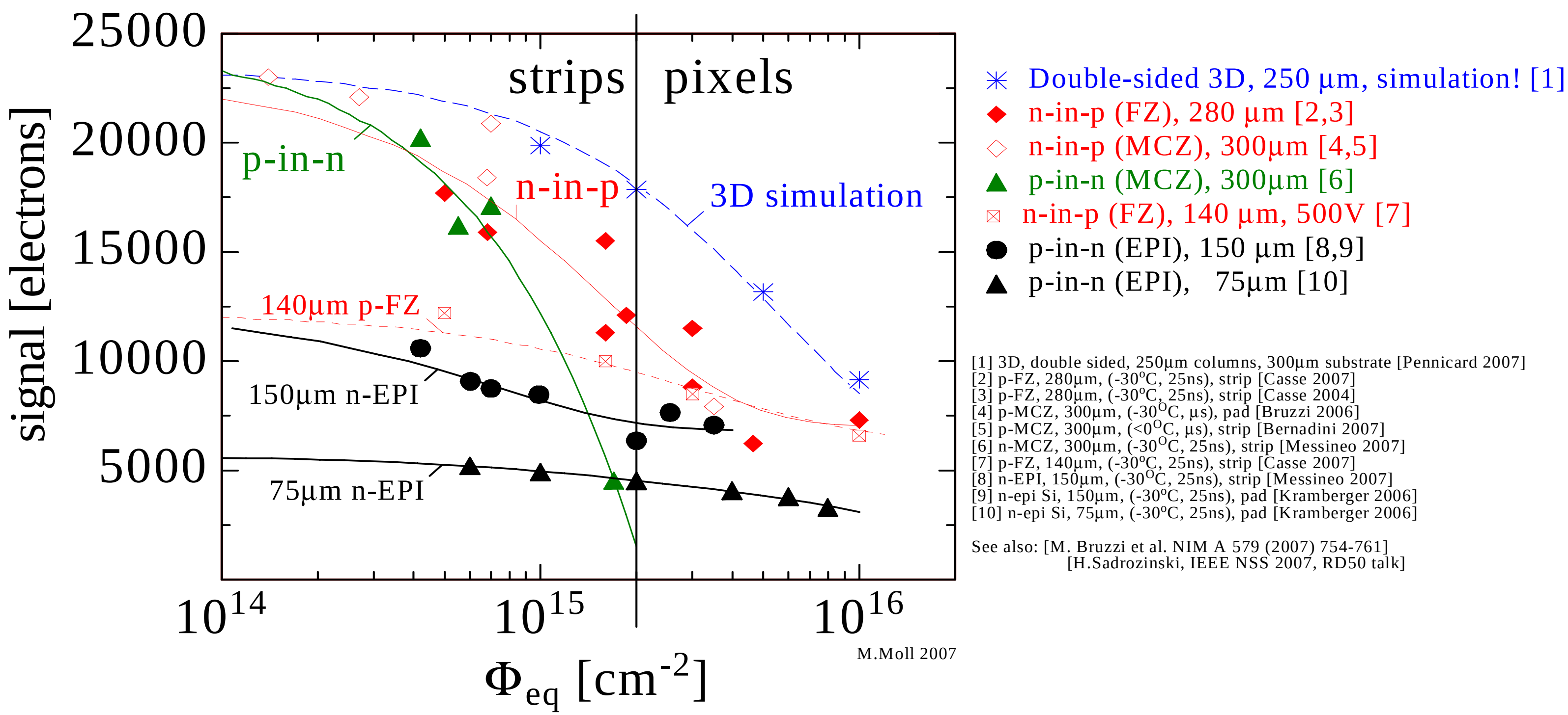
- Improved 3D structure proposed by G. Pellegrini (CNM): n- and p-type columns etched from opposite sides
- Similar design (DDTC) produced independently by FBK-irst (Trento)
  - Columns do not pass through full substrate thickness
  - Reduces low field regions, **field becomes driven by bias voltage**
- Expect faster signals and higher CCE
- Should compare well to conventional 3D design





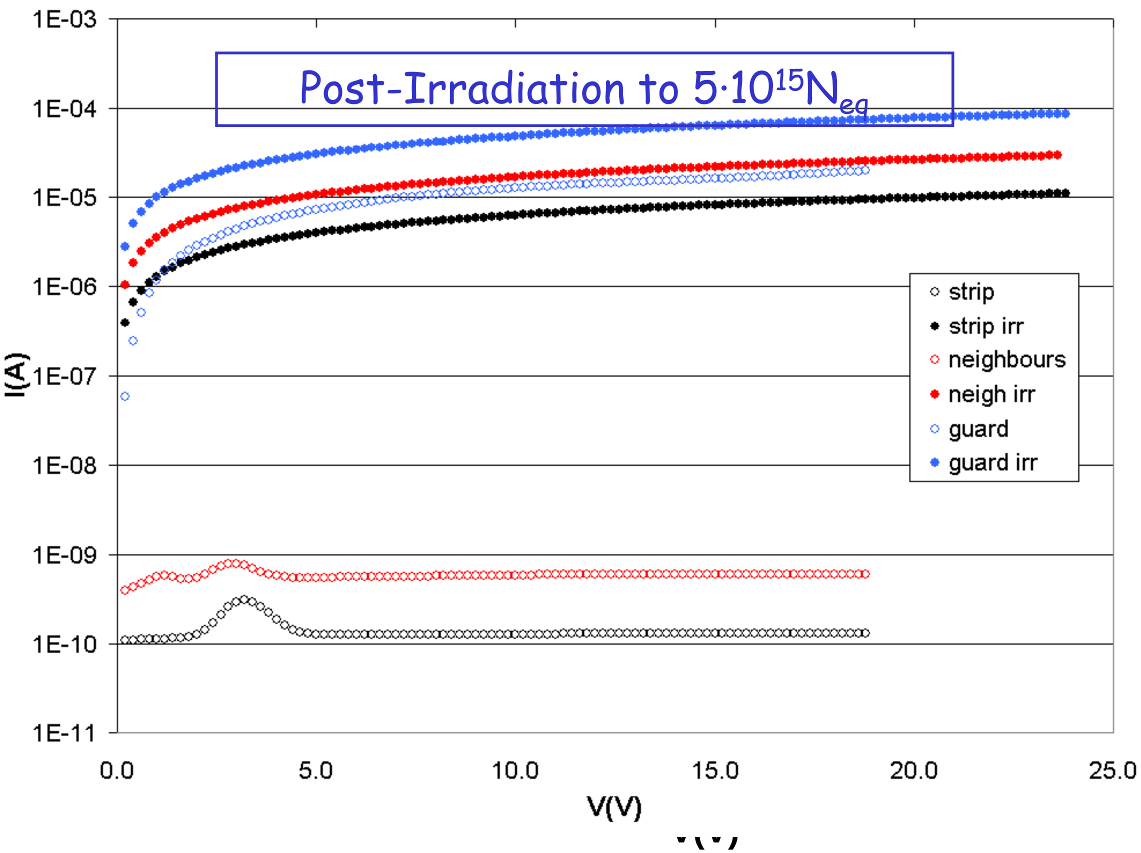
Double Type Column Detectors: DDTC

- First detectors exist
- Simulations predict superior radition hardness



First DTC Results: Strip detector IV

- CNM 3D DTC detectors
- 128 strips, 50 holes/strip, pitch 80µm, length 4mm
- Strip currents ~100pA (T=21°C) in all 4 detectors
- Can reliably bias detectors to 50V (20 times lateral depletion voltage), no breakdown
- Capacitance 5pF / strip
- Guard ring currents vary:
  - Highest 20µA at 10V
  - Lowest 0.03µA at 50V



- Irradiated with $5{\cdot}10^{15}$ N_{eq} in Ljubljana
- IV curves roughly as expected for fluence

Conclusions & Outlook

- Extensive tests on modules with STC 3D detectors. STCs are functional detectors, and radiation hard
  - Too slow for a 40 MHz SLHC (field configuration)

- Radiation hardness of planar designs can be increased with equivalent 3D design
  - higher noise, higher price
  - ATLAS has large 3D program for pixel detector underway

- Future 3D tests will concentrate on DTC devices
  - Simulations and first tests indicate faster charge collection
  - 2008 Test Beam (CMS/RD50) data are on tape

Related Talks & Posters:

G. Pellegrini "*Fabrication and simulation of Novel Ultra Thin 3D Silicon Detectors…*"

D. Gunning *"High spacial resolution probes for neurobiology applications"*

N. Wermes *"Pixel detectors for charged particles "*

C. Fleta *"Characterization of double-sided 3D Medipix 2 detectors"*

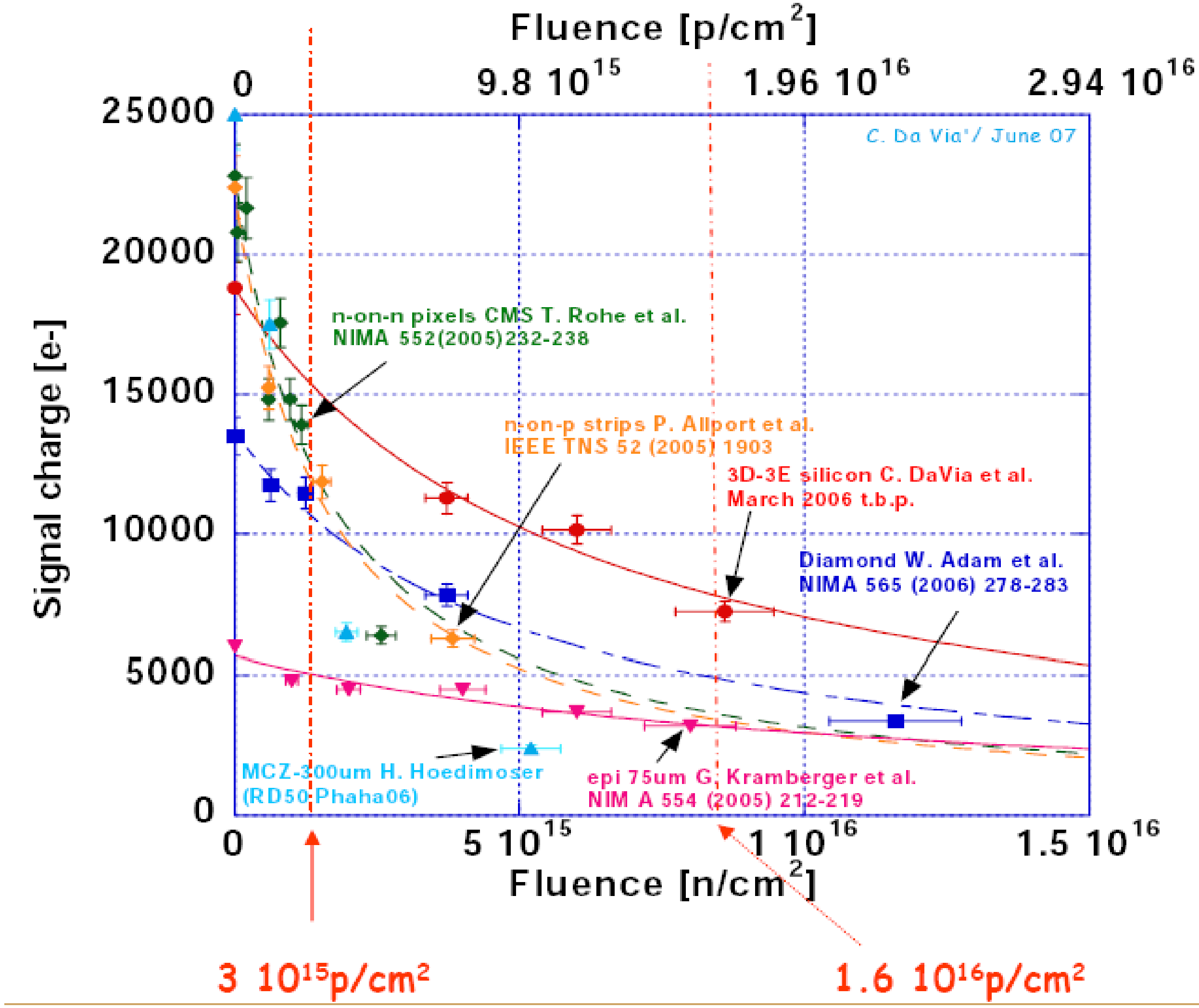
F.G. Huegging *"Sensor concepts for future hybrid pixel detectors"*

A. Zoboli *"Laser and beta source setup characterization of 3D DDTC detectors… "*

BACKUP ONLY

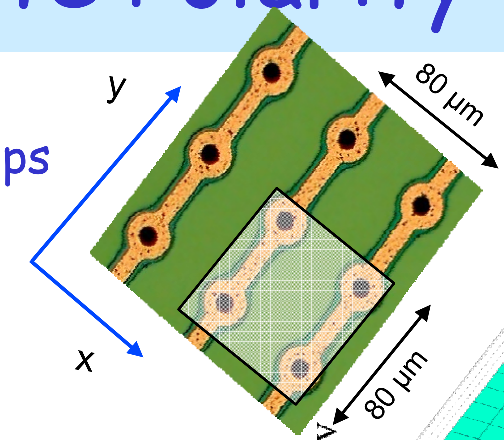
3D Results Overview

- Summary of results from planar and 3D detectors by Cinzia
- Superior radiation hardness (ATLAS 3D pixel collaboration)
- Results for 3D strip detectors above $10^{15} N_{eq}$ still unavailable

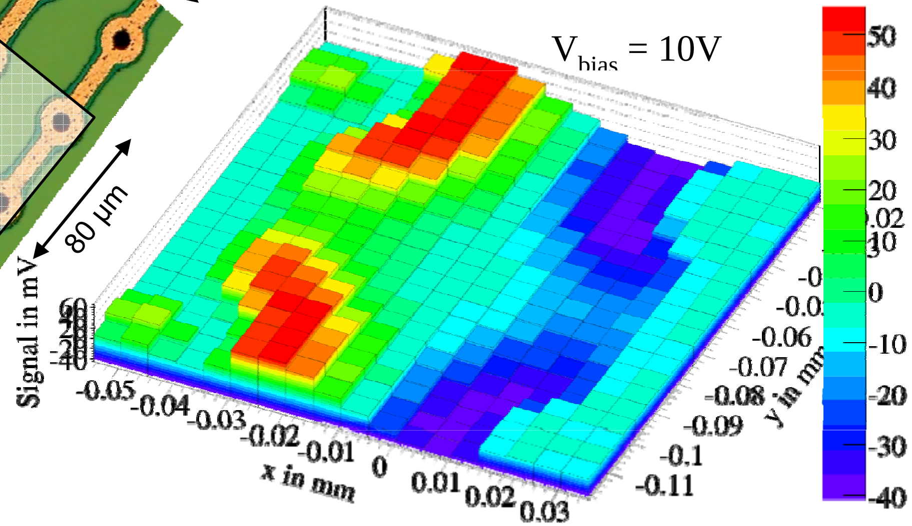


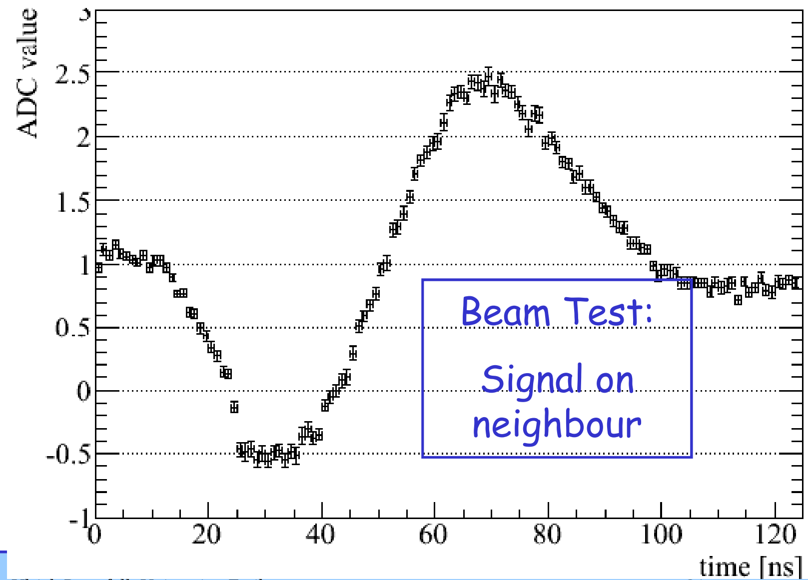
Opposite Polarity Signals

- 3D STC: Opposite polarity signals on neighbouring strips
- Seen very clearly in Laser
- Also visible in Beam Test
  - Traditional clustering algorithms would fail
- Effect only observable for neighbouring strips, but must also be present within one strip
  - low charge for hits between columns of the same strip
- Reason is field configuration
  - charges drift mainly sideways to/away from columns
  - low field means slow hole drift to backside, t_{drift} >25ns
- This is an effect of STC design
- Given sufficient statistics and resolution, this could be visible in Test Beam analysis



IR-Laser

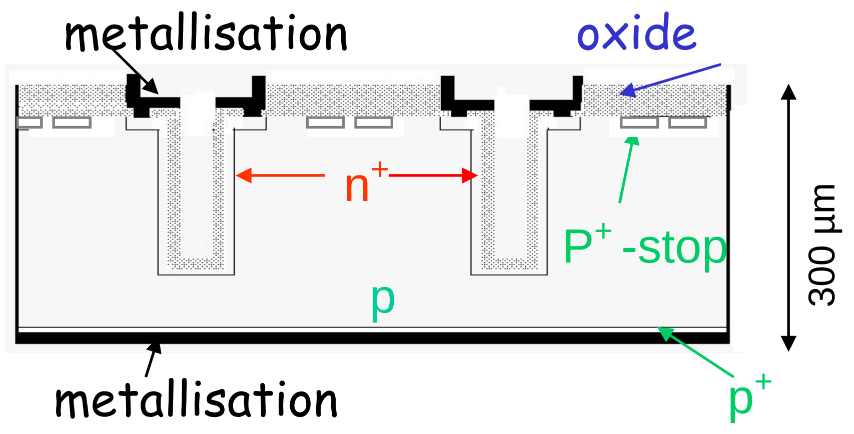




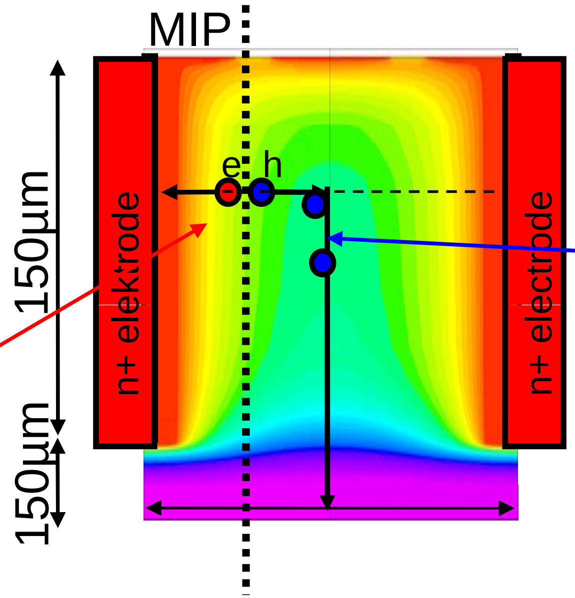
3D Single Type Columns Design

- Single Type Column (STC) 3D design:
  - Columns not completely etched through wafer → no support wafer necessary
  - STC sensors made by FBK-irst (Trento)
- Processing less complex and costly compared to standard 3D
- Si bulk can be n-in-p material
  - no type-inversion
  - Collection of e^- (faster, less trapping)
  - Wafers: Czochralski or Floatzone-Si
  - P-spray or p-stop isolation (to avoid conductive layer between n-implants)
- Low field region exists (slow drift)
  - field given by doping level (not U_{bias})
  - LHC is fast, so expect reduced CCE at 40 MHz
  - 3D STC strip designs interesting for innermost strip layers
  - 3D STC strip detectors are ***"like planar strips plus columns under the strips"***

Cross section between two electrodes:



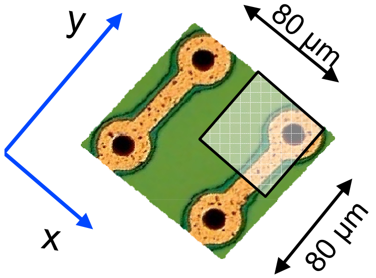
Piemonte et al. NIMA 541 (2003) 441



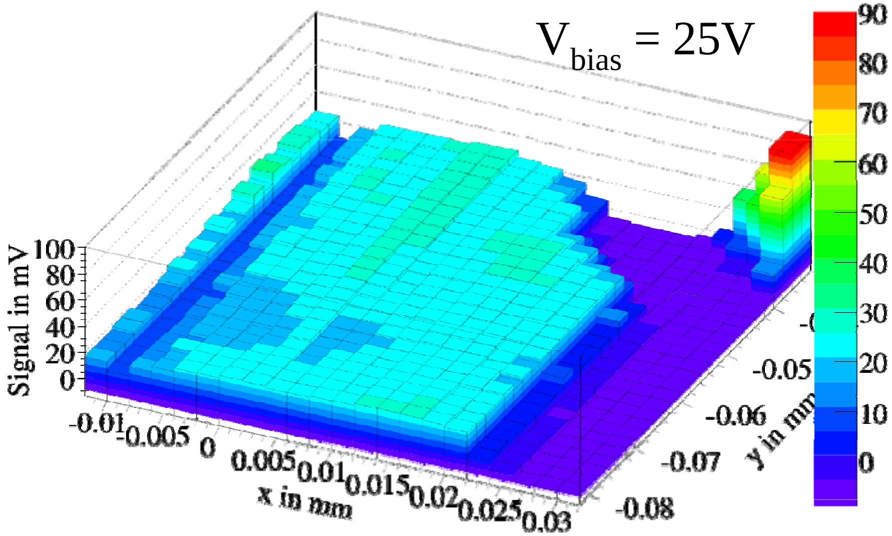
Electrons are swept away by the transversal field

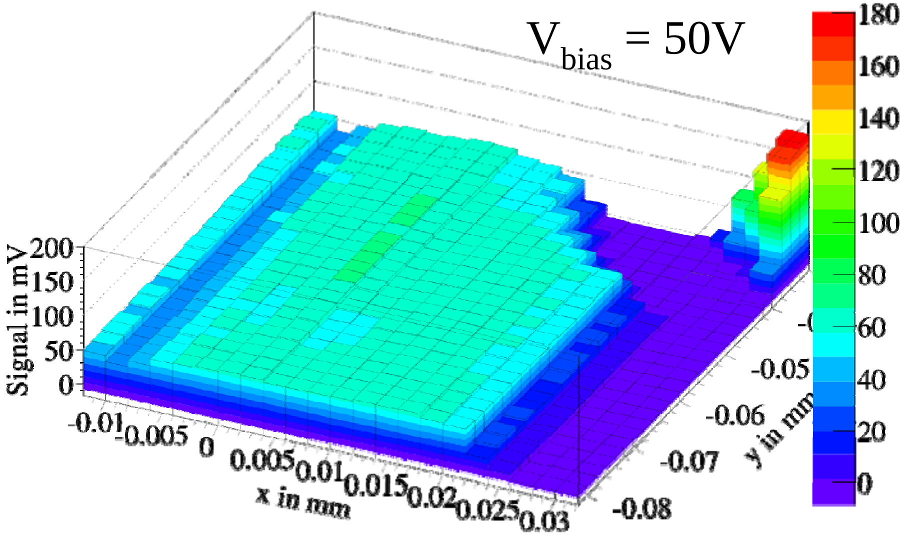
Holes drift in the central region and diffuse towards backside contact

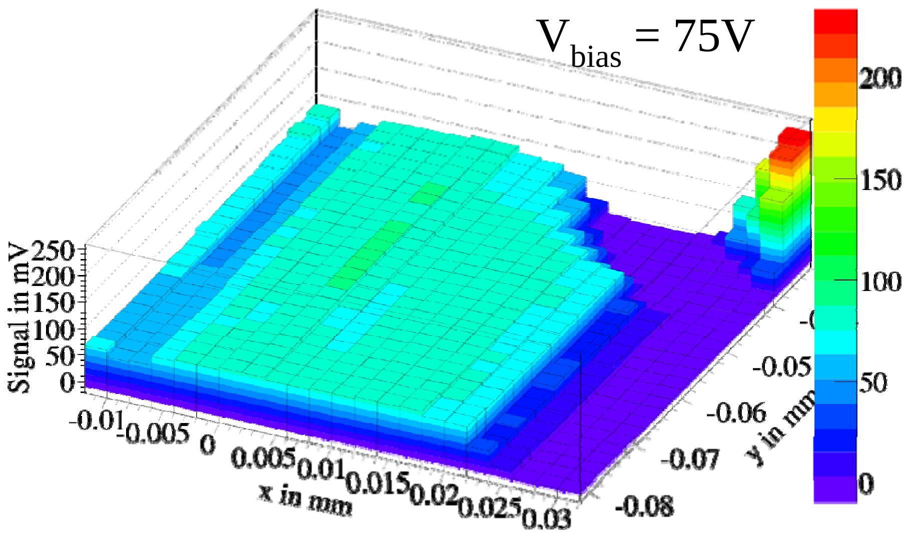
High Resolution Laser Scan



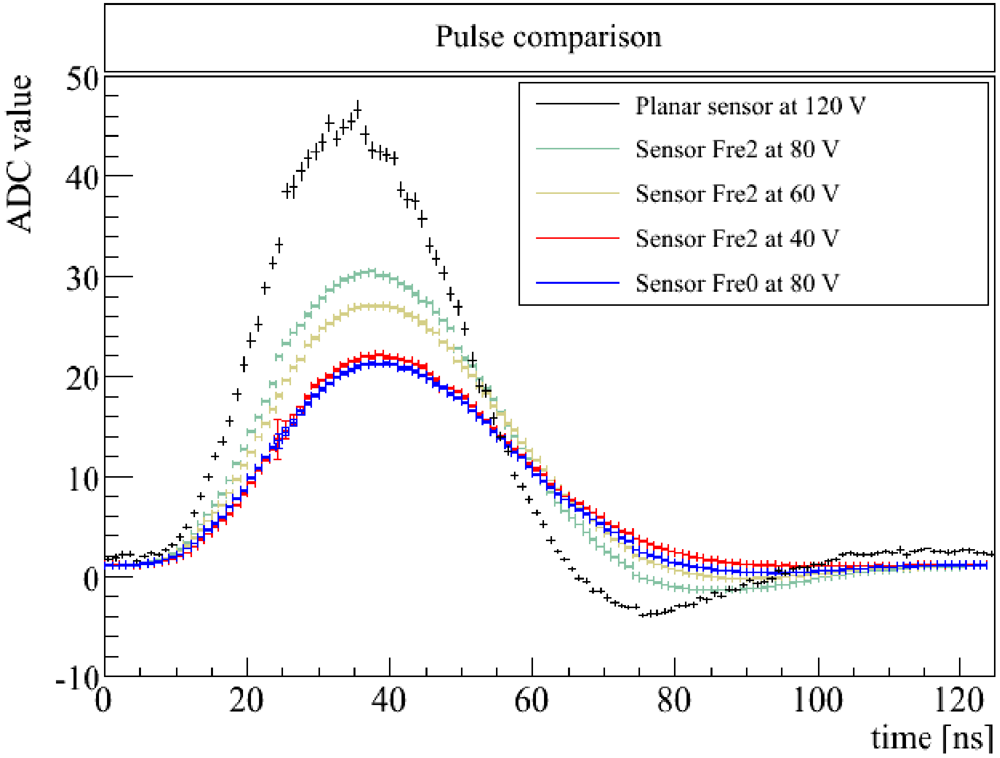
- *2μm step size*
- *50μm×50μm area*
- *y-axis along the strips*
- *At variable bias voltage*

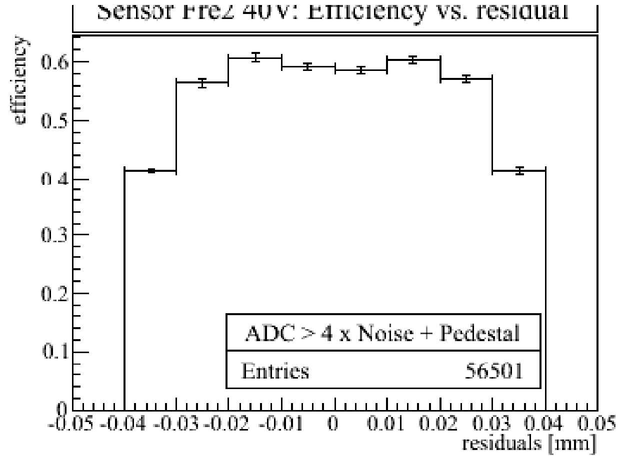


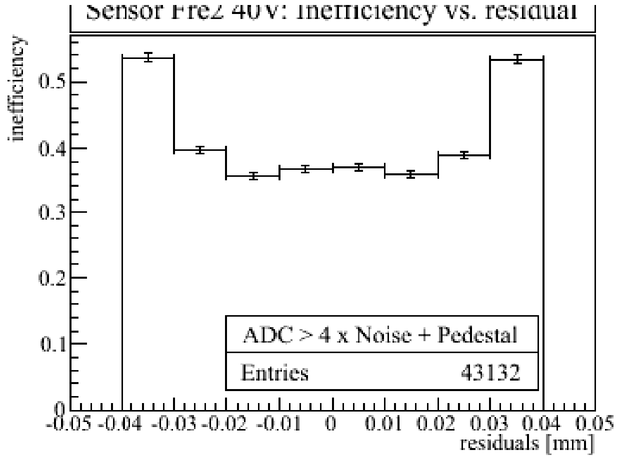




– Width independent of bias for V_{bias} > 25V


Pulse comparison
ADC value
time [ns]
Planar sensor at 120 V
Sensor Fre2 at 80 V
Sensor Fre2 at 60 V
Sensor Fre2 at 40 V
Sensor Fre0 at 80 V
-10
0
10
20
30
40
50
0
20
40
60
80
100
120


Sensor Fre2 40V: Efficiency vs. residual
efficiency
residuals [mm]
ADC > 4 x Noise + Pedestal
Entries 56501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inefficiency
residuals [mm]
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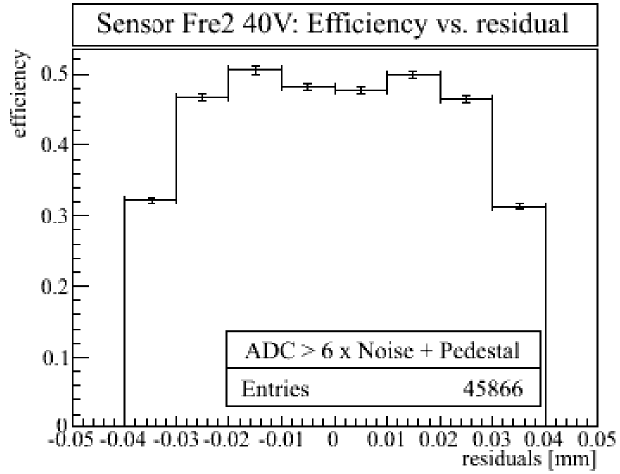
Entries 43132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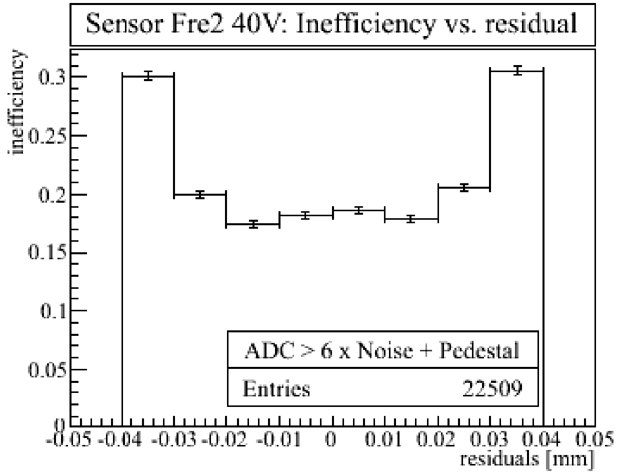
efficiency
residuals [mm]
ADC > 6 x Noise + Pedestal
Entries 45866


Sensor Fre2 40V: Inefficiency vs. residual
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residuals [mm]
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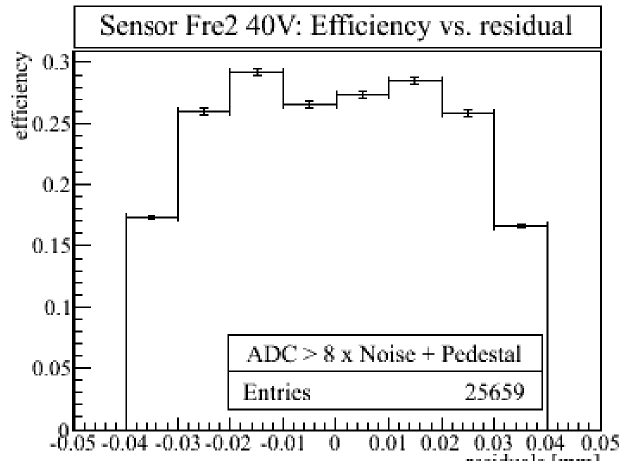
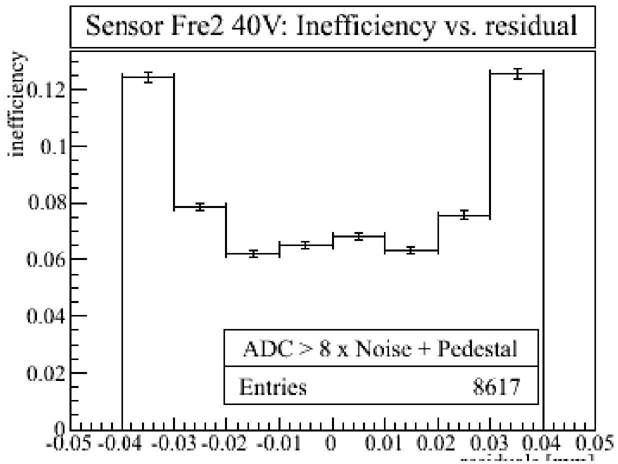
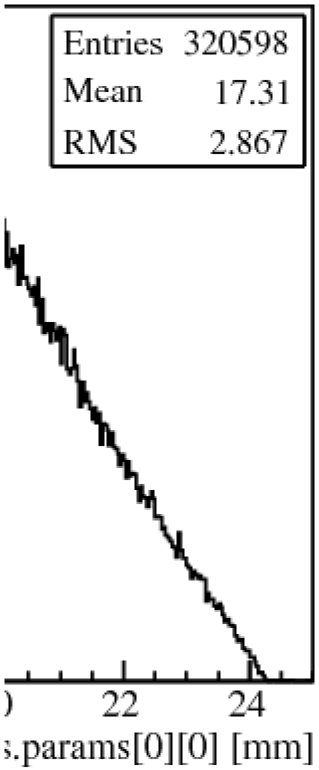
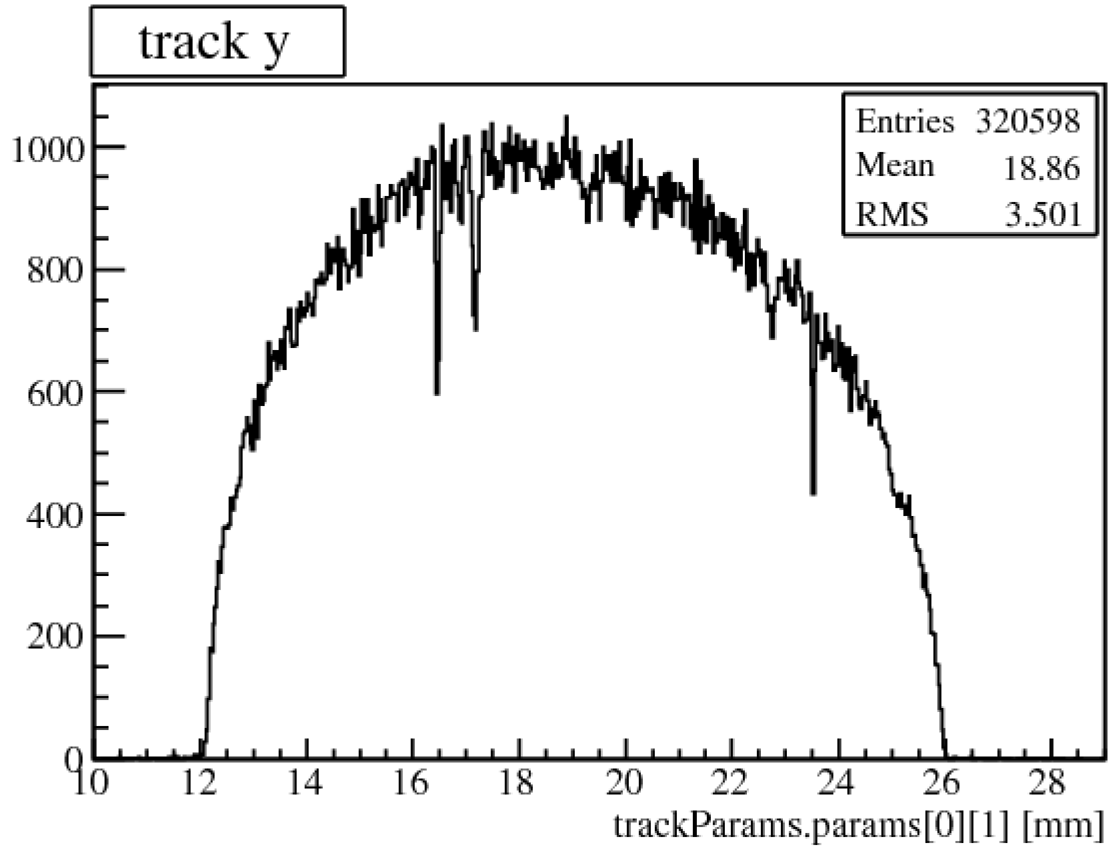
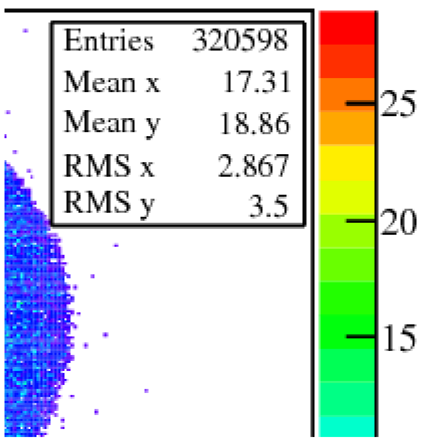
Entries 22509

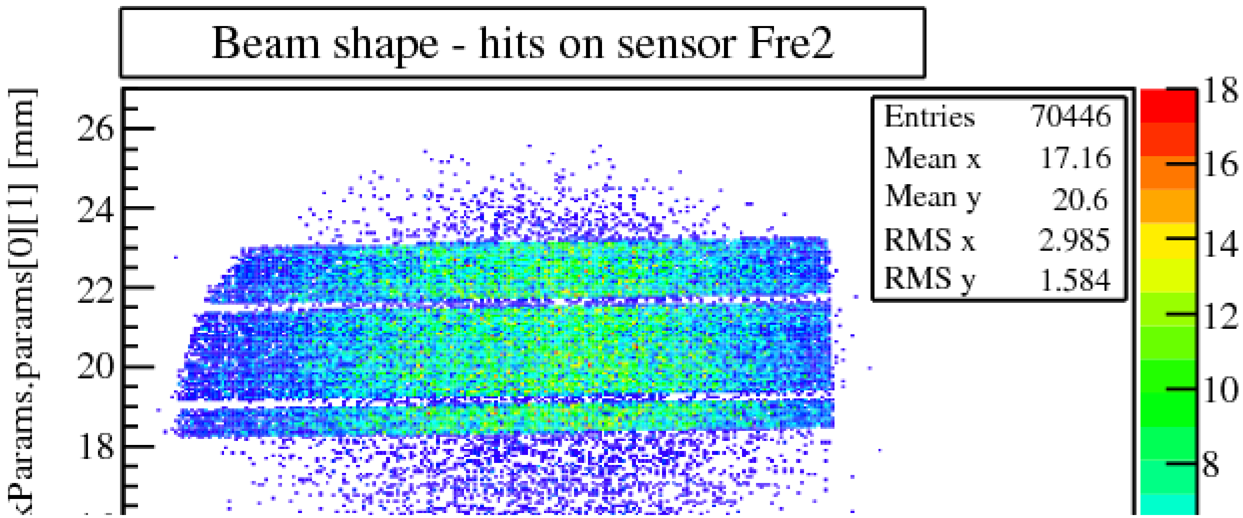

Sensor Fre2 40V: Efficiency vs. residual
efficiency
ADC > 8 x Noise + Pedestal
Entries 25659


Sensor Fre2 40V: Inefficiency vs. residual
inefficiency
ADC > 8 x Noise + Pedestal
Entries 8617


Entries 320598
Mean 17.31
RMS 2.867
22
24
s.params[0][0] [mm]

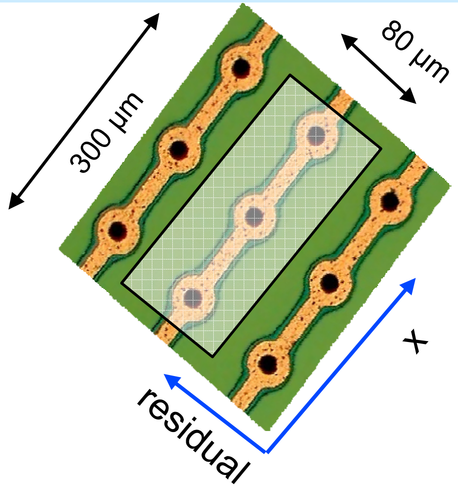

track y
Entries 320598
Mean 18.86
RMS 3.501
1000
800
600
400
200
0
10
12
14
16
18
20
22
24
26
28
trackParams.params[0][1] [mm]


Entries 320598
Mean x 17.31
Mean y 18.86
RMS x 2.867
RMS y 3.5
25
20
15


Beam shape - hits on sensor Fre2
Entries 70446
Mean x 17.16
Mean y 20.6
RMS x 2.985
RMS y 1.584
kParams.params[0][1] [mm]
26
24
22
20
18
16
14
12
10
8

Efficiency

- Repeat study also in 2D
- Fold all data onto one small cell (80µm x 300 µm)
- Inter-strip regions coincide with steep drop to lower efficiency



- Columns just about visible as low efficiency areas?
- Testbeam analysis still ongoing with improved tracking, re-alignment and more statistics