The CMS Silicon Tracker

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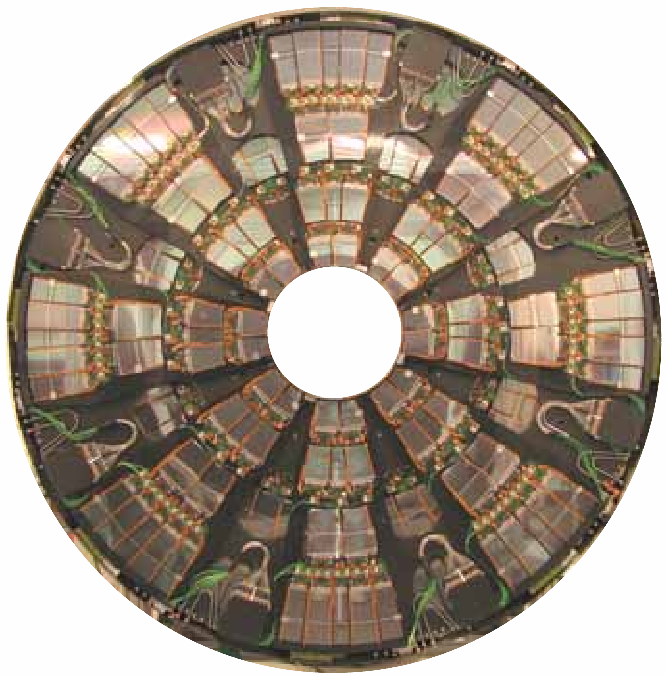
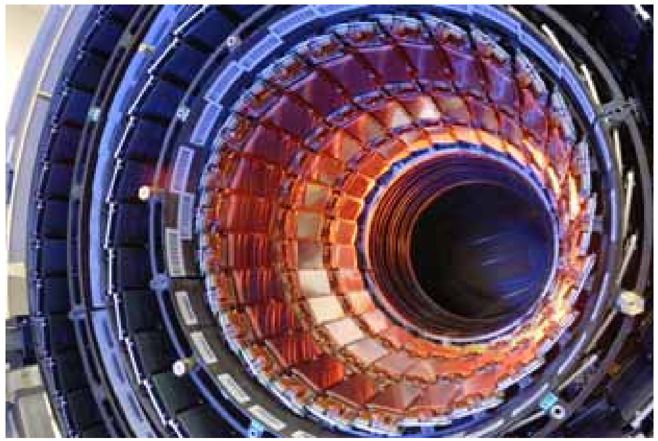
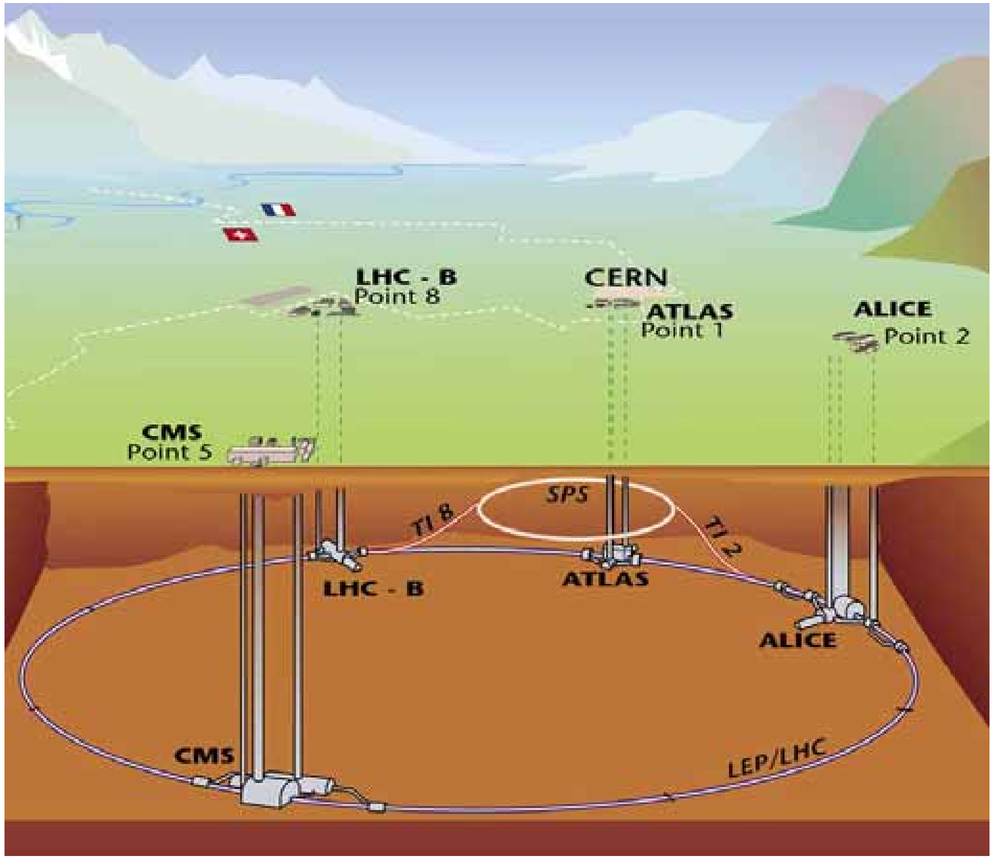
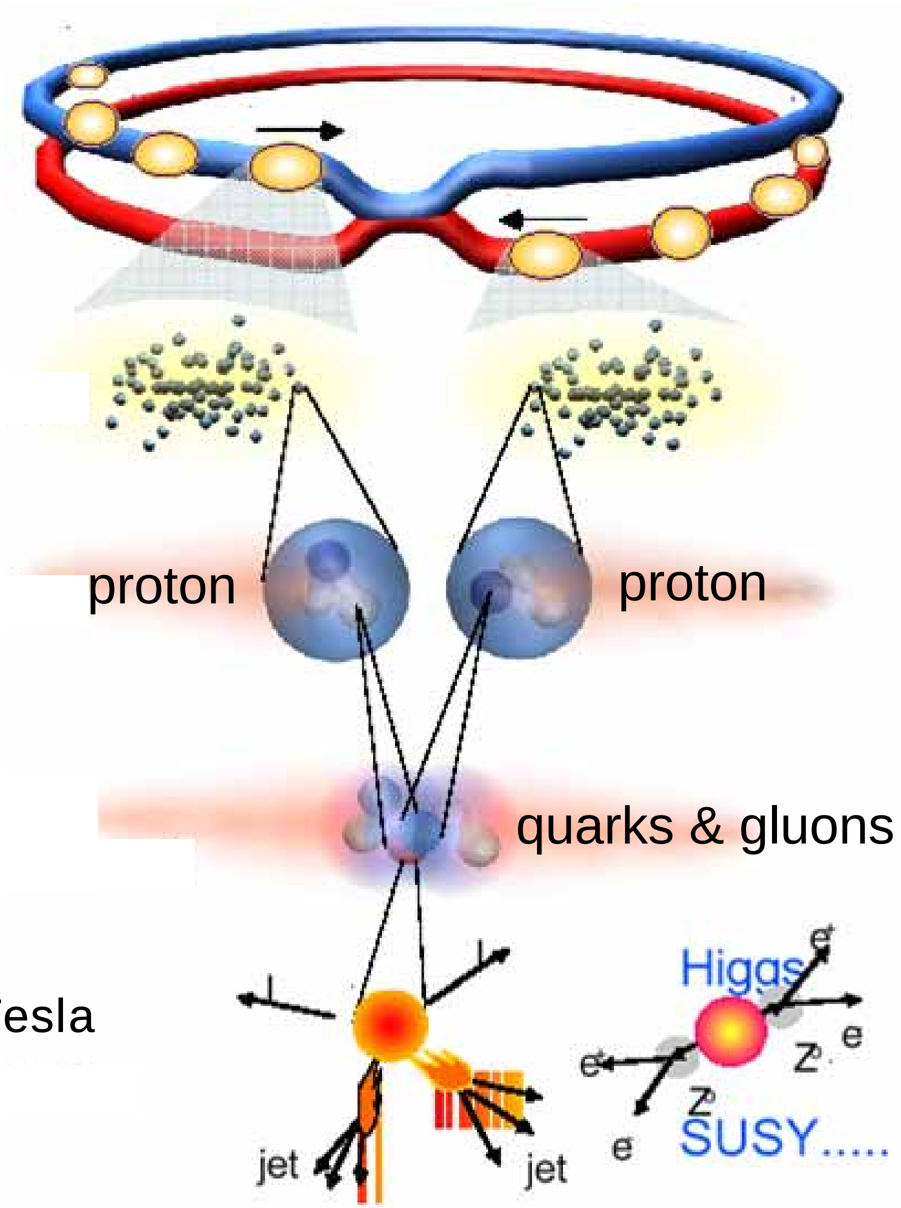




Large Hadron Collider am CERN





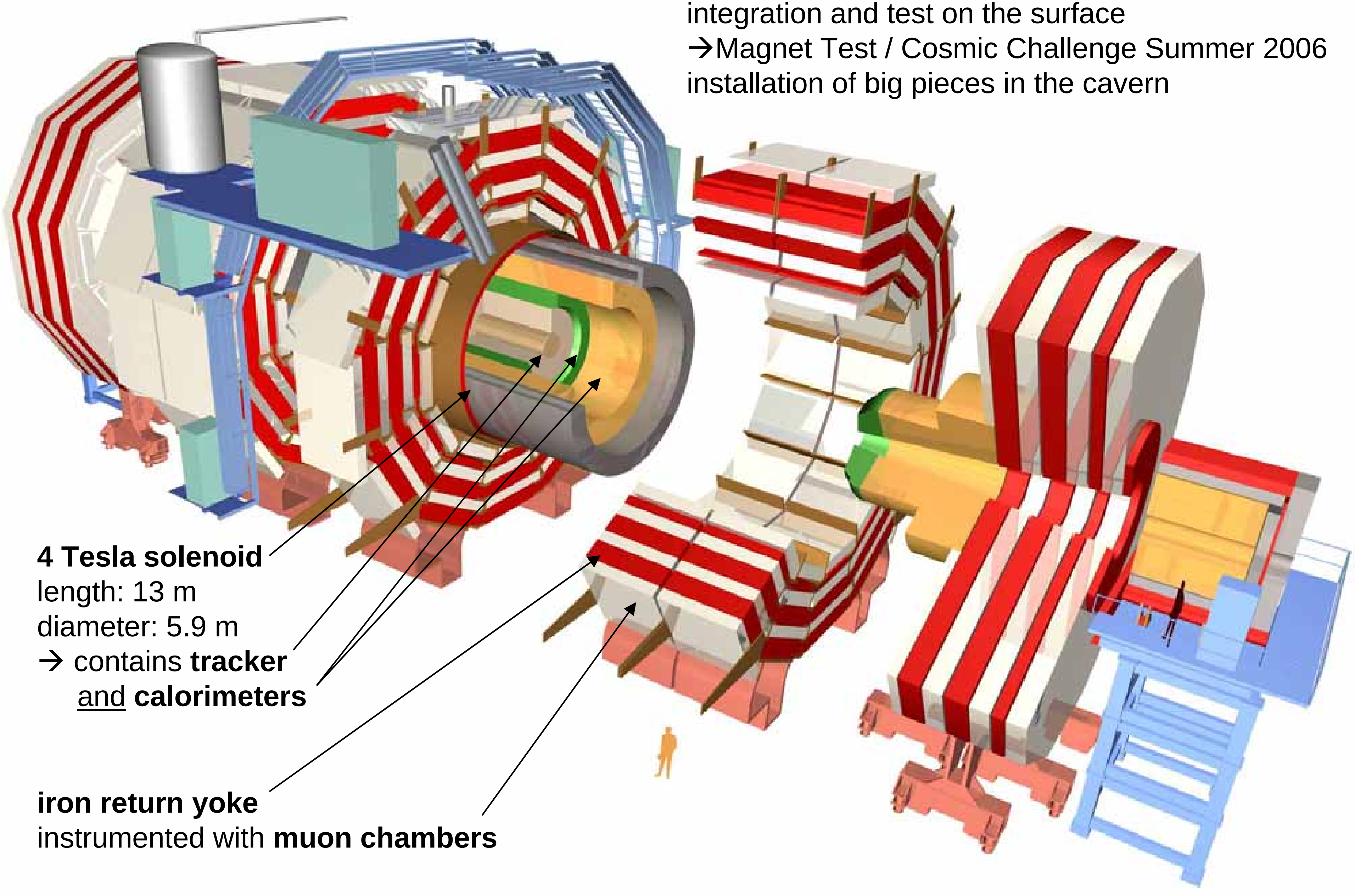
- circumference 27 km
- 1200 superconducting dipoles of 8.4 Tesla

→ 7 TeV proton momentum

→ 14 TeV pp center-of-mass energy

The CMS Detector at LHC

Baukastenprinzip:
integration and test on the surface
→Magnet Test / Cosmic Challenge Summer 2006
installation of big pieces in the cavern

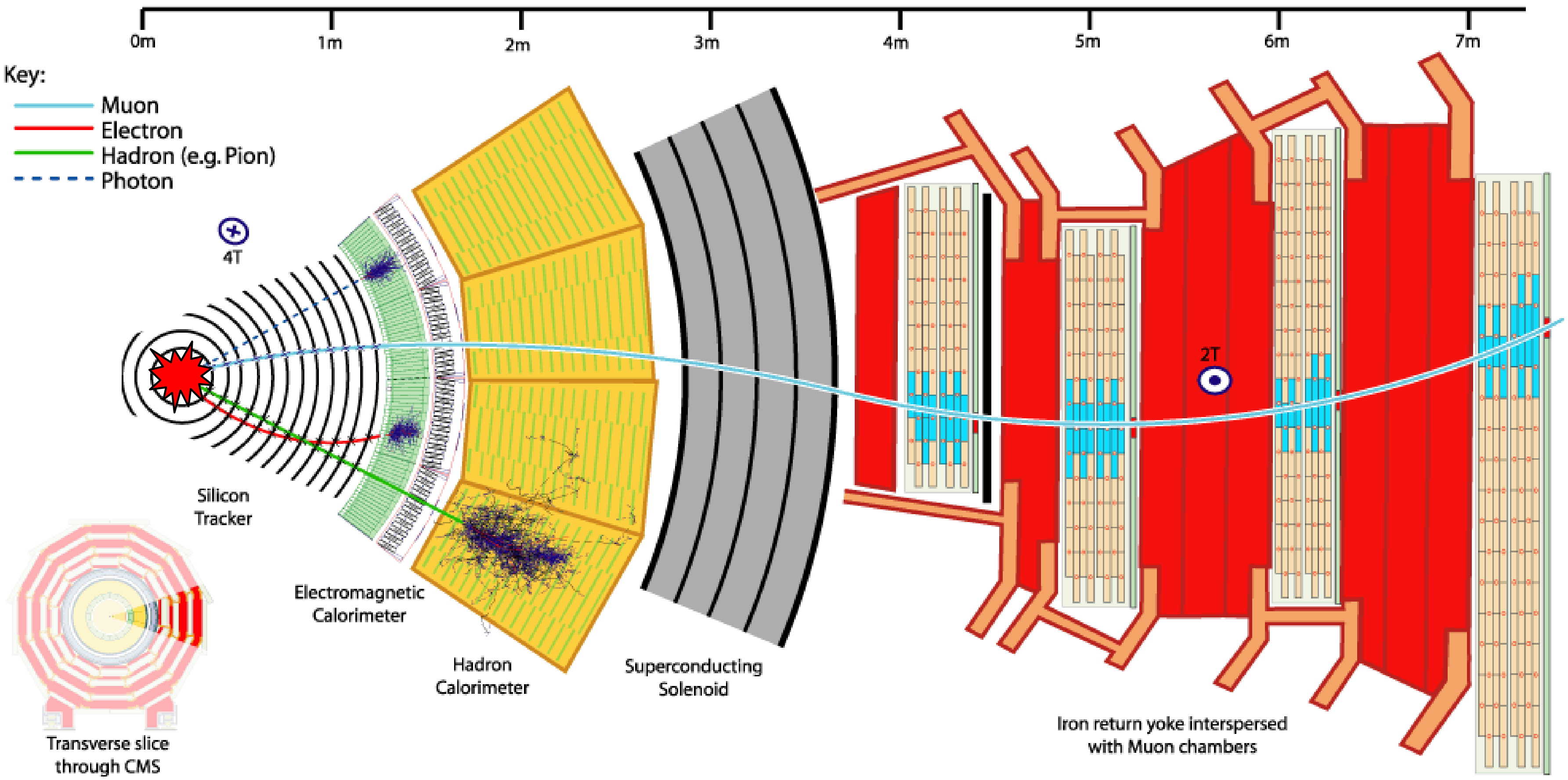


4 Tesla solenoid
length: 13 m
diameter: 5.9 m
→ contains **tracker**
and **calorimeters**

iron return yoke
instrumented with **muon chambers**

CMS Central Section arrived Underground

CMS cross section perpendicular to beam axis



Requirements for Accelerator and Detectors

Signal cross sections are tiny
e.g. one Higgs in 10^{10} pp collisions

→ we need **high luminosity**:
$10^{34} cm^{-2} s^{-1}$ (100 times more than before)
→ **25ns bunch crossing time**

→ in every bunch crossing
  → **~23 pp collisions**
  → **1000 particles** in central region
  hit rate of 60 kHz/mm² at r=22 cm

→ novel requirements on tracking detectors
  → **~25 ns** readout time
  → **high granularity**
  → **radiation hardness**
  high spatial resolution (typ. 10µm) is a result of these requirements

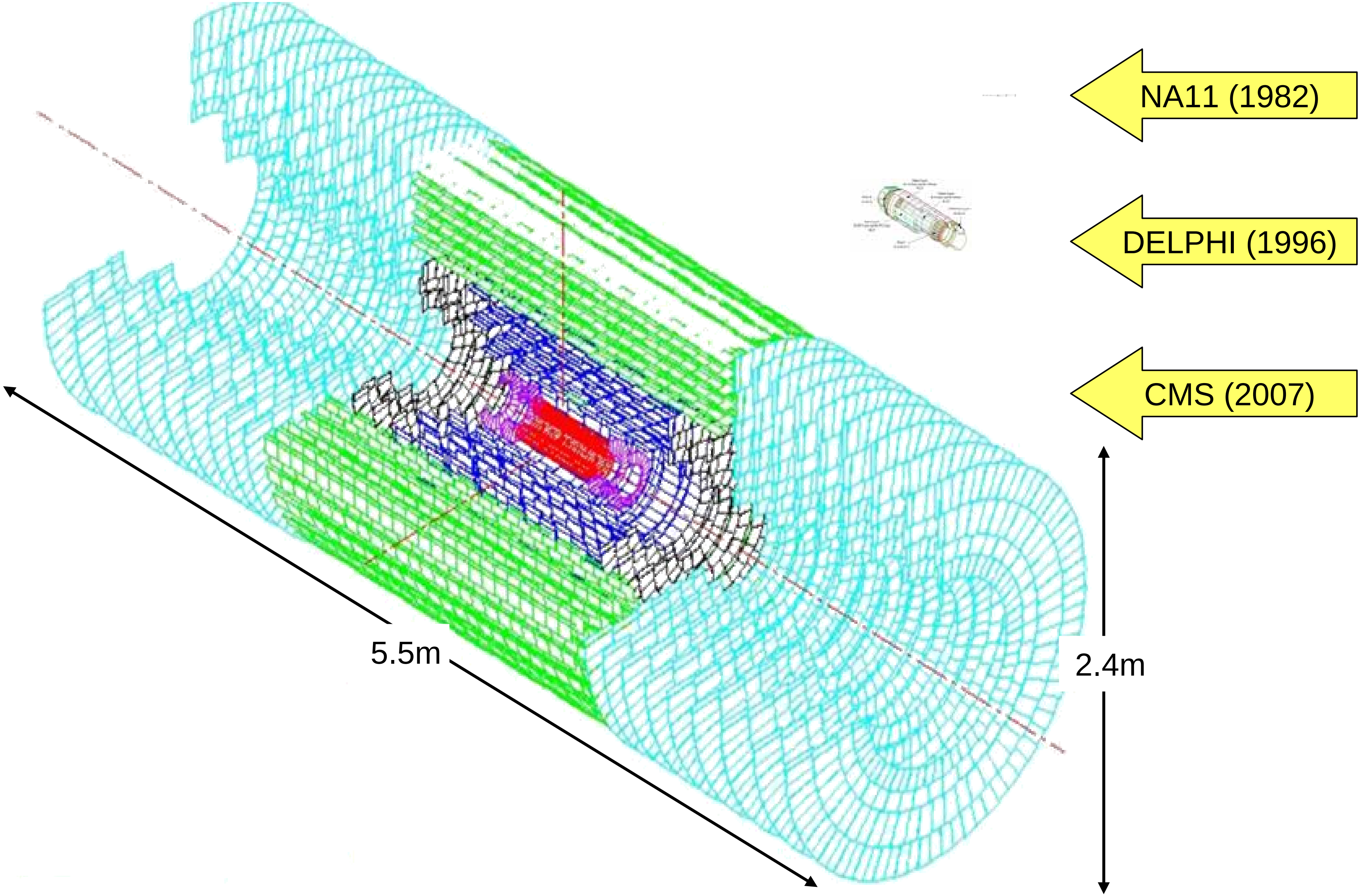
→ traditional tracking chambers cannot be used

  → **Silicon Tracker**

rates for L = 10^{34} cm^{-2} s^{-1}		
inelastic pp collisions	10^9	/ sec
bb pairs	5 x10^6	/ sec
t t pairs	8	/ sec
W → e **n**	150	/ sec
Z → e e	15	/ sec
Higgs (150 GeV)	0.2	/ sec
Gluino, Squarks (1 TeV)	0.03	/ sec

Focus in this talk on Silicon Microstrip Tracker

A new domain for Silicon Detectors

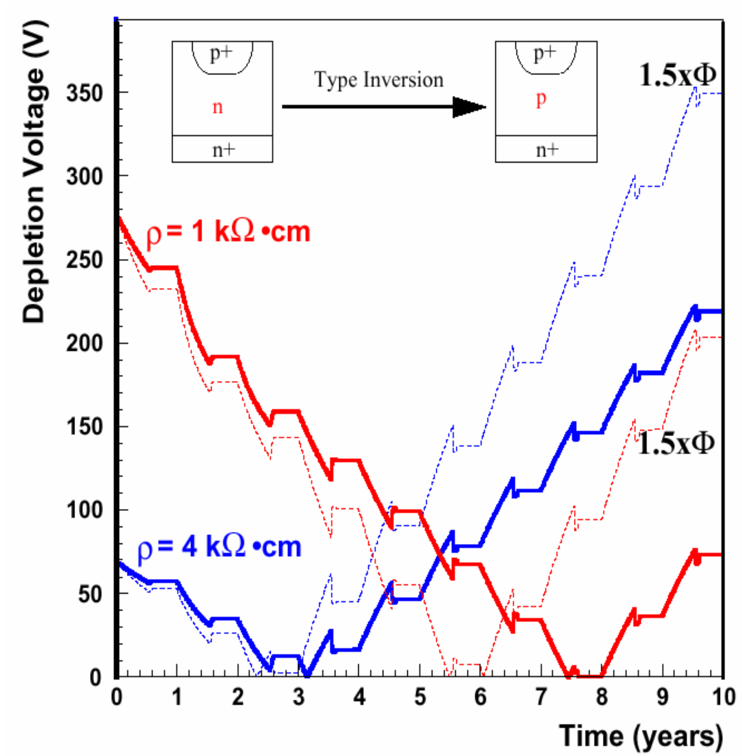


Radiation Damage at LHC

strip detectors in 10 years:
~1.5x10^14 1-MeV-neutrons/cm^2
~60 kGy

Two types of radiation effects:

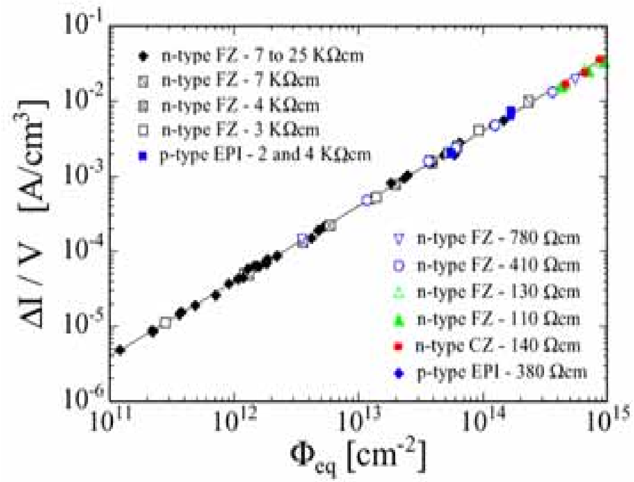
- ionizing energy loss
  → creates fixed **oxide charges**
- non-ionizing energy loss
  → **defects in silicon cristal lattice**
  → new energy levels



Sensors

- change of depletion voltage
- increase of dark current
- loss of signal charge

$$V_{FD} = d^2 N_{eff} \frac{q}{2\varepsilon\varepsilon_0}$$



Read-out ASICs

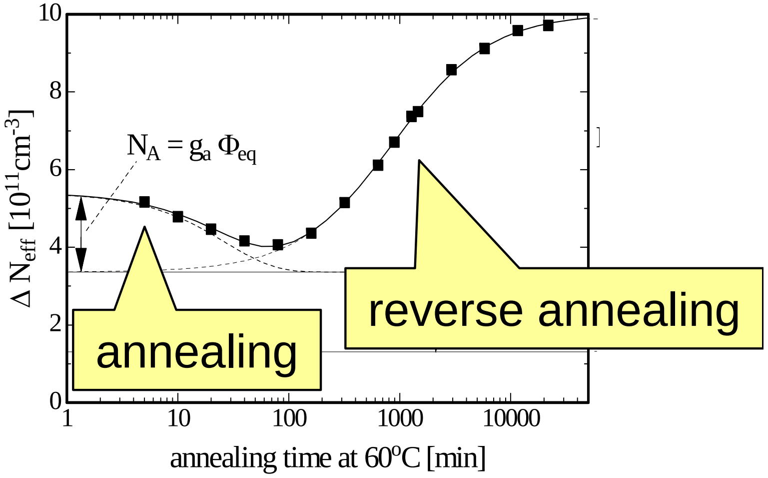
- change of flat band voltage of MOS structures
- generation of parasitic currents and structures
- transient phenomena like bit flips etc.

Measures to achieve radiation hardness

- limit depletion voltage by appropriate choice of sensor thickness and initial doping

- allowing for high voltage operation (up to 500V) by sensor design which avoids high fields

- freeze ‚reverse annealing‘ by cooling permanently to T<0°C



- avoid positive feedback loop due to silicon self heating (‘thermal runaway’)

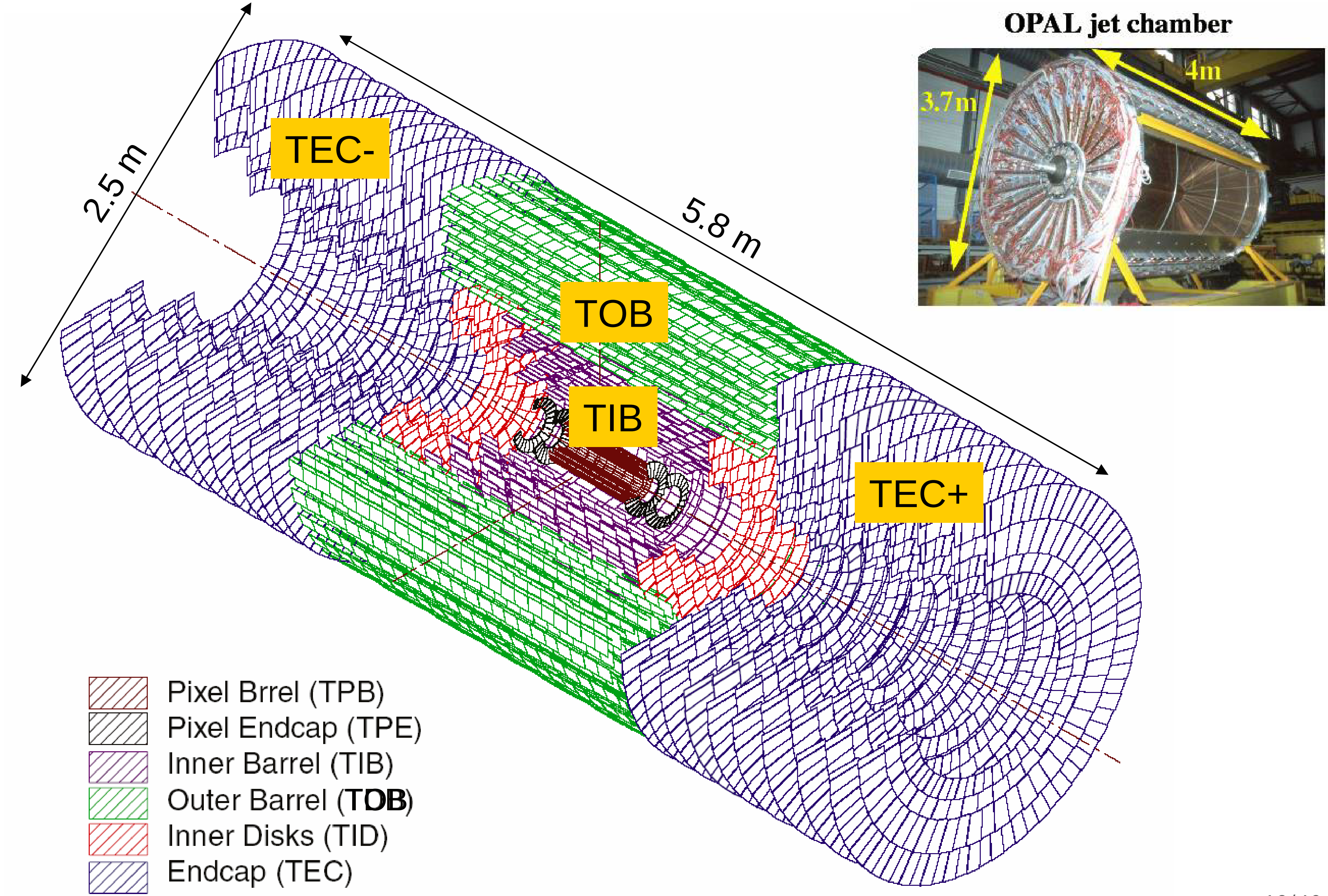
  dark current x bias voltage after 10 years:
  2 mA x 500 V = 1 W !

$$I \propto \frac{1}{\tau_g} \times T^2 \exp\left(-\frac{E_g}{2kT}\right) \times volume$$

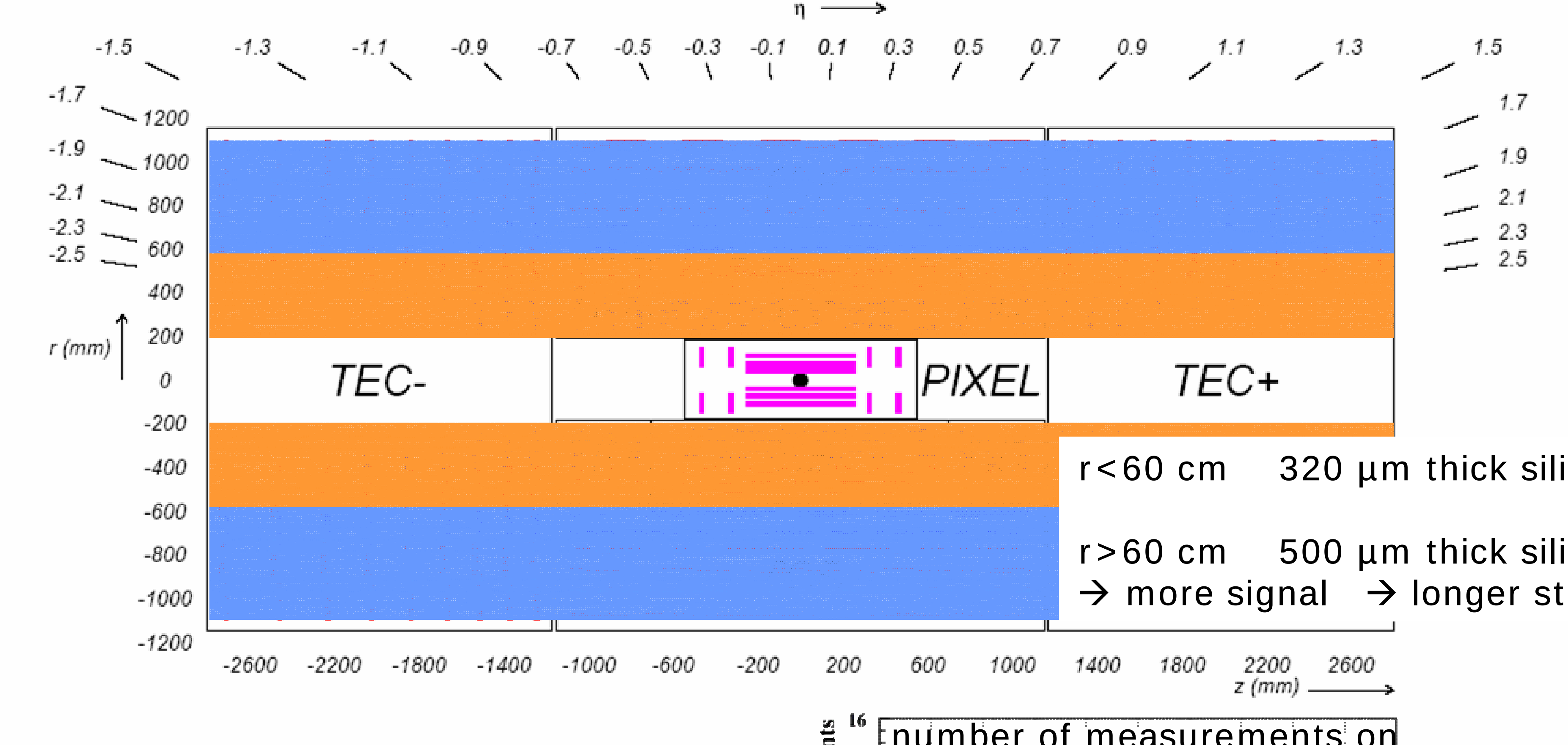
  by
  - operation at around –10°C
  - efficient cooling with small temperature gradients
  - thermal separation of sensors and electronics

→ **radiation hardness can be achieved**

CMS All Silicon Tracker



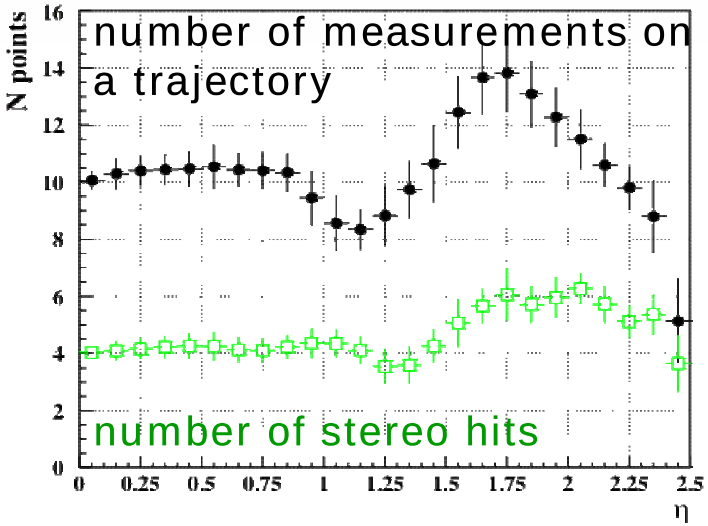
CMS All Silicon Tracker



r<60 cm   320 μm thick silicon

r>60 cm   500 μm thick silicon
→ more signal   → longer strips

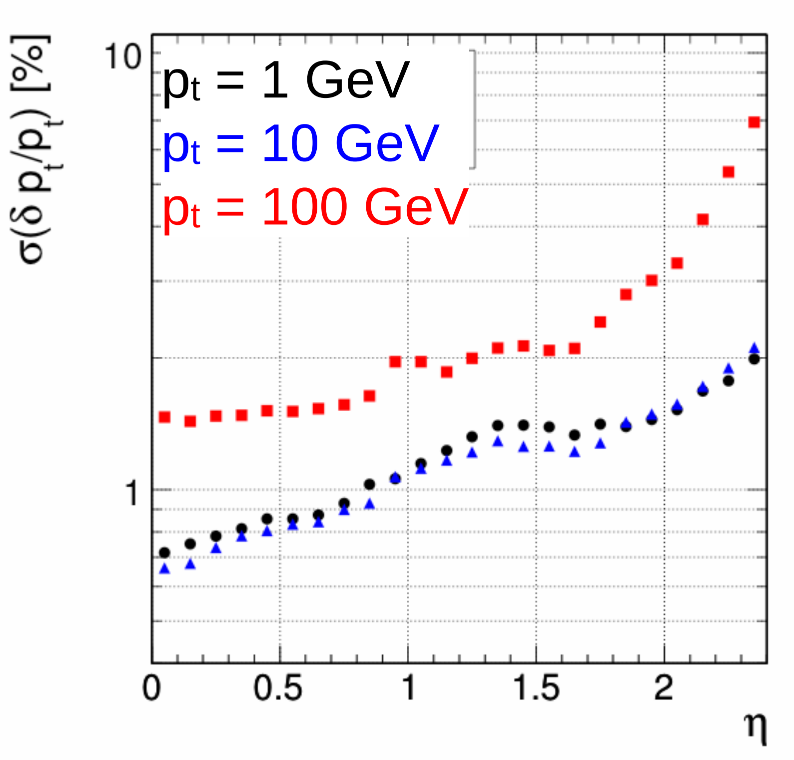
15,148 silicon strip detector modules
single sided or mounted
back-to-back with stereo angle of 100 mrad



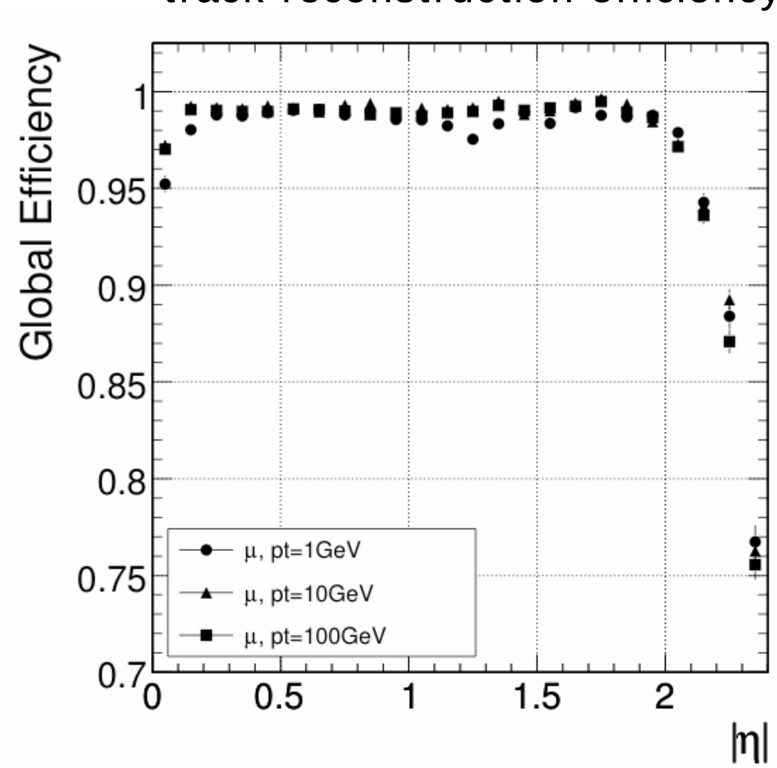
Expected Performance of CMS Tracker

for single muons

transverse momentum resolution



track reconstruction efficiency

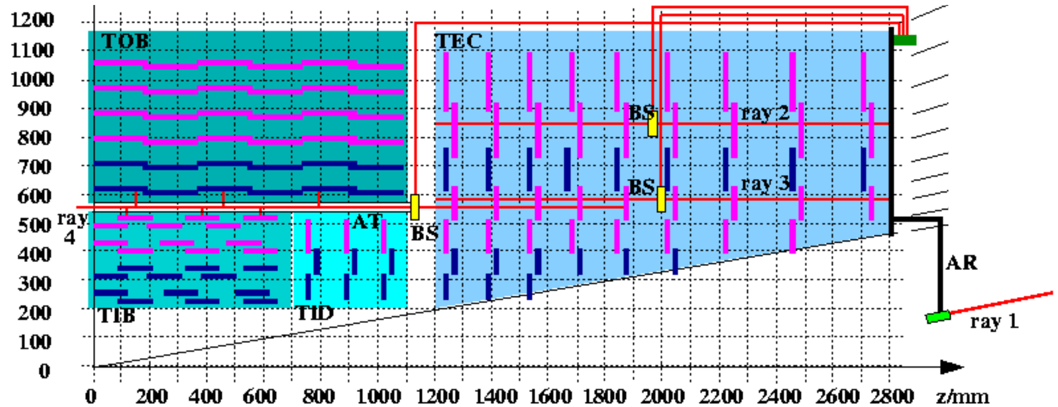


...requires a well aligned tracker

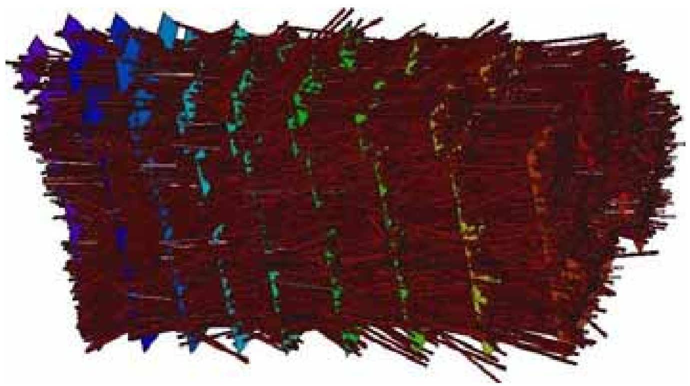
Alignment of the CMS tracker replies on three sources of information:

- survey measurements at all stages of detector assembly

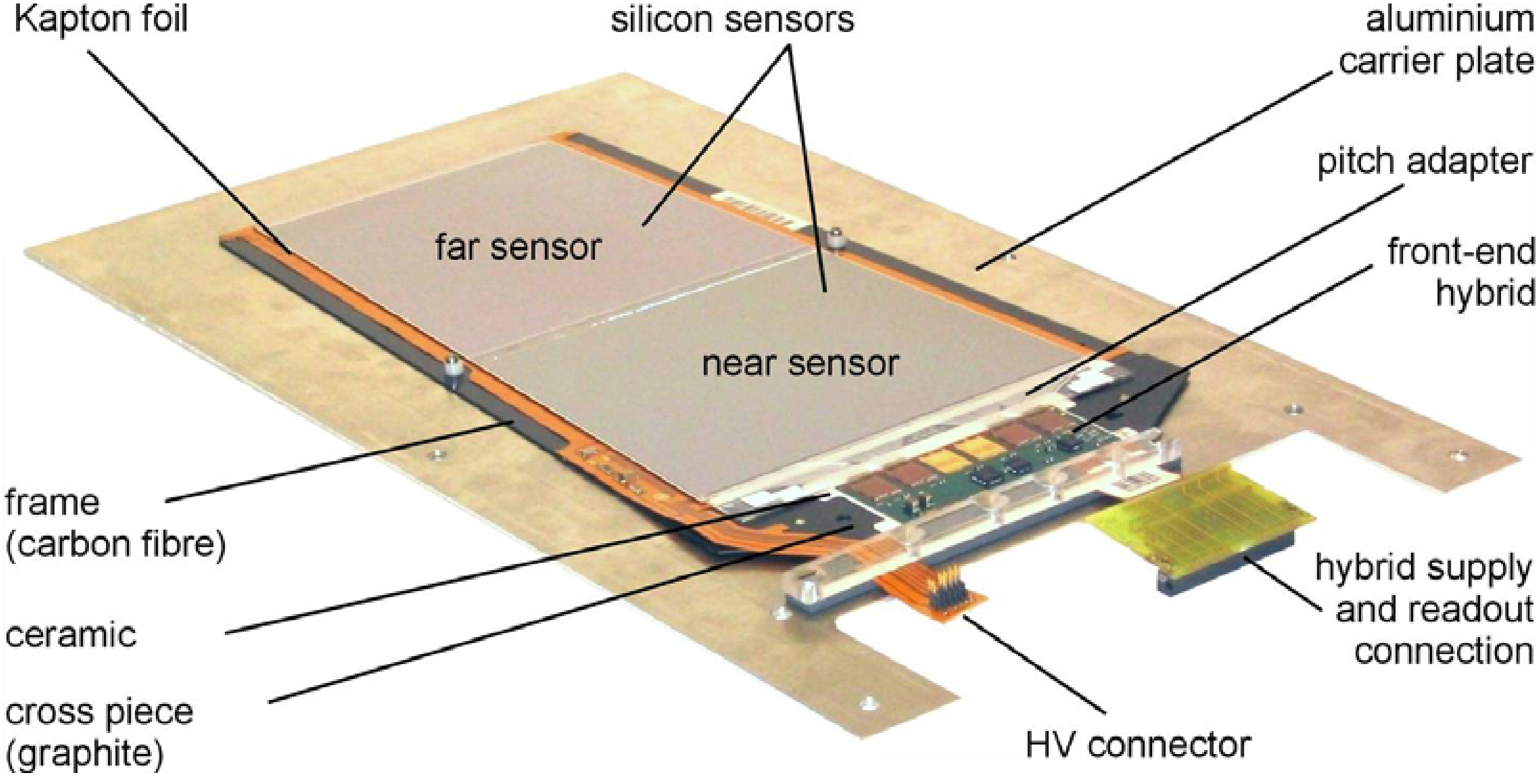
- laser alignment system for fast response position monitoring of large structures



- alignment with particle tracks will provide the best precision

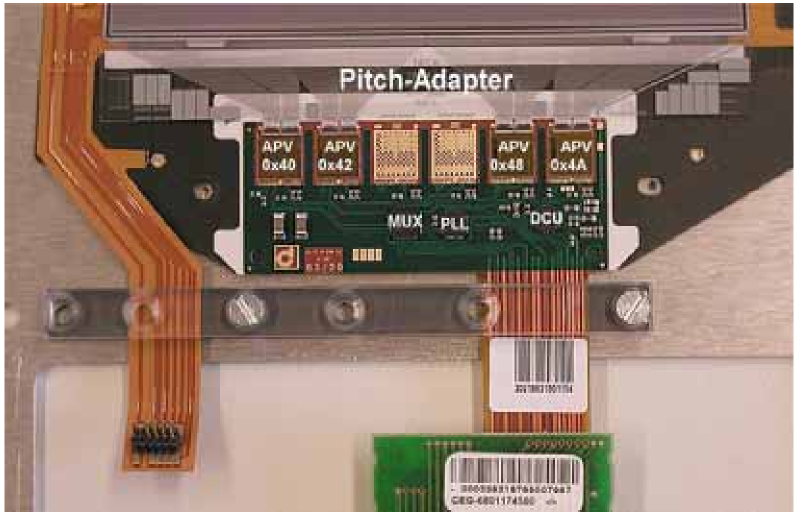


CMS Silicon Microstrip Detector Module



silicon sensors	512 or 768 strips with 80 to 200 µm pitch, p-in-n, AC coupled 320 µm or 500 µm thick, processed on 6” wafers
module frame	carbon fiber or graphite
bias voltage	supplied by Kapton cable
hybrid	4 layer copper/Kapton circuit with integrated cable on ceramic carrier

Hybrid and Read-out ASICs



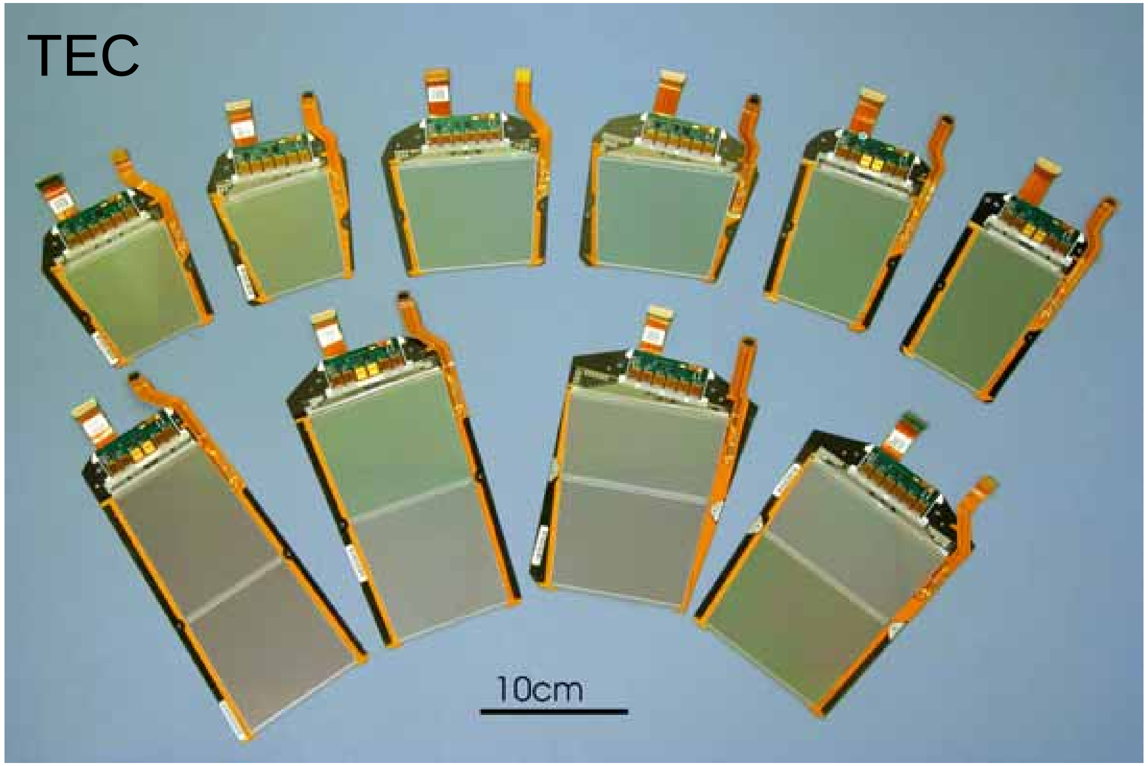
hybrid 4 layer copper/Kapton circuit with integrated cable on ceramic carrier
carries 4 or 6 read-out ASICs
and ASICs for multiplexing, clock/trigger and temperatures/voltages/currents

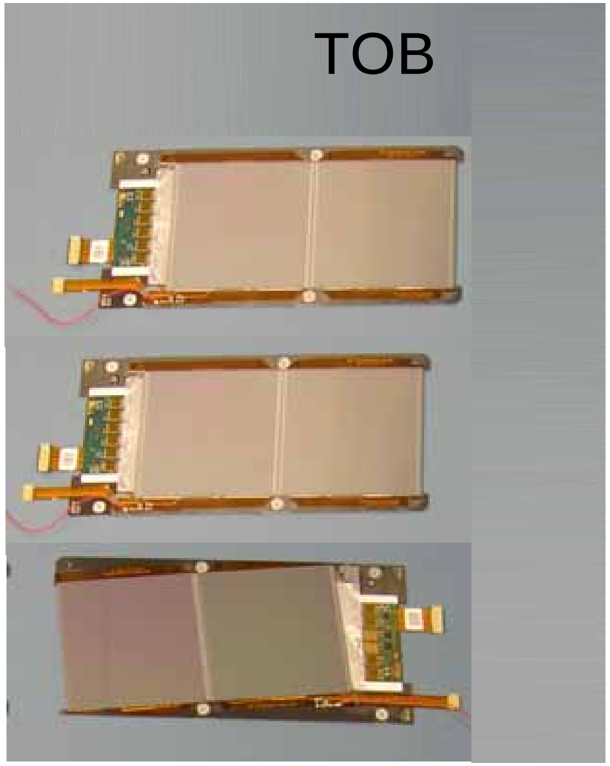
read-out ASIC **APV25**
128 channels of charge sensitive amplifier, 50 ns shaper (peak mode),
analogue pipeline (4 µs), deconvolution (50ns →25ns)

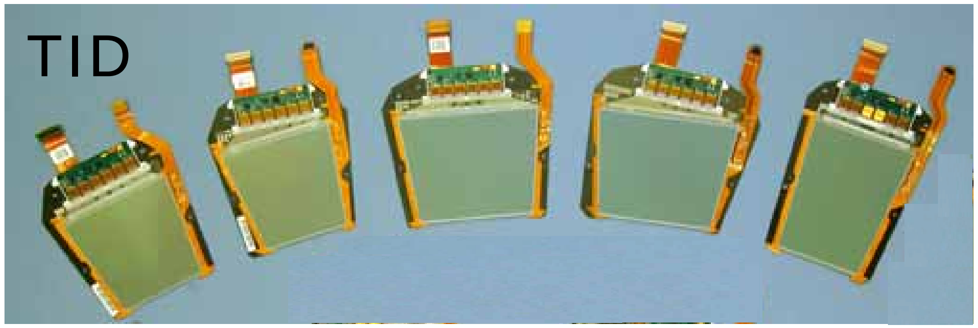
full **analogue** information is sent to ADCs in the service cavern

0.25µm IBM CMOS process → radiation tolerant
no significant change in operation up to 100 kGy

...29 different module types are needed



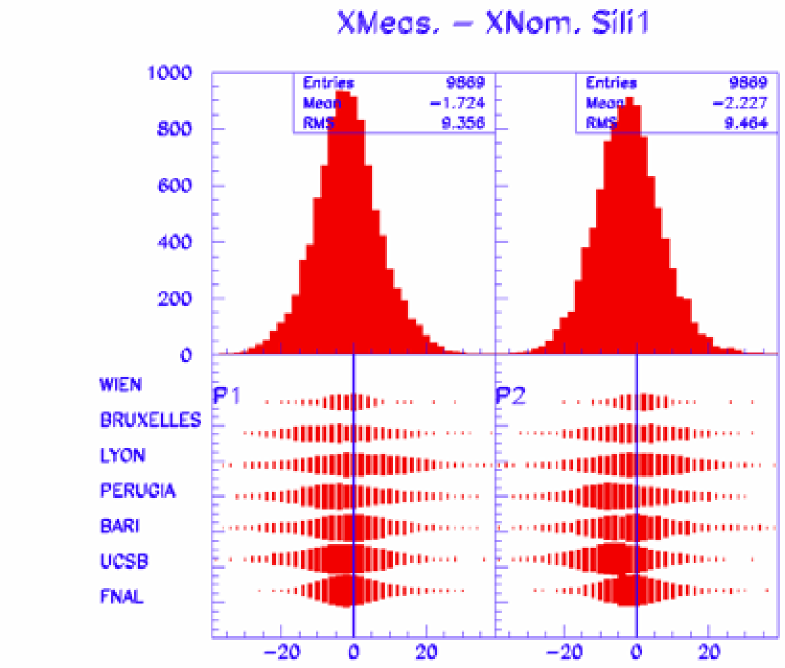




TIB

Module Production

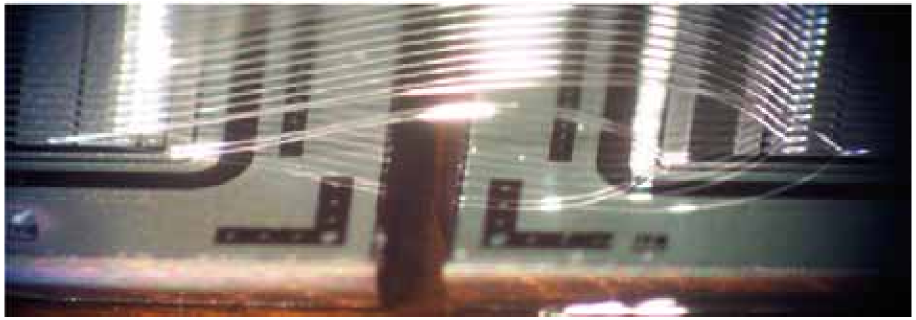
automated module assembly
and wire bonding



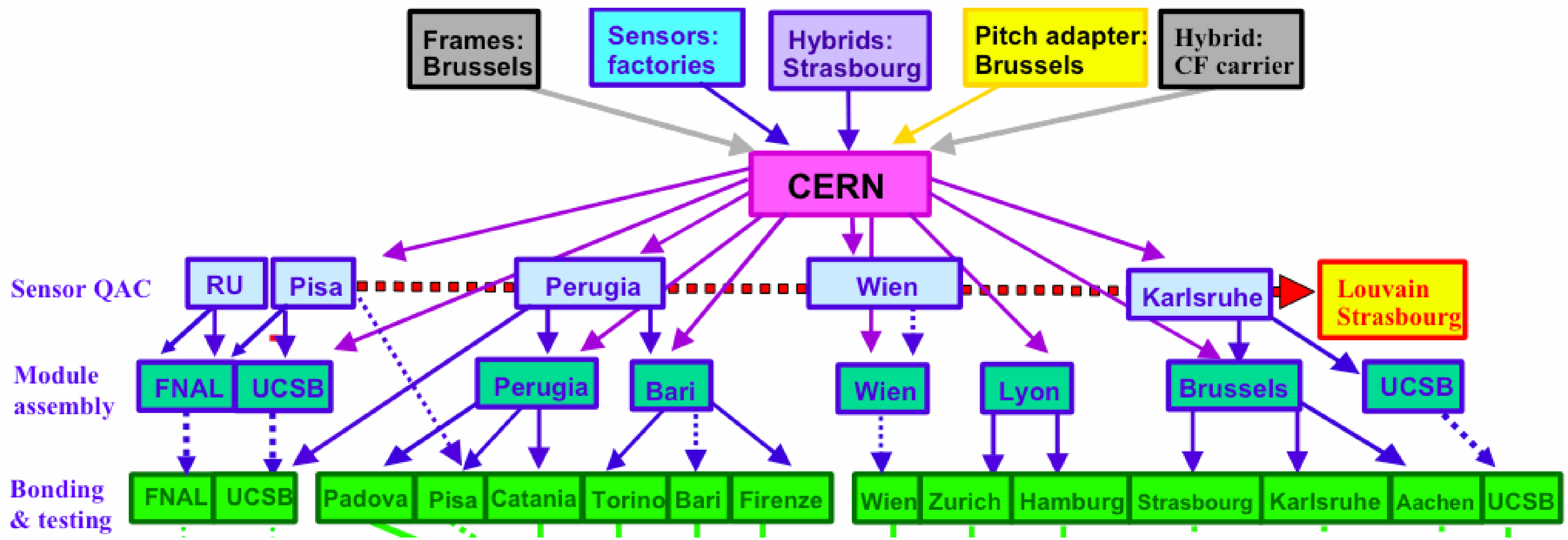
6 gantry (module assembly) centers
20 modules per gantry per day

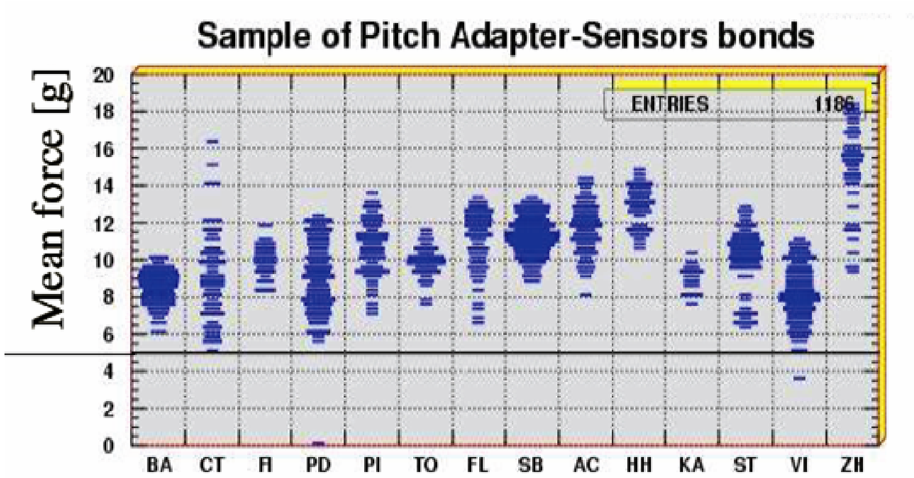
typical RMS of placement 10 μm

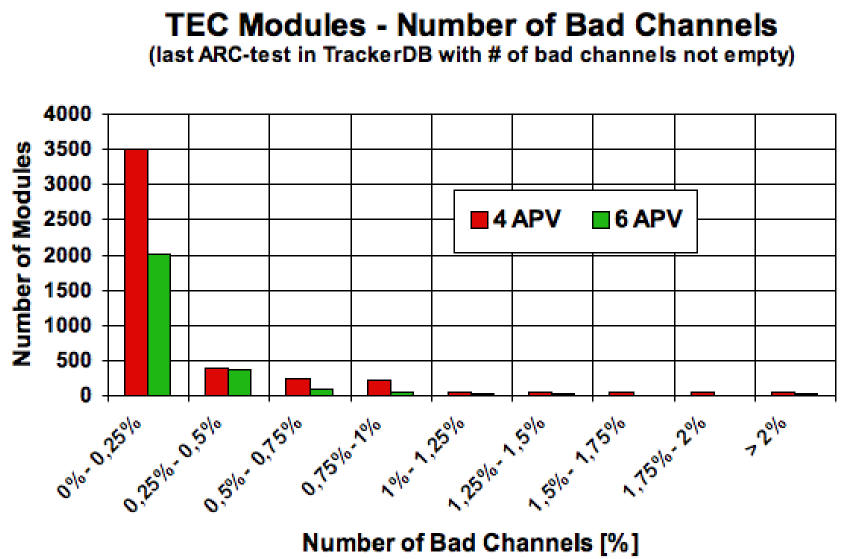
wire bonding rate ~ 1 Hz



Module Production … an Industry of its own





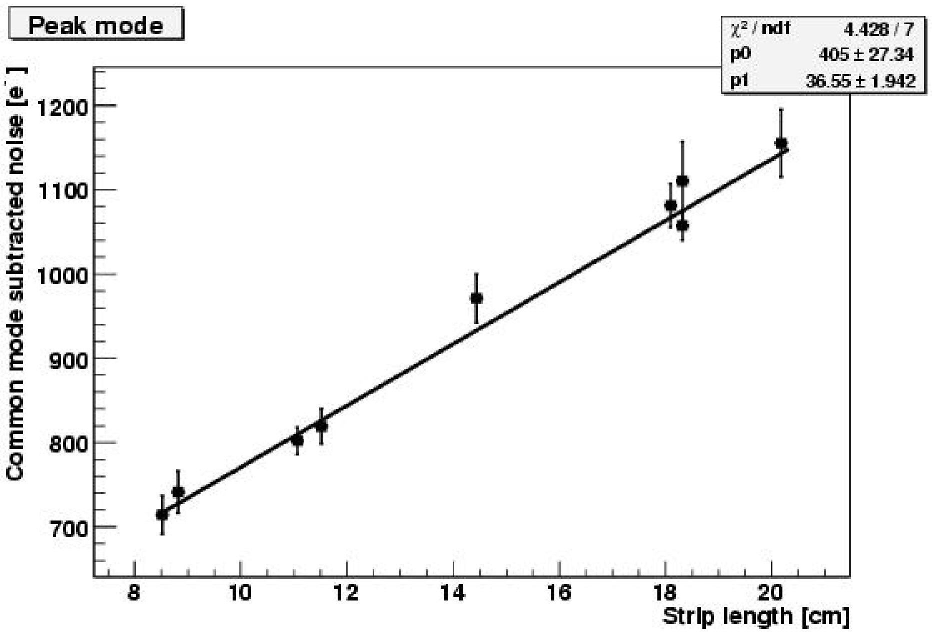


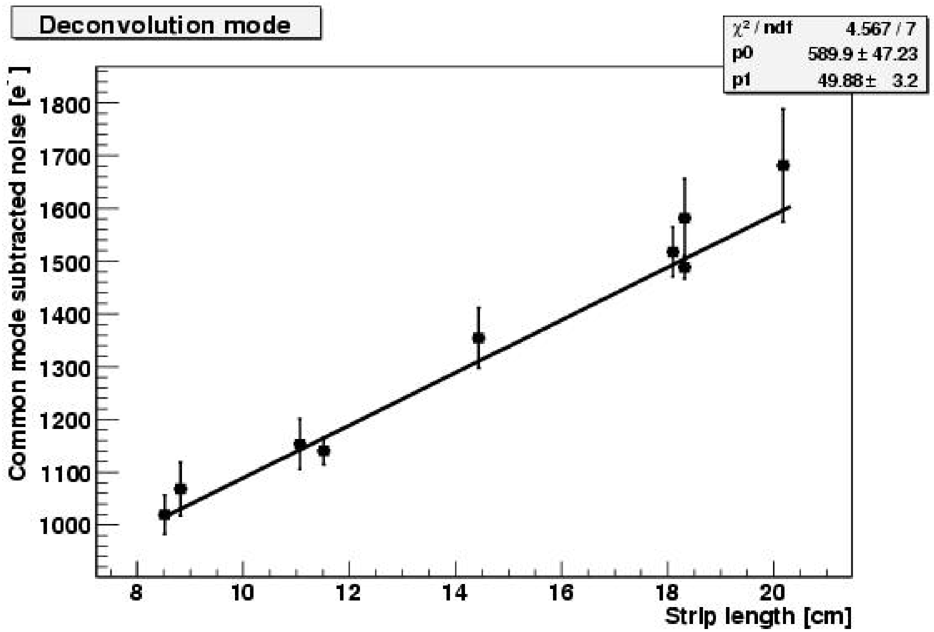
Module Performance: Testbeam Data

Module type	Pitch [μm]	Strip length [mm]	S/N Peak mode	S/N Dec. mode	ENC [e^-] Peak mode	ENC [e^-] Dec. mode
IB1	80	116.9	25.8 ± 1.3	18.3 ± 0.5	931 ± 48	1315 ± 37
IB2	120	116.9	29.5 ± 1.4	20.3 ± 0.6	815 ± 37	1182 ± 31
OB1	122	183.2	36	25	1110 ± 47	1581 ± 75
OB2	183	183.2	38	27	1057 ± 17	1488 ± 22
W1TEC	81-112	85.2	33.1 ± 0.7	21.9 ± 0.6	714 ± 23	1019 ± 37
W2	113-143	88.2	31.7 ± 0.5	20.7 ± 0.4	741 ± 25	1068 ± 51
W3	123-158	110.7	29.2 ± 0.6	20.0 ± 0.4	802 ± 16	1153 ± 48
W4	113-139	115.2	28.6 ± 0.5	19.2 ± 0.3	819 ± 21	1140 ± 26
W5	126-156	144.4	42.2 ± 1.1	24.1 ± 1.1	971 ± 29	1354 ± 57
W6	163-205	181.0	37.8 ± 0.6	23.0 ± 0.4	1081 ± 26	1517 ± 47
W7	140-172	201.8	35.5 ± 1.0	20.3 ± 1.1	1155 ± 40	1681 ± 107

peak mode: $\tau = 50$ ns

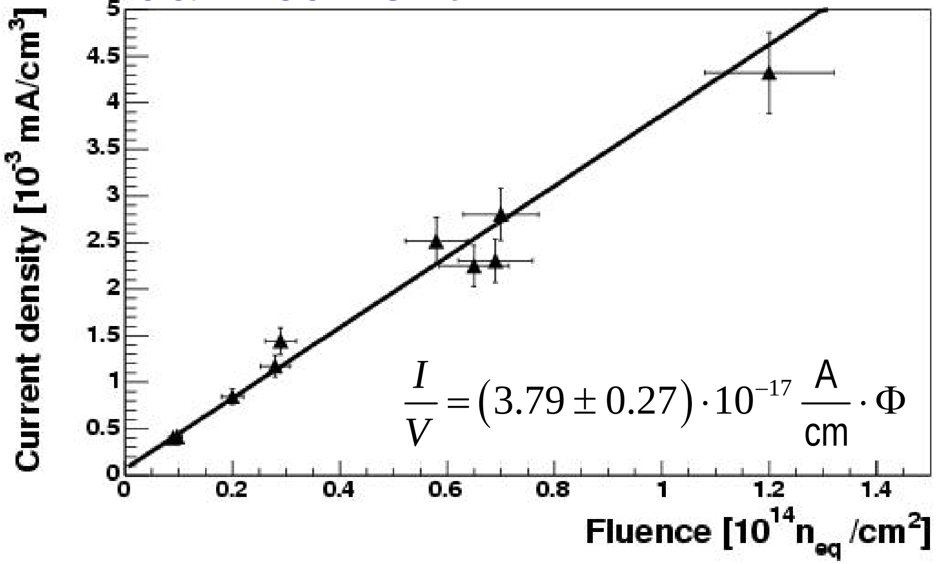
deconv. mode: $\tau = 25$ ns



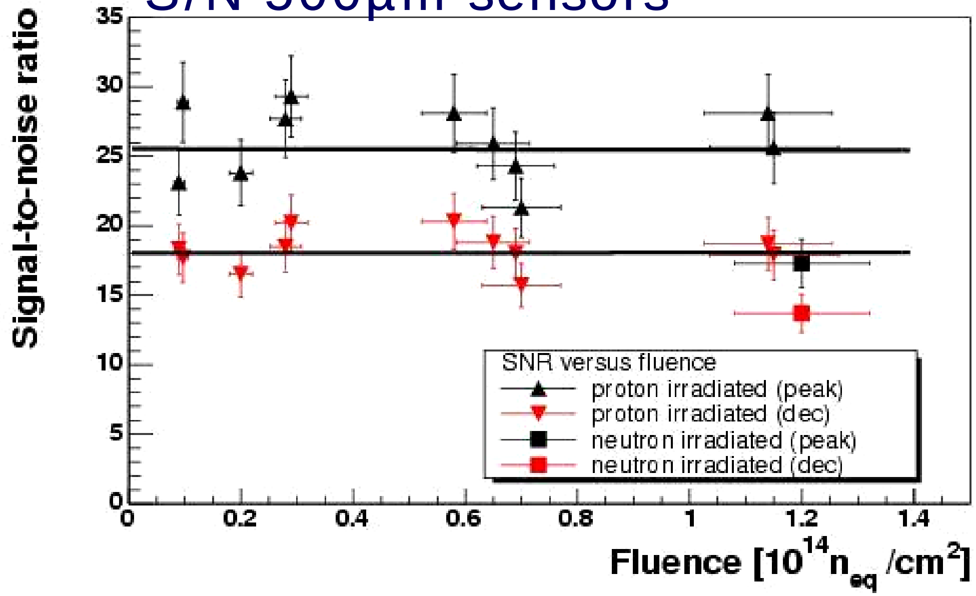


Module Performance after Irradiation

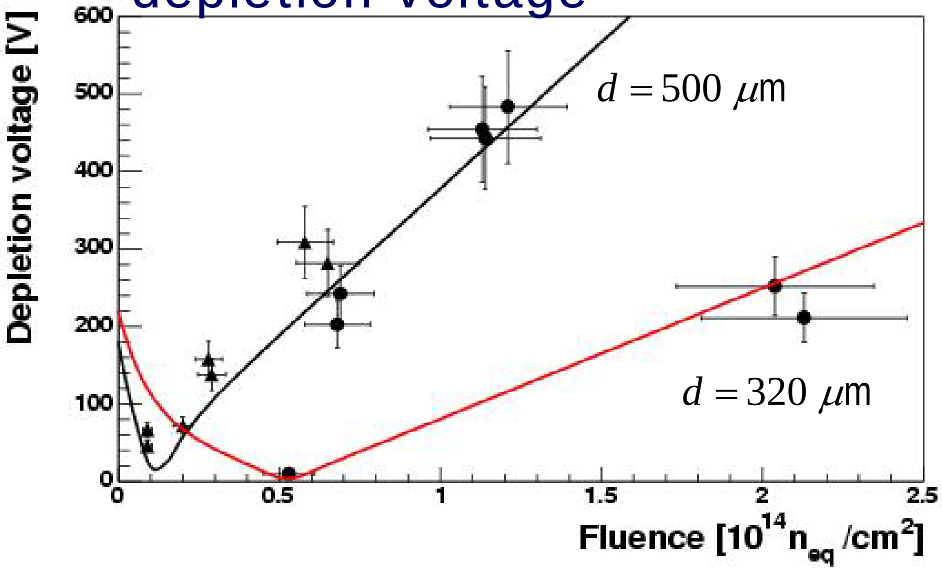
dark current



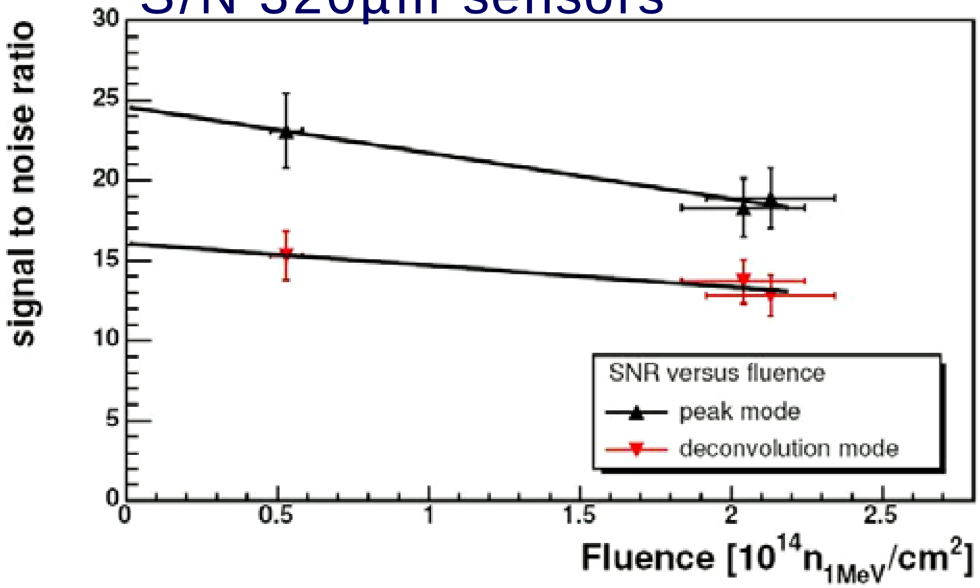
S/N 500µm sensors



depletion voltage



S/N 320µm sensors

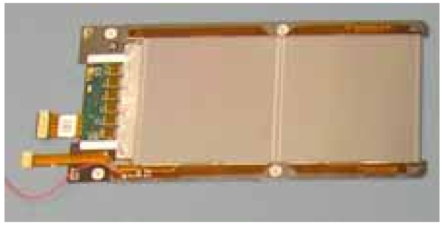


Integration of Modules into Subsystems

modules

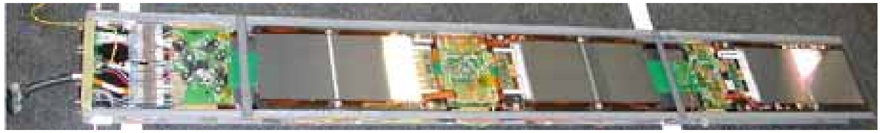
2724+816

TIB



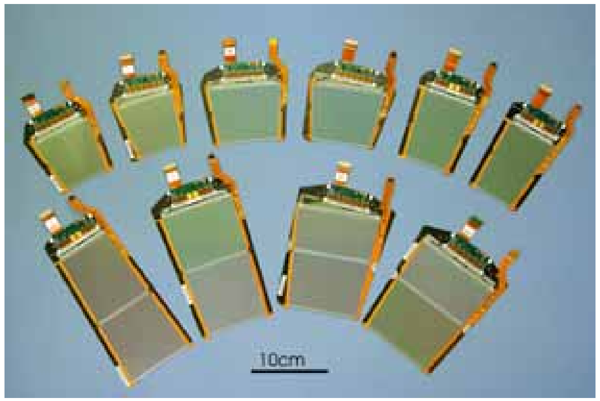
5208

rod



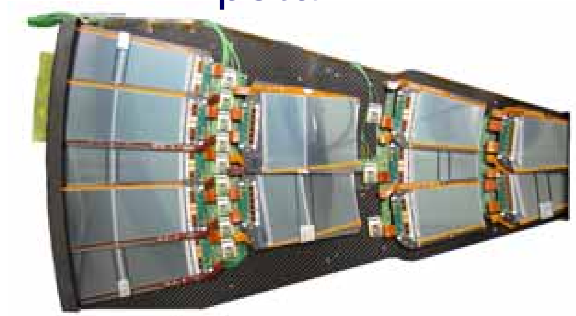
688

TOB



6400

petal

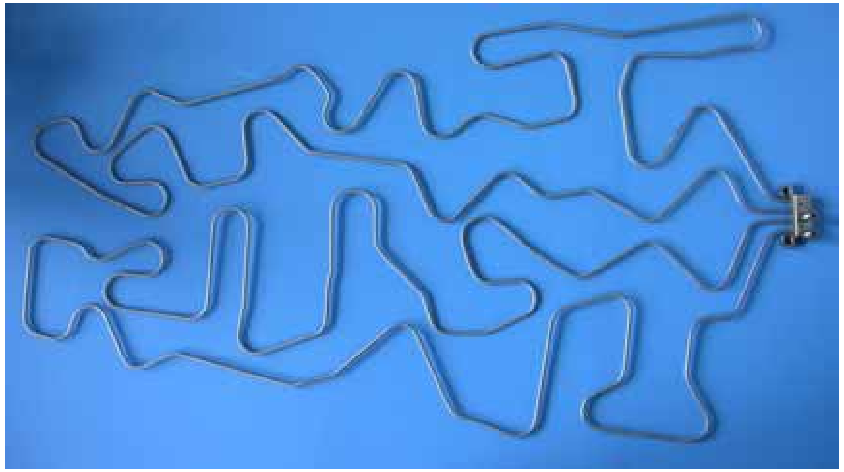


288

TEC (x2)

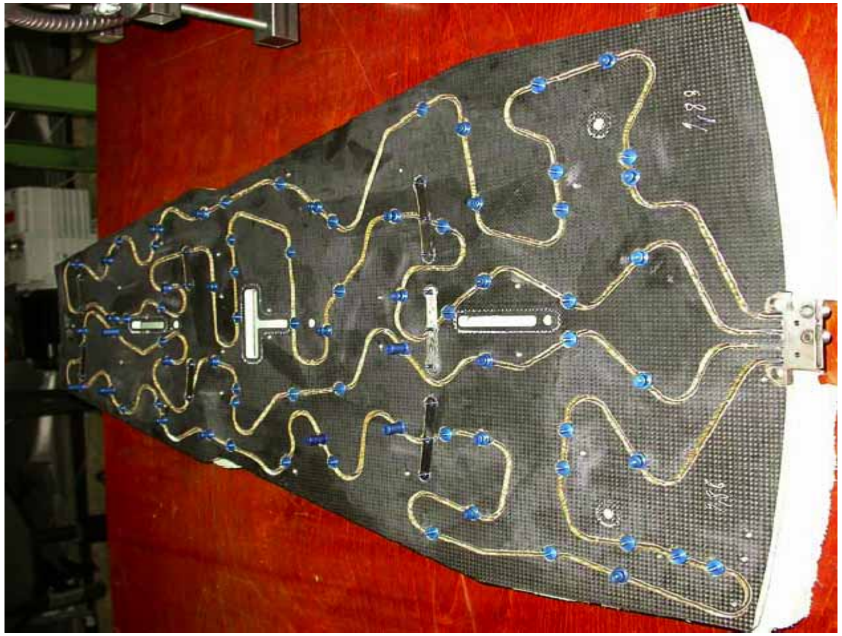
Example: TEC Petals

7 m titanium cooling pipe



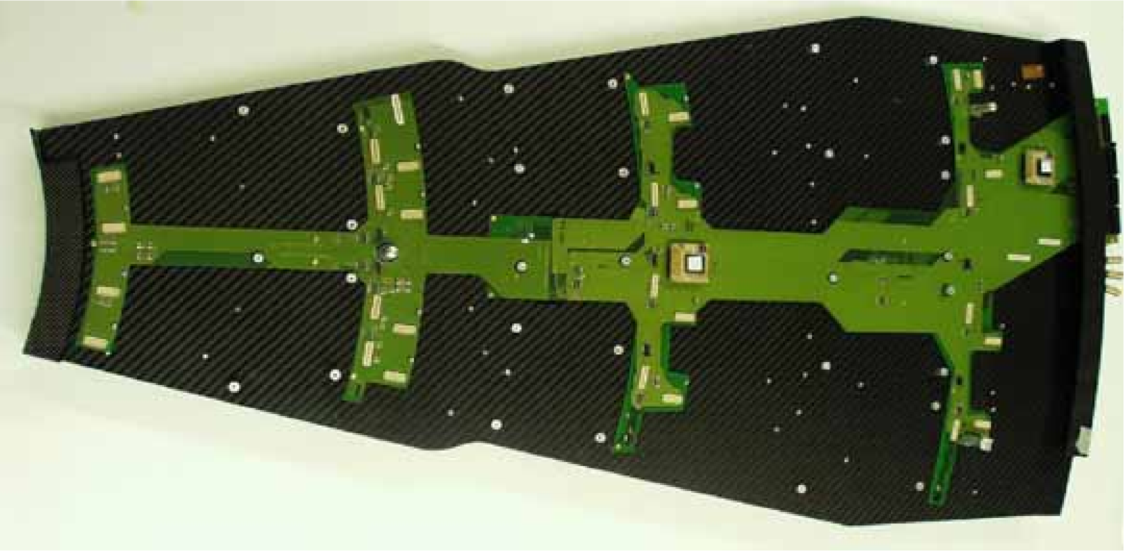
carbon fiber / honey comb plate

accommodates cooling pipe and module mounting inserts

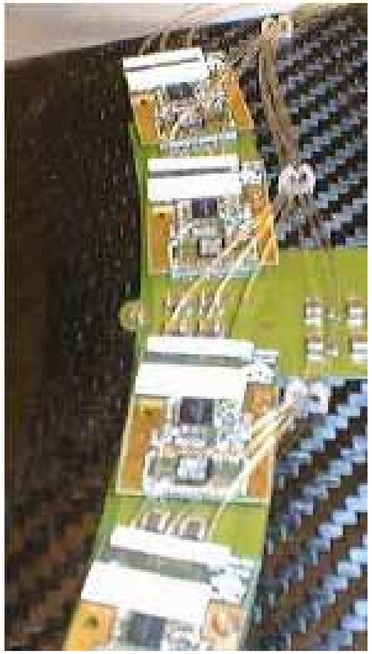


Example: TEC Petals

inter connect board
for distribution of
- low voltages
- high voltage
- clock
- commands
- triggers
- slow control information



opto hybrids
for analogue
and digital
data tansmission



Example: TEC Petals

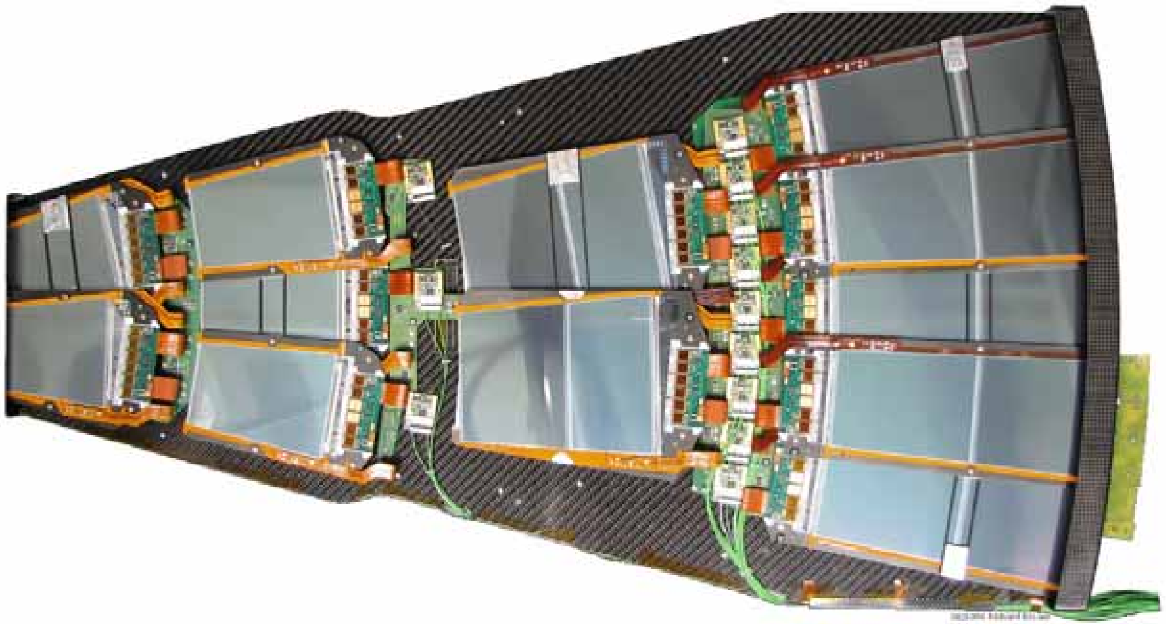
up to 28 modules in
up to 7 rings

radial overlap between
rings on both sides

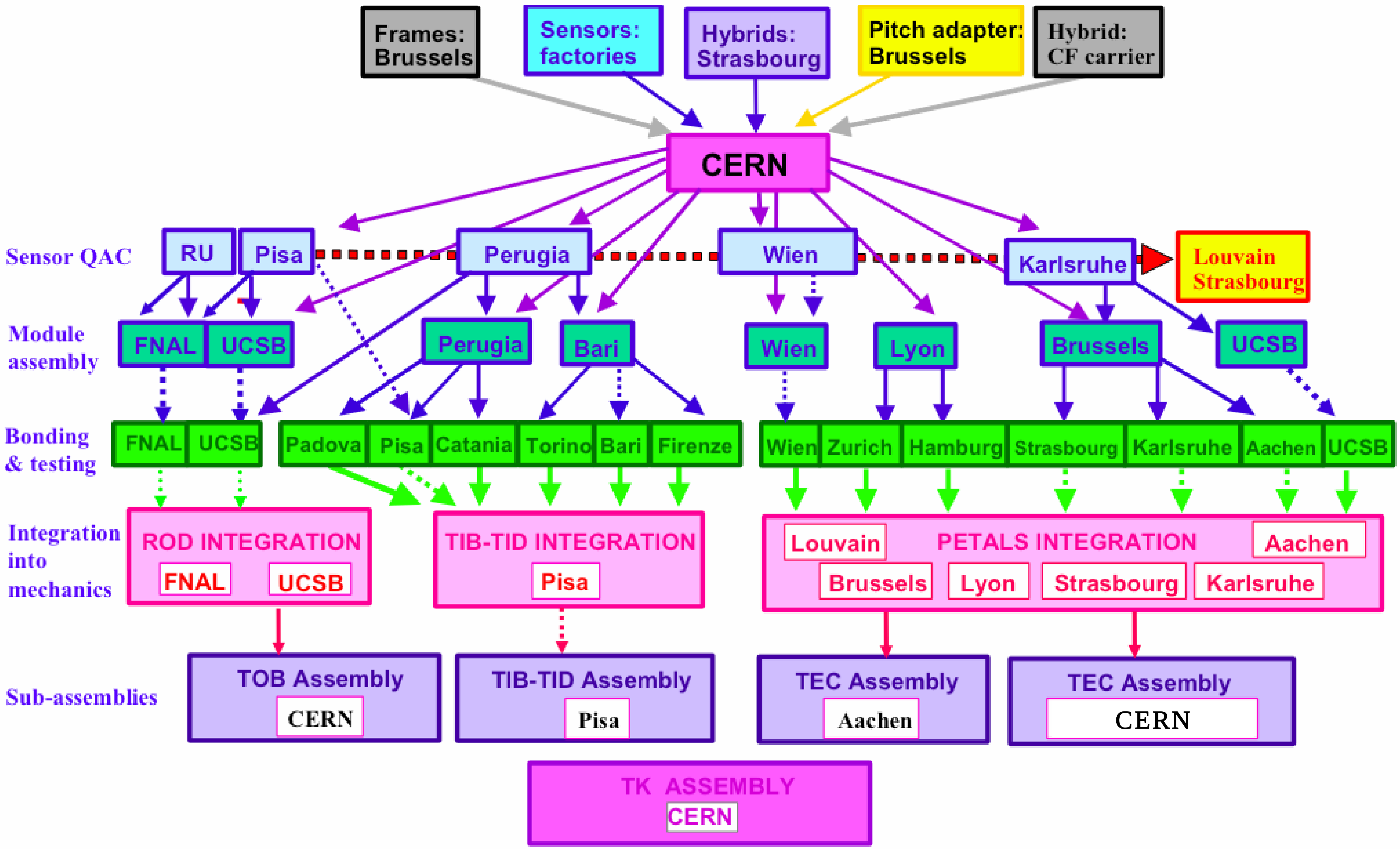
azimuthal overlap between
neighboring modules and
petals

petals were assembled and
tested by 5 centers

2 petals / week / line



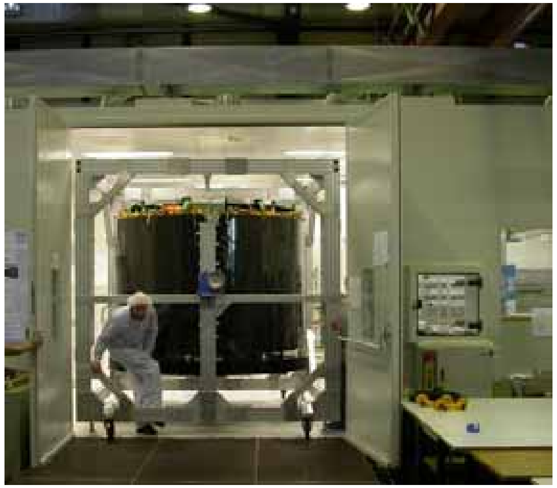
CMS Tracker Logistics



TEC Integration: what is needed

144 petals

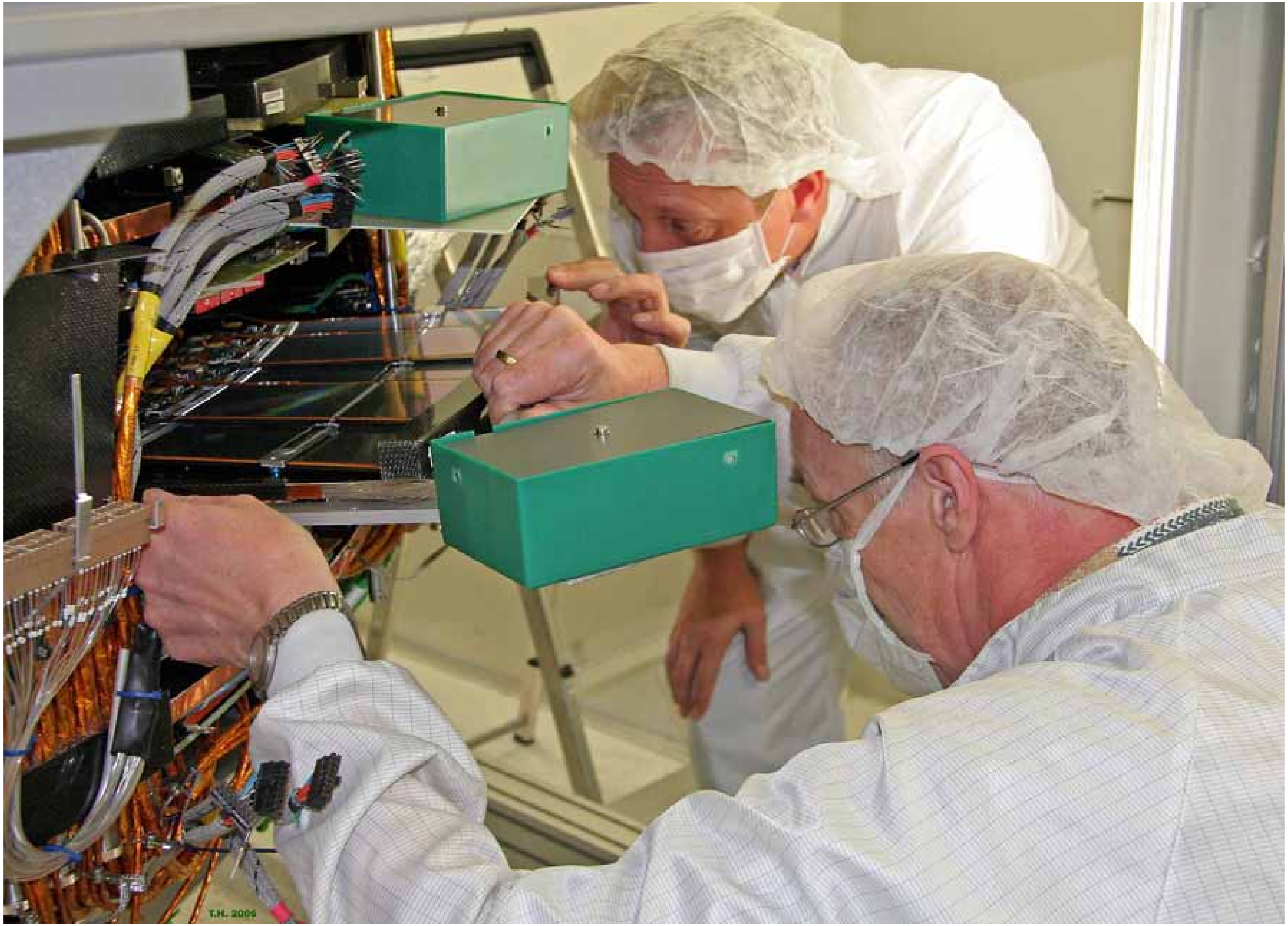
a large clean room



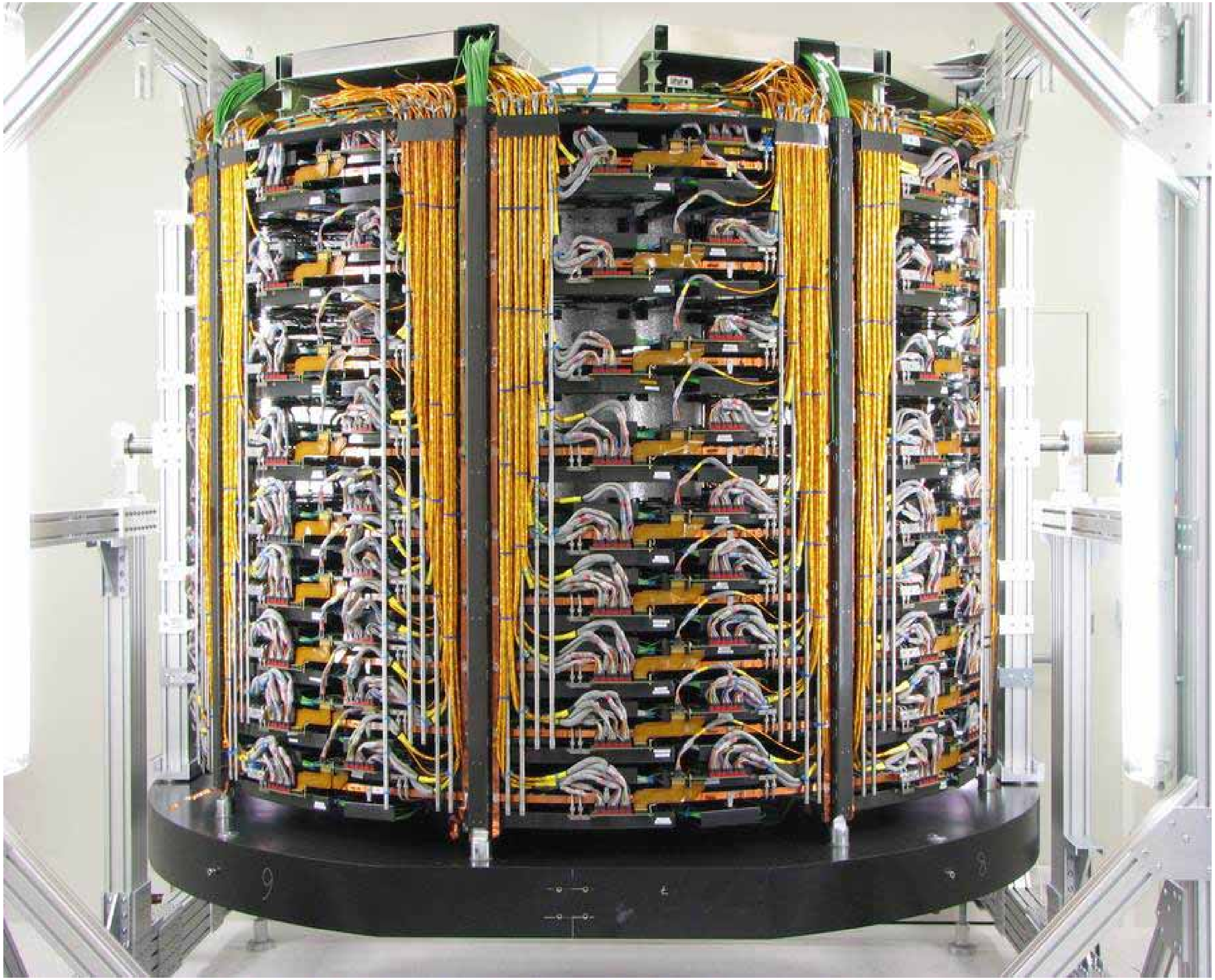
an empty TEC

and a huge test system: read-out for 400 modules, 2.5 km final cables, cooling ...

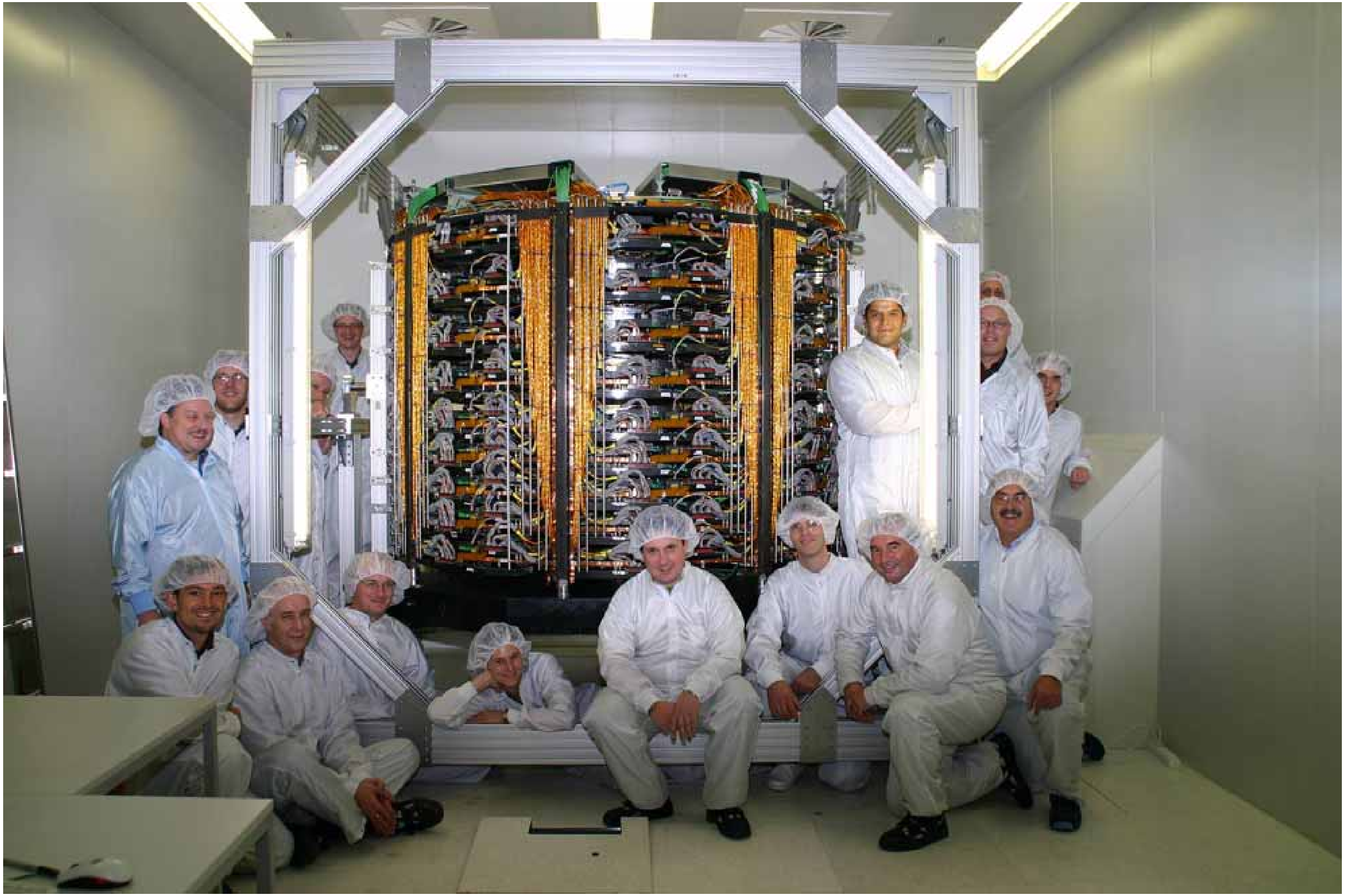
...and skilled people



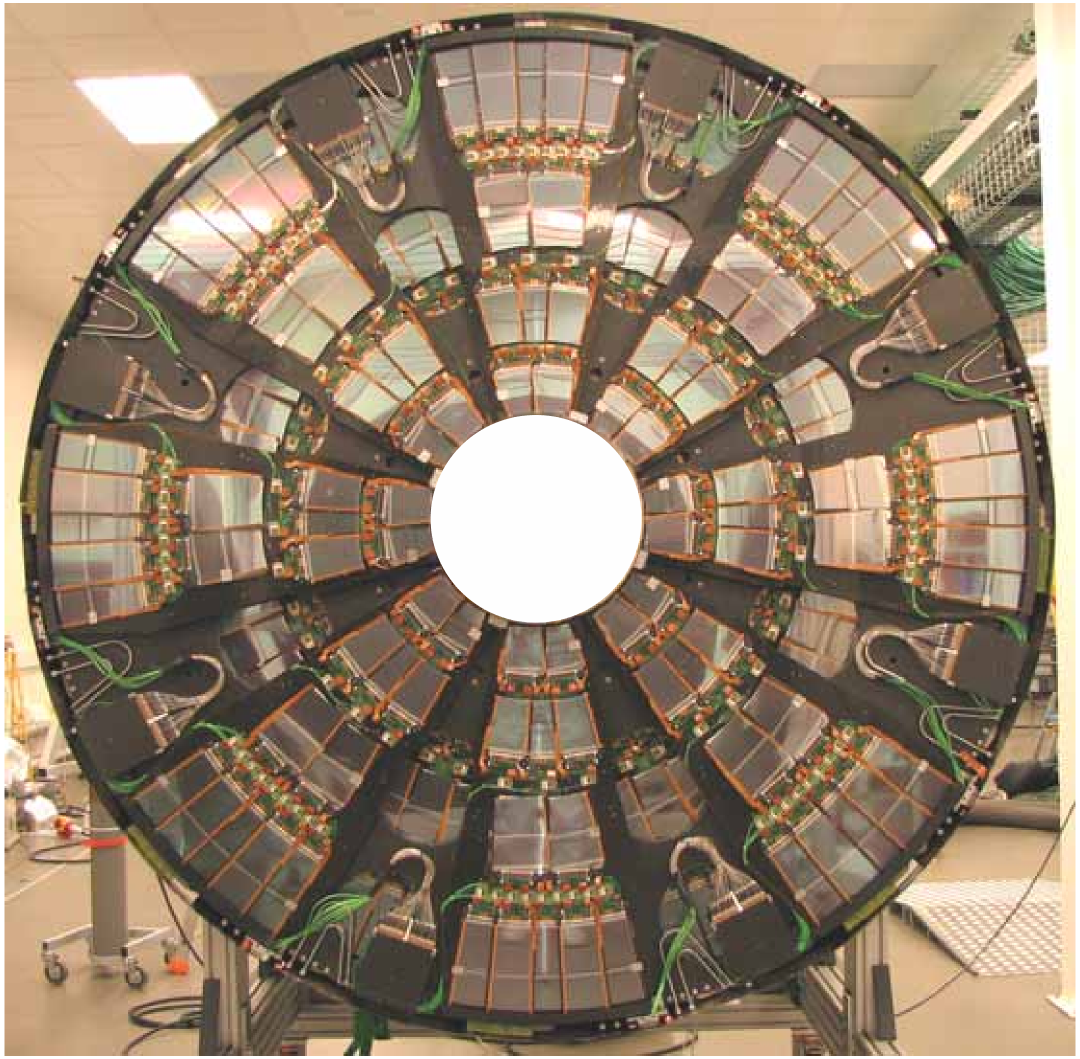
Finished TEC+ in Aachen

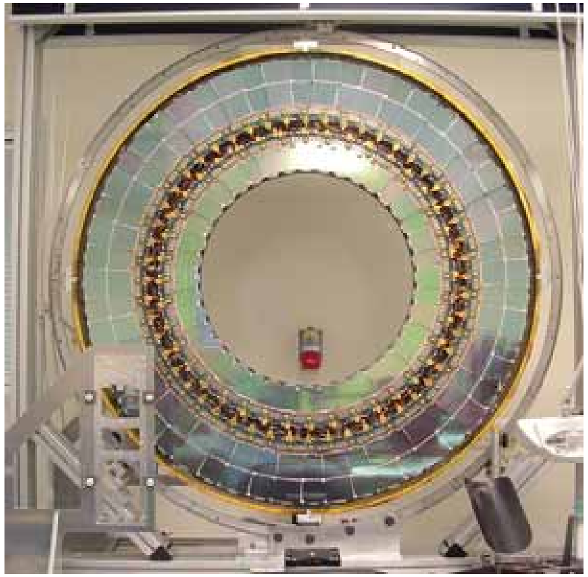


Finished TEC+ in Aachen



...and at CERN



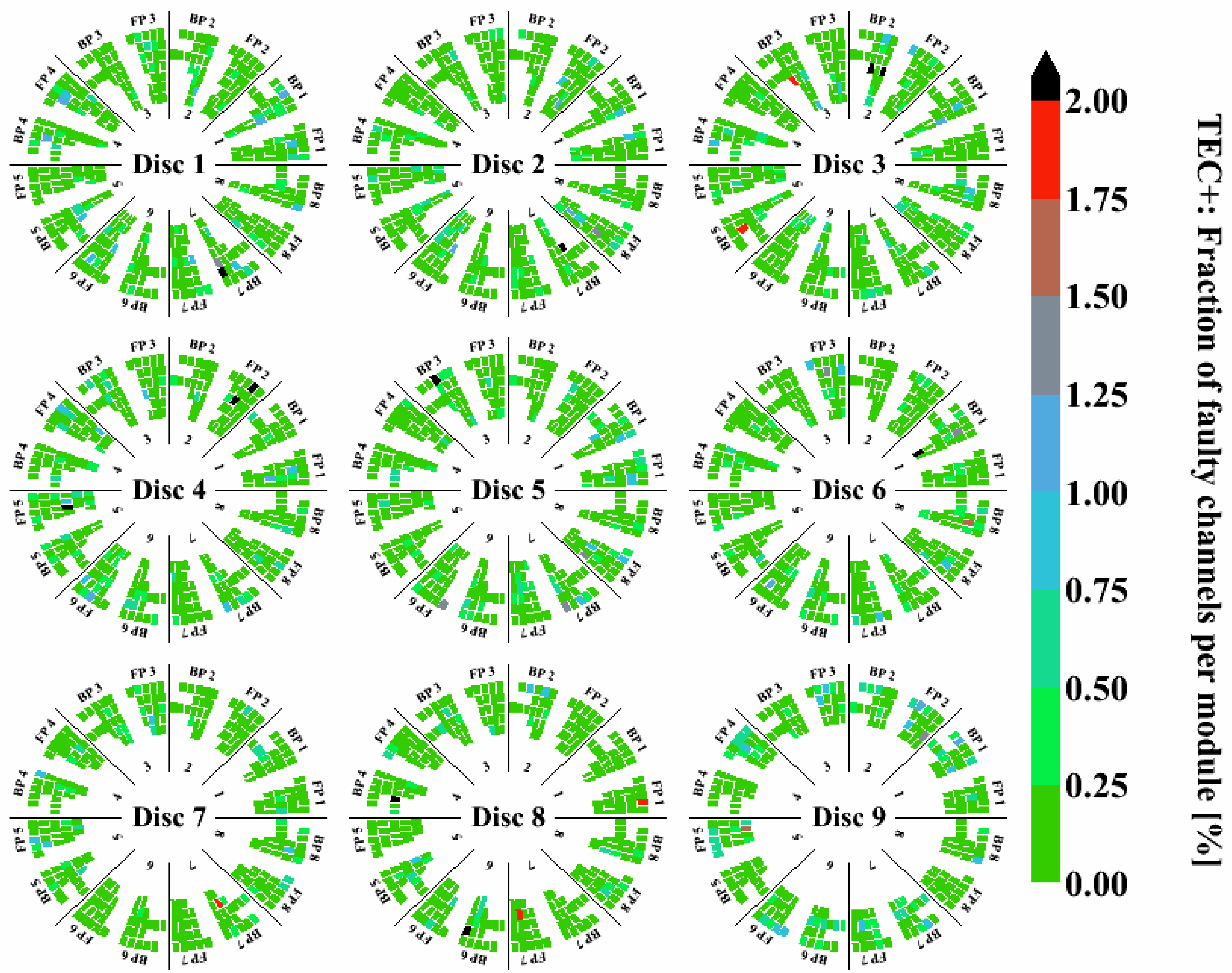


modular structure:
petals as self-contained, pre-tested units

“monolithic” structure:
modules mounted onto disks

Performance of integrated Structures

fraction of faulty channels per module for one complete end cap: total 0.3%

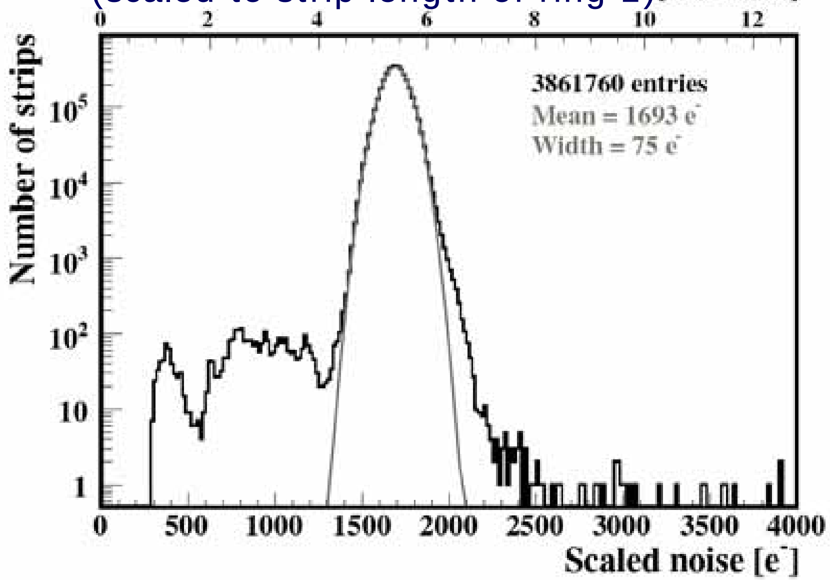


Performance of integrated Structures

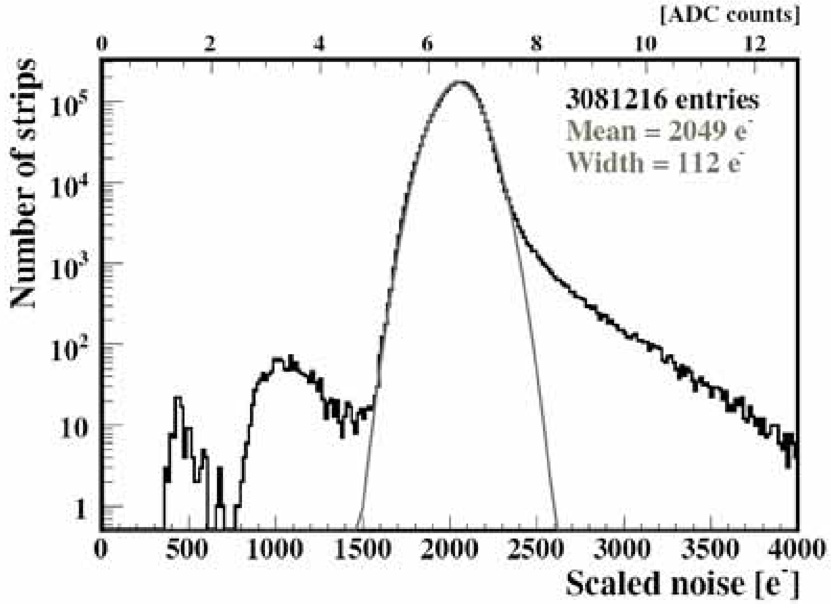
noise of (almost) all channels in the CMS tracker (25 ns mode)

TEC

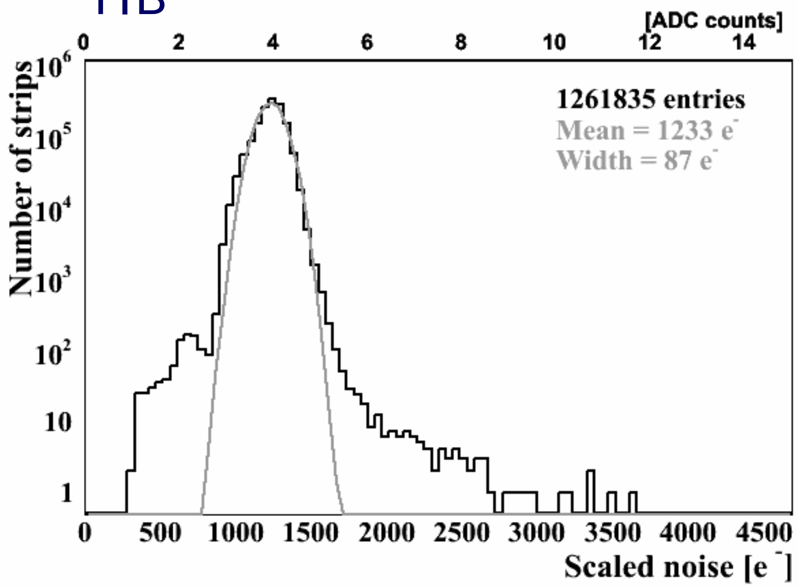
(scaled to strip length of ring 1)



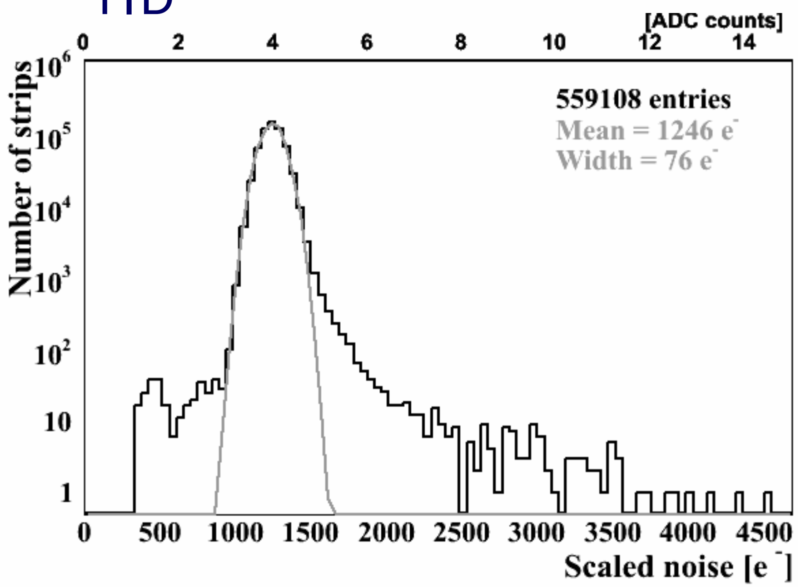
TOB



TIB

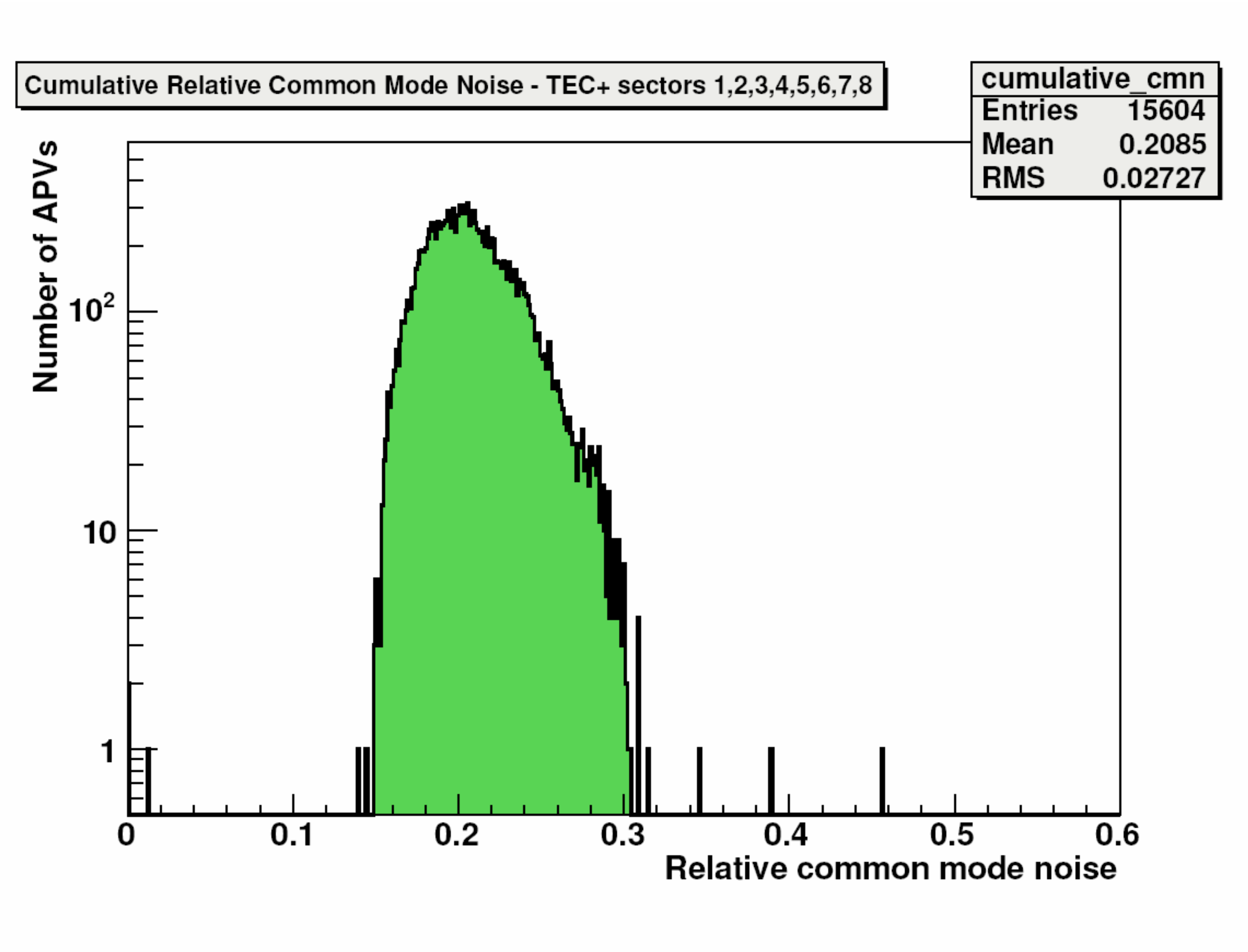


TID



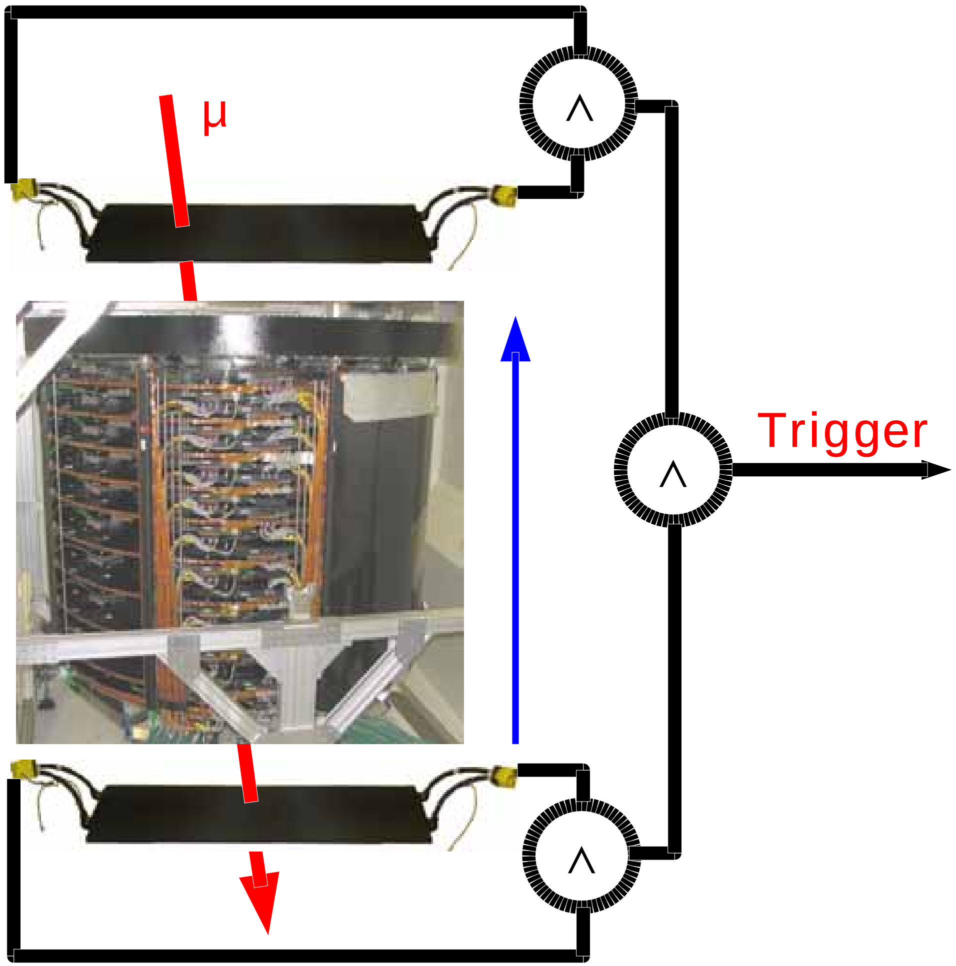
Performance of integrated Structures

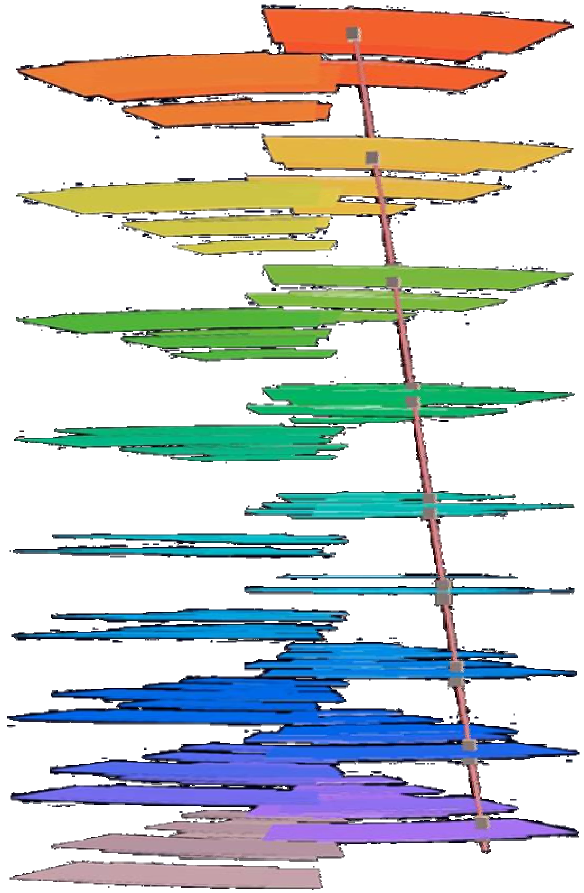
common mode noise relative to intrinsic noise: less than 30%



Performance of integrated Structures

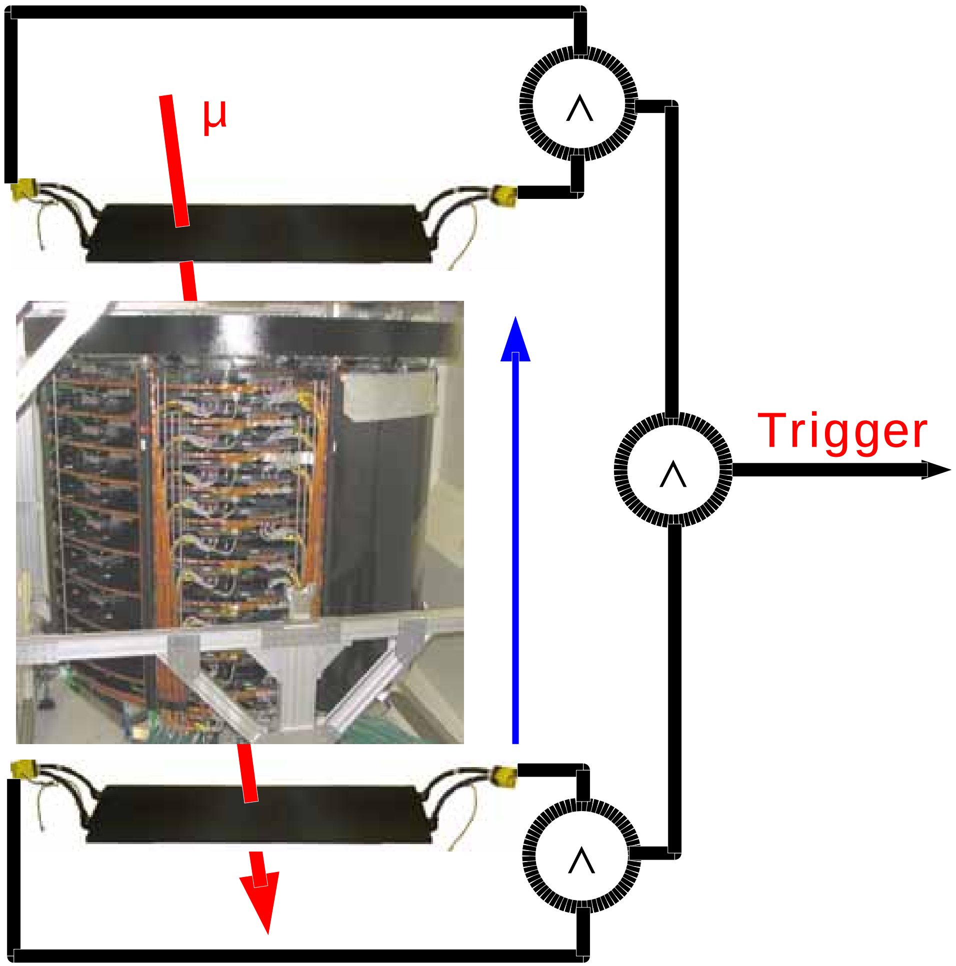
cosmic muons recorded in one end cap

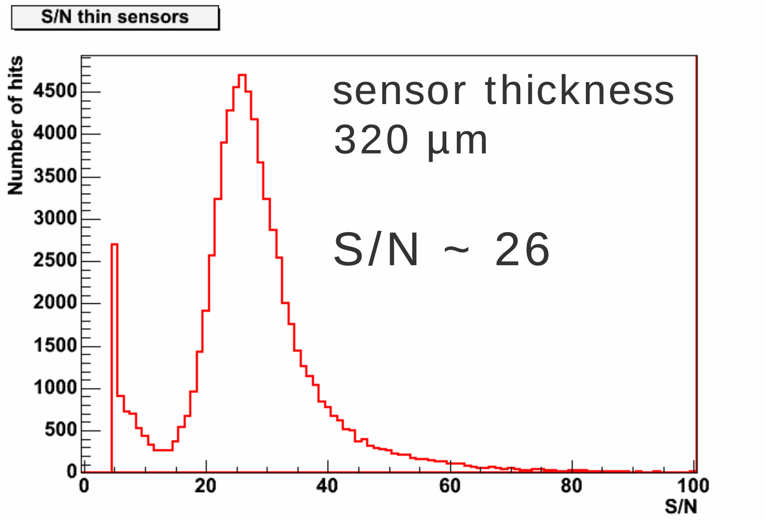


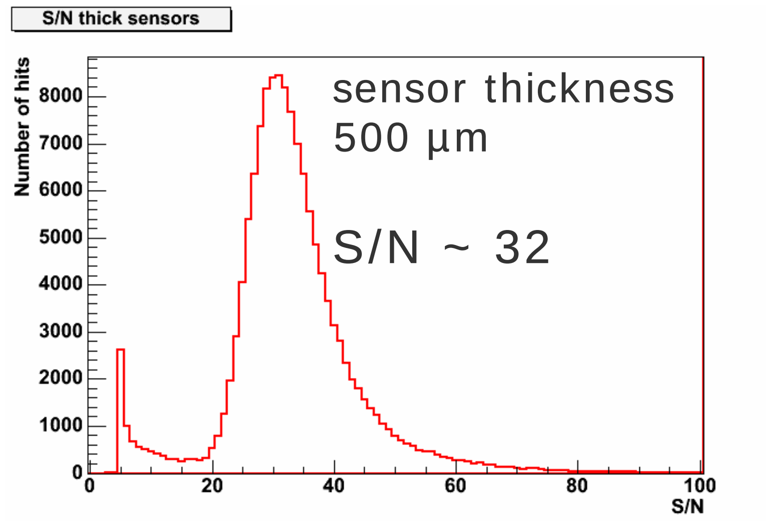


Performance of integrated Structures

cosmic muons recorded in one end cap (50 ns shaping time)





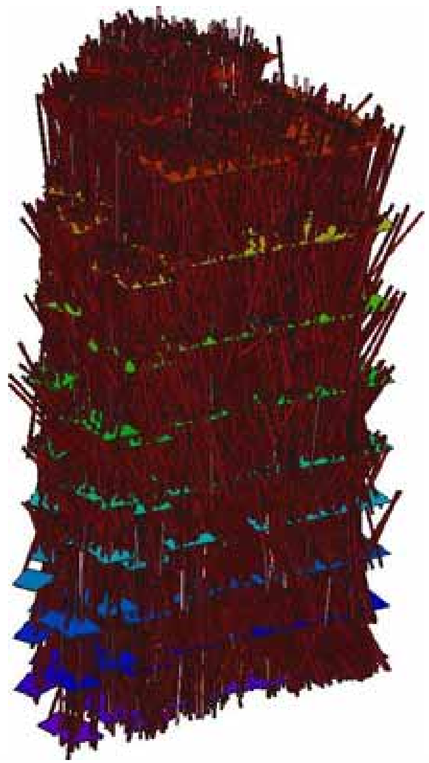


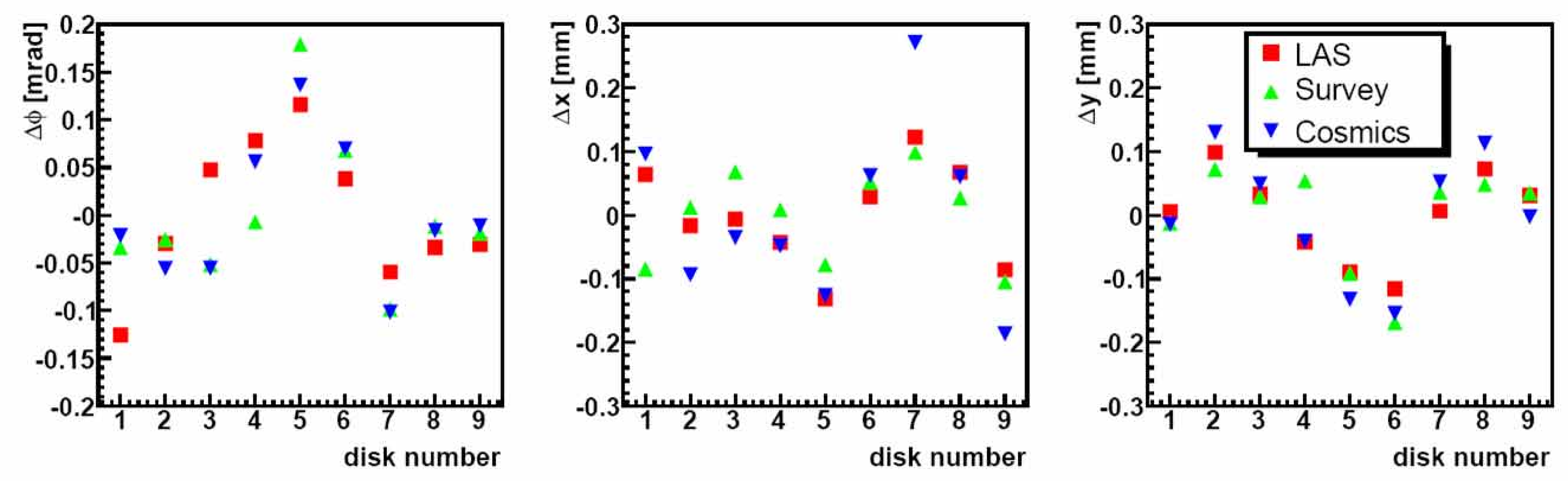
caveats: muons are not exactly MIPs
rough timing adjustment

Tracker Alignment

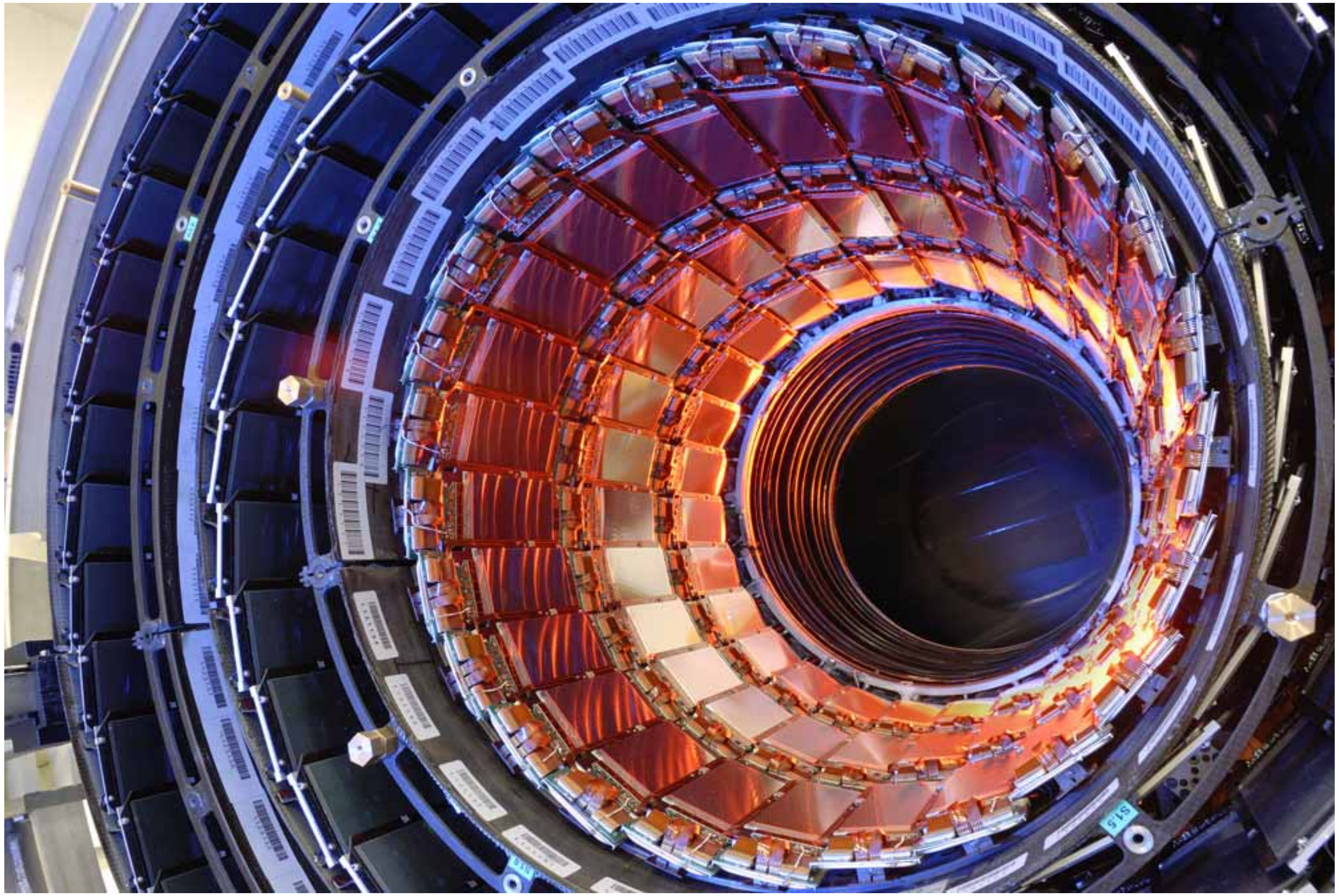
cosmic muon tracks in TEC+ can be used to align this part of the CMS tracker before installation into the tracker

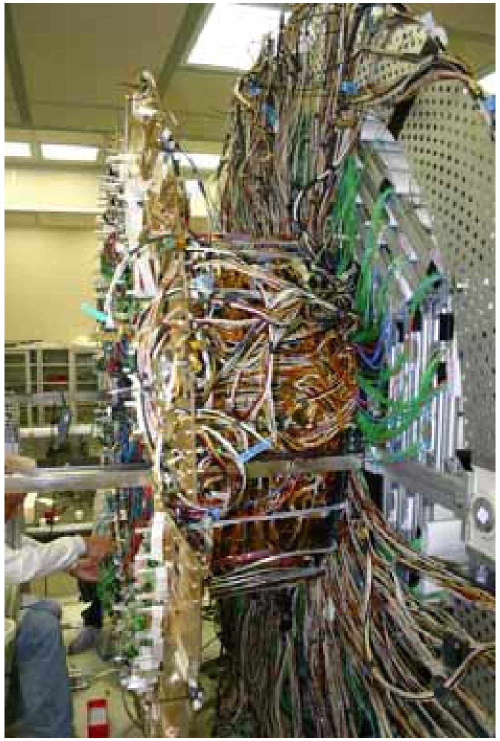
comparison to
survey measurements and
laser alignment system



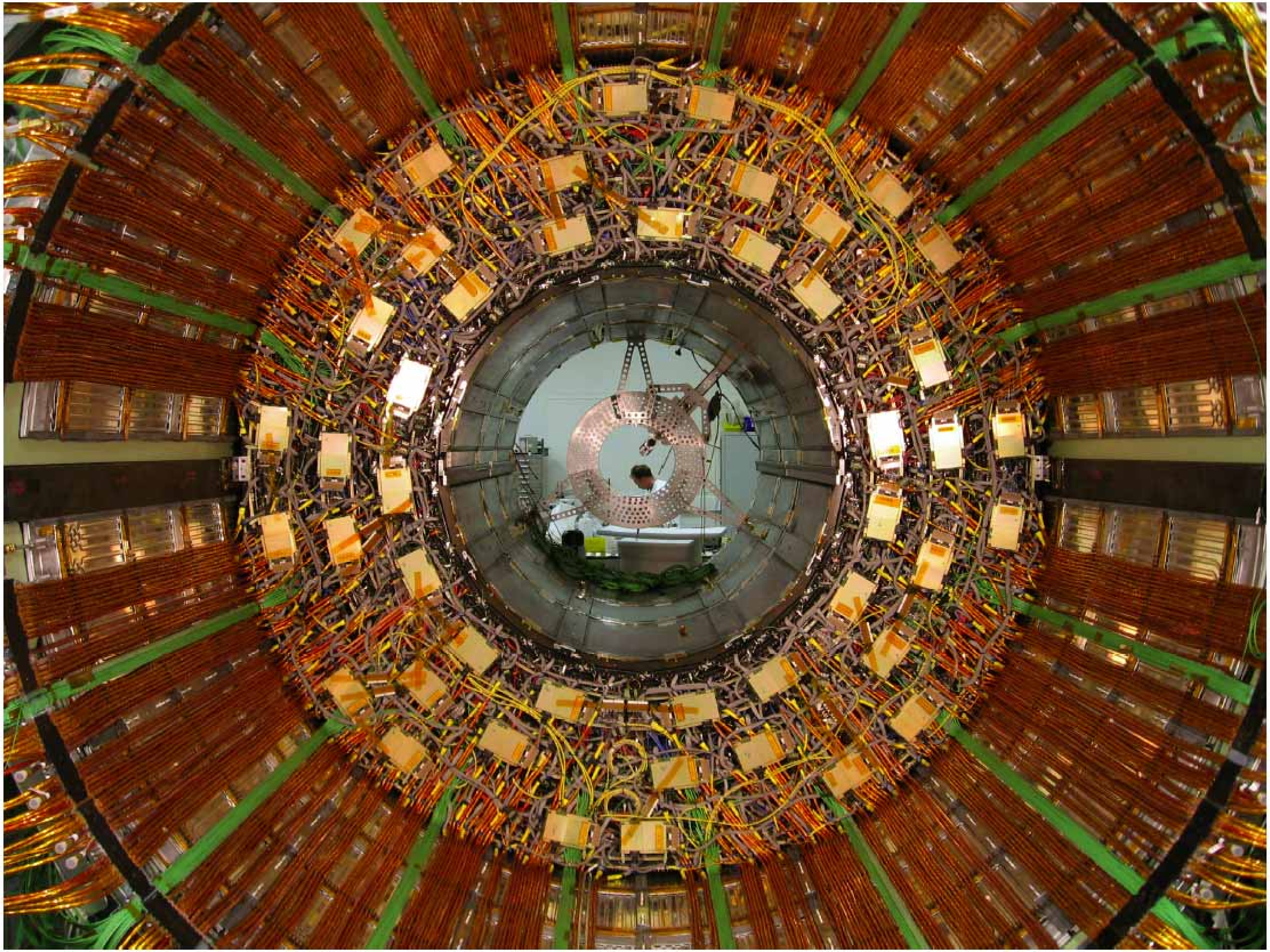


Finished TIB

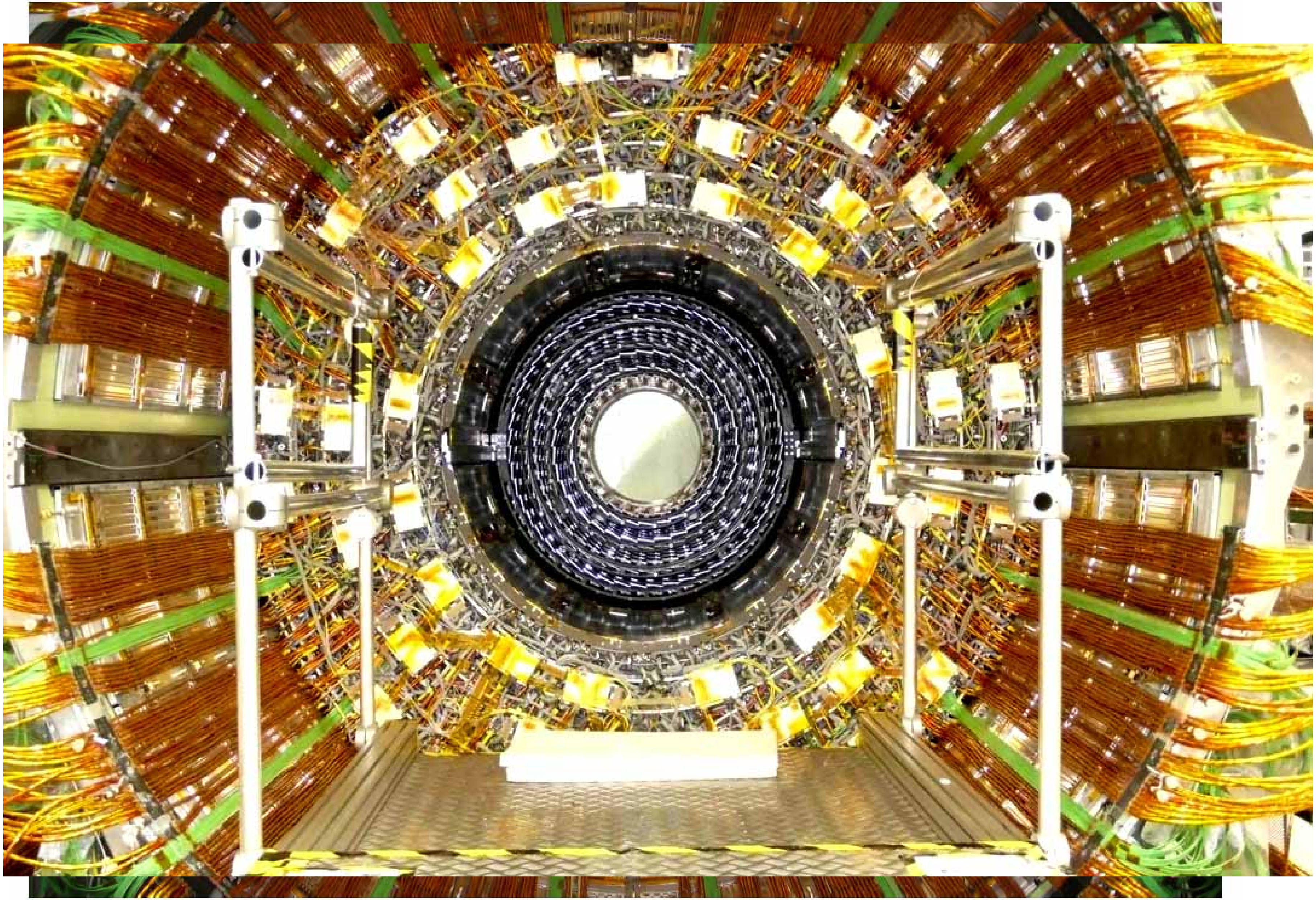




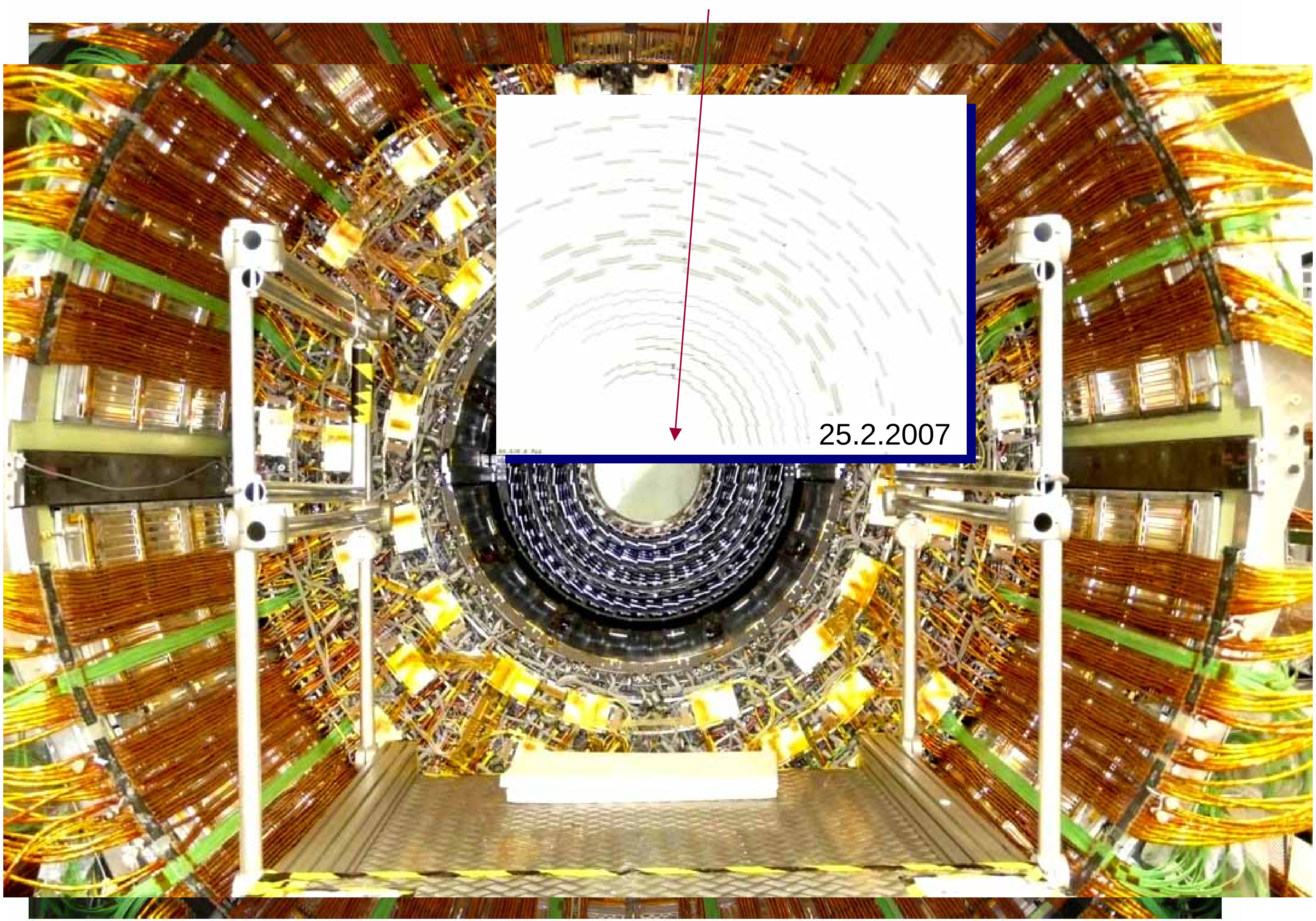
Finished TOB



Finished TOB with TIB inside



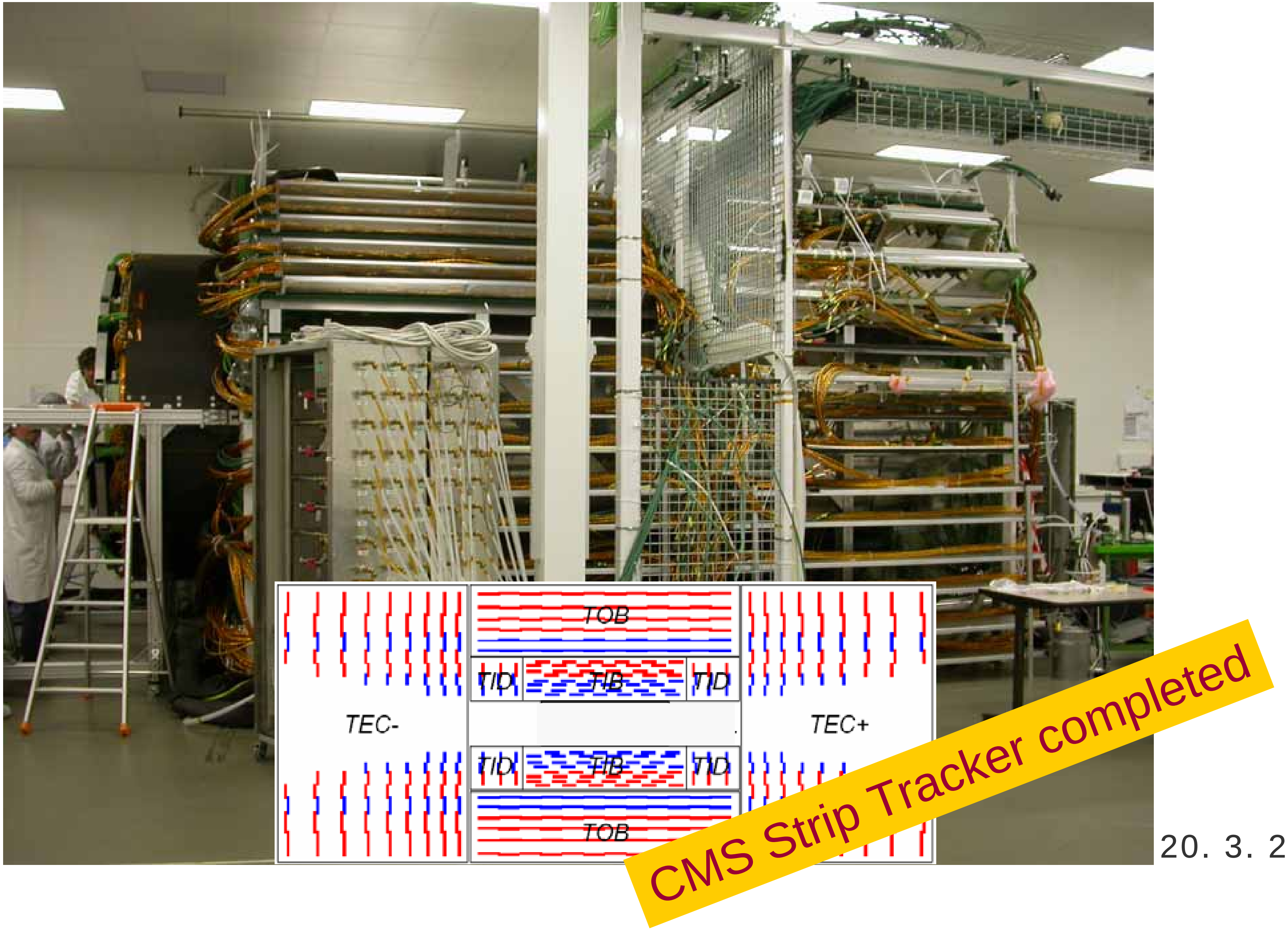
Finished TOB with TIB inside and cosmic muon signals



Insertion of TEC+ into the CMS Tracker

28. 2. 2007

Insertion of TEC- into the CMS Tracker



20. 3. 2007

...the CMS tracker (mock-up) approaching its final destination

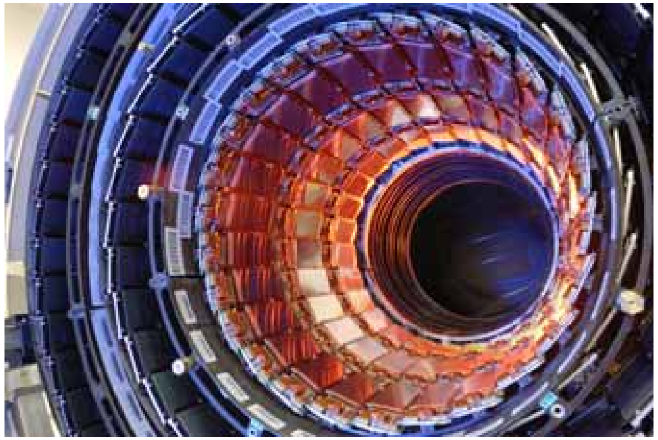
What have we learned?

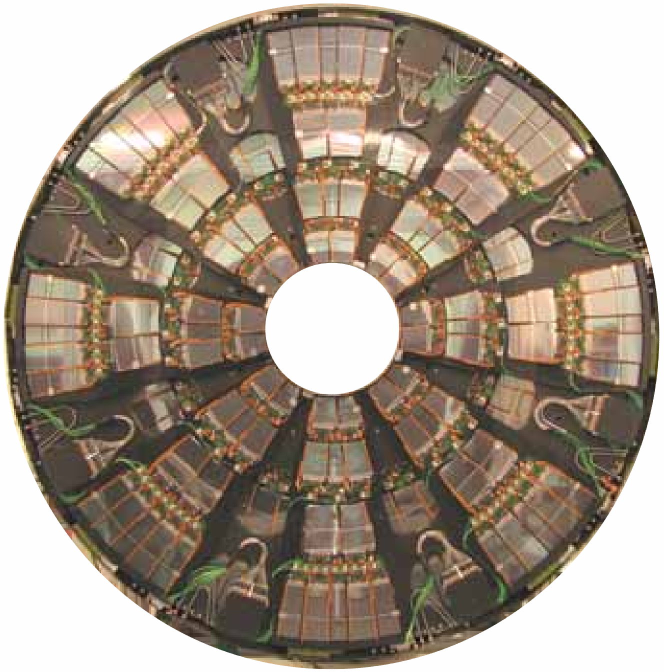
- it took about 5 years of R&D before we knew which tracker to build
- after we knew rather precisely what we wanted to build
  it took again more than 5 years to actually do it
- decisions which at the time seemed rather late and risky (move to all silicon tracker, change of ASIC to deep sub-micron etc.) proved to be the right choice
- clean solutions and clear procedures pay off
- (over-) optimization created many different varieties of sensors, hybrids, modules etc. which made production difficult and turned logistics into a nightmare
- there are problems and hick-ups everywhere
- problems and delays were often related to low tech and “standard products”

What went wrong?

- the attempt to purchase silicon micro-strip sensors from other companies than Hamamatsu
- hybrid fabrication due to lack of quality control and marginal design
- conductive glue bias contacts to sensor backplane
- laser welding of thin walled titanium pipes
- automated crimping of connectors to cables with rad-hard insulation
- noise susceptibility of certain module positions in the outer barrel
- logistics was really difficult (partly unavoidable)
- the material budget of the tracker is high despite all attempts to keep it minimal: 0.35 X_0 in the center, going up to 1.4 X_0 around $|eta|=1.5$

Summary and Outlook





- CMS Silicon Strip Tracker is now completed
- Performance is very good:
  - about 0.3% bad channels
  - S/N well above 10,
    expected to be maintained
    over the full lifetime of 10 years
- Integration into CMS planned for August 2007
- Preparations for an upgrade of the tracker for operation at the **S**LHC (10 times higher rates) have started