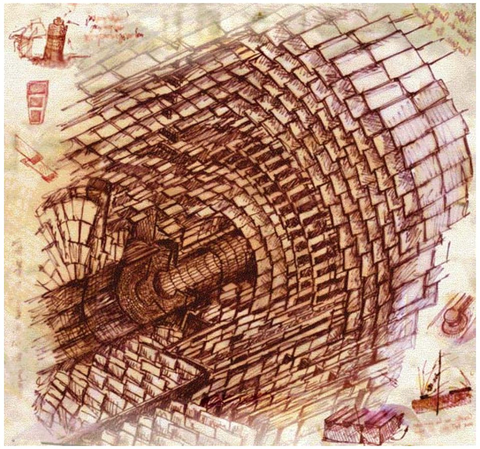
The CMS Silicon Strip Tracker experience

Gabriella Pásztor

University of California, Riverside



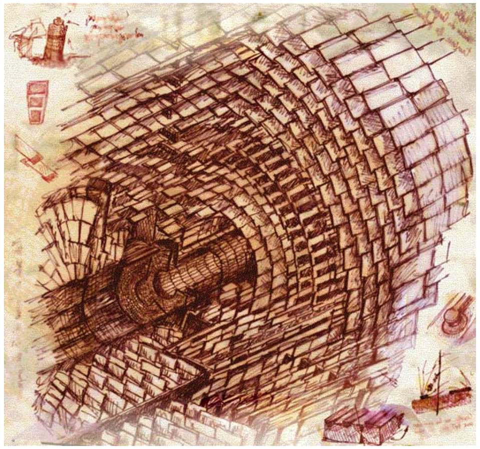
ECFA ILC Workshop, SiLC Meeting

Vienna, 18 November, 2005

The CMS Silicon Strip Tracker experience

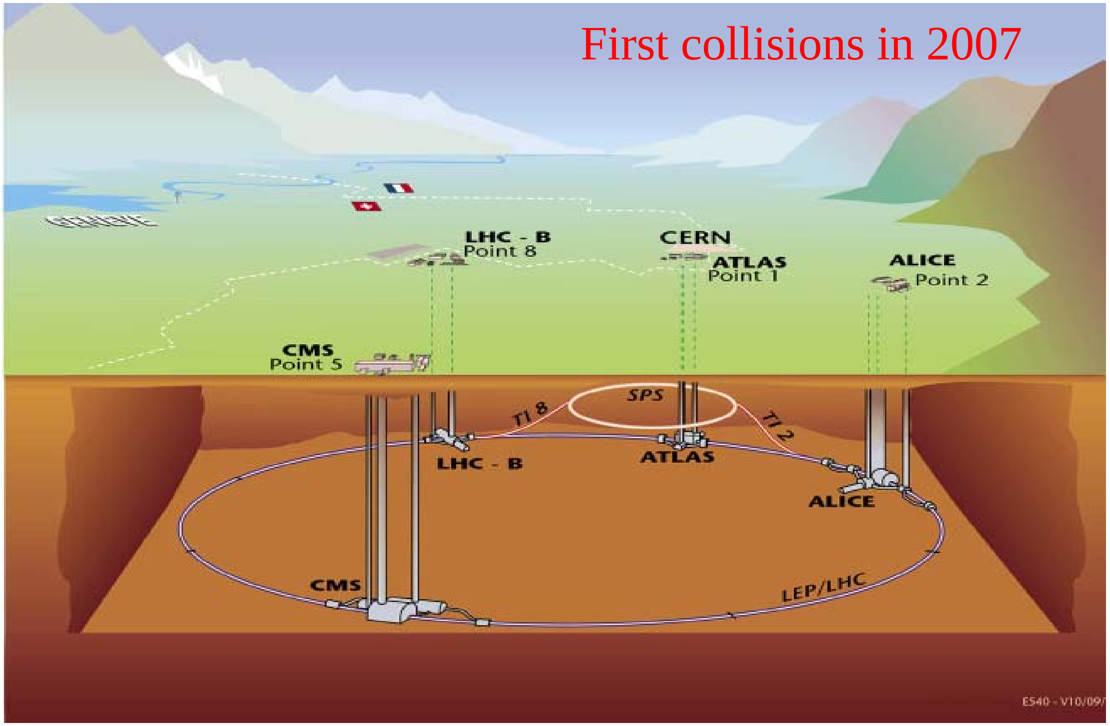
...with some emphasis on problems

Gabriella Pásztor
University of California, Riverside



ECFA ILC Workshop, SiLC Meeting
Vienna, 18 November, 2005

The LHC machine


First collisions in 2007


LHC tunnel starts to fill up...

LHC beam	Energy (TeV)	Luminosity (cm^{-2} s^{-1})
p p	14	10^{34}
Pb Pb	1312 (5.5/N)	10^{27}

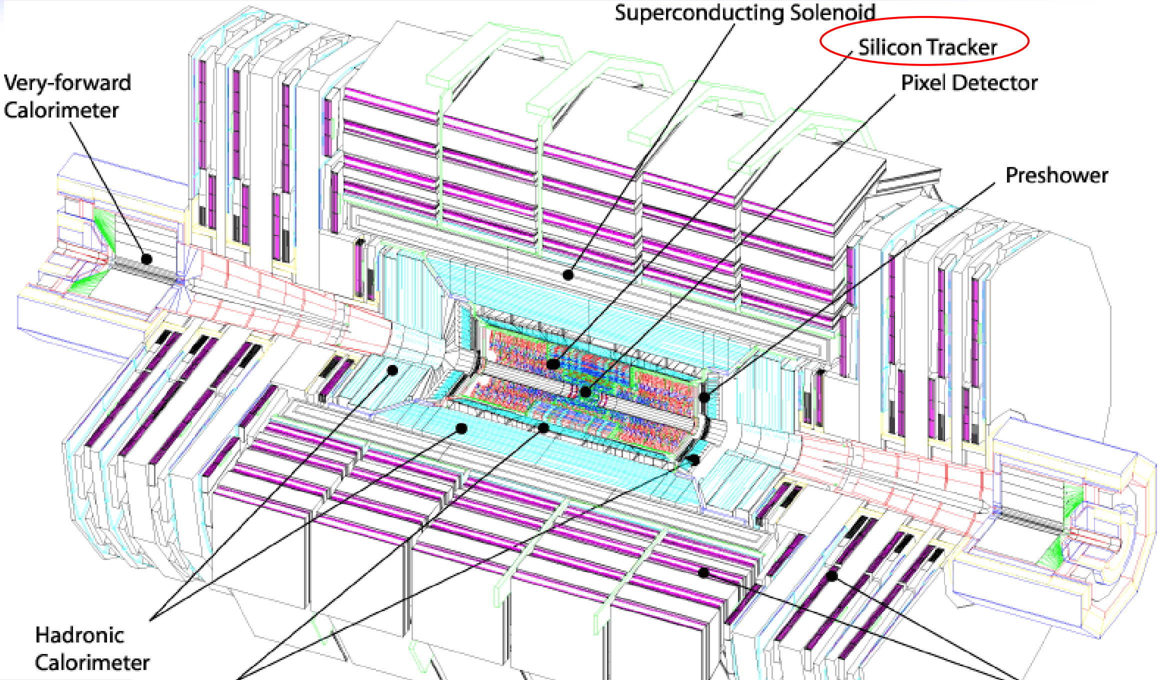
- *beam diameter: 20 μm*
- *bunch length: 75 mm*
- *protons/bunch: 10^{11}*
- *bunches/beam: 2835*
- *beam crossing rate: 40 MHz*
- *annual $\int L$: $5 \bullet 10^{40}$ cm^{-2}*

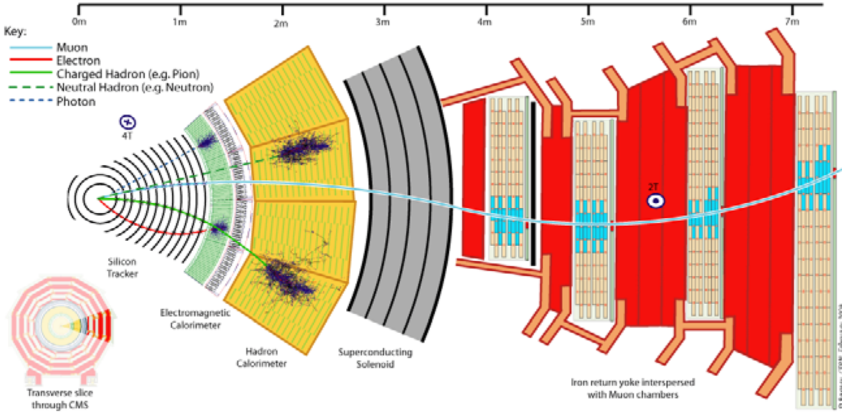
- *inelastic cross-section: ~70 mb*
- *interactions/bunch: ~20*
- *tracks / unit rapidity: ~140*
- *charged tracks / cm^2 :*
  1 @ 10 cm from IP
  0.1 @ 25 cm from IP
  0.01 @ 60 cm from IP
- *L1 trigger delay: 3.2 μs*
- *mean L1 trigger rate: <100 kHz*

The CMS detector

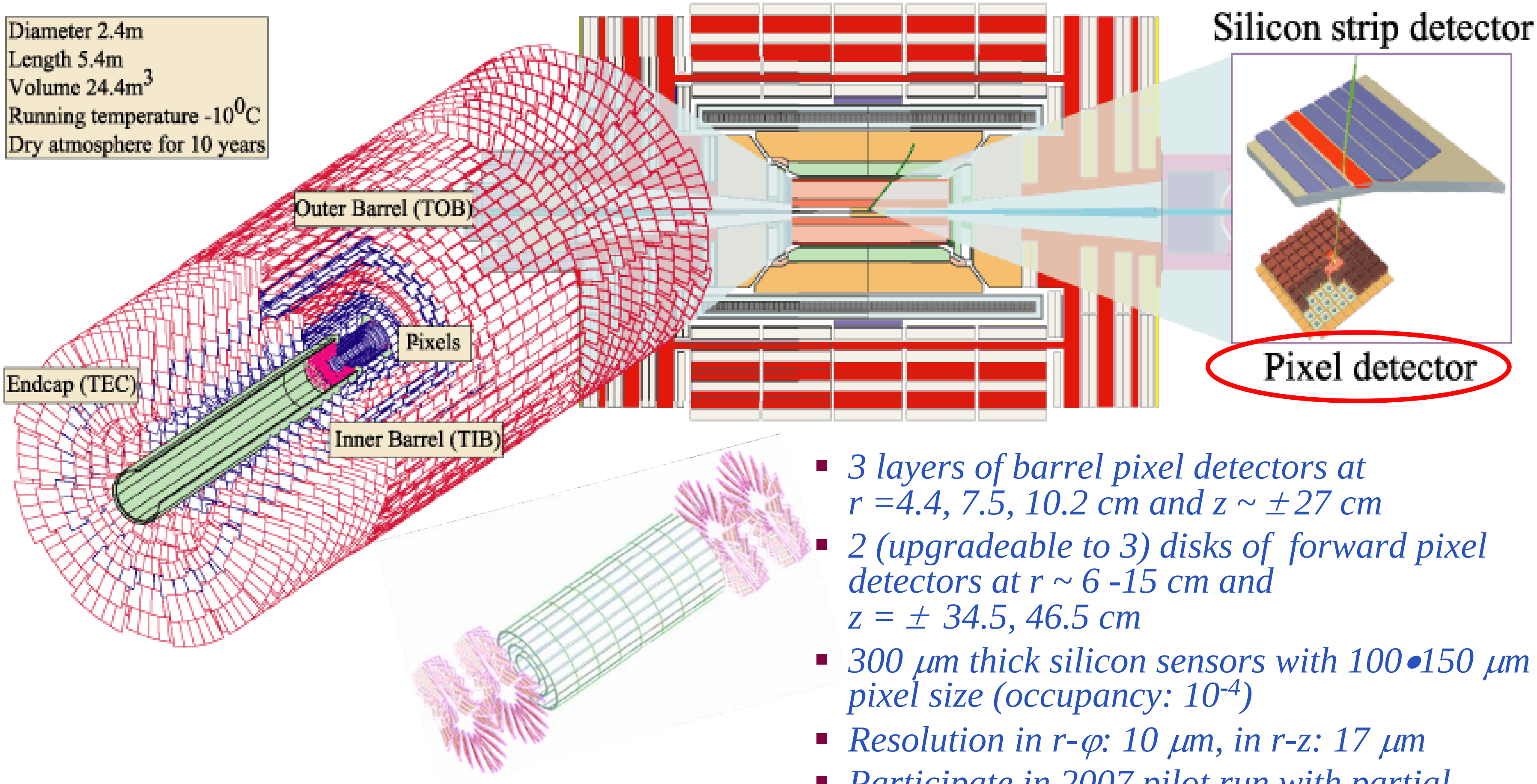
Compact
Muon
Solenoid
detector

Magnetic field: 4 T
Weight: 12500 t
Length: 21.6 m
Diameter: 15 m





The Silicon Tracker



Diameter 2.4m
Length 5.4m
Volume 24.4m^3
Running temperature -10^{0}C
Dry atmosphere for 10 years

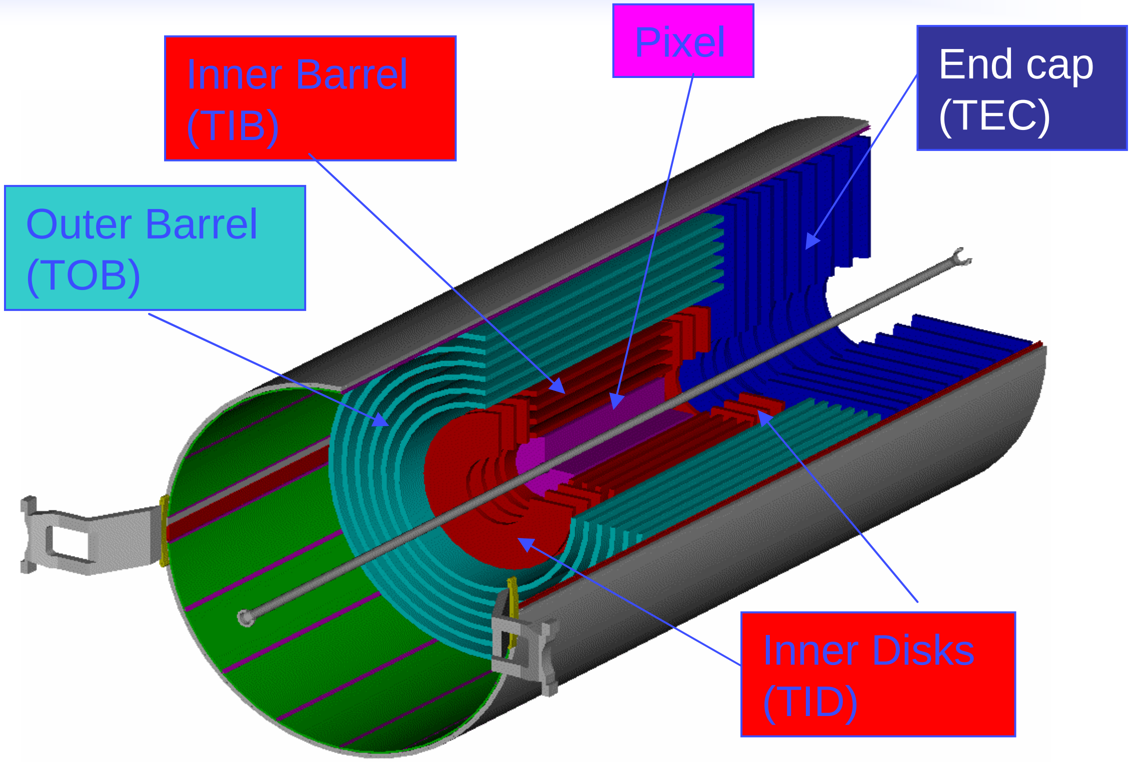
- 3 layers of barrel pixel detectors at *r =4.4, 7.5, 10.2 cm and z ~ ±27 cm*
- *2 (upgradeable to 3) disks of forward pixel detectors at r ~ 6 -15 cm and z = ± 34.5, 46.5 cm*
- *300 μm thick silicon sensors with 100•150 μm pixel size (occupancy: 10^{-4})*
- *Resolution in r-φ: 10 μm, in r-z: 17 μm*
- *Participate in 2007 pilot run with partial detector, install for 2008 physics run*

The Silicon Tracker

15 148 modules
24 244 silicon sensors
210 m^2 active silicon area
75 000 readout chips
9 600 000 readout channels
(=silicon strips)
25 000 000 wire bonds

37 000 analog optical links
3000 km optical fibres
440 Front-End Drivers

29 module designs
16 sensor designs
12 hybrid designs



Fluences in n(1 MeV equiv..)/cm^2:
Inner region: ≤1.6 10^{14}
Outer region: ≤3.5 10^{13}

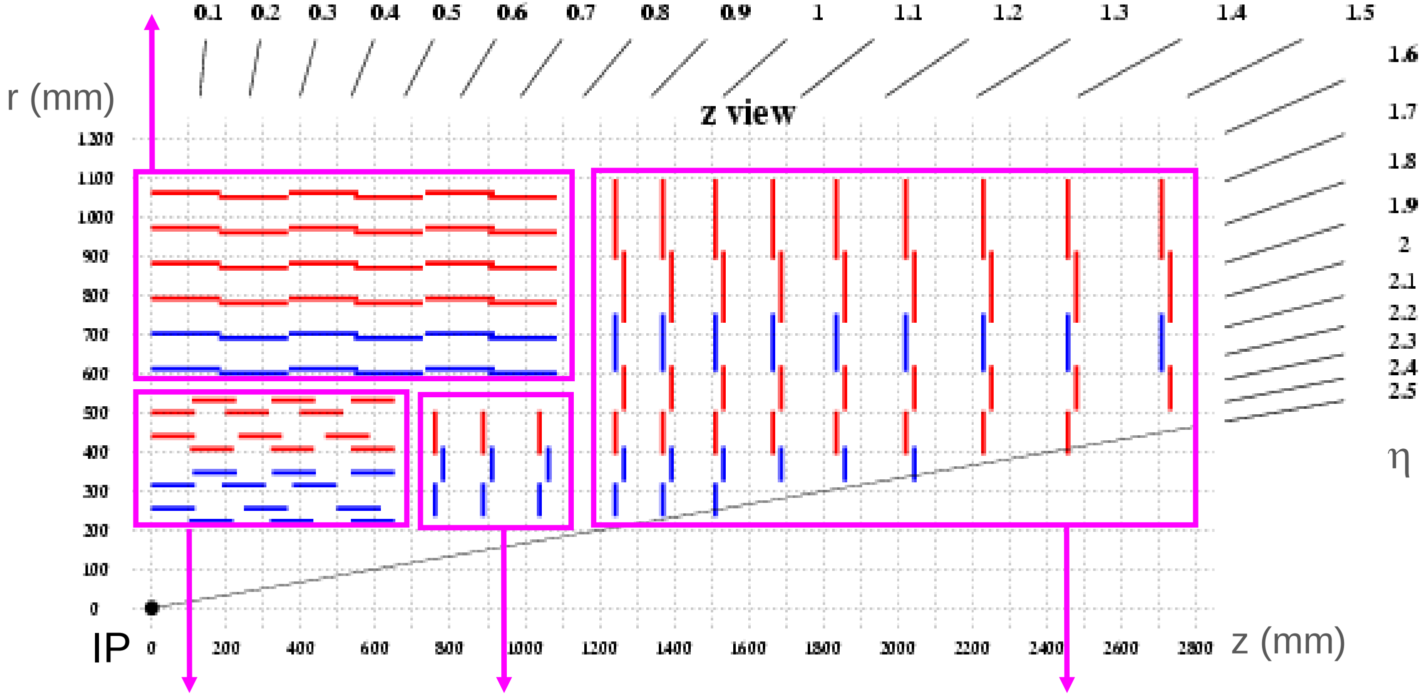
Length: 5.4 m *Diameter: 2.4 m*
Volume: 24.4 m^3 *Weight: 3 t*
Running temperature: below -10 C
Dry (<30 RH%) atmosphere (inert nitrogen)
Power dissipation: 45 kW

The Silicon Strip Tracker layout

TOB
6 layers
5208 modules

Single sided

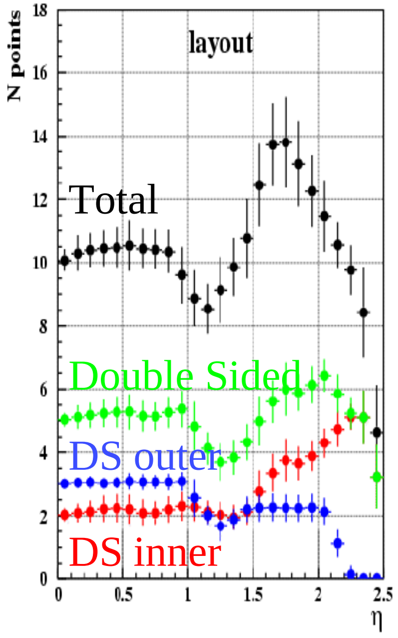
Double sided
(100 mrad stereo angle)



TIB
4 layers
2724 modules

TID
2x3 disks
816 modules

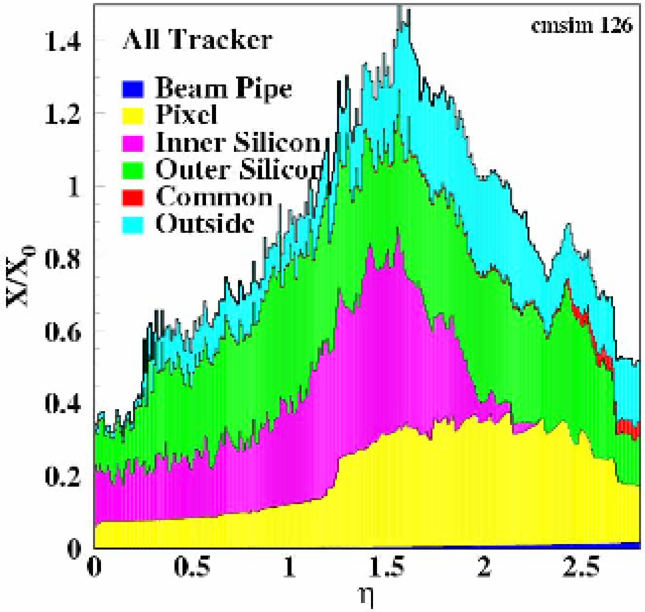
TEC
2x9 disks
6400 modules

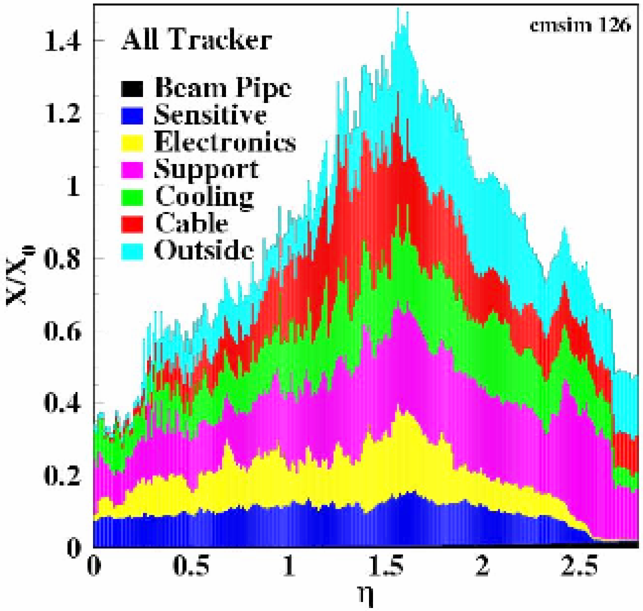


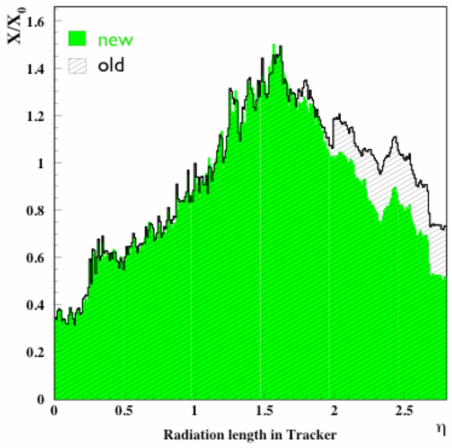
Barrel: strips parallel to beam
End cap: strips in radial direction

Material budget

- Design goal in 1999: $X/X_0 < 1$
- Most of the material is electronics related (electronics, cooling, cable, ...)
- New description (with most importantly a better description of the bulkheads collecting the services behind the endcaps) predicts less material in the forward region





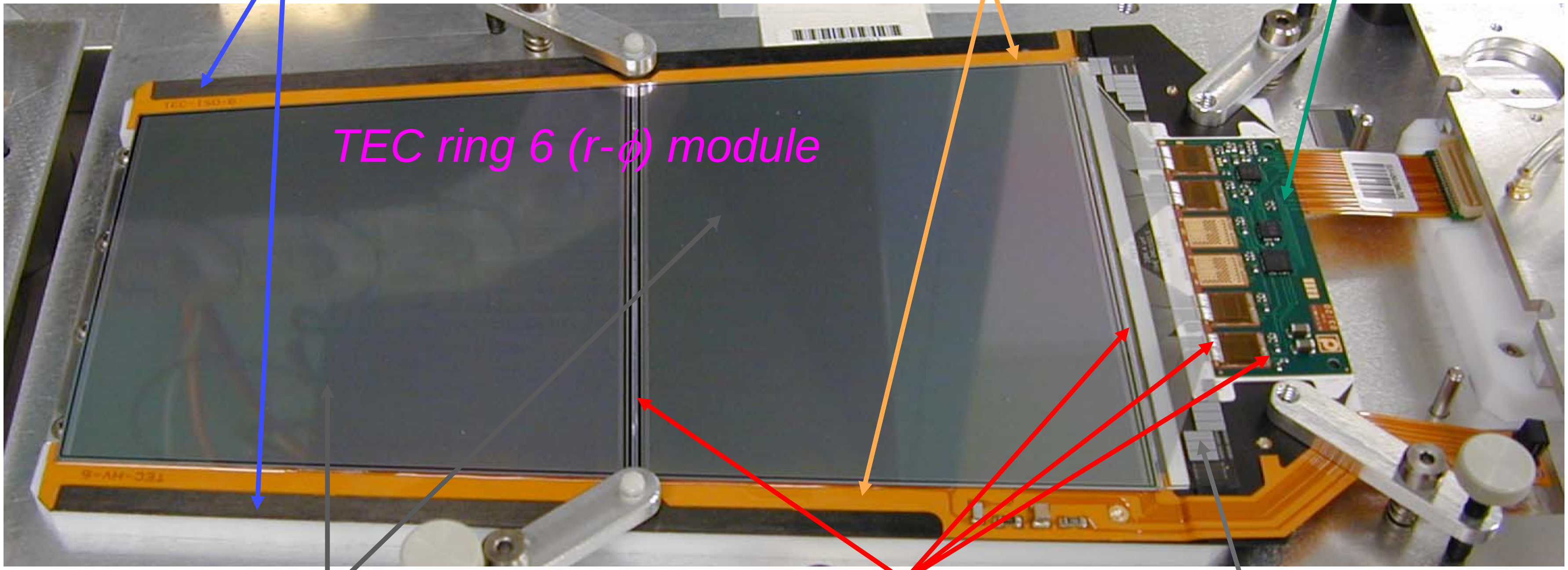


The basic element: the module

Support frame
(graphite and carbon fiber)

Kapton circuit
- *bias voltage*
- *backplane isolation*
- *temperature sensor*

Front-end hybrid
with flex tail



Silicon sensors
- 1 or 2 per module

micro-bonds

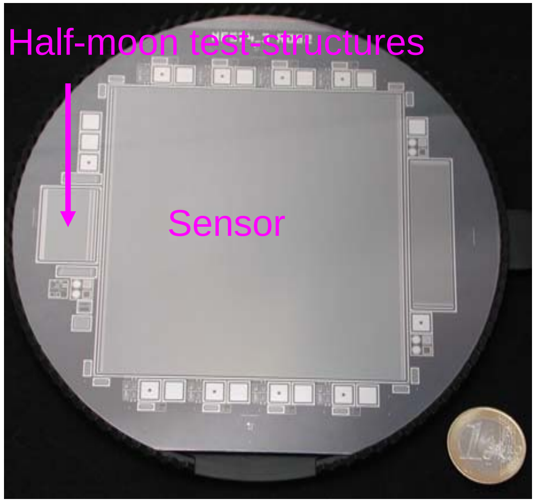
Pitch adapter (glass)
- fan-out from readout chip to sensor

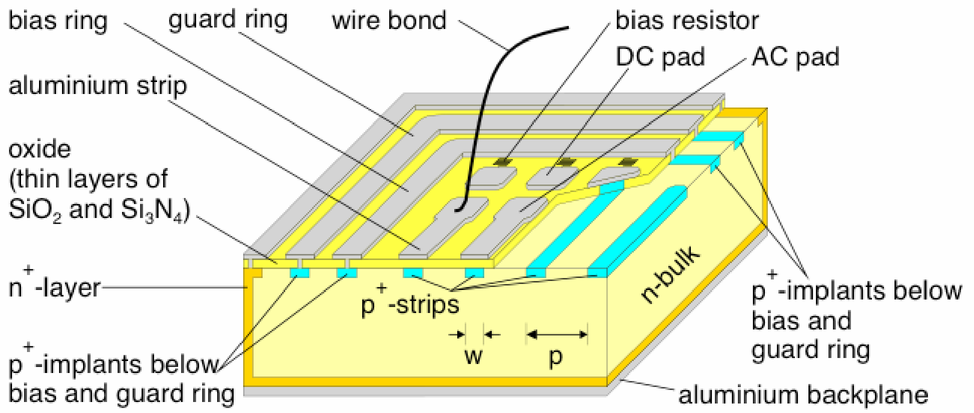
Double sided modules are constructed from two independent single sided modules mounted back to back with a stereo angle of 100 mrad

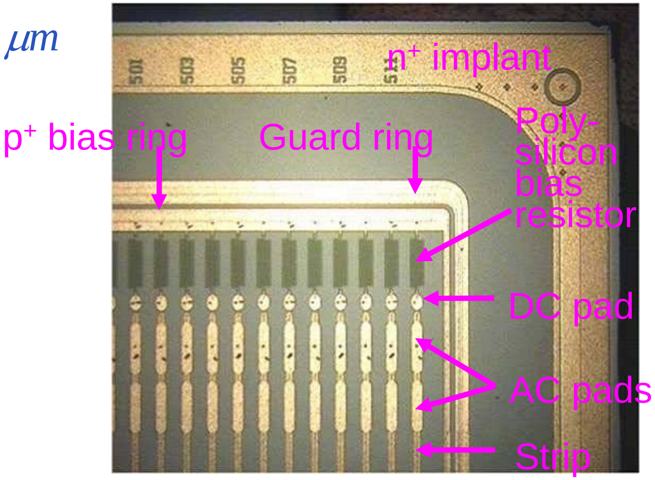
Silicon strip sensors

Simple and robust design, compatible with mass production

- *16 different sensor designs, all single sided*
- *Rectangular or wedge-shaped sensors with typical size of 10x10 cm made on 6” wafer*
- *n-type bulk, not oxygenated,<100> lattice orientation*
  Inner region: low resistivity 1.5-3.5 $k\Omega cm$, thin 320 μm Outer region:high resistivity 3.5-7.5 $k\Omega cm$, thick 500 μm
- *512 or 768 p^+ strip implants with pitch = 80-205 μm, width/pitch = 0.25*
- *Al readout strips, AC coupled, metal overhang 4-8 μm*
- *p^+ guard ring floating, metal field planes extend beyond implantation of guard ring*
- *Distance between the implant region and edge: 2·thickness+110 μm*
- *Identical test-structures on every wafer type*





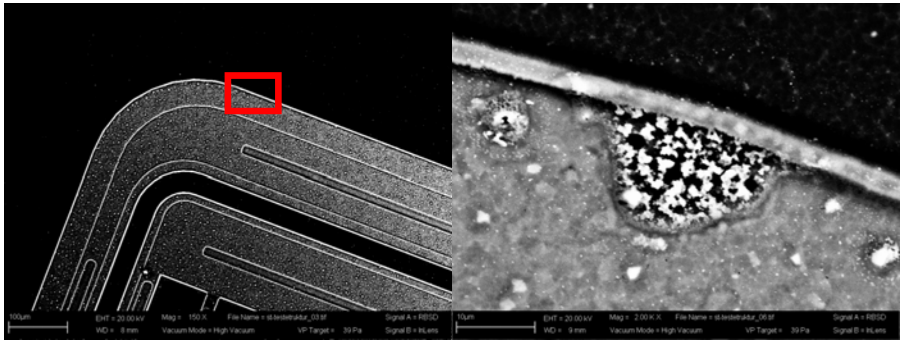


Sensor production

- *Thin sensors: Hamamatsu Photonics (HPK)*
- *Problems with thick sensors from SGS Thomson Microelectronics (STM) during mass production (low yield, unstable/high leakage current, mechanical stress dependence, high common mode, high flatband voltage, low interstrip resistance, scratches, Al corrosion...) → bulk of thick sensor production shifted to HPK*
- *An unprecedented extensive study of delivered wafers: 16 electrical parameters measured on about 13000 structures (8673 sensors and 4144 test-structures) by the end of September 2005*

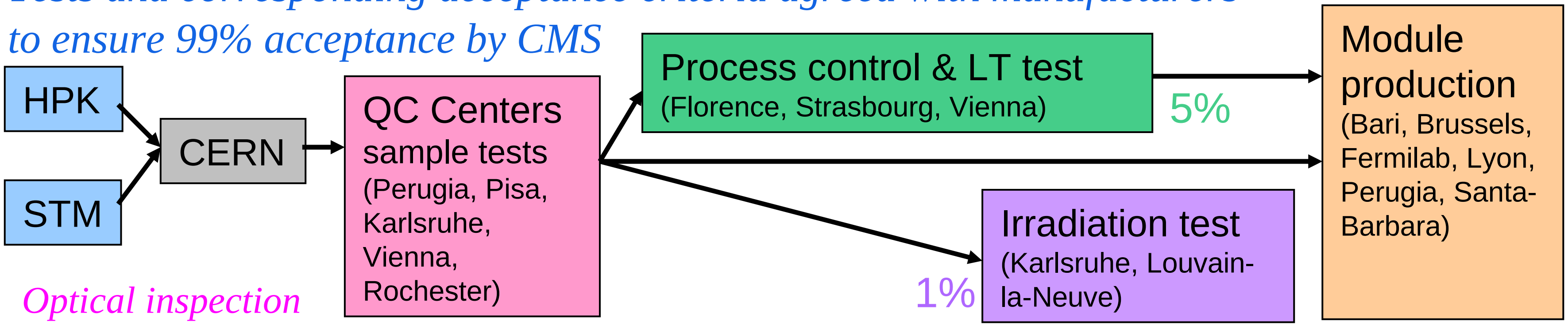
Aluminium corrosion of ST sensors

- *Development of dots and stains on the Al surfaces of STM sensors*
- *Electro-chemical corroding process: increase with time only when sensor is biased in the presence of humidity (>30%r.h.), leading to deep local micro-corrosions of Al surface*
- *Probable explanation: Potassium (remaining from $Si0_2$ etching?) forms an acid (We suspected previously Phosphorus that is present in 4% concentration in passivation oxide)*
- *Probable (but not proven) effect on long-term behaviour by compromising the metal overhang design*
- *Main reason to cancel the 19000 sensor ST contract*



Sensor Quality Assurance

Tests and corresponding acceptance criteria agreed with manufacturers to ensure 99% acceptance by CMS



HPK

STM

CERN

QC Centers sample tests (Perugia, Pisa, Karlsruhe, Vienna, Rochester)

Process control & LT test (Florence, Strasbourg, Vienna)

5%

Irradiation test (Karlsruhe, Louvain-la-Neuve)

1%

Module production (Bari, Brussels, Fermilab, Lyon, Perugia, Santa-Barbara)

Optical inspection

Electrical characterization

- *IV (0-550 V reverse bias)*
  - *Leakage current*
  - *Breakdown voltage*
- *CV (0-350 V)*
  - *Sensor capacitance*
  - *Depletion voltage*
  - *Thickness*
- *Strip scan @ 400 V bias*
  - *Single strip leakage current*
  - *Poly-resistor value*
  - *Coupling capacitance value*
  - *Dielectric current at 10 V (pinholes)*

<1 hour / test structure

- *IV on mini-sensor*
- *IV on gate-controlled diode*
- *CV on diode*
- *CV on MOS (flatband voltage)*
- *Interstrip capacitance*
- *Interstrip resistance*
- *Surface current*
- *p^+ implant resistivity*
- *Aluminum resistivity*
- *Poly-silicon resistivity*
- *Coupling capacitance*
- *Oxide breakdown voltage*

26 MeV protons (Karlsruhe)

~20 MeV neutrons (Louvain)

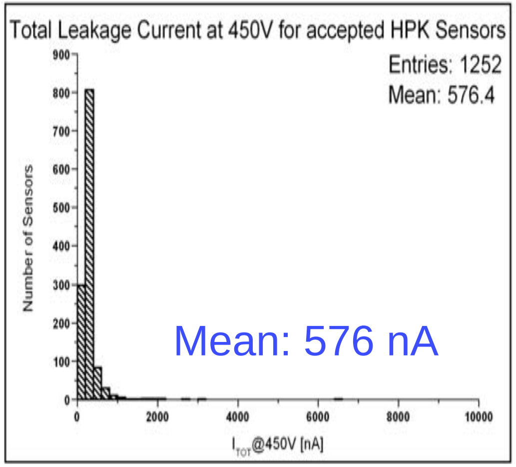
Measurements before and after irradiation:

- *IV, leakage current*
- *CV, depletion voltage*
- *Strip parameters*

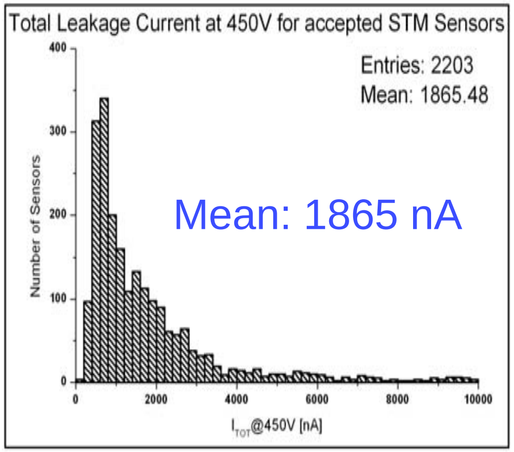
Qualification results

Leakage Current at 450V

max: 10μA



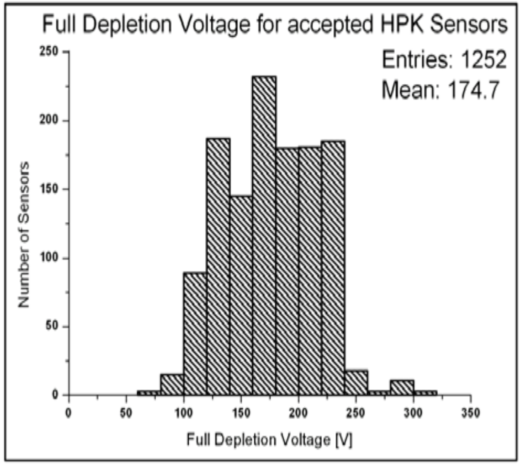
Mean: 576 nA

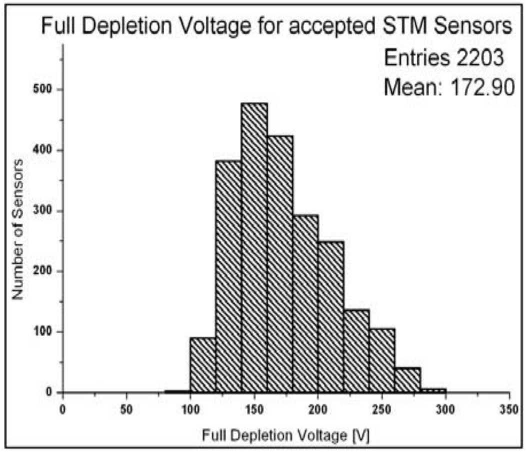


Mean: 1865 nA

Full Depletion Voltage

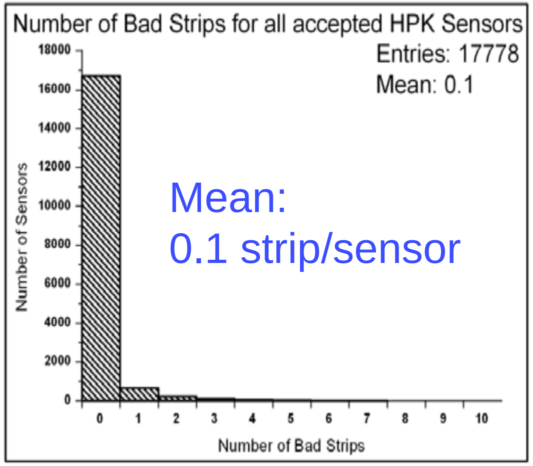
Specification: 100 V – 300 V



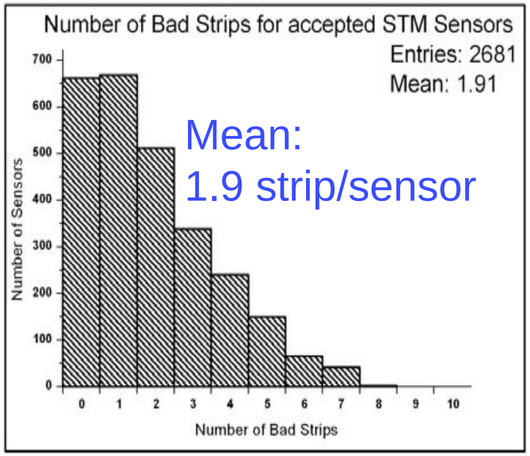


Number of Bad Strips

max: 1% of 512/768 Channels



Mean:
0.1 strip/sensor



Mean:
1.9 strip/sensor

Bad Strips

(pinholes,
out of range poly-res,
Al shorts,
broken Al,
open implants,
leaky strips...)

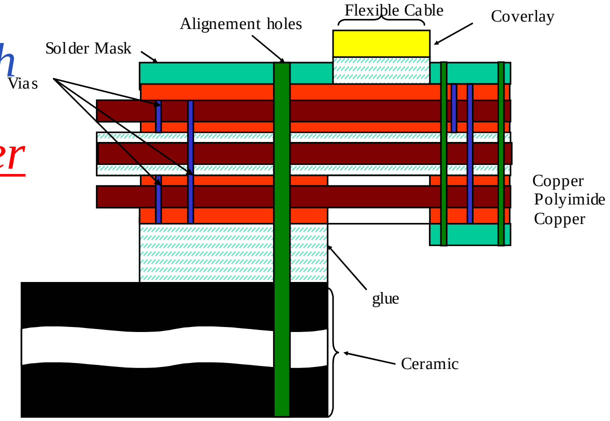
0.02%

0.3%

Overall percentage of good strips in accepted sensors: 99.94%

The front-end hybrid

- Diverse functionality - strict constraints: mechanical and electrical interface to pre-defined elements, low mass, high reliability, inexpensive



4-layer kapton substrate (flex) laminated to a ceramic carrier

- 12 different designs based on 3 layouts
- 120 μm minimum feature size

4 or 6 APV25 readout chips

- Radiation hard 0.25 μm CMOS technology (ASIC)
- 128 channels multiplexed to 1 analog output
- Charge sensitive amplifier with τ=50 ns, CR-RC shaper
- 192 cell pipeline (4.8 μs) per channel (trigger latency 3.2 μs) with max. 32 cell readout buffer
- Peak mode: 1 sample, τ=50 ns
- Deconvolution mode (for high luminosity): weighted sum of 3 samples, τ=25 ns, higher noise
- Multi mode
- Calibration circuit

- V_{supply}: 0, 1.25, 2.5V
- Power / channel: 1.9 mW analog + 0.4 mW digital

MUX (Multiplexer)

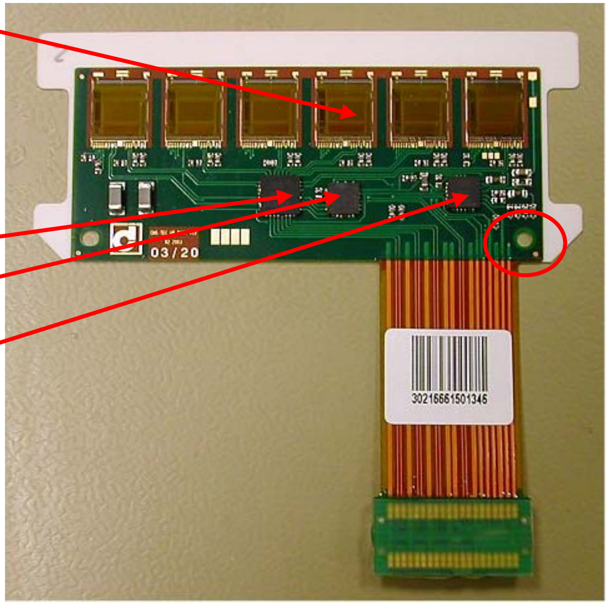
- 2 APV outputs multiplexed to 1 data line

PLL (Phase-locked loop)

- Decodes clock & trigger signals

DCU (Detector Control Unit)

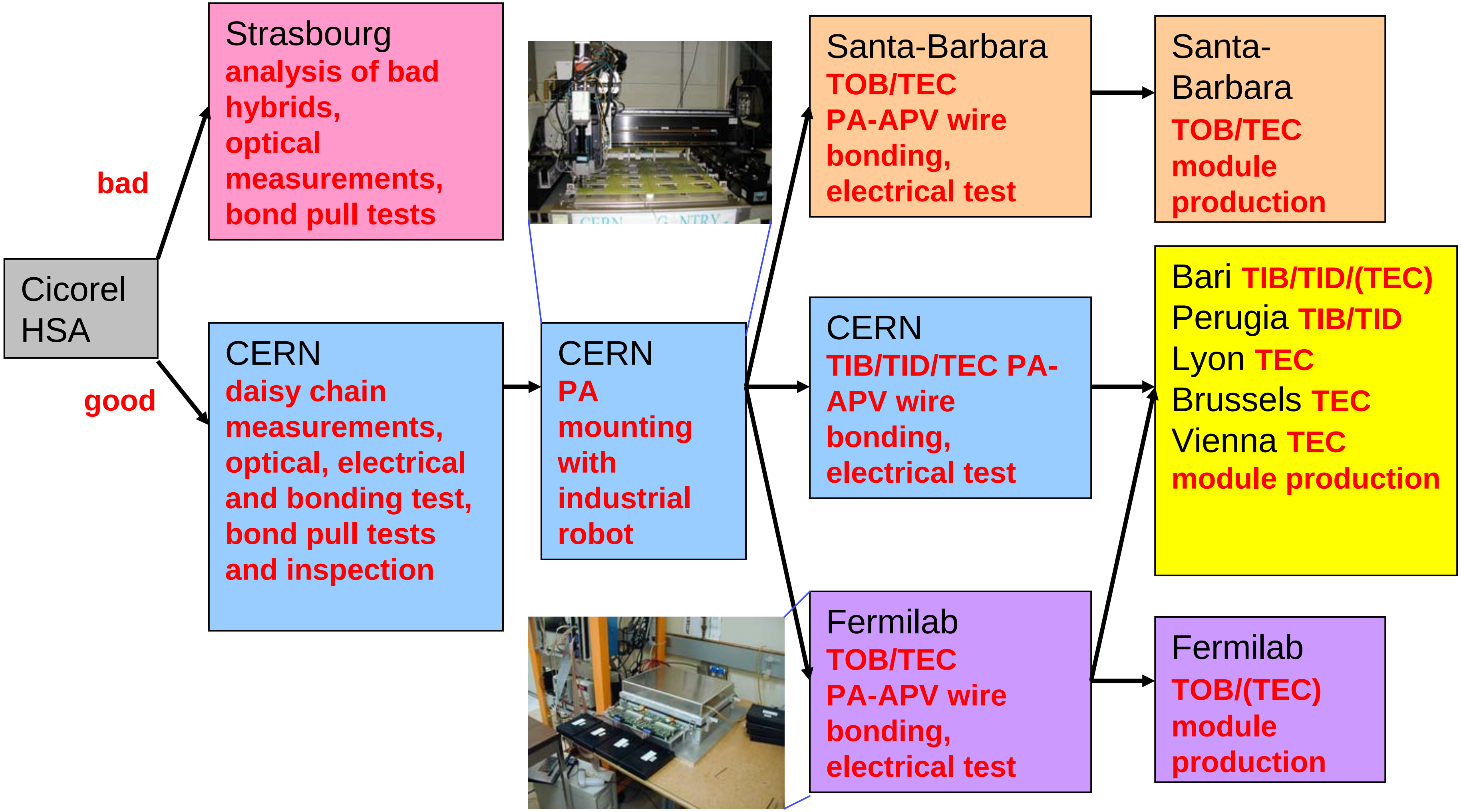
- 12-bit ADC for 8 channels: hybrid and sensor temperatures, leakage current, low voltages



Front-end hybrid production

- Flex circuits produced by Cicorel, assembly done by Hybrid SA
- Provided supplier with a test setup (Front-end Hybrid Industrial Tester)
  - Connectivity, electrical and functional tests in ~ 1 minute per hybrid
- Several problems at start-up and during mass production
  - Fast production (schedule presure) but slow QA feedback (under staffed), problems typically found in production module tests
  - Producer does not analyse reasons for test failures
  - Irreversible addition of value when mounting hybrid on sensor module, large effort to recover
- Response to problems
  - Strengthen QA/QC at producer and within CMS
  - A CMS collaborator visit the producer weekly to check production quality (analyse rejects)
  - Establish a backup hybrid line
(flex circuits from GS Präzision, assembly at AmTech)
- Production rate finally stabilized at 300 then 400 hybrids / week

Front-end hybrid flow



Cicorel HSA

bad

Strasbourg
analysis of bad hybrids, optical measurements, bond pull tests

good

CERN
daisy chain measurements, optical, electrical and bonding test, bond pull tests and inspection

CERN
PA mounting with industrial robot

Santa-Barbara
TOB/TEC PA-APV wire bonding, electrical test

CERN
TIB/TID/TEC PA-APV wire bonding, electrical test

Fermilab
TOB/TEC PA-APV wire bonding, electrical test

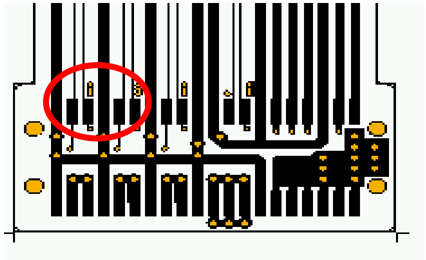
Santa-Barbara
TOB/TEC module production

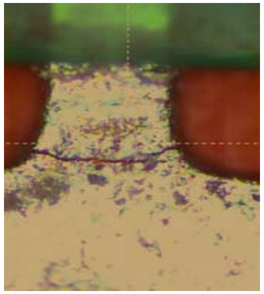
Bari **TIB/TID/(TEC)**
Perugia **TIB/TID**
Lyon **TEC**
Brussels **TEC**
Vienna **TEC**
module production

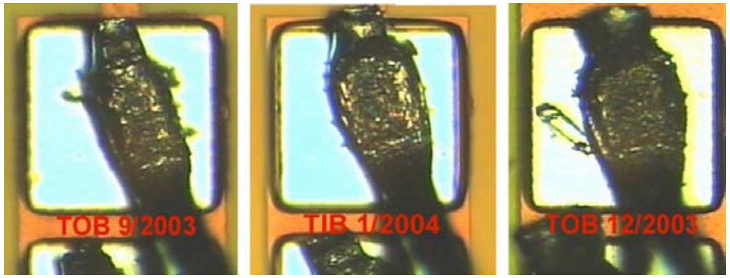
Fermilab
TOB/(TEC) module production

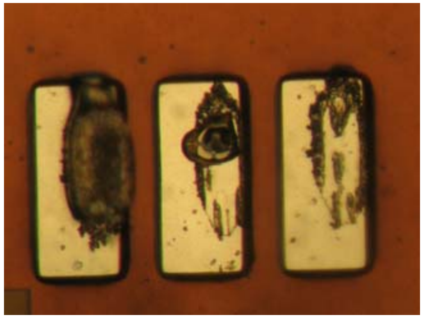
Problems during production

- *Lamination on ceramic (at start up)*
- *Cracked lines near connector – fragile Ni/Au pads on kapton*
  solution: FR4 rigidifier + layout modification
  900 hybrids and 2 months lost
- *Contamination of connectors by solder flux and other residues from the production process of adapter cards (cleaneable but complicates life and if not discovered before mounting modules on structure may cause intermittent failures during operation)*
- *Batches with unreliable wire bonds due to overdeformation*
  840 hybrids and 270 modules affected
- *Bonding quality and long-term reliability remains main concern (over-deformation, cratering)*
  - *Large (continuous) effort to optimize and maintain bonding quality with several production stops*









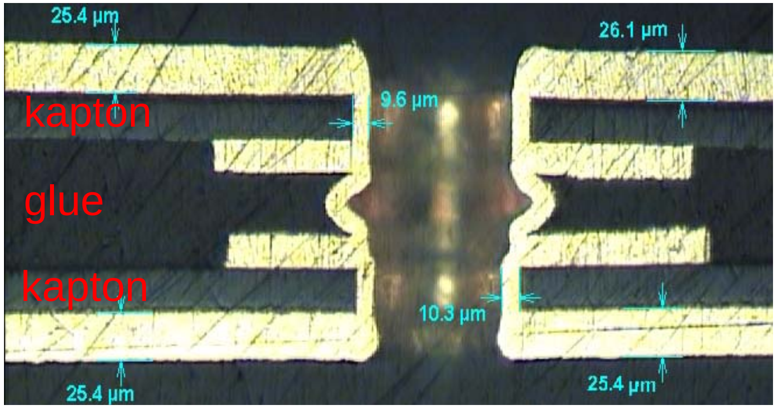
Cratering: damage to Si during bonding
- very nasty problem, raising long-term reliability issues but...
- our excessive aging tests did not reveal problems (we had to accept these hybrids)

Problems during production

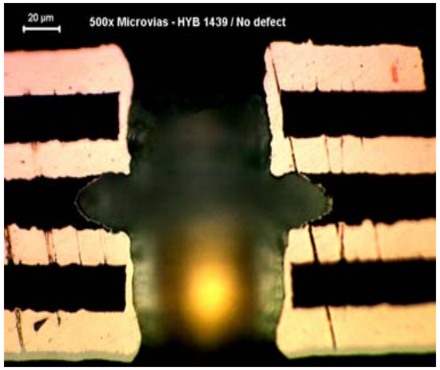
Unreliable via's

- *100 μm vias with broken contact found in module long-term test (anomalous pedestal behavior in a 10-20 minute period)*
- *hidden defect, not picked up by fast FHIT test (~1 minute)*
- *all vias tested at Cicorel, these must have broke during further processing*
- *serious concern with hybrid reliability:*
  ~2180 hybrids rejected and ~320 modules affected
- *solution: increase via diameter to 120 μm and add additional kapton layer*

Old design



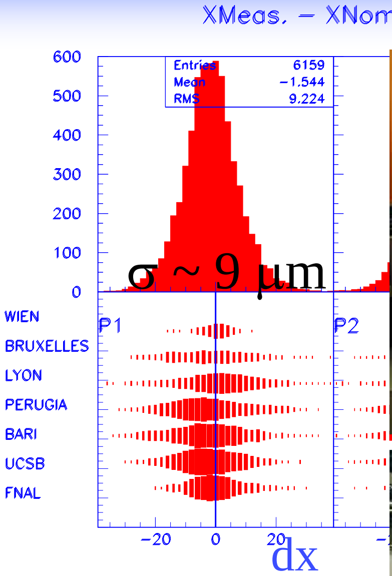
Bad via

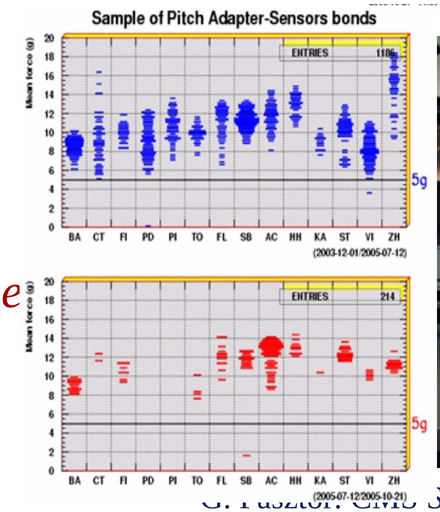


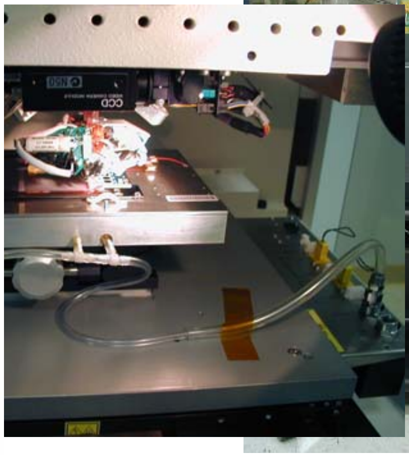
New design

Module production and test

- *Robotic assembly of modules at 6 gantry centers: gluing the sensors and the FE hybrid to the frame with high precision (e.g. x ⊥ strips < 39 μm) → 99% within specifications*
- *Wire bonding between pitch adapter and sensor(s) using 23 automatic bonding machines*
- *Single module test with ARC (APV Readout Controller) and long-term test using a CMS like DAQ system including several thermal cycles:*
    - *Noise*
    - *Pulse-shape*
    - *Bad strips (disconnected/shorted strips, pinholes, noisy channels)*
    - *IV curve*
    - *Pipeline errors*
- *0.1-0.3% of bad strips/module*
- *Module production yield (including mechanical and electrical problems): 94-99%*



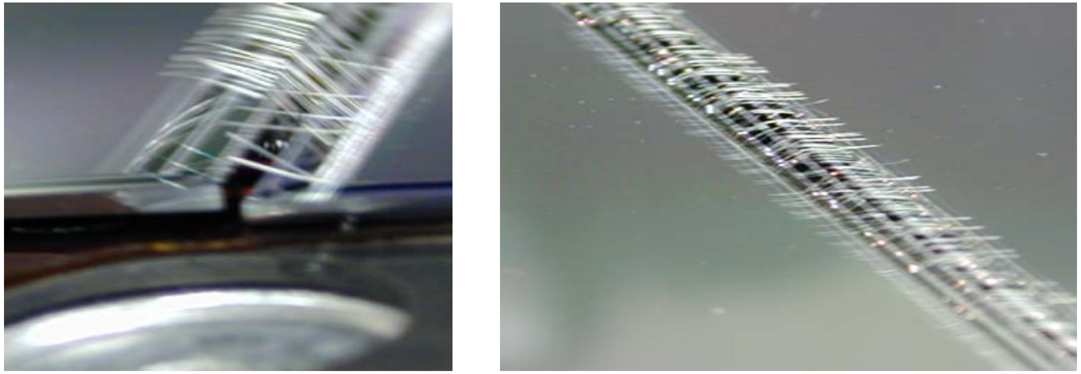


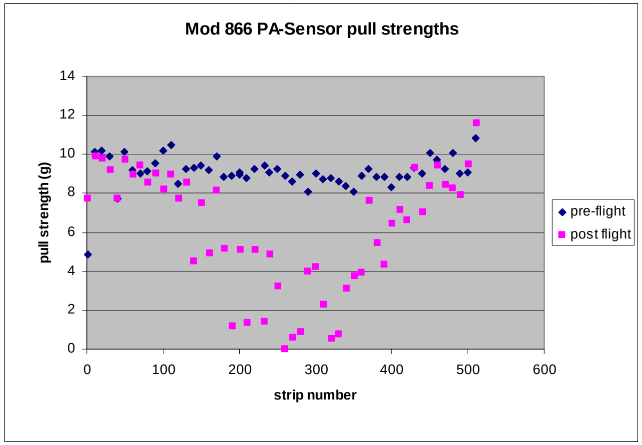


Module production problems

- *Damage to wire bonds during shipping of modules from US to CERN (due to vibration)*

→ Needed to modify and then verify module design





TOB solution: reinforce the module by adding Si based Sylgard glue (elastic from –50→200^{0}C) line to the back side

TEC solution: add a ceramic stiffener under the bonding area

Tests performed:

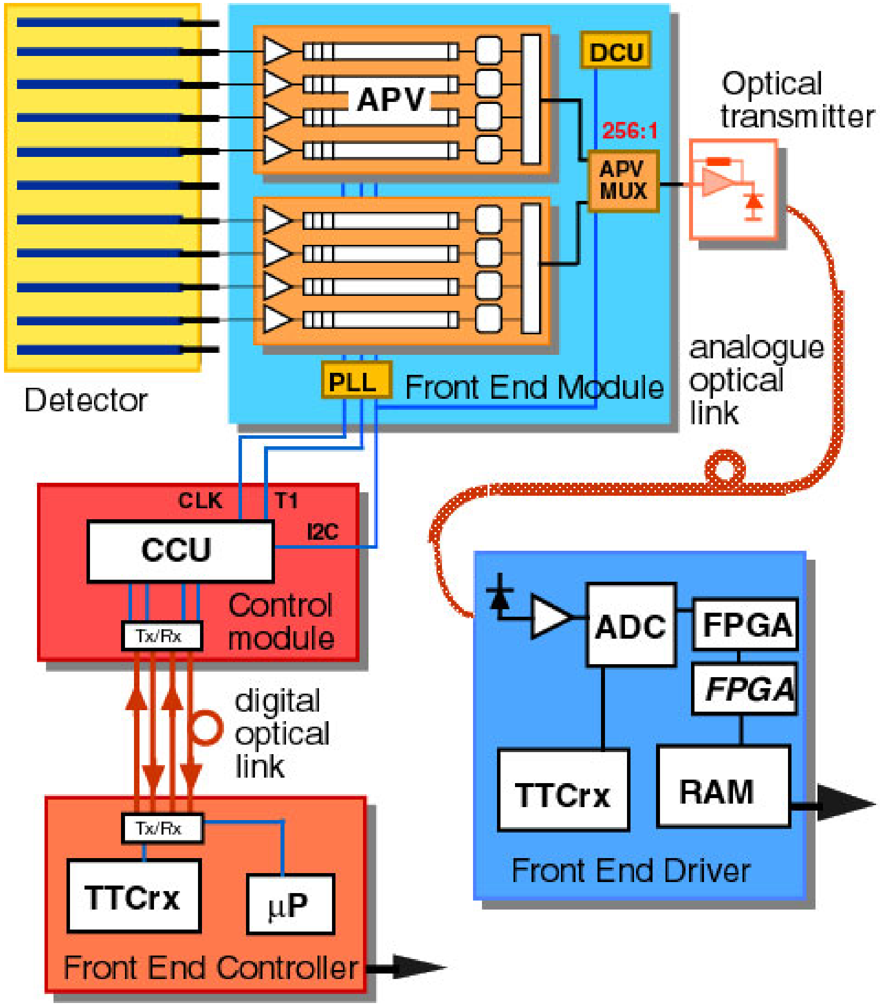
- *Drop and vibration tests*
- *FEA analysis,*
- *Thermal efficiency (cooling) measurements on module and on substructure*
- *Deformation study (due to bimetal effect)*

- *Unreliable bias connections (failing conductive epoxy)*

→ Need to re-work (wire-bonding + electrical test) ~1400 TOB modules

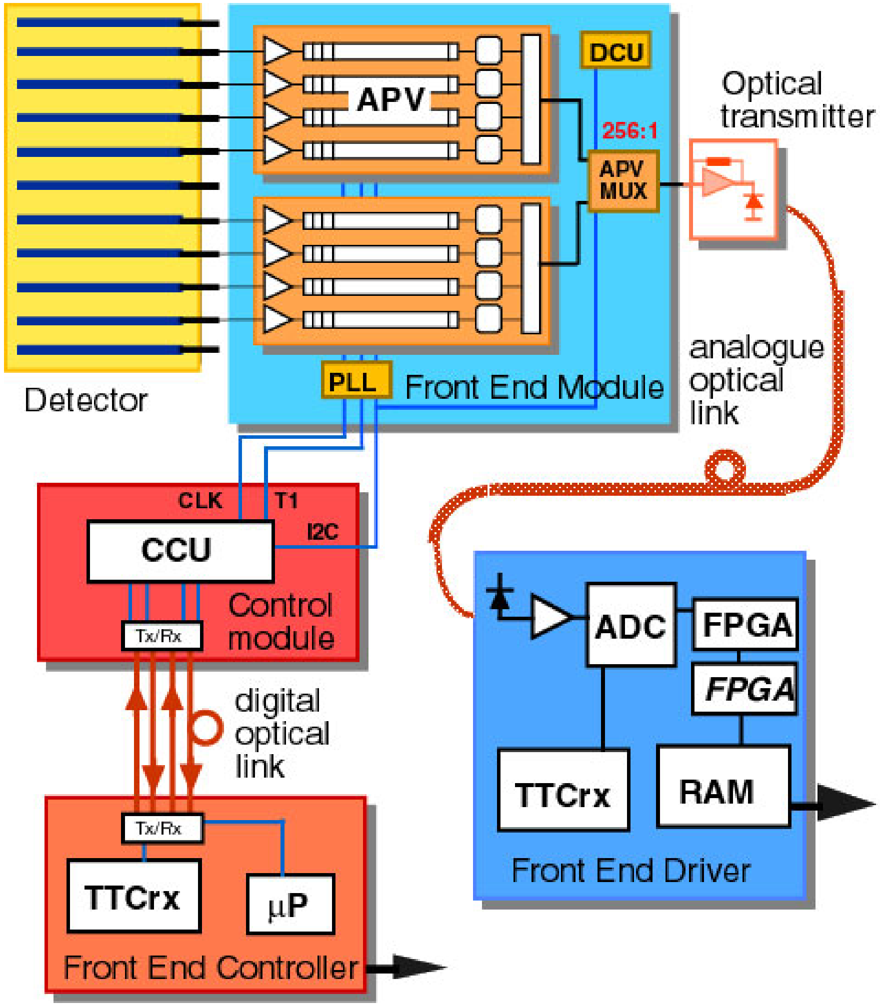
Readout and control architecture

- APV25 readout chip samples and then stores the analog pulse height data for first level trigger latency of 3.2 μs
- On L1 trigger, the pulse height data processed and multiplexed from pairs of APVs onto a differential line to the Analog Opto-Hybrids (AOHs) located at a few cm distance
- AOHs consist of laser drivers that modulate the drive currents of edge-emitting InGaAsP laser diodes (λ=1300 nm)
- After electrical to optical conversion the data is transmitted over ~100 m single-mode fiber optic cable to the Front-end Drivers (FEDs) in the counting room (~40000 links @ 40 MS/s, ~50 mW/256 channels)
- The FEDs, 96-channel VMEbus readout boards equipped with optical receivers, provide digitization (10-bit ADC) and first processing of the data (frame finding, reordering, pedestal subtraction, optionally cluster finding)
- The data is stored in a local memory until requested by the higher levels of DAQ
- FED input data rate: 3.4 GB/s, output rate: 200 MB/s

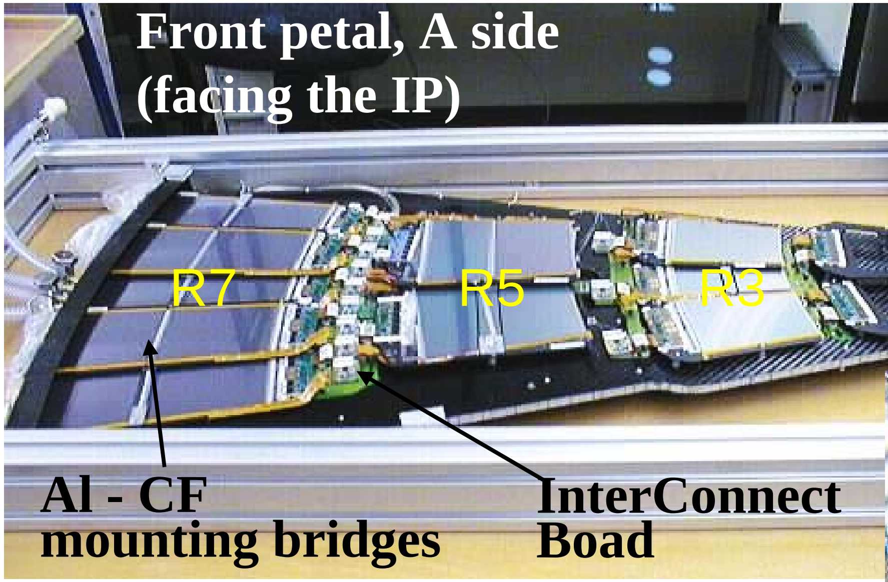


Readout and control architecture

- *The control of electronics is handled by VMEbus boards, the Front-end Controllers (FECs)*
- *FECs distribute the LHC clock (40.08 MHz) and L1 trigger signals (up to 100 kHz rate) received from the global LHC Timing and Trigger Command (TTC) system*
- *Timing and control signals are transmitted to the detector via digital optical links (~2000 links @ 40 MHz)*
- *The signals are encoded by the Communication and Control Units (CCU25 chips) mounted on small PCBs called CCU modules (CCUM) located on the motherboards of the petal, rod,...substructures*
- *CCU25 communicates with FEC via token ring protocol and distributes timing signals to the PLL chips located on the FE hybrids*
- *Control signals are distributed via I^{2}C protocol to the addressed chips on the appropriate devices (modules, AOHs)*

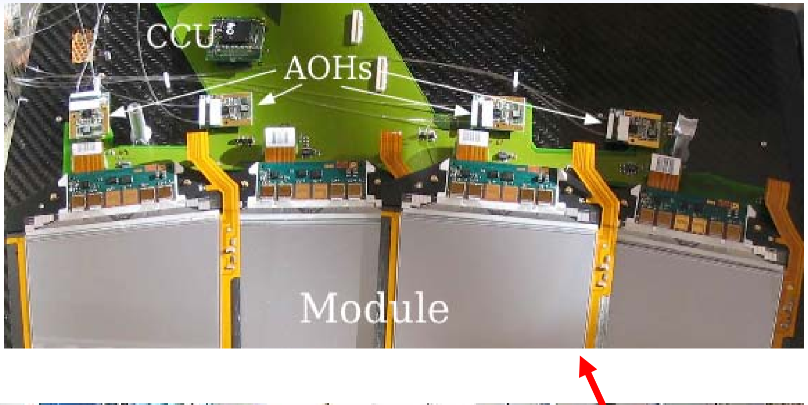


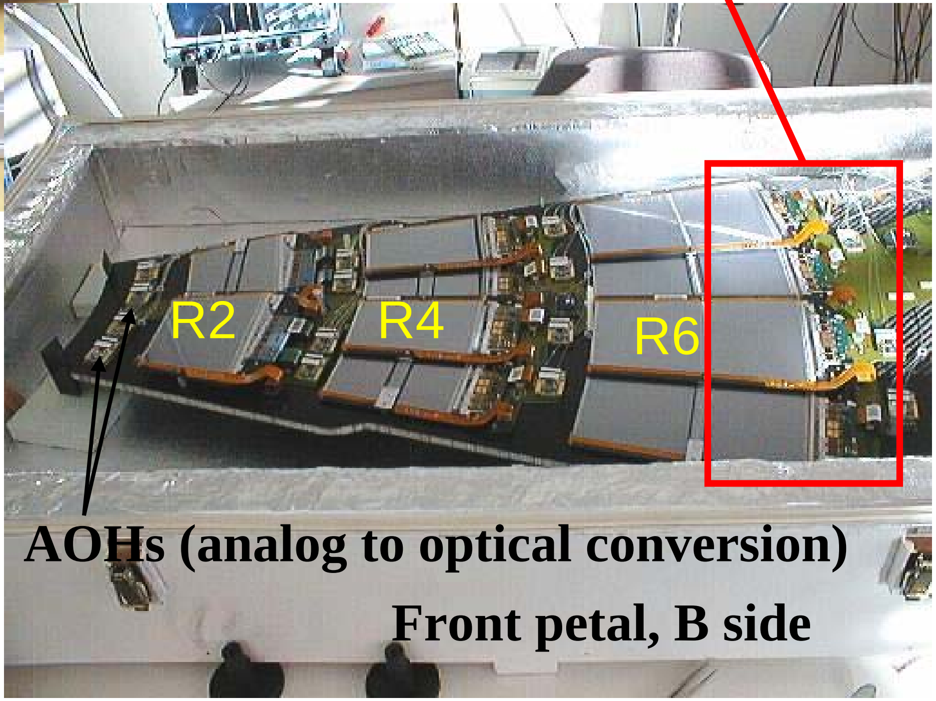
TEC sub-structure: petal


Front petal, A side (facing the IP)

Cooling:

- *titanium pipe of 3.9 mm inner diameter and ~7 m length embedded inside the petal*
- *modules and AOHs mounted on Al inserts glued directly to cooling pipe (precision mounting, thermal contact)*

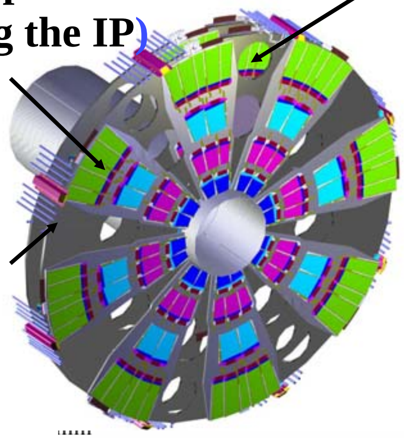


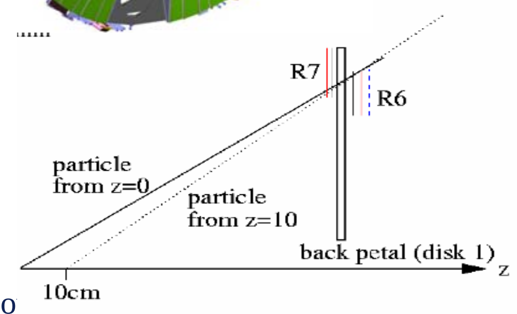

AOHs (analog to optical conversion)

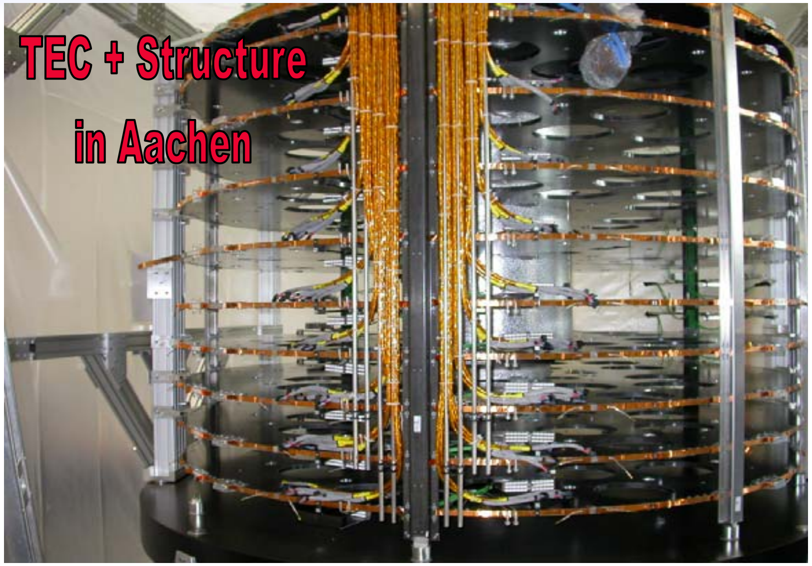
Front petal, B side

TEC structure

- 2x9 CF disks
- basic substructure - petal: wedge shaped CF support plate carrying up to 28 wedge shaped modules arranged in 7 radial rings
- Front and back petals have different geometry and have different number of modules







Clearance problem spotted during petal assembly (after the completion of petals for sector 1). Why not before?

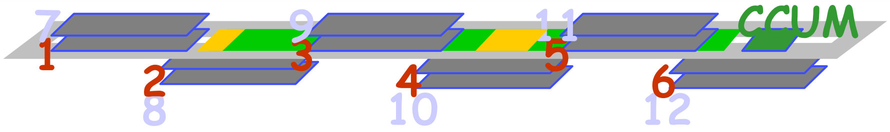
- Height of individual components on Inter-Connect Board not implemented on mechanical drawings
- Tolerances (petal thickness, module leg thickness, height and soldering of components...) are large and poorly known
- Mechanical forces are apparently small and no electrical problem occured

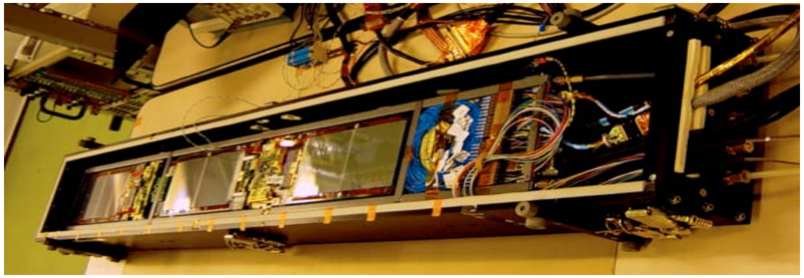
Implications of design change

- Cooling performance still seems ok but worse by 1.58 K/W
- Hermeticity for particles still sufficient

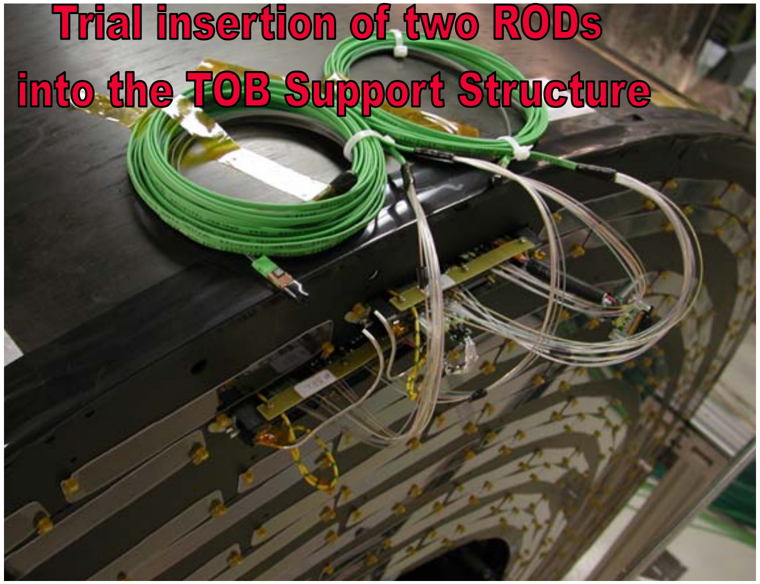
TOB sub-structure: rod

- *6 cylindrical layers*
- *basic substructure - rod:*
  carbon fiber support frame carrying 3 single or 3 double sided thick modules on each side





TOB Support Structure (wheel) at CERN



Trial insertion of two RODs into the TOB Support Structure

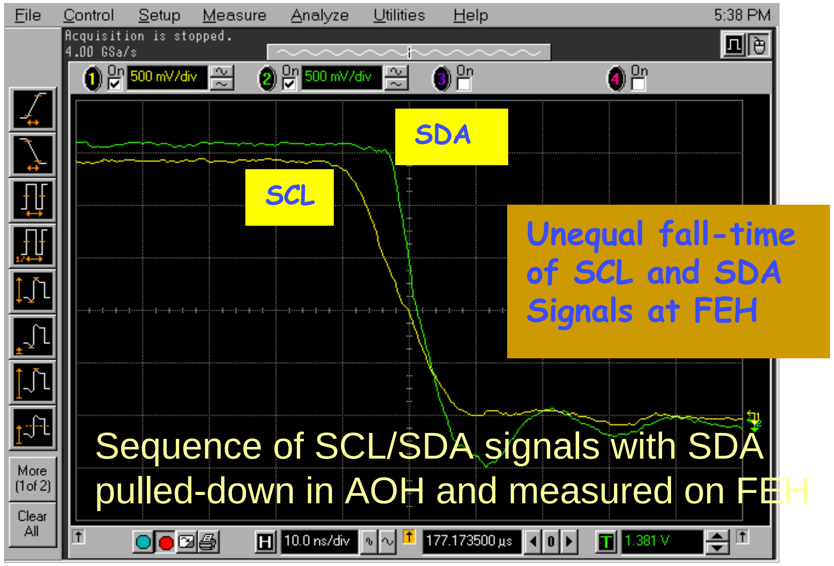
I^2C problems on TOB rod

I^2C errors were seen in first TOB rod acceptance tests at low T

- *Combination of several factors:*
    - *Series resistors plus parasitic capacitances → different timing behaviors of APV on FEH and LLD on AOH*
    - *Different logic thresholds on APV and LLD*
- *For certain data patterns, AOH acknowledge interpreted as I^2C 'start' by APV giving an I^2C error*
- *From several solutions considered the final choice: redesign Inter-Connect Cards (achives ~10 ns margin in SCL and SDA edges on FEH)*
- *Important to have good margin as timing affected by temperature, radiation damage (and ageing?)*

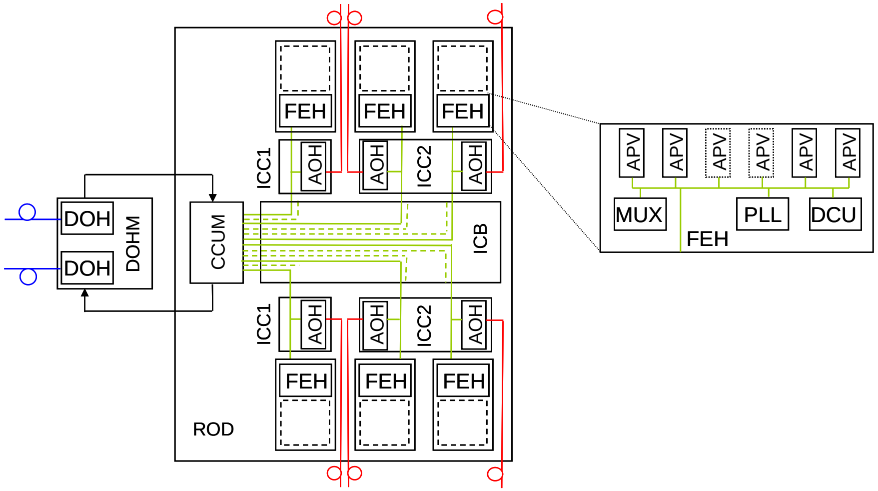
TEC: safety margin is 8 ns, with the addition of a single capacitor in the SDA line extra 3 ns gained

TIB: seeing I^2C errors in layer burn-in (may not be the end of the story...)



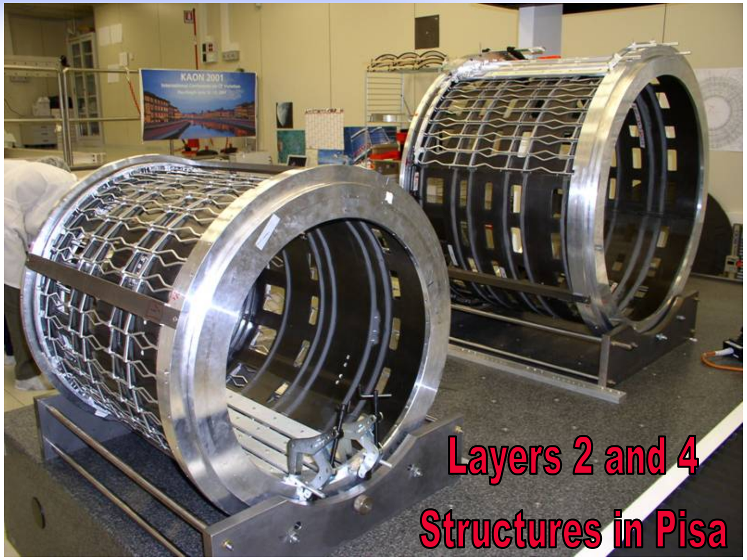
Unequal fall-time of SCL and SDA Signals at FEH

Sequence of SCL/SDA signals with SDA pulled-down in AOH and measured on FEH



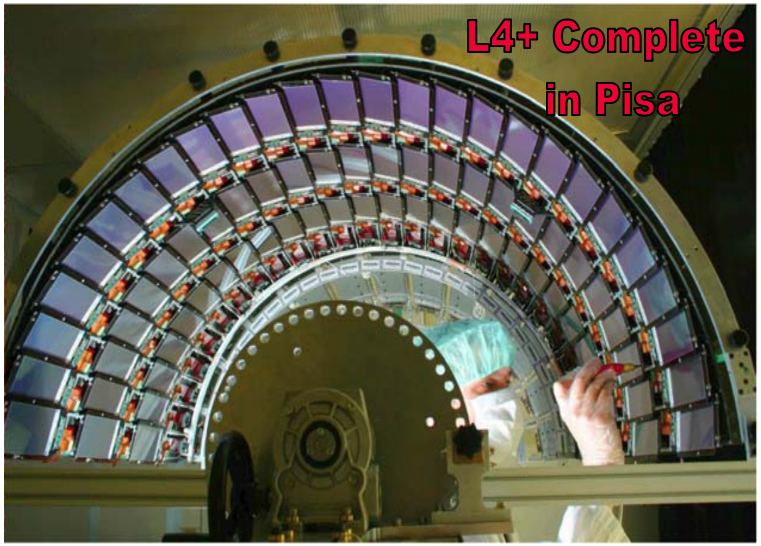
TIB structure

- *4 cylindrical layers each made of 4 carbon-fiber half-shells*
- ***strings** of 3 thin modules are mounted inside and outside the half-shells*



Layers 2 and 4 Structures in Pisa

L3+ Lower Complete in Florence



L4+ Complete in Pisa

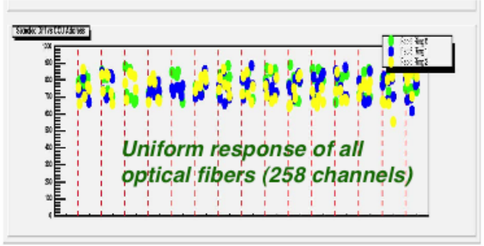
TIB layer 3 burn-in

Burn-in procedure

- Connect optical fibers to optical ribbons
- Connect power cables and switch on
- Timing alignment of all modules
- Optical gain adjustment
- Take data (peak and deconvolution mode)
- Flux dry air & cool down climatic chamber and repeat data taking
- If some modules do not respond to I2C communication: change the modules (~2%)

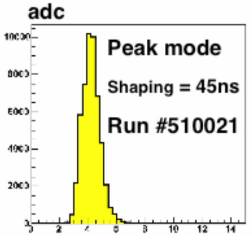
Analog Opto Hybrid gain:

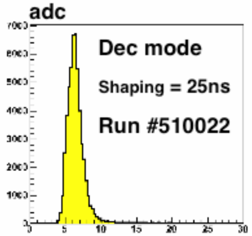
- Gain is adjusted according to the *tick mark*


Uniform response of all optical fibers (258 channels)

Data taking:

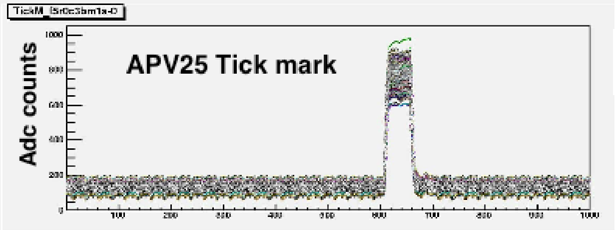
- Parallel readout of the full layer
- Noise distribution in peak mode and deconvolution mode (66048 strips)

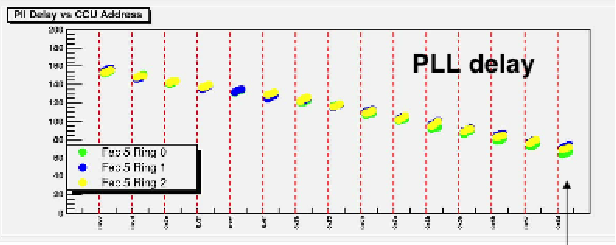




Timing:

- All modules (129) are powered
- All *tick marks* are reconstructed and aligned
- PLL delays are selected to synchronize all modules: *consistent with logical position inside the ring*





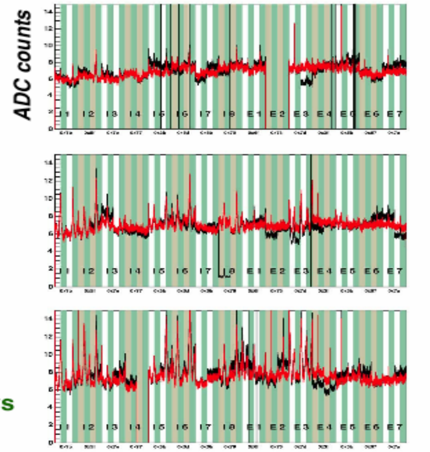
Ultima posizione nel ring

Peak mode: very good noise distribution

Dec mode: higher noise in modules close to the end flange

-> better grounding & shielding needed

Modules far from the end-flange

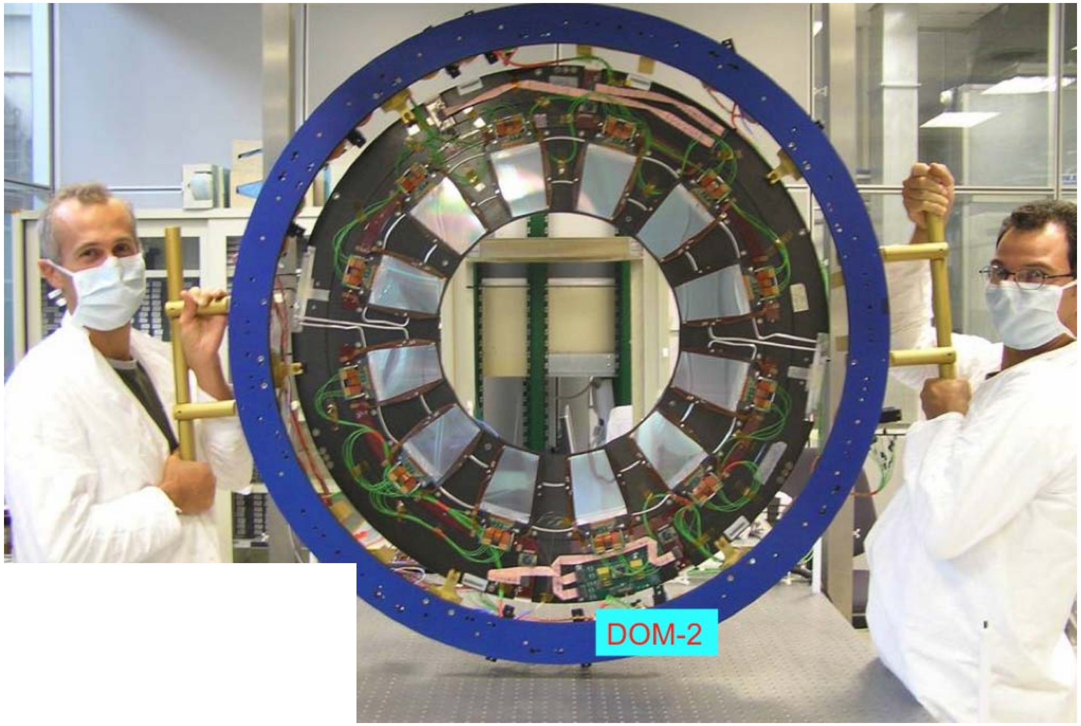


Modules close to the end-flange

Noise Distribution vs Strip number (DEC INV-ON)

TID structure

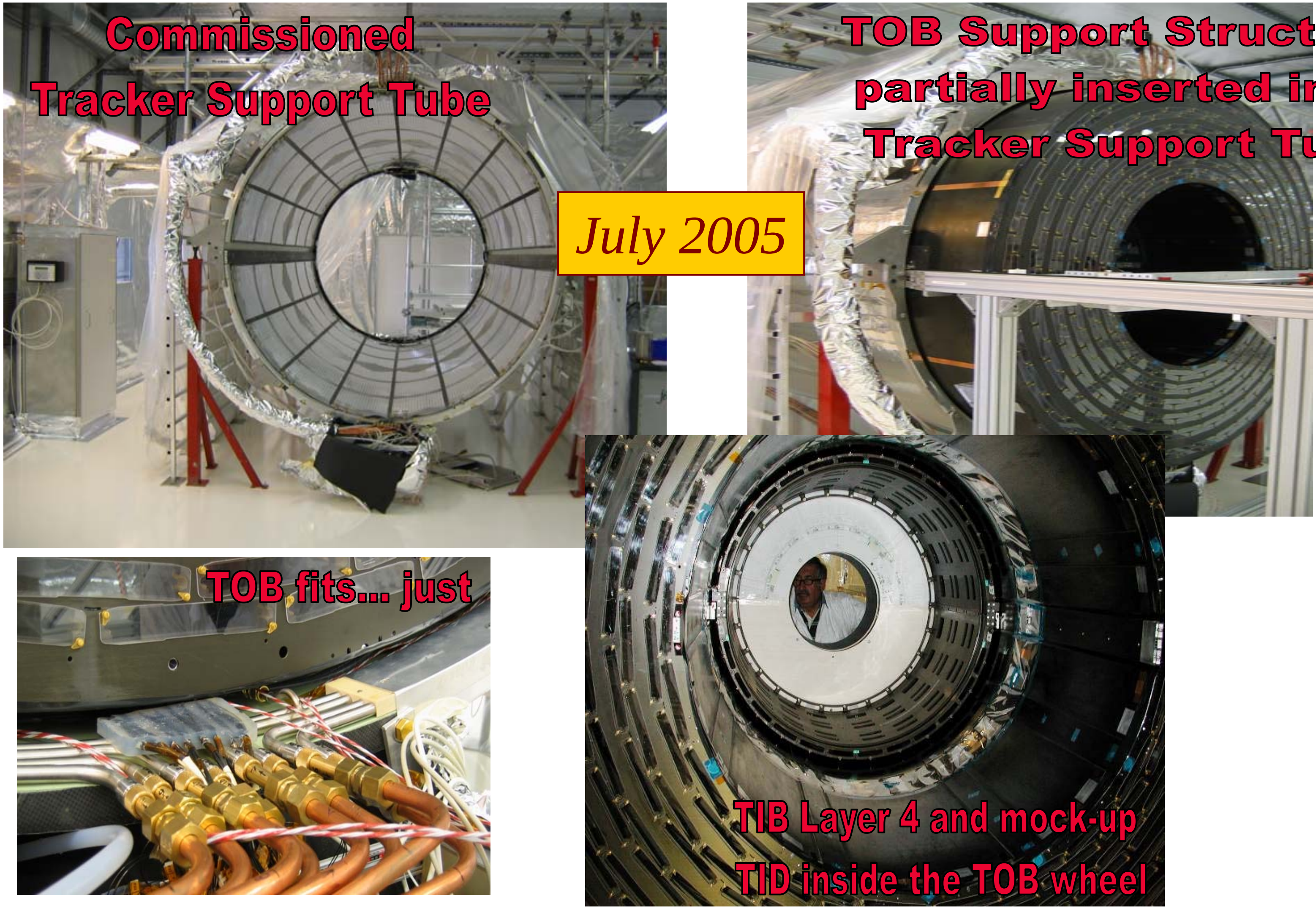
- *On 2 x 3 disks modules arranged in 3 rings*
- *Delay due to late delivery of DAQ SW + time spent on fighting noise*



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

2 control rings:
Noise tails on ring 2 become more pronounced when ring 1 is on
Final grounding and shielding scheme to be implemented

Integration test



Commissioned Tracker Support Tube

TOB Support Structure partially inserted into Tracker Support Tube

July 2005

TOB fits... just

TIB Layer 4 and mock-up TID inside the TOB wheel

Substructure performance in testbeam

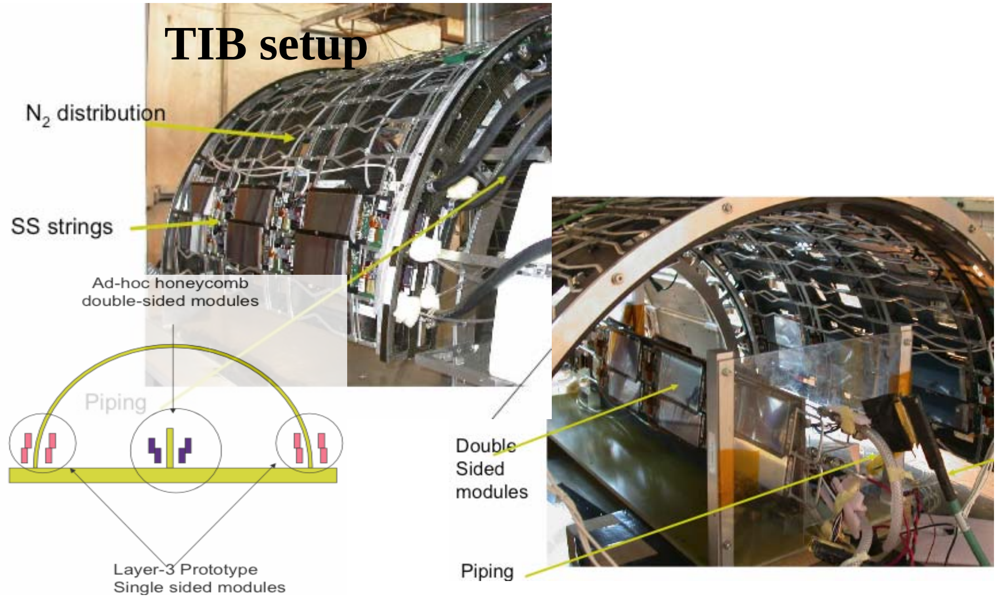
Beam: 120 GeV pions or 70-120 GeV muons at CERN X5 in 2004

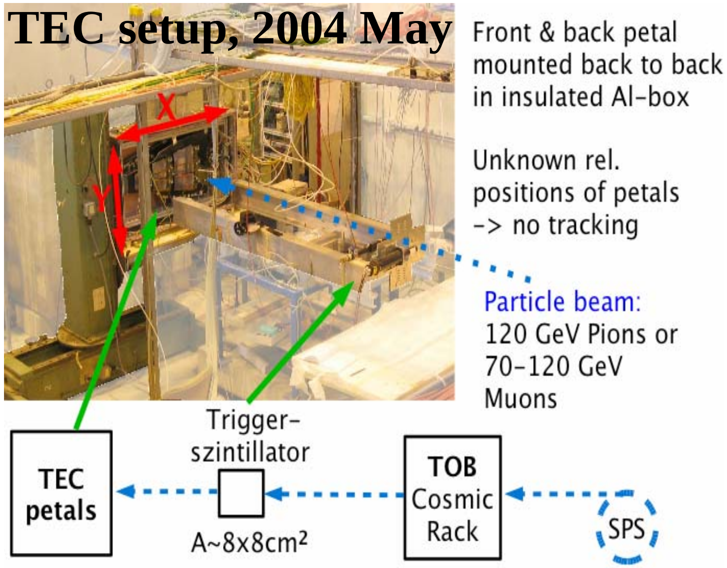
Including:

- *2 TEC petals (1 complete control ring with 51 modules, 1% of TEC)*
- *6 TOB rods in Cosmic Rack (precision support structure with integrated cooling) operated at CMS temperature (~-10 C)*
- *TIB Layer 3 prototype plus some double sided strings on an ad-hoc structure*

Excellent system behavior:

- *Stable communication and readout at all temperatures*
- *Uniform noise distribution, small common mode*
- *Signal/noise ~ 20*
- *Equivalent noise charge consistent with expectation from measurements on single APVs*



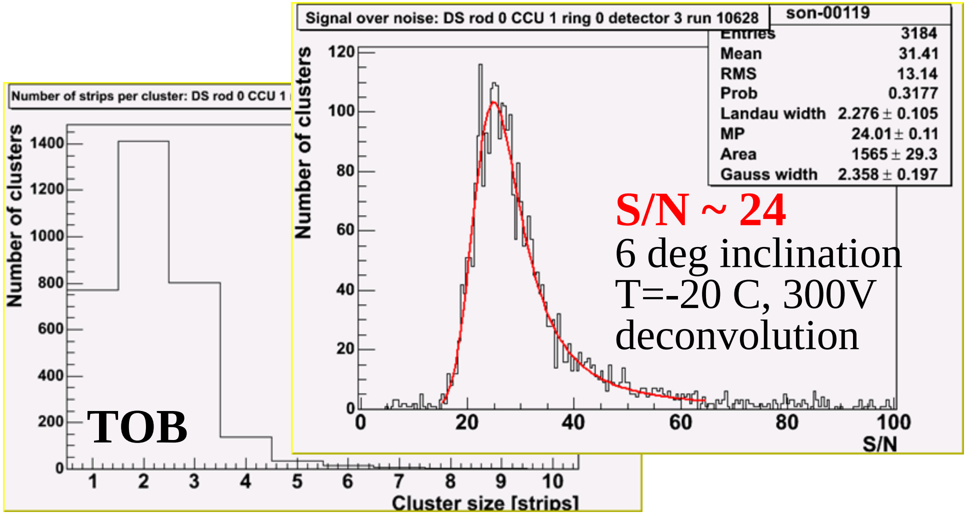

TEC setup, 2004 May

Front & back petal mounted back to back in insulated Al-box

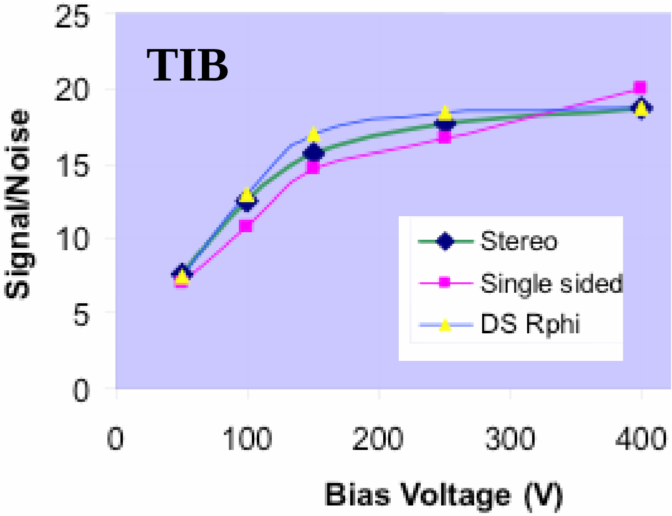
Unknown rel. positions of petals -> no tracking

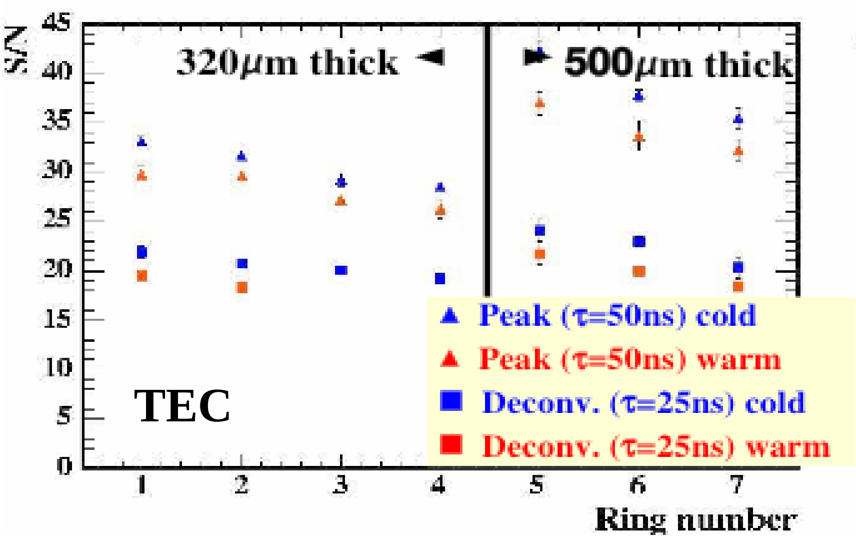
Particle beam: 120 GeV Pions or 70-120 GeV Muons

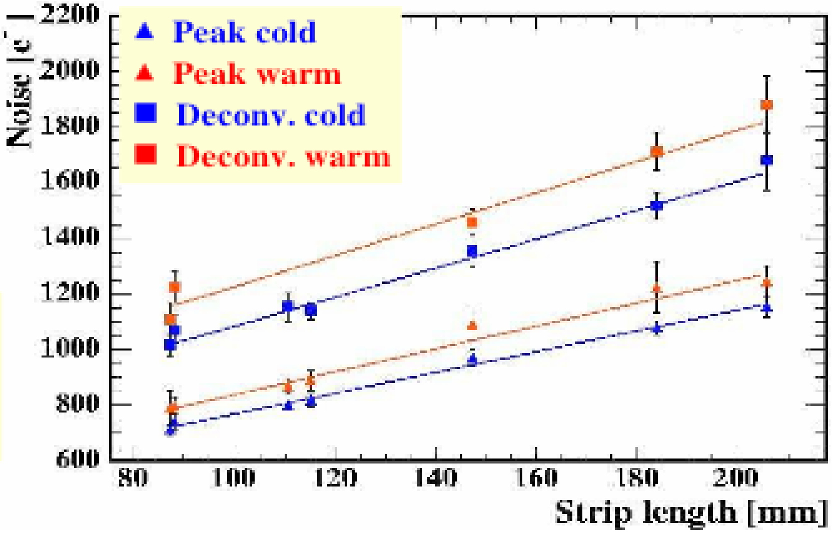
Signal / Noise performance



S/N ~ 24
6 deg inclination
T=-20 C, 300V
deconvolution



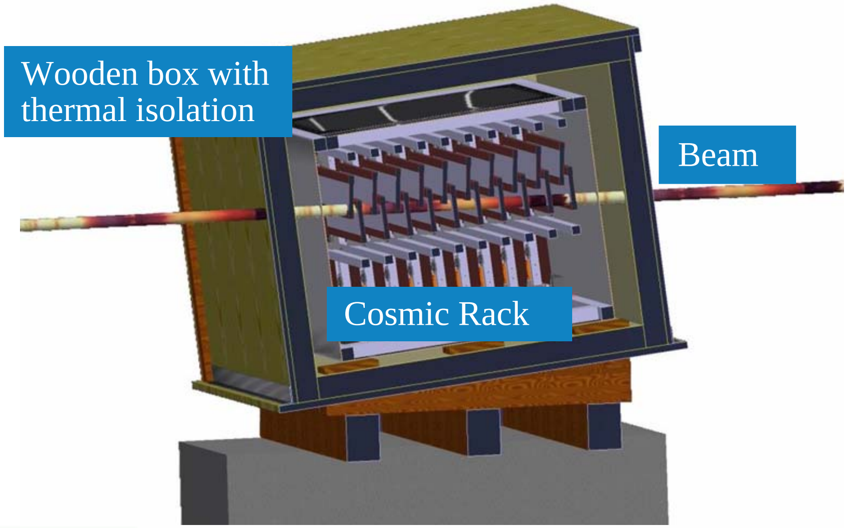


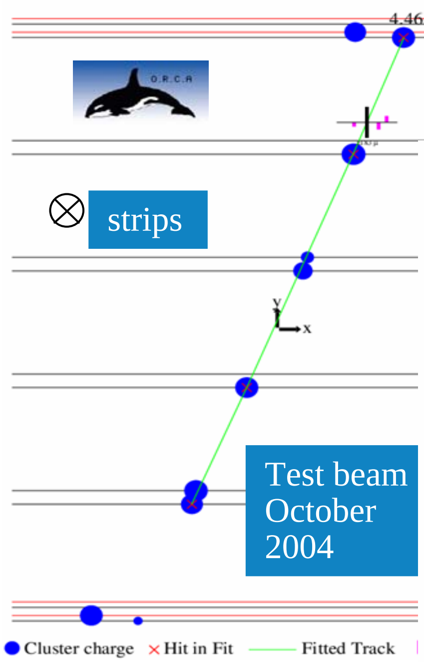


Tracking studies with Cosmic Rack

Successful tracking in Cosmic Rack using official CMS software (ORCA)

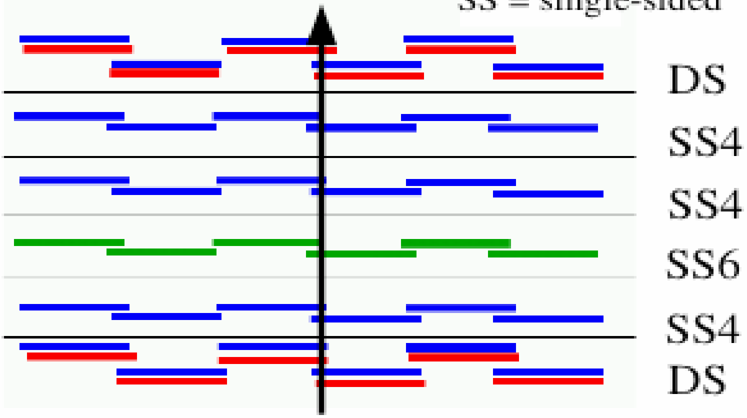
- *Spatial resolution agree with expectation*
- *Resolution improved for inclined tracks as in average 2 strips are hit*





Test beam October 2004

DS = double-sided
SS = single-sided

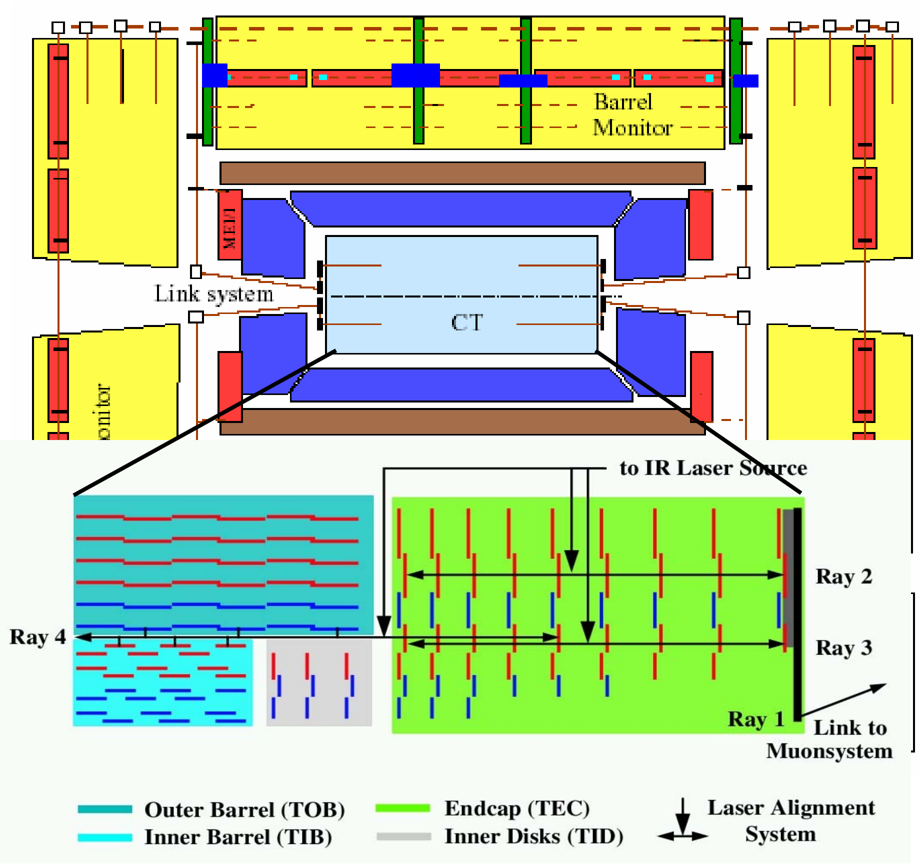


σ_may (μm)	σ_sept (μm)
straight tracks	6° inclination
45	29
45	34
42	38
35	28
54	33
50	30

pitch/√12=35μm (SS6) and 53μm (DS, SS4)

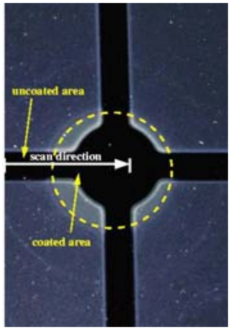
Alignment system

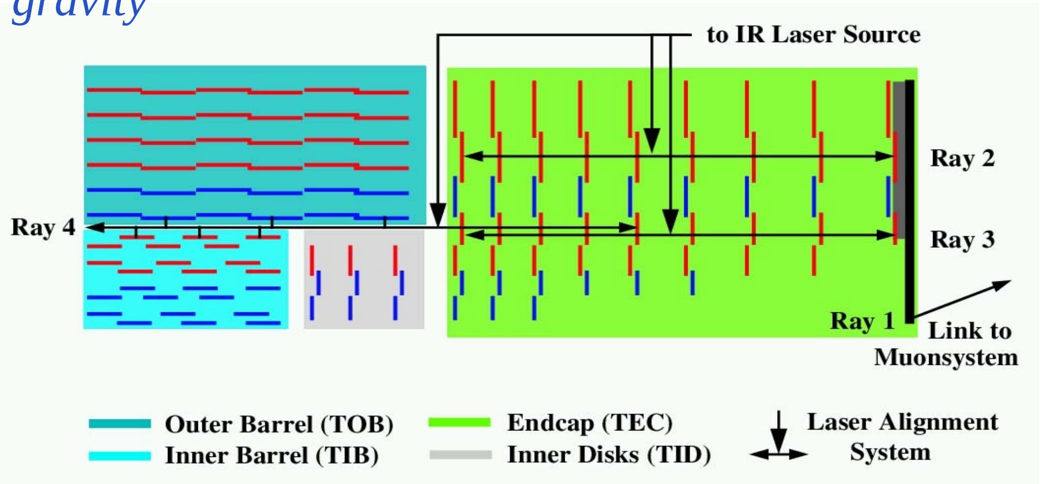
- Assembly tolerances and measurements:
    - individual silicon modules within SST subdetectors ~50 μm
    - between subdetectors ~ a mm
- Intrinsic detector resolution 10 (r-φ) and 17 (r-z) μm for pixel and ~10-60 (r-φ) , 500 (r-z) μm for an SST module
- Using charged tracks and minimizing the track residuals in an iterative procedure, the tracker can be aligned to ~ a few μm
- … but tracking must be possible for the iteration to be started → hardware alignment system (MB, ME, SST, Muon - SST link system):
    - Monitors the tracker support structure (mechanical and thermal stresses may change the alignment during operation), generates online alignment info
    - Provides an absolute detector positional accuracy of 100 μm, needed for tracking input to HLT

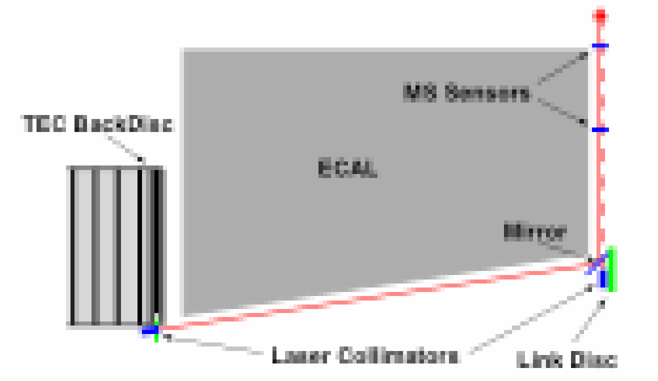


Implementation

- *Si partially transparent to IR light*
- *Hit Si with (naturally straight) laser beams of λ=1080 nm that are sensed by the modules*
  - *Ray 1: 6 beams couple SST to muon system on each side of the SST*
  - *Rays 2, 3: 2x8 beams (symmetrically distributed in ϕ) align all 9 TEC disks*
  - *Ray 4: 8 beams connect TIB, TOB and and both TECs*
- *For each beam, the laser coupled to an optical fiber and fed into a beam splitter*
- *Use special sensors for endcap with anti-reflective coating and a 10 mm hole in the back-metal which enables the transmission (~20%) of the laser beams*
- *Tilt-meters also monitor the orientation of SST and the muon system wrt to gravity*

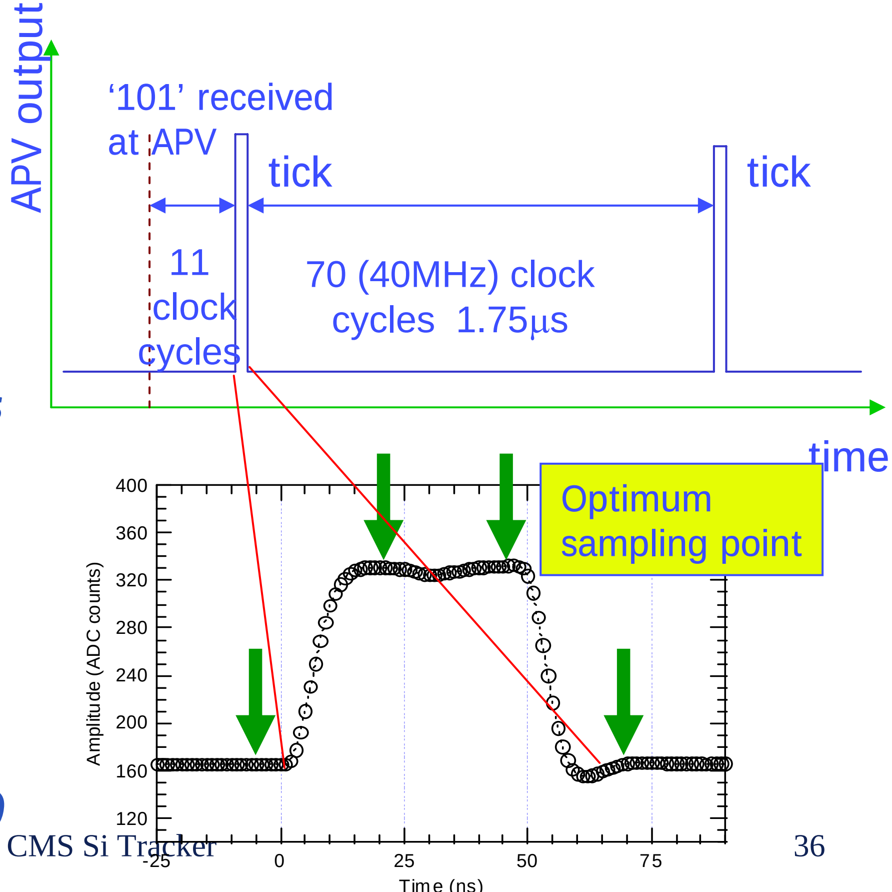






Synchronization

- Readout system as a whole need to be synchronized in order to capture data from the correct bunch crossing (25 ns) and to transmit this data with optimal signal-to-noise ratio, i.e. sample the analog data at the appropriate moment in time (with few ns tolerance)
- Achieved in two steps: (1) relative: APVs with each other (2) absolute: SST to LHC beam
- Main tool: APV 'ticks' every 70 clock cycles starting at a fixed time after 're-synch' (101) signal received at APV, providing precise probes of timing skew between APVs
- Tick transmitted over analogue optical link to FED
    - Measure arrival time at FED
    - Calculate time when the ticks left the APVs knowing analogue optical link lengths from database
- Intelligence: FED reads 8•12 inputs and has a delay FPGA before front-end FPGA
    - Coarse clock skew (25ns steps) to analyse same APV sample across the 12 inputs
    - Fine clock skew (1ns steps) to allow enough settling time for the signal (~20ns)



APV output

'101' received at APV

tick

tick

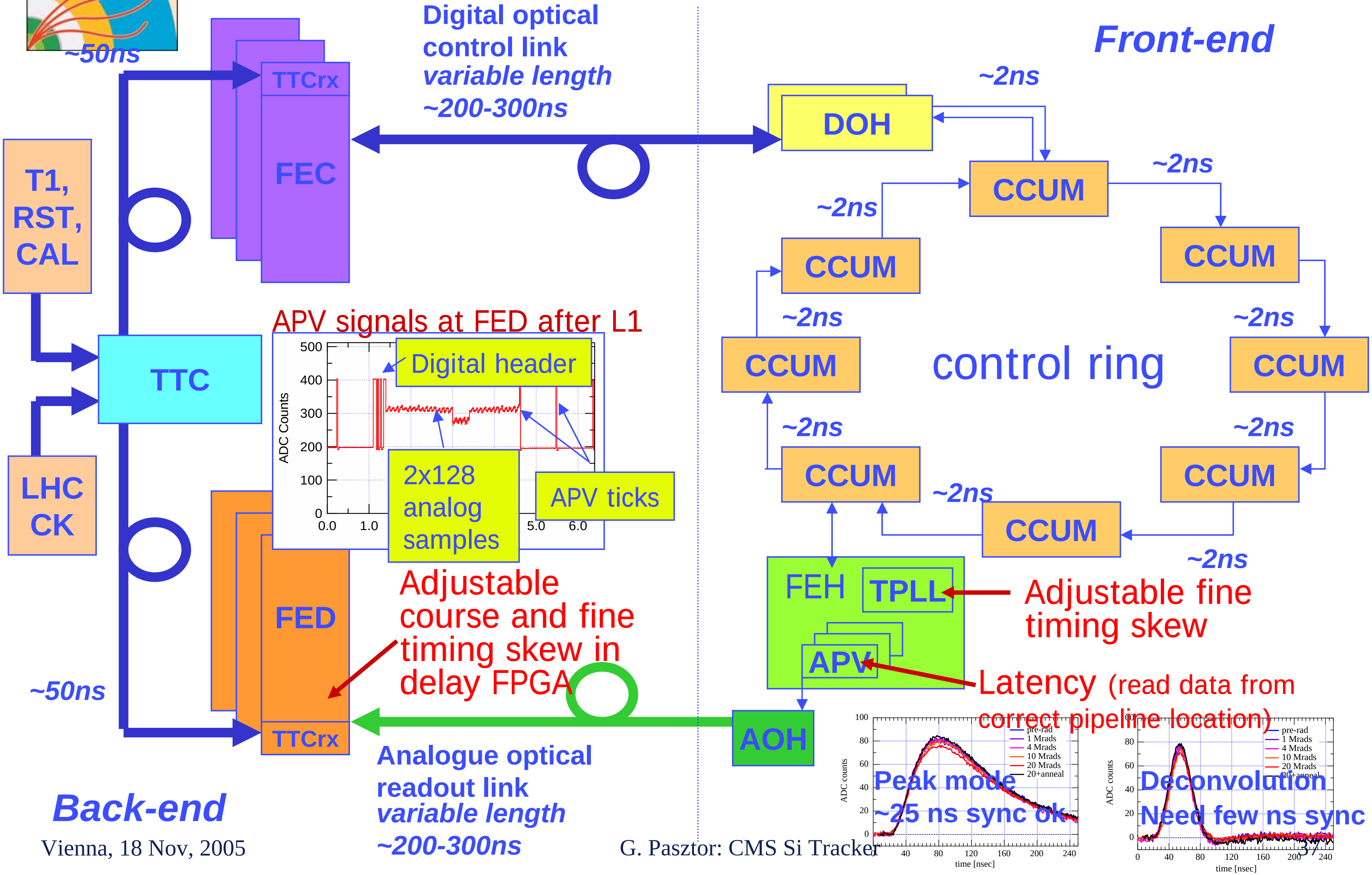
11 clock cycles

70 (40MHz) clock cycles 1.75µs

time

Optimum sampling point

Timing issues in readout system



~50ns

T1, RST, CAL

LHC CK

TTC

TTCrx

FEC

Digital optical control link *variable length ~200-300ns*

Front-end

~2ns

DOH

CCUM

CCUM

CCUM

CCUM

CCUM

CCUM

CCUM

CCUM

~2ns

~2ns

~2ns

~2ns

~2ns

~2ns

~2ns

~2ns

control ring

APV signals at FED after L1

Digital header

2x128 analog samples

APV ticks

FED

TTCrx

Adjustable course and fine timing skew in delay FPGA

~50ns

FEH

TPLL

APV

AOH

Adjustable fine timing skew

Latency (read data from correct pipeline location)

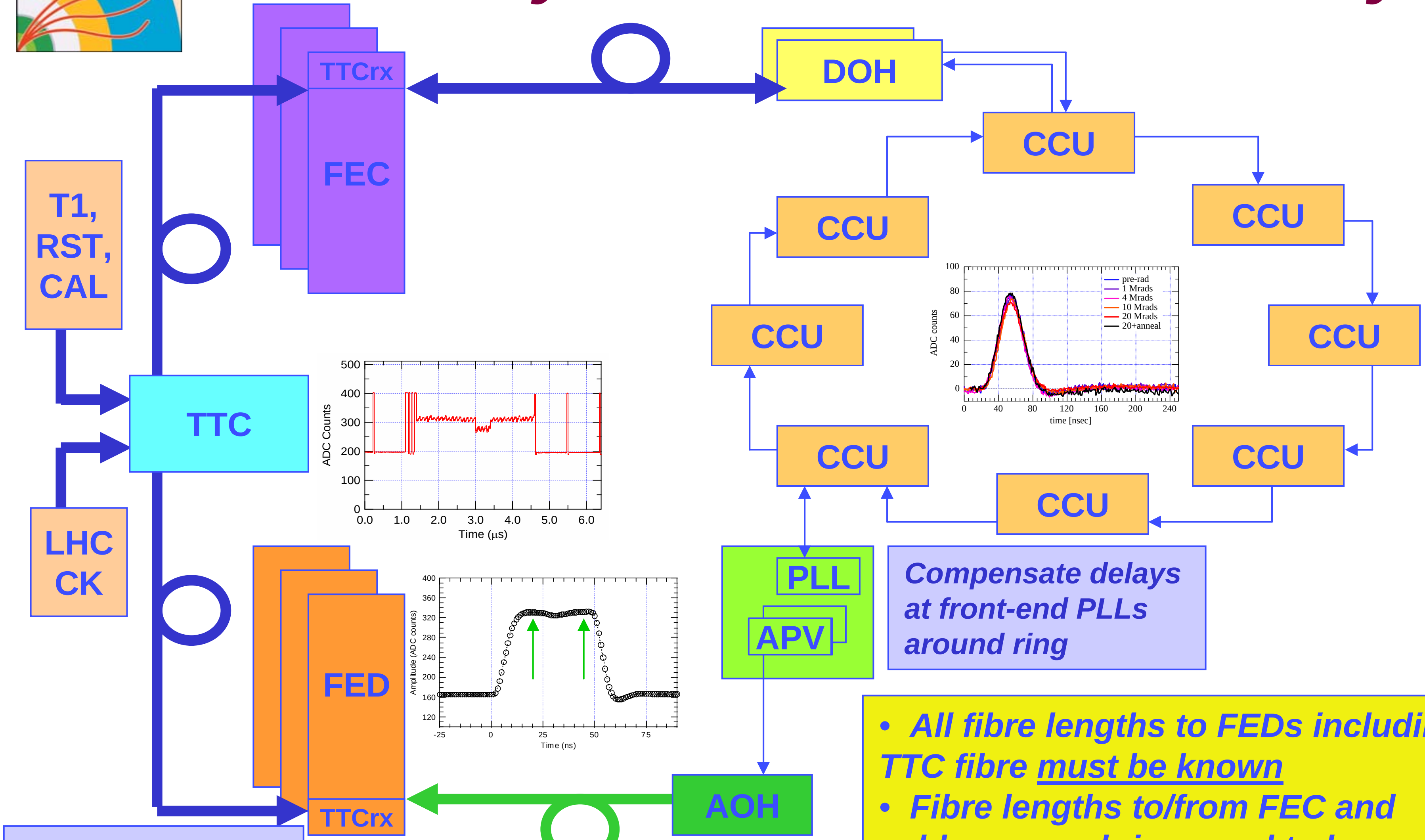
Analogue optical readout link *variable length ~200-300ns*

Back-end

Peak mode ~25 ns sync ok

Deconvolution Need few ns sync

Relative synchronization summary



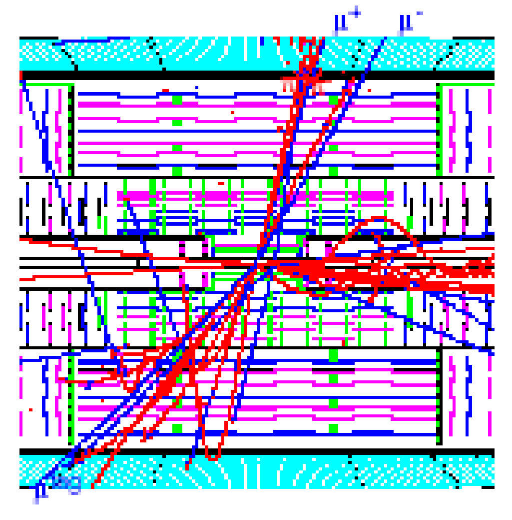
Compensate delays at front-end PLLs around ring

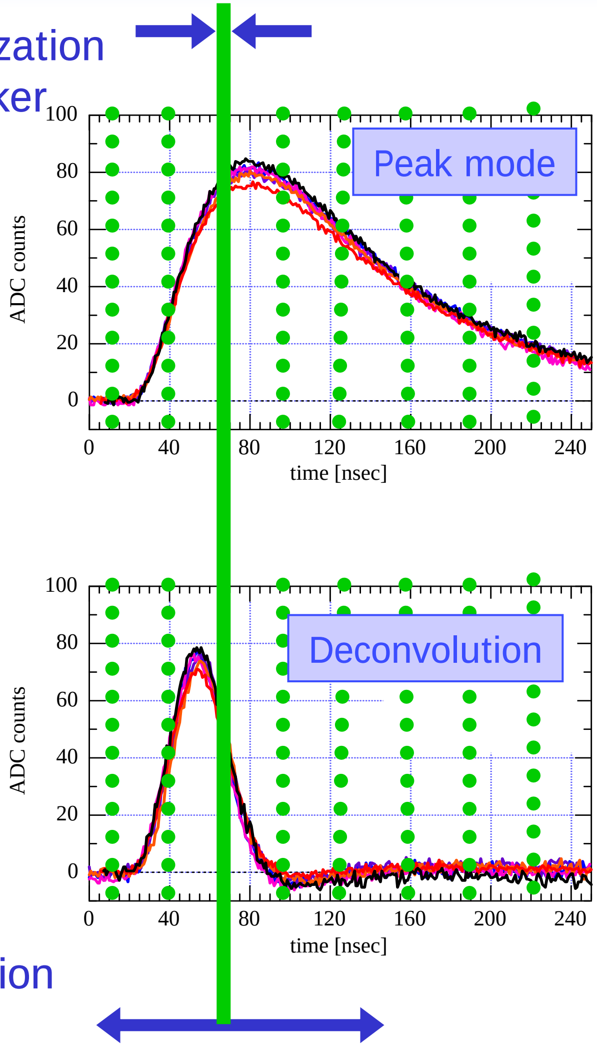
set timing on delay FPGA at FED

- *All fibre lengths to FEDs including TTC fibre __must be known__*
- *Fibre lengths to/from FEC and cables around ring good to know __but not critical__*

Absolute synchronization

Relative synchronization
to set up the Tracker

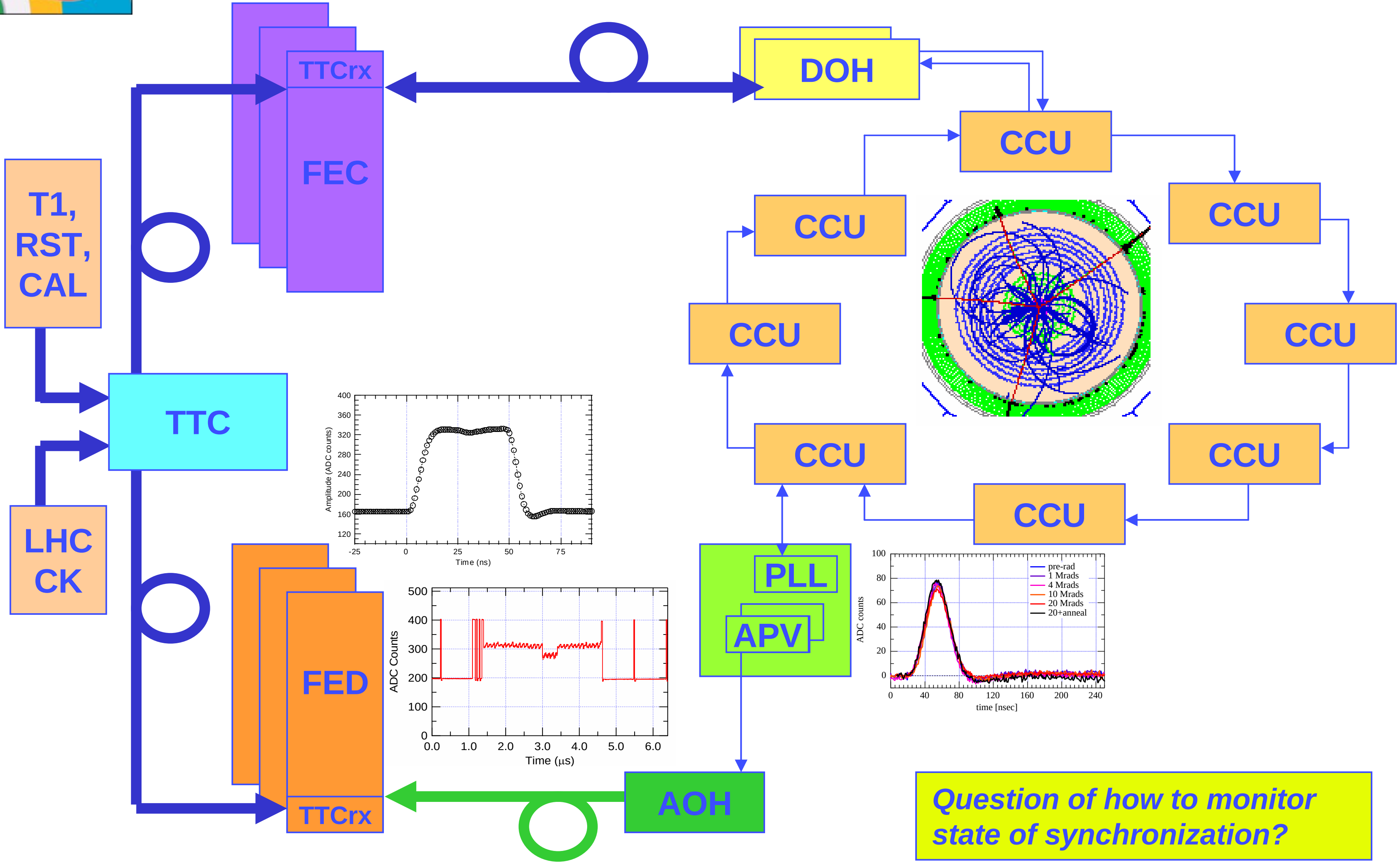




Absolute synchronization
to find the particles...

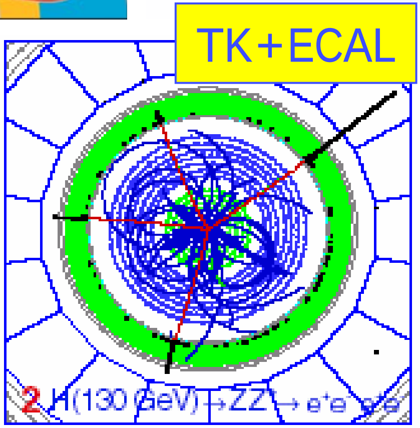
- *Relative synchronization aligns APVs with respect to one another*
  - *but not to LHC collisions*
  - *or rest of CMS*
- *Need to align APV sampling to signal generated in silicon strips by passing particles*
  - *Coarse timing*
    - *adjust latency at APV*
  - *Fine timing*
    - *re-adjust PLLs at front-end*
- *Same procedure used in beam-tests*

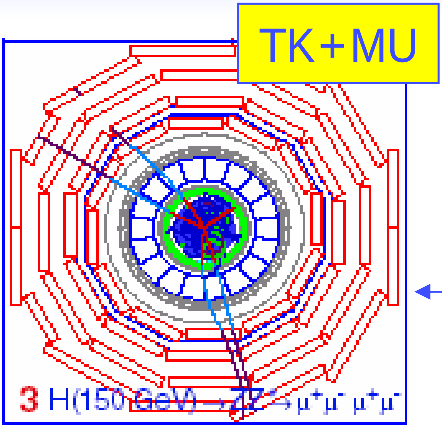
Synchronization summary

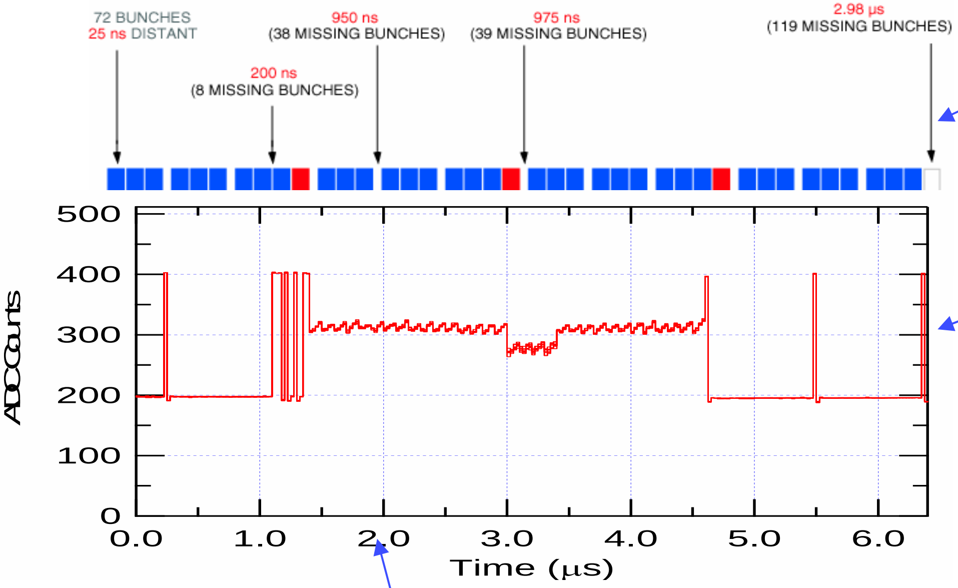


Question of how to monitor state of synchronization?

Monitoring synchronization


TK+ECAL


TK+MU



Digital header

Synchronization may be lost for example due to a SEU damaging the PLL delay or APV latency register content

Tracker data should be consistent with rest of CMS

FED occupancy should match LHC bunch structure

FED compares 8-bit APV pipeline address in header on every channel with the expected one

- *Coarse timing defects easy to see*
- *Fine setting problems more difficult*

CMS SST cost (kCHF)

Si detector production	29 284
Sensors	**20 952**
Kapton	547
Frames	1 703
Pitch adapters	1 055
FE hybrid	2 065
Tooling and box	311
ICB, CCUM, DOH and bus	1 628
Module pre-series	1 023
Electronics	21 578
Module electronics	2 980
Analog link	**10 494**
Digital link	663
Analog opto-hybrid	847
Digital opto-hybrid	44
FED	**6 330**
FEC	220
Power	8 600
Power supplies	**5 742**
Cables installed	2 858

Mechanical structures & general cooling	9 936
Inner barrel	1 033
Inner Endcap	358
Outer barrel	572
Outer barrel rods	1 220
Endcaps	1 260
Endcaps petals	905
General cooling	2 348
Integration (st, ts, ...)	2 240
Monitoring	950
Position Monitoring System	600
Temperature	350
Data Acquisition	1 680
Test stands	1 680
Installation Manpower	1 000
Installation Manpower	1 000
Total	**73 028**
Deficit	-4 950

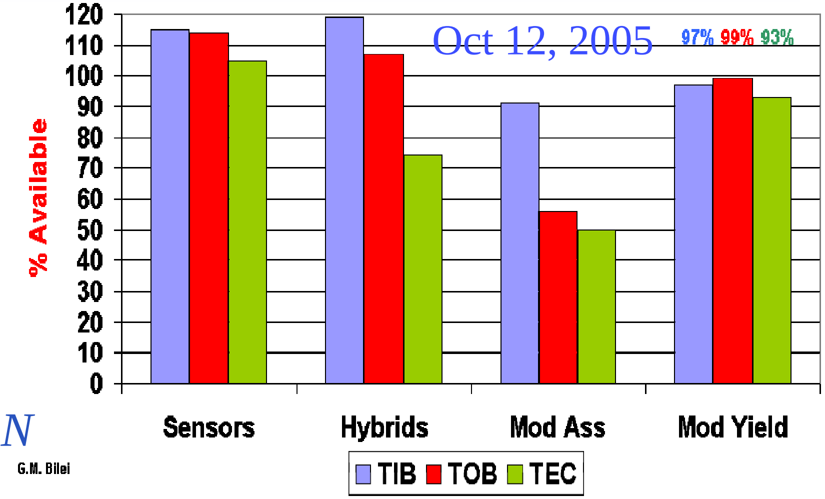
Beware: costing does not include

- Spares (~2.5 MCHF)
- Labor (provided by different agencies in different forms, impossible to estimate)
- Local exploitation budgets (often used for every day work, believed not to be a big correction)
- M&O

- TDR Addendum (2000 Feb) SST cost estimate: 69 343 kCHF

- Pixel: 8.2 MCHF (estimate not updated since a very long time, expected to move up)

Summary



G.M. Bilei

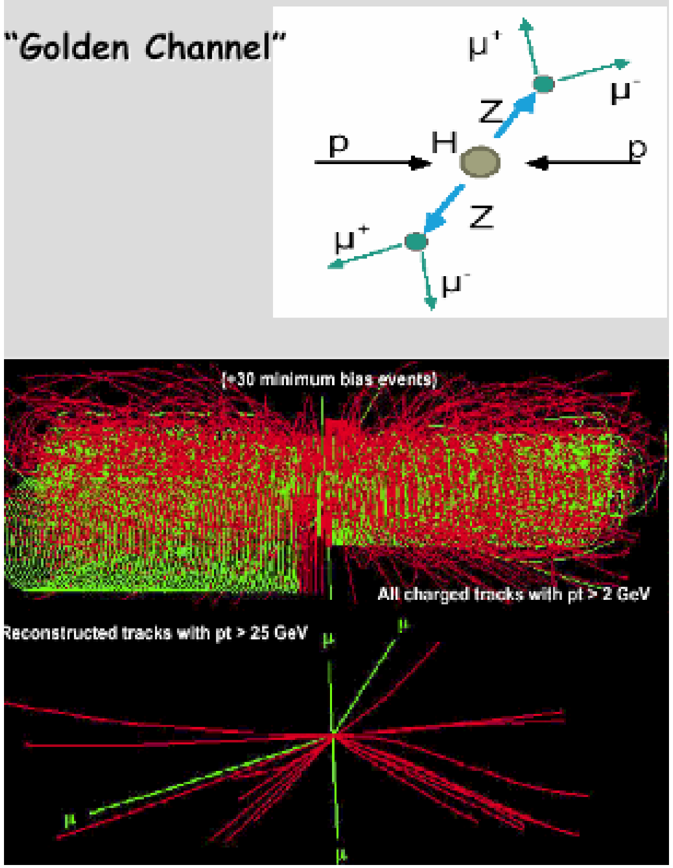
- TOB rod production re-started
- 50/288 TEC petals built
- Integration process started
    - TIB L3+, L4+ complete
    - Tracker Support Tube commissioned
    - TOB support structure complete
    - TEC+ support structure (almost) complete TEC – being prepared for transport to CERN
    - Trial integration successful
- The quality of substructure is found to be excellent both in system tests and in test beam experiments
- Full Tracker integration is about to start
- Commissioning by readout tests of 25% of the Tracker with final DAQ system is expected from March 2006
- We have a rather bumpy road with many adventures toward the completion of CMS SST and I am sure new challenges are ahead us
- It is very demanding to deliver a tested SST to LHC Point 5 by November 2006... but we (hopefully) learned from past problems and mistakes and are motivated

- The high energy physics community should draw conclusions and avoid to make the same mistakes at ILC

Backup Slides

Physics requirements for Tracking

The quest for Higgs driven the design of LHC detectors to a large extent but other physics of interest (SUSY, CP-violation...) require the same capabilities



Efficient tracking

- *Fine granularity to resolve nearby tracks*
- *Fast response time to resolve bunch crossings*
- *Number of layers to recognise trajectories*

Reconstruct high p_T tracks and jets for precise reconstruction of heavy narrow particles

- *High magnetic field*
- *Large lever arm (alignment of inner Tracker and Muon system)*
- $\sigma(p_T)$ = *1-2% for 100 GeV muons*

Reconstruct low p_T tracks (down to 1-2 GeV) for effective isolation criteria

b and τ tagging (for new physics, top tagging, CP violation)

- *Impact parameter resolution ~ 10-20 μm*

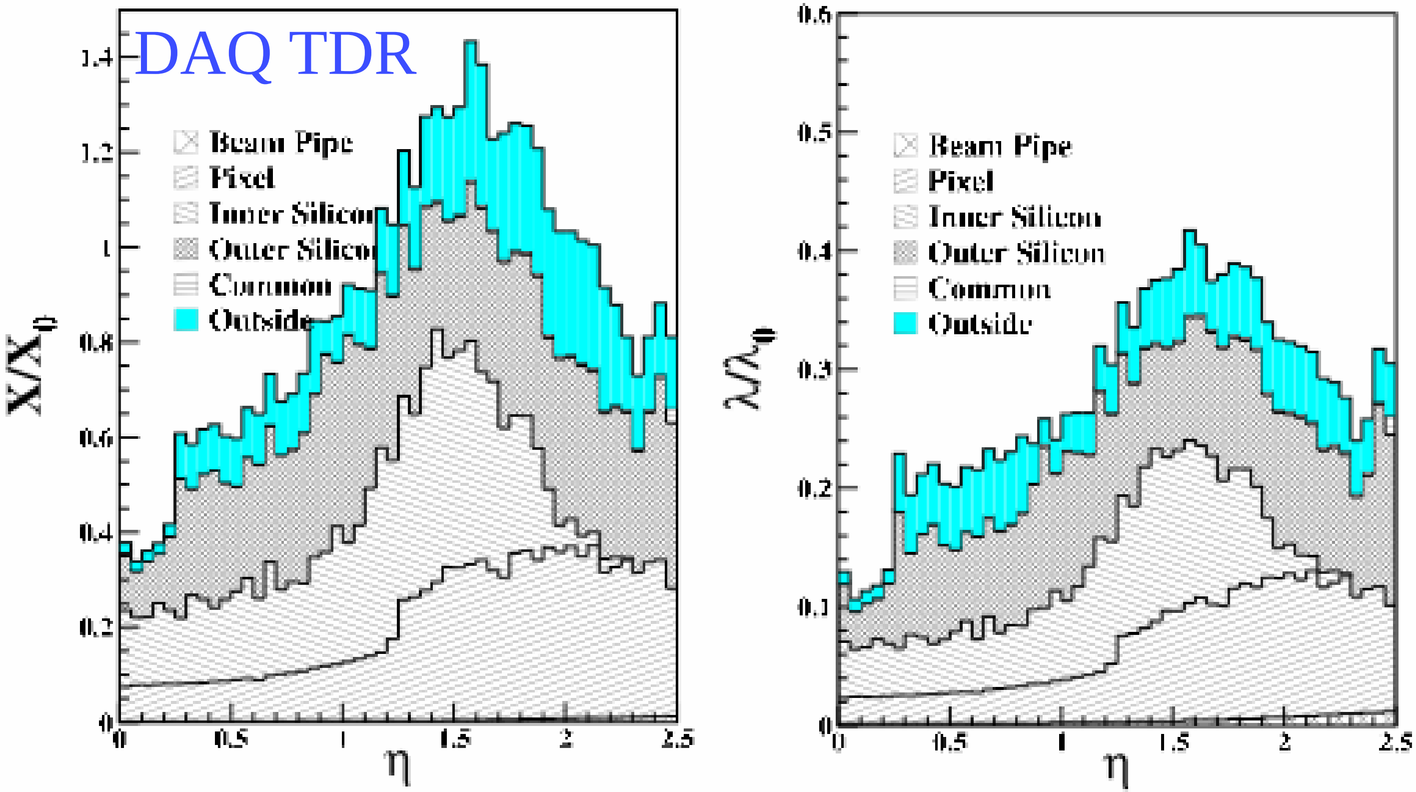
Minimal perturbation

- *Minimise material, low Z desirable (multiple scattering, hadronic interactions, effects on electron and photon detection and isolation due to brehmstarhlung and conversion)*

Radiation hard

Cost

Material budget

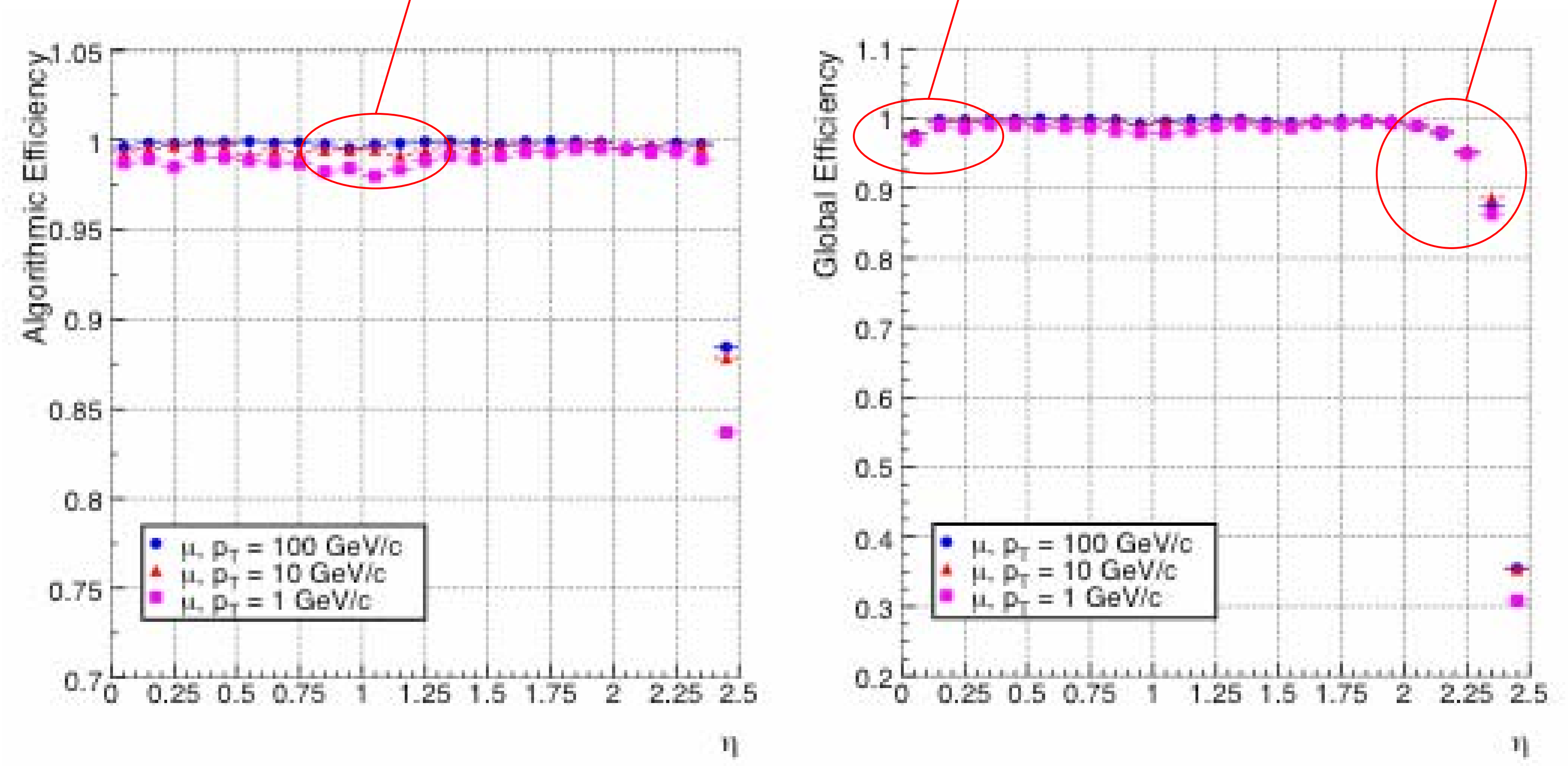


Track reconstruction efficiency

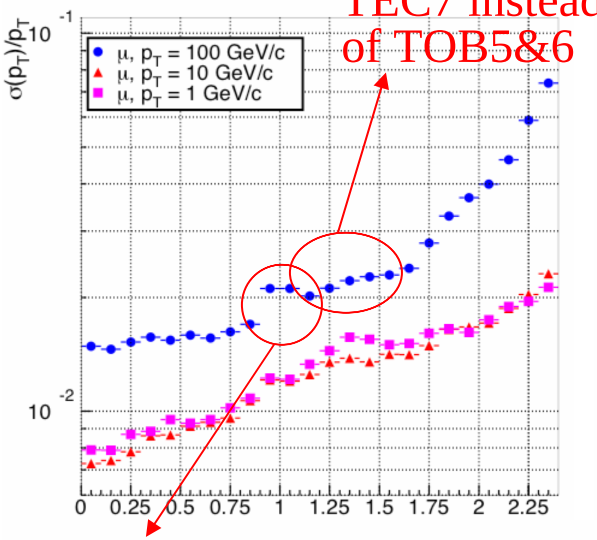
Gap between barrel and endcap systems

Gap between two half barrels of pixel

Loss of endcap disk coverage

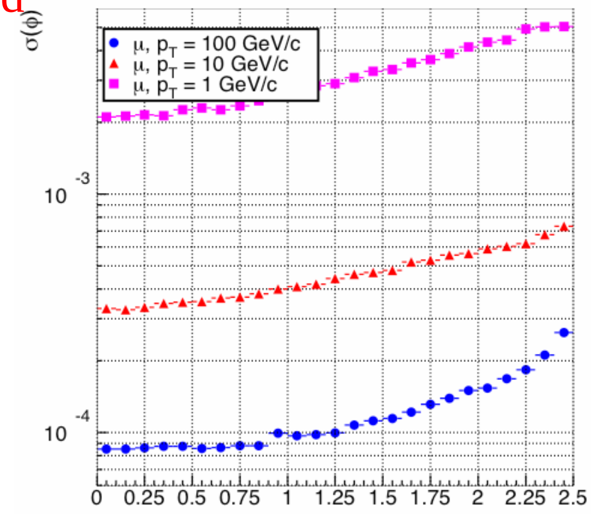


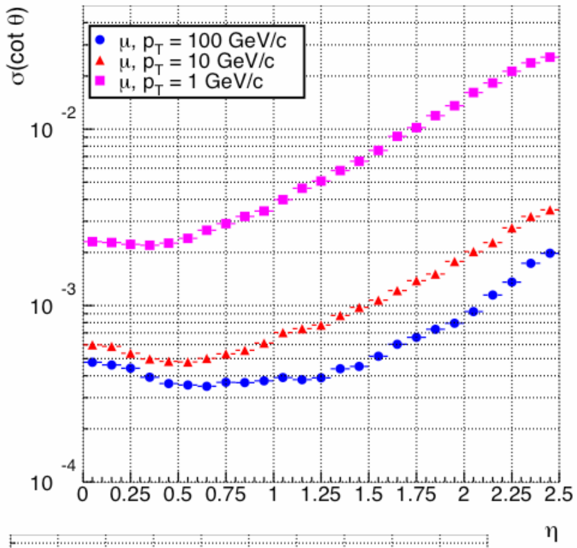
Track parameter resolutions

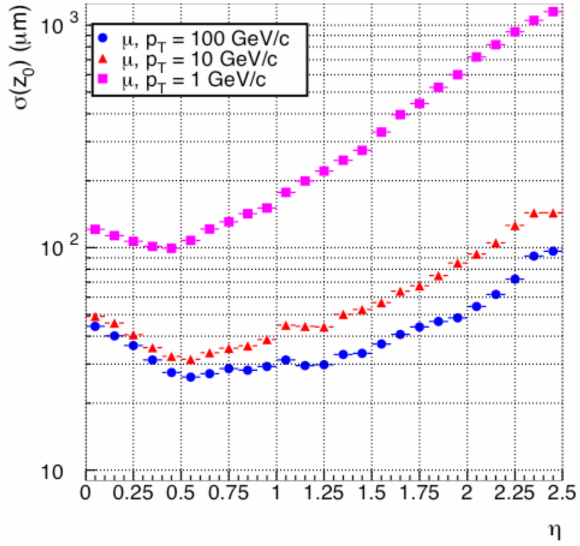


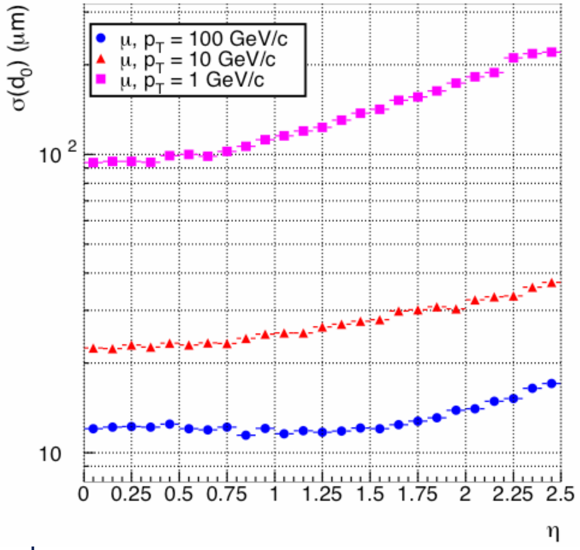
TEC7 instead of TOB5&6

Gap between barrel and endcap systems



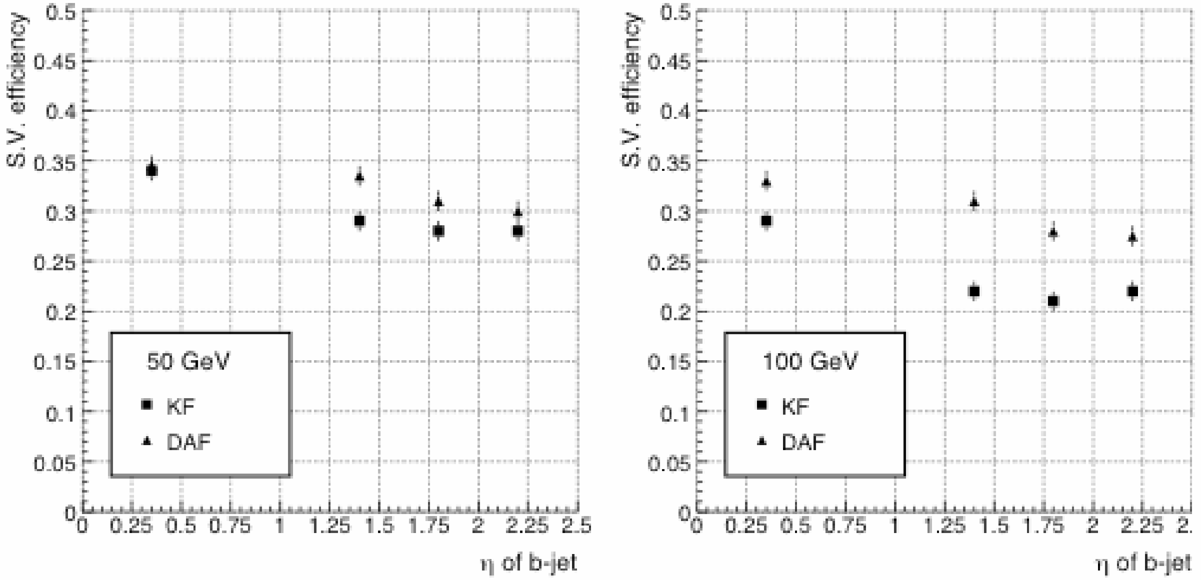


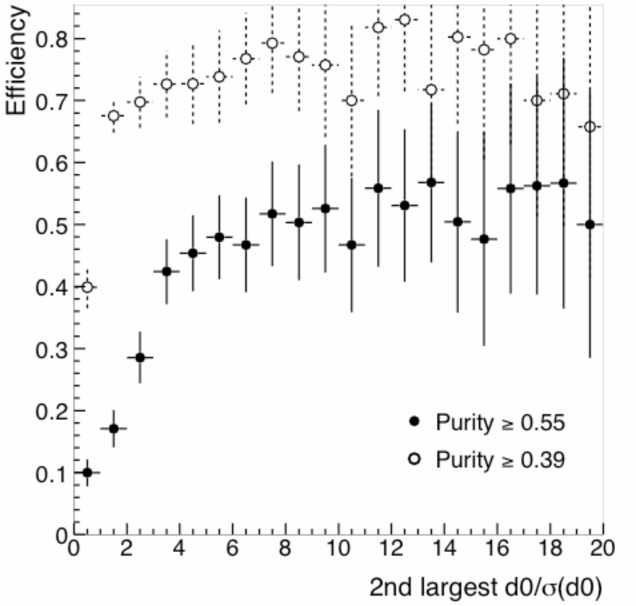




- Low momenta: dominated by multiple-scattering
- 100 GeV track: 20-30% of $\sigma(p_T)$ comes from tracker material

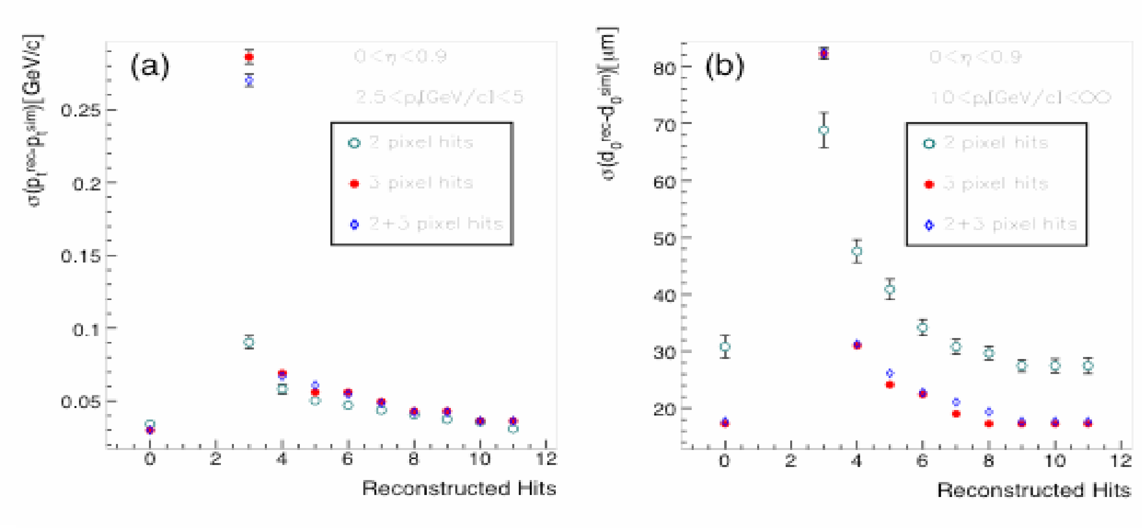
Secondary vertex finding efficiency inside a b-jet

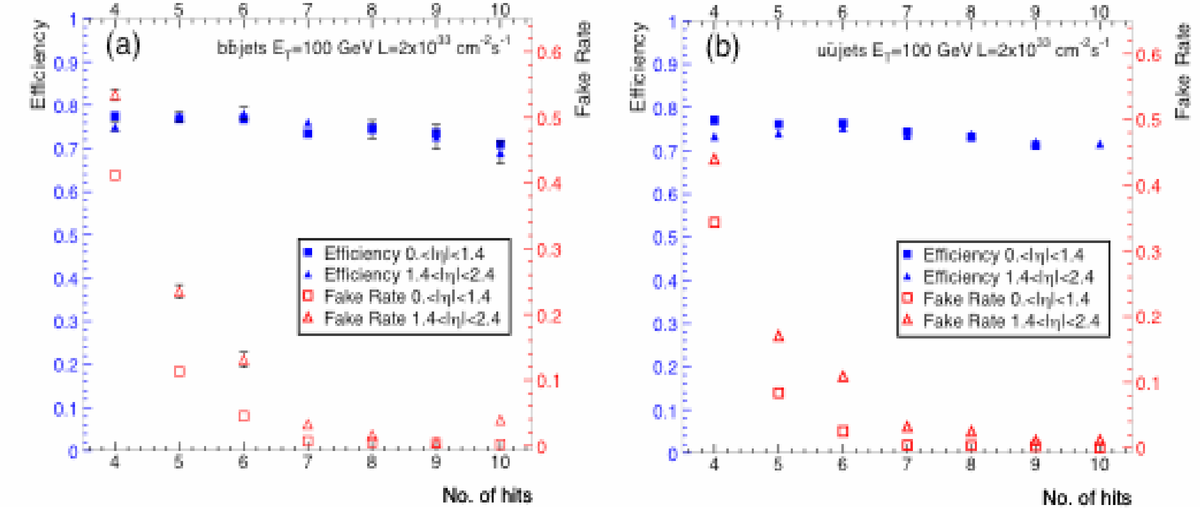




Secondary vertex efficiency as a function of the impact parameter significance of the track with the 2nd largest impact parameter

Partial track reconstruction

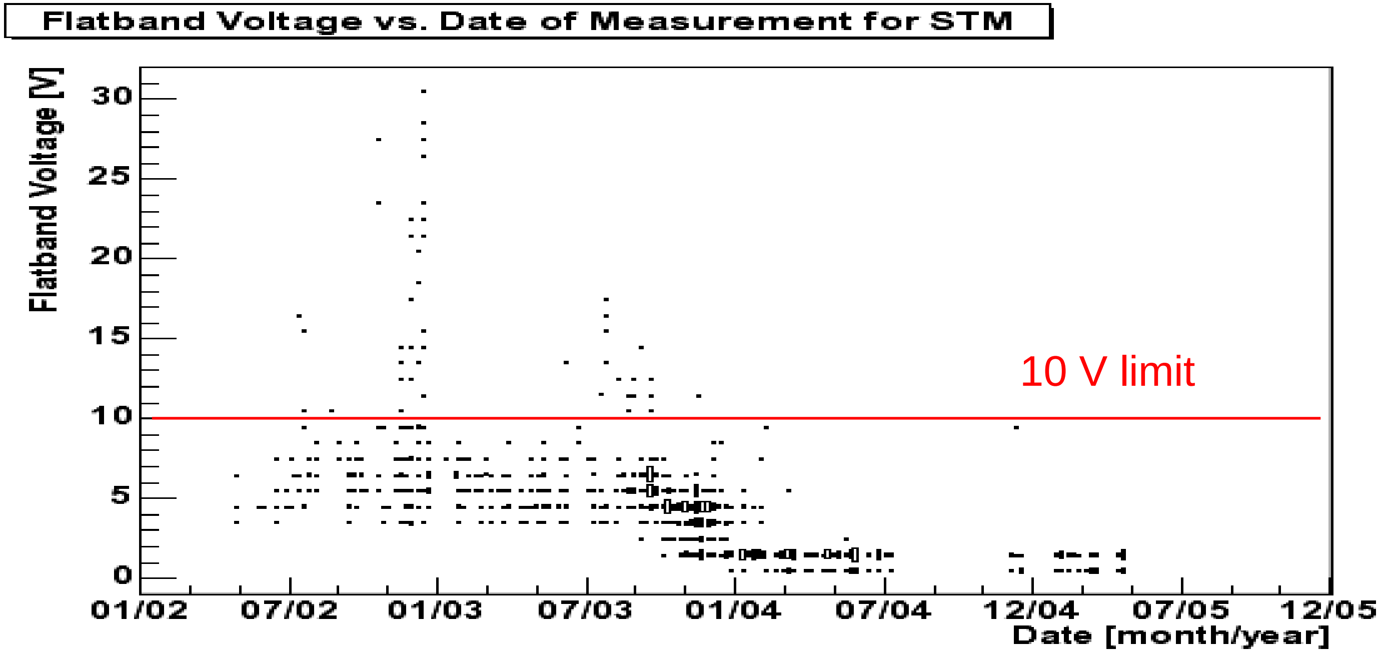




Problems during mass production

Too high flatband voltage for some STM batches

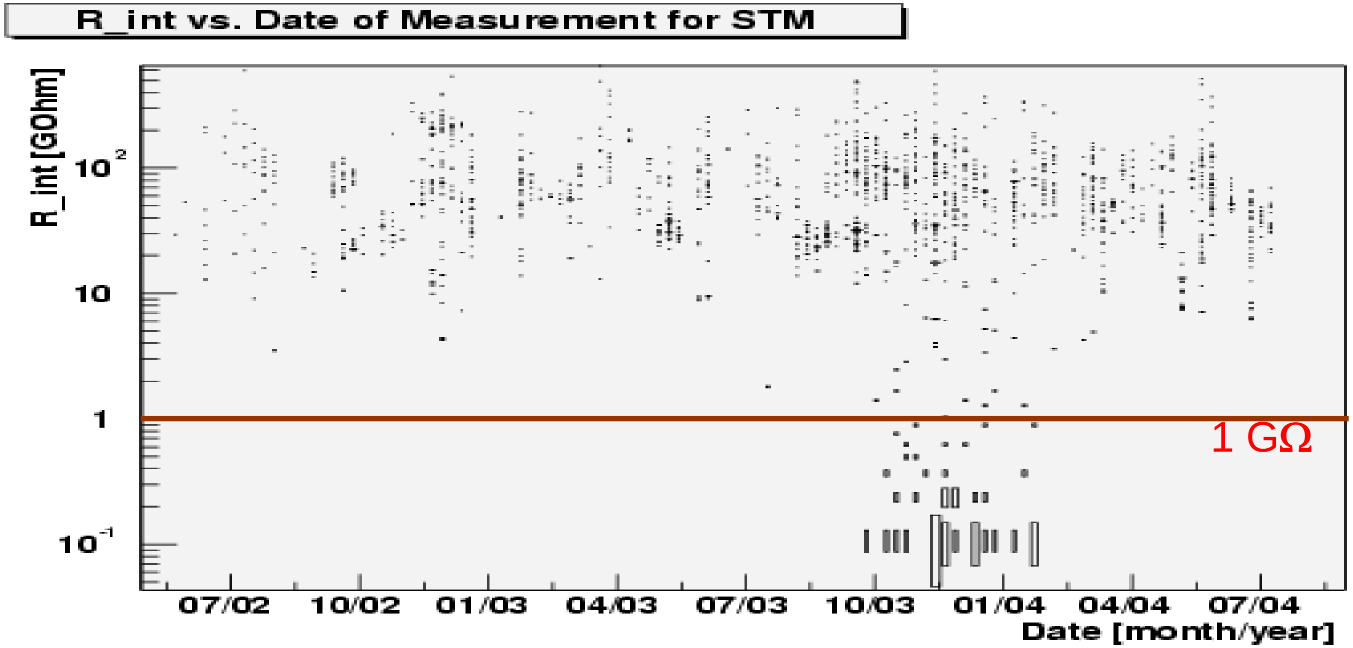
- A consequence of a high flatband voltage is a large increase of the interstrip capacitance after irradiation
- The failure was traced back to a contamination of a single machine in the production line



Problems during mass production

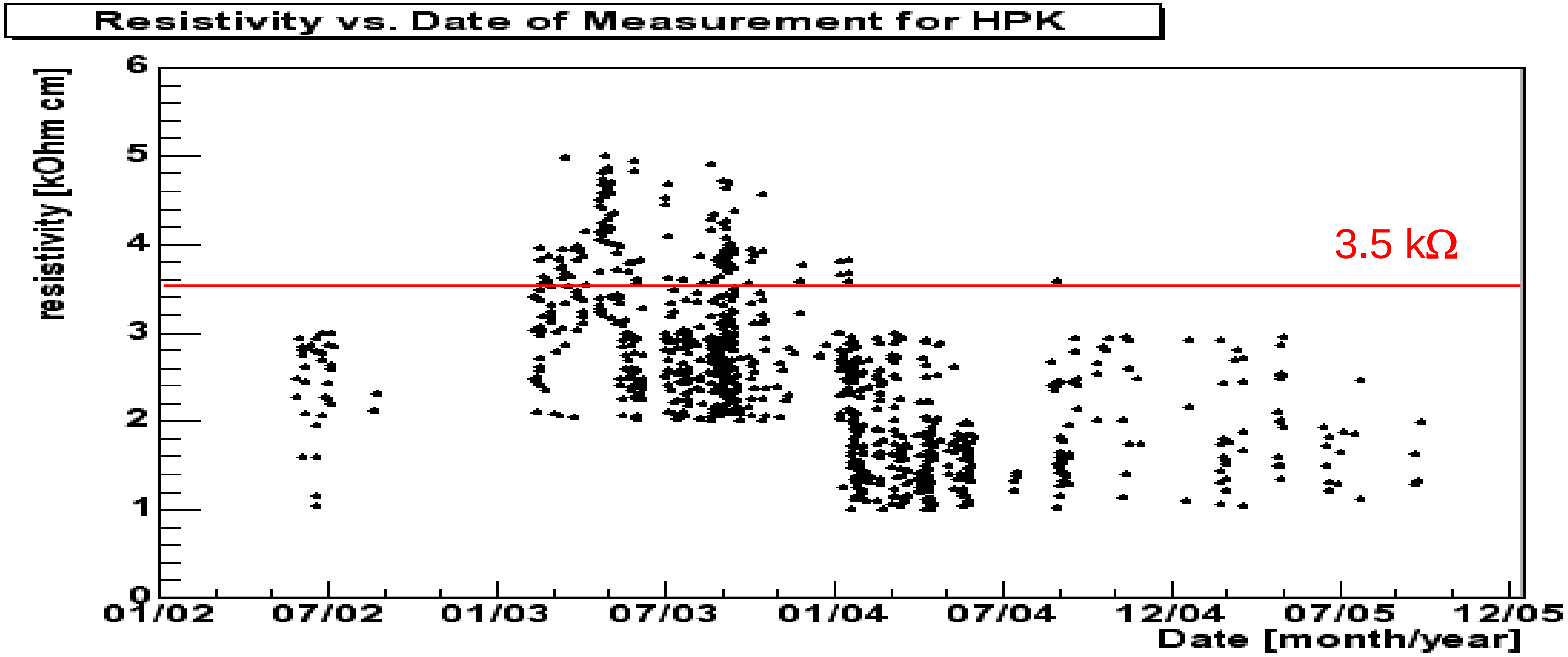
Too low interstrip resistance for some STM batches

- The limit is 1 GΩ to ensure good electrical separation of adjacent strips
- The failure was traced back to a small parameter variation in the production line



Problems during mass production

Thin sensors (HPK) produced during a certain period with wafer material of too high resistivity



TOB module - rod production cycle


Quick test hybrids on ARC

Wire bond


Thermal cycle hybrids

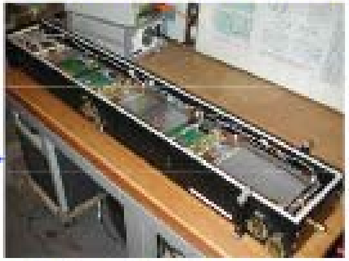

Gantry makes modules.

Wire bond


Modules test on ARC


Thermal cycled module


Final pinhole test on ARC

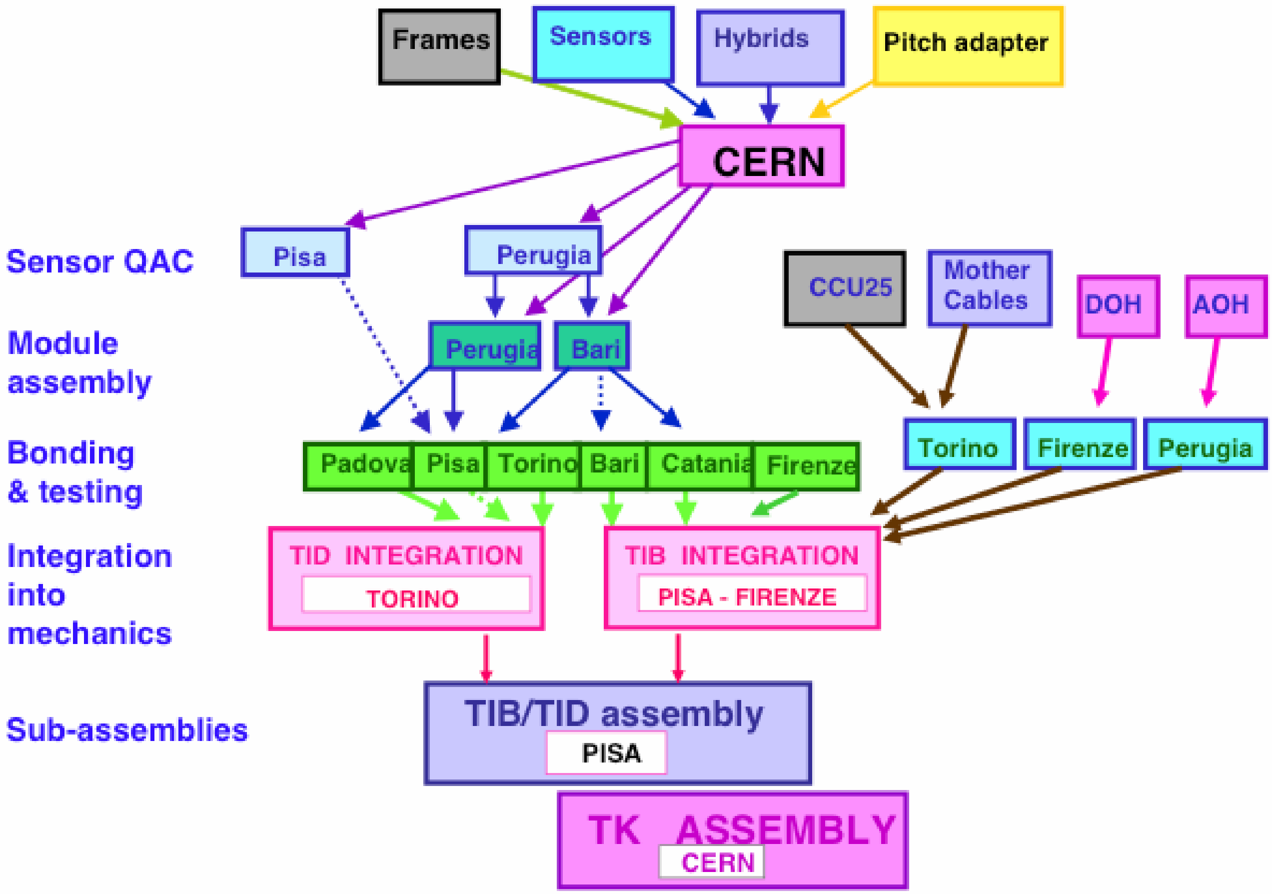

Assemble rods from modules


Rod burn-in

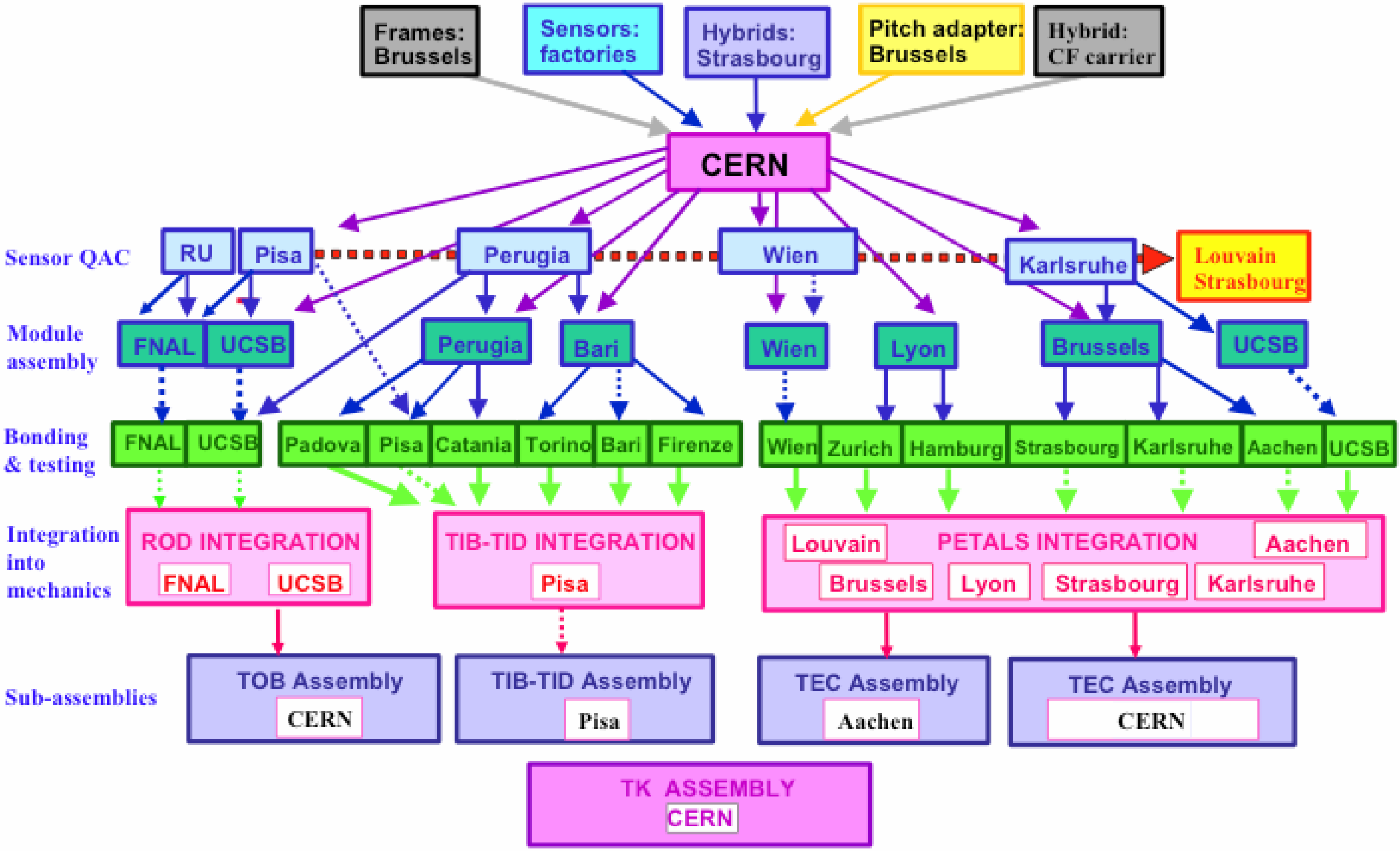

Rods shipped to CERN

TIB/TID logistics

TIB/TID General Organization



Tracker logistics



Frames: Brussels

Sensors: factories

Hybrids: Strasbourg

Pitch adapter: Brussels

Hybrid: CF carrier

CERN

Sensor QAC
- RU
- Pisa
- Perugia
- Wien
- Karlsruhe
- Louvain Strasbourg

Module assembly
- FNAL
- UCSB
- Perugia
- Bari
- Wien
- Lyon
- Brussels
- UCSB

Bonding & testing
- FNAL
- UCSB
- Padova
- Pisa
- Catania
- Torino
- Bari
- Firenze
- Wien
- Zurich
- Hamburg
- Strasbourg
- Karlsruhe
- Aachen
- UCSB

Integration into mechanics
- ROD INTEGRATION: FNAL, UCSB
- TIB-TID INTEGRATION: Pisa
- PETALS INTEGRATION: Louvain, Aachen, Brussels, Lyon, Strasbourg, Karlsruhe

Sub-assemblies
- TOB Assembly: CERN
- TIB-TID Assembly: Pisa
- TEC Assembly: Aachen
- TEC Assembly: CERN

TK ASSEMBLY

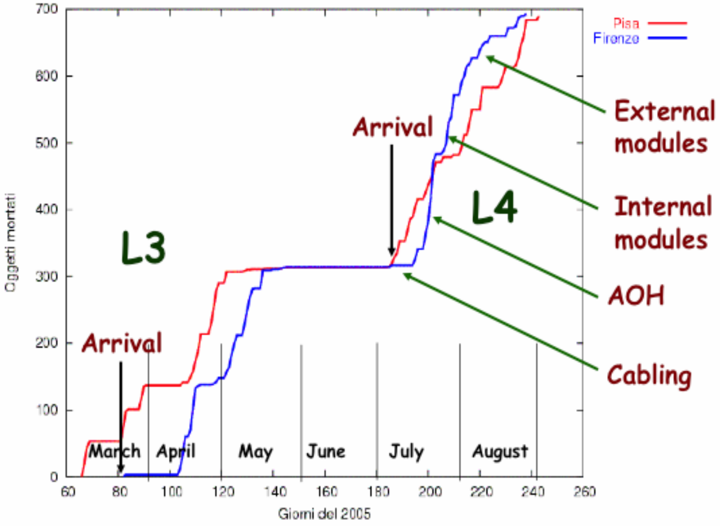
CERN

TIB layer integration

Integration procedure

- Mounting of Analog Optohybrids (and fibers)
- Cabling of Digital Opto Hybrids and ring test (also redundancy)
  - Digital Optohybrid Modules already tested in Florence
  - Mother Cables and CCU25 already tested in Torino
- Mounting of Modules
  - HV and readout test for every string (3 modules)
- Final mounting of Digital Opto Hybrids (again ring test)
- All components and test results stored in integration DB
- The structure is moved to burn-in test

How long we needed to integrate Layer 3 & 4 ?



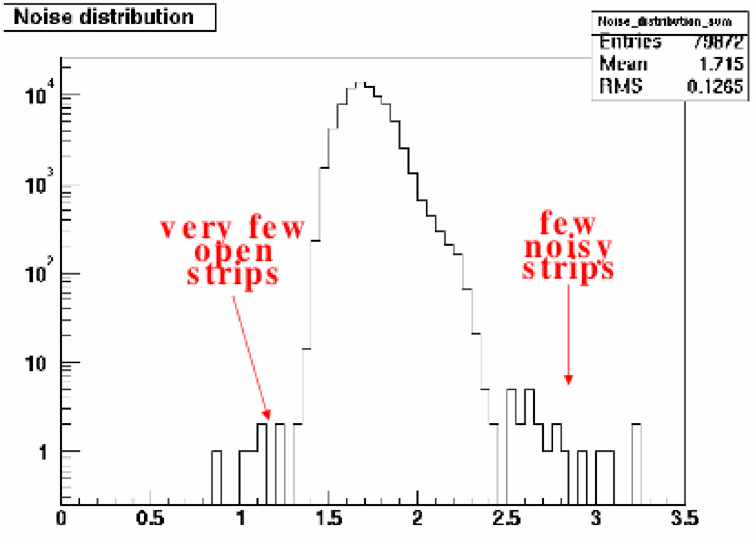
TIB performance during integration and burn-in

Test performed during integration
- *I²C communication*
- *Control ring communication and redundancy*
- *Readout per string using prototype readout system*

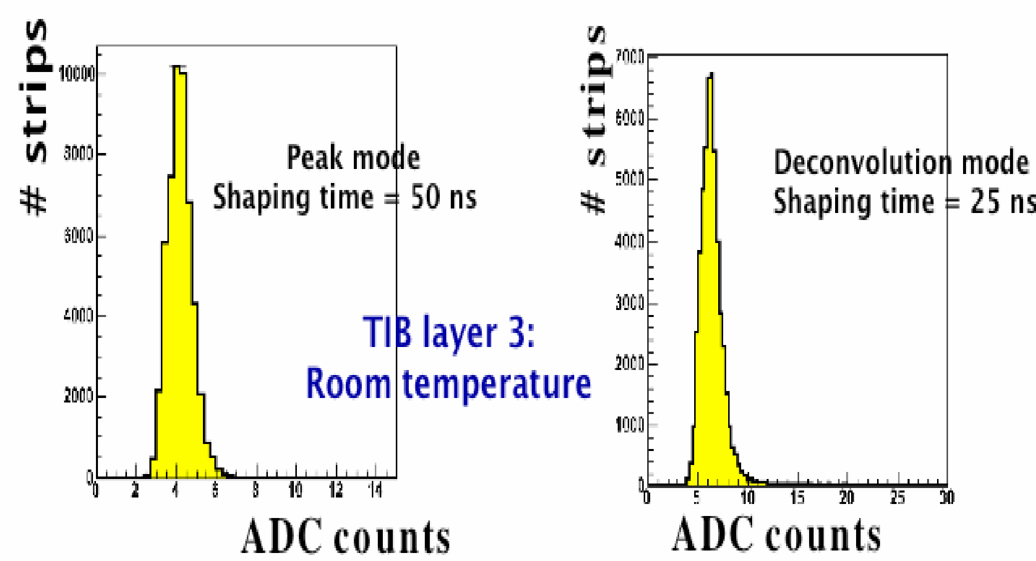
After integration, each half cylinder undergoes a complete validation test (burn-in) using final components (power supplies, cables, DAQ for readout of full half cylinder) including thermal cycles from -25 to +10 C

Layer 3 burn-in successfully completed

Single strip noise in deconvolution mode (all mounted TIB layer 4 modules)



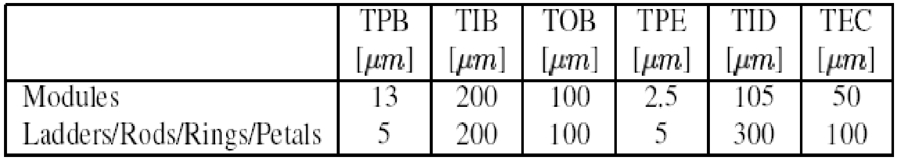
Noise distribution



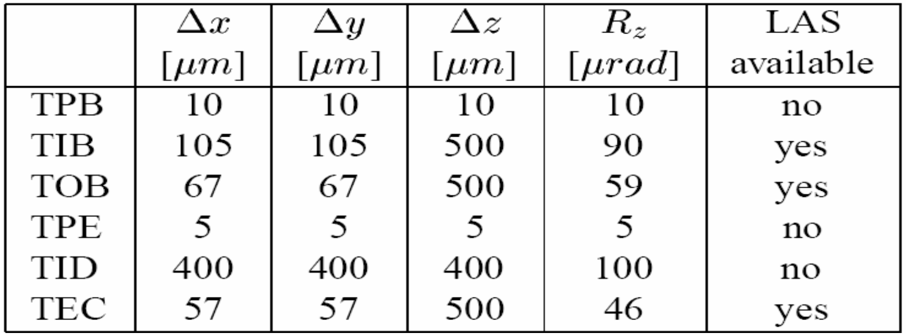
Alignment strategy

- *Assembly tolerances and measurements*
  - *Mechanical accuracy to position individual silicon modules within the subdetectors (TIB, TOB, and TECs) is about 50 µm*
  - *Mechanical accuracy between the subdetectors likely be ~ a mm*
- *Laser alignment system for large structures (not for TID and Pixels):*
  - *Monitors the tracker support structure (each module can not be monitored) and generates alignment info to correct the tracker data online*
  - *Provides the required absolute detector positional accuracy of 100 µm for the stable operation of the pattern recognition system, needed for HLT*
- *Track-based alignment (online TBA for Pixels and full TBA offline with high statistics)*
  - *Achieves the ultimate measurement accuracy of ~10 µm, needed for offline track parameter and vertex reconstruction*
  - *Uses sufficient statistics of reconstructed tracks (several days of data taking)*

Expected RMS values after mechanical constraints and laser alignment:



	TPB [μm]	TIB [μm]	TOB [μm]	TPE [μm]	TID [μm]	TEC [μm]
Modules	13	200	100	2.5	105	50
Ladders/Rods/Rings/Petals	5	200	100	5	300	100

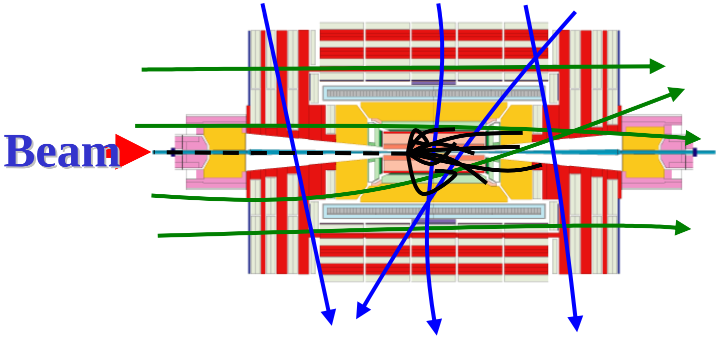


	Δx [μm]	Δy [μm]	Δz [μm]	R_z [μrad]	LAS available
TPB	10	10	10	10	no
TIB	105	105	500	90	yes
TOB	67	67	500	59	yes
TPE	5	5	5	5	no
TID	400	400	400	100	no
TEC	57	57	500	46	yes

Alignment with tracks

Before physics runs:

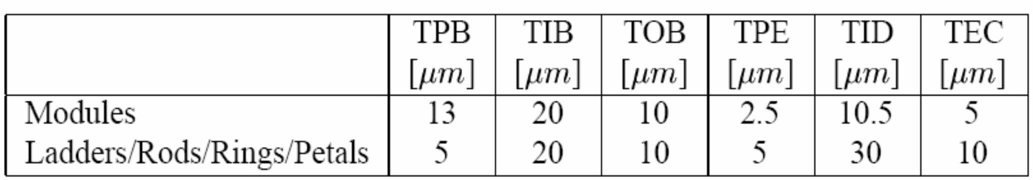
- *High energy cosmic muons traversing vertically (60 Hz in Tracker for E>10 GeV, barrel region)*
- *Beam Halo muons (hadrons) crossing almost horizontally (200 Hz for E>100 GeV, endcap region)*
- *Beam-gas interactions resembling collision events with a very soft p_T spectrum E ~ 115 GeV (large rate at single beam operation)*



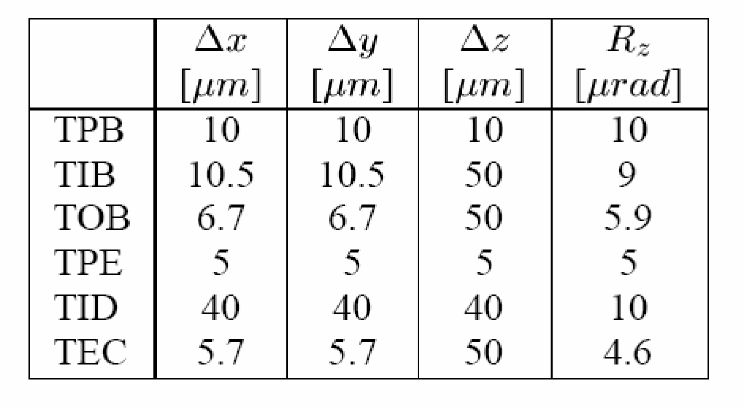
During data taking:

- *Generic tracks, isolated muons e.g. from W decays, $Z \rightarrow \mu\mu$*

Expected RMS values after 10 fb^{-1}

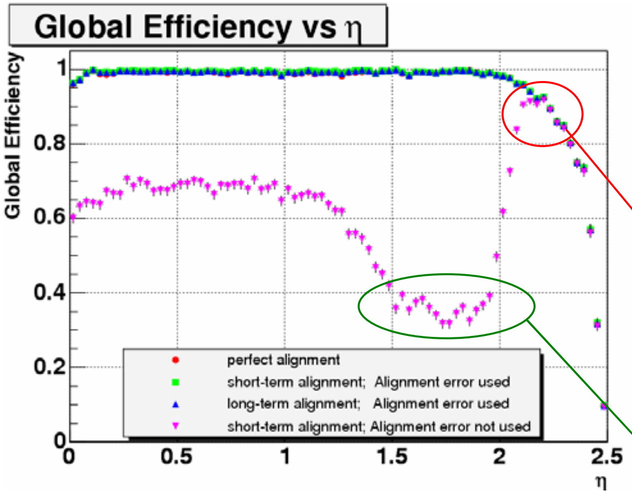


	TPB [μm]	TIB [μm]	TOB [μm]	TPE [μm]	TID [μm]	TEC [μm]
Modules	13	20	10	2.5	10.5	5
Ladders/Rods/Rings/Petals	5	20	10	5	30	10



	Δx [μm]	Δy [μm]	Δz [μm]	R_z [μrad]
TPB	10	10	10	10
TIB	10.5	10.5	50	9
TOB	6.7	6.7	50	5.9
TPE	5	5	5	5
TID	40	40	40	10
TEC	5.7	5.7	50	4.6

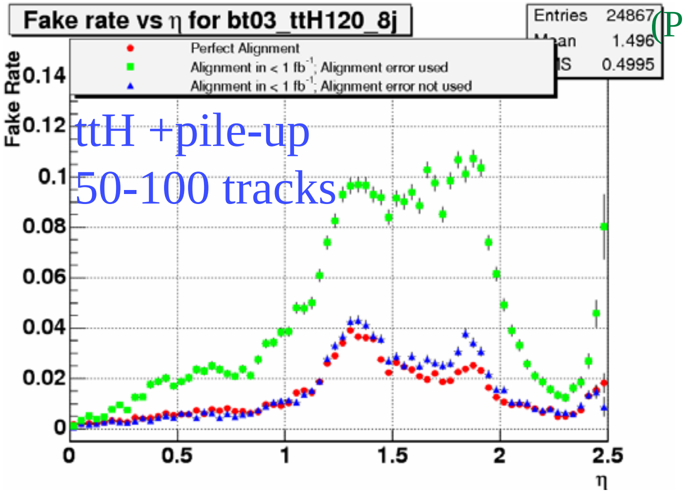
Track based alignment



- *Enlarge errors assigned to the reconstructed hits by $\sigma_{alignment} = \sigma_{superstruct} \oplus \sigma_{struct} \oplus \sigma_{module}$ at track fitting*
- *Increases fake rate significantly but tracker redundancy is enough to keep this still at an acceptable level*

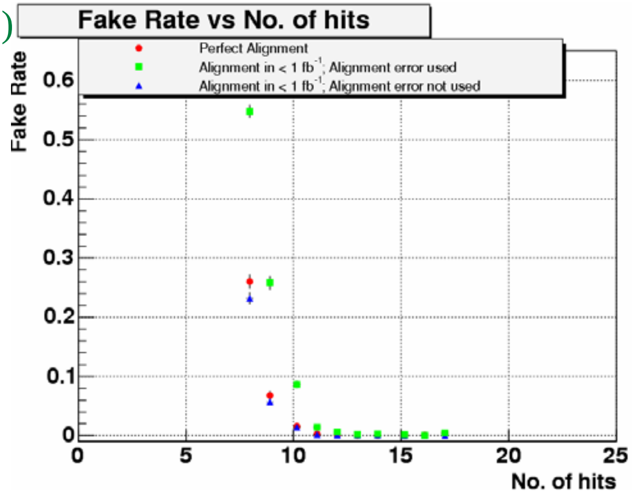
TID (with large mis-alignment) not used (Pixel Endcap, TEC)

TOB not used (Pixels, TIB, TID)

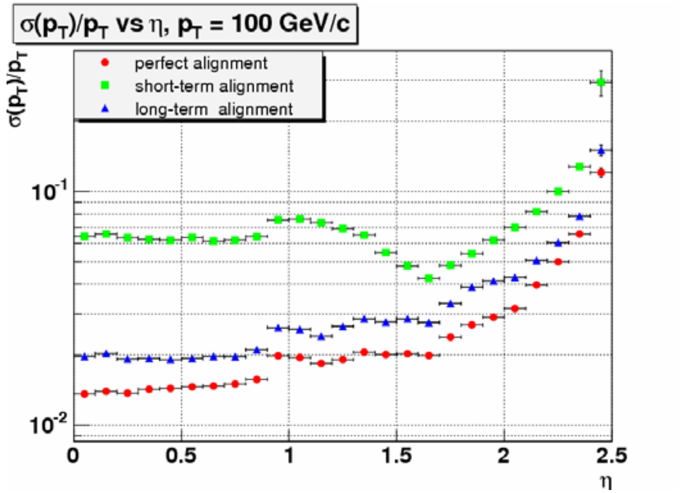


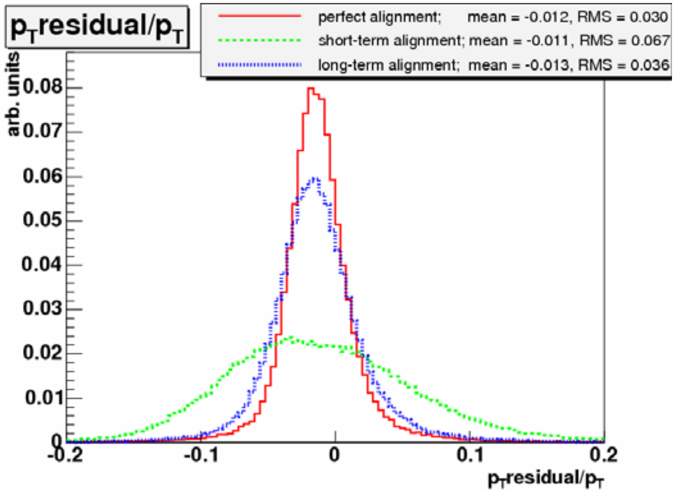
ttH +pile-up

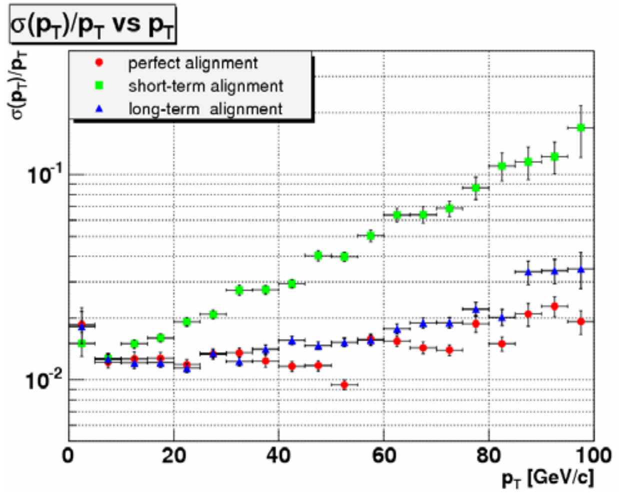
50-100 tracks

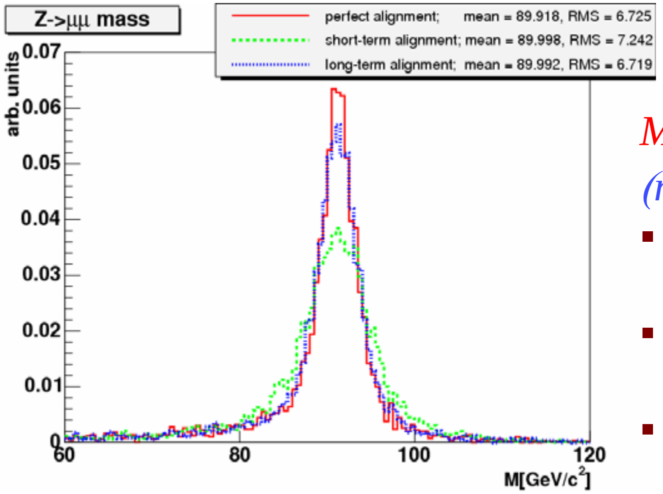


Effect of mis-alignment





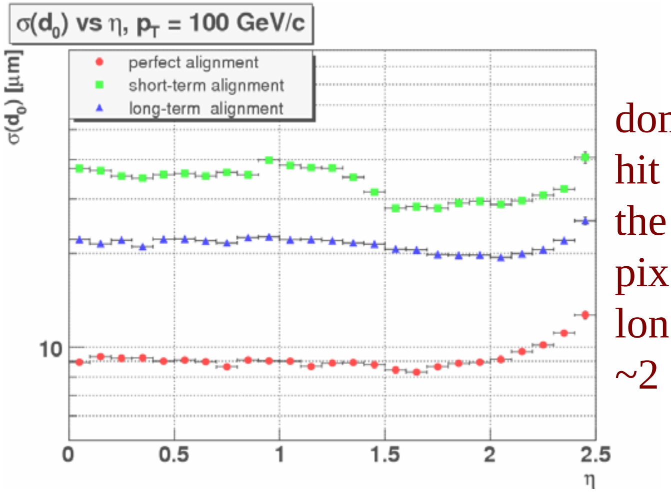




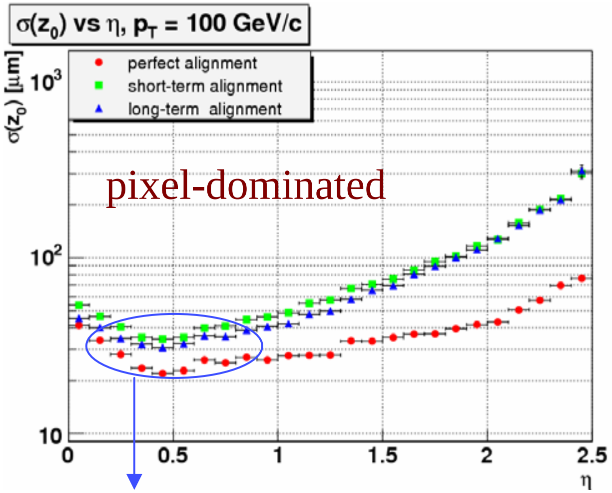
Muons in $H \to ZZ \to ee\mu\mu$ ($m=300$ GeV) at low luminosity

- *Mis-alignment affects high-p_T more*
- *Multiple scattering dominates below 10 GeV*
- *Mass resolution ~10% worse on short-term*

Effect of mis-alignment

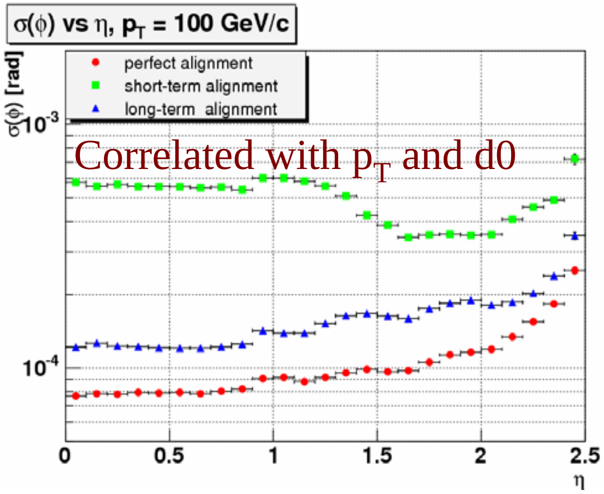


dominated by the hit resolution of the first hit in the pixel detector, long-term: factor ~2 degradation

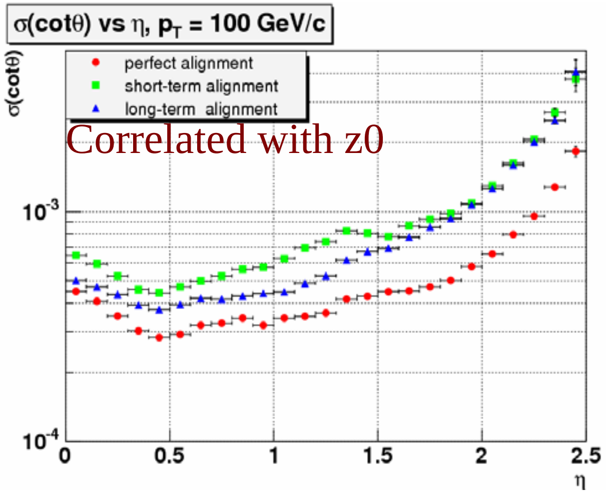


pixel-dominated

clusters become wider improving pixel-hit resolution



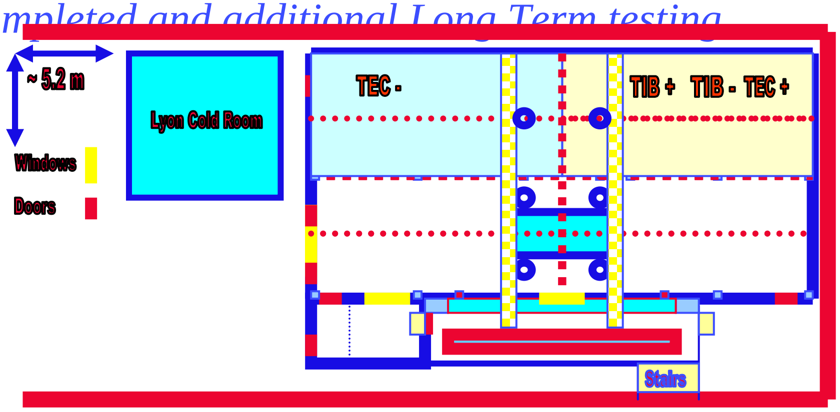
Correlated with p_T and d0



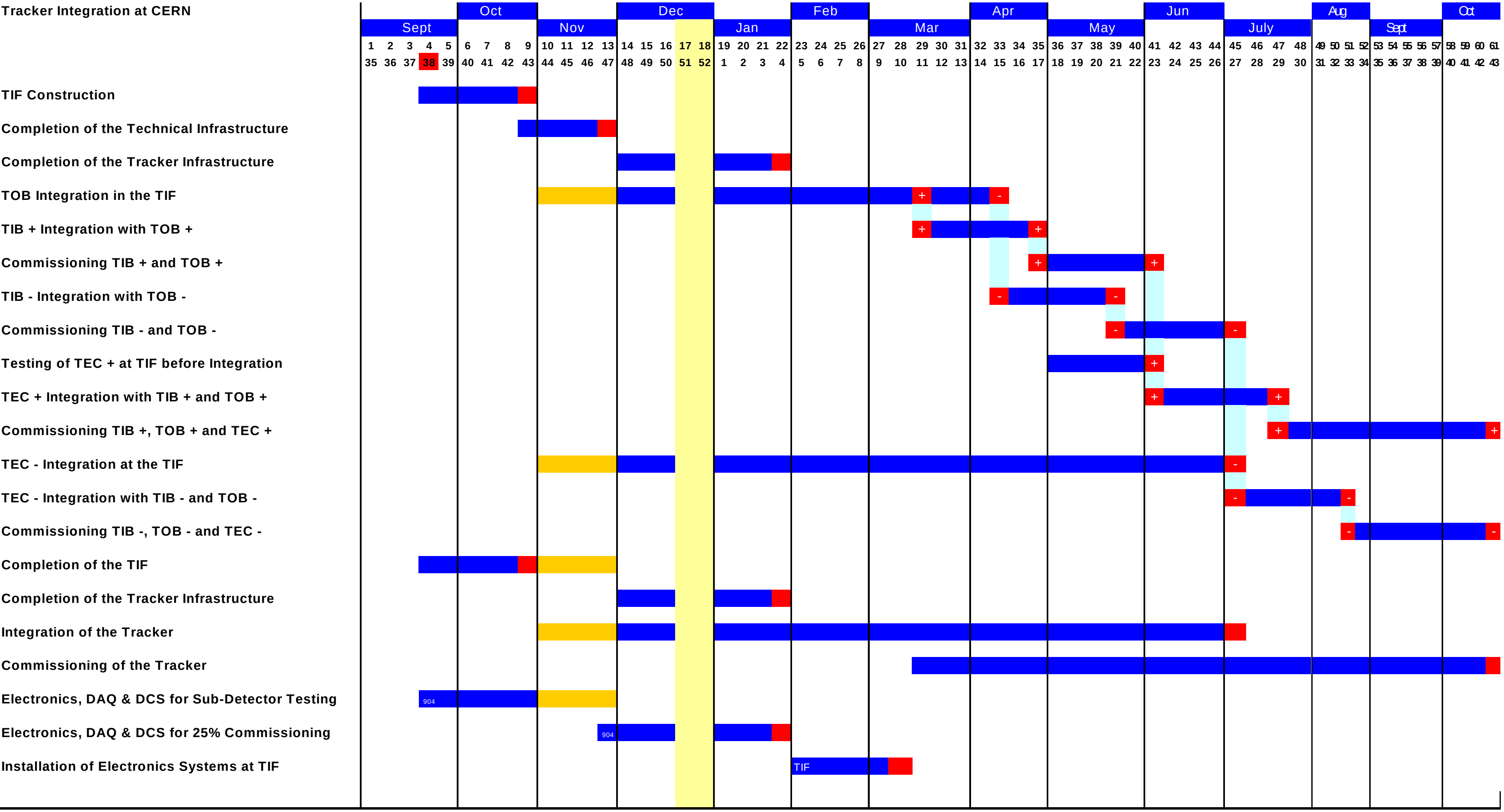
Correlated with z0

Tracker Integration

- *Integration and Commissioning of the Tracker was reviewed last week*
- *Integrate all of the Tracker at CERN starting in November 2005 with an Integration and Commissioning Team of 60 people*
- *New Tracker Integration and Commissioning Facility (TIF) at CERN to be complete at the end of October*
- *The TIB + and TIB – sub-detectors will be integrated in Italy (Pisa and Florence) and then moved to CERN (TIB/TID+ in January 2006, TIB/TID- in April 2006), tested and inserted into TOB+ and TOB – .*
- *TOB + and TOB – will be integrated at CERN with Quality Assured rods fabricated in the USA (UCSB and FermiLab)*
- *TEC + will be integrated in Aachen and TEC – structure will be shipped to CERN in November and integrated there*
- *TEC is on critical path: to accelerate the TEC programme, TEC modules will be fabricated in Italy and the USA after TIB and TOB modules have been completed and additional Long Term testing facilities will be provided at CERN*
- *Have 'Standard' Electronics and DAQ Systems in November*
- *25% tests of the Tracker from March 2006 (cooling, power, readout, DAQ, DCS, cables)*



Integration schedule



Comissioning tasks

- *The Construction Project includes the Integration of the Tracker*
- *The Operations Project will involve commissioning the Tracker*
  1. *Safety and Interlock Systems*
  2. *Cooling Systems*
  3. *Power Supply Systems*
  4. *DCS and DAQ Systems*
  5. *Interfaces to the CMS Trigger Systems*
  6. *Database Systems*
  7. *Data Quality Monitoring*
  8. *Track and Vertex finding algorithms*
  9. *Alignment algorithms*
  10. *Interfaces to the physics analysis.*

In collaboration with Software Project

- *Data Quality monitoring will be developed to monitor the performance of the Tracker from remote sites*

Commissioning

- *A first review of commissioning plans will be held in December*
- *A first review of the plans for installation at Point 5 will be held in the March 2006*

- *Initial commissioning of the Electronics, DCS and DAQ will take place in the CMS Electronics Integration Center (EIC) so that only complete working systems are transferred to TIF & USC55. This should be ready to transfer to the Integration Facility for the 25% tests in January, and be fully commissioned by March 2006. The remaining electronics will go to Point 5*
- *The Tracker has been allocated 5 racks to 'burn in' the power supplies, and 5 racks to commission the FEDs, FECs with the CMS TTC and Trigger Systems in EIC*
- *The use of production cables will ensure that control, voltage drop and timing issues are understood as early as possible*
- *'Cosmic Ray' trigger will give straight tracks to commission the track finding and alignment algorithms*
- *After transport to Point 5 and installation of the Tracker into CMS, the cabling and systematic checks of the System, the commissioning process can continue in CMS*
- *There should be ~ 6 months to continue the commissioning in CMS at Point 5*
- *It is important to have a similar 'cosmic trigger' at both TIF and CMS, so that the commissioning of the High Level Trigger and 'Off –line' software continues without disruption.*
- *The Forward Pixels will use TIF from Q4 2006*