The evolution of Vertex Detectors

From Gas to Silicon Strips

Better and better Silicon Strips

From Strips to (Fast, Micro) Pixels

(From Off-line Vertex to On-line Track Seeding)

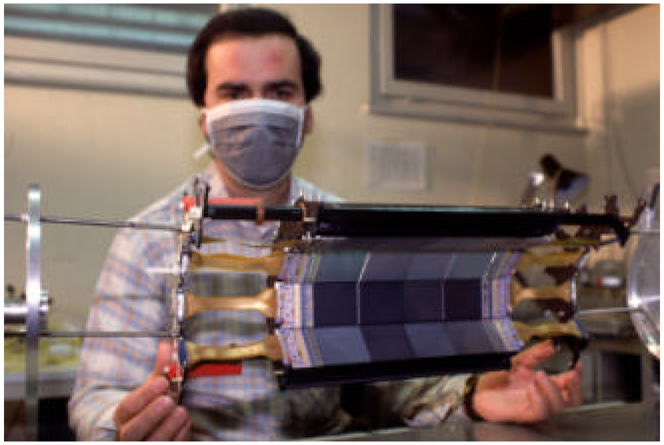
Bigger and bigger Silicon Strip systems:
From Strip Vertex detectors, to Strip Trackers

From Wire Chamber to Silicon Strips

The 4 LEP experiments started with gas chambers, both for tracking and vertex reconstruction.

The 4 LEP installed Silicon Strip Vertex Detectors, either single or double-sided, within a couple of years of LEP startup

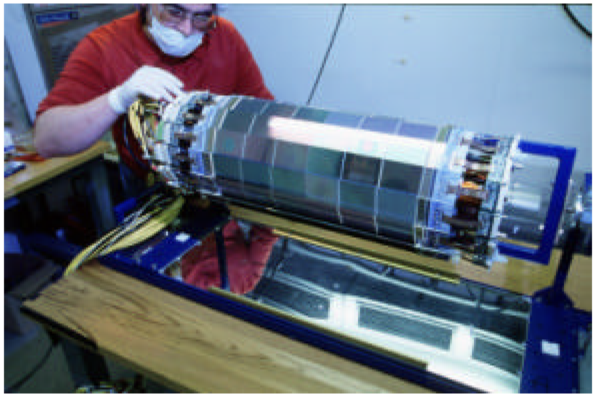
These opened the way for precision b-physics at LEP



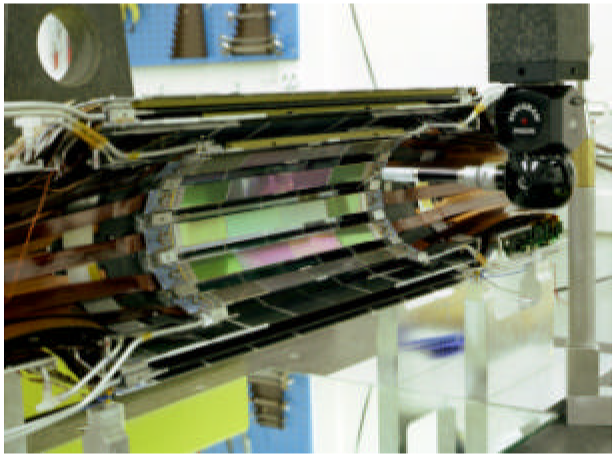
Aleph 1991

Upgraded to become better & better, Bigger & bigger

Aleph 1998



Delphi 1998



Better and better Silicon Vertex detectors

Very low mass systems

Use double sided sensors
Where ever possible

Highly specialized Geometries:

Very light mechanical structure
CF, Be space frames etc

Very light electrical services,
Material displaced outside
Fiducial acceptance region

There are examples
Of this in every HEP lab:
CLEO, Babar, Belle…
CDF, D0…

More and more imaginative names:
LHCb VELO: VErtex LOcater

Pixel Vertex detector for the LHC

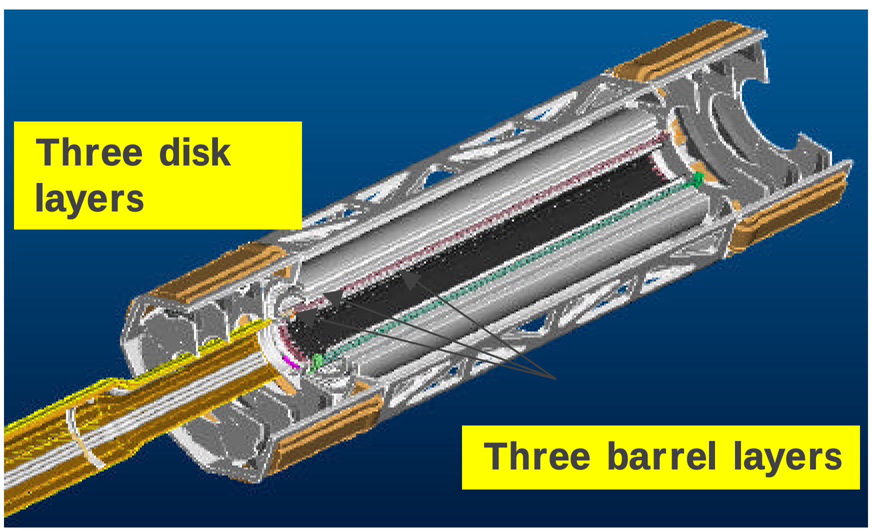
The region below 20cm is instrumented
with Silicon Pixel Vertex systems

The Pixel area is driven by FE chip
Shape differently optimized for resolution
ATLAS ~ 50 * 400 mm^2
CMS ~ 150 * 150 mm^2

With this cell size occupancy is ~ 10^{-4}
This makes Pixel seeding the fastest
Starting point for track reconstruction
Despite the extremely high track density

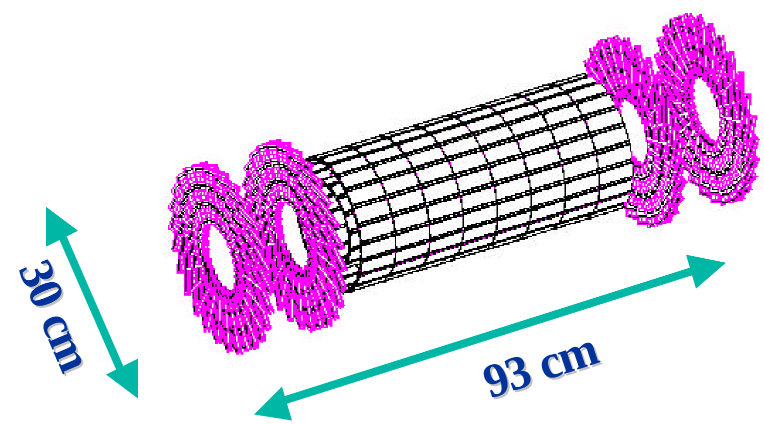
$IP_{trans.}$ resolution ~ 20 μm
for tracks with P_t ~ 10GeV

The ATLAS Pixel Vertex $2m^2$, 8 10^7 pixels



The CMS Pixel Vertex

4 10^7 pixels



Pixel Vertex detectors for the LHC

Highest radiation environment:

– Specific program of sensor R&D

– Partial depletion, despite High V_{bias}

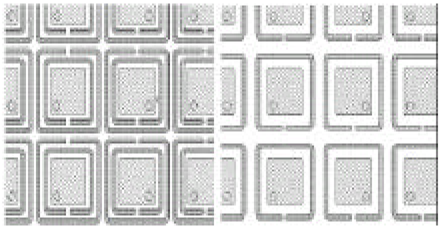
– n-on-n technology

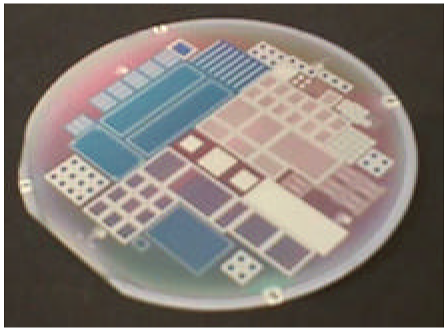
- The "back-side" of a double-sided sensor
- Uses much of that know-how
- Specific issues:

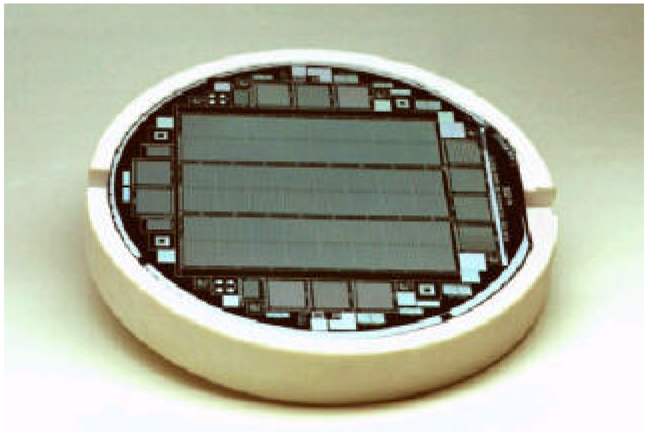
P-stop design to ensure pixel biasing & isolation

Open p-stop, "p spray" …

– Oxygenated bulk may allow lower bias voltage operation, especially for charged hadron induced damage (dominant)



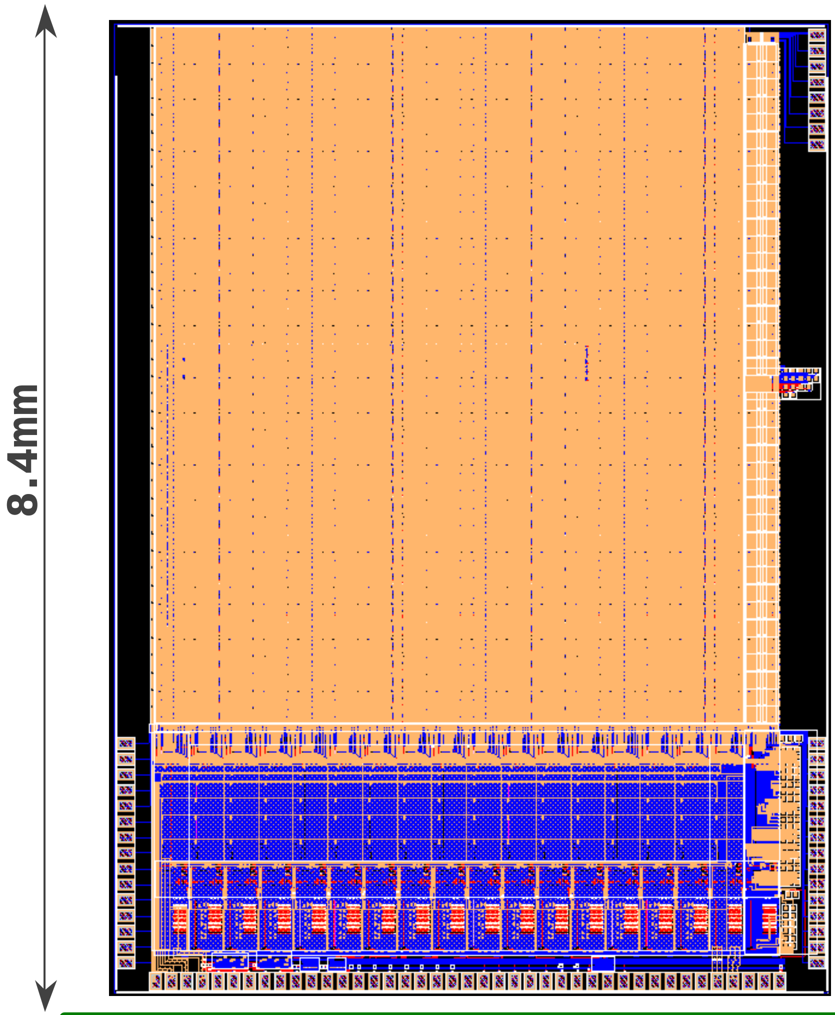




PIXEL CHIP WITH FINAL ARCHITECTURE: CMS

(submitted Aug./Sept 2000 in DMILL)

DM_PSI41

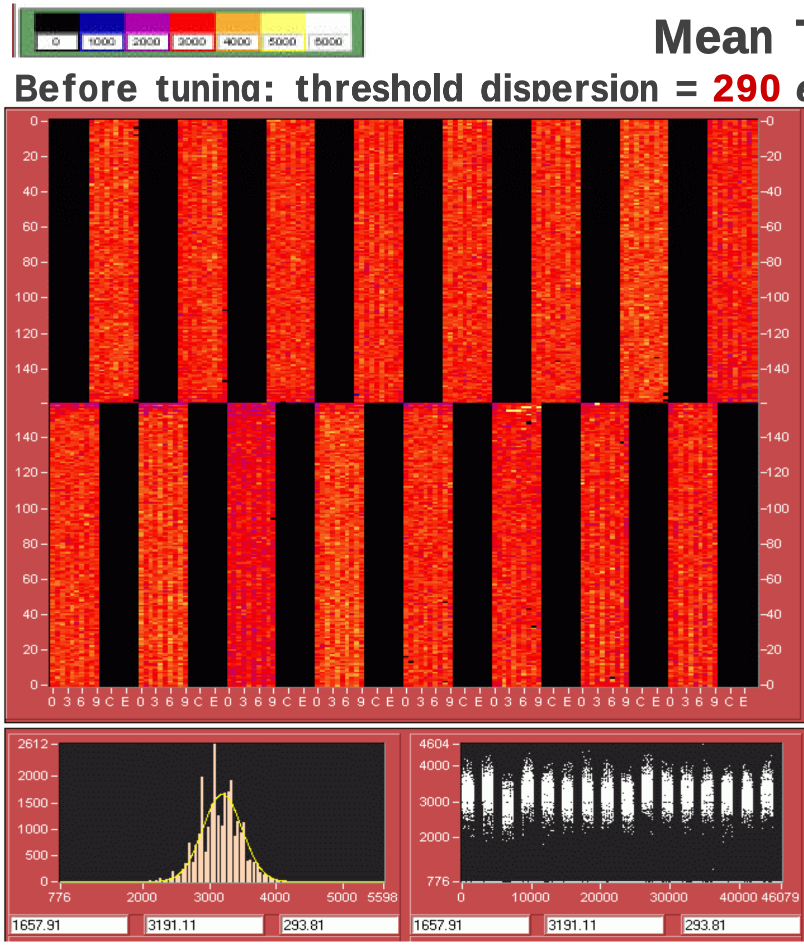


- ~50% pixels of final 52x53 pixel ROC
- final Column Drain Architecture
  - fast hit scanning mechanism (>GHz)
  - double hit capability during DC scan
- final Double Column Periphery
  - 8 timestamp buffers / double column
  - 24 pixel data buffer / double column
- test chip with 36x40 pixels (~240K transistors)
  - L1 trigger delay up to 255 bunch crossing
- final Analog Readout Chain
  - 6 clock cycles per pixel hit
  - analog coded column & pixel address
  - analog readout of pixel pulse height
- missing Control & Interface Block ‼
  - DAC's, Voltage Regulators, fast I2C etc.

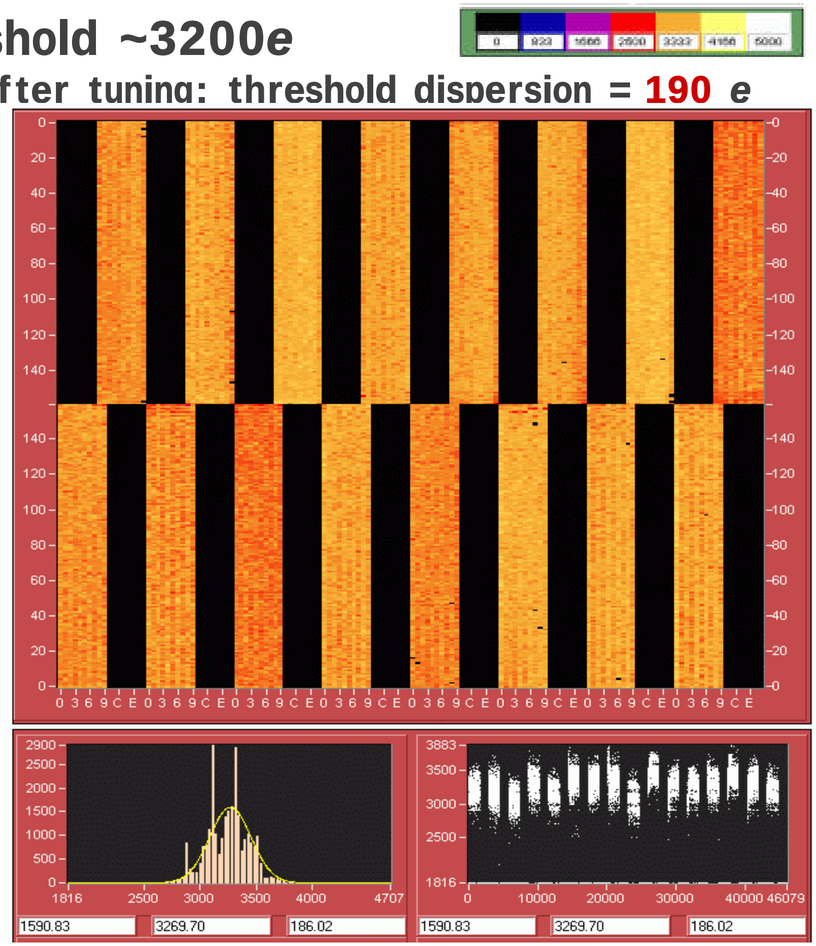
Noise and Threshold uniformity: ATLAS

Mean Threshold ~3200*e*

Before tuning: threshold dispersion = **290** *e*



After tuning: threshold dispersion = **190** *e*



Status of ATLAS & CMS Pixel Vertex Systems

Both collaborations have developed FE chips with full functionality (or close to it)

Reliable rad-hard implementation is critical

Honeywell SOI no longer available

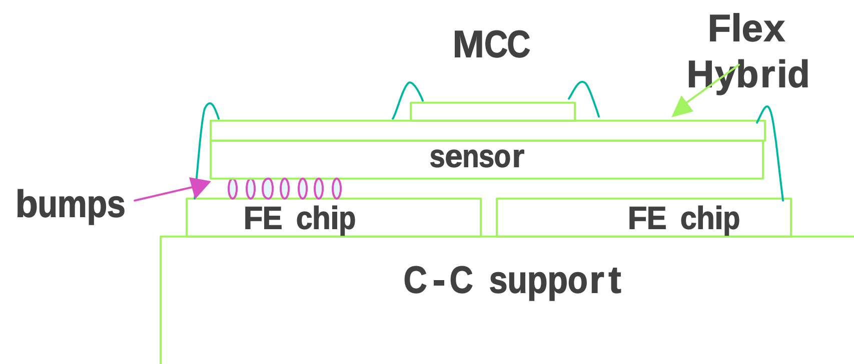
Unexpected yield problem with DMILL: requires re-design of the ATLAS circuit

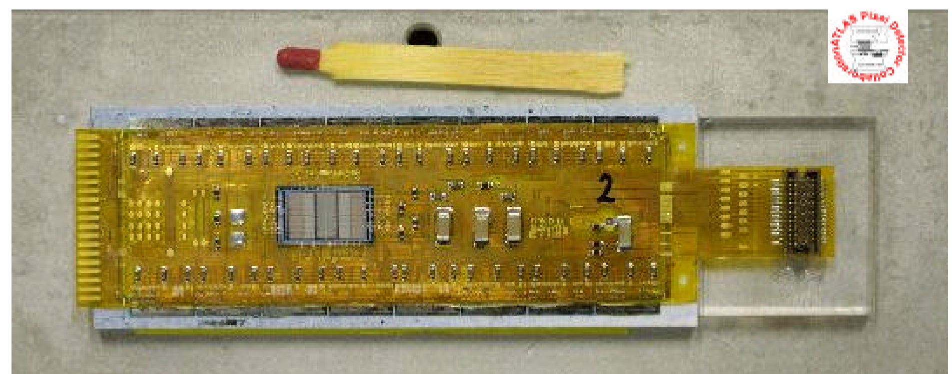
Concerns a feature not used in CMS design
CMS August '00 submission:
functionality ~ OK, Yield?
Engineering Run winter 01-02:
Determine yield, build full size modules

ATLAS has made a first pixel chip submission in 0.25mm IBM technology

CMS is preparing such a submission For spring 2002

Module hybridization is well advanced (including high yield bump-bonding)





ATLAS Flex hybrid, bump bonded module

From strip Vertex to strip Tracking

Single-sided, AC coupled, polysilicon biased sensors have become a mature technology

Costs have decreased, and large scale production is now possible

High level of expertise for FE IC design and system aspects of $O(10^{5})$ channels

Move to detectors with a high level of independent tracking capability

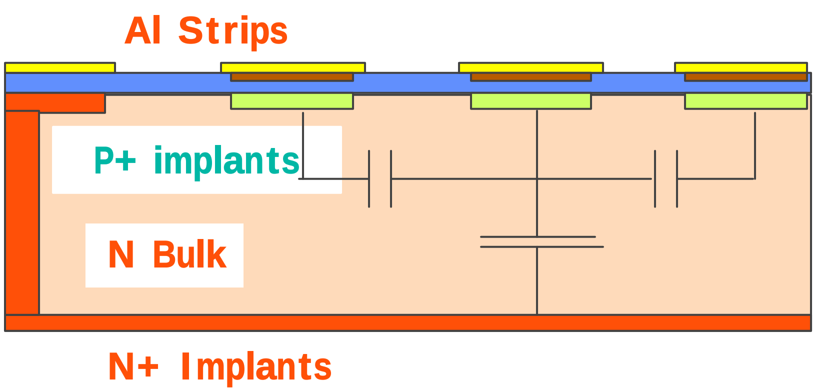
- ⇒ A few m^2 : CDF – D0
- ⇒ Several * $10^1 m^2$: ATLAS
- ⇒ A couple * 10^2 m^2 : CMS

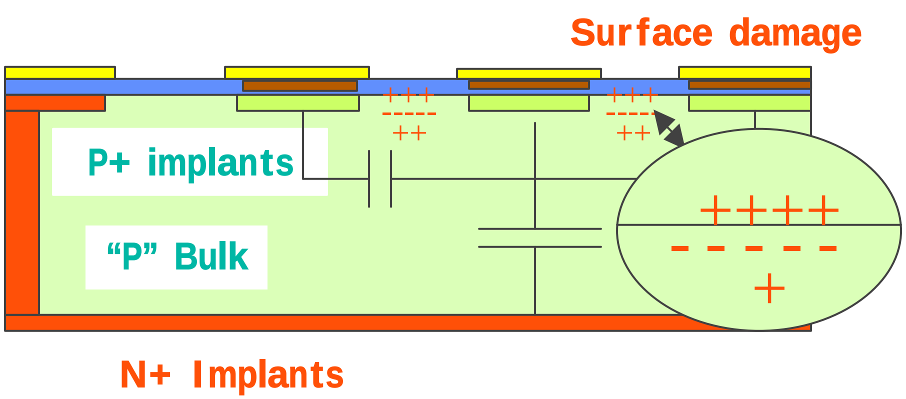
The radiation hard P-on-N strip detector

ATLAS, CMS, ROSE …

Single-Sided Lithographic Processing

(AC, Poly-Si biasing)





Radiation hardness "recipe"

P-on-N sensors work after bulk type inversion,
Provided they are **biased well above depletion**

Match sensor resistivity & thickness to fluence
To optimize S/N over the full life-time

Follow simple design rules
for guard & strip geometries

Use Al layer as field plate to remove high field
Region from Si bulk to Oxide
(much higher V_{break})

Take care with process: especially implants…

Surface damage can
increase strip capacitance & noise

Use <100> crystal instead of <111>

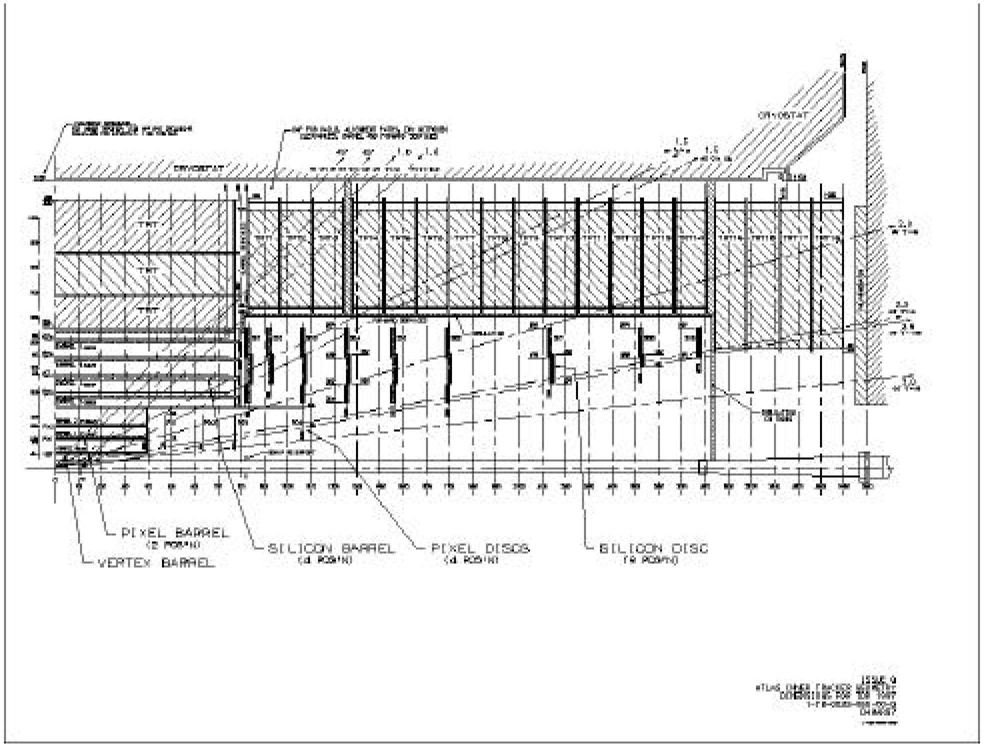
The ATLAS Inner (Tracking) Detector

The region 60 < R < 110cm is instrumented
with a Straw Tube tracker
which provides ~ continuous tracking
and incorporates Transition Radiation
detectors, for electron identification (TRT)

The region 25 < R < 55cm is
instrumented
with a Silicon Strip tracker (SCT)

The SCT has active area ~ 60m^2
and provides at least 4 stereo hits
With pitch ~ 80μm

The sensors are single sided p-on-n with
Integrated AC coupling & PolySi bias
They are fabricated on 4" wafers

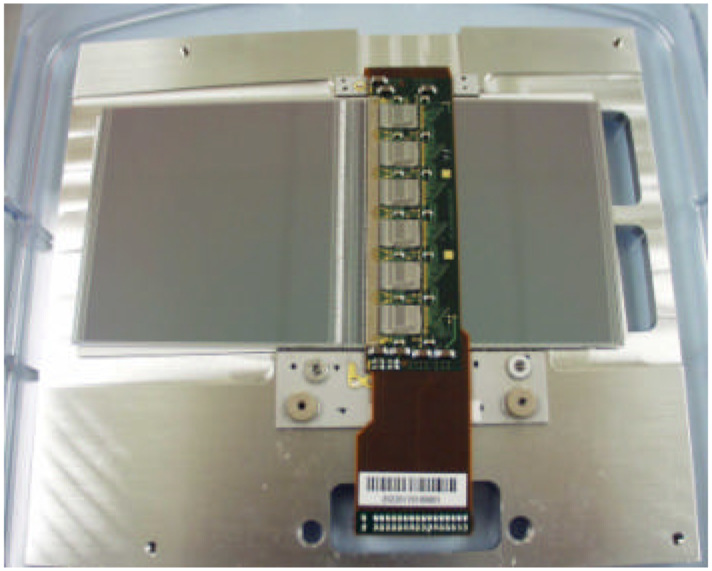


Silicon sensors are arranged back-to-back
at a stereo angle within a module

The Atlas Silicon Tracker (SCT)

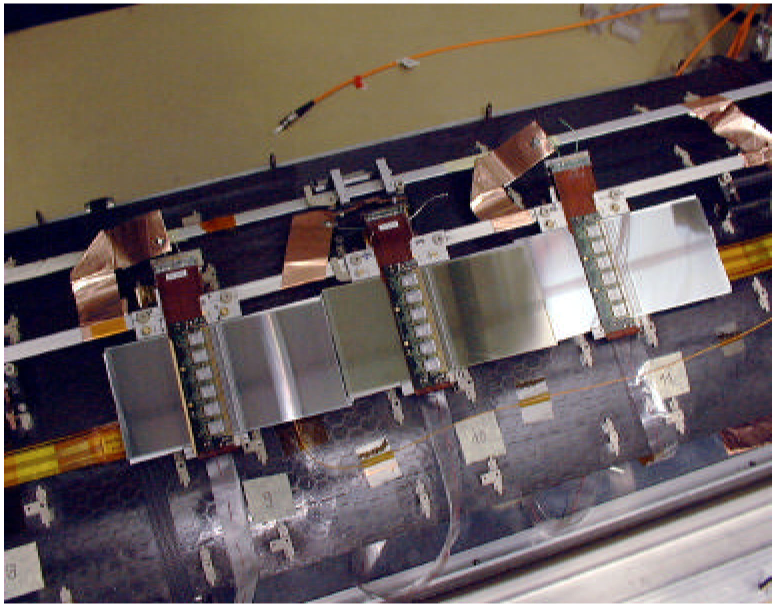
Sensor pre-production has been completed
Production is now well under way

Pre-production FE chips under test



Modules finalized & Pre-series module production is under way

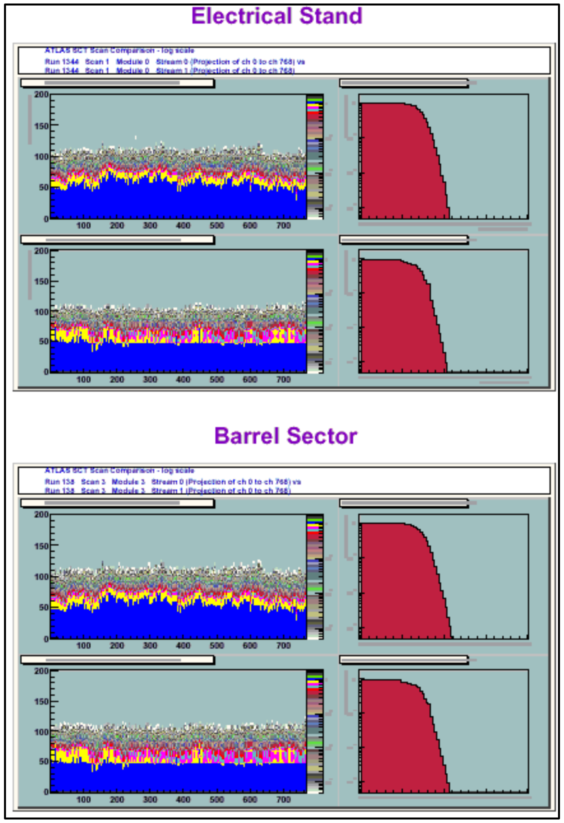
Need to demonstrate "single component" performance is retained in complex system

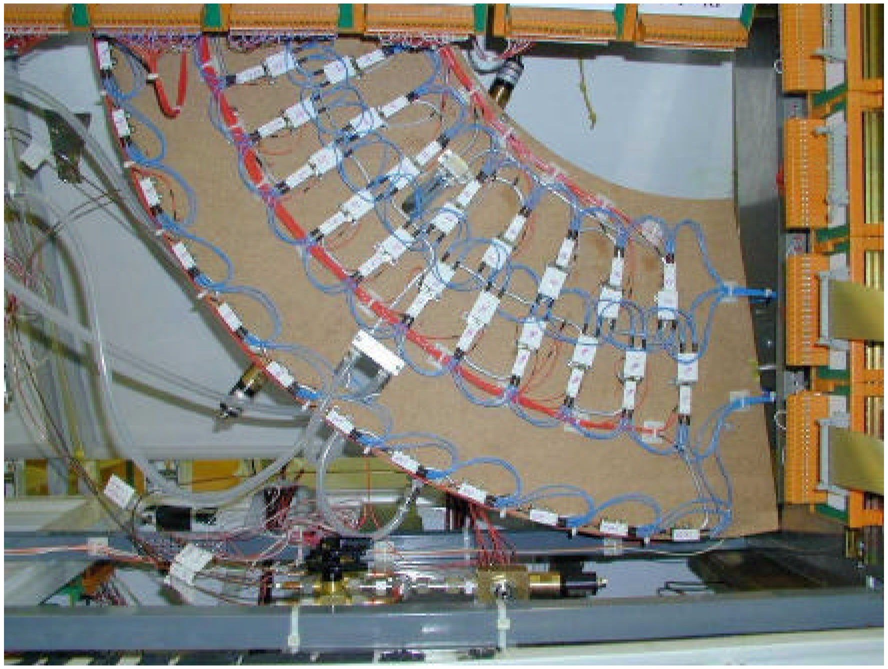


Large scale electrical system verification underway, study various grounding & shielding configurations with encouraging results

The Atlas Silicon Tracker (SCT)

Binary read-out: on chip discrimination

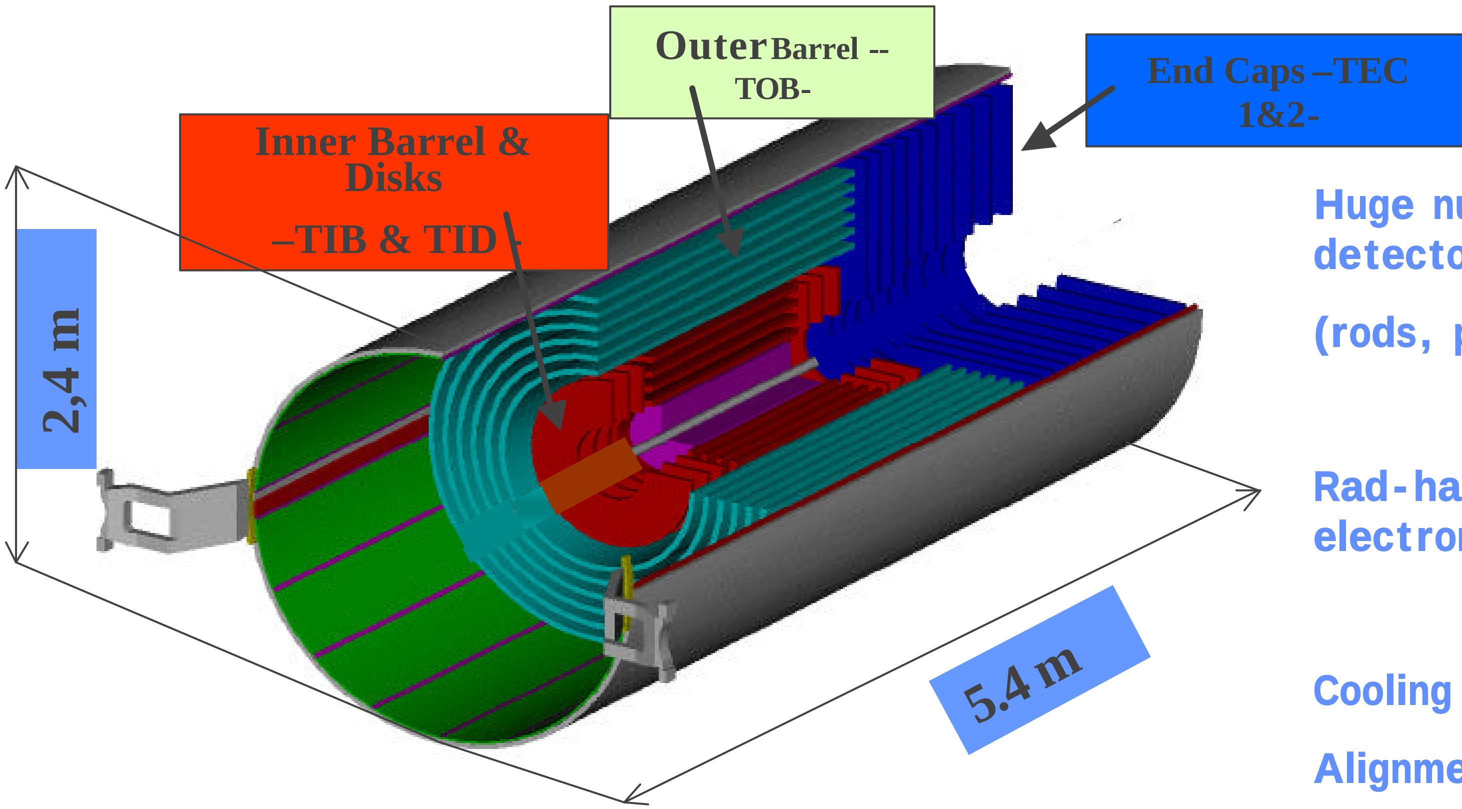




No excess noise for Barrel (sub)Sector with respect to single module operation

Mechanical structures now well advanced/finalized, detailed optimization of local cooling & services integration are converging

CMS Silicon Strip Tracker: SST



Huge number of silicon detectors

(rods, petals, shells)

Rad-hard modules and electronics

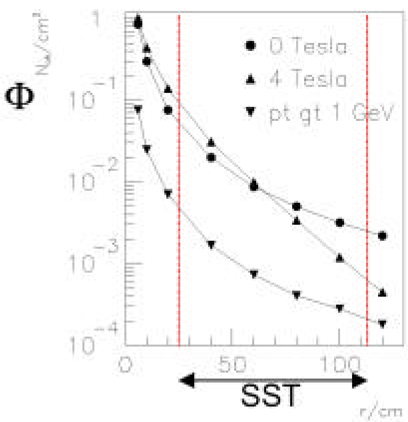
Cooling and –10 ºC

Alignment

“low” mass

Design considerations for CMS SST

Efficient & clean track reconstruction is ensured provided occupancy below few %



At small radii need cell size < 1cm^2
and fast (~25ns) shaping time
This condition is relaxed at large radii

$\Delta P_t / P_t \sim 0.1 {*} P_t$ (P_t in TeV)
allows to reconstruct Z to $\mu^+\mu^-$ with
Δm_Z < 2GeV up to P_t ~ 500GeV

Twelve layers with (pitch/ $\sqrt{12}$) spatial resolution and 110cm radius give a momentum resolution of

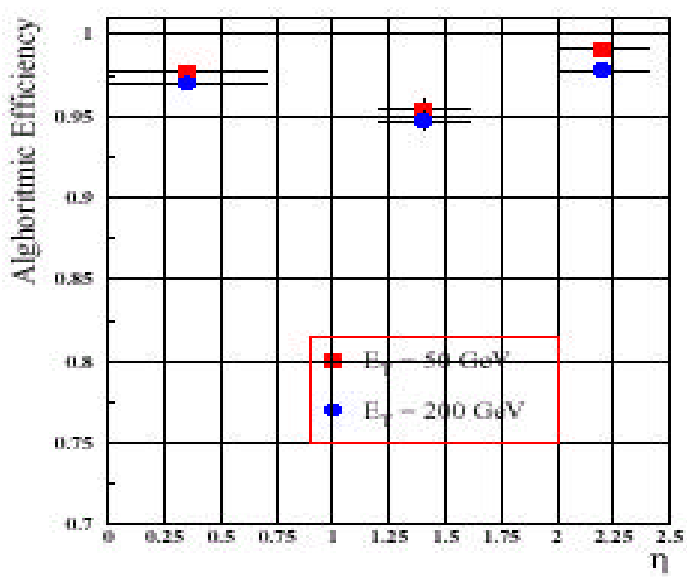
$$\frac{\Delta p}{p} \approx 0.12 \left(\frac{pitch}{100mm}\right)^1 \left(\frac{1.1m}{L}\right)^2 \left(\frac{4T}{B}\right)^1 \left(\frac{p}{1Tev}\right)$$

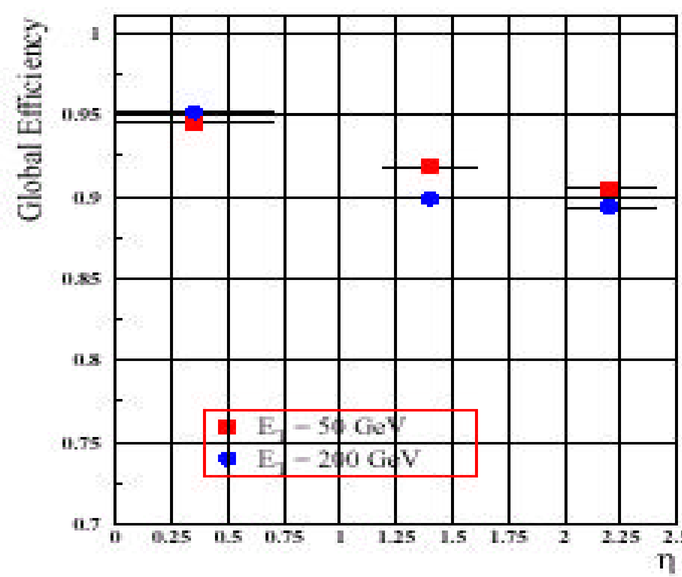
A typical pitch of order 100μm
is required in the phi coordinate
To achieve the required resolution

Strip length ranges from 10 cm in the inner layers to 20 cm in the outer layers.

Pitch ranges from 80μm in the inner layers to 200μm in the outer layers

Track reconstruction efficiency in jets





Efficiency for particles in a 0.4 cone around jet axis

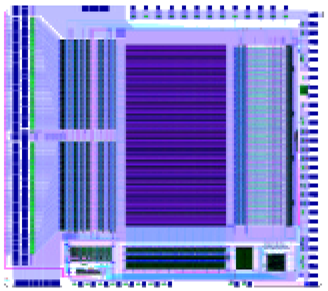
No significant degradation compared to single pions

Loss of efficiency is dominated by hadronic interactions

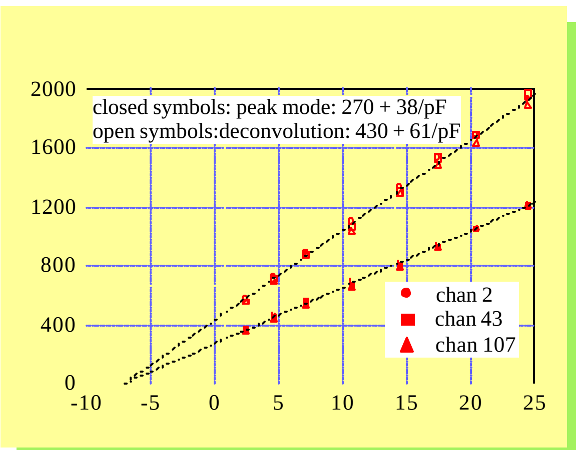
in Tracker material

Status of CMS Silicon Strip Tracker

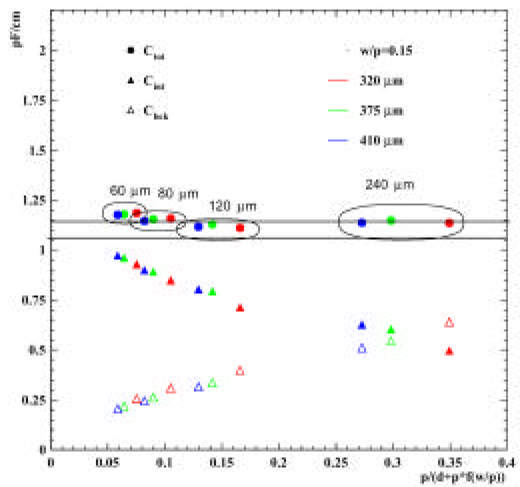
APV25 chip: 0.25m
ready for production

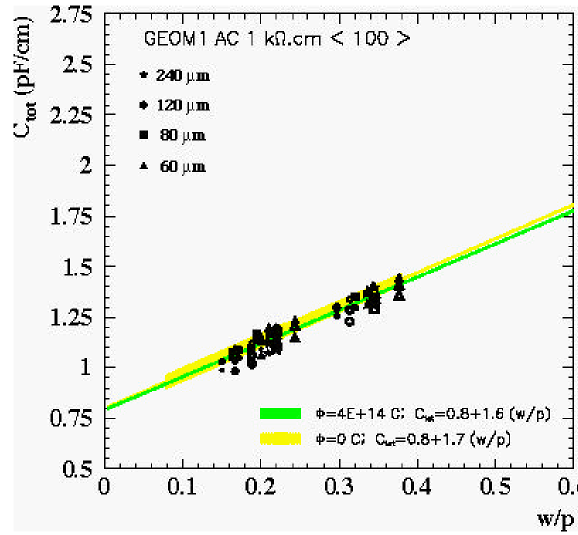


Radiation insensitive
Excellent noise performance



Strip capacitance ~ 1.2pF/cm for w/p = 0.25
Independent of pitch and thickness
Insensitive to irradiation for <100> crystal

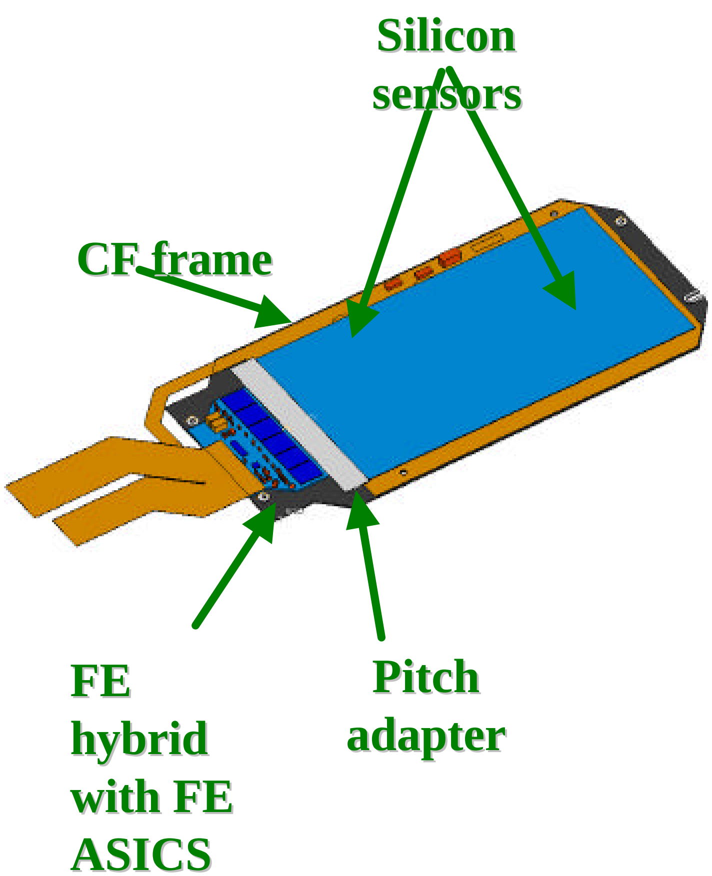




Use 320mm thick Si for R < 60cm, L_{strip} ~ 10cm
Use 500mm thick Si for R > 60cm, L_{strip} ~ 20cm

Expected S/N after irradiation
S/N ~ 13 for thin sensors, short strips
S/N ~ 15 for thick sensors, long strips

SST Module level Components



6,136 Thin sensors
18,192 Thick sensors

6,136 Thin detectors
(1 sensor / module)
9,096 Thick detectors
(2 sensors / module)

440 m² of silicon wafers
210 m² of silicon sensors

Large scale 6" industrial sensor production

9,648,128 strips º channels
75,376 APV chips

Reliable, High Yield Industrial IC process

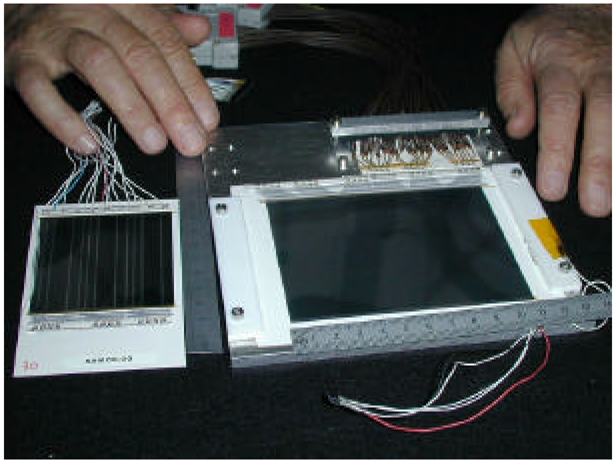
3112 + 1512 Thin modules
(ss +ds)
5496 + 1800 Thick modules
(ss +ds)

Automated module assembly

25,000,000 Bonds

State of the art Bonding machines

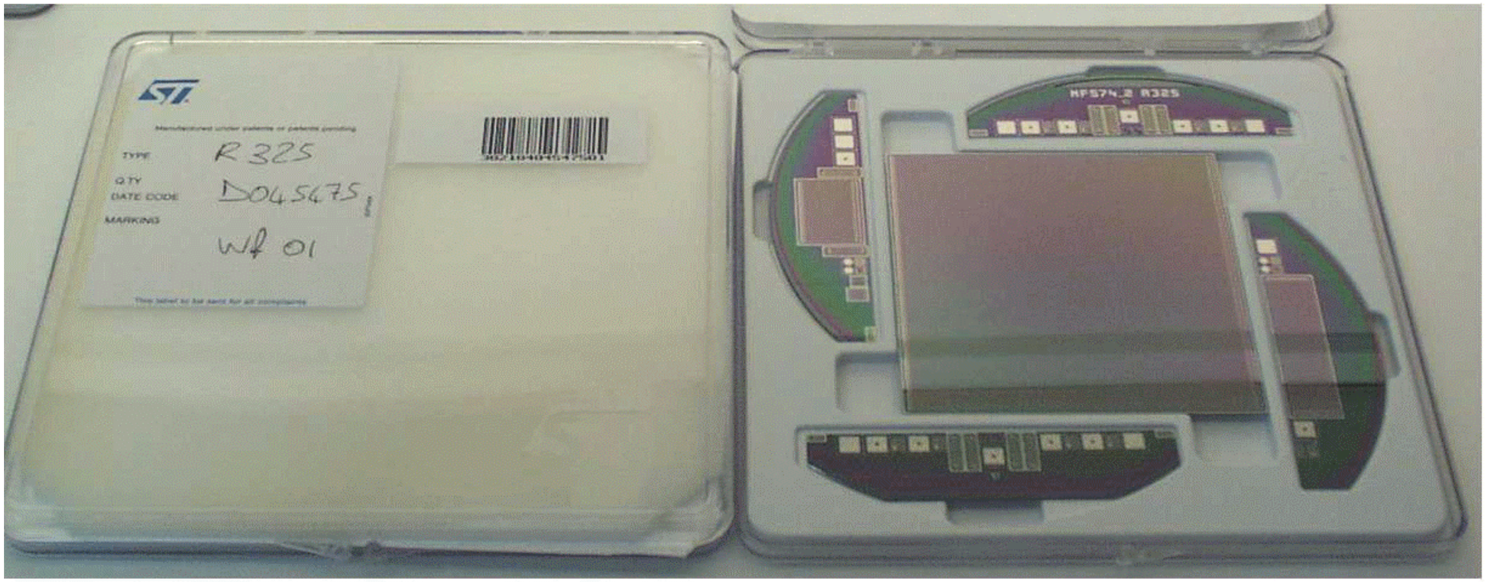
Status of CMS Silicon Strip Tracker (SST)



The CMS SST exploits 6” technology:

Useful surface/wafer ~ 2.5 * that of 4” wafers

Large scale high quality sensor production in modern Industrial lines available from more than one vendor

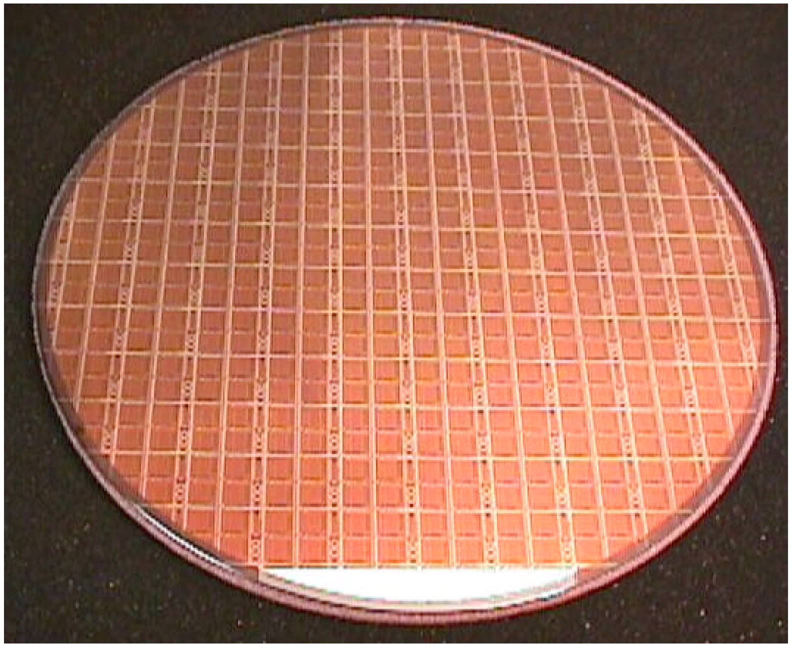


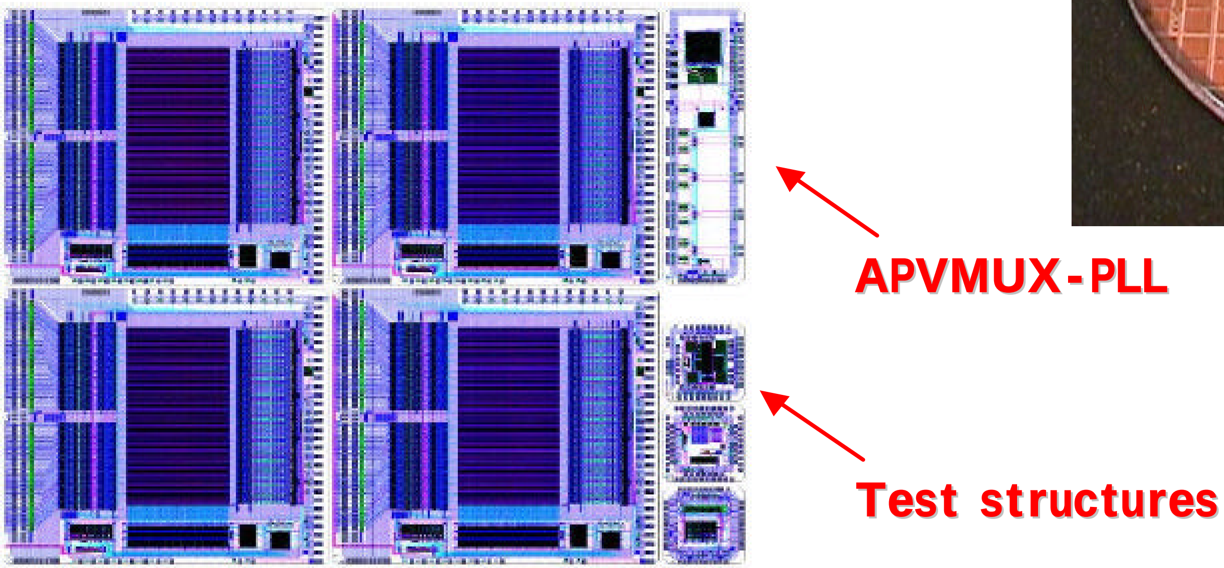
0.25m FE chip set: Production wafer layout

Now APVMUX corrected, revised masks can be finalised

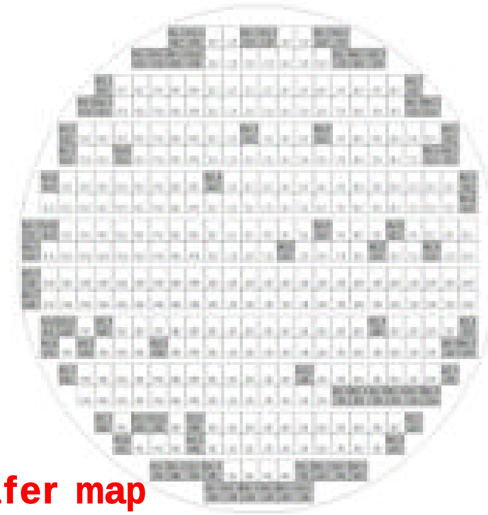
Wafer

- Overall size 200mm
- APV25 die ˜ 400
- APVMUX+PLL die ˜ 100





APV25 test results



Typical tested wafer map

Automatic wafer probing

- 9 wafers probed - 75% yield of perfect chips
  - most failures at wafer periphery

Two cut wafers retested as individual die

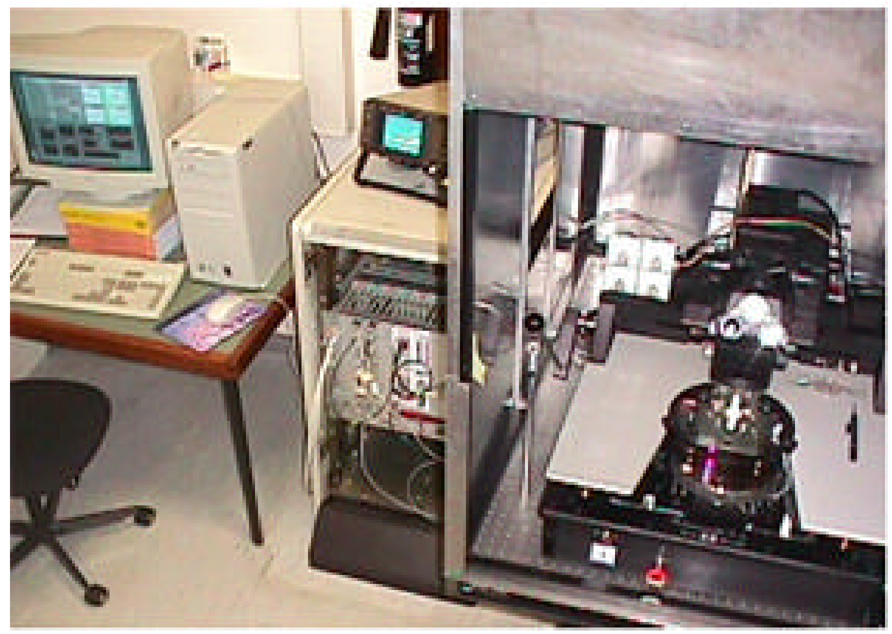
- statistics limited: upper limit 1% good die failed
- but no bad chips accepted

Test time < 2mins/chip

- 1 8inch wafer per probe station per day
- can complete testing in ~1-2 years

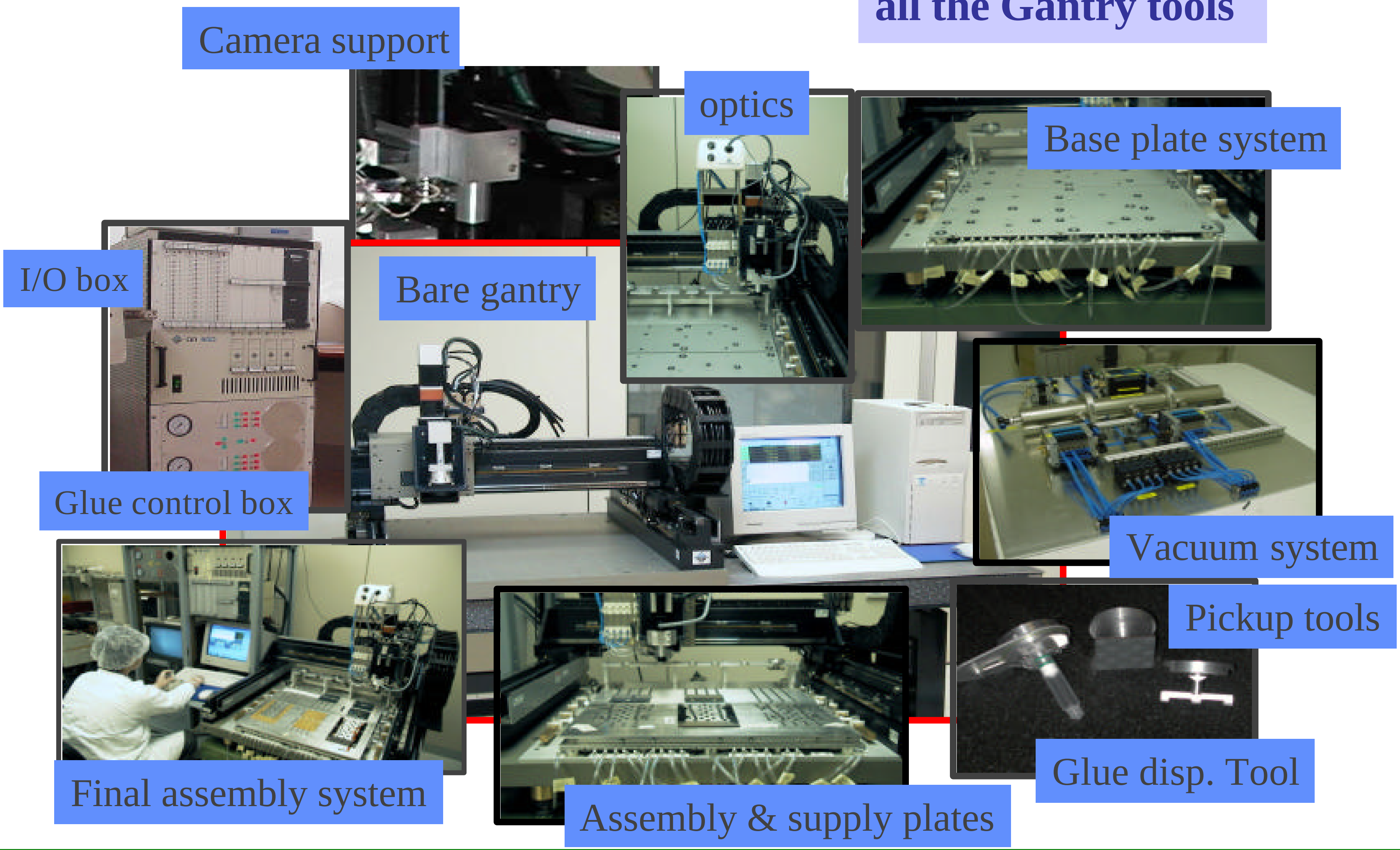
Irradiation results

- x-ray, pion & neutron - all excellent
- tests with heavy ions and pions
  - 8 chips x 10 LHC years
  - low SEU rate, no permanent damage or latch up

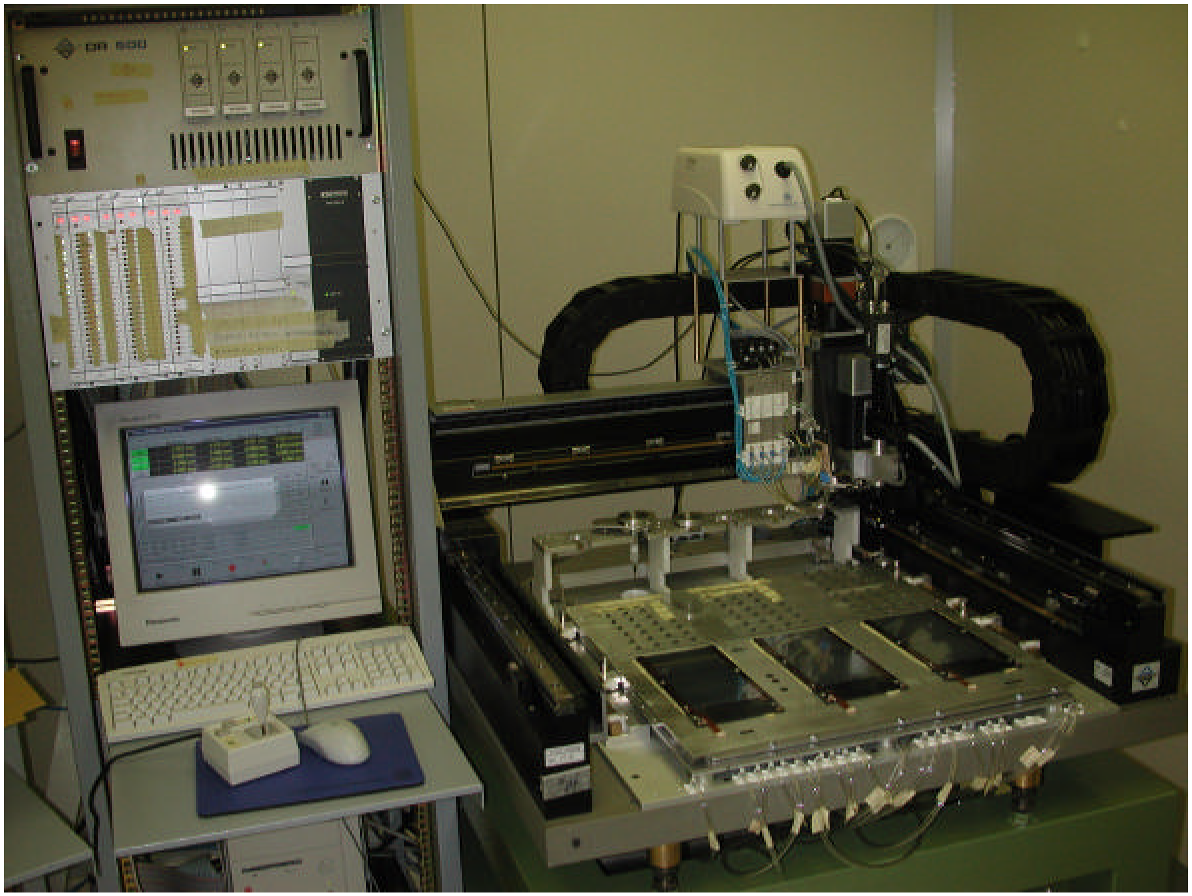


High precision glue dispensing and Pick & Place Robotic Device: The “Gantry”

all the Gantry tools



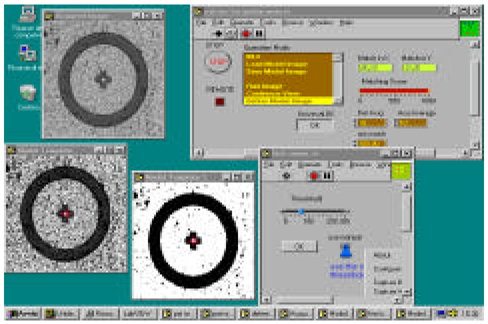
The Gantry in action



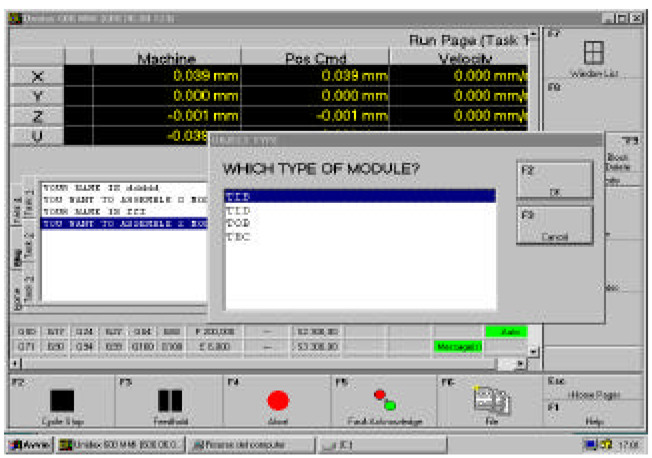
Three TOB final design modules under glue curing after the assembly in a gantry centre

"Gantry See, Gantry Do"

Pattern recognition: ready and implemented



Interface with Data Base: ready and operational



Data Collection before assembling

- Request at the operator:
  1. Operator name
  2. Number of module to assemble
  3. Type of sensors → number of sensor
- **Automatic information:**
  1. Date and time
  2. Temperature and humidity

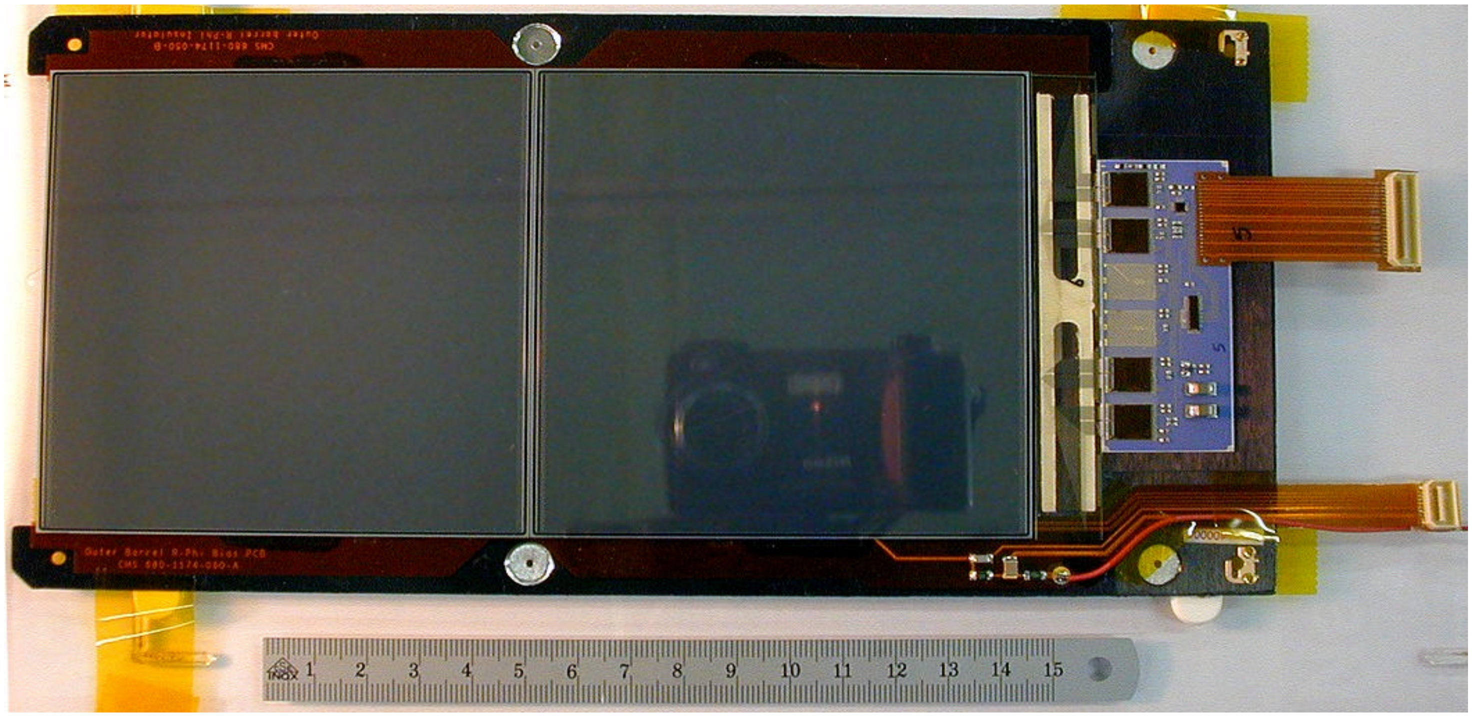
Information after the assembling

- Automatic information:
  1. Position of the sensors fiducial marks before and after the glue curing
  2. Position of hybrid fiducil marks before and after the glue curing
  3. Alignment angle
  4. Curing time

Quality control

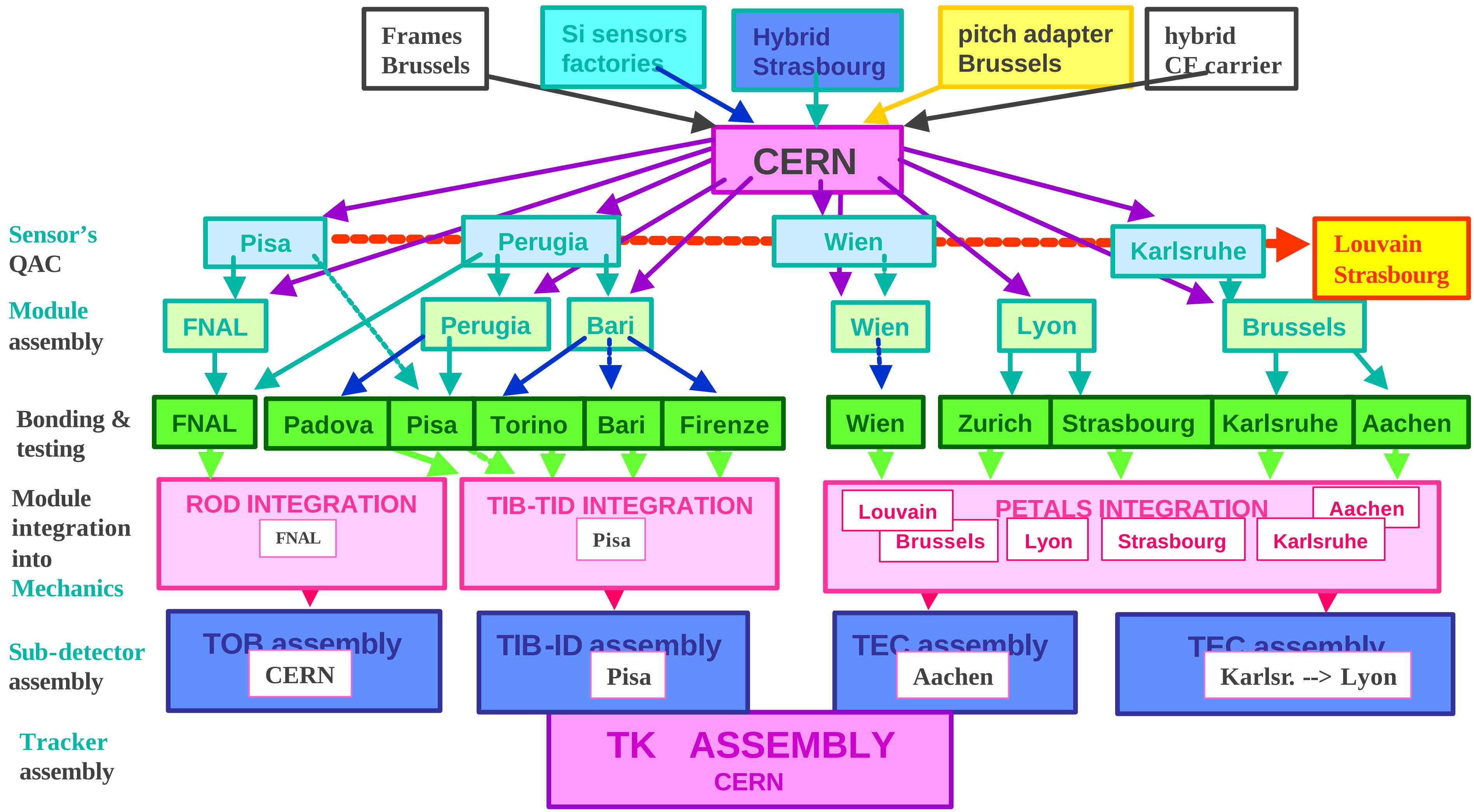
- Automatic information:
  1. Comparison with input parameter
  2. Validation flag → :0: if the module is ok…..
  3. Status → Valid, not valid, refernce
- Request at the operator:
  1. comment (the operator can choose among a set of possible comments)

A fully assembled CMS SST Module (TOB)



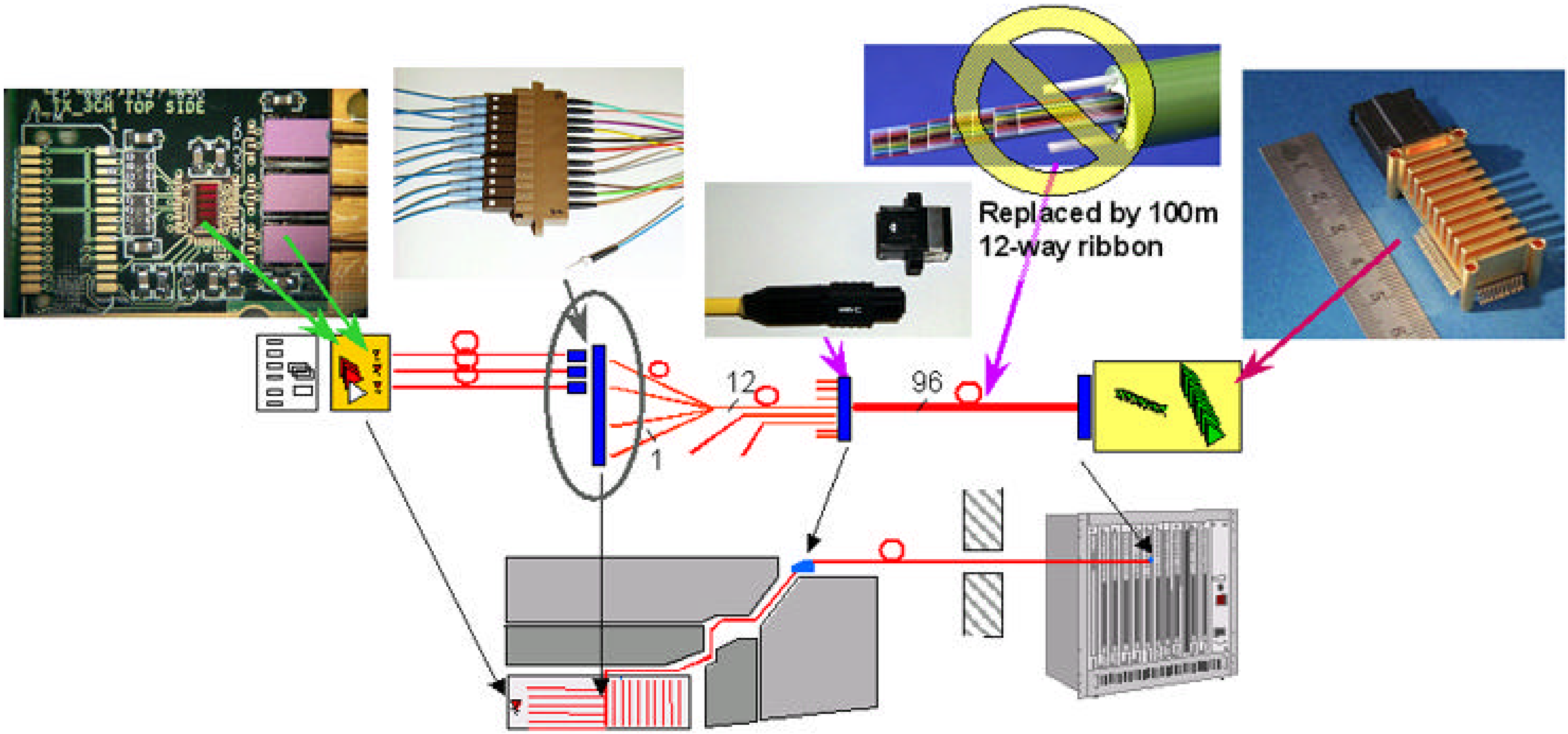
Situation is rapidly evolving toward full module production

CMS SST Assembly Logistics:
A lot of horse power & a great deal of organization

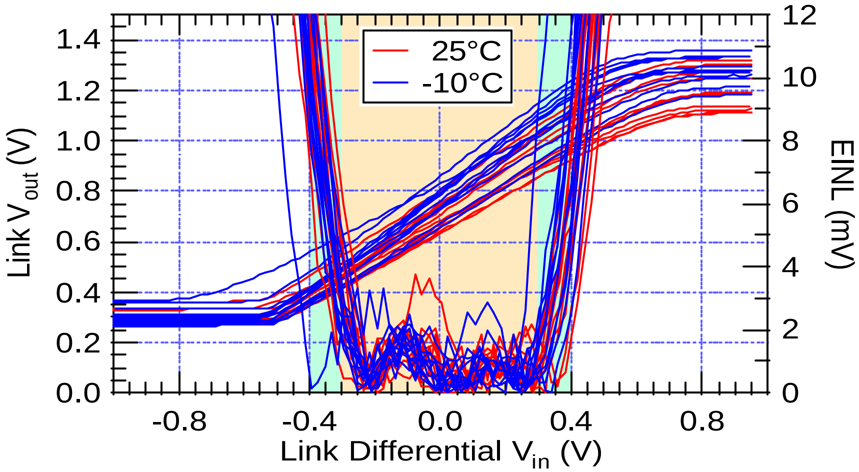


Full Link Test: a) components

First successful operation of all pre-final components in full link, including 4 TEC-type Optohybrids (4x3 fibres)



Full Link Test: b) Results

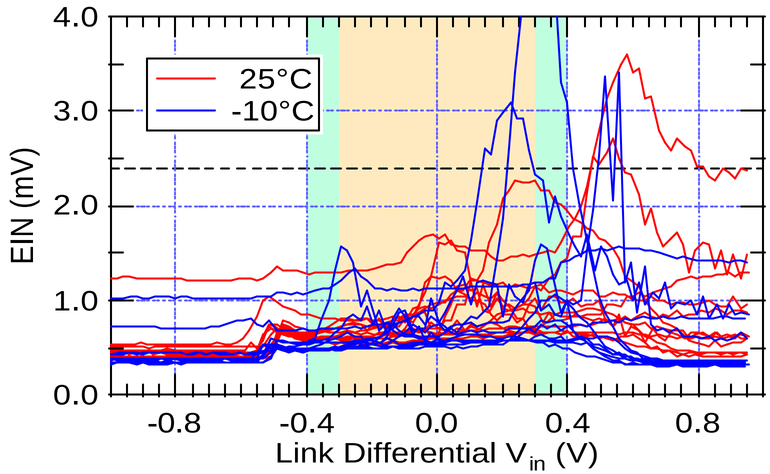


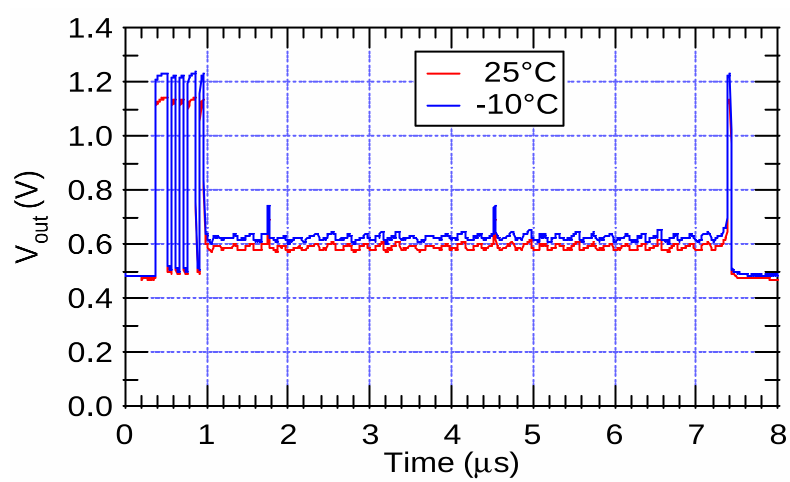
Very encouraging results of pre-final components for both 25°C and -10°C at front-end.

Slight gain increase at lower temp.

Noise and Linearity ok at low temp.

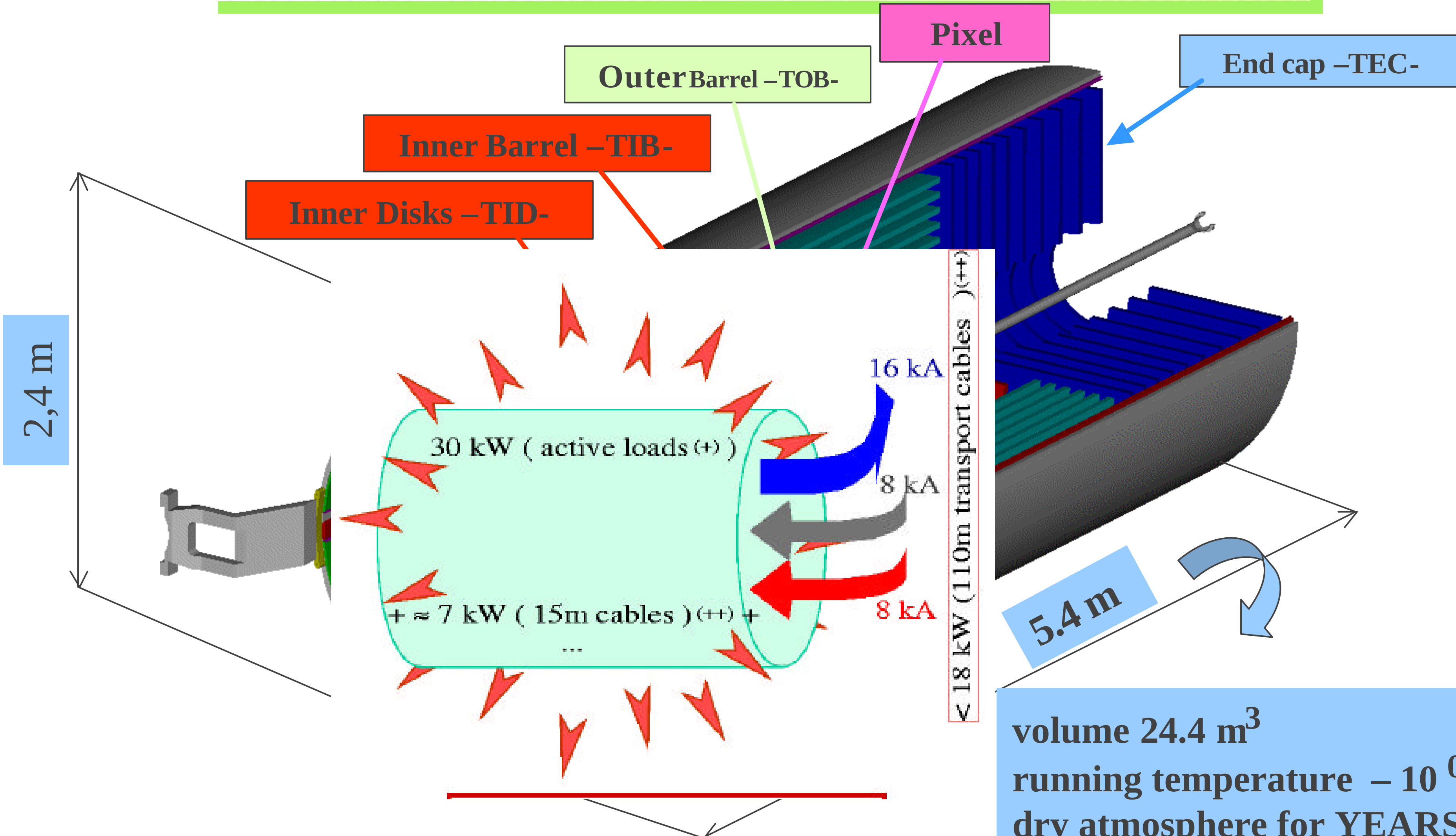
Ready for integration into Tracker system test.





Note: 1MIP=100mV at input

The CMS Tracker services



volume 24.4 m^3
running temperature – 10 ^{0}C
dry atmosphere for YEARS!

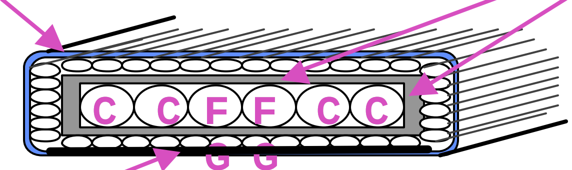
10 m long cable channel prototype

cal

Experimental results in good Agreement with FE calculation

Aluminum enclosure

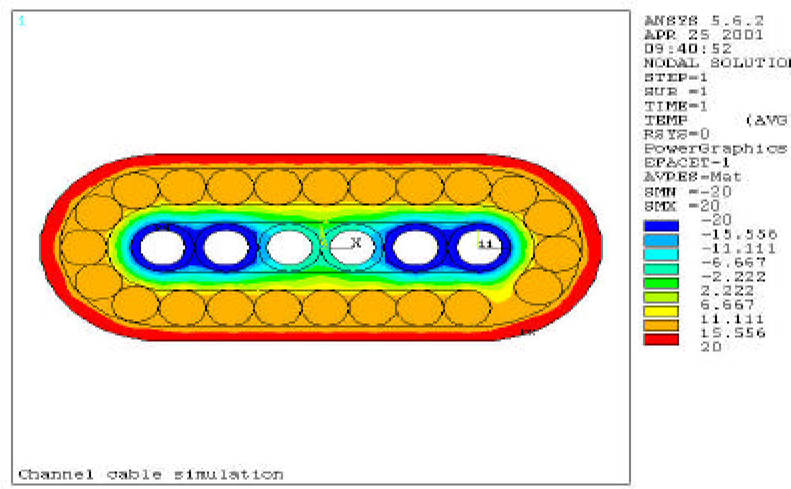
Inner Insulation foam 1



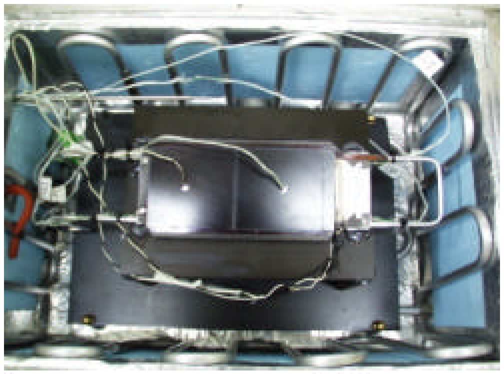
Heating foils for power compensation

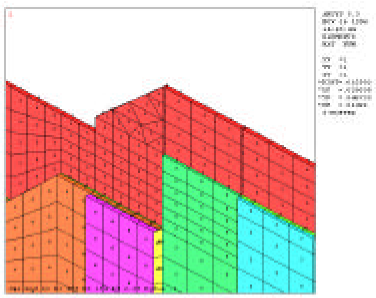
C : cooling pipes (C6F14)

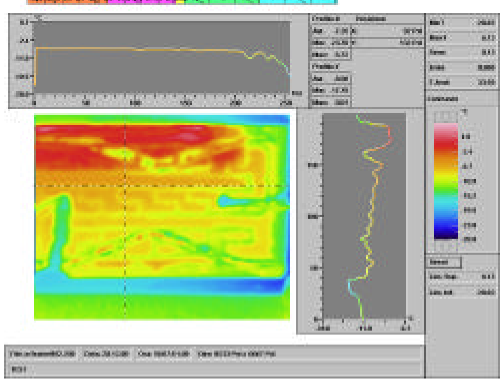
FG : flushing gas pipes (N2)



TIB Module - Cooling test







Single-Sided Module: results in agreement with FEM analysis

- Cooling Fluid temperature = -25C;

- Test in an isolated box with minimum external heat exchange;
- Air volume around the module comparable with the final configuration;
- Test prototype equal to Milestone 200 TIB modules;
- .Fluid condition (flow) and tube diameter equal to the design values;

- Read-out Hybrid Power = 2 W;
- Silicon power dissipated = 0.7 W;

- Maximum Silicon Temperature = -12.7 C.

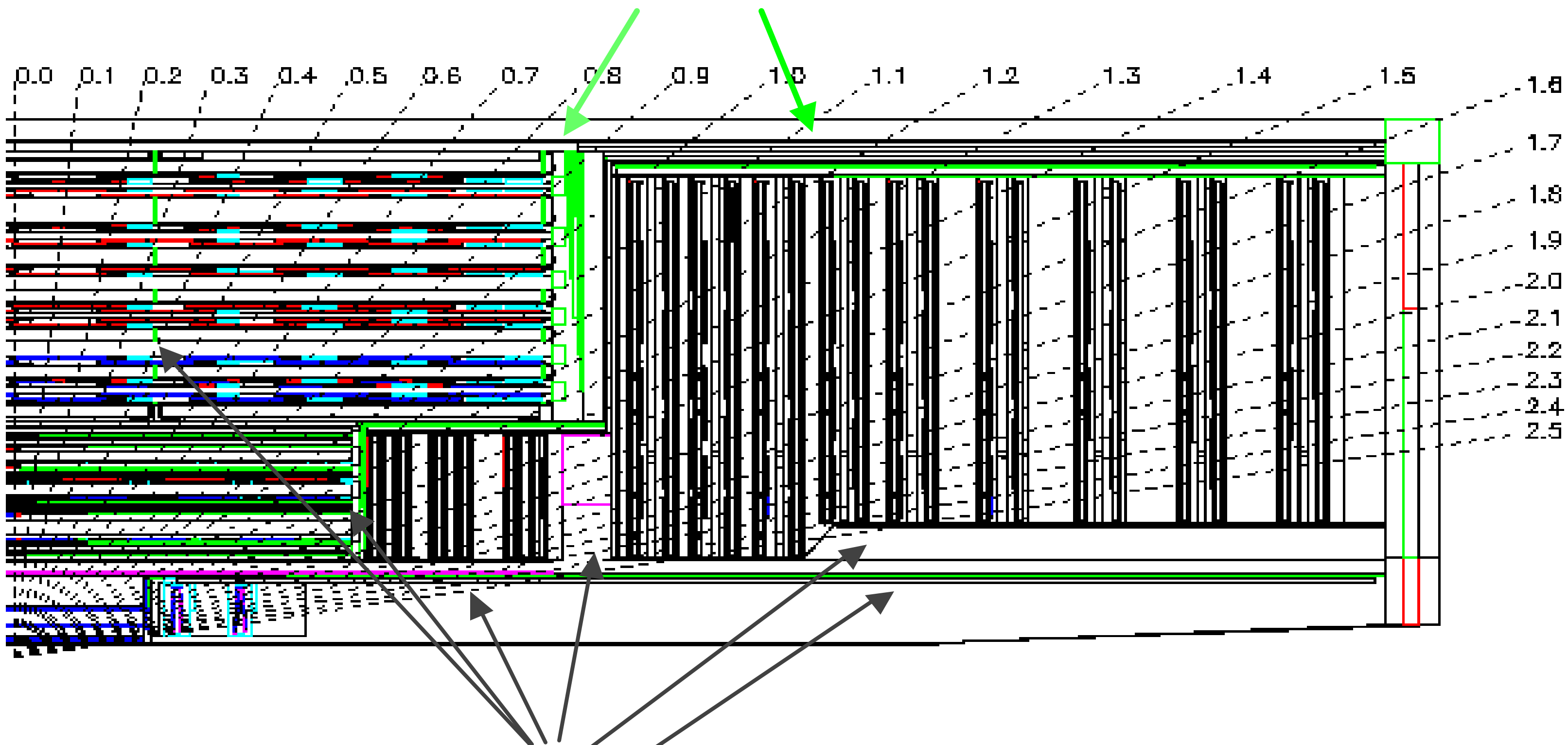
Double-Sided Module under test

- Maximum Silicon temperature close to the minimum value acceptable (-10C);
- Improvements in the interfaces between the two modules are possible and presently under study.

Material Budget

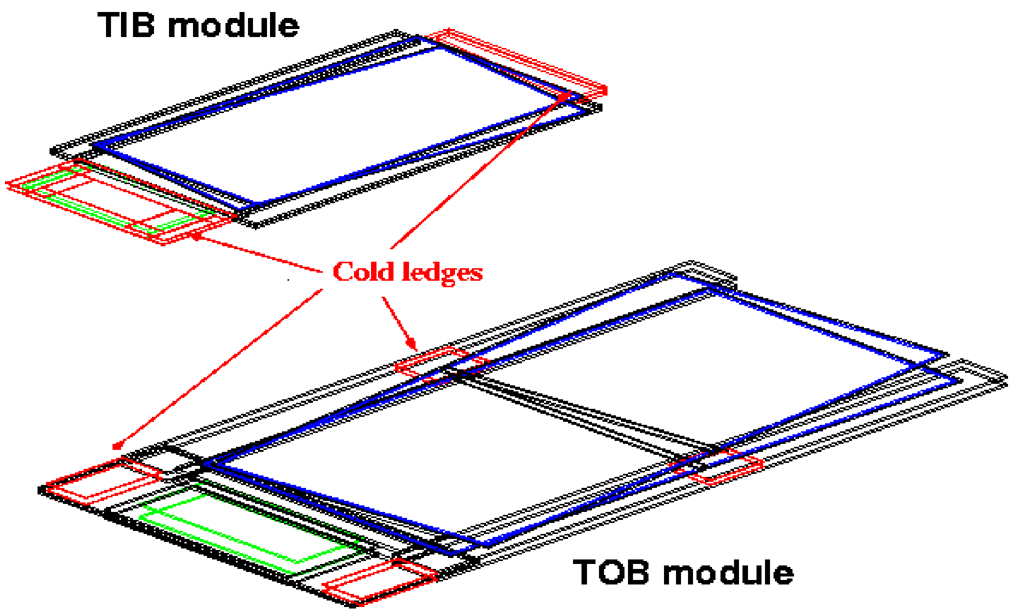
- Determined from detailed GEANT simulation which includes latest engineering design

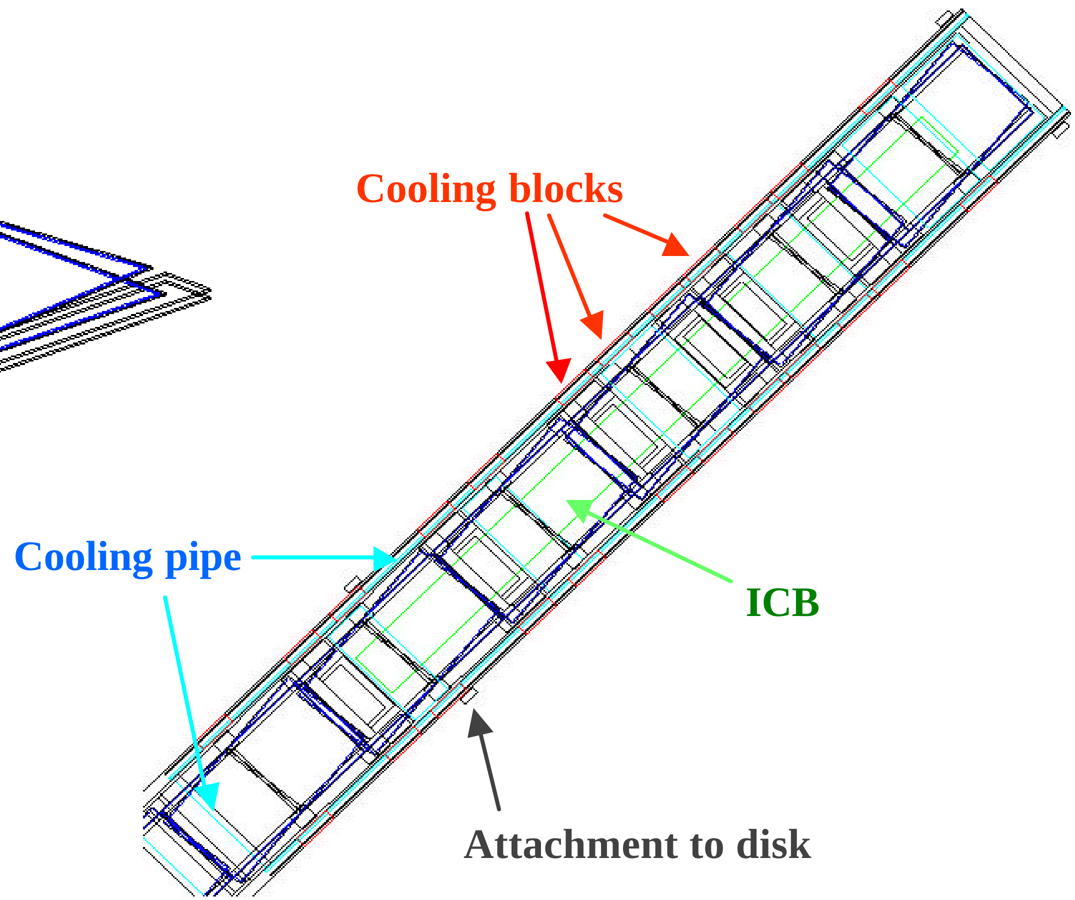
Cable paths



Support structures

Material budget: Detail of Modeling





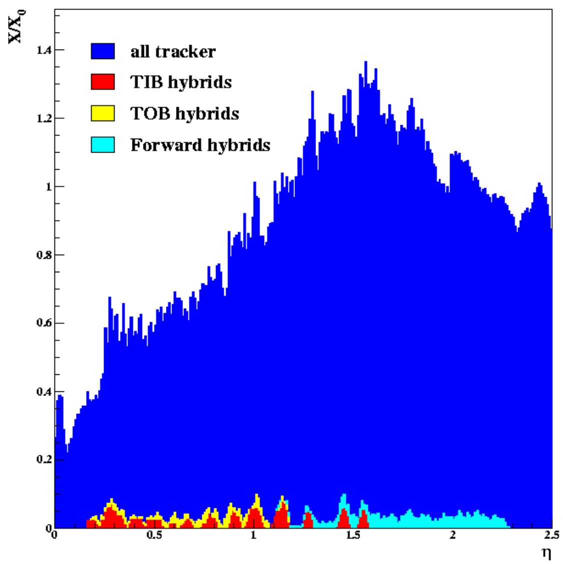
Care has been taken to model localized heavy material (e.g. Aluminum for cooling) separately

Efforts to reduce material budget (1)

- Light support structures
  - End cap wheels with holes ® 30 % reduction of material
- Cables inside the tracker have Aluminum as conductors
- For the smaller inner barrel (where the material hurts the most) the “mother cable” distributing power and signals will be Cu on Kapton

- Hybrids: choice of Gold on Ceramic

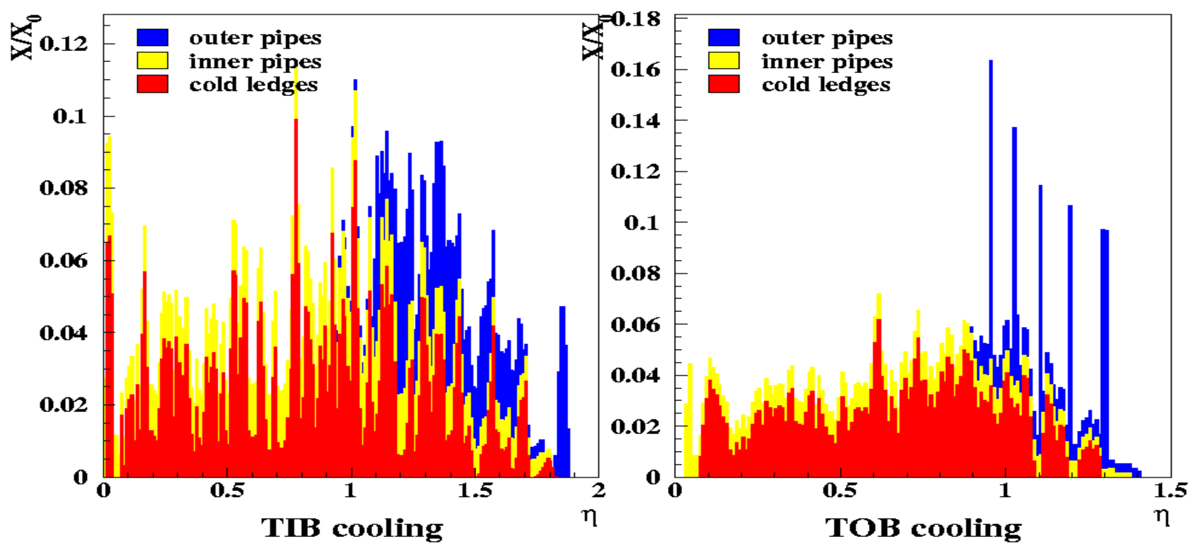
Most dense module component
Other technologies (Cu/Kapton) discarded as development incompatible with construction schedule



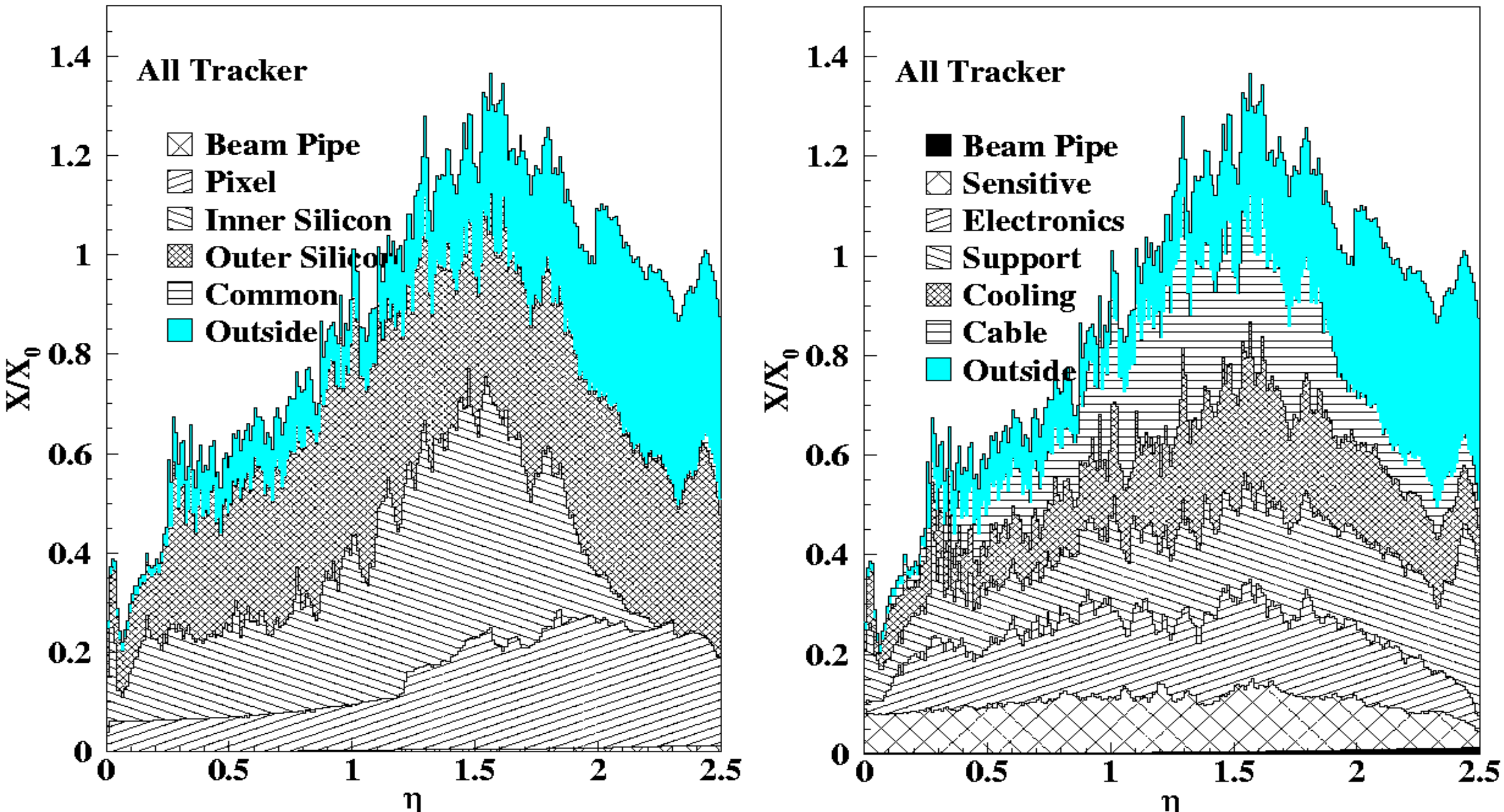
Contribution of hybrids to tracker X_0

Efforts to reduce material budget (2)

- Cooling pipes of inner detector are Aluminum
- Radii and wall thickness have been minimized as much as possible,
- e.g. TOB arc pipes at end flanges: diameter 6 mm, skin 0.2 mm
  was 7.6 mm, 0.2 mm
- Cooling inserts (Al) are heavy, but cooling requirements are very stringent. Realistic cooling tests have been and are performed to see if further optimization is possible.

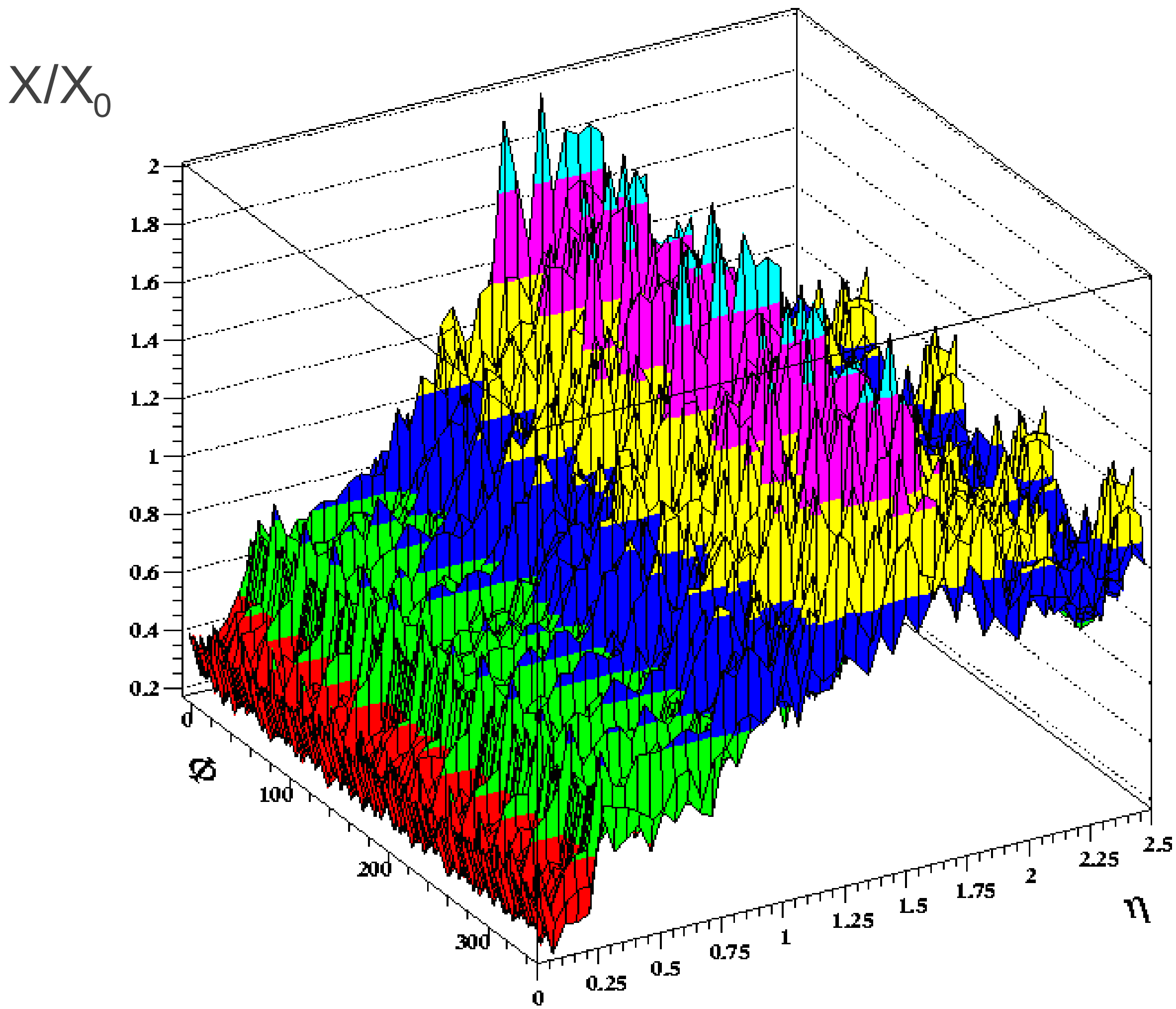


Radiation Length in the Tracker

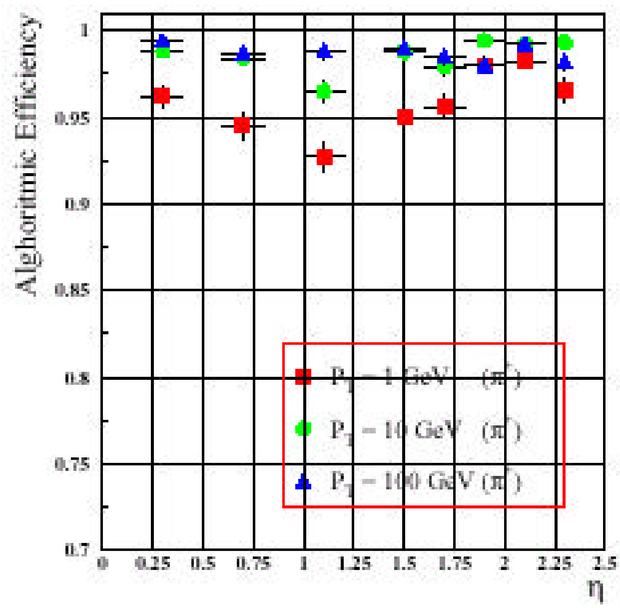


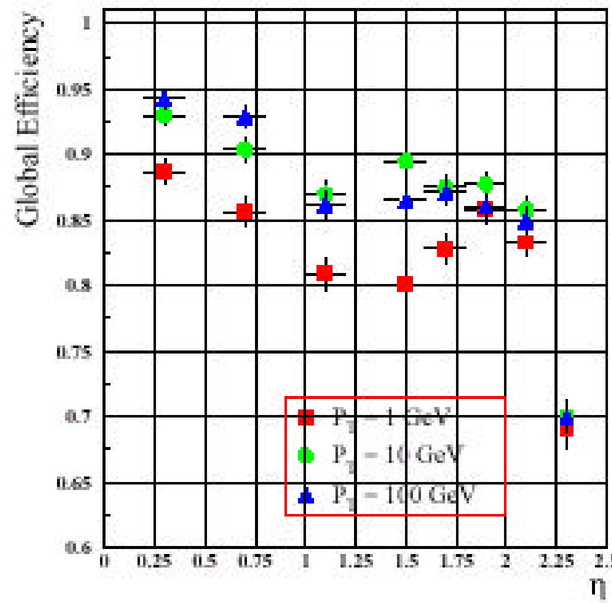
Nothing sticks out particularly, it just all adds up…

Radiation Length in the Tracker



Track finding efficiency (Pions)





Same efficiency definition as for muons

Efficiency is lower compared to muons due to secondary interactions in the Tracker

Efficiency can be increased by relaxing track selection

Conclusions

The technology used for Vertex detectors has evolved
from Strips (single or double-sided) with $O(10^5)$ channels,
to Pixels, with $O(10^7 - 10^8)$ channels

Strip technology, developed for use in Vertex detectors, has evolved to be deployed in very large scale Tracking detectors

Currently, most extreme example of this trend in the CMS Silicon Tracker

These steps forward have been made possible by combination of:

- Build up of expertise within the HEP community: LEP was a big part of this
- Extensive and successful R&D to understand sensor operation in high fluence environments
- Moving production of strip sensors to large volume 6” industrial lines
- The ability to substitute “standard” 0.25mm technology for custom Radiation Hard Front End read-out electronics

Conclusions

Challenges lying ahead:

Make the LHC Vertex & Tracking detectors as successful
As the LEP Vertex (and Tracking) detectors have been!

The LHC Pixel Vertex and Silicon Strip Trackers suffer from
a great deal of material within the fiducial acceptance region

This is driven in large part by the high power dissipation and high current requirements of the current generation of Front-End electronics

The next generation of "bigger and bigger, better and better" solid state Vertex and Tracking detectors will probably require important break-trough's in low power, low current, Front-End electronics