



CMS Tracker Module Production

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Workshop on Quality Issues in Current and Future Silicon Detectors
CERN 3-4 November 2011

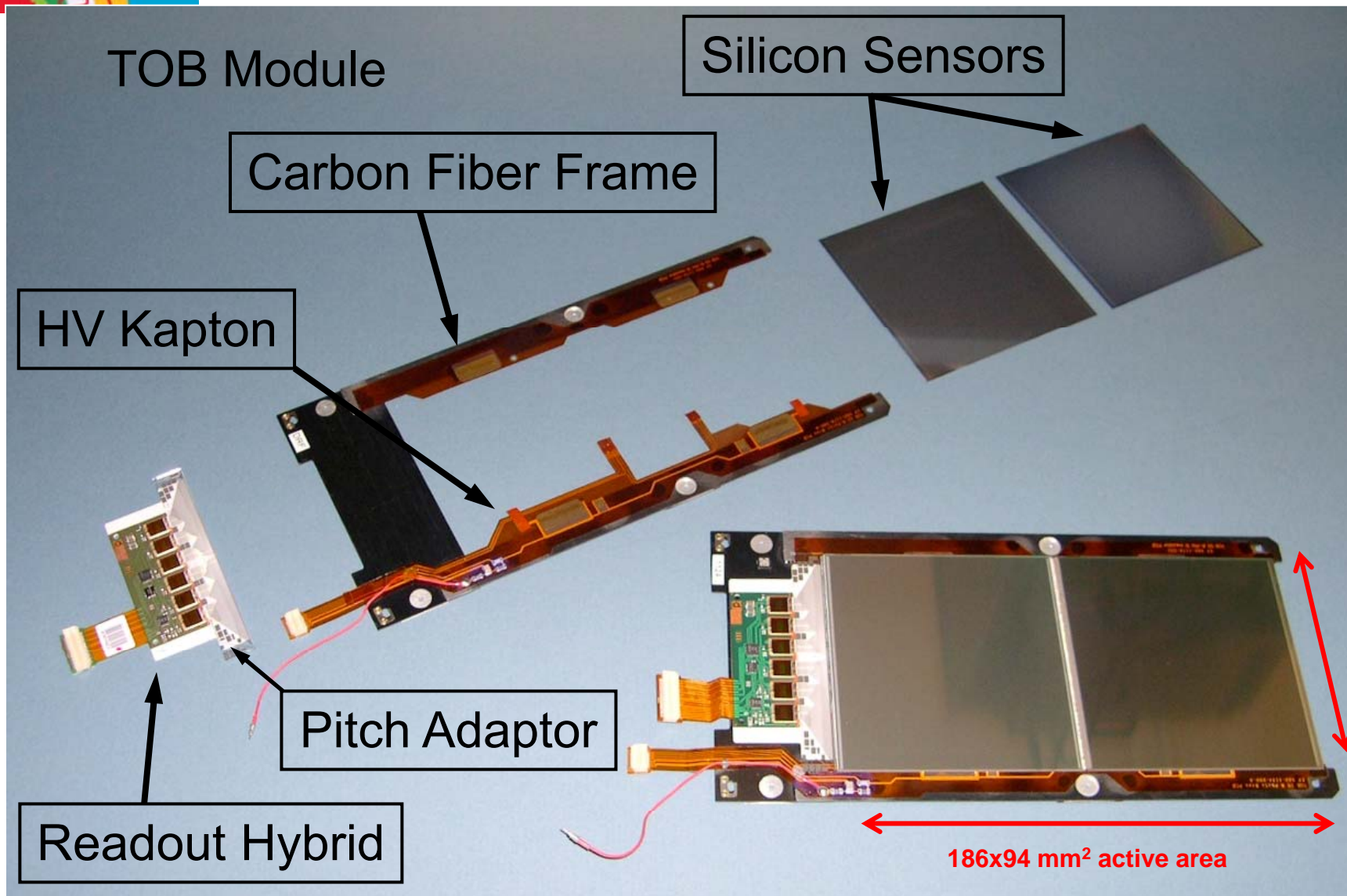


Introduction

- ♣ CMS Tracker Module Production has been a complex, time consuming, task spanning over many years:
 - ♦ We started working on our test and Quality Assurance in 1999... and Module production ended in 2006.
- ♣ It required high level of attention and care during all production years: no relax at any time!
- ♣ We have been trying to keep under control every production step and measure every parameter we estimated to be relevant for QA:
 - ♦ Did we succeed?
 - ♦ Did we make the right estimation?
- ♣ I will try to give you an overview of Module Production with some examples taken from problems we encountered and tried to solve



The "Module" and its Components

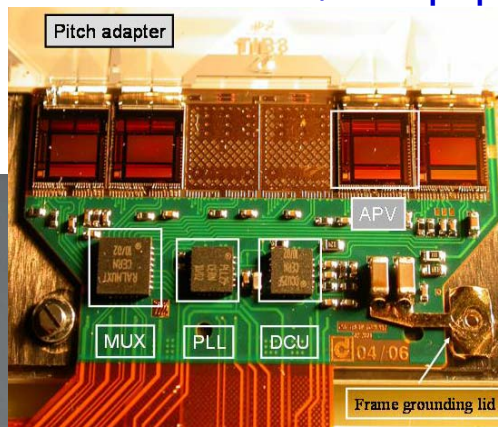
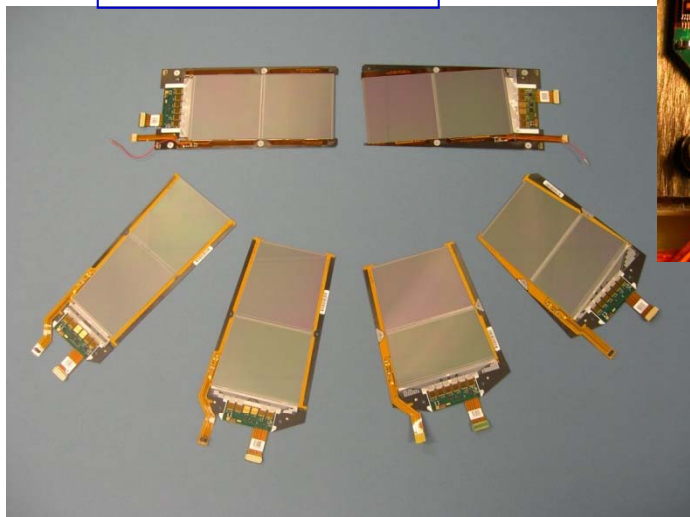




CMS Tracker Needs

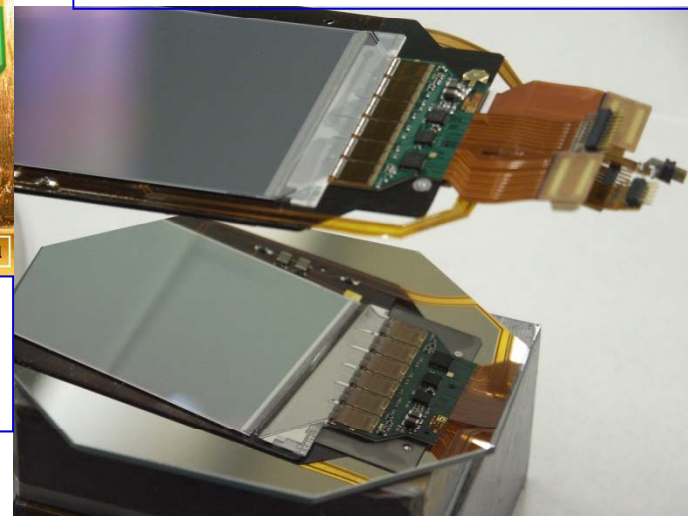
- ♣ The module is the basic detector unit consisting of 1 or 2 Si sensors daisy chained and bonded to a front end hybrid with readout and control electronics
- ♣ 15148 Detector Modules (320 μ m and 500 μ m thick detector counted together)
 - ♦ TIB 2724, TID 816, TOB 5208, TEC 6400
 - ♦ Total number of APVs is 72784 (9316352 readout channels)
- ♣ Modules came in different thickness, strip pitch, size and shape

TOB and TEC



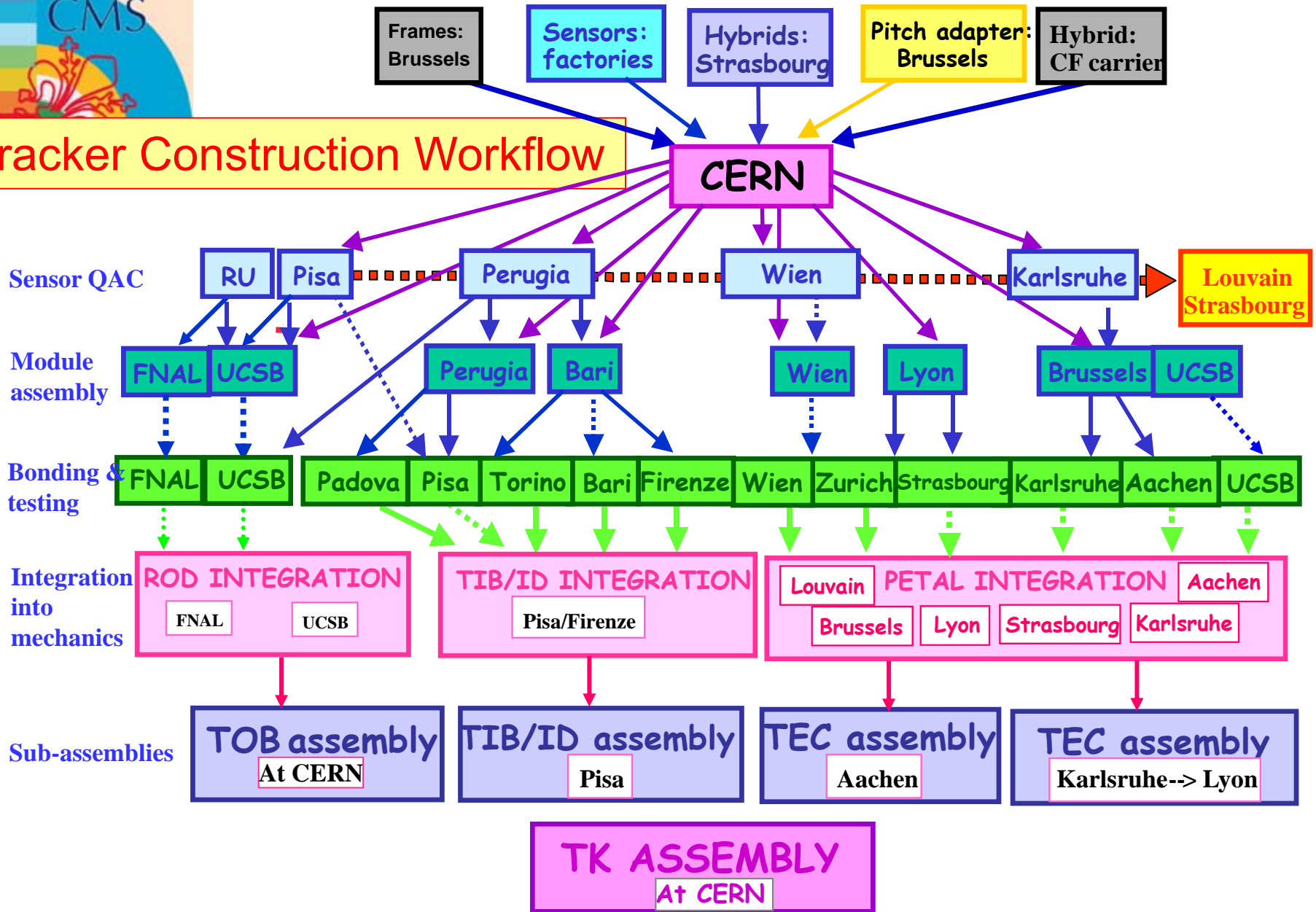
A 4 APVs TIB Hybrid with DCU, PLL, MUX, P.A., Grounding Lid

TIB double side “sandwich”





Tracker Construction Workflow





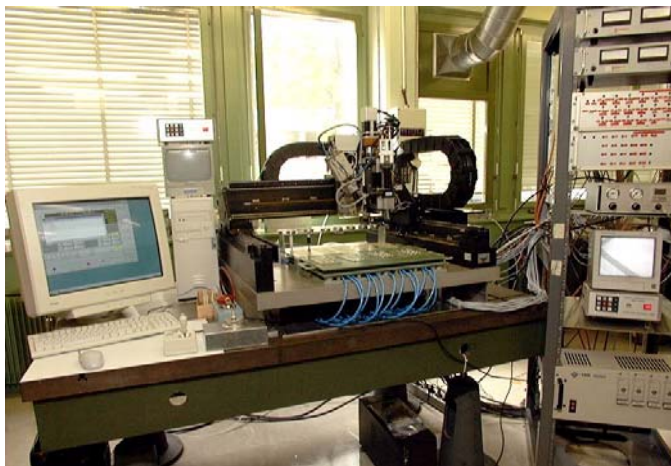
Module Production Chain

- ♣ The organization of the production was spread all over Europe and USA. Parts and modules were travelling a lot (often back and forth).
- ♣ Could these factors be a source of problems?
- ♣ Probably yes, but given the size and cost of silicon trackers, we had no other choice but a production distributed among many Laboratories. This is likely to stay valid also for future trackers.
- ♣ Many Institutes, with their personnel, history and skills are willing to contribute to production: profit by experienced people, encourage and provide help to newcomers.
- ♣ Then it becomes necessary to organize all the work according to stringent QA requirements.
- ♣ All participating personnel must adhere to the QA concept! (well, not that easy anyway...)

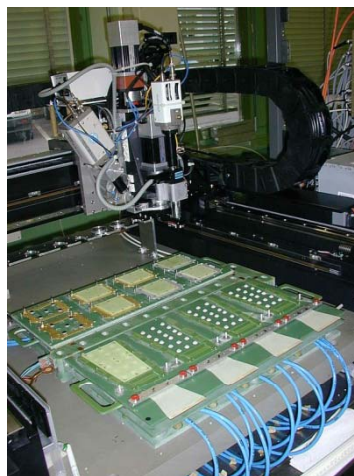


In House Production vs. Industry

- ♣ All the design effort was done inside the collaboration (ASICs, sensor masks, mechanics, frames, Kapton circuits, hybrids, pitch adapters etc.) the production split: Industry or Institutes
- ♣ ASICs, sensors, frames, Kapton and interconnect circuits, hybrids, pitch adapters **production was done in industry**
- ♣ **In our labs:** Module assembly and gluing - the CMS gantry, a really good example of automation - bonding, testing → full qualification (leading later on to TK Integration)



Workshop on Quality Issues Nov. 2011



Marco Meschini, INFN Firenze

Excellent result: 99.5%
modules within specs after
gantry assembly (TEC)

In house vs Industry is a
critical point and should be
carefully evaluated. No
simple solution, answer is
specific-case dependent



Production Steps Sequence in our Labs

* More on Hybrids tomorrow in Mannelli's talk



Wire bond hybrid*



Thermal test hybrid



Assemble module



Thermal test module



Test bonded module



Wire bond module

Here we split in 3 different streams

TIB half-layers

TEC petals

TOB rods



String integration



Single rod test



Rod burn-in

Petal burn-in



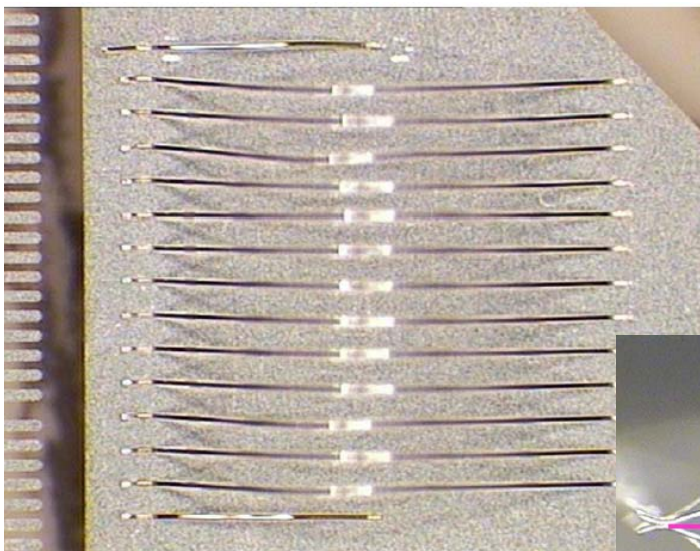
Test Procedures & HW

- ♣ The basic assumption of Module Production was that all components were already tested and qualified prior to assembly
- ♣ Modules were tested at every single production step, starting from hybrids up to final qualification for integration on tracker substructures.
- ♣ No sample test: 100% of production tested more than once
- ♣ The tests included optical inspections, mechanical tests (like bond-pull and thermal stress) and all sort of electrical tests.
- ♣ This implied a variety of HW setups, adaptable according to needs and tuned for each test phase. (Integration centres required more sophisticated, CMS-like, HW).
- ♣ Three Main HW systems used in production to equip participating labs: ARC, FHIT, Long Term (the latter including a cooling “Vienna box”)
- ♣ To be qualified for test, all centres had to measure the same specific module and find all of its faults in a consistent way



Test of Wire Bond Quality

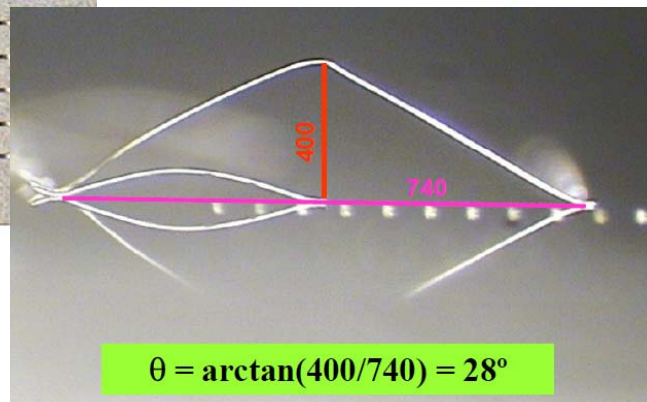
- ♣ Big effort spent on bonding
- ♣ The quality of bonds was monitored during the whole production
- ♣ Bond pull force tests were performed on the majority of modules



P.A. pull test

Pull strength > 8g
RMS 1g

Triangle deformed bond for
correction factor calculation



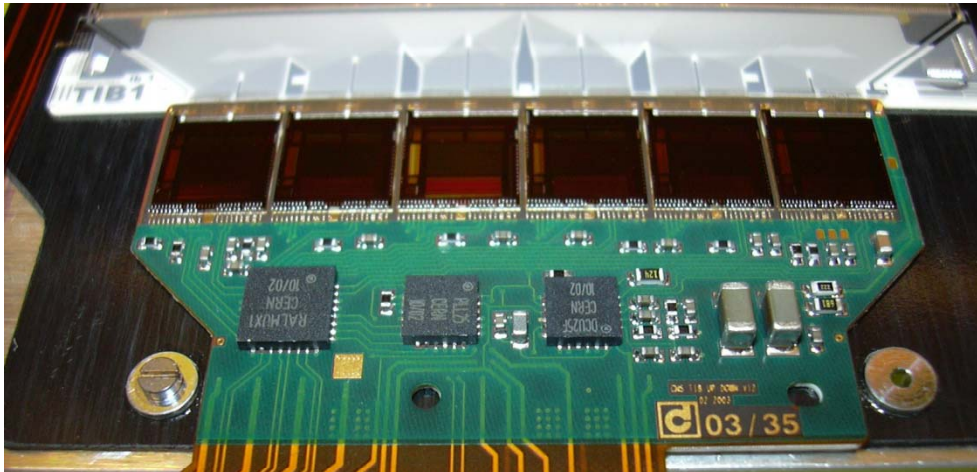
DAGE 3000 pull tester





HW Equipment: FHIT

♣ FHIT (Front-end Hybrid Industrial Tester)



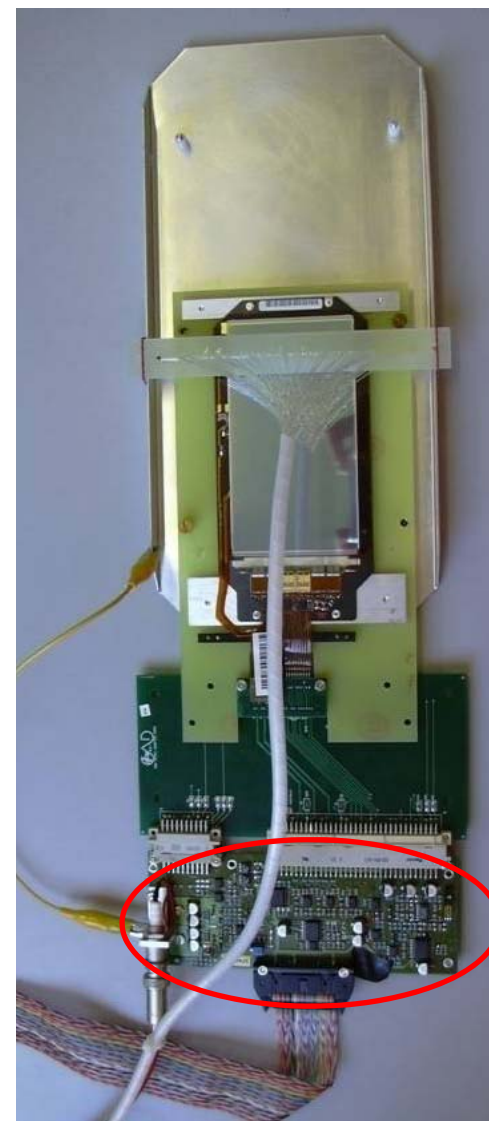
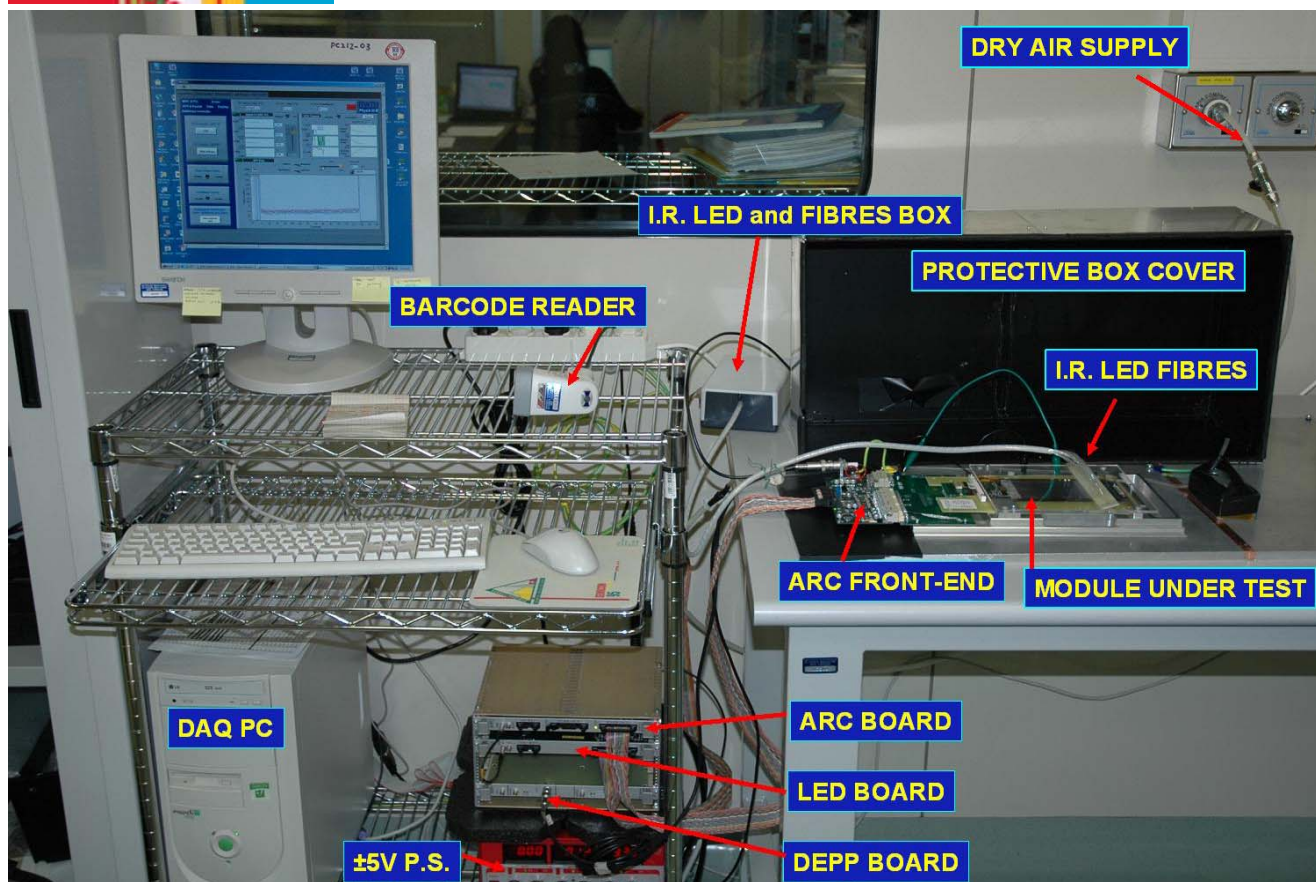
There is a Light version “LFHIT” for use in labs for electrical functionality verification, very fast, Yes/No output

Industry Model





HW Equipment: ARC System



- ♣ ARC used both for Fast and Deep tests
 - ♦ Stand-alone system, compact and not expensive
- ♣ Highly efficient for pinhole finding



HW Equipment: Long Term System

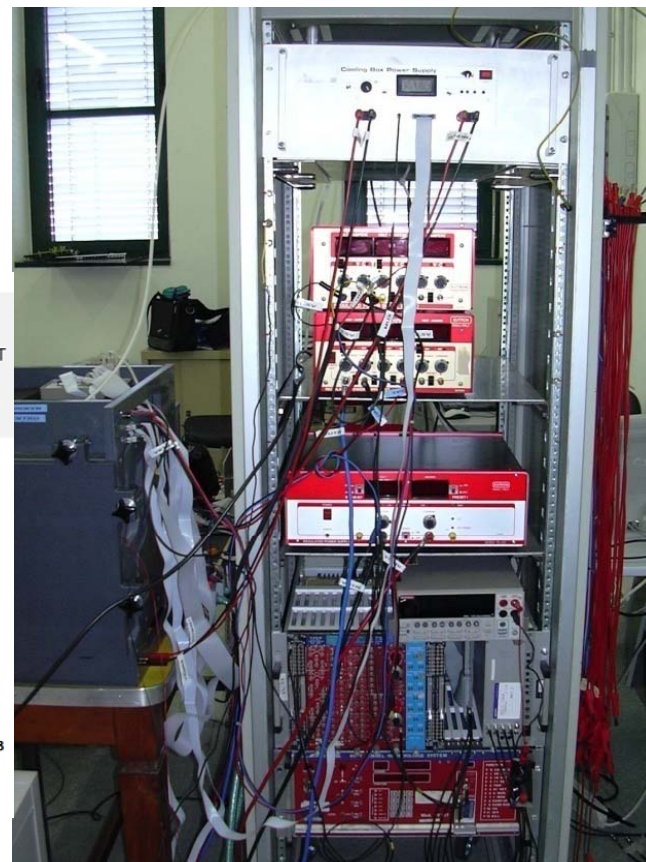
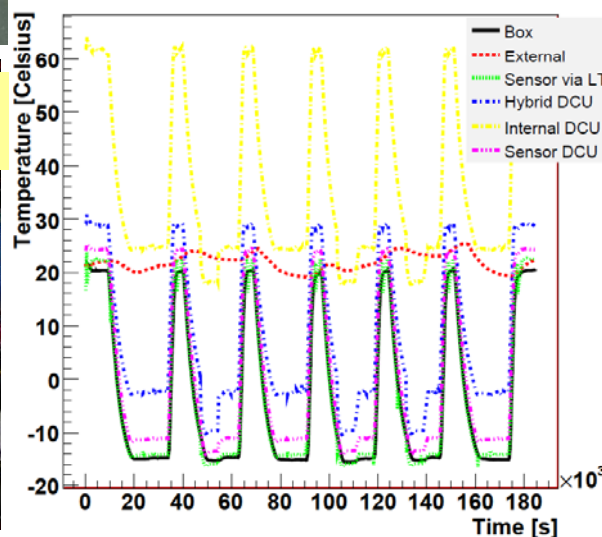
- ♣ The LT is a complex system, with many interfaces, not cheap but very flexible
- ♣ Usually 3 days tests with thermal cycles, then reduced to 1 day



Temperature [°C]
Measurements vs time in LT



Same box now in use
for Upg. Sensors R&D





Test Sequence, HW and QA

- ♣ The electrical tests measured, at different levels, many quality-related “observables” like IV currents, LV currents, Single Readout Channel Noise, Common Mode Noise, Signal Amplitude; in addition all the Module ASICs were exercised and the output parameters recorded, together with measurements of temperature and humidity during tests.
- ♣ During Long Term tests all the measurements were repeated while thermal cycling the modules
- ♣ Beware! No operation is risk free

Module broken during optical inspection: the microscope lens fell down on the sensor ☹
After this event we added a line in the checklist:
Once/wk: verify screw tightening of all optical equipment





Repair centres

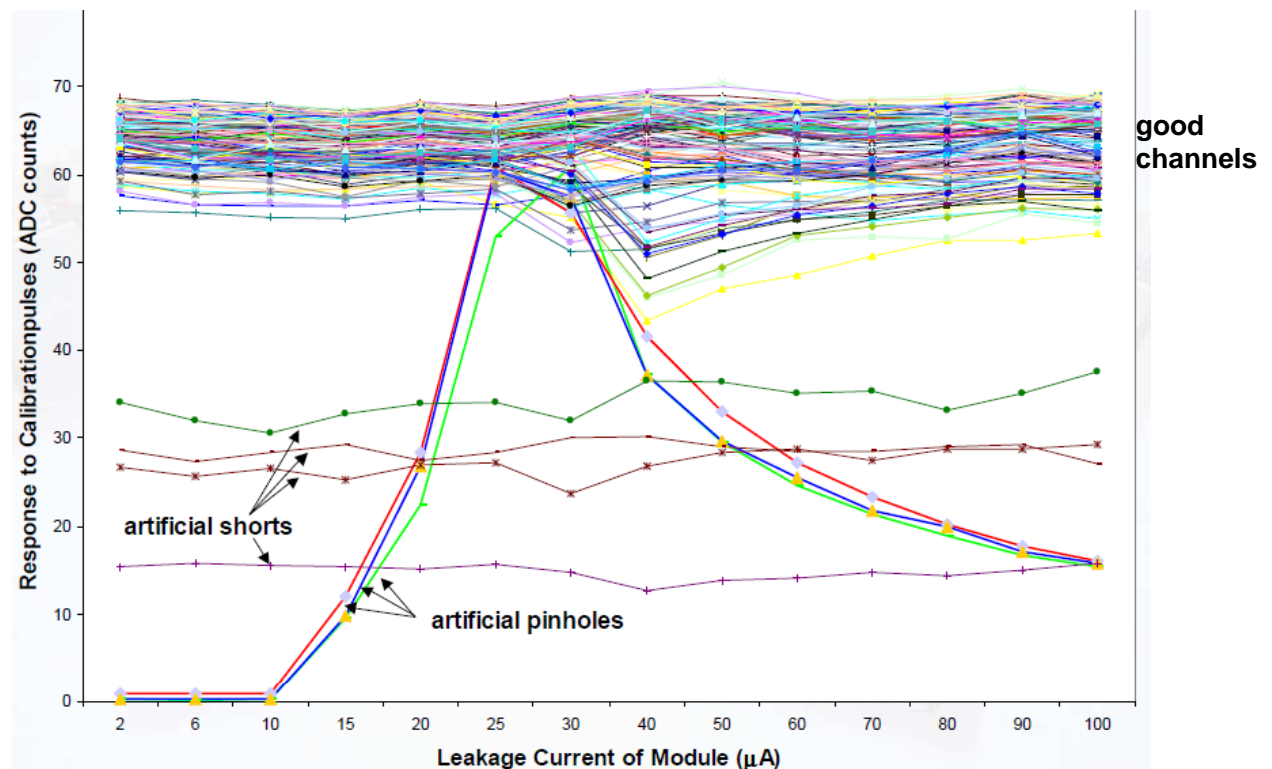
- ♣ Some defects could be, under special circumstances, be repaired and modules or parts be recovered
 - ♦ Touched/broken bonds (not on APV)
 - ♦ Too much/not enough glue
 - ♦ Hybrid/carbon fibre Frame defects → Sensor recuperation
 - ♦ Sensor scratches are mostly fatal → Hybrid/Frame recuperation
- ♣ Repair centres set up both in Europe and USA
- ♣ This was very helpful since we had limited number of spares
- ♣ Particularly useful during integration, which was an operation with high risk of damage, when module production was already finished



"Standard Problems"

- ♣ Pinholes: identified by a noise and signal amplitude measurement done in combination with a high photon-generated bulk current flowing through the detector.
- ♣ No known pinholes missed. A few cases of other defects identified as PH

Signal Amplitude vs Induced Leakage Current plot for a module with artificial pinholes and shorts





"Standard Problems"

- ♣ Dead/Noisy/Electrically Shorted channel: identified by noise and signal amplitude measurements → un-bond from APV
- ♣ All tests repeated in the 4 APV working modes:
 - ♦ Peak
 - ♦ Deconvolution
 - ♦ Inverter on
 - ♦ Inverter off
- ♣ Humidity: some sensors were prone to high humidity, giving rise to high leakage currents. The first solution was to not expose them to humidity (try to dry them in case it happened) and test them in conditions with a Relative Humidity around 30% → standard procedure. But this was not the end of the story...



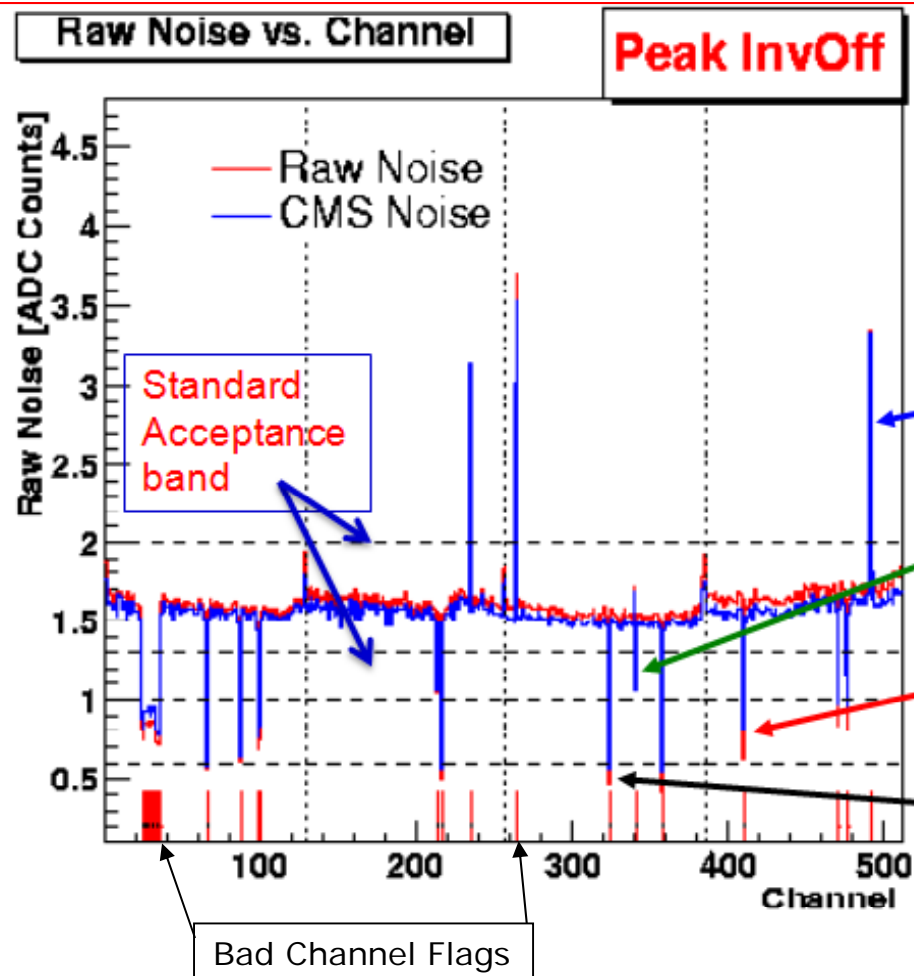
How to Identify Faults

Noise Measurement on a 4 APV Module

Need the fault types to have significantly different responses in order to fully automate fault finding

Different threshold values used to select different defects

Full efficiency in defects finding!



Noisy Channels

1 Sensor Opens

2 Sensors Opens

Pinholes

CMS has many different module types: finding sets of cuts and thresholds to identify defects was a very long job



“Hard-to-find” Failures

- ♣ A general problem: “simple” defects can be spotted very easily with normal experience, “good practice” and well written SW code as seen before. But during CMS module production we were confronted with many subtle problems which delayed significantly our production
- ♣ These kind of problems usually fall in one or more classes:
 - ♦ intermittent in time
 - ♦ appearing after long operation period
 - ♦ appearing only under special conditions
 - ♦ appearing in subsets of modules and not affecting all batches
- ♣ Here a philosophical question arises: how to find a balance between paranoid search for every single possible unknown defect and the time slot allowed for production? If we miss the equilibrium solution we rush into disaster:
 - ♦ **a poorly working detector or**
 - ♦ **an incomplete detector.**
 - ♦ **In both cases we may eventually end with no detector at all**
- ♣ I have no definite answer here. We can just study each case and find an ad-hoc solution... or find a QA expert who knows about HEP world!



Examples of hard to find defects: vias on Hybrid

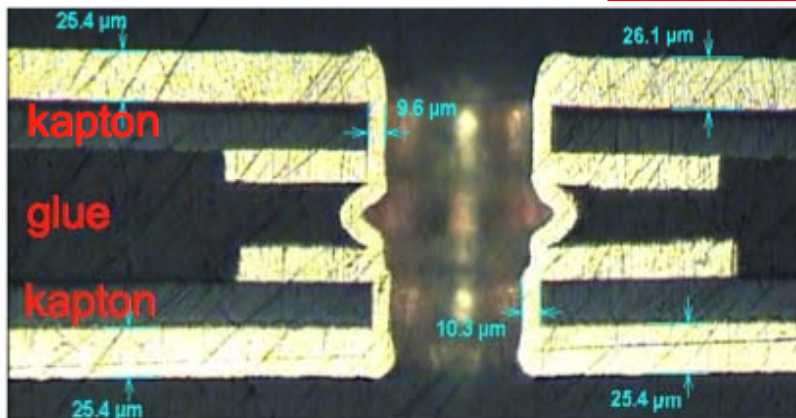
- ♣ Readout chips were failing due to thermal and mechanical stresses: vias were inconsistently plated and becoming open
- ♣ Low rate of failures, from 0.5% in TIB up to 5% max in TOB. Intermittent and difficult to reproduce

The effect was seen, in some cases, as a drift towards 0 of the APV output baseline

To overcome the problem the firm improved via drilling technique, improved QA, and modified hybrid design

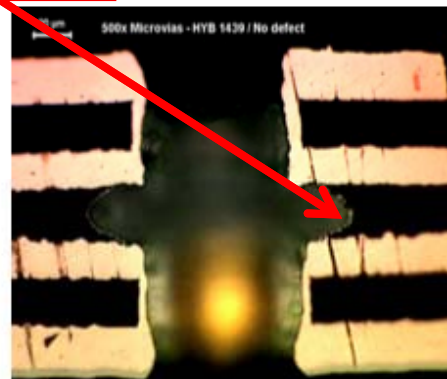
100 μ m diameter via

Old design



Poor copper deposition, bad contact

Bad via



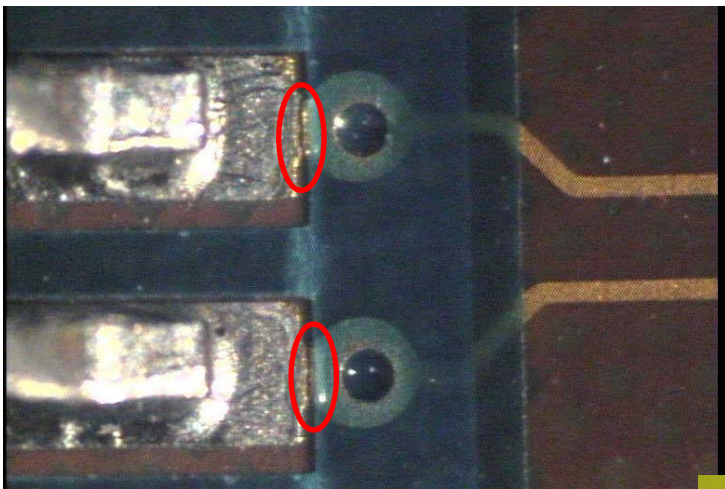
New design





Examples of hard to find defects: Kapton tail on Hybrid

- ♣ The Kapton tail printed circuit could break under mechanical stress, but might still made contact in case of no stress



A Stiffener added just
behind critical area
Circuit layout modified

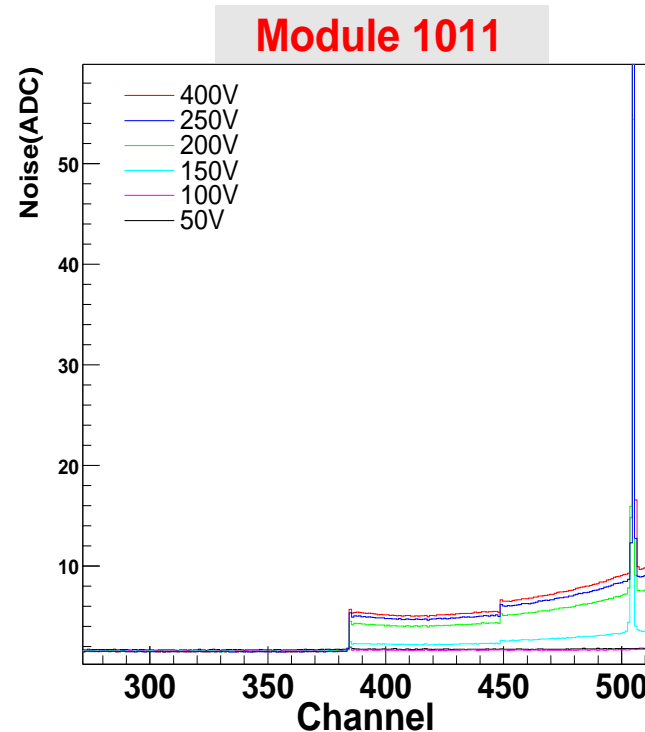




A Serious Problem (with non-negligible consequences)

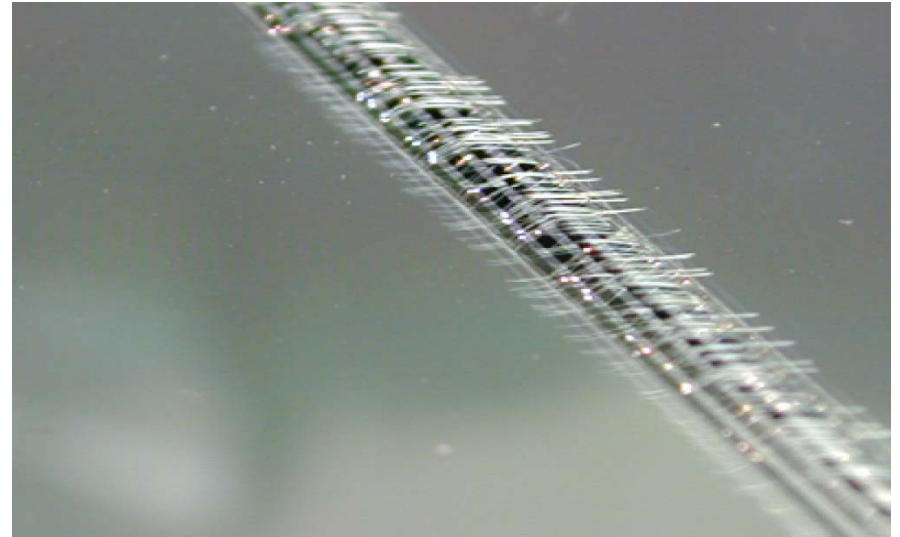
- ♣ An important fraction of thick modules showed Common Mode Noise problem on single APV chips during Module Test
- ♣ A correlation was found with 1 or 2 noisy strips, connected to the APV, possibly showing HV micro-discharges. Humidity made things worse
- ♣ High HV current flows through those strips and degrades noise performance

Seen on TOB modules then also on TEC, becoming worse with time/humidity. AKA “Dots and Stains”.
Difficult to understand the origin, firstly attributed to Mishandling, or to HV equipment or setup problem.
Long discussion inside community, only STM sensors affected... eventually the cause was Aluminum corrosion: it degraded HV performance.
STM requalification process needed.
New thick sensors ordered to HPK.
There are still left-overs from this event...





Learning: something not going “perfectly fine”?

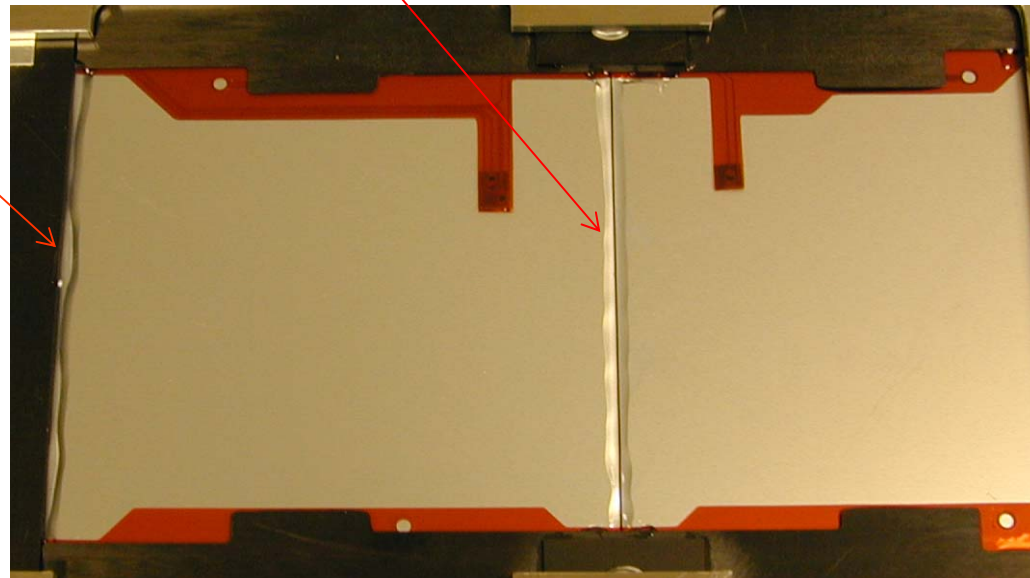


- ♣ Four shipments of modules from the USA to CERN by 3 different methods of transport:
 - ♦ All were damaged in similar manner.
 - ♦ Many broken bonds – particularly between sensor and pitch adapter.
- ♣ At UCSB they performed extreme drop tests that also resulted in sensor to sensor bonds being broken as shown above
- ♣ After ample discussion it was decided to add “elastic” glue in critical areas



Must Be Elastic and React to Stress

- ♣ Sylgard is a silicon based elastomer
 - ♦ Used to encapsulate ALL wire bonds on innermost layer of CDF
 - ♦ Working temperatures -50°C to 200°C
 - ♦ Radiation hard
 - ♦ Low thermal conductivity
- ♣ Applied long or short beads of this material to back sides of modules at sensor-pa joint and sensor-sensor joint

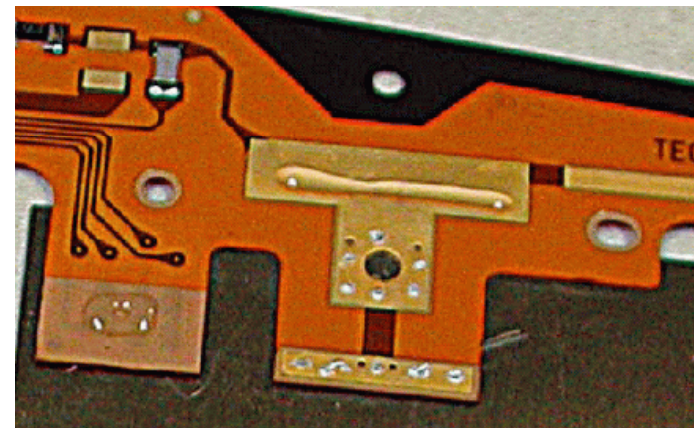




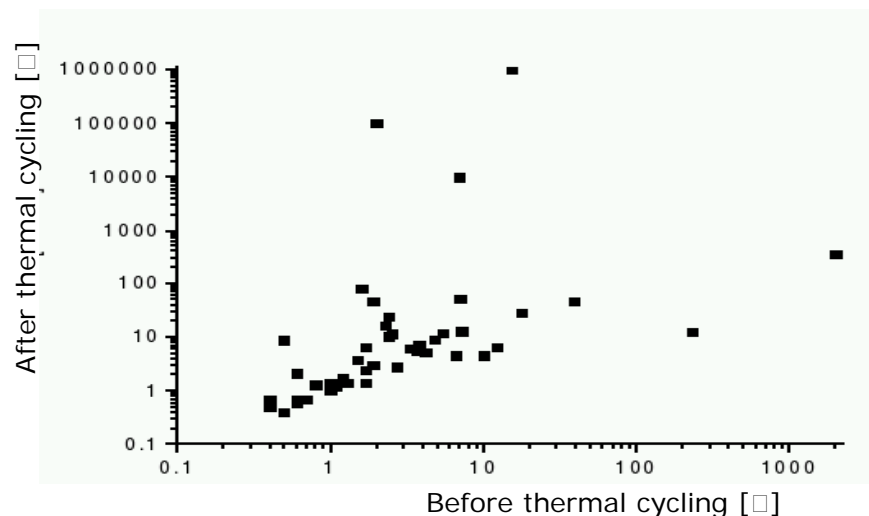
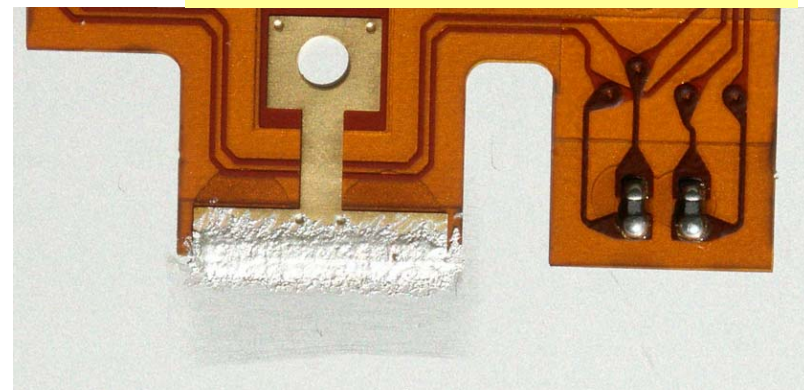
HV Backside Connection

- ♣ Problem for TEC and TOB: bias contact to backplane getting more and more resistive with time
 - ♦ TEC: gold surface on Kapton circuit pad glued to sensor back plane → silver Epoxy glue spots on aluminum unreliable
- ♣ First approach: “glue enhancement”, partially satisfactory due to possible oxydation

TEC: silver epoxy
old-type backside contact



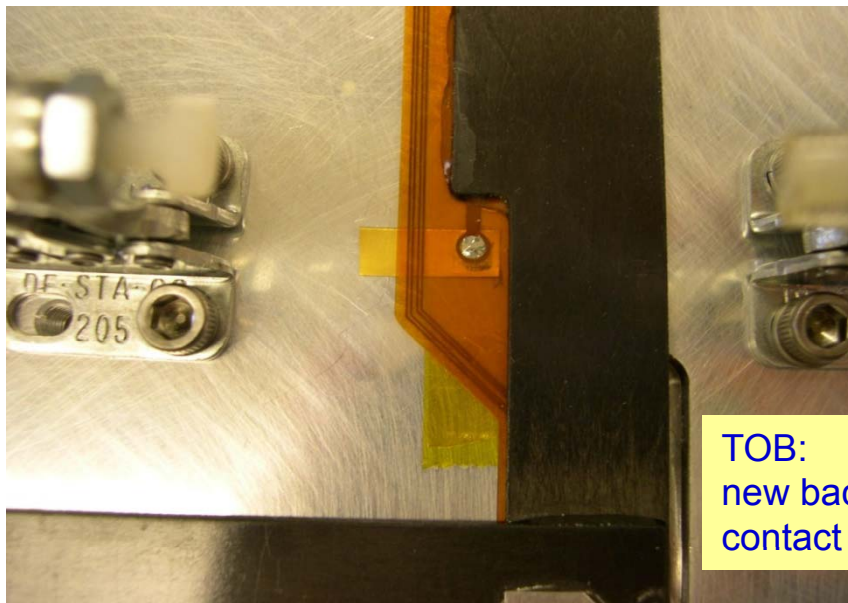
TEC: silver epoxy enhanced
new-type backside contact



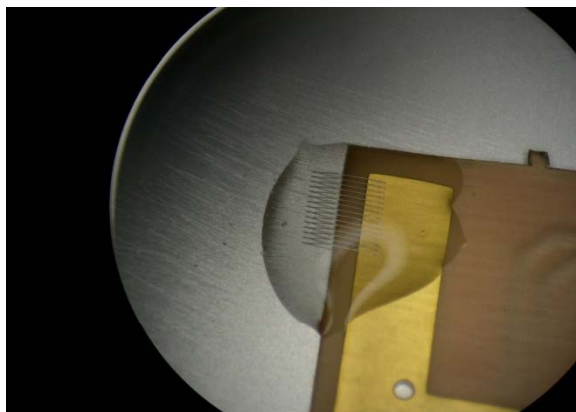


HV Backside Connection

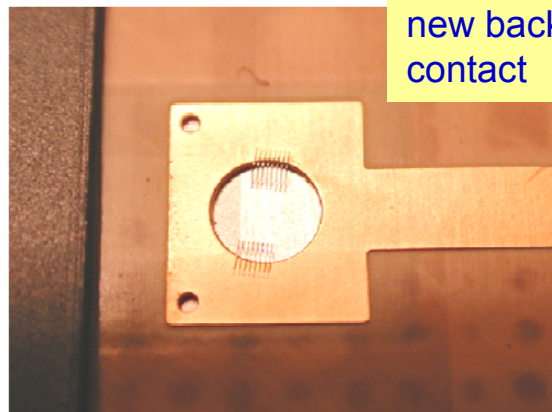
- ♣ Solution: HV contact was wire-bonded for the complete production, retrofitting already built modules (TOB), 355 in TEC with enhanced glue
- ♣ Hint for the future: **always go for bonding**, do not rely on conductive glue for long term reliability



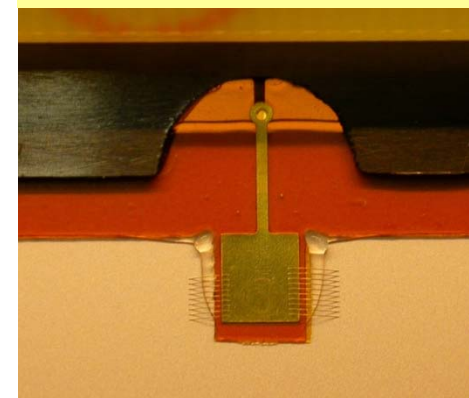
TOB:
new backside
contact



TEC:
new backside
contact

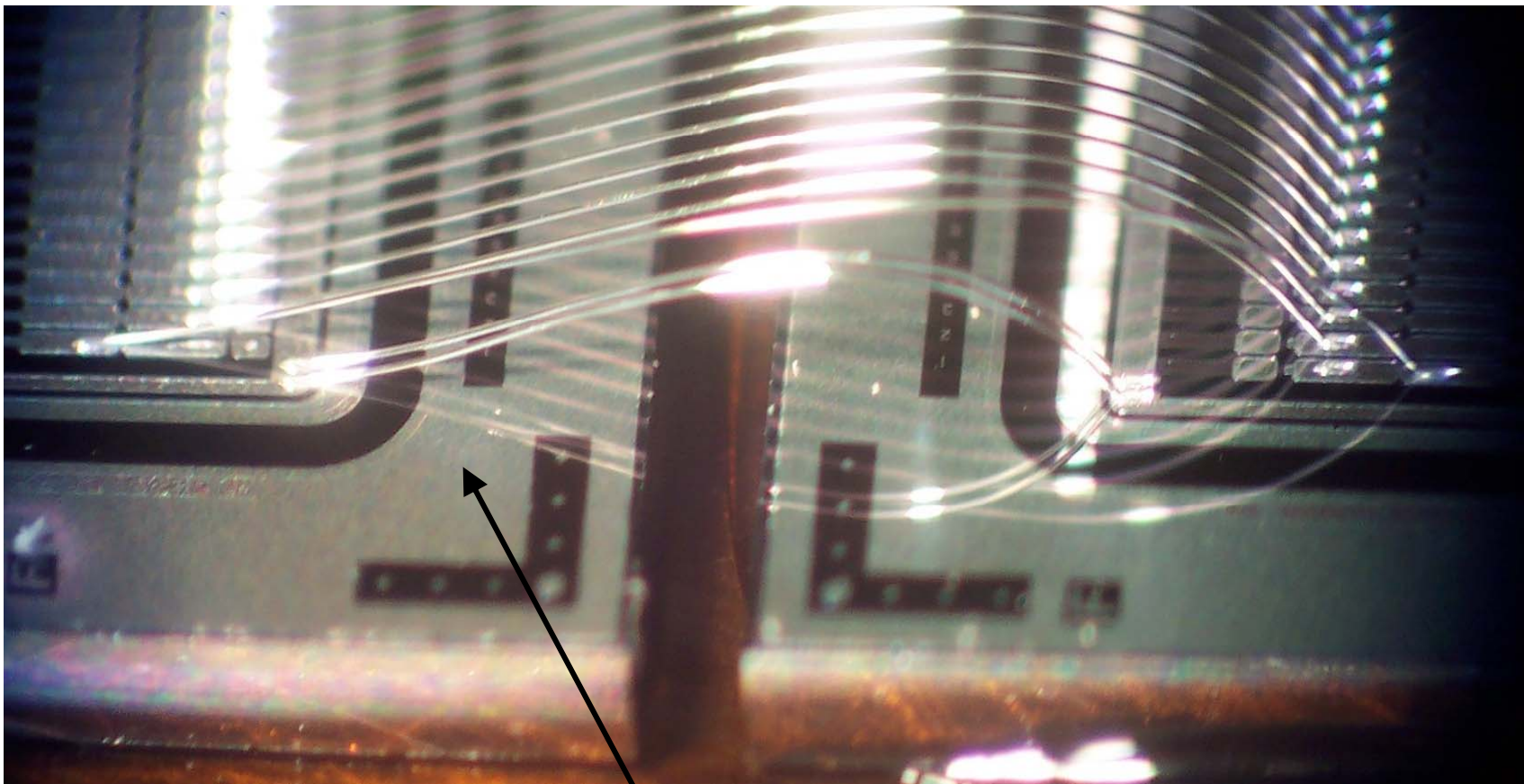


TIB: standard backside
contact, conductive glue
never used here





HV Sparks



Bonds are at ground, this area (n^+) is at bias voltage (400 V). The height of the bonds over the area is $\sim 100 \mu\text{m} \Rightarrow 4\text{MV/m}$ E field: DANGER!

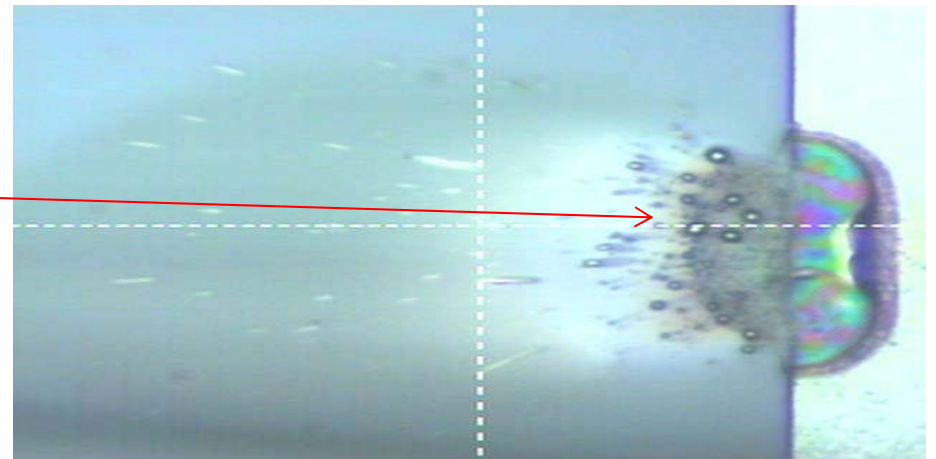
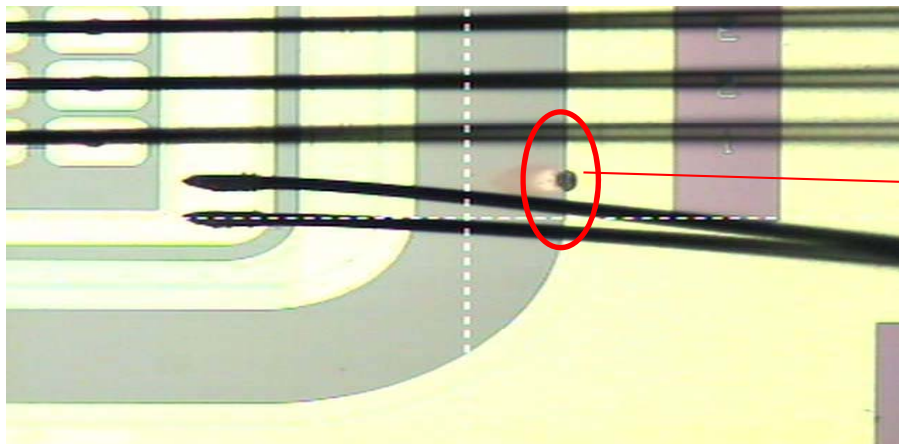


HV Sparks Solution

♣ Sparking was found during rod testing; maybe due to HV supply malfunctioning?

- ♦ Revealed weakness in the sensor bonding that should be addressed. Low bonding loop height

♣ Re-bonded low bias wires and encapsulated to increase safety margin

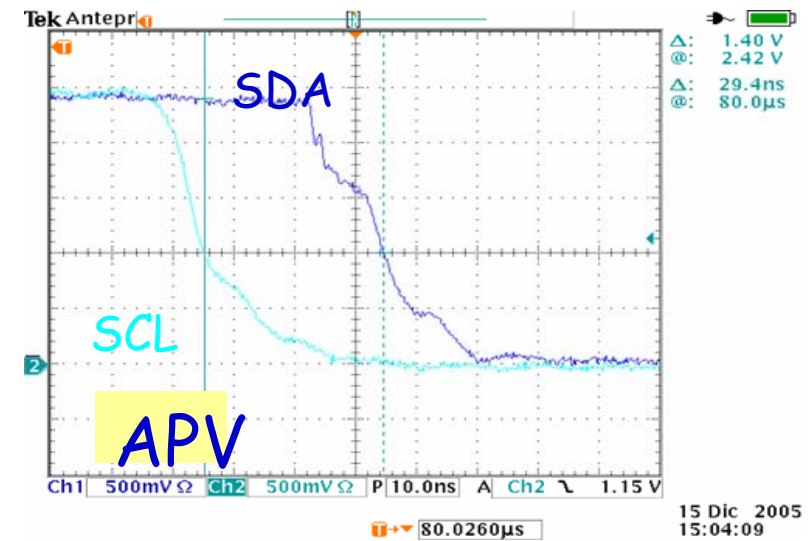
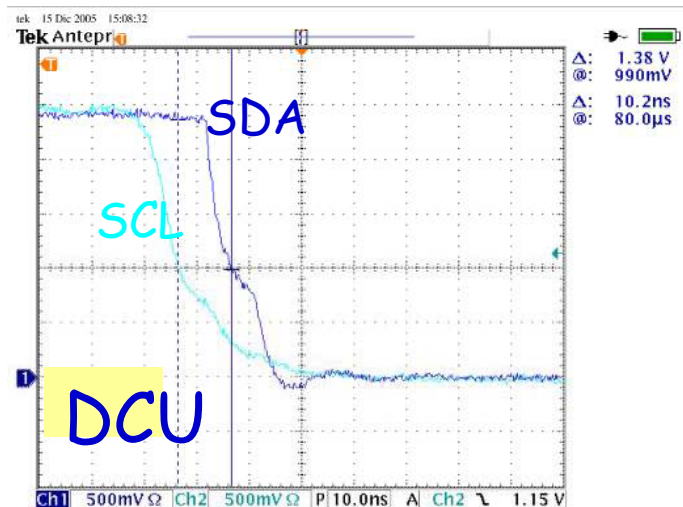


Caveat: new bonding specifications



I²C

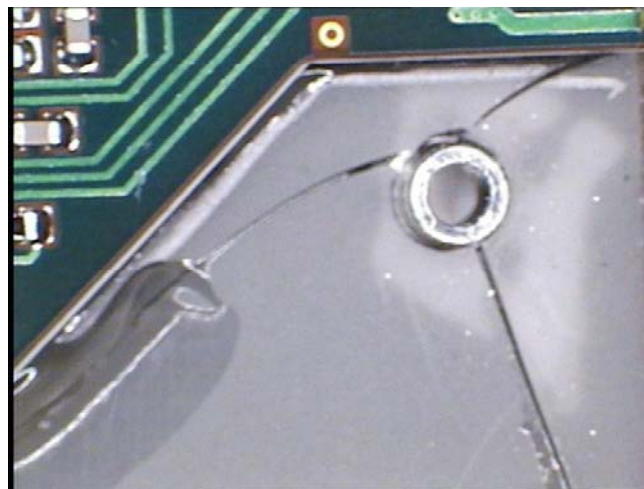
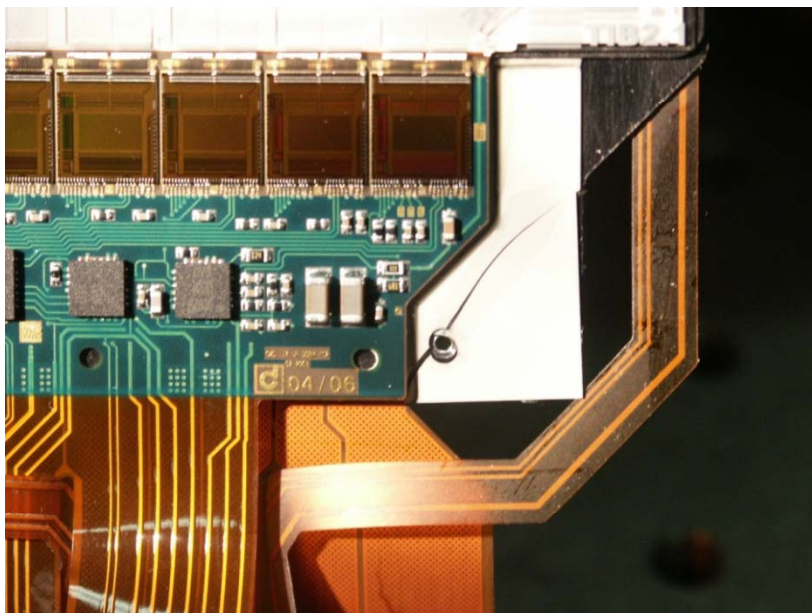
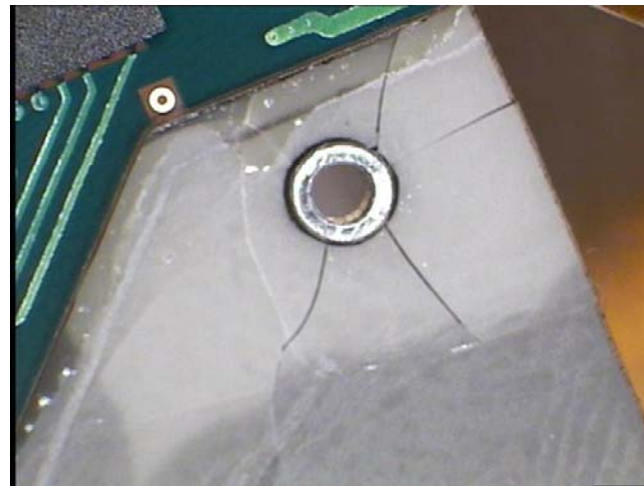
- ♣ Communication problems: I²C
- ♣ First issues seen during Long Term test in cold: lost communication with one or more modules. Later on seen also in TIB Integration.
- ♣ Extremely tricky to find the origin of the fault, no module failed in “stand-alone”, try to force failing with extreme conditions, very low temperatures
- ♣ Since then a lot of studies in all sub-detectors showed some marginality in the I²C clock /data levels and transition times (TOB rods)
- ♣ Modification in I²C distribution circuits fixed the problem
- ♣ We'll see when we'll go really cold in P5!





"Minor" (?) Problems

- ♣ During integration a few Double Sided modules with Ceramic Plate with cracks were found: this had nothing to do with module test, since DS module were paired in "sandwich" after tests
- ♣ Almost impossible to trace back WHEN exactly the cracks appeared (during pairing? assembling? packaging? shipping?)
- ♣ Might affect thermal performance/cooling

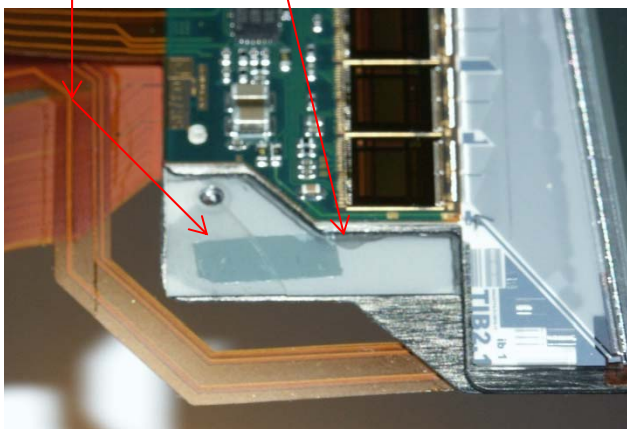
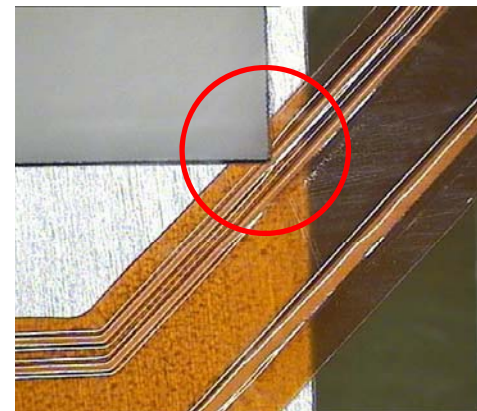


Did it require
to be better
engineered for
QA?

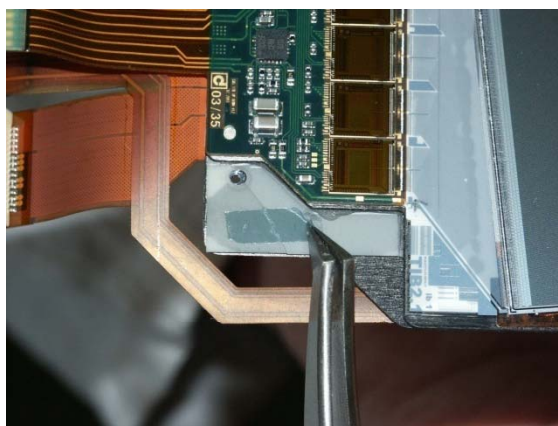


Lesson for the Future: It should not happen...

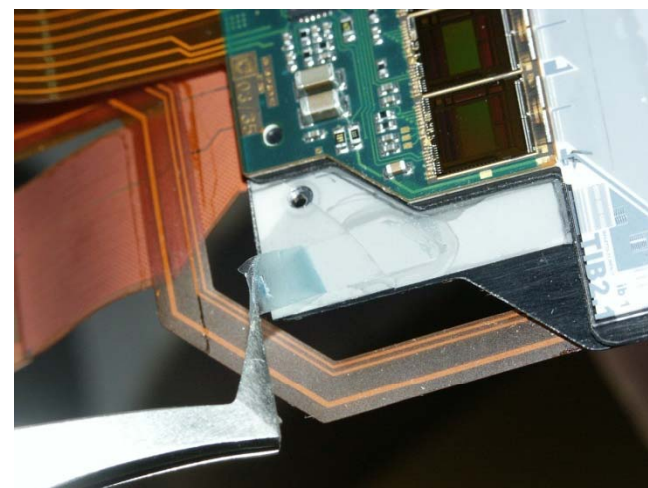
- ♣ Cracks and glue excess are source of troubles
- ♣ This happened at the end of module production, so
 - ♦ no more time to build new module
 - ♦ no more time to react
 - ♦ almost no spares available
- ♣ This kind of issues should be spotted and addressed well in advance
- ♣ Scotch tape on a ceramic crack is NOT a solution
 - ♦ obviously enough it was removed: a lot of work and a risky operation
 - ♦ glue excess and not-perfect positioning make integration impossible



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Tracker Module Production Summary

*	Modules produced	Good after assembly	Bad	% good
TIB/TID (inner barrel/disks)	3945	3810	135	97%
TOB (outer barrel)	5434	5348	86	98%
TEC (Endcap disks)	7228	6761	467	94%
Total	16607	15919	688	96%

- ♣ Bad Channels after Module Production for qualified modules was definitely below 0.1%
- ♣ We have built sturdy Modules of excellent quality: they survived the hostile campaign of Tests and Integration
- ♣ These results answer our question: QA has been working in CMS Module Production and we identified and measured the relevant quantities to spot defects.

* Modules built with non-qualified hybrids not included in this table



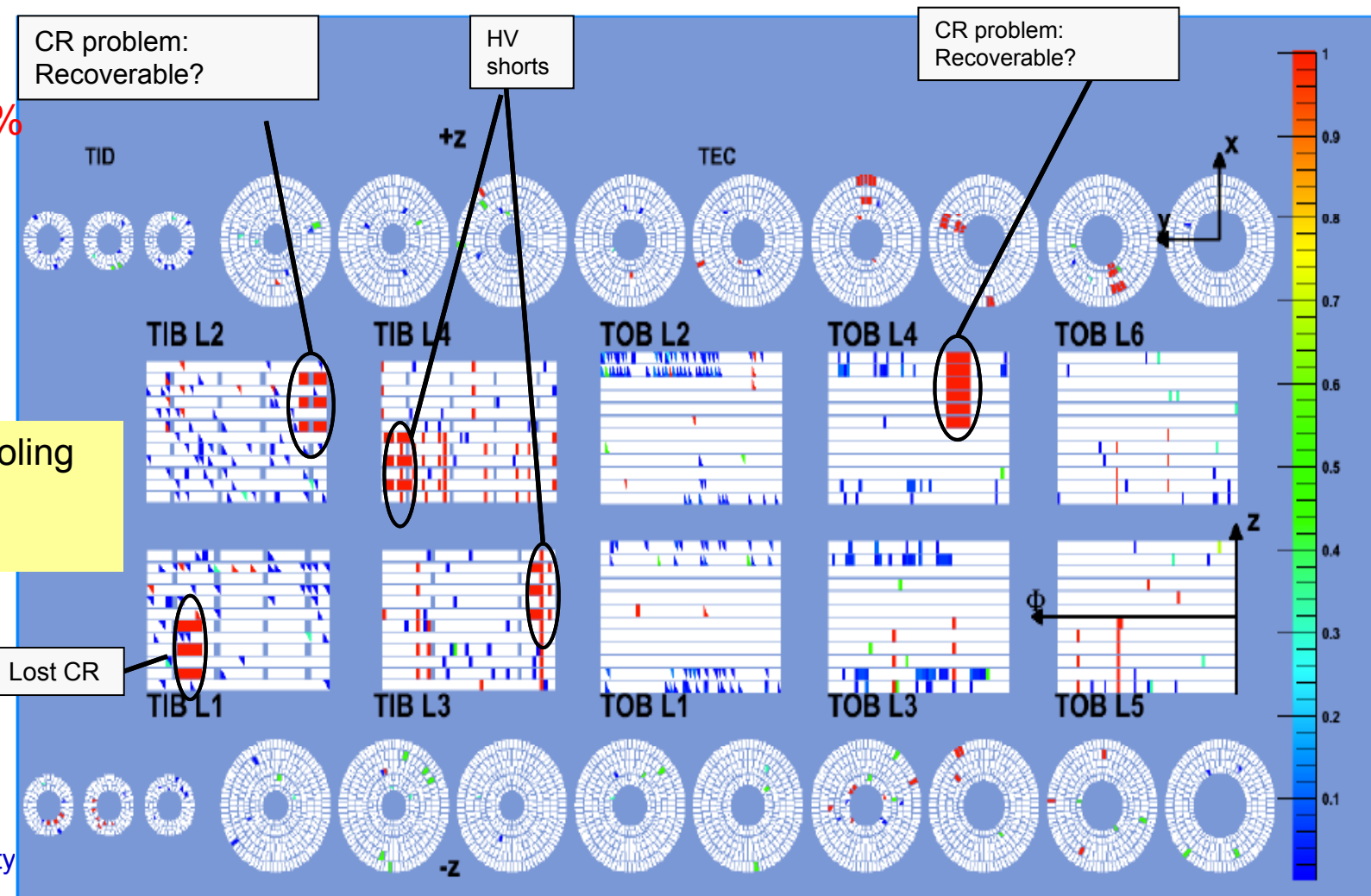
CMS Tracker Today

Tracker 2011

Alive modules
are stable:
97.8%

TIB/TID: 95.2%
TOB: 98.3%
TEC+: 98.8%
TEC-: 99.1%

Take in mind cooling
accident and its
consequences!





QA: Series of Thoughts (1)

- ♣ QA on components and fully assembled modules is only a part of the game: the other part is a real system test in a “final” configuration. This is a Dream. In real world we have to rely on approximations, which make our results appear as a more or less credible “educated guess”, and we must accept and take into account this aspect.
- ♣ The Construction Database was a fundamental tool: what is not in DB is lost forever. Our experience tells us that is somewhat difficult to decide a priori which measurements should go in DB
 - ♦ An example is DCU calibration, we are still struggling to get the correct calibration factors: no dedicated measurement went in DB
- ♣ DB should have some flexibility to accommodate unforeseen needs
- ♣ People should be convinced to use DB for every action



QA: Series of Thoughts (2)

- ♣ Distributed Production organization (sociological problem?)
 - ♦ it works, but learning time is long; probably not 100% efficient
 - ♦ the goal is to bring all production and test centres to a very high technical level; deep understanding of all issues is a must. This requires huge efforts from all involved parties
 - ♦ HW equipment standardization and distribution: not always possible, and depending on parts availability; HW is not COTS! Costs and delivery time are usually underestimated. If HW not standard, then results are hard to be interpreted. HW for testing is evolving continuously, impossible to freeze. Obsolescence of our HW w.r.t. commercial HW during a multi-year production
- ♣ Detailed procedures for every construction step are necessary
 - ♦ writing procedures is time consuming
 - ♦ procedures must evolve and follow the state of the art
 - ♦ well balanced: easily readable, including details, but not 500 pages ☹
 - ♦ impossible task if production and test outsourced to industry



Other Aspects Affecting QA

- ♣ We saw “weird” results really difficult to be interpreted: after careful investigation and a lot of time and effort most of them could be traced back to
 - ♦ Bad grounding
 - ♦ Power Supplies (Commercial, not CMS final ones)
 - ♦ Faults in the testing equipment itself
 - ♦ Unexpected SW crashes (often connected to HW problems)
- ♣ In the end the “culprit” is not always the module!
- ♣ Beware of:
 - ♦ **Tight Schedule**
 - ♦ **Fast Solutions**
- ♣ Reactions times: serious failures affect production. The process of finding the issue, creating a task force, going back to industry, eventually solving the problem, may require order of one year.
- ♣ Think about contingency!



Conclusions

- ♣ The CMS Tracker performance during data taking gives us some confidence that we did a very good job in Module Production
- ♣ For sure something could have been done better. Profiting from this experience we can certainly make better detectors for future experiments
- ♣ We must take in mind that requirements and complexity for future trackers are increasing a lot, and this has to be faced well in advance if we want to succeed
- ♣ We need time, money and strong arguments to build new Silicon Detectors



Acknowledgements

- ♣ Hoping not to forget too many people...
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