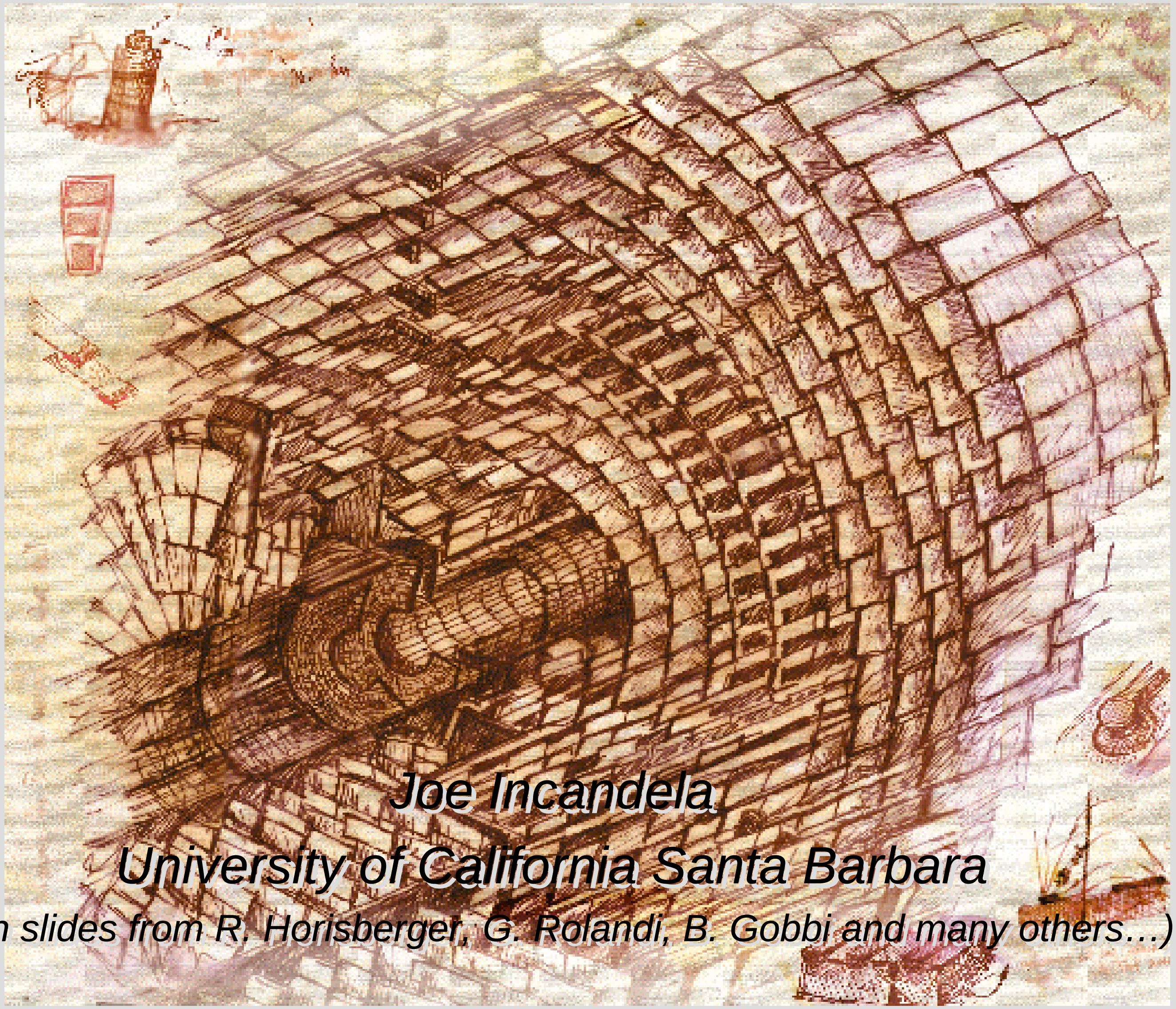
The CMS Tracking Detectors

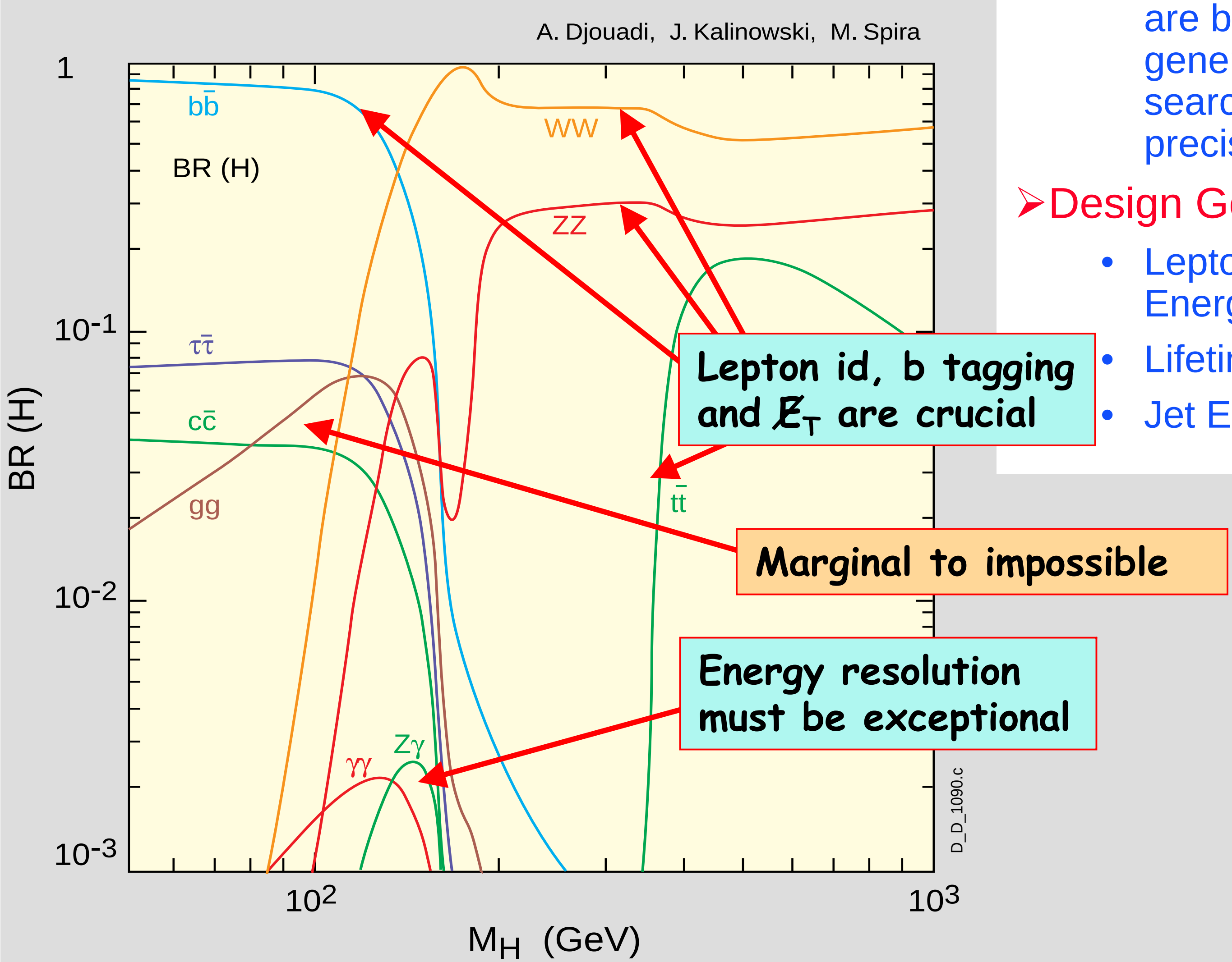


Joe Incandela

University of California Santa Barbara

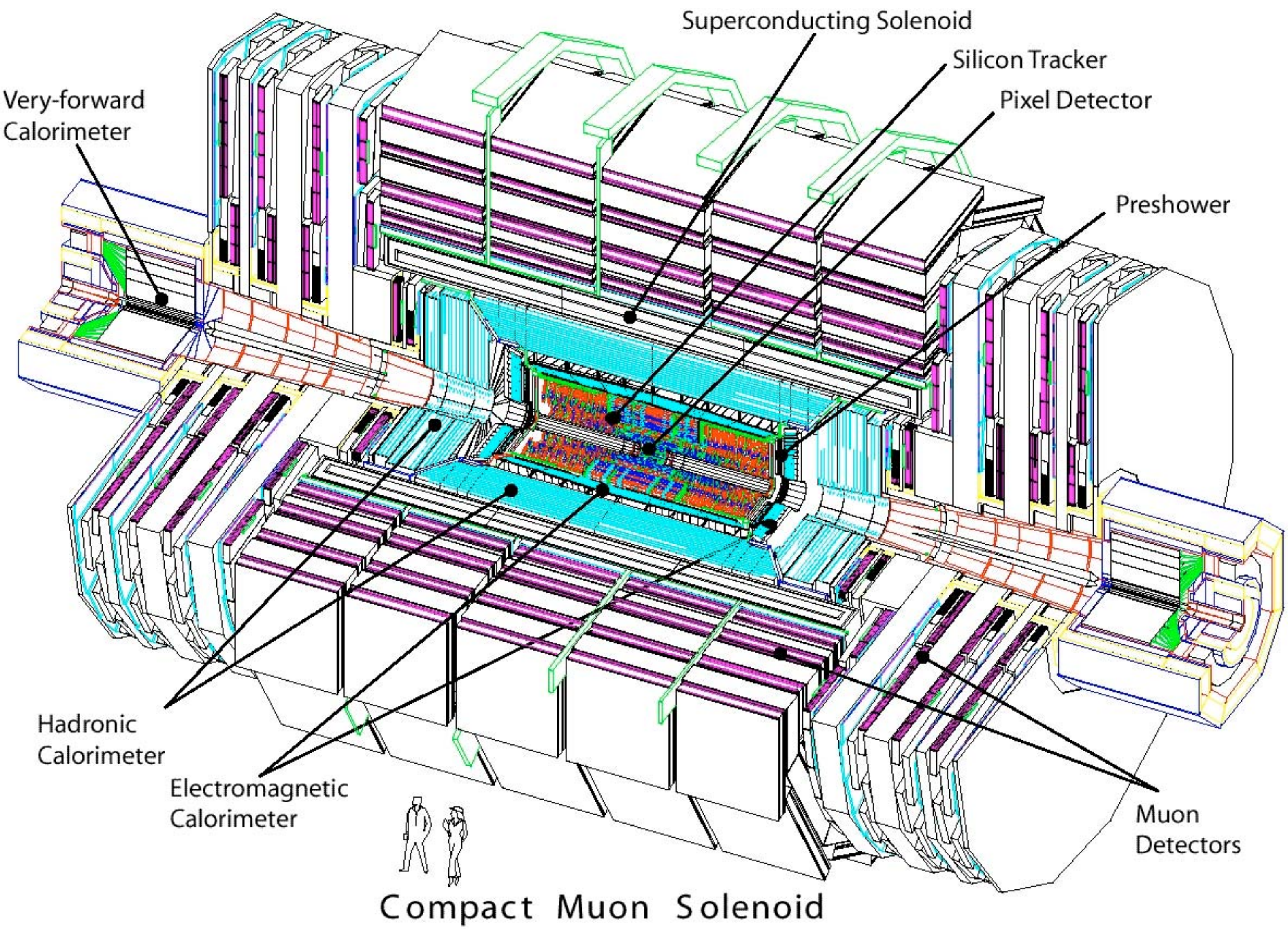
(with slides from R. Horisberger, G. Rolandi, B. Gobbi and many others…)

Design Criteria

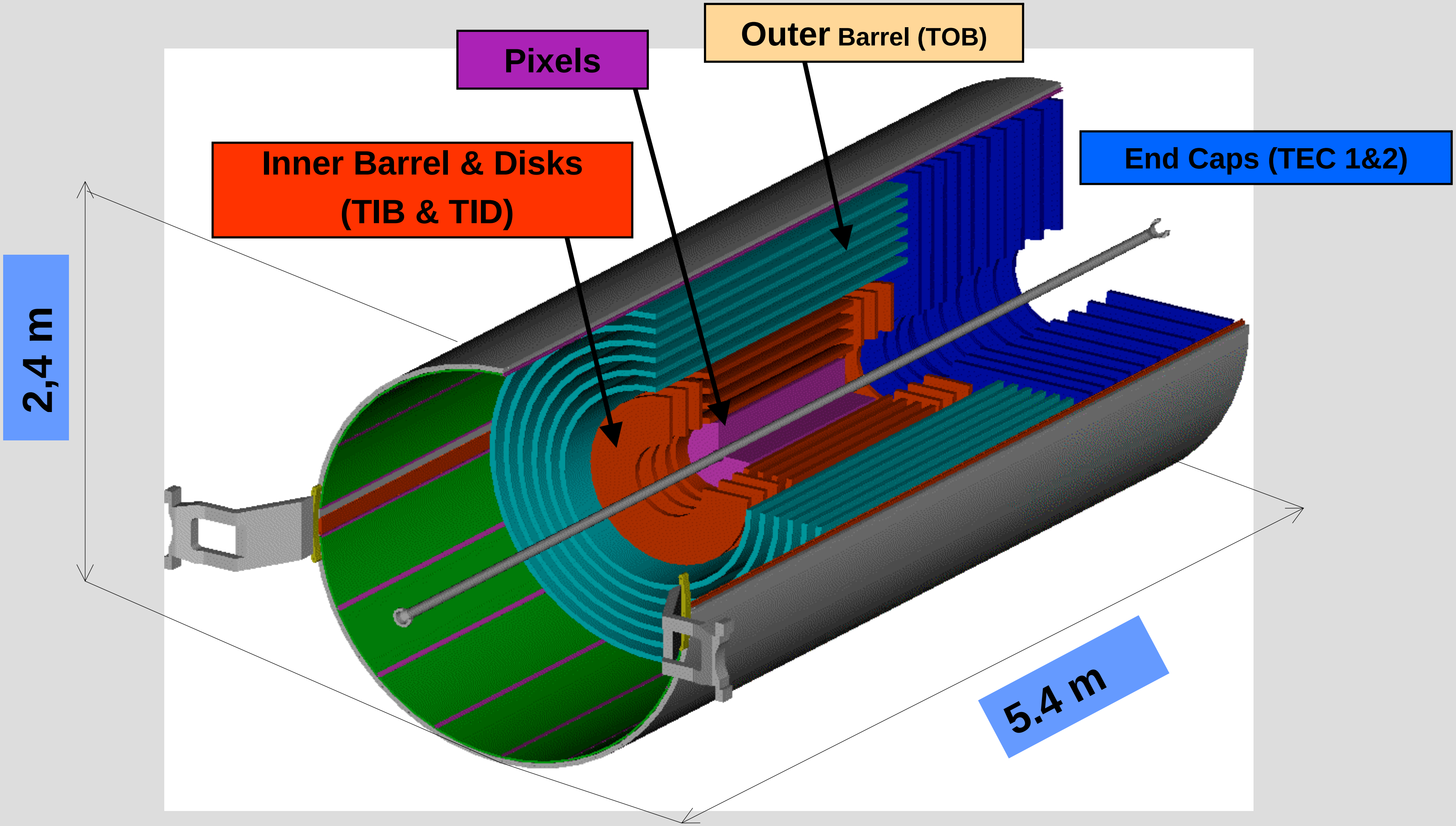


- **Higgs as benchmark**
  - Notably Higgs' requirements are broad and somewhat generic - hence applicable to searches for new physics or precision SM measurements
- **Design Goals**
  - Lepton & photon ID and Energy resolution
  - Lifetime tagging
  - Jet Energy and MET resolution

Compact Muon Solenoid

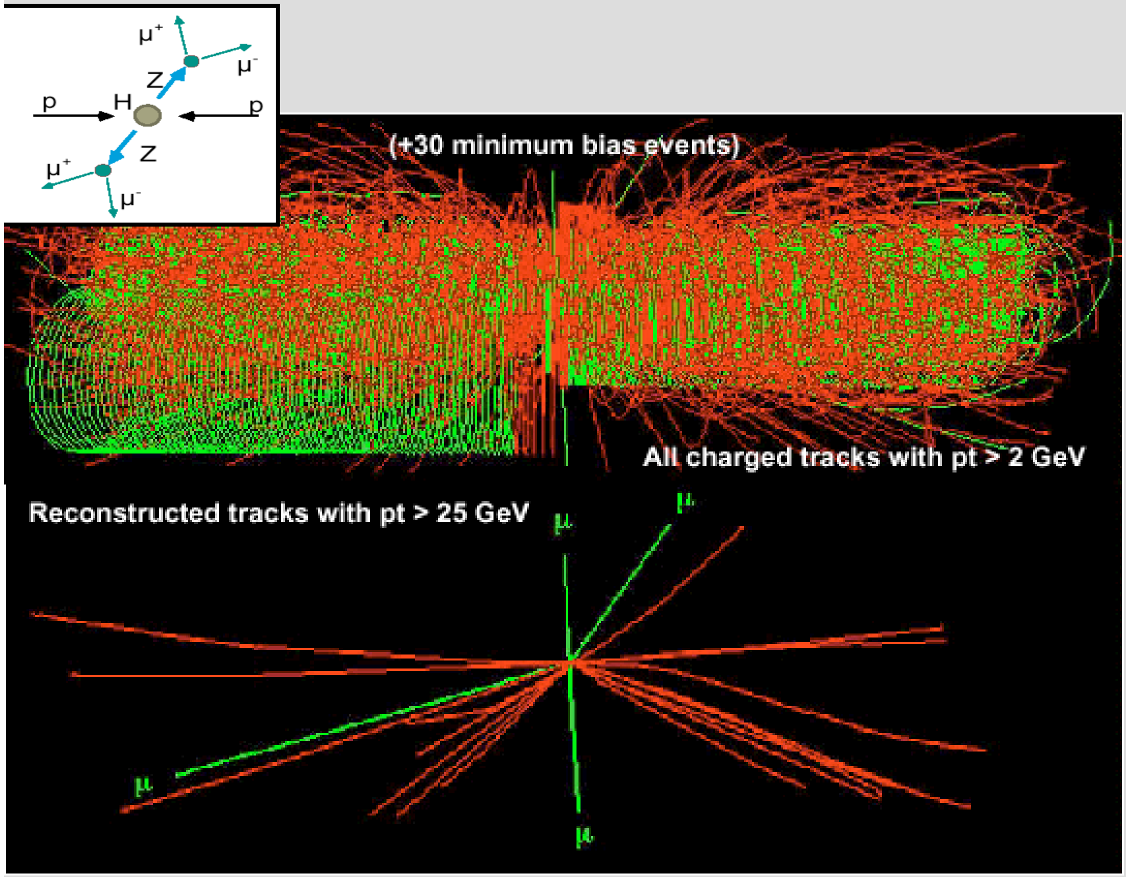


CMS Tracker



Pixels
Outer Barrel (TOB)
Inner Barrel & Disks (TIB & TID)
End Caps (TEC 1&2)
2,4 m
5.4 m

Tracking Goals

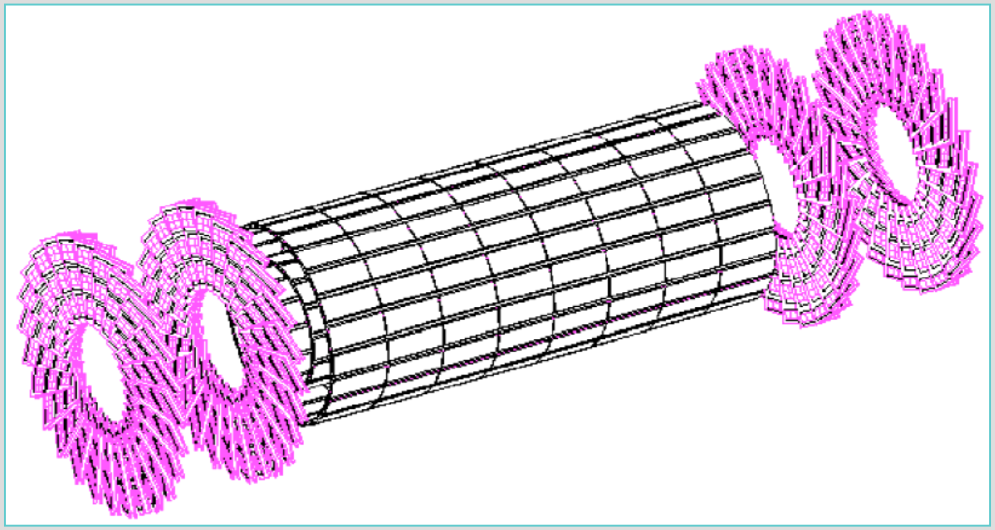


- Efficient & robust Tracking
  - Fine granularity to resolve nearby tracks
  - Fast response time to resolve separate bunch crossings
  - Radiation tolerance

- High pt tracks and jets
  - ~1-2% P_T resolution at ~100 GeV (for μ's)

- Lifetime tag of b,c,τ
  - Asymptotic: σ_d ~ 20μm

Pixels: Design Considerations



Why Pixels ?

*This is why we **like** them*

High resolution 3D space points

Granularity

- Peak occupancy ~ 0.01 %
  - Good starting point for tracking

*This is why we **need** them*

Radiation tolerance

CMS

- 45 million channels
- Radii: 4, 7 and 11 cm
- Full Pseudorapidity coverage to 2 and partial to 2.5

Other Considerations

• TDR: Replace Pixels after $6x10^{14}/cm^2$ (…may live longer…)

<u>3 LAYERS</u>: r = 4.3cm 7.2cm 11.0cm $\Rightarrow$ Area Barrel = 0.78 m^2
Disk = 0.28 m^2
Total ~ 1 m^2

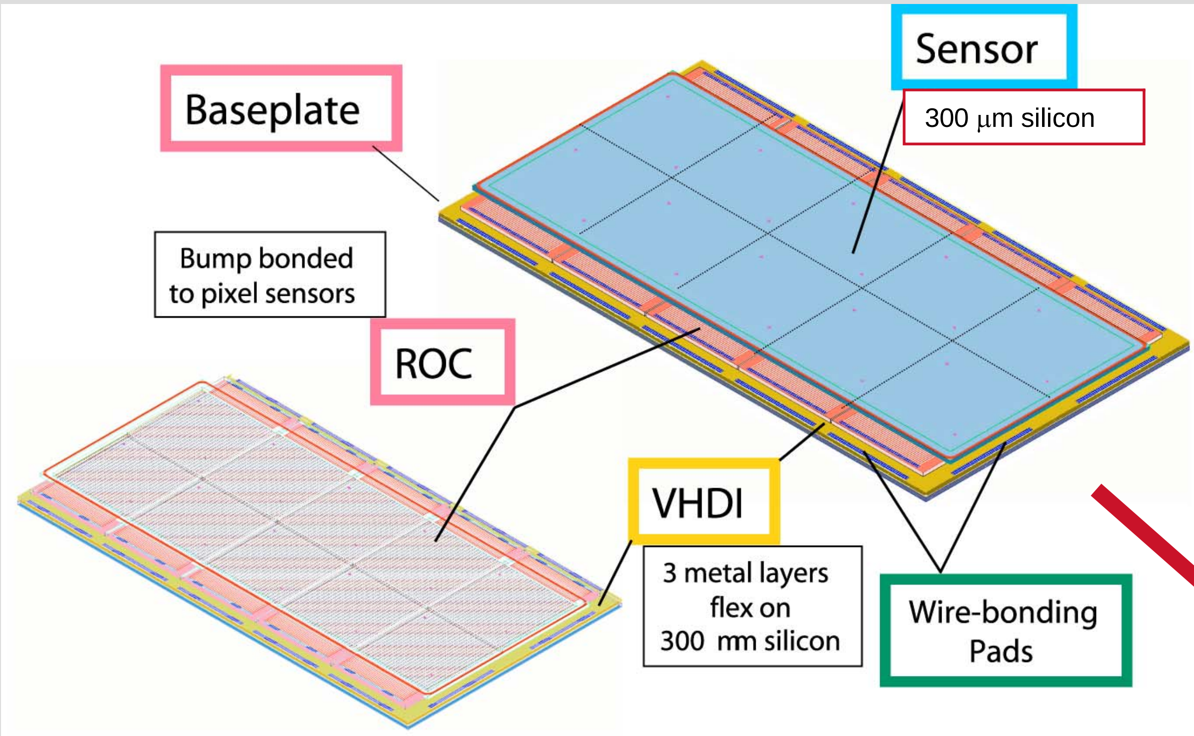
Fluence limited
→ t_{max}~ 2 years

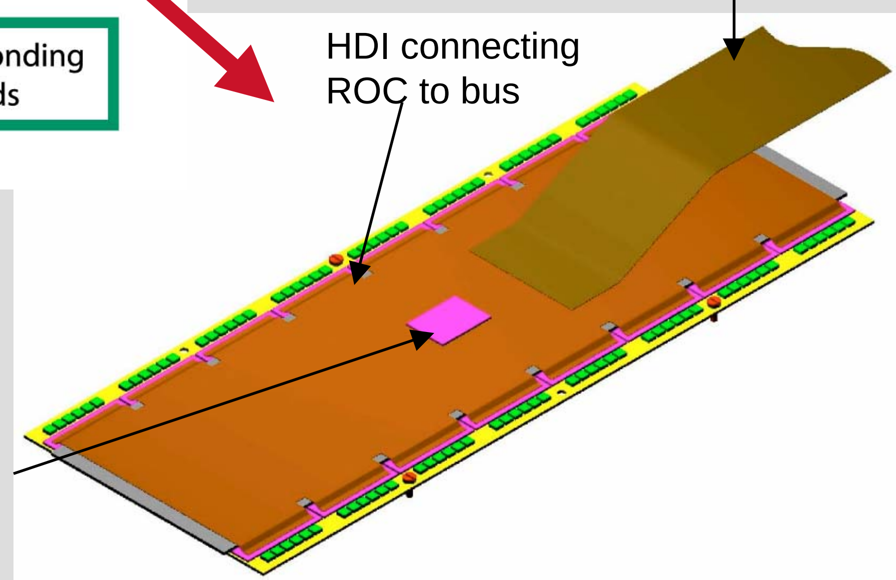
Cost limited !!
→ r_{max}

•400 modules required for both of the inner 2 Layers
•400 modules required for the outer layer alone

•Production of modules scheduled to start in Spring 2005

Pixel Barrel Module





CMS Detector Unit

Sensors (300 μm)

- 150 μm x 100 μm pixel
- Oxygenated n+/n with p-stop isolation.

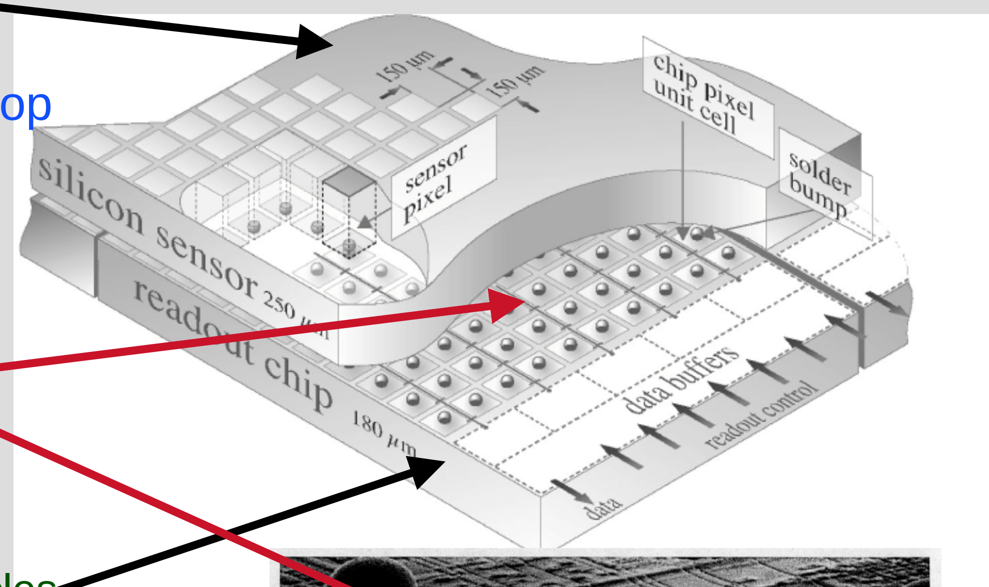
  -10º C operation

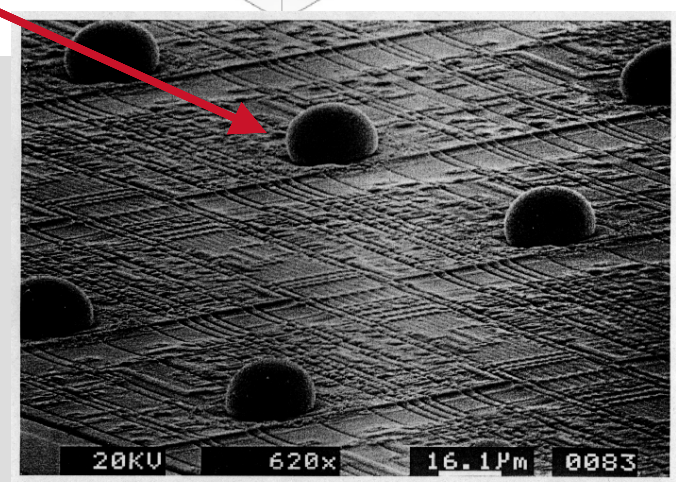
➢Bump bonding

- 25 μm PbSn, Indium
- Failure Rates
  - ~ 1.5 E-6
  - ~ 6E-6 after 50 thermal cycles

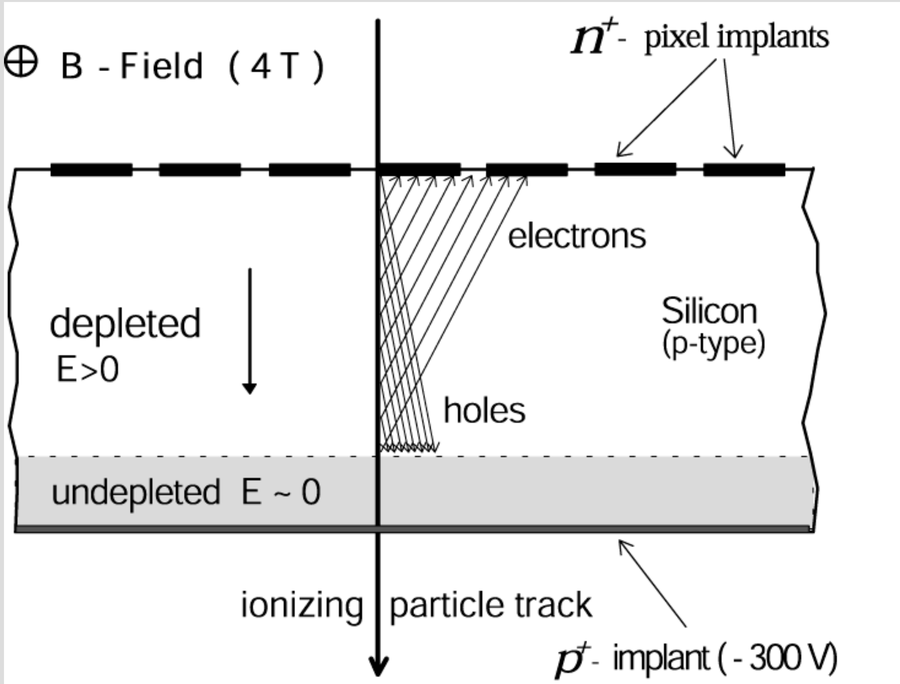
➢Readout Chip (ROC)

- 0.25 μm bulk CMOS
  - Rad-tolerant
  - SEU tolerant
- 40 MHz standard operation





Sensor



- **Operation**
  - Collect electrons w/ 34º drift
- **Radiation tolerance**
  - Depletion starts at pixels
  - Signal/noise high
    - Capacitance ~ 80 fF (~ 500 e)
    - Signal ~ 11000 e per 150 μm
- **Status**
  - **CiS** and **Sintef** detectors tested at CERN H2 testbeam ('03) for irradiation fluences up to 10^{15} cm^{-2} .

Preliminary results are available:

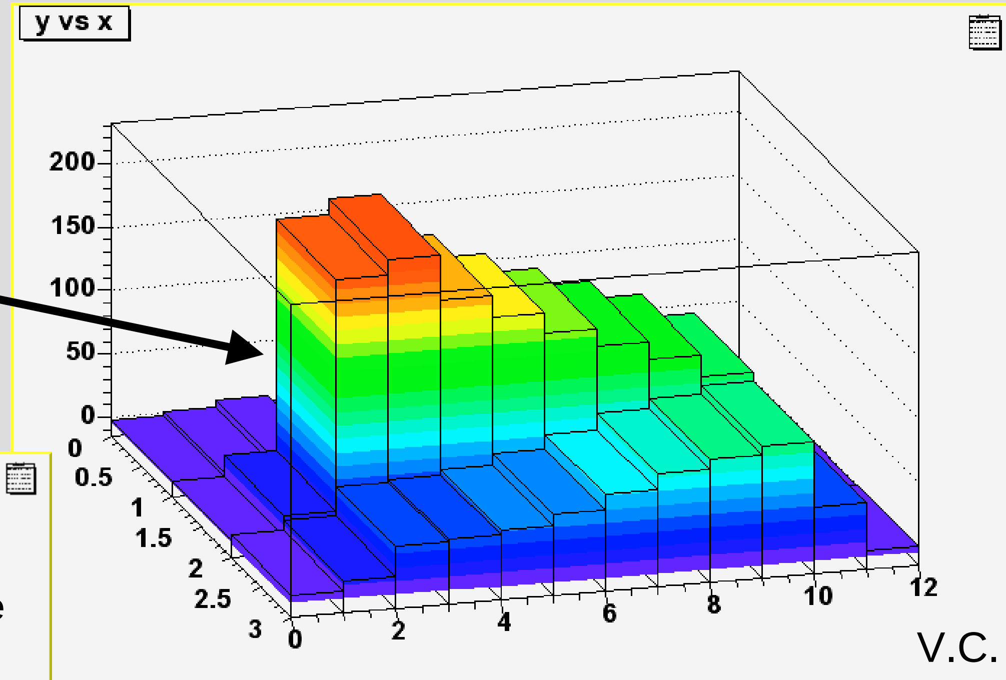
Depletion depth and trapping (grazing angle of 15º in zero field)

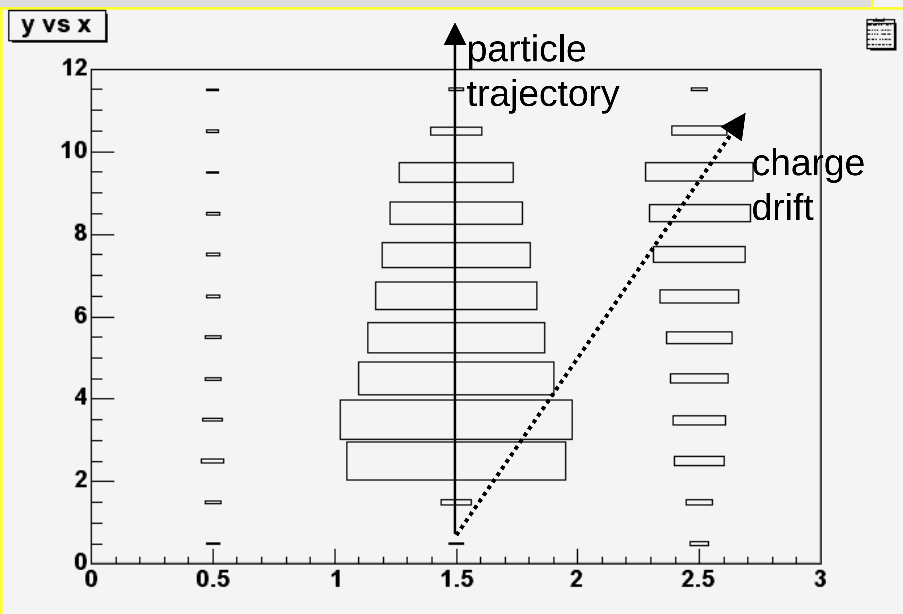
Lorentz angle and cluster shape (grazing angle of 15º and 3 T field, irradiated and non-irradiated detectors)

Lorentz Angle

Dot-1 (CiS)
unirradiated
150 V
3 Tesla
15º grazing angle

incoming particle





Fluence Limits

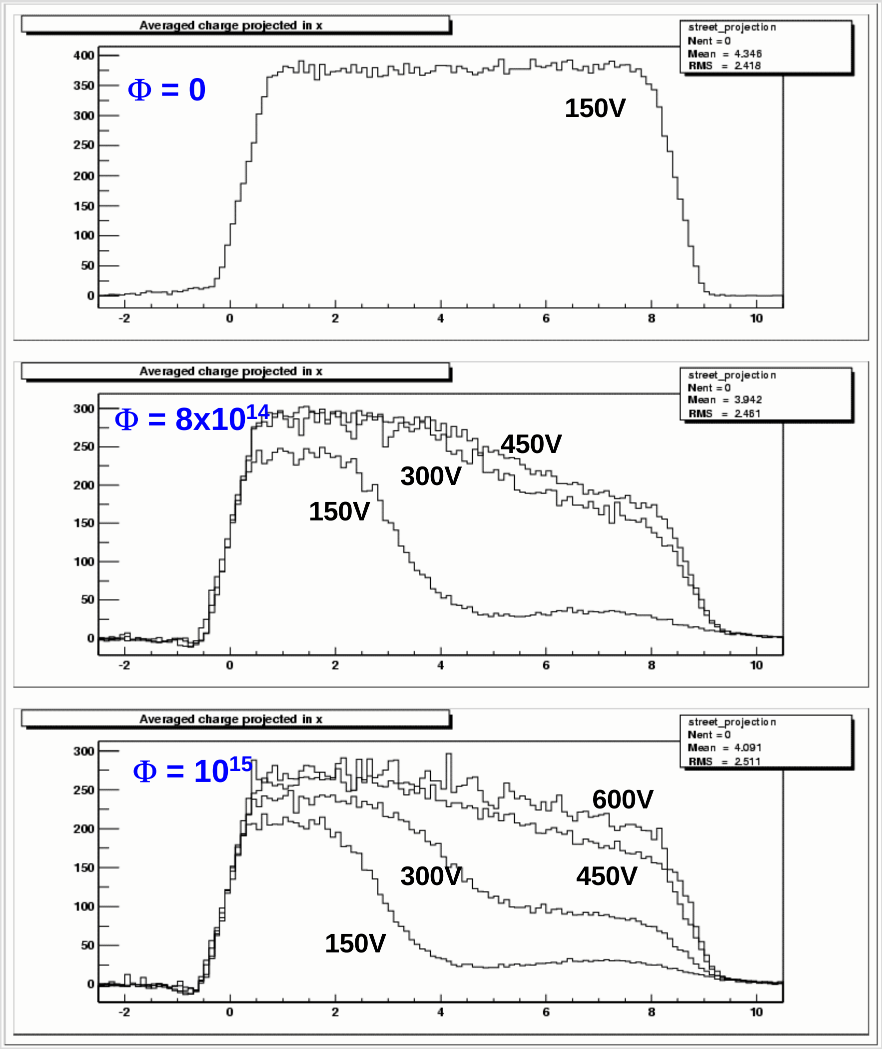
Tilman Rohe, PSI

- Oxygenated CMS pixel sensors
  - Double sided, n+ on n – silicon
  - 285μ thickness

- Test beam at CERN – 2003

  (15º grazing angle of tracks for depletion depth studies)
  - Almost fully depleted at 450V!
  - See trapping !
  - Can likely operate beyond F = 6x10^{14}

    (assumed in TDR)



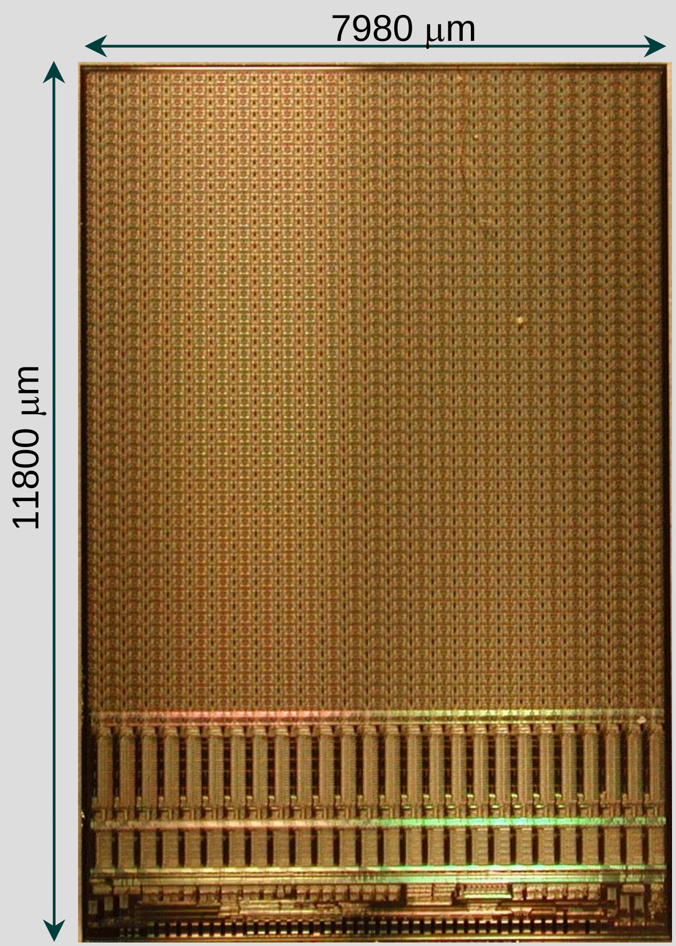
Read Out Chip (ROC) Pixel Unit Cell (PUC)

- Minimal complexity $\Rightarrow$ periphery does most of the work
- Basic pieces
  - Charge sensitive pre-amp and shaper
  - Comparator
    - Have chip-wide threshold and individual pixel trim!
- Note: ROC hit rate ~ 5-10 MHz
  - Column hit rate ~0.5 – 1.0 MHz
    - Determines no. of time stamp registers on periphery
  - On average 2 hit pixels per hit column
    - Determines periphery buffer size

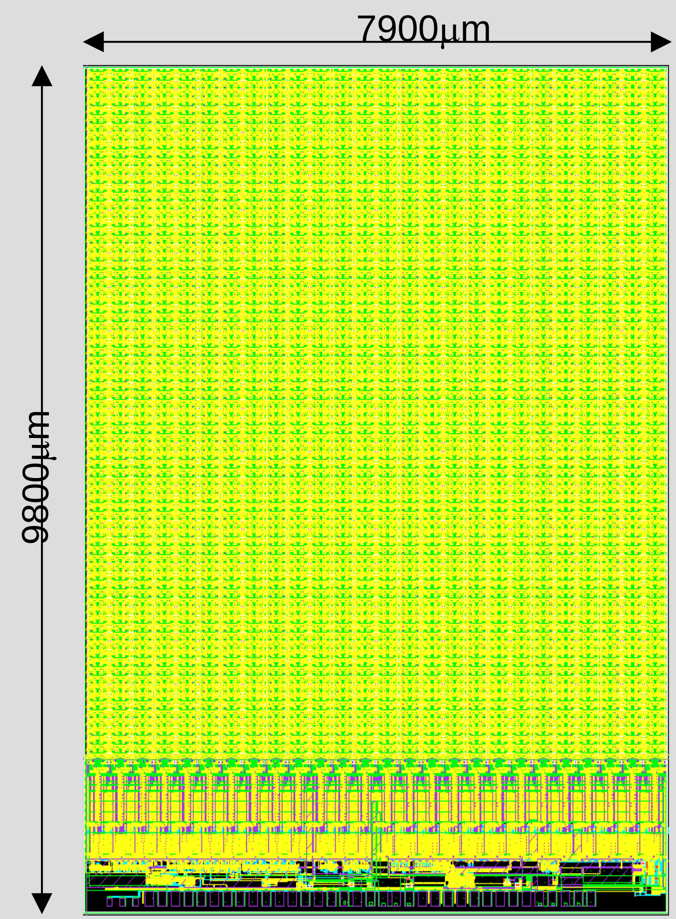
ROC:Translation to 0.25 μm

8 wafers of final architecture DMILL received in April 02 work well

Translation to 0.25 μm started in ’02. First chips were produced and work well !



52 x 53 pixels of 150μm x 150μm, 430k Transistors



52 x 80 pixels of 100μm x 150μm, 1280k Transistors

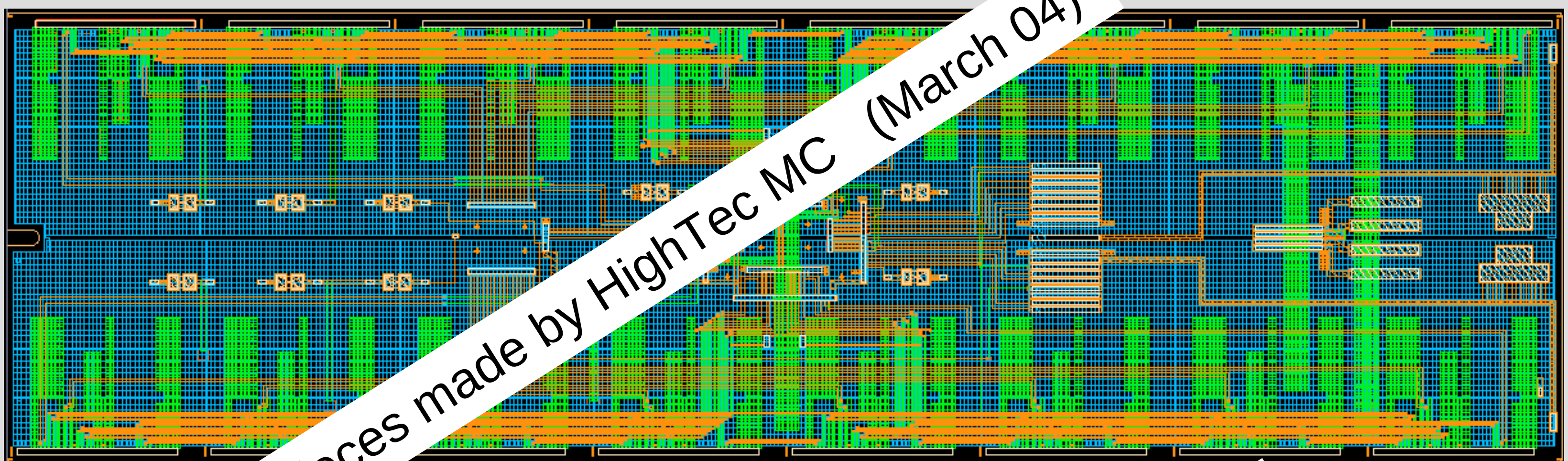
First measurements of new 0.25m ROC

- Overall judgment : Chip works very well !!!
  - max. operating frequency = 74MHz (68 MHz after 12.4Mrad)
  - Uniformity of address levels is now very good.
  - Chip irradiated to 25Mrad works fine.
    - See shift in band-gap reference (CERN design target was 1Mrad)
    - New Band gap variations designed and under evaluation now
- Low power dissipation: 29 μW/pixel
  - (cf. 67 and 99 μW/pixel for ATLAS and ALICE)
- New features
  - Column Drain 3rd hit capability
  - More timestamp & data buffers

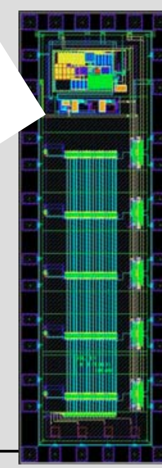
    ⇒Data loss rate drops from ~5% to less than 1% !

HDI for new DSM Pixel ROC

- 3 layers
- Improve mounting and bonding capability (lesson of 1st iteration)

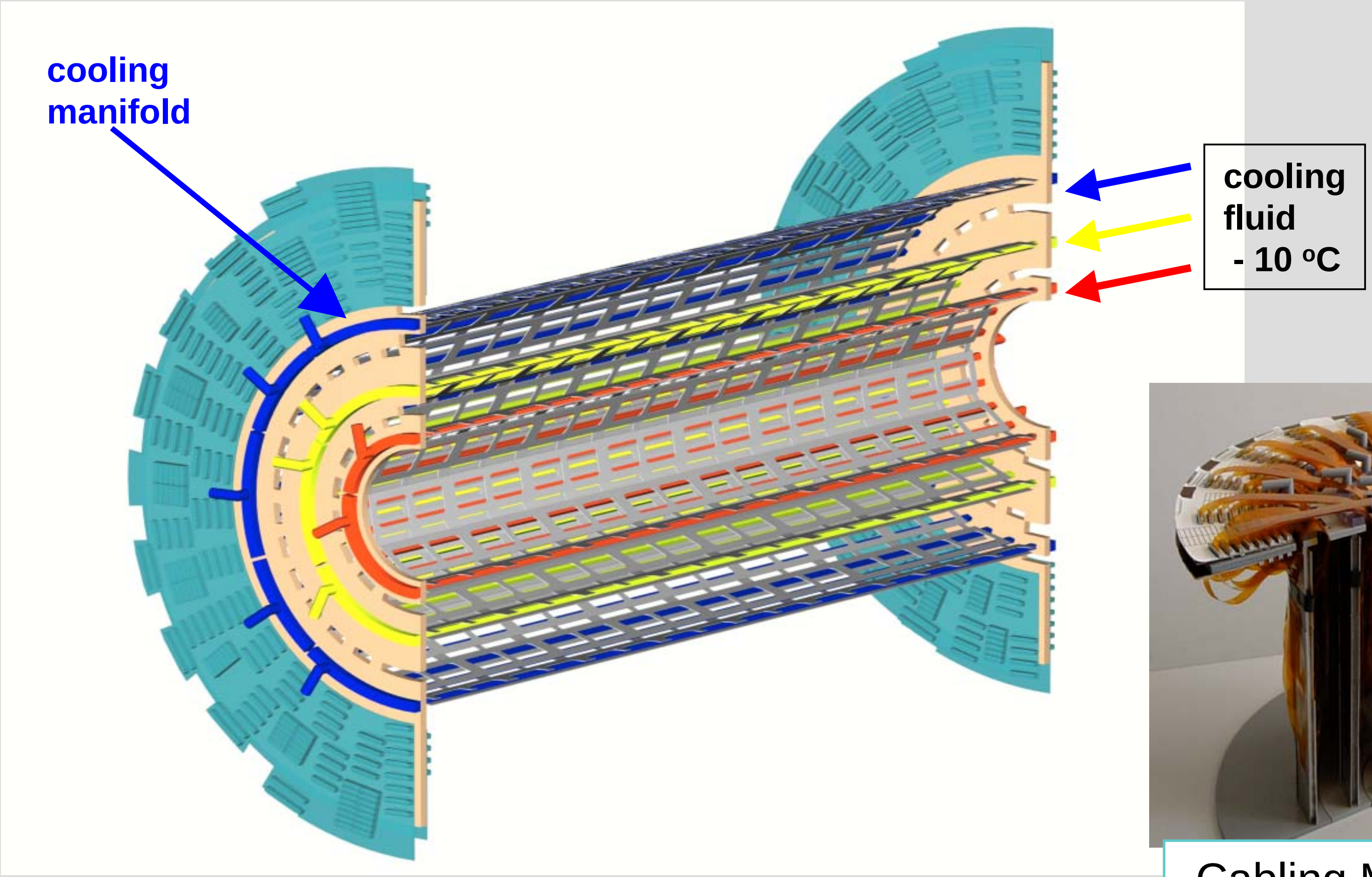


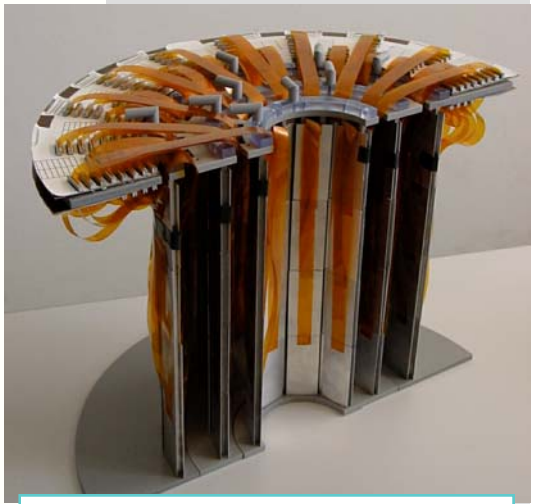
40 pieces made by HighTec MC (March 04)



Kapton-Cable-Driver Chip
also well advanced

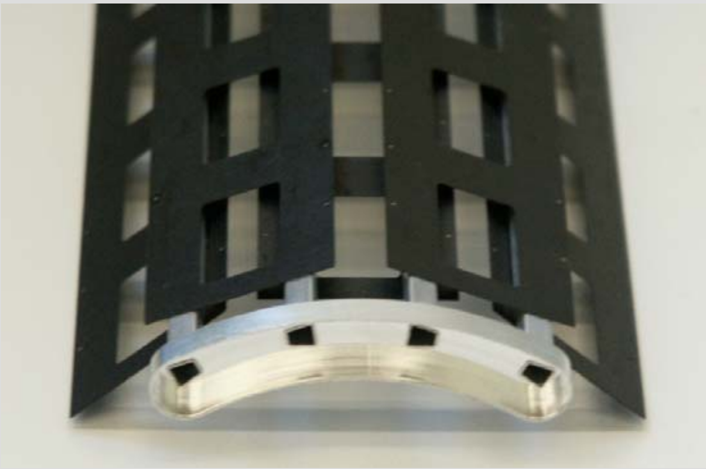
Barrel Mechanics





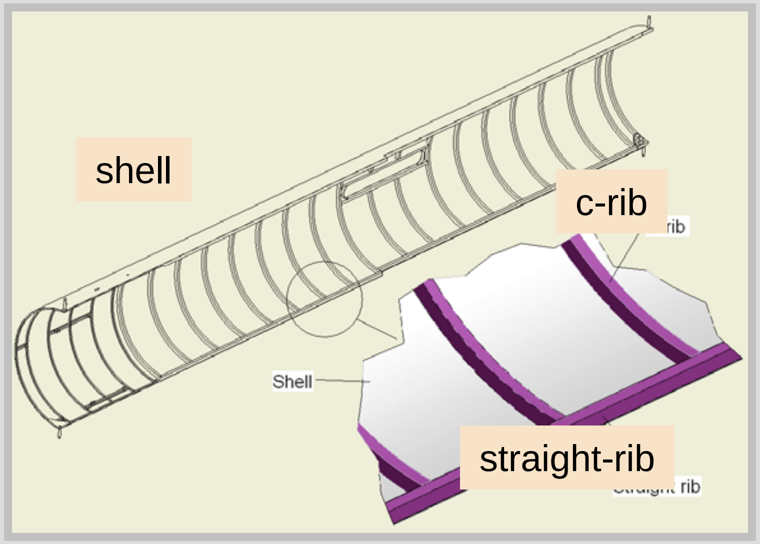
Cabling Mockup

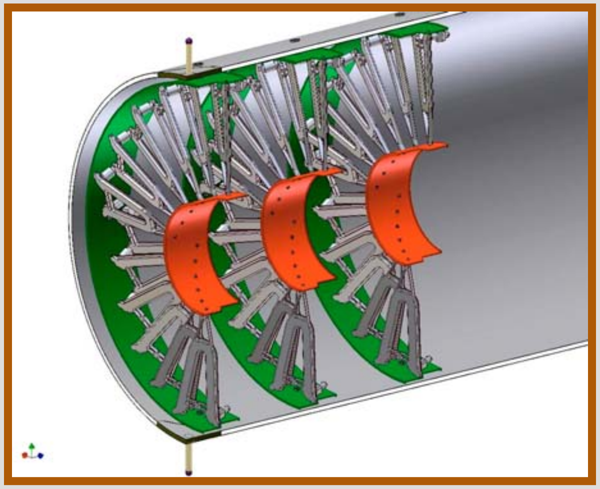
Barrel Mechanics: No Longer Virtual



FPix Mechanics (Status May ’04)

- Service Cylinder
  - Section assembled, tested, extensive FEA



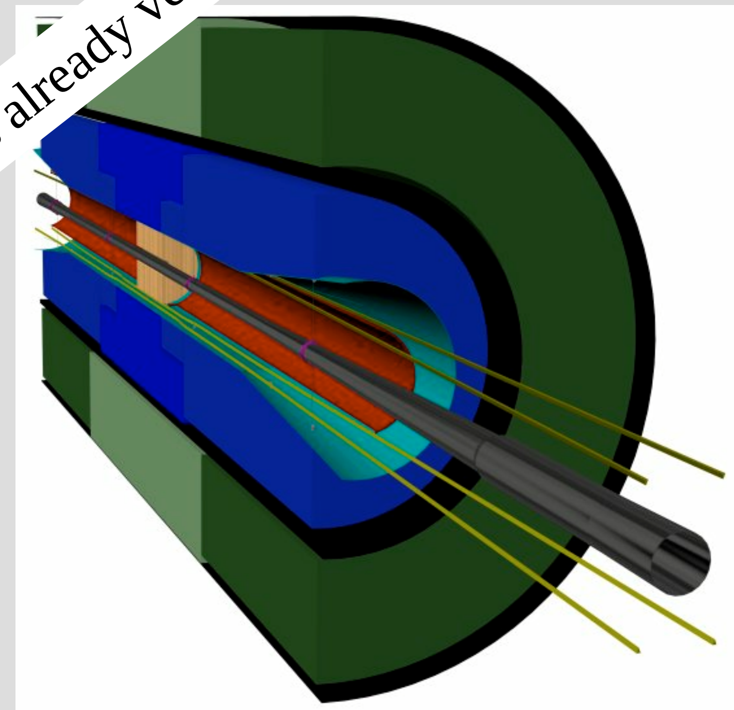


  - Prototype ready by Fall ’04
- ½-Disk
  - Order prototype by end ‘04

Pixel Installation

- Pixel detector is last to install (…we hope…)

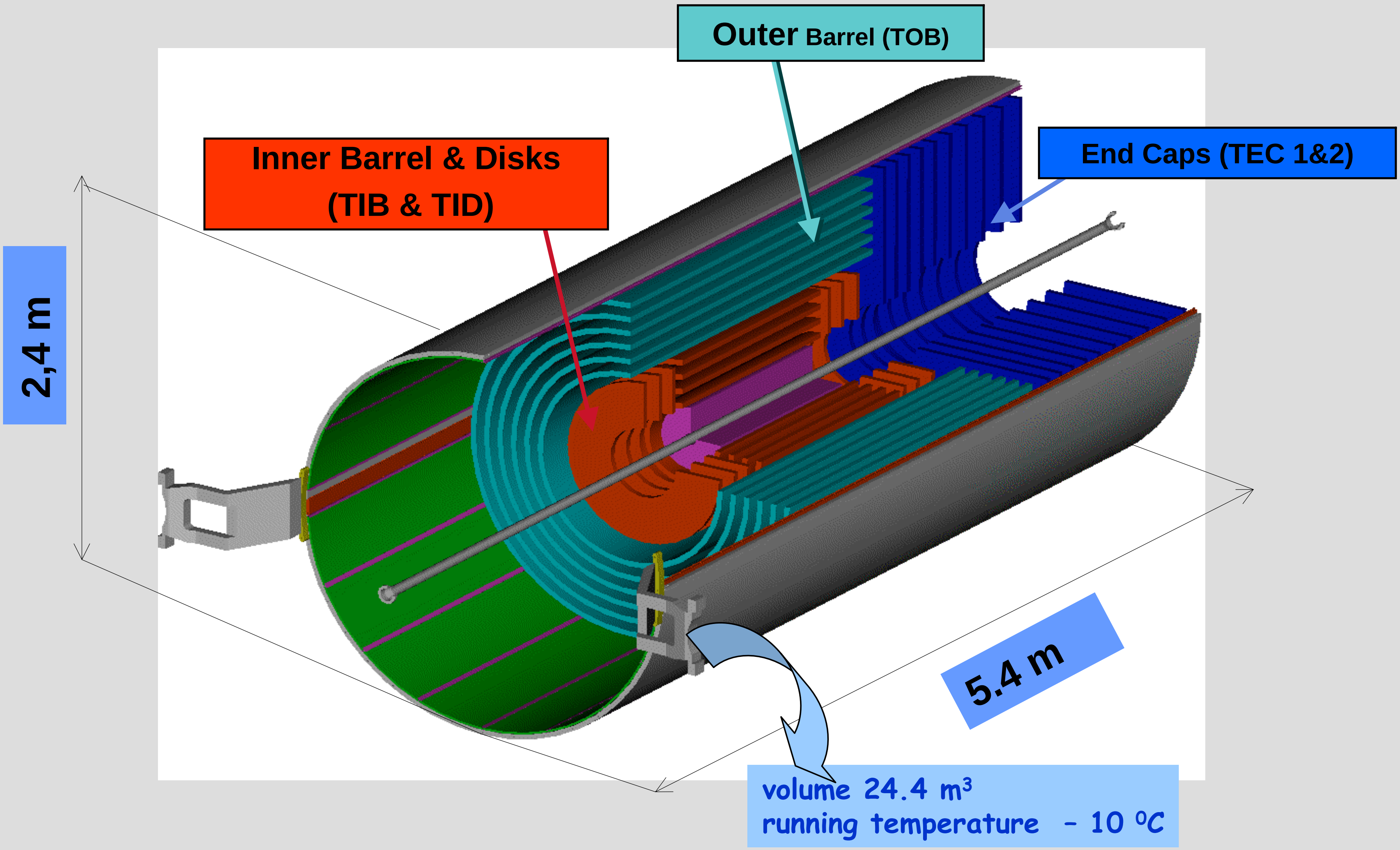
Installation is already very well understood!



- Mechanical model for pixel insertion & cabling tests

Focus now is on the supply tube

210 m^2 of Silicon Strips



CMS Technical proposal

"The design goal of the central tracking system is to reconstruct isolated high pt tracks with an efficiency of better than 95% and high pt tracks within jets with an efficiency better than 90%.."

"The momentum resolution required for isolated charged leptons in the central rapidity region is

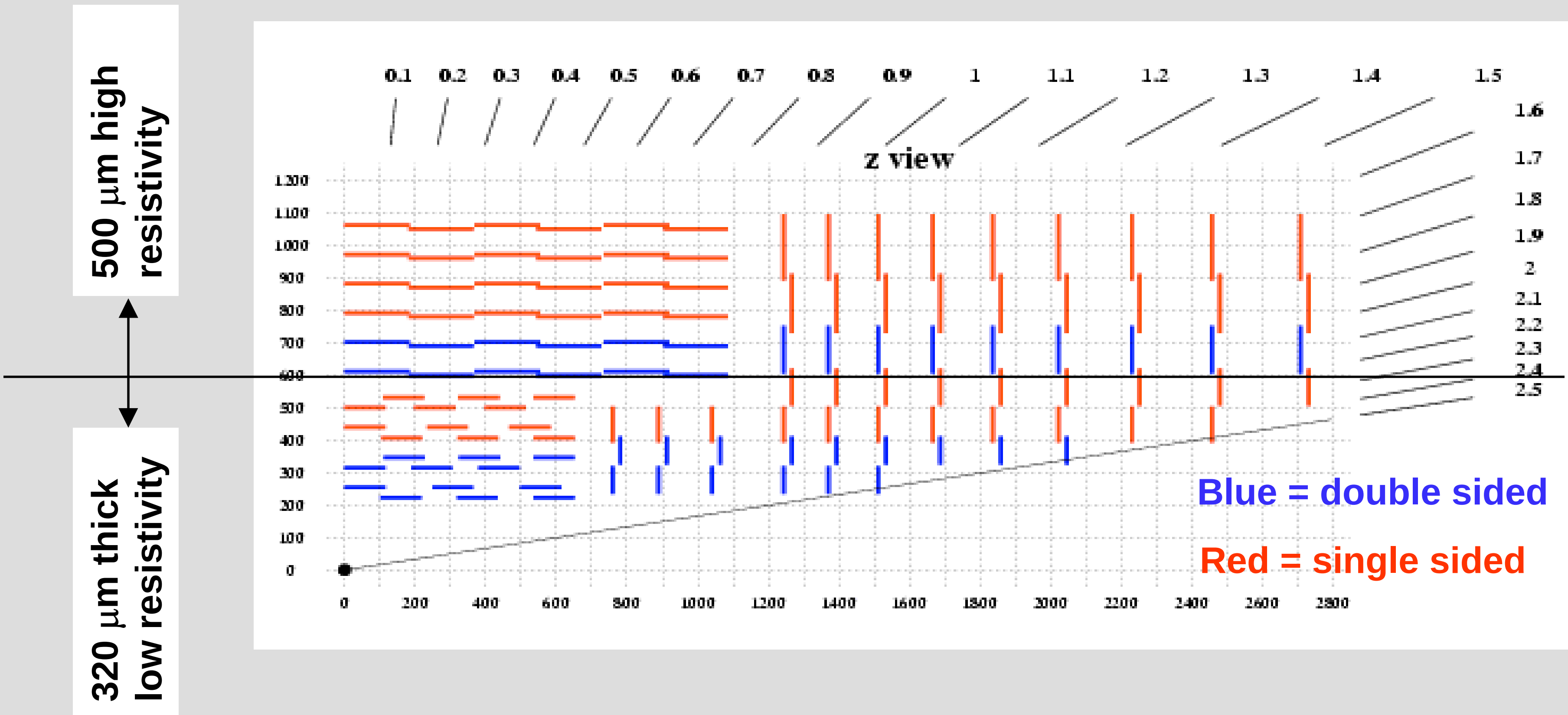
$$\Delta p_T/p_T = 0.1\ p_T\ (\text{TeV})..\text{"}$$

$\Rightarrow$ $Z \rightarrow \mu+\mu-$ with $\Delta m_z < 2$ GeV up to $P_z \sim 500$ GeV

12 layers have momentum resolution:

$$\boxed{\frac{\Delta p}{p} \approx 0.12\left(\frac{pitch}{100\,\mu m}\right)^{1}\left(\frac{1.1m}{L}\right)^{2}\left(\frac{4T}{B}\right)^{1}\left(\frac{p}{1Tev}\right)}$$

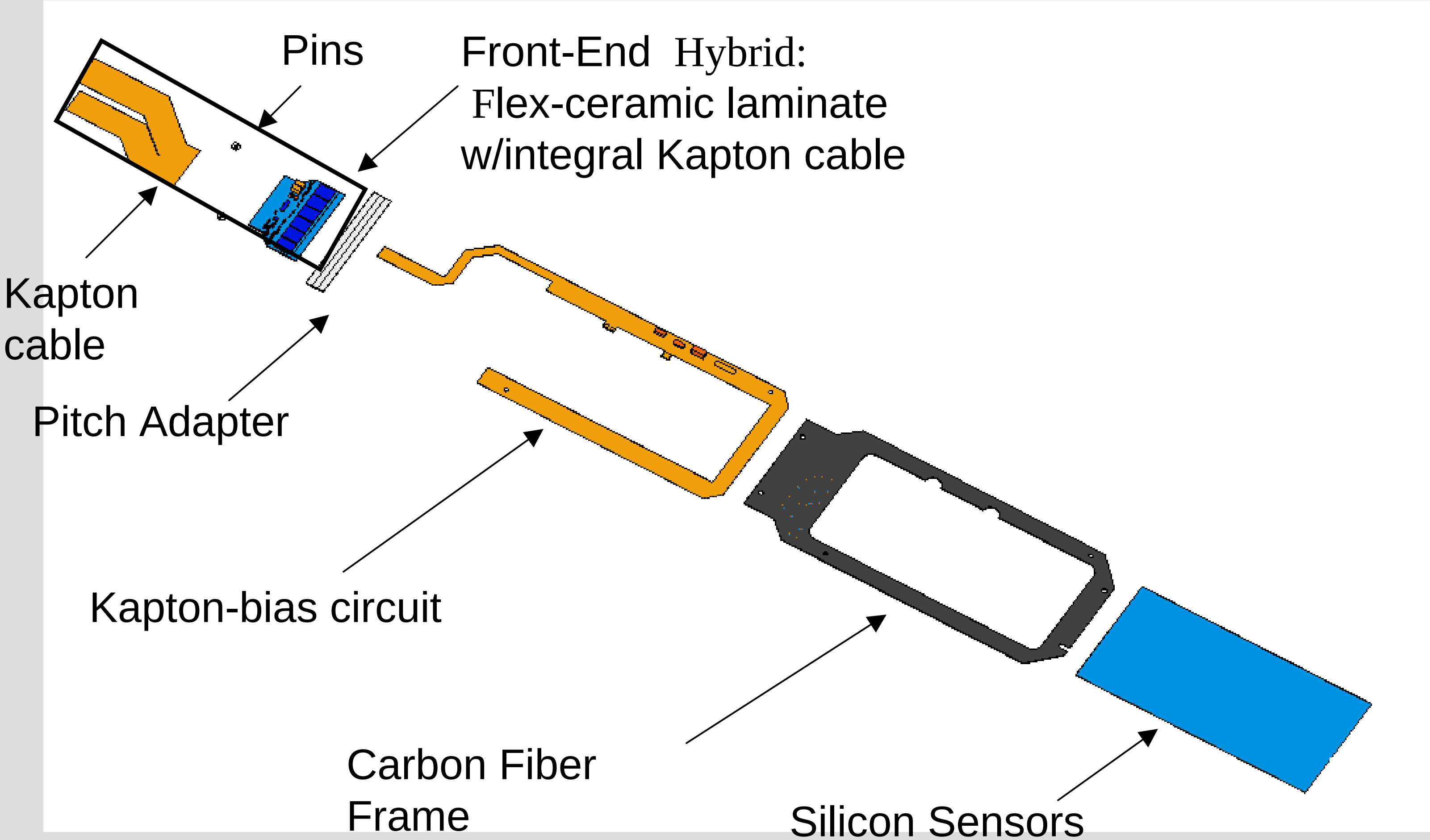
Silicon Strips



Strip lengths 10 cm (innermost) to 20 cm (outermost)

Strip pitches 80μm (innermost) to 200μm (outermost)

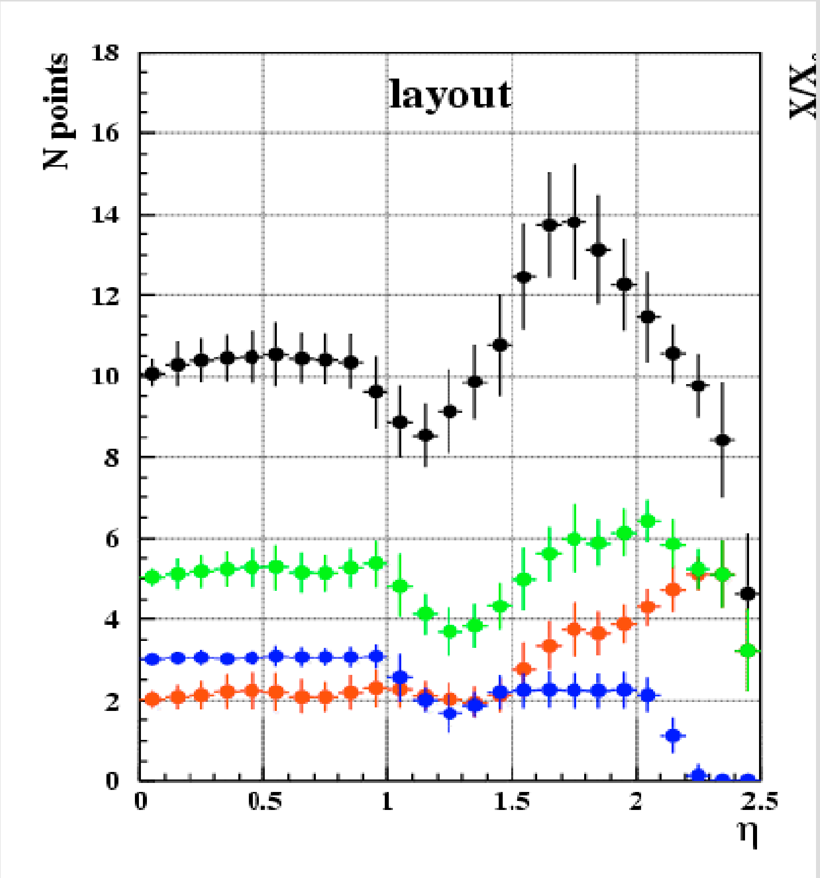
Module Components

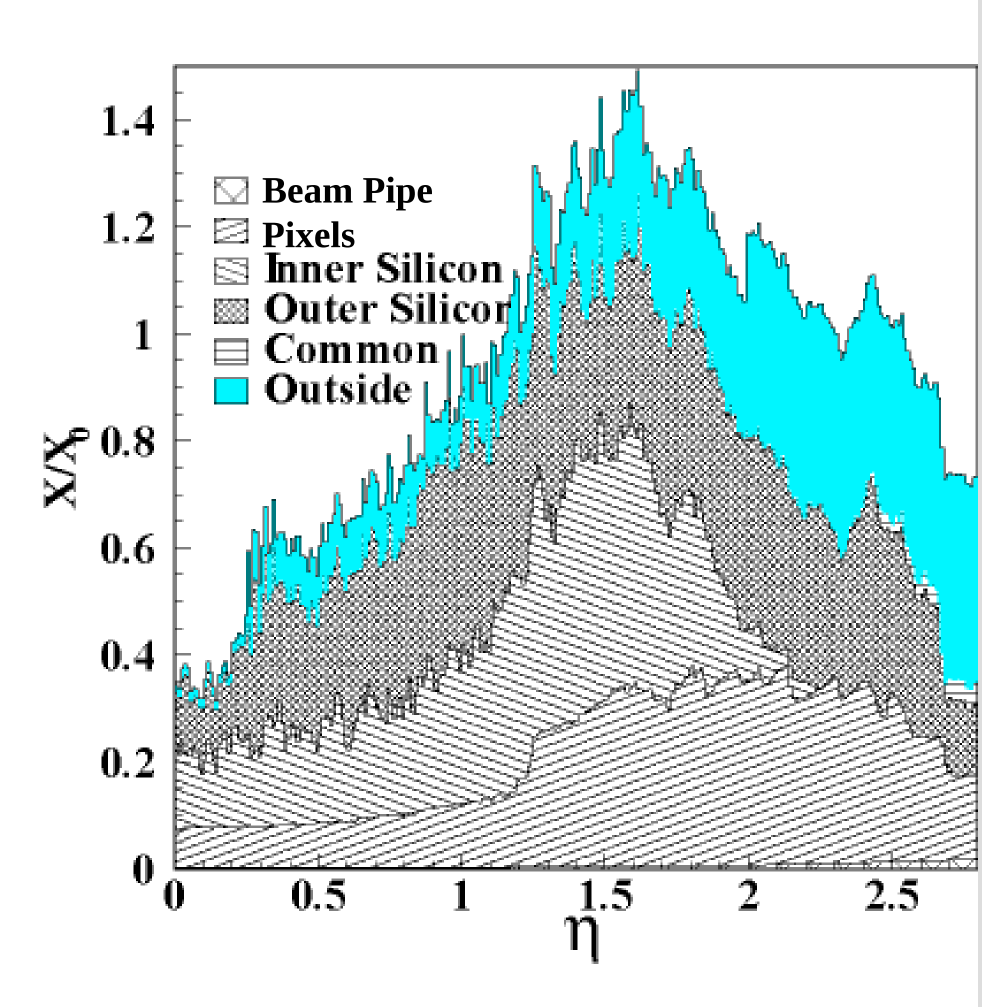


Technology

- Single sided p/n
  - Industry standard
  - Mass producible at low cost
- Surface radiation damage
  - Increases strip capacitance (noise)
  - p/n ok after inversion if adequately over-depleted
- High Breakdown Voltages
  - Specific design and processing rules for guard & strip geometries
  - Al strip layer acts as a field plate to remove high field region from Si bulk to Oxide

Tracker Coverage & Material!

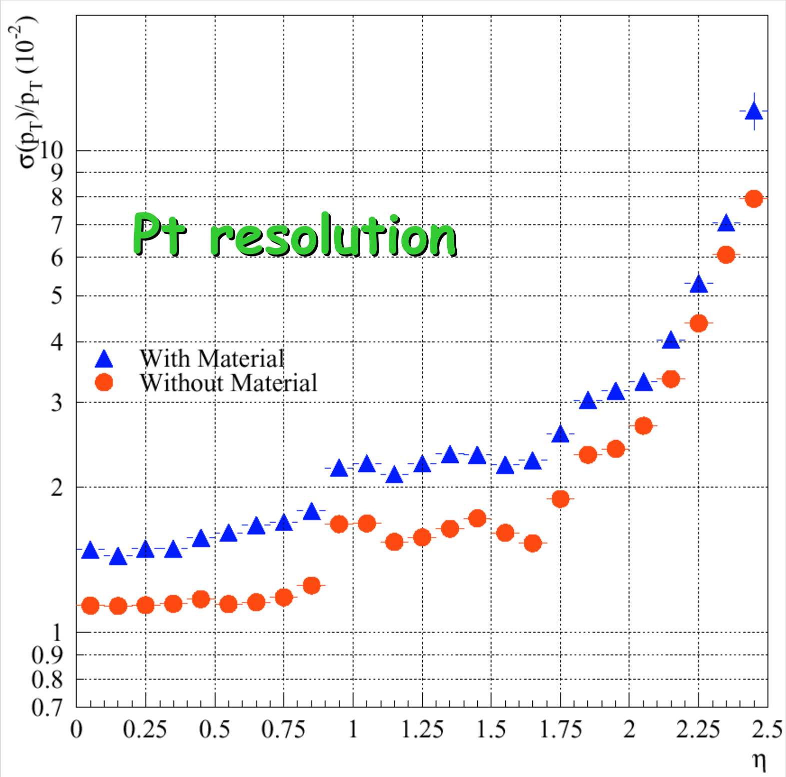


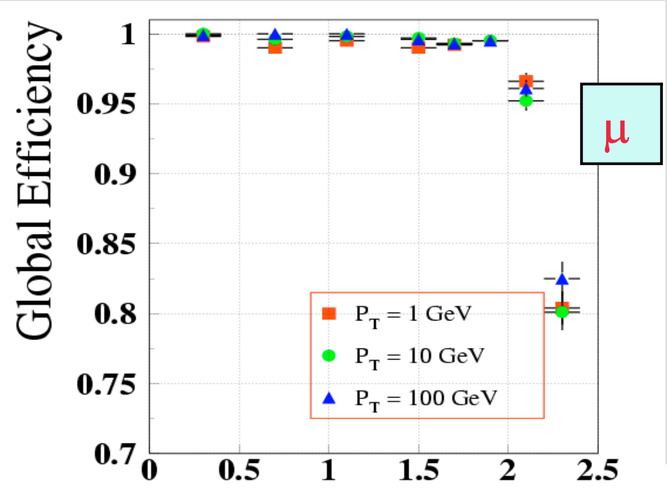


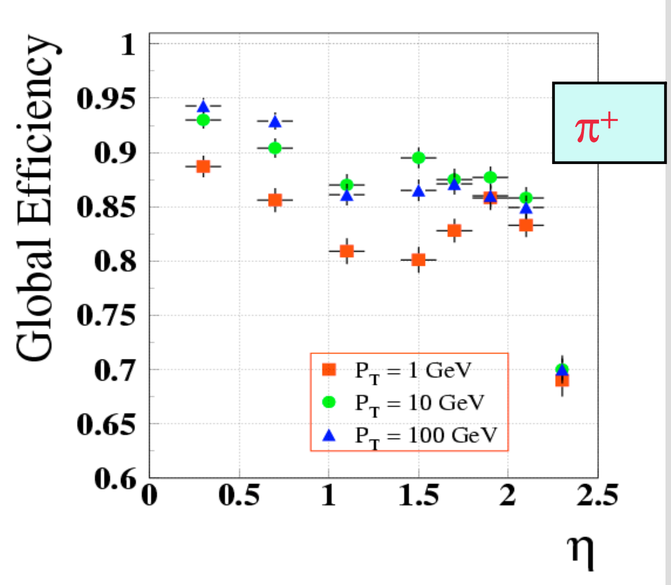
Tracking layers vs. pseudorapidity:

All, All double layers (axial+stereo), double inner, double outer.

Material Effects







Silicon Strip Tracker (SST) Status

➢ Good and Bad news

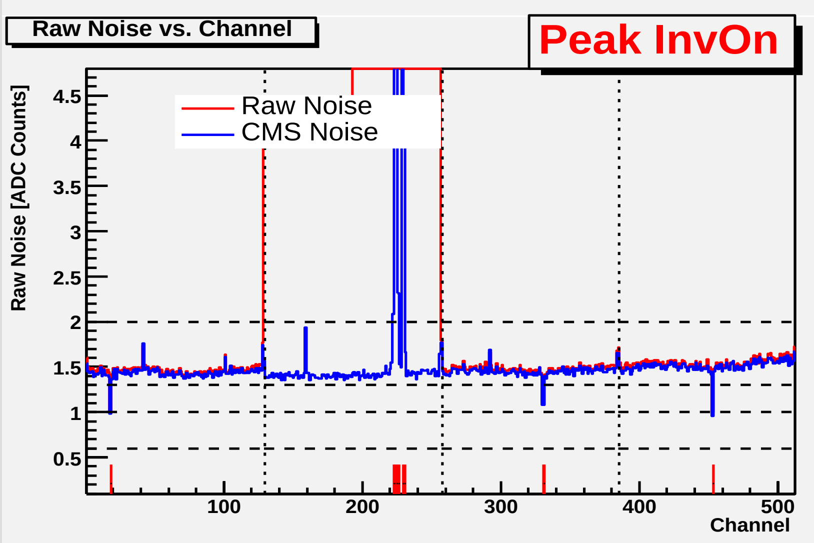
- Bad
  - We have found fatal flaws in every key component.
    - Most of them were first uncovered by the exceptional quality control of the US tracker group
    - Have caused more than 1.5 y delay in the project.
- Good
  - The broader tracker group is now much more serious about QC.
    - SST will be late but it will also more likely last for 10 y of LHC running!
  - DAQ is well advanced - large systems have operated well in beam
  - Production capabilities are at incredible levels w/unprecedented quality
    - US CMS has the capacity later this year to produce the equivalent channel count of the Tevatron Run 2 CDF or D0 silicon in 6 weeks.
    - Less than 0.1% bad channels created during assembly vs 1-2% in the past.

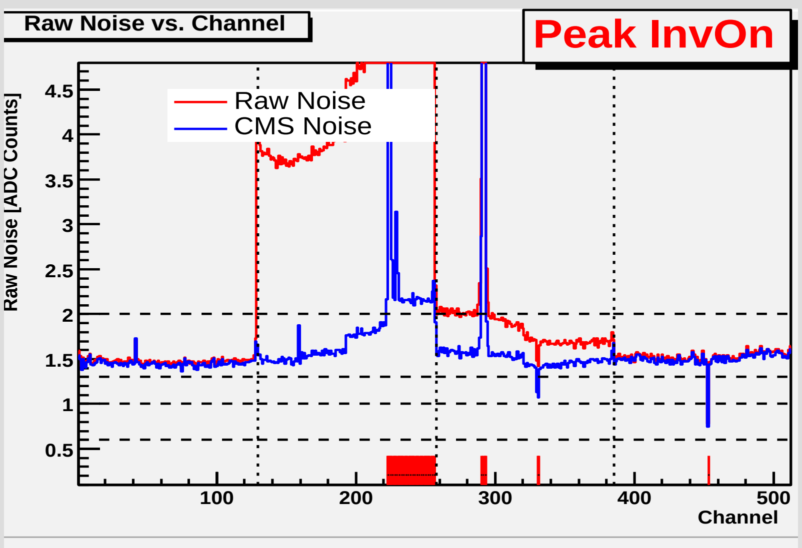
Crisis#1: The Sensors

- Sensors
  - US uncovered problem with ST sensors summer 2003
    - Initially disregarded by many, by **December ‘03** was the sole focus of a 3 day workshop at CERN
      - Indications of some kind of degradation in time (?) or some kind of problem with testing of sensors. US suggests chemical deterioration.
    - **January ’04:** Place orders with HPK for masks and prototypes
    - **February ’04:** ST agrees to significant changes in QC and stable processing with the aim of being re-qualified at July ‘04 tracker week. Also agrees to cut order from 18000 to 11000. CMS places order with HPK for 7000 sensors
    - **May-July ’04:** ST delivers 1000 qualification sensors. US builds 177 modules. Sees time evolution in at least 2 modules. Sensor groups see time evolution in 5% of sensors probed.
    - **Tracker week - July ’04:** probing groups together with ST uncover definitive evidence of corrosion resulting from large phosphorous content in surface oxide. ST is not qualified by CMS.
      - Will ST help CMS by letting us out of the contract peacefully?
      - Can HPK produce all of our sensors?
      - How do we find 2.5M$ to complete the purchase all thick sensors from HPK?

ST Problems: 1.Common Mode Noise (CMN)

Situation as of early'04





CMN effect features:

- Group of noisy strips with a "turn-on" voltage at which all 128 channels show high noise
  - can appear after thermal cycles
  - often accompanied by other types of degradation such as pinhole development, more CMN
  - Often correlated with high current

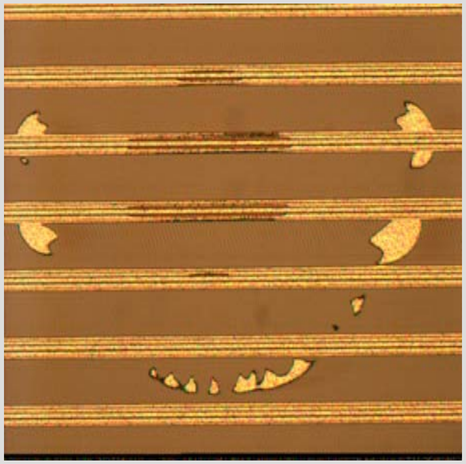
Example: second chip now has a high noise channel which causes common mode noise

Channel previously only had a slightly higher noise (0.3 ADC)

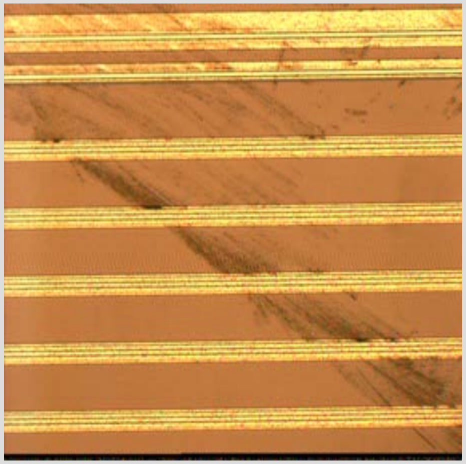
2.Processing defects/damage

Some observed defects:

30210434589131

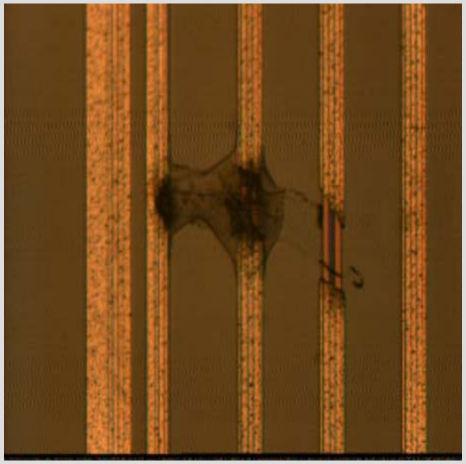


30210434273420



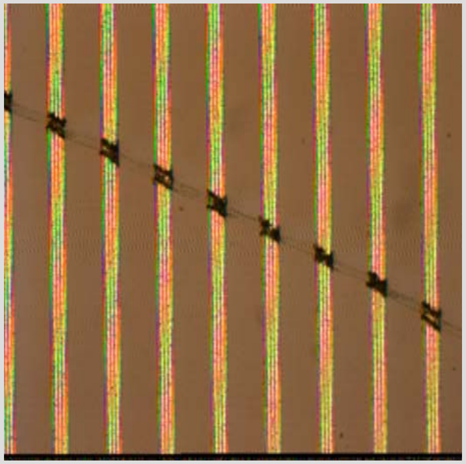
*

30210433980303



*

30210434560446

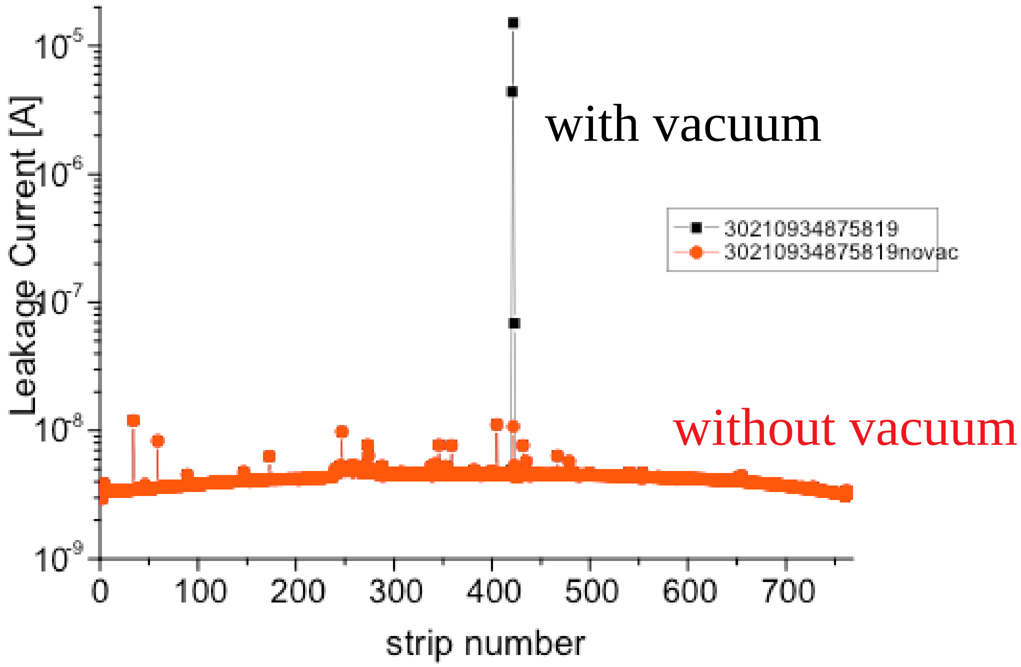


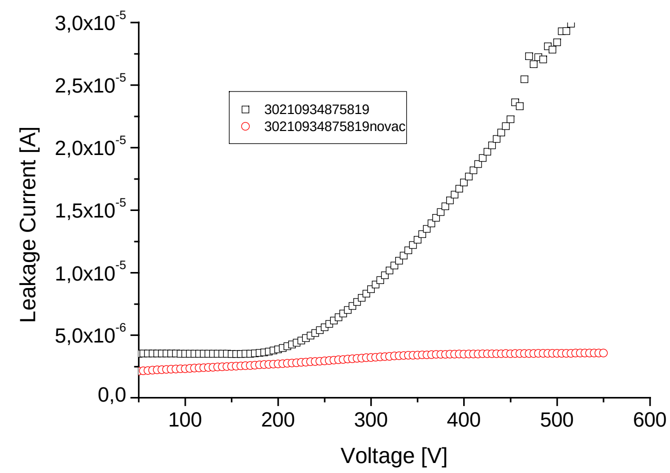
*

* = No electrical effects

As of early‘04

3.Vacuum effect - single strips !

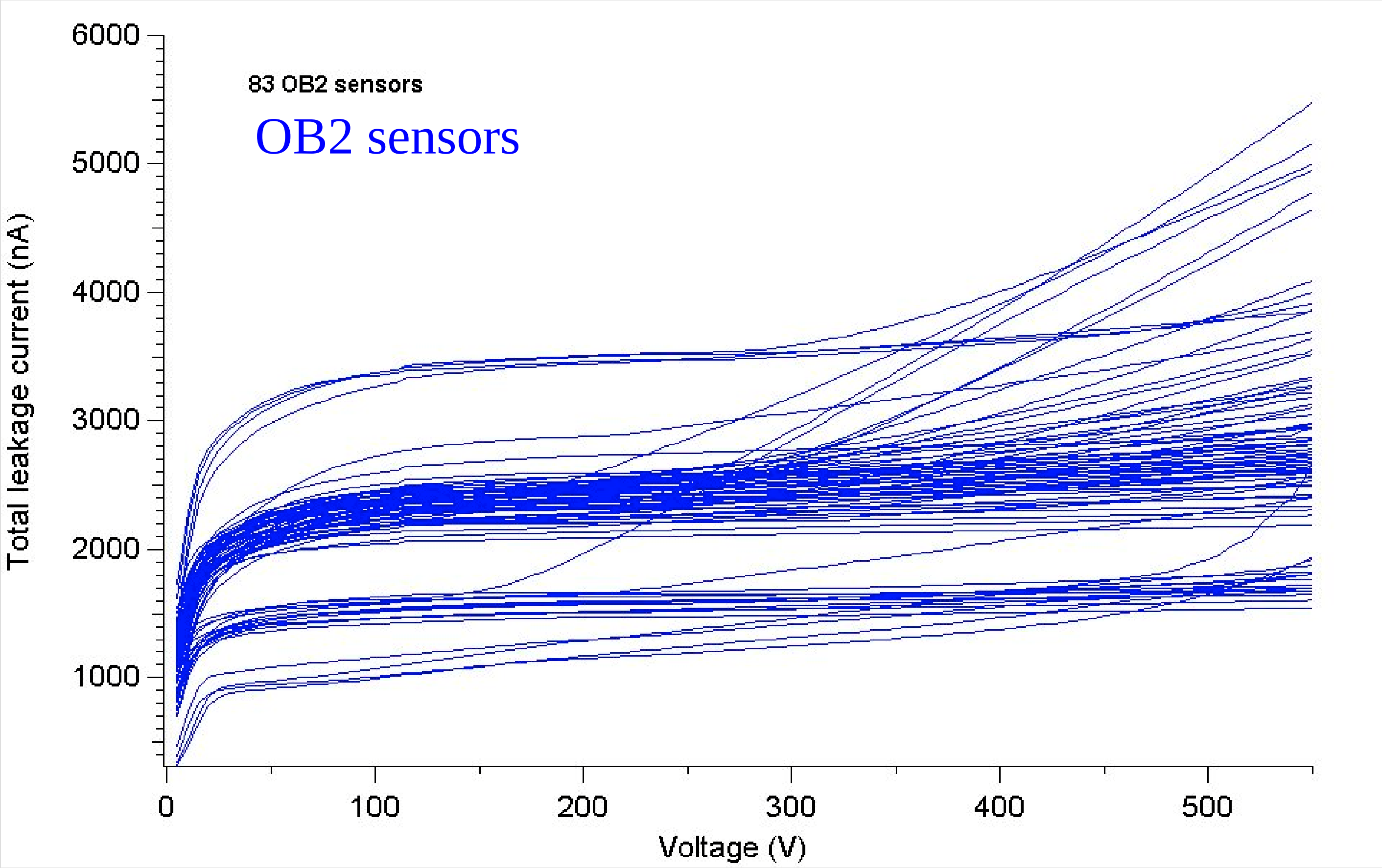




Strip 420 & 421 (4µA 15µA).
Switching probe chuck vacuum on and off switches these strips on and off.
Effect is reproducible.
No visible defect seen.

As of early'04

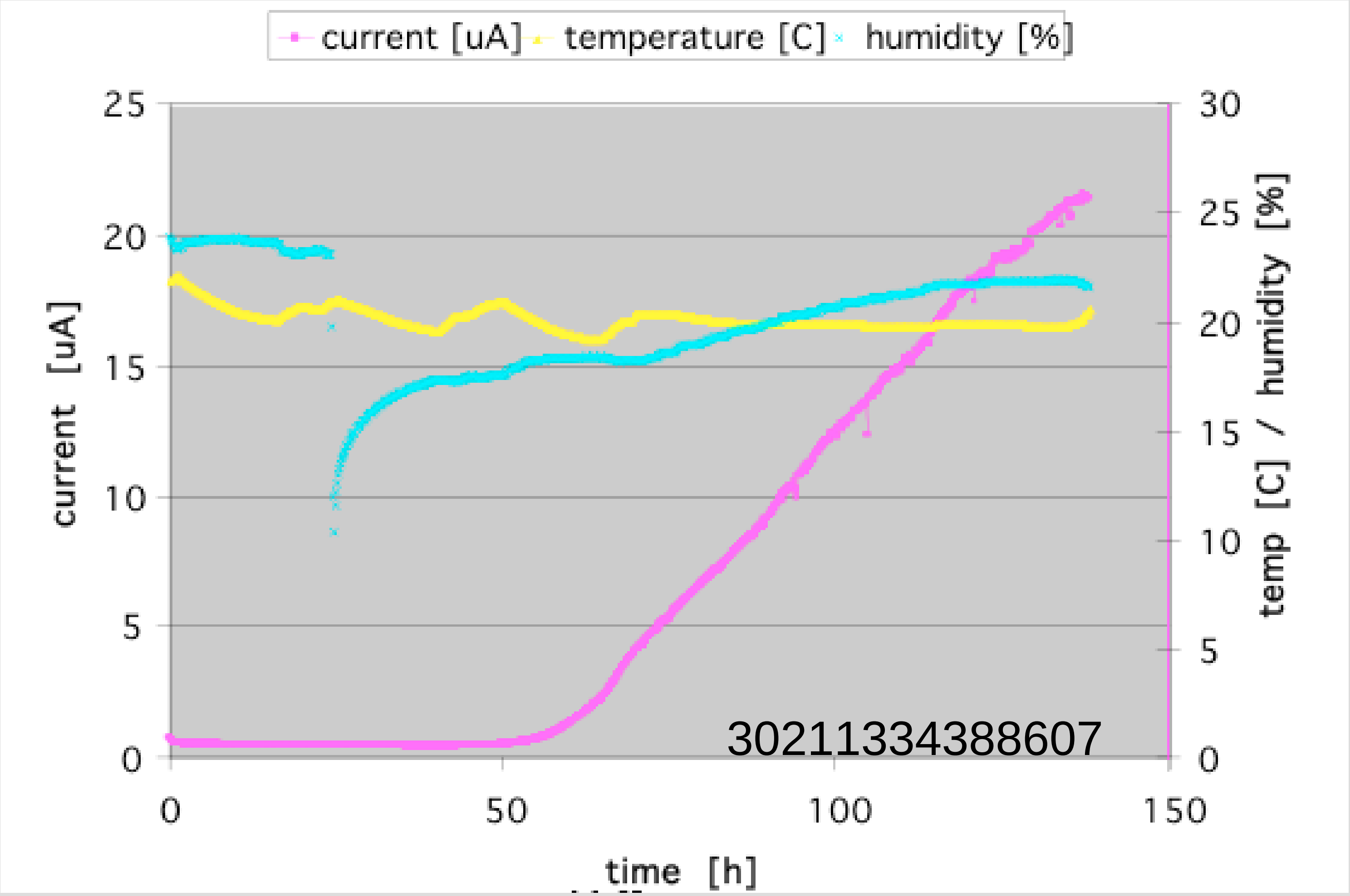
4. Strange IV curves in late ’03 early ’04



“It’s like no diode I’ve ever seen Gromit” - Wallace

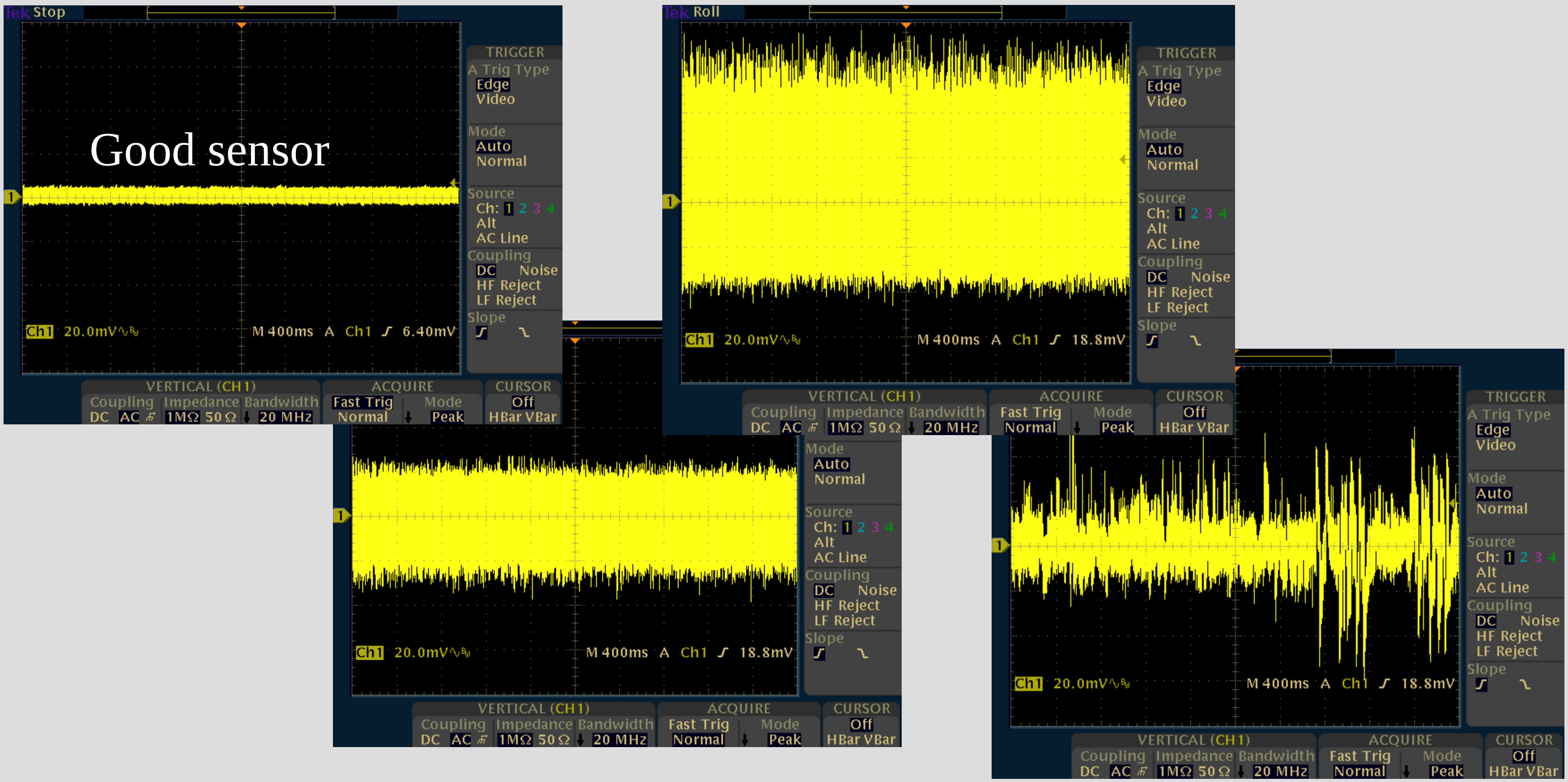
As of early‘04

6. Long term instability



As of early'04

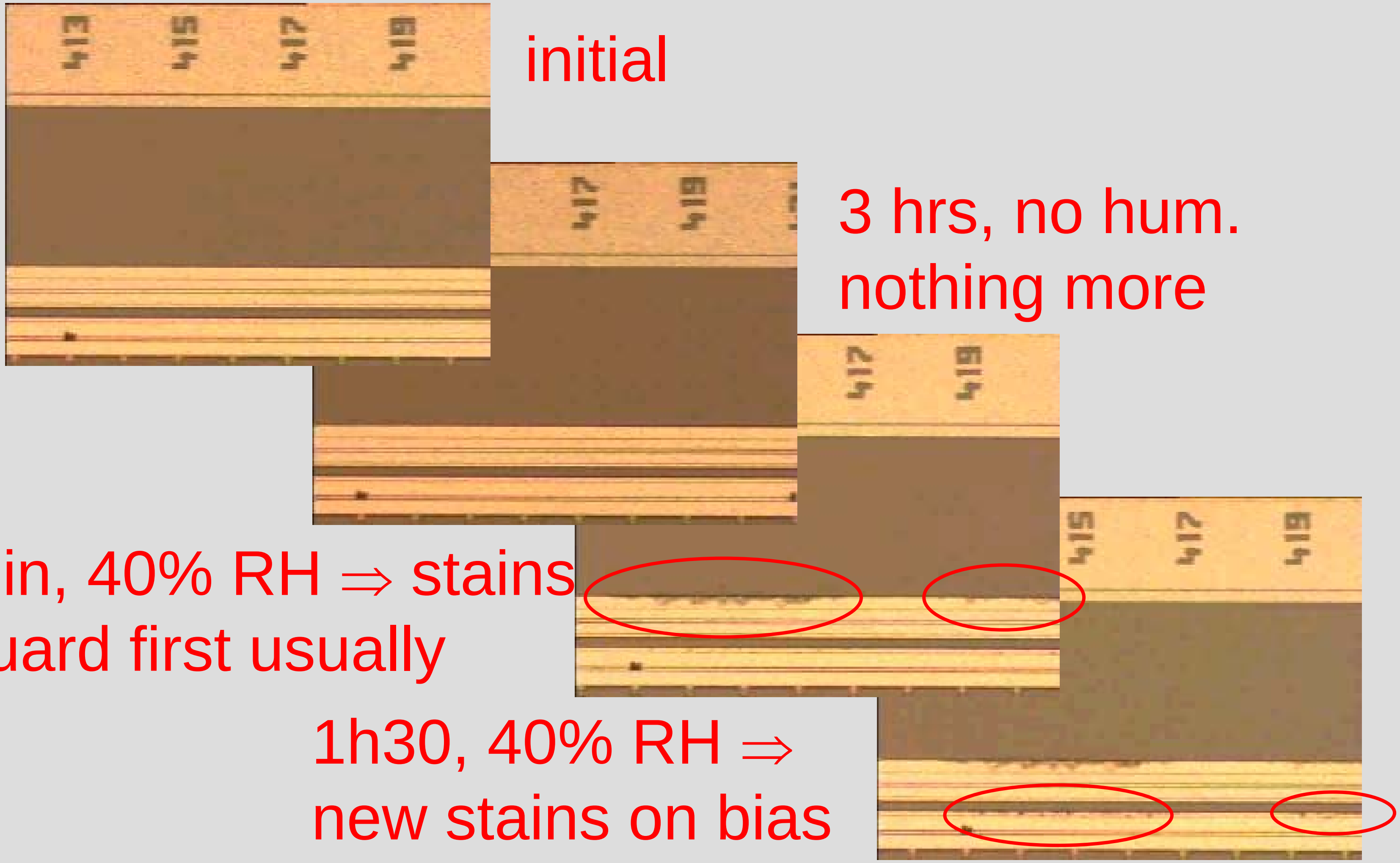
7.Time structure in leakage current



As of early‘04

As of July ’04 tracker week

8."Dots and Stains" development



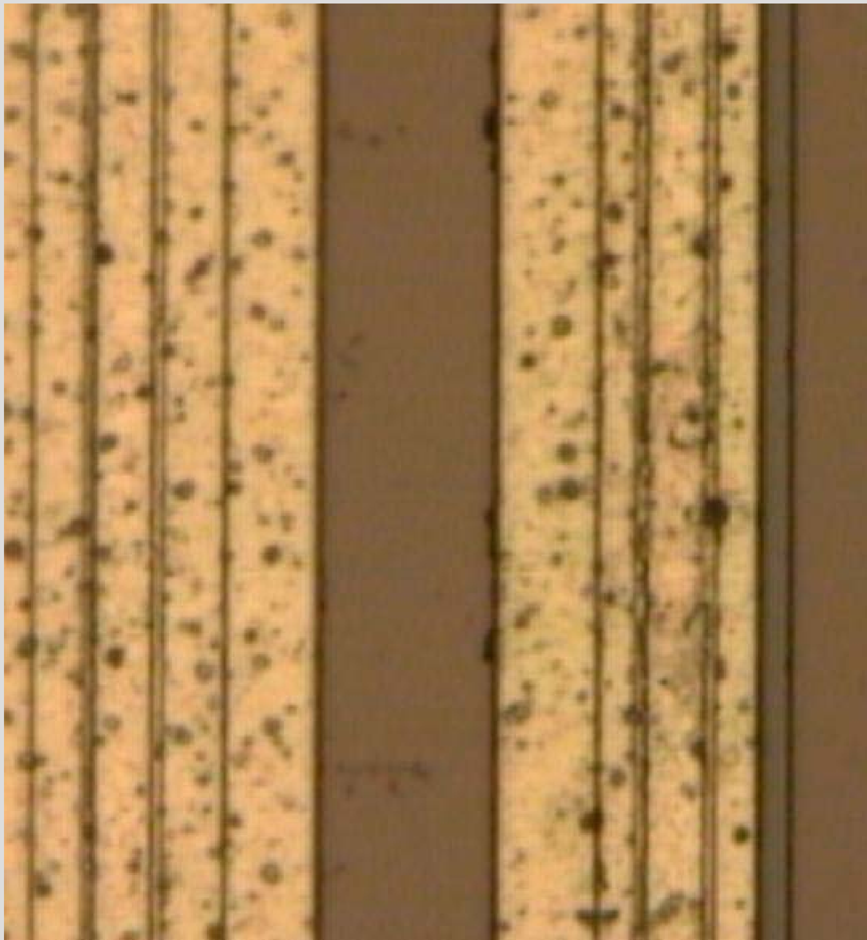
initial

3 hrs, no hum.
nothing more

30 min, 40% RH ⇒ stains
on guard first usually

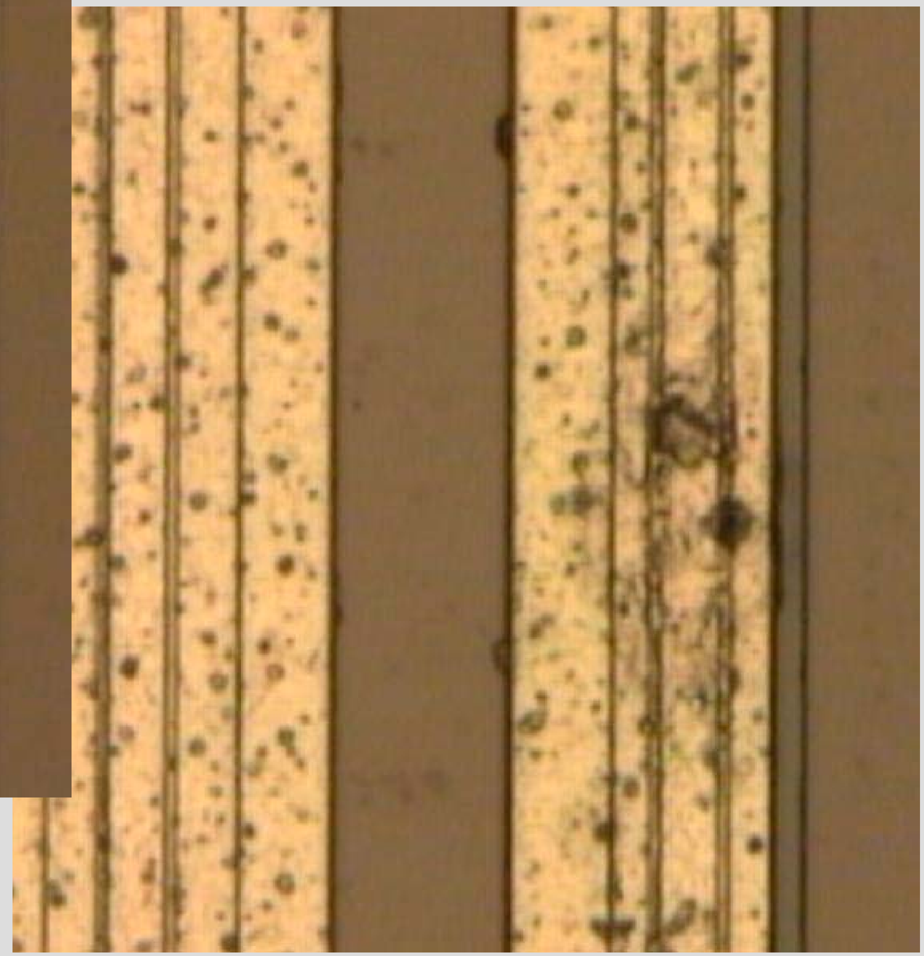
1h30, 40% RH ⇒
new stains on bias
(not always visible on video, see later)

"Dots and Stains" development



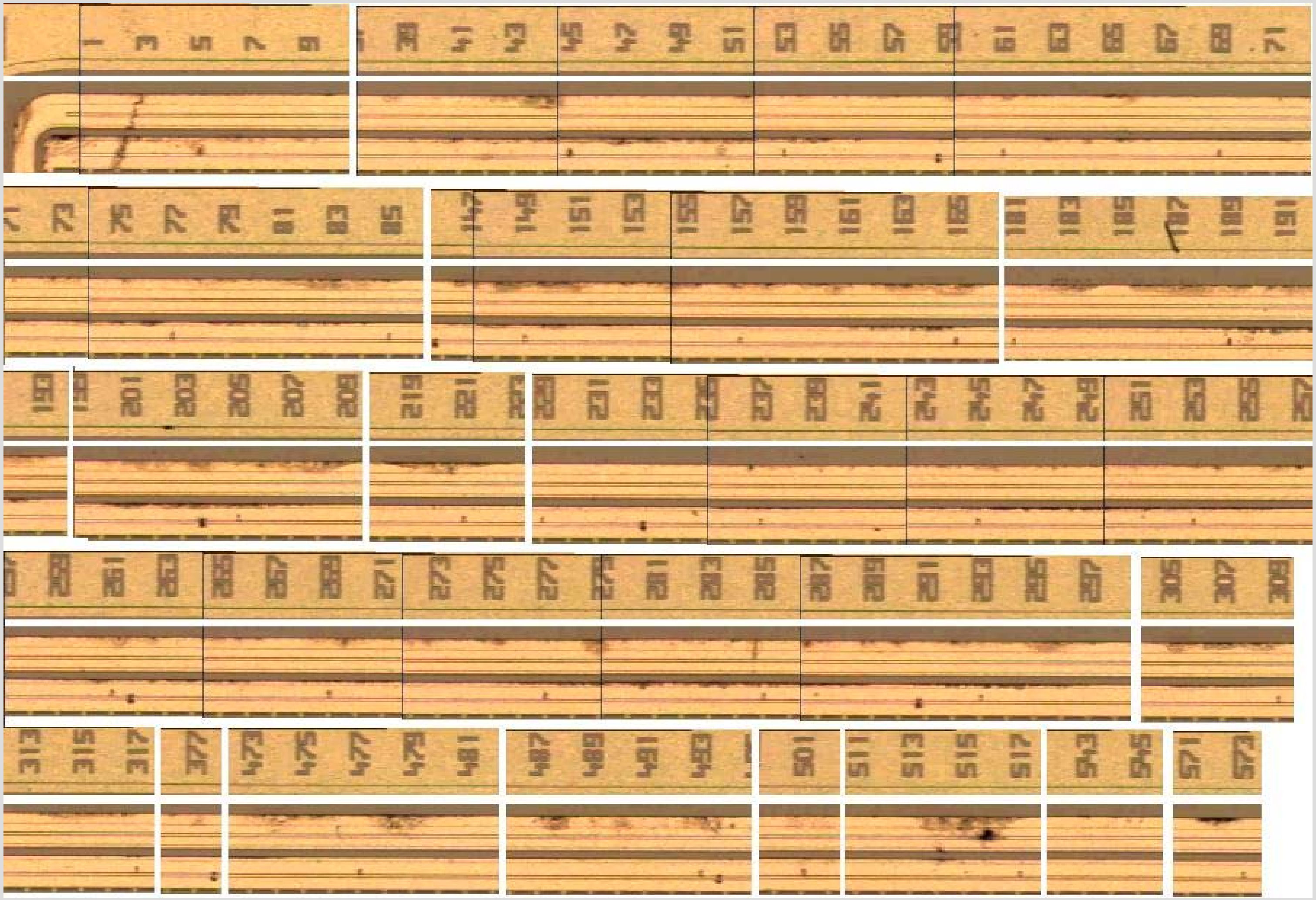
30 min, 40% RH

1h30, 40% RH



As of July ’04

example shown here: 30% of the length affected!



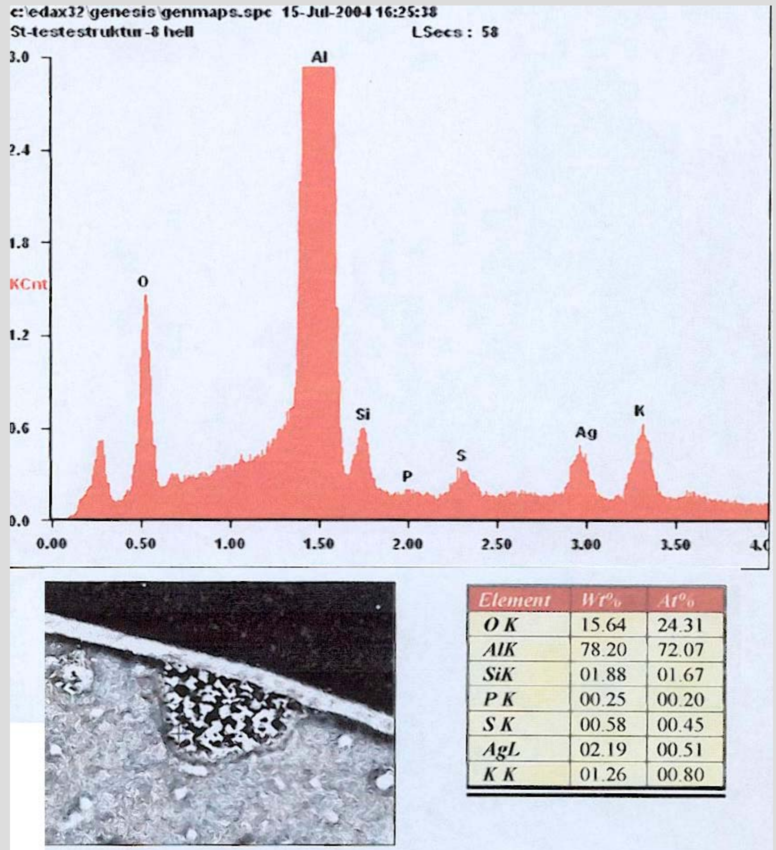
As of July ’04

"Dots and Stains" origin

Investigation by Strasbourg and Karlsruhe
(with help of the Fraunhofer Institute Chemische Technologie)

The ratio of elements in white areas of stains indicates the existance of Aluminum-oxide

Corrosion !

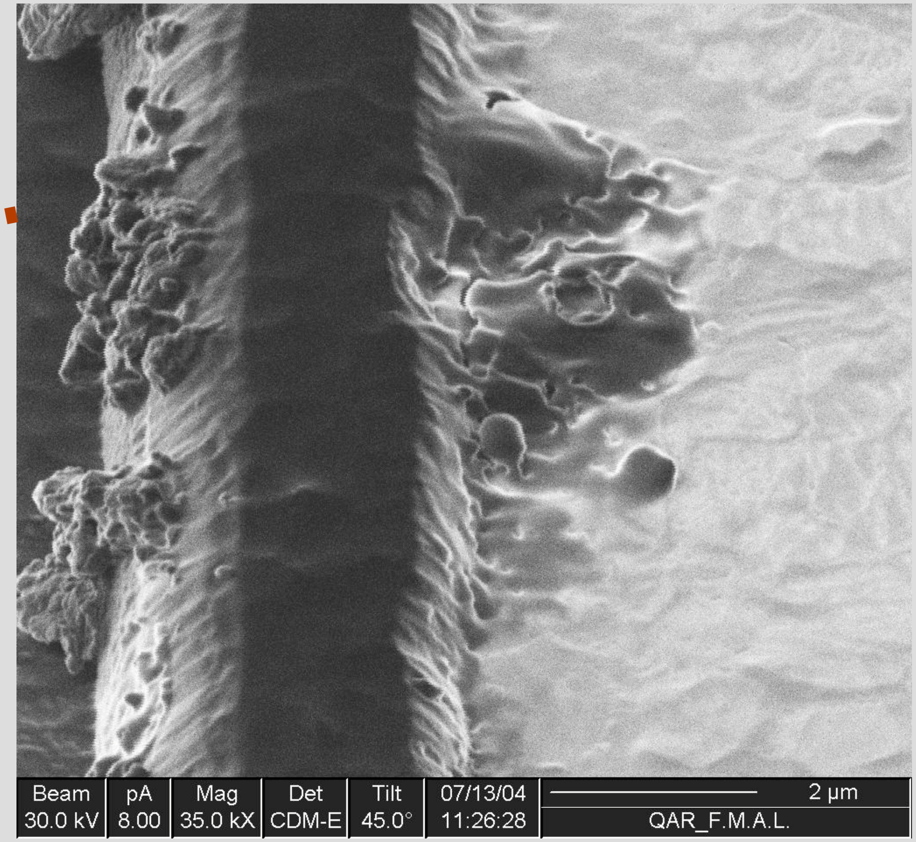


Element	Wt%	At%
O K	15.64	24.31
AlK	78.20	72.07
SiK	01.88	01.67
P K	00.25	00.20
S K	00.58	00.45
AgL	02.19	00.51
K K	01.26	00.80

Confirmation by ST

2 sensors were sent to ST together with corresponding pictures of 'dots and stains'

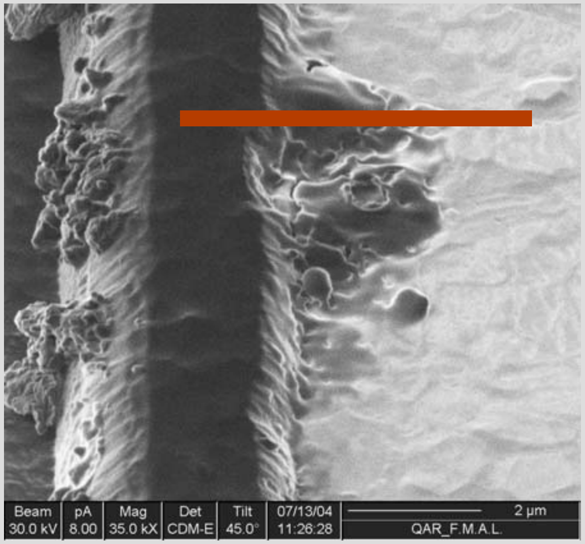
View by optical microscope



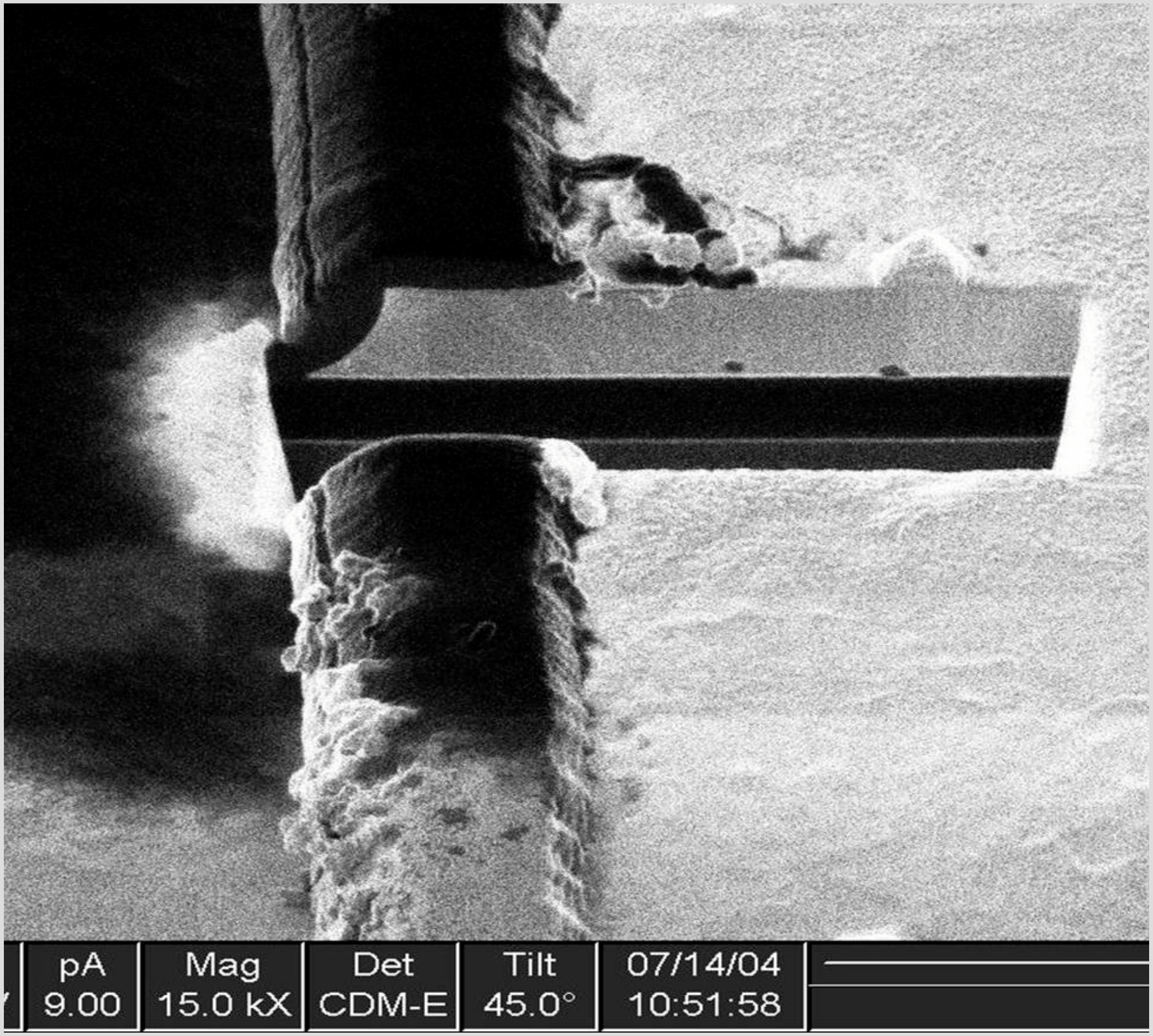
Focused ion beam (FIB) microscope

As of July ’04

Cut by ionic beam & cross section viewed via FIB



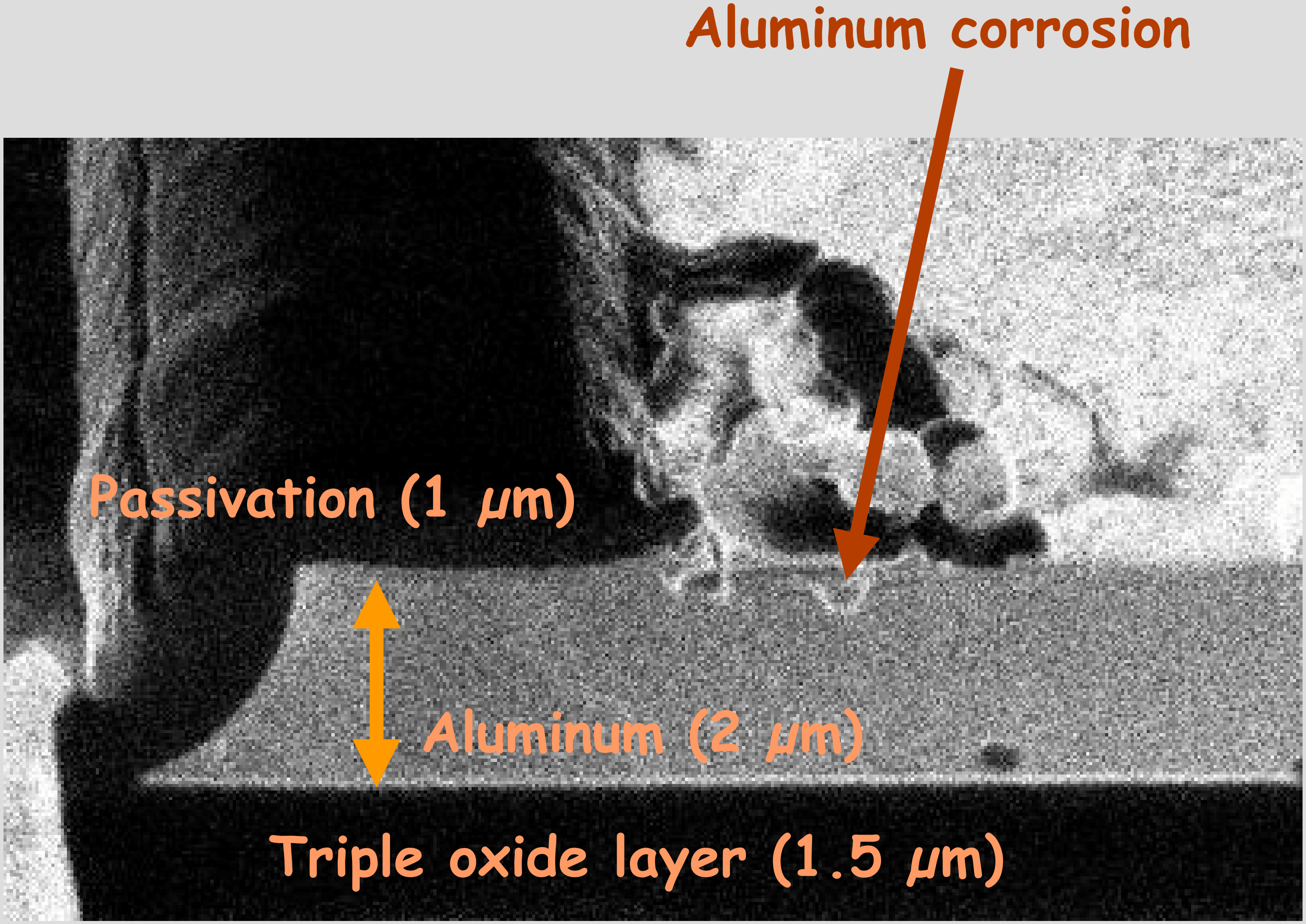
Cut line



Cross view (FIB)

As of July ’04

Close-up


Aluminum corrosion
Passivation (1 μm)
Aluminum (2 μm)
Triple oxide layer (1.5 μm)

Origin of dots & stains: corrosion of Al

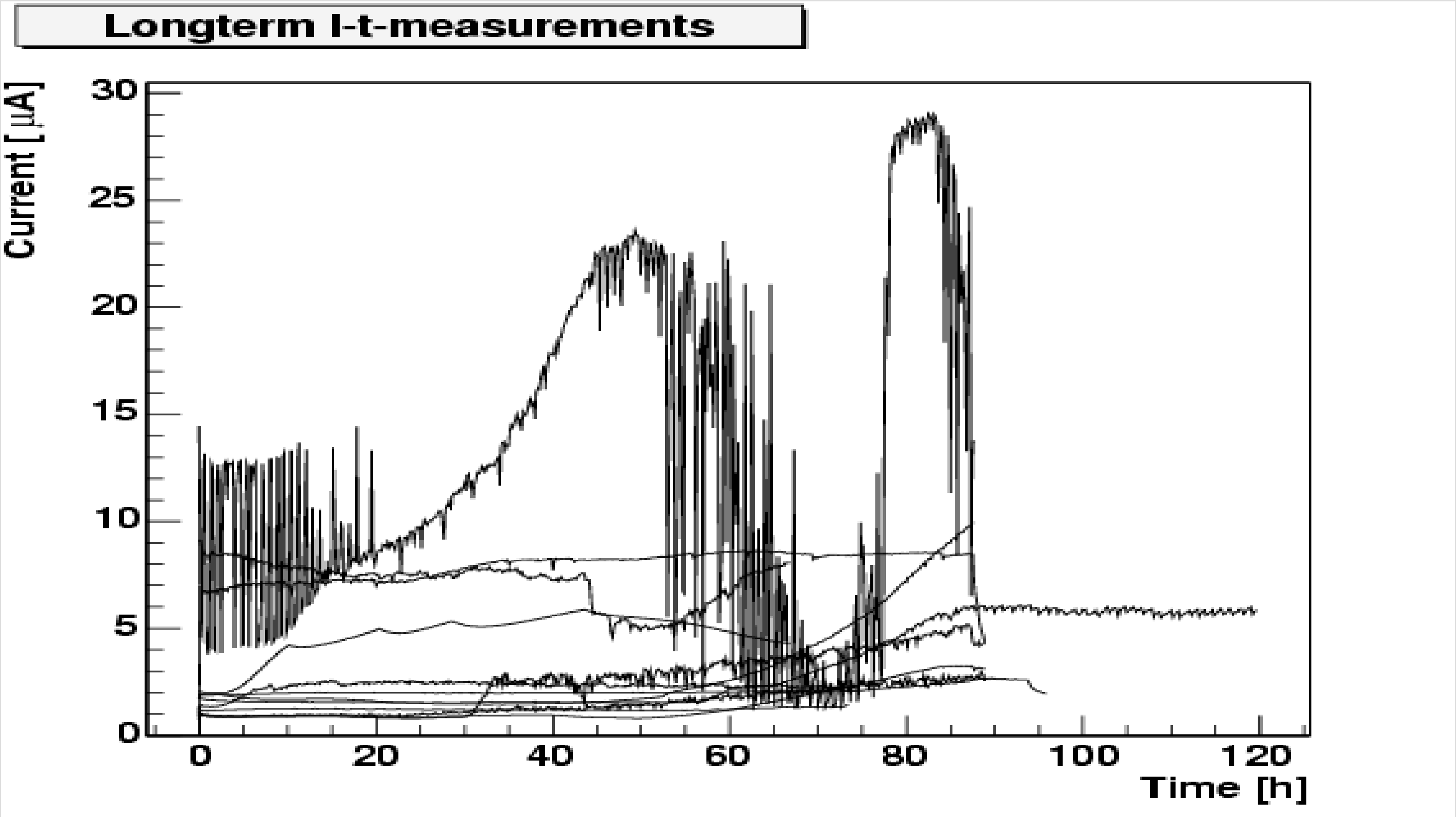
Both dots and stains are micro-corrosions of the aluminum surface. The mechanism that drives this phenomenon can be the following:

Humidity reacts with Phosphorus (present in a 4% concentration into the passivation oxide) and forms an acid (probably H_3PO_4), that corrodes a superficial layer of Aluminum.

Longterm tests of “Qualification Sensors” show continuing instabilities

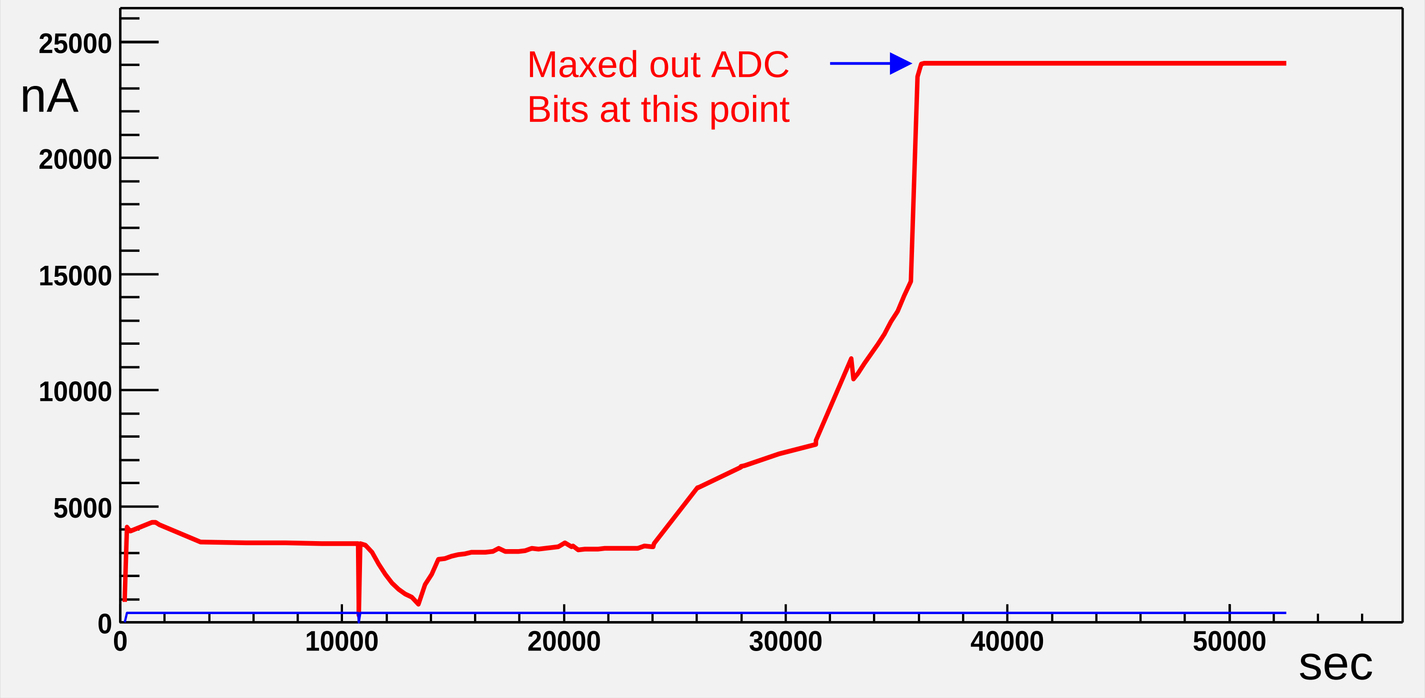
○ 233 sensors tested 72h (room temeperature, r.h.=25-30%)

Failure rate of qualification sensors in 72 h period is 5%



As of July ’04

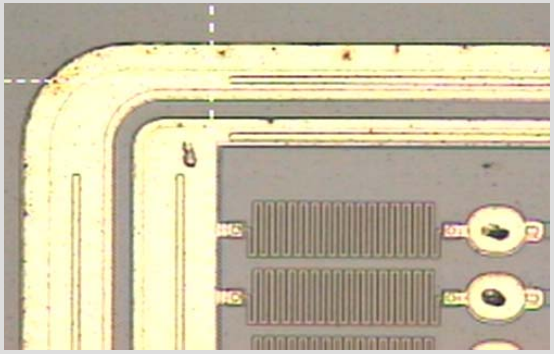
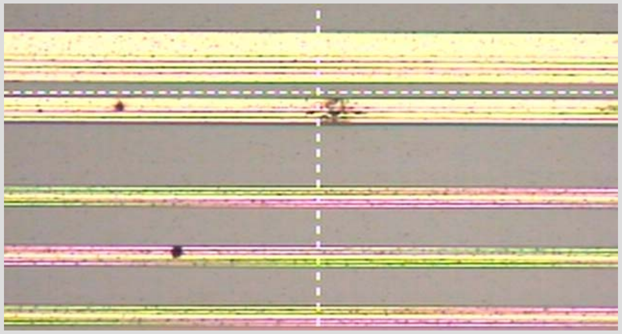
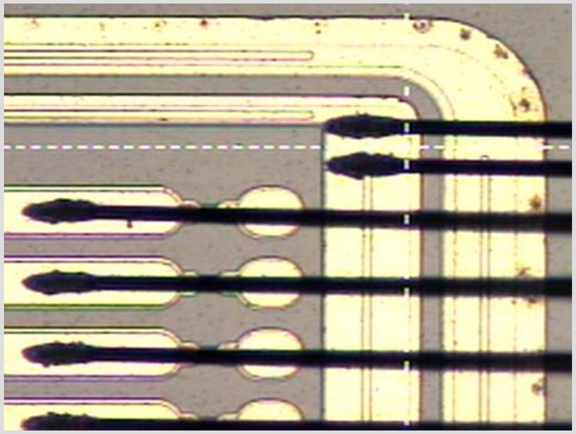
9. Modules that deteriorate



- Module 5379: After 7 hours, bias current of module started to increase
- Post LT test reconfirmed current increase
    - New high noise channels seen in subsequent tests

As of July '04

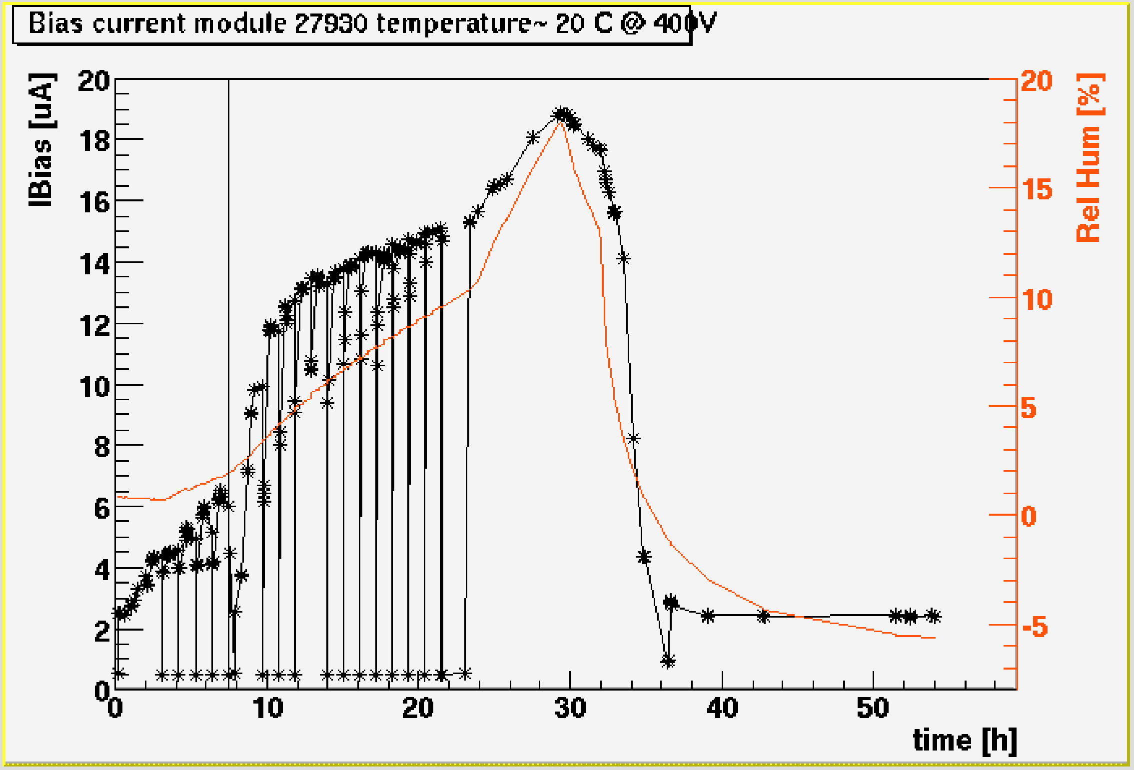
Longterm Module Failure

- Dark marks on bias ring occur near high noise channels

Results from TEC Modules

22 modules tested
1 module with current increase during LT test



As of July ’04

Sensor Issue Now

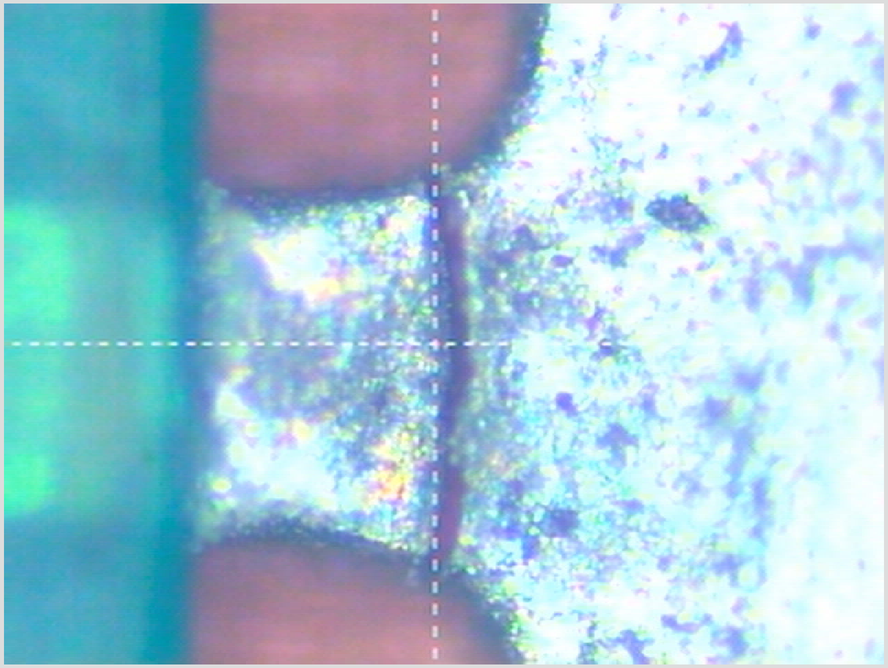
- The situation is far from over
  - Will end up with 7000 ST sensors in hand
  - 3000 are “re-qualification grade” – most are said to be central barrel
    - We will be under financial and political pressure to use these
  - Some influential groups are still pushing for a larger ST fraction in the tracker
  -

Crisis#2: The Hybrids

- Summer 2003 US finds broken cable traces
  - US reviews handling and studies alternative handling schemes
  - CERN finds breaks are widespread
  - Vendor says design is fatally flawed
    - New design implemented after 2 months delay
- Winter 2004 US find strange failure in modules
  - US traces the problem to the hybrid
  - CERN responds instantaneously – halts all hybrid production
  - Working with Vendor it is determined that vias are not properly plated with breaks occurring at unknown rate
    - US Halts production of TOB and TEC modules except for ST qualification
    - TEC and TIB communities have already built many modules and continue building more for installation
  - Summer 2004: Vendor bought out.
    - New management fires person leading our production effort.
    - However, it appears that management is more serious about solving this problem and may have better resources.
    - 4 variations of design are now being processed and will be ready in mid-November.
- Full scale hybrid production not likely before January!!
  - Meanwhile we will have stockpiled something like 5000-9000 HPK sensors!

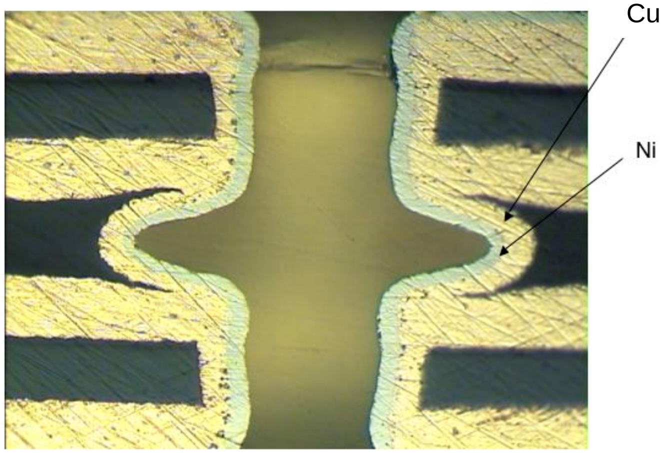
1.Hybrid Cable Problem

- Flex cable fragility
  - Problem was quickly solved
    - Good US/CERN relationship
    - CERN relationship with vendor

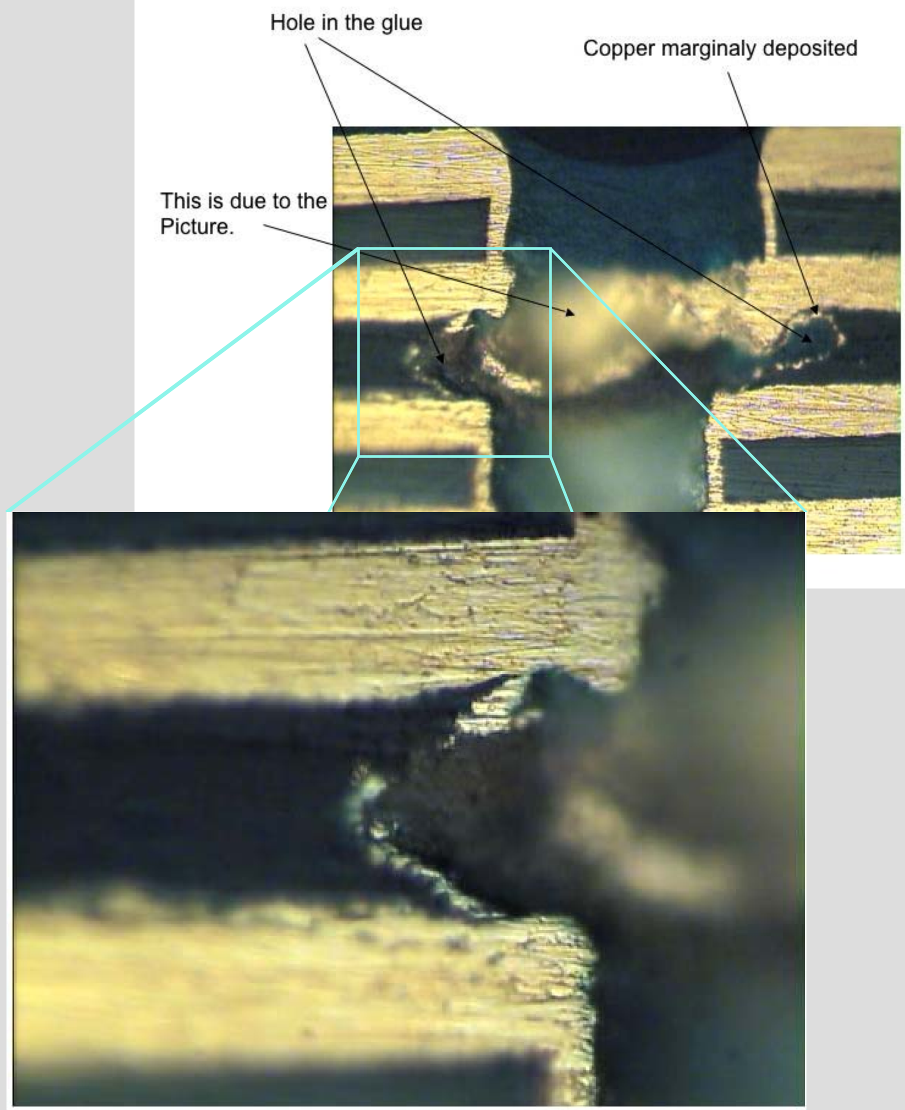


Good Vias and Bad Vias

Example of a good via



Example of a bad via

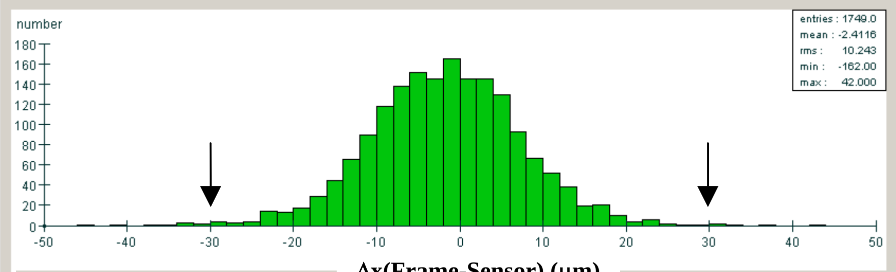


Crisis#3: Module and Rod Transportation

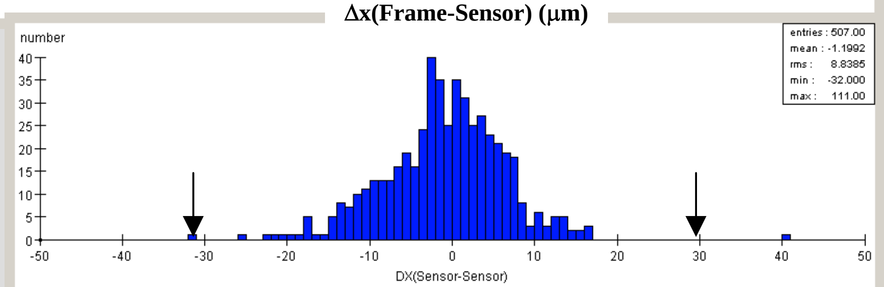
- Winter-Spring ’03: CERN reports that modules arriving from US have huge numbers of damaged wirebonds
  - US proposes a successful solution (encapsulate joints)
  - CERN confirms
- Winter-Spring ’04: Rochester studies find flexible mother cable in rod can damage module wirebonds in transport
  - CERN/US engineers study problem and design Al stabilizers.
- Averted disaster but fortunately also had no added delays

Module Mechanical Precision

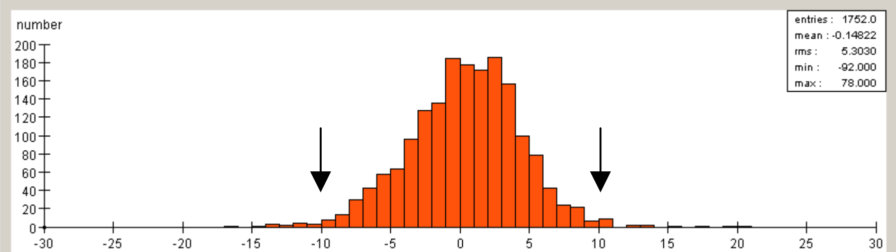
- 97% modules meet the current stringent geometric specs
  - Few failures are just outside the relative angular requirement
- US now applies 2nd order corrections
  - No new modules outside specs
- Production quality excellent!
  - Single Sensor Modules
    - 0.20% Faulty strips
      - Introduced faults **< 0.1% rate**
  - Two Sensor Modules
    - 0.55% Faulty Strips
      - Introduced faults **< 0.1% rate**
    - Will be much lower w/HPK



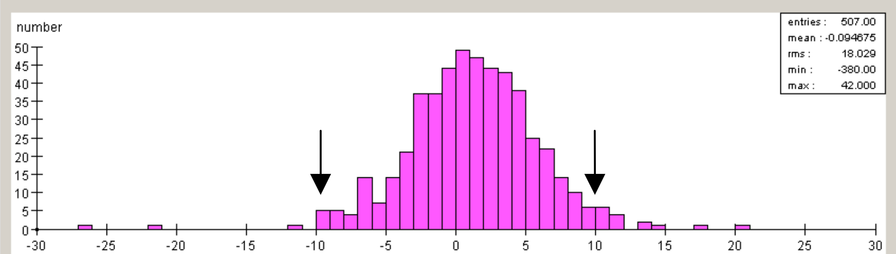
Δx(Frame-Sensor) (μm)



Δx(Sensor-Sensor) (μm)

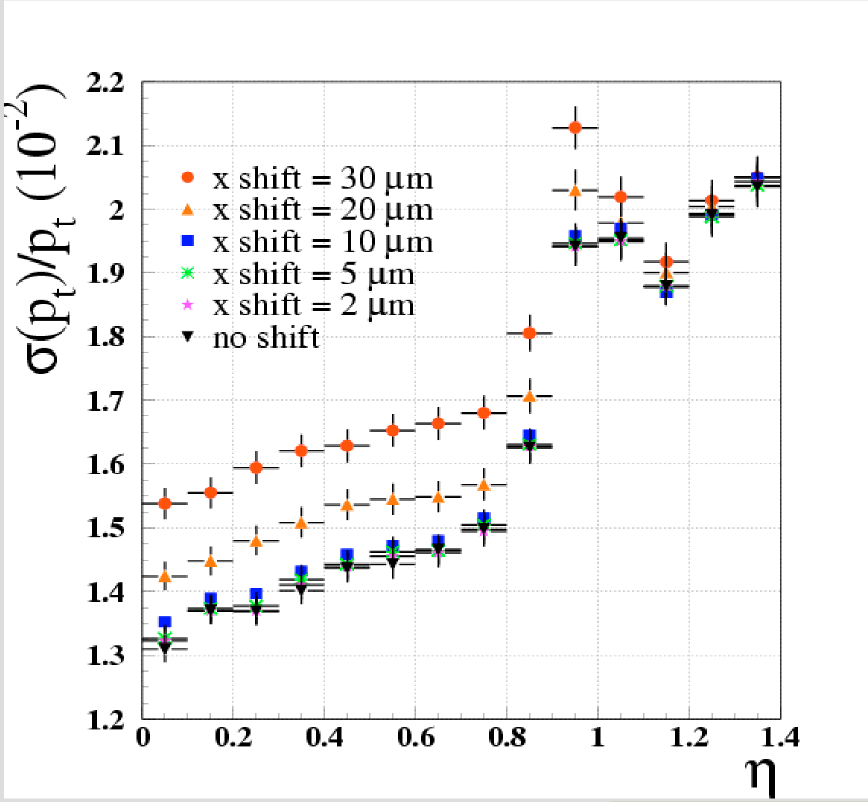


$\Delta\theta$(Frame-Sensor) (mdeg)



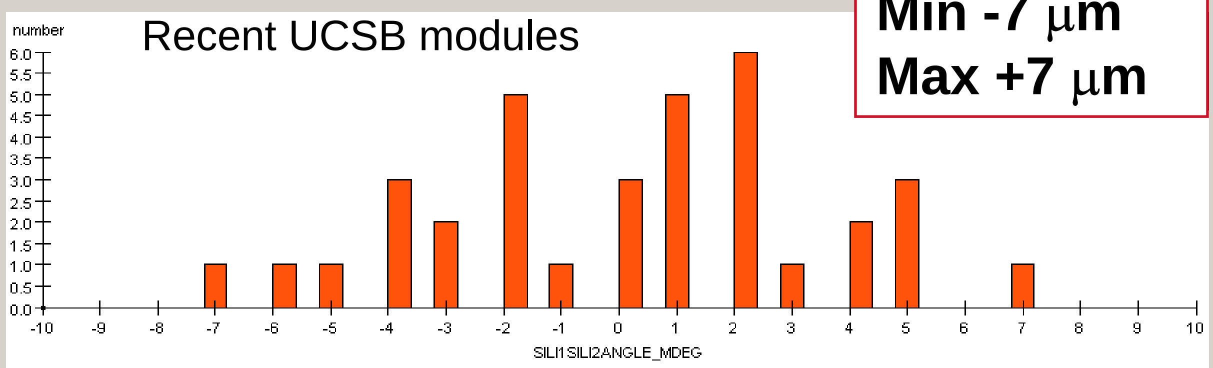
$\Delta\theta$(Sensor-Sensor) (mdeg)

Misalignments and P_T Resolution



MC Study of effect of misalignments on pt resolution:

single μ sample, p_T=100 GeV



Mean 0.0
RMS 3.5 μm
Min -7 μm
Max +7 μm

First HPK Module Results From UCSB

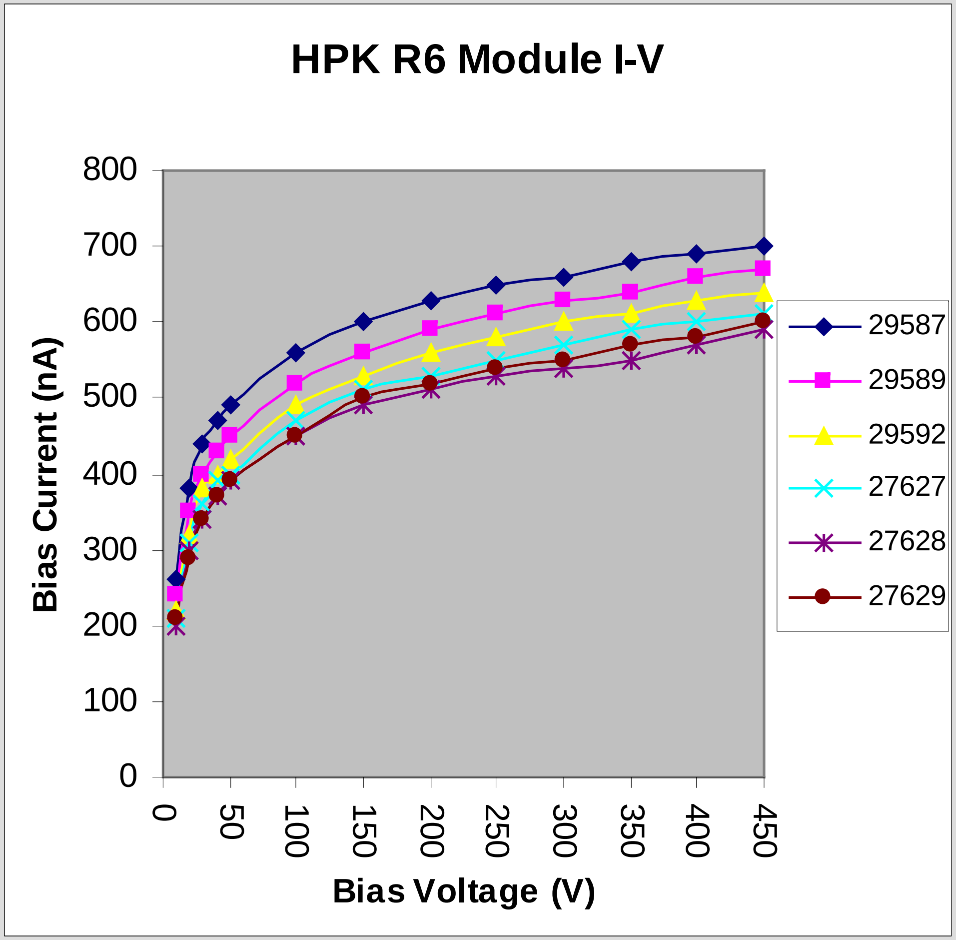
6 R6 modules built using new HPK sensors

All 6 modules are perfect

- ***Not a single flaw***

IV profile as expected

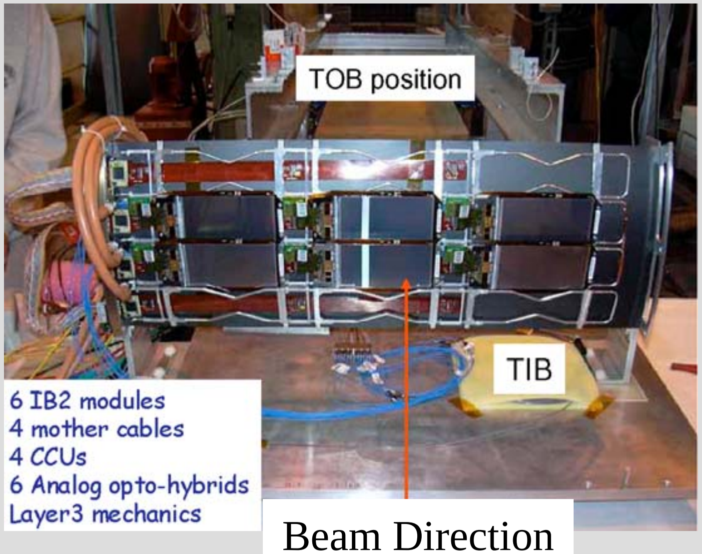
- Turn-on at low voltage
- Plateau bias current ~ 600-700 nA

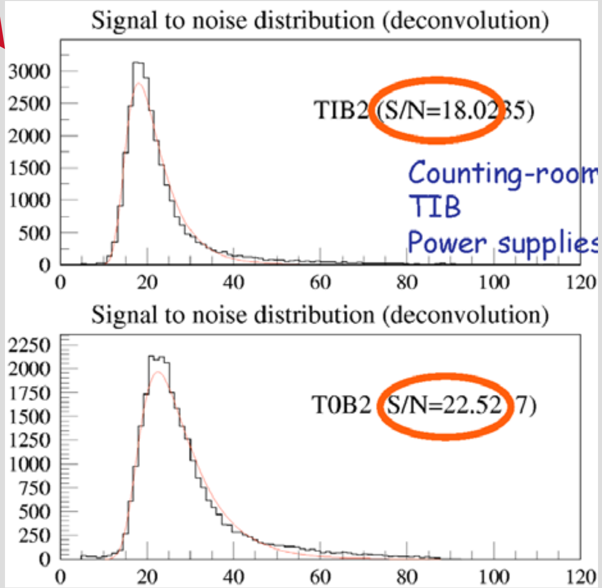


Substructures in Test Beams

- May 2003 Beam Test (Bunched 25 ns beams of muons and pions)
  - Systems of 6-10 TIB, TEC, TOB modules

Detector performance as expected!



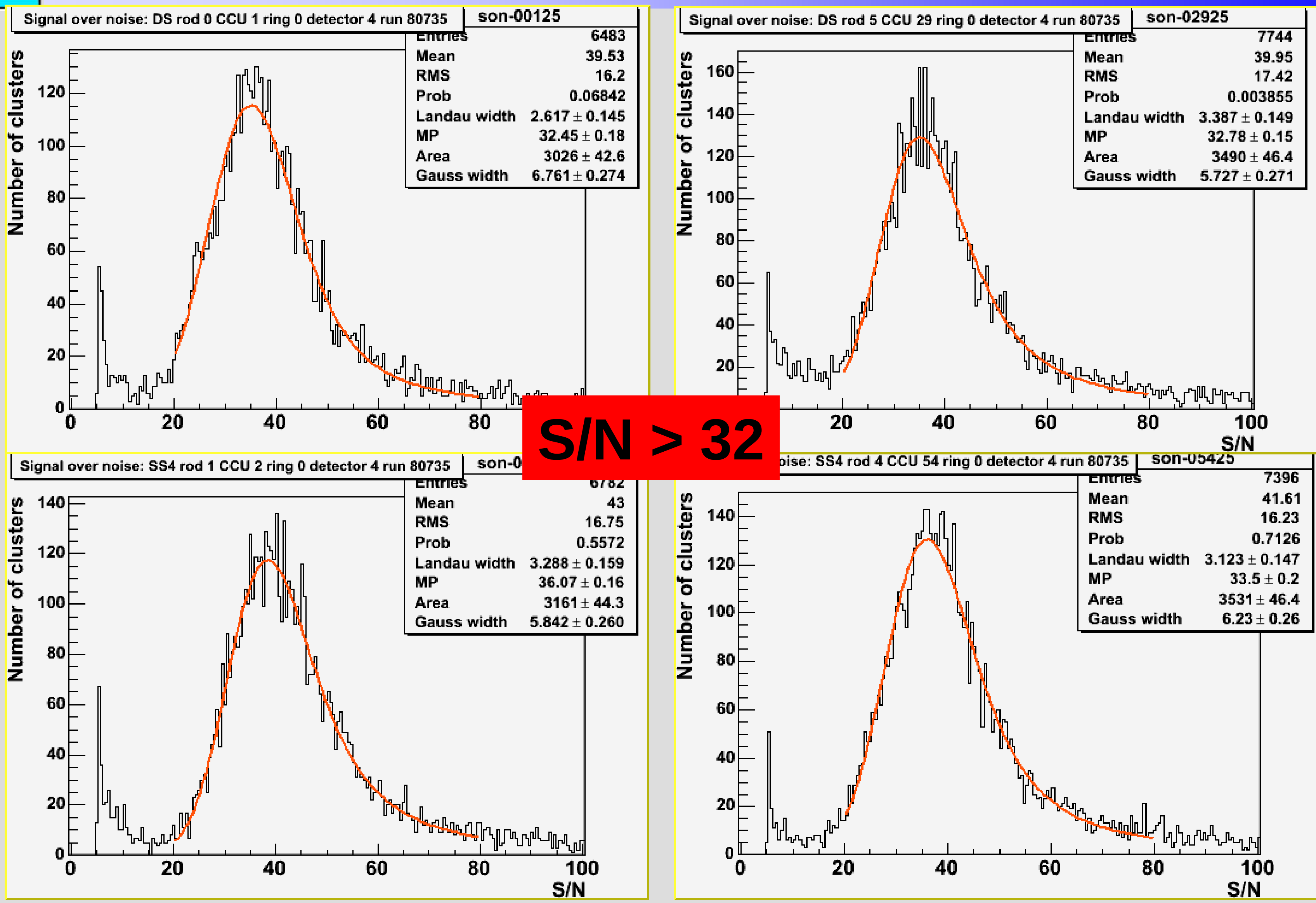


- May 2004 Beam Test
  - Multiple rods, petals, and shells
  - Larger system integration tests
  - Tracking tests
    - Position resolution, hit efficiency

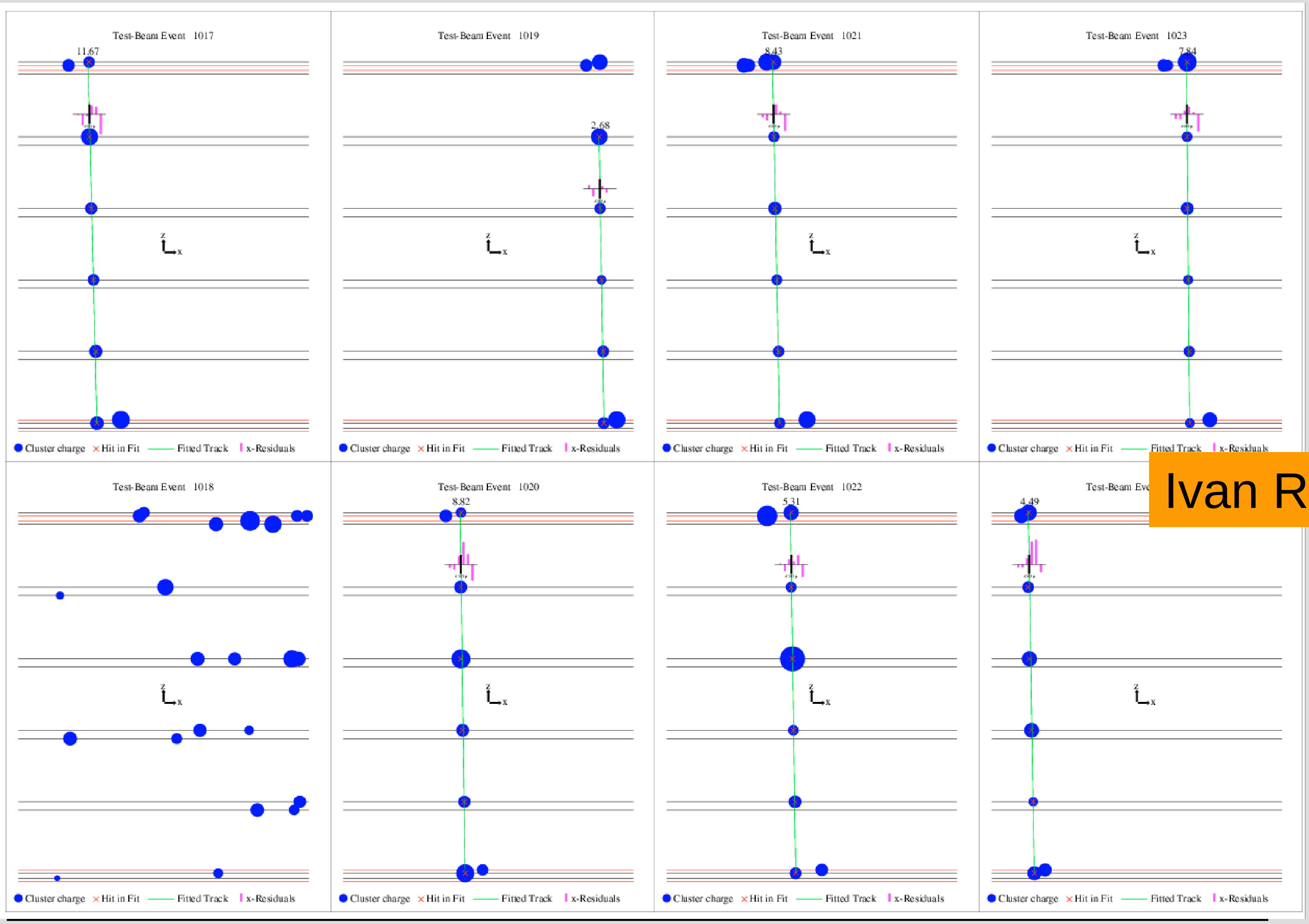
The TOB Cosmic rack in the test beam in June 2004

- Michael Eppard (CERN)
- on behalf of TOB CERN
- 23rd July 2004

S/N Module 4 @ 300V (PEAK)



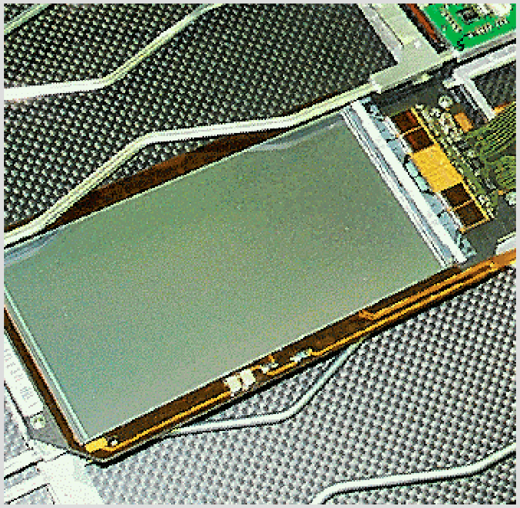
ORCA reconstruction of tracks

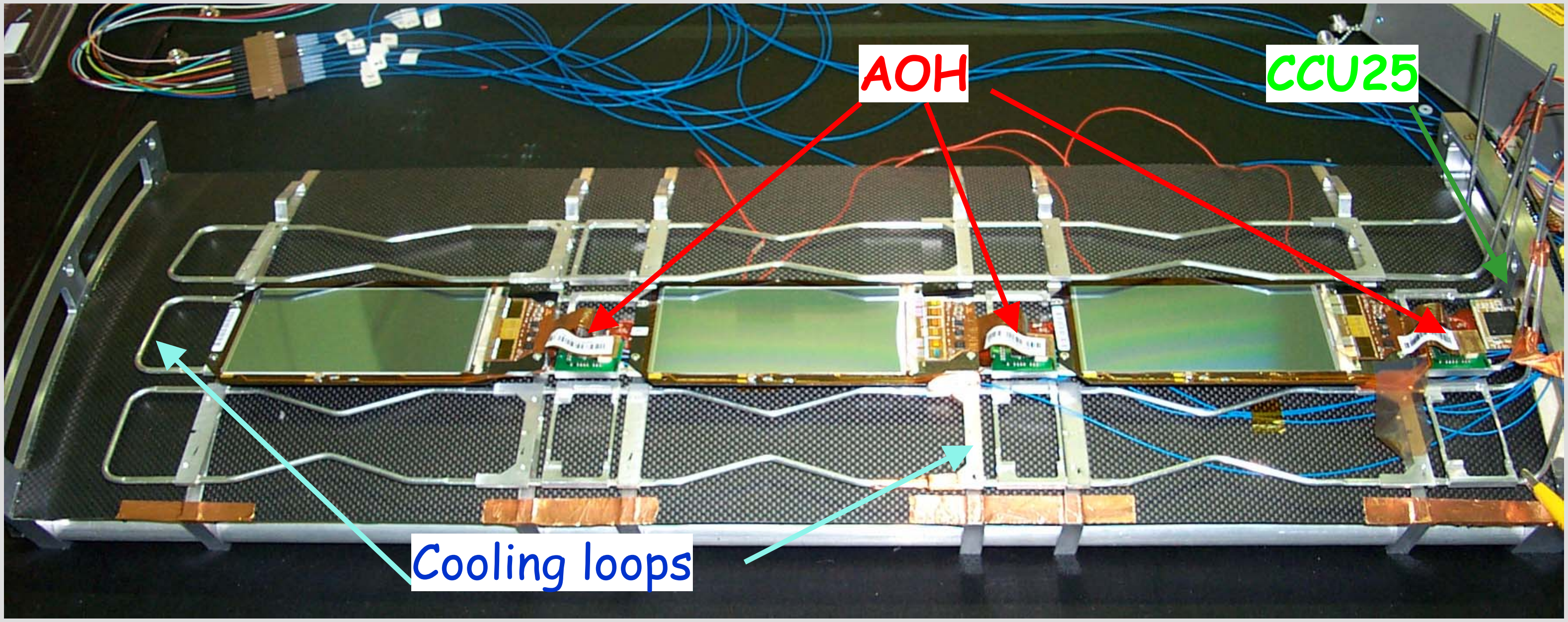


Ivan Reid

Mechanics: Tracker Inner Barrel

Support mechanics : CF space frames and/or Honeycomb structures





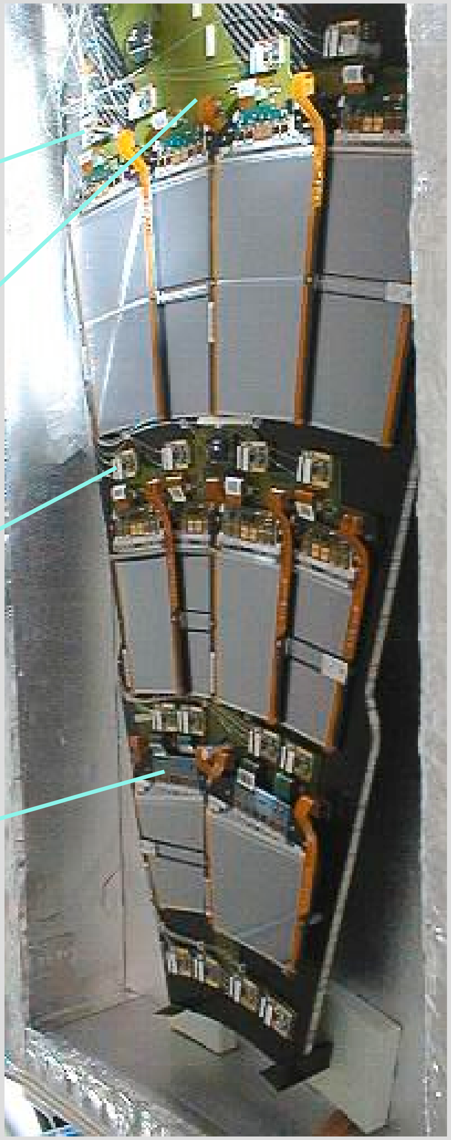
Mechanics:Tracker End Caps

Digital Optical Hybrid

Interconnect Board

Analogue Optical Hybrid

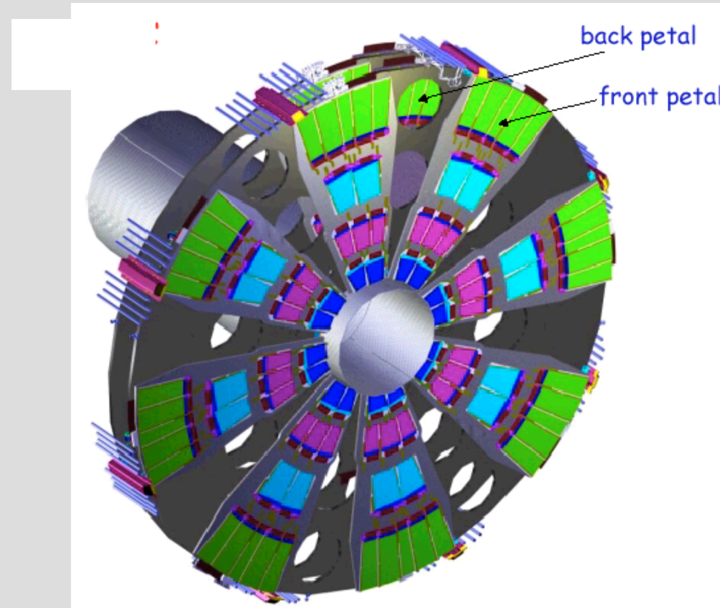
Frontend Hybrid

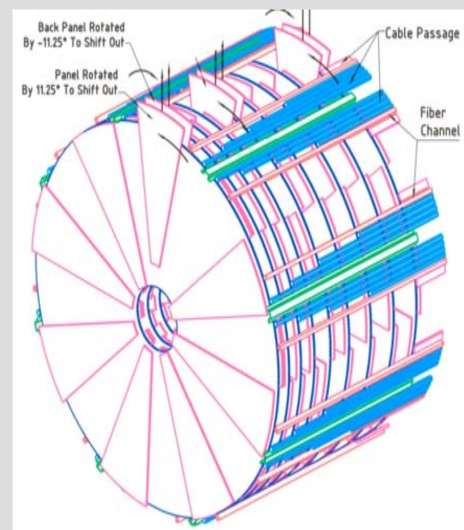


R#6

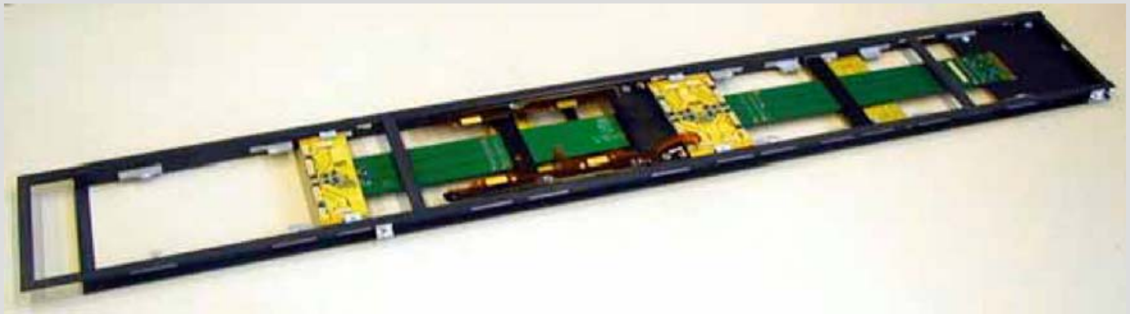
R#4

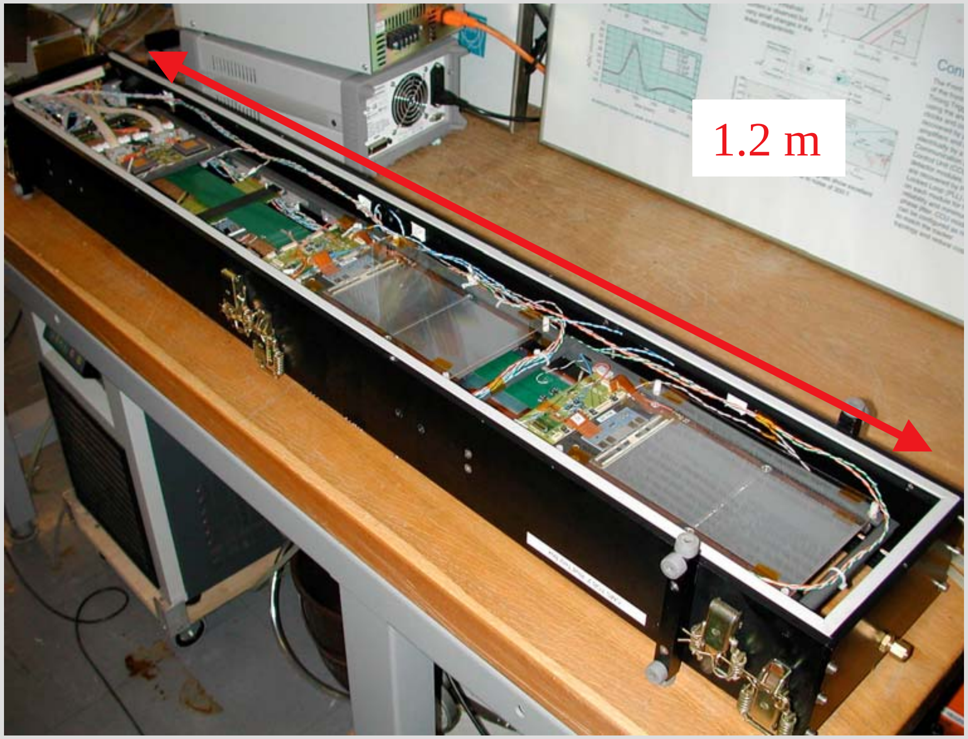
R#2



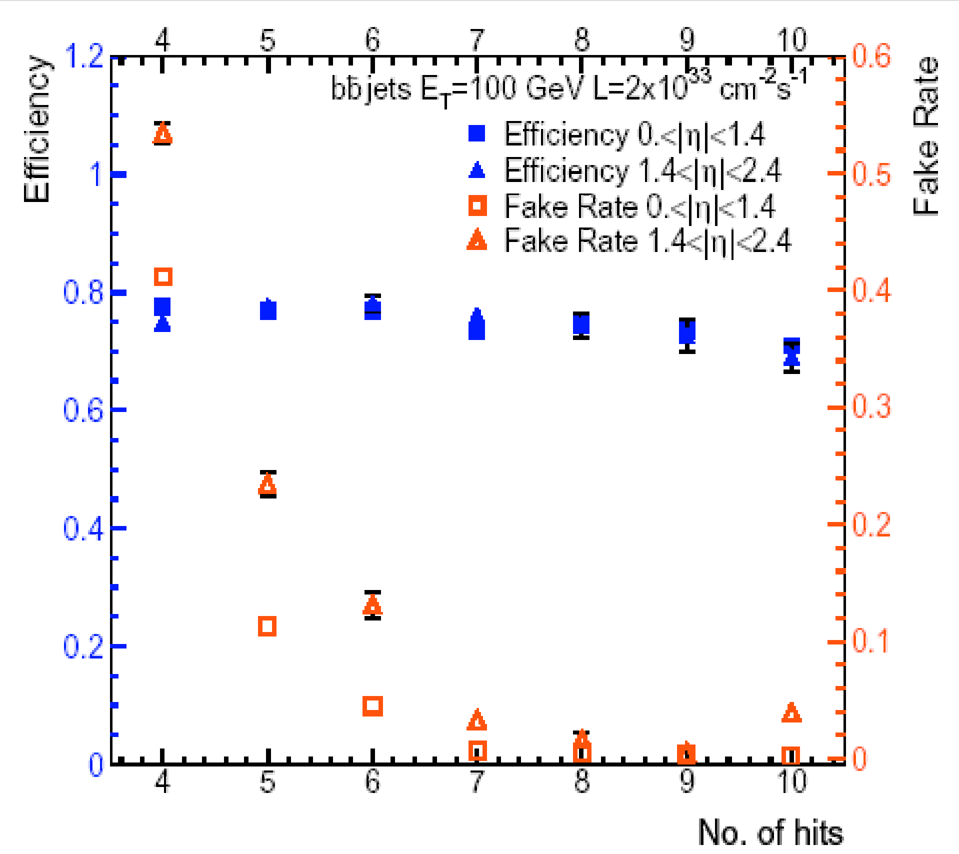


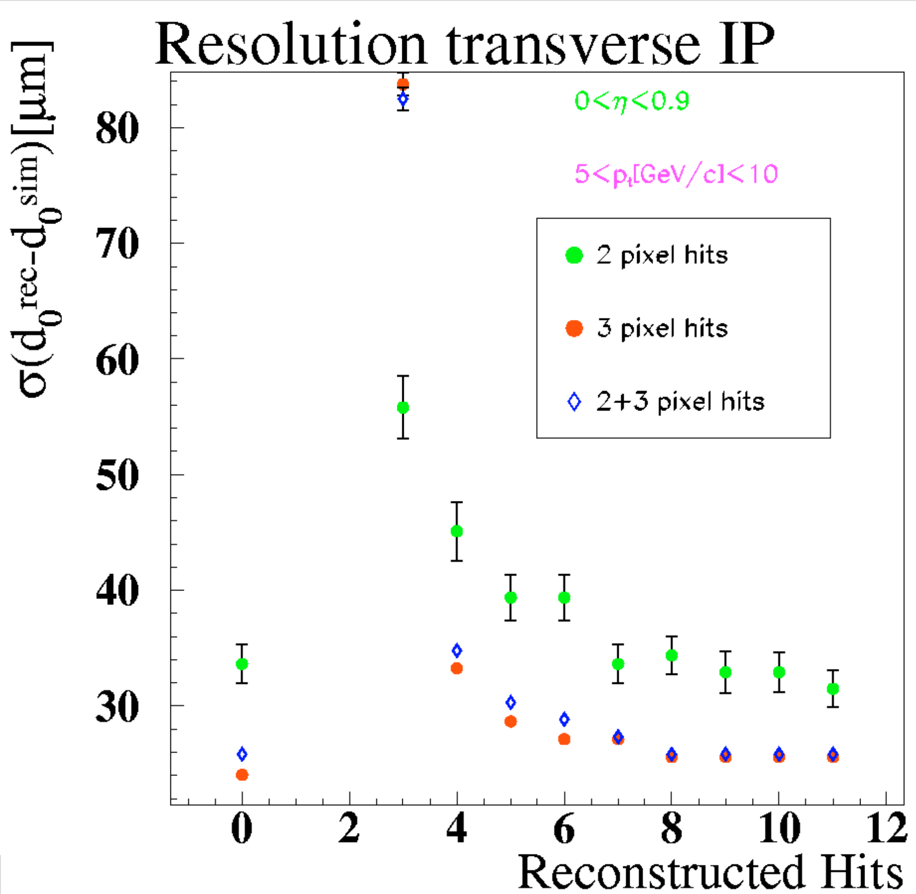
Mechanics:Tracker Outer Barrel





MC: Efficiency, Purity, Resolution





Help wanted

(taken from FPix talk May 04)

- For this project to succeed, the number of physicists, with experience in working at complex HEP projects must be urgently increased.
- Ideally, they should be committed to the Pixel project full time or for a definite period adequate for completing a given task.

Conclusion

- Tracker is an essential ingredient of CMS
  - Tracker is all Silicon: Pixels + Strips
  - Low occupancy, good resolution
- Pixels are no longer an R&D project.
  - All critical components well advanced and well-demonstrated
  - Mechanics are being readied for final assembly to start in ‘05
- Strips have been at war with poor components
  - ST sensors have too many uncertainties: switch to HPK
  - Hybrids problem is extremely well understood and will be solved but not immediately!
    - additional schedule hit
  - US Role has been extremely important
- The tracker will be late…but it may even work
- More of those who intend to use these devices have to step up to contribute now!