The CMS All Silicon Tracker

A Detector for the Exploration of the Terascale

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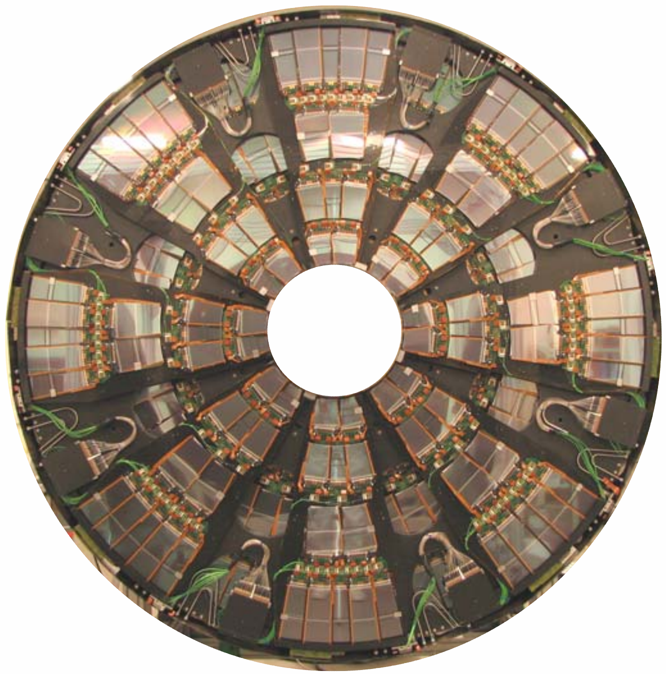
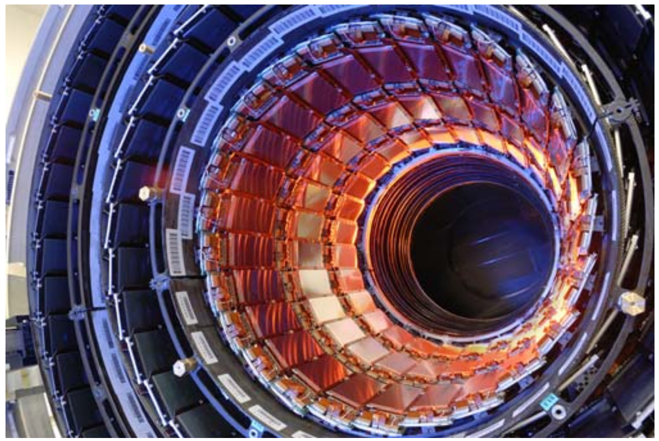




The LHC Physics Program

Large Hadron Collider **LHC** will explore a new energy domain: the

Terascale

proton proton collisions at 14 TeV pp center-of-mass energy

Find the origin of **electroweak symmetry breaking**

Higgs mechanism? → find a Higgs-Boson with 114 GeV < m_H < 1 **TeV**

Look for physics **beyond the Standard Model** ... many ideas

e.g. Supersymmetry → new particles in **TeV** range

Perform many **precision measurements on heavy particles**

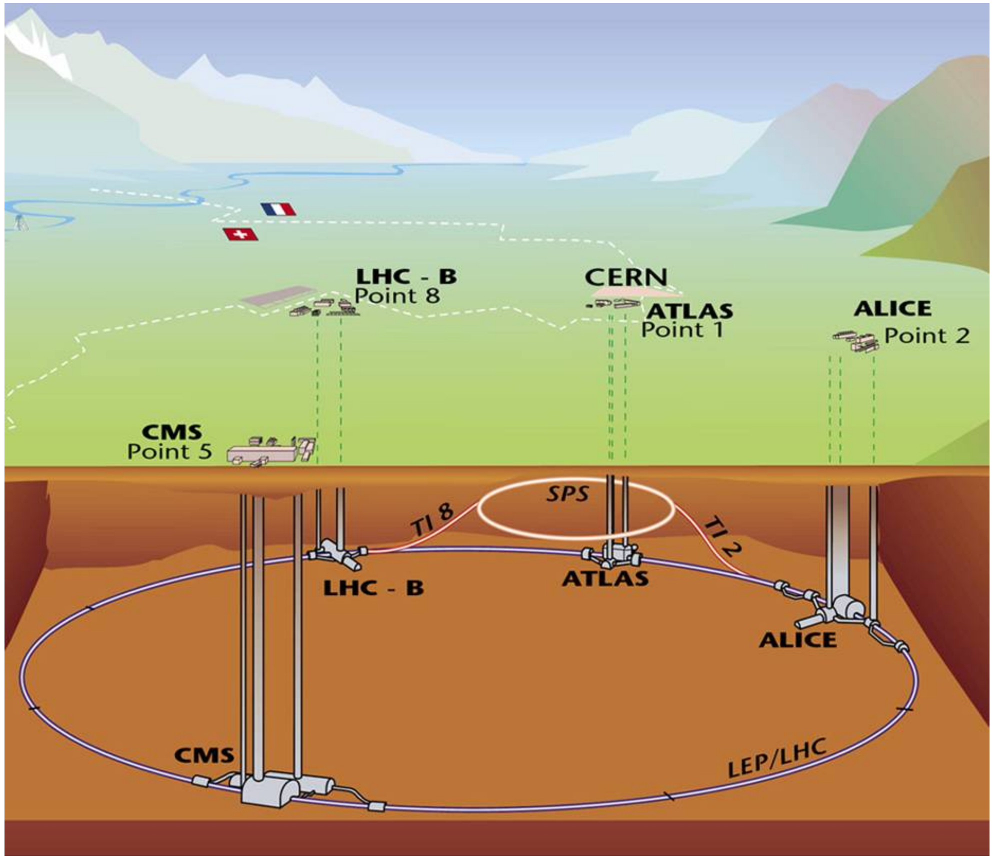
W mass, WW scattering, WWZ and WWγ couplings, b physics, t physics, ...

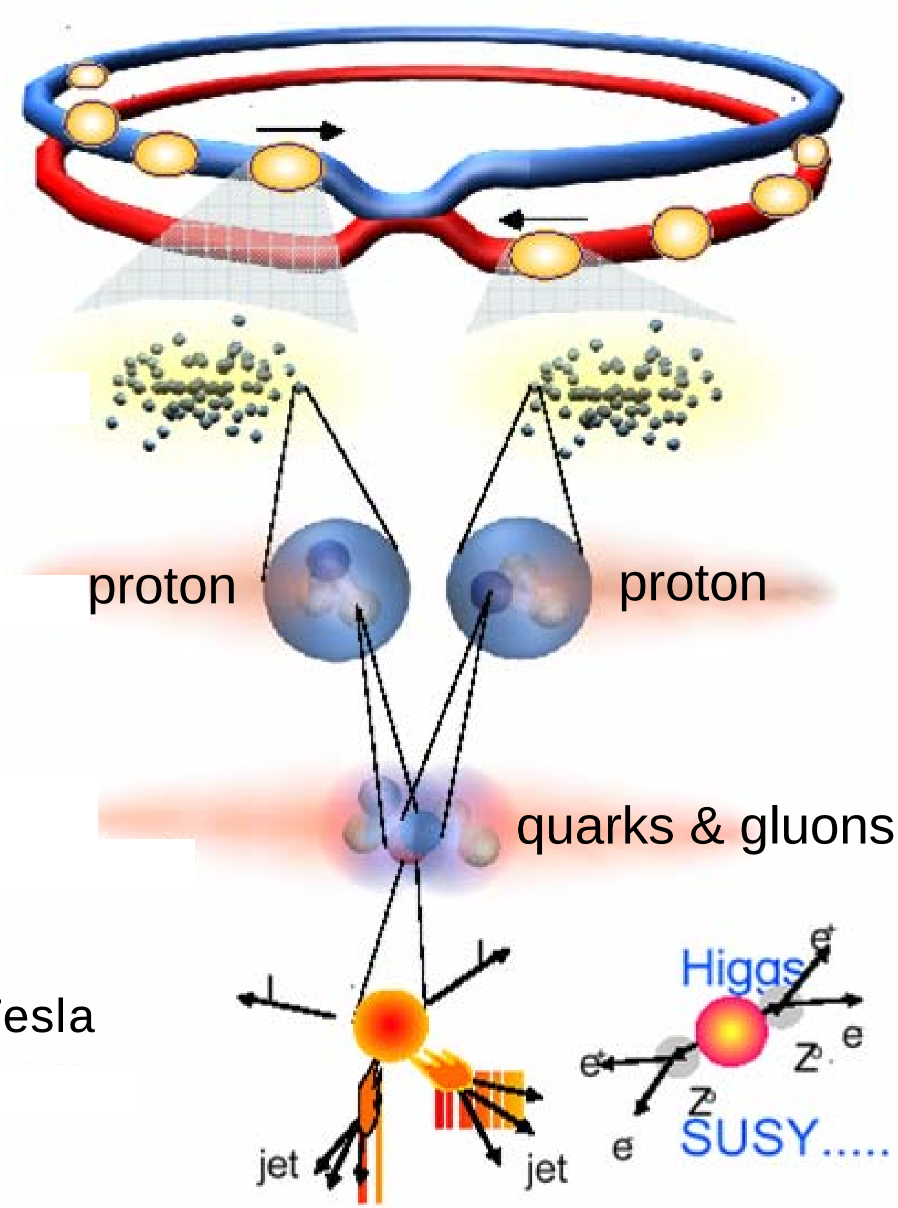
Be prepared for the unexpected: detectors must be as versatile as possible

LHC is mainly a **discovery machine** and will be the work horse of particle physics for the next ~10 years.

These Discoveries will be made Here:

Large Hadron Collider am CERN

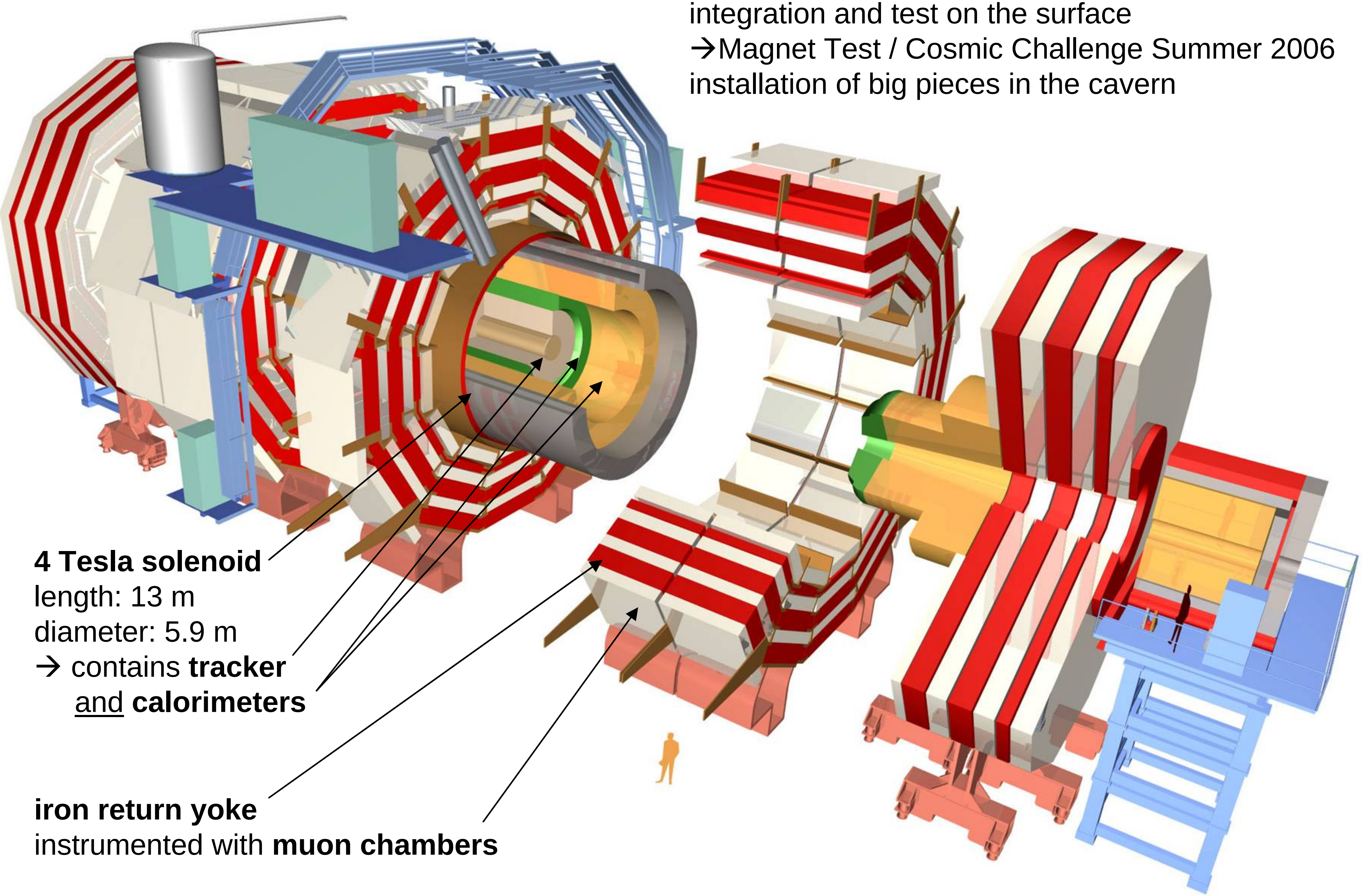




- circumference 27 km
- 1200 superconducting dipoles of 8.4 Tesla
- → 7 TeV proton momentum
- → 14 TeV pp center-of-mass energy

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

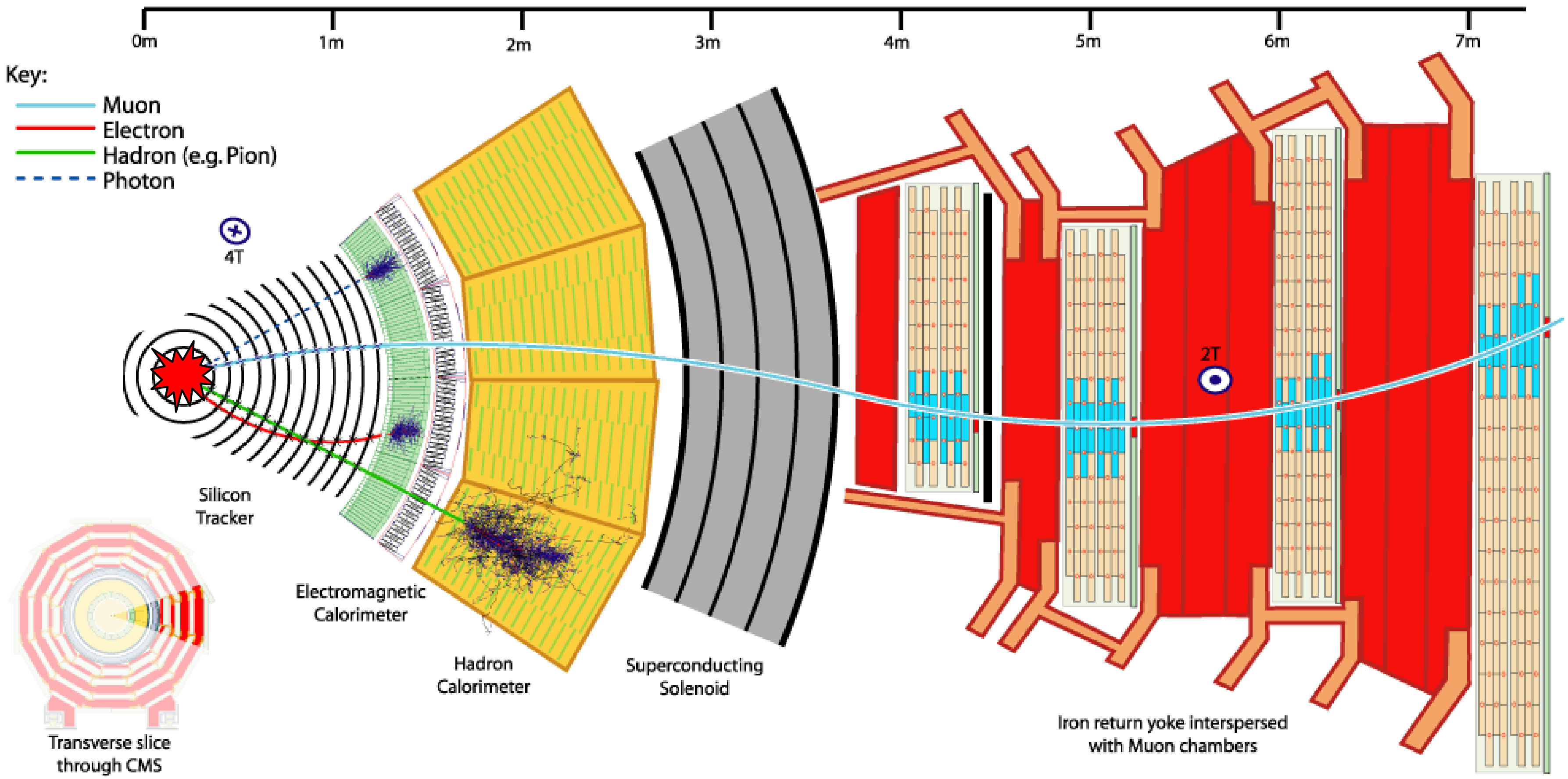


4 Tesla solenoid
length: 13 m
diameter: 5.9 m
→ contains **tracker**
<u>and</u> **calorimeters**

iron return yoke
instrumented with **muon chambers**

CMS Central Section arrived Underground

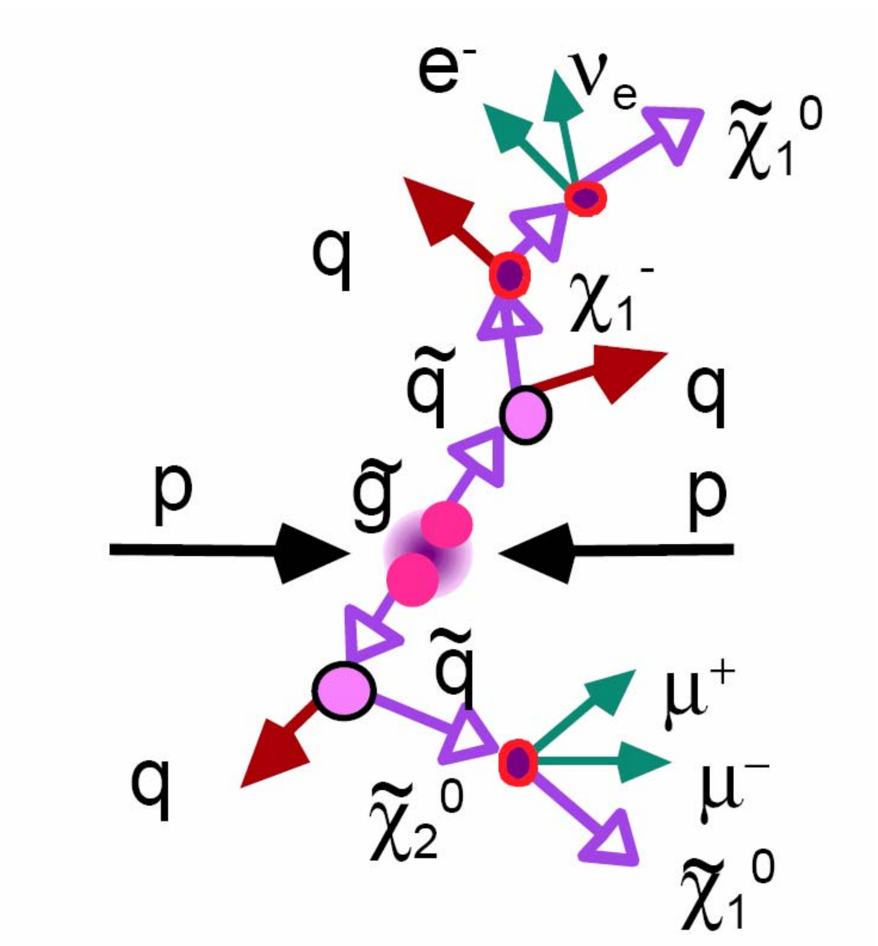
CMS cross section perpendicular to beam axis

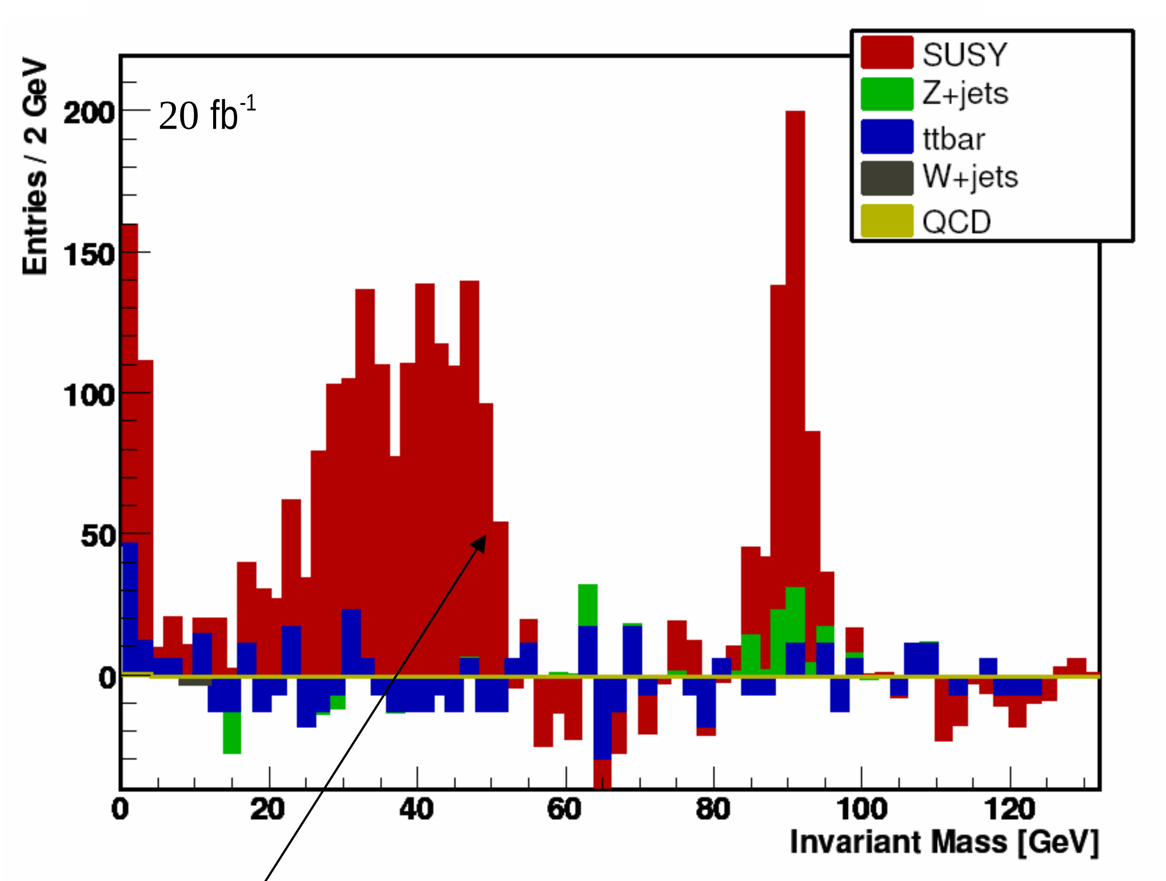


Discovery of supersymmetric particles

and measurements of their properties

Example: neutralino masses





edge at $M\left(\tilde{\chi}_2^0\right) - M\left(\tilde{\chi}_1^0\right)$

width given by detector resolution

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

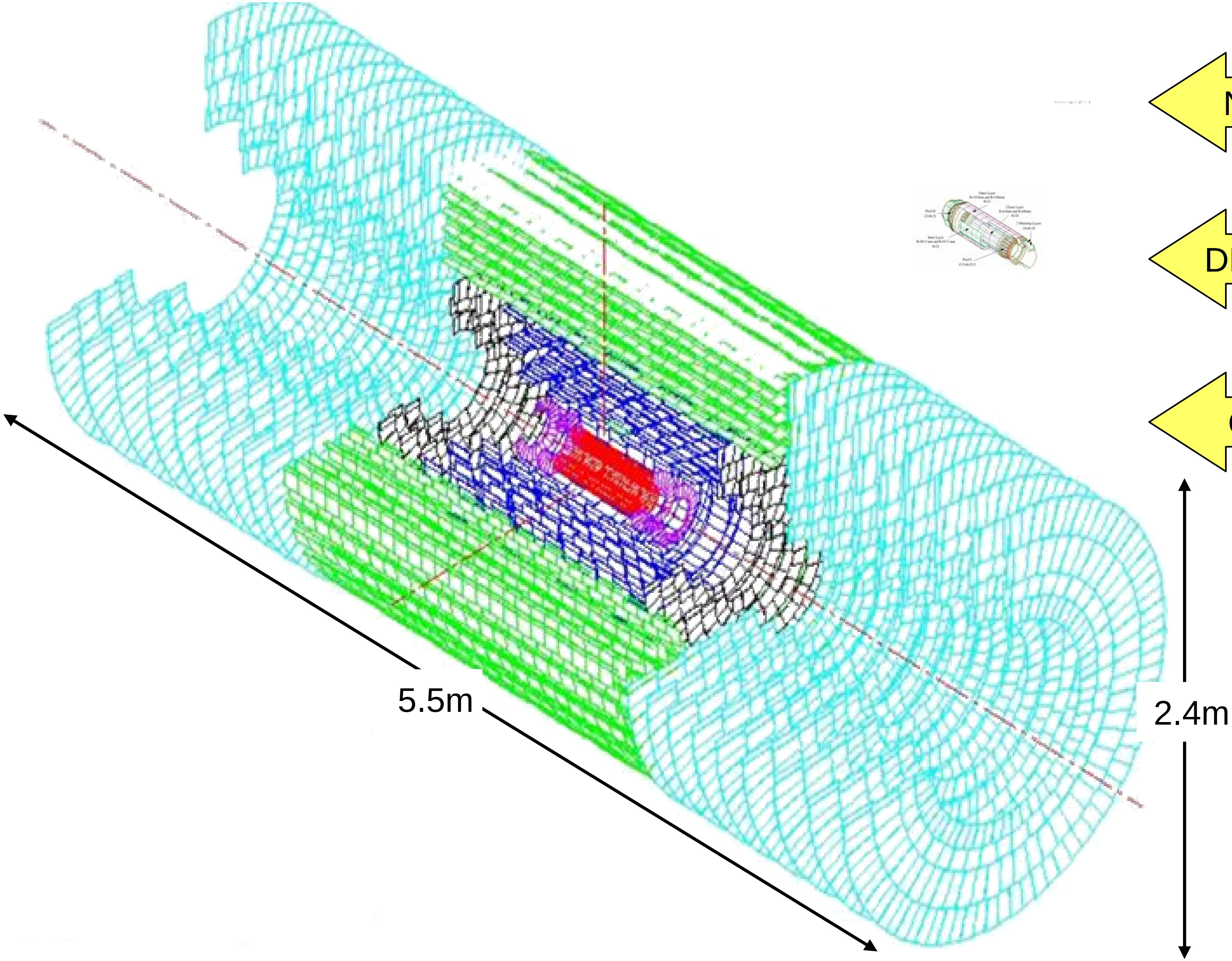
→ traditional tracking chambers cannot be used

→ **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 $\rightarrow e \nu$	150	/ sec
Z $\rightarrow$ e e	15	/ sec
Higgs (150 GeV)	0.2	/ sec
Gluino, Squarks (1 TeV)	0.03	/ sec

…will focus on the strip tracker and leave pixels to following speaker

A new domain for Silicon Detectors



NA11 (1982)

DELPHI (1996)

CMS (2007)

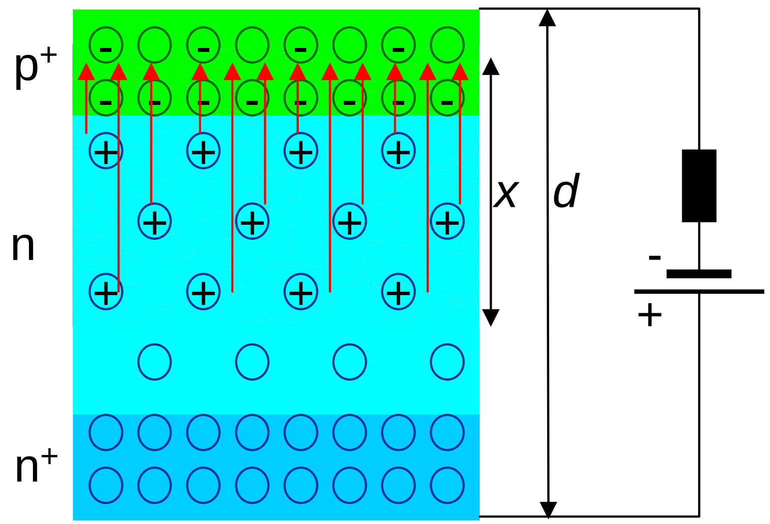
Working Principle of a Silicon Detector

1. **create a depleted volume**

   voltage for depletion of full sensor thickness:

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

   effective doping concentration N_{eff} given by
   - original doping
   - radiation induced changes



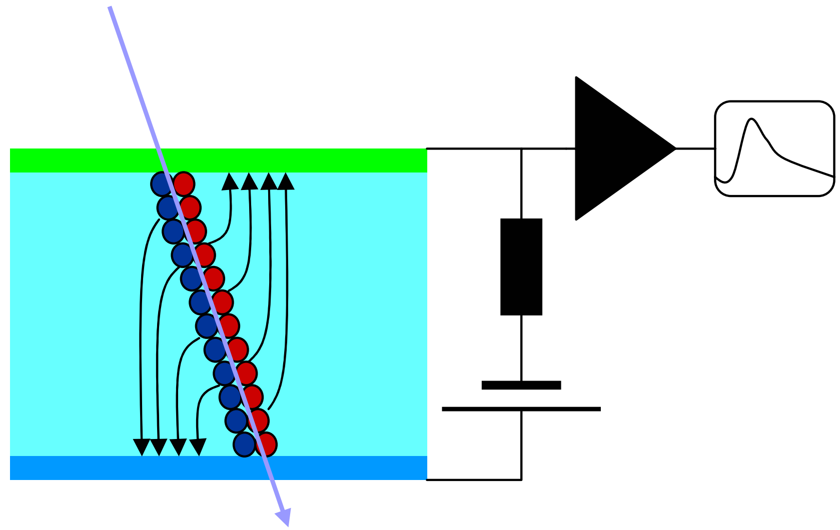
2. **minimize dark current**

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

   charge carrier life time τ_g given by
   - original cristal quality
   - radiation induced changes

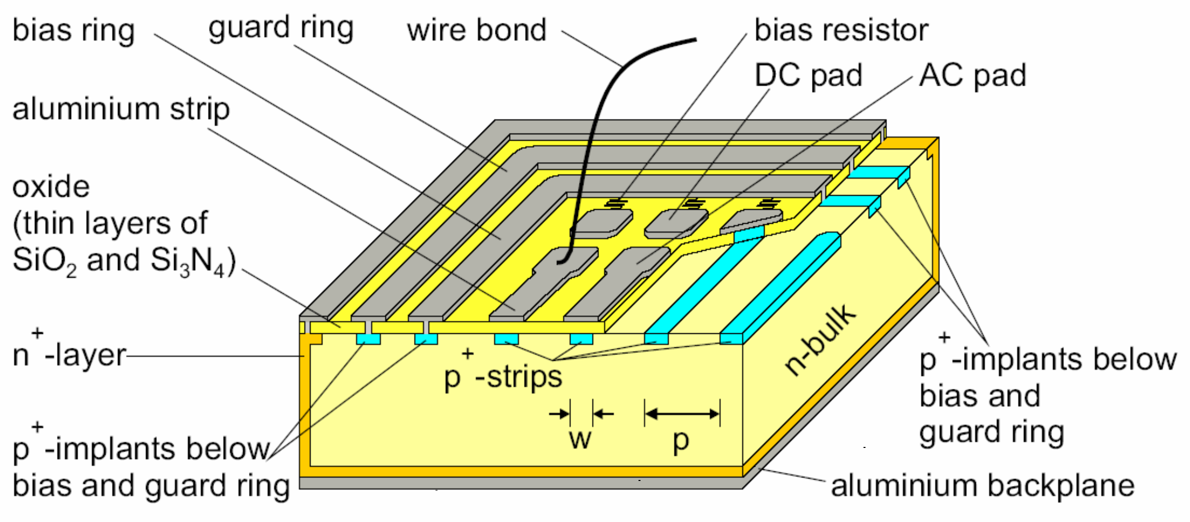
3. **ionizing particles create electron hole pairs**

4. **charge carriers drift to electrodes and induce signal**



Silicon Microstrip Sensors

- photolithographic segmentation of diode → **spatial resolution**
- strip pitch 50-200 µm and length can be adapted to occupancy → **high granularity**



- charge collection < 10 ns → **fast response**
- segmentation of p side („p-on-n“) easiest and cheapest: 5-10 CHF/cm^2 → can **cover large areas**
- MIP signal in 300µm Si: **~24000e**
- strip capacity ~1.5pF/cm →noise for 12 cm strips typically **~1500e** (τ=25ns) → longer strips possible for thicker sensors (more signal)

→ **silicon detectors fulfill all requirements IF we can achieve:**

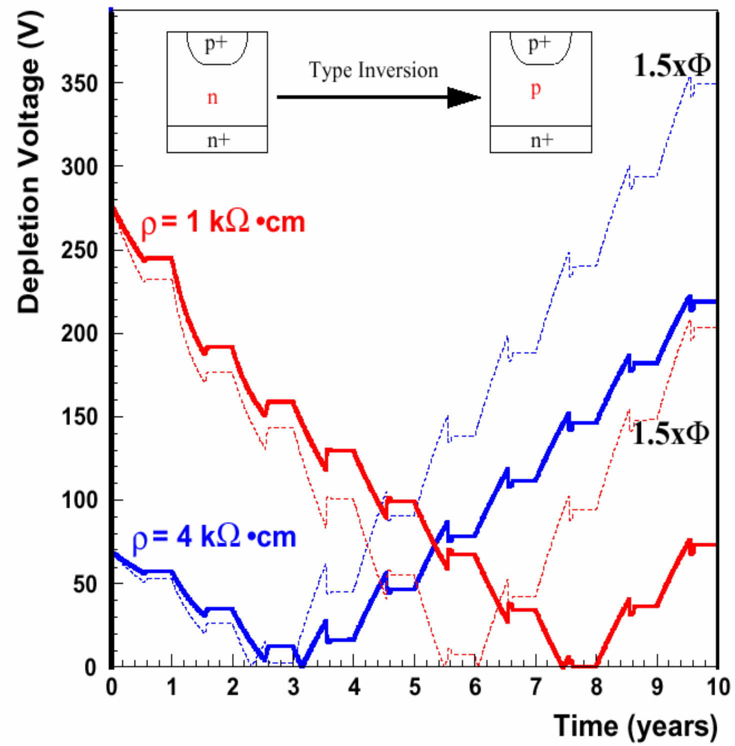
- **radiation hardness** ...requires high voltage operation and efficient cooling

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



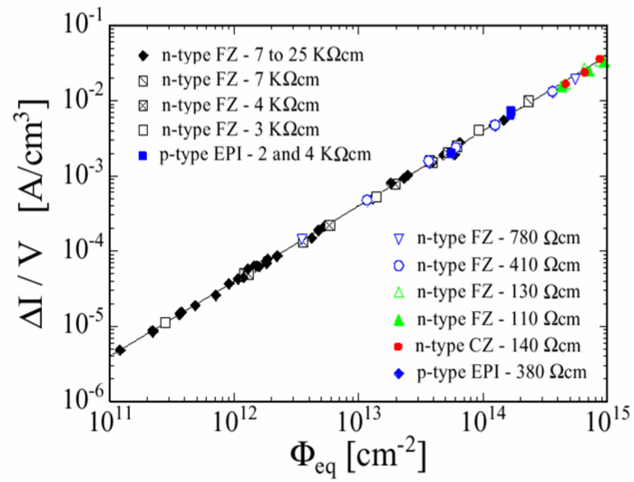
Sensors

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

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

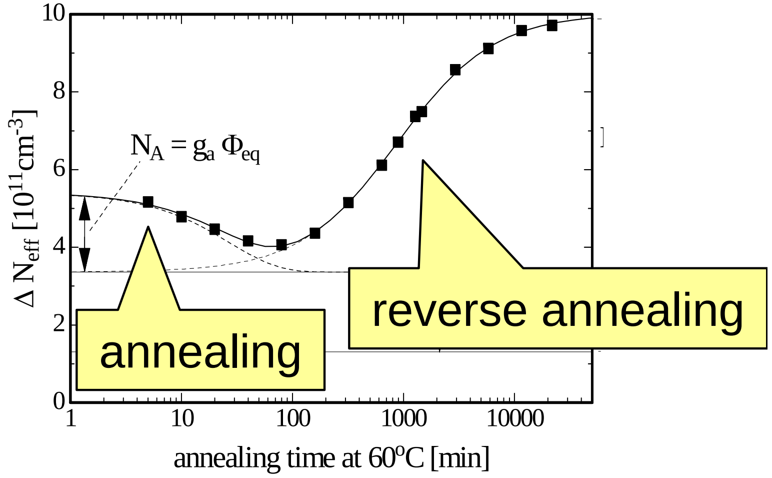
Read-out ASICs

- 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’)

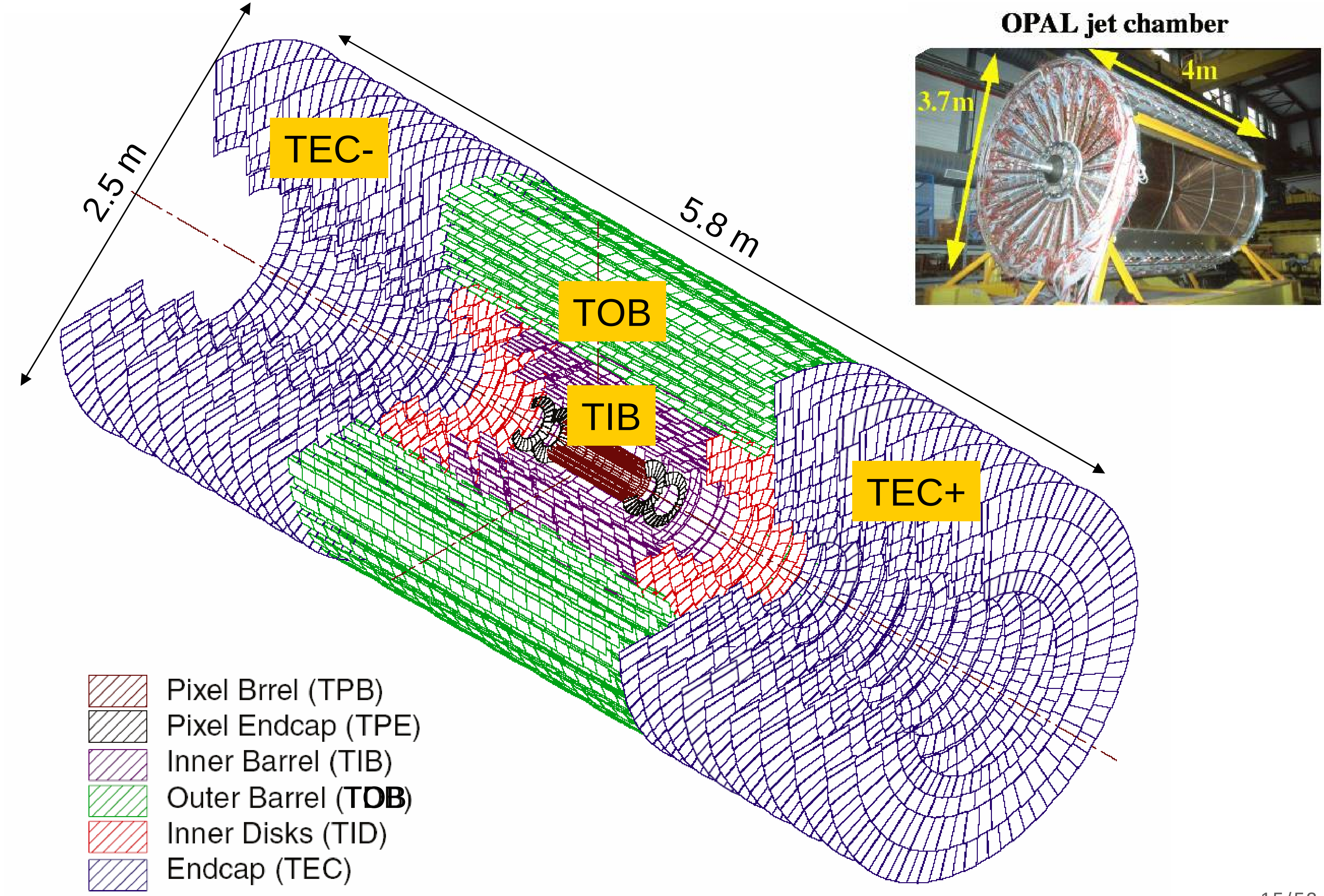
  dark current x bias voltage after 10 years:
  2 mA x 500 V = 1 W !

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

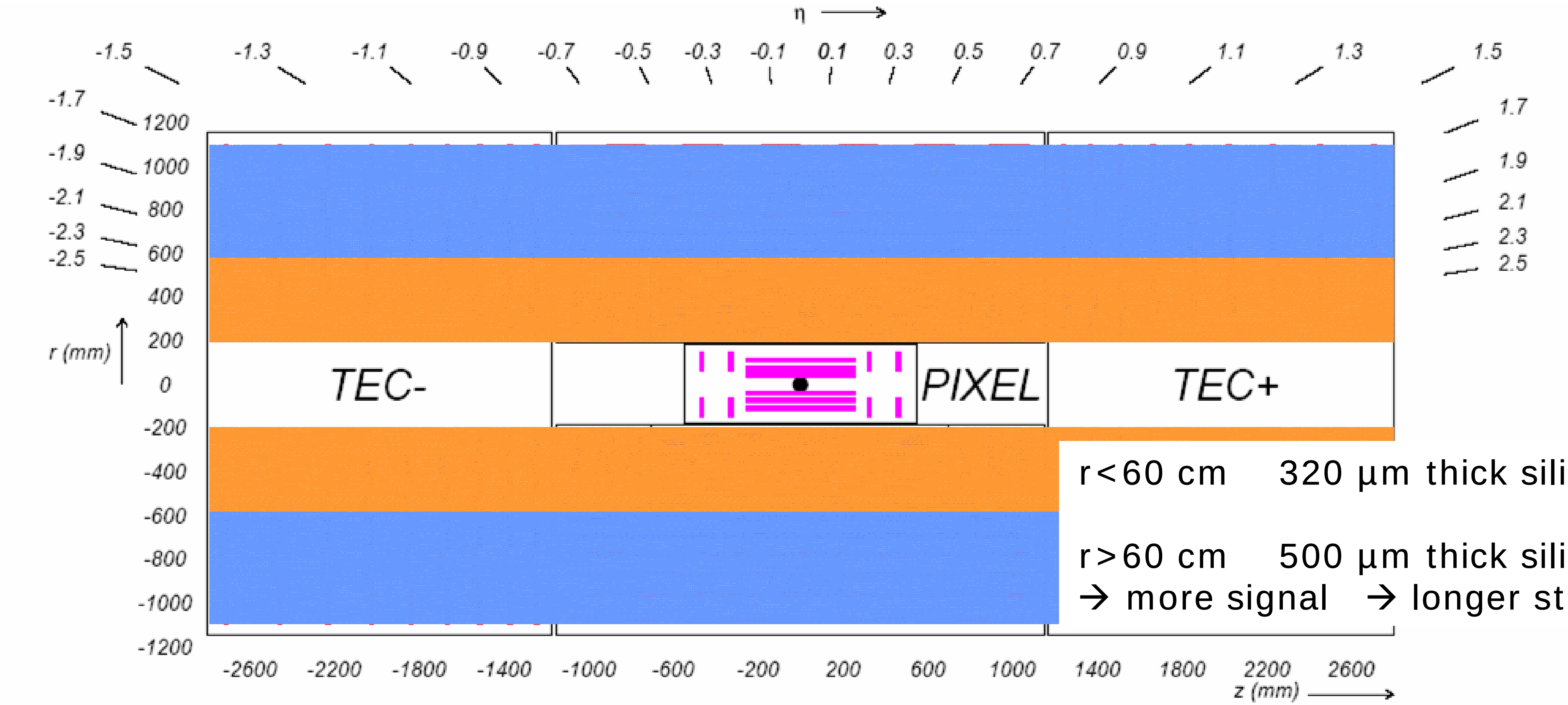
  by
  - operation at around –10°C
  - efficient cooling with small temperature gradients
  - thermal separation of sensors and electronics

→ **radiation hardness can be achieved**

CMS All Silicon Tracker



CMS All Silicon Tracker



r<60 cm 320 µm thick silicon

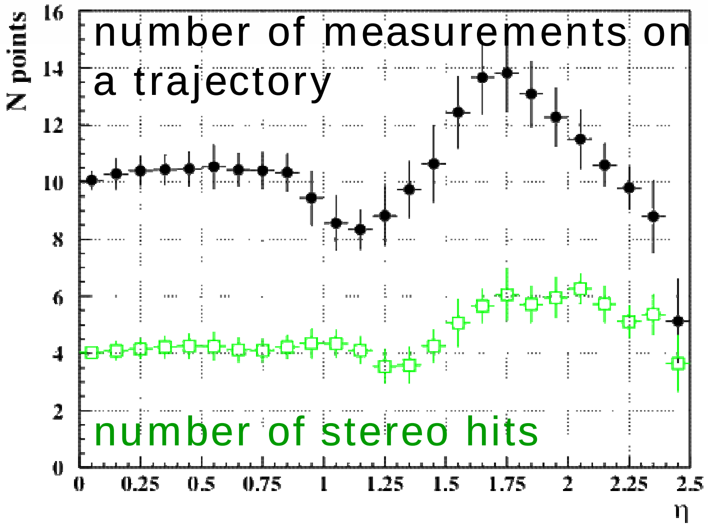
r>60 cm 500 µm thick silicon

→ more signal → longer strips

15,148 silicon strip detector modules

single sided or mounted

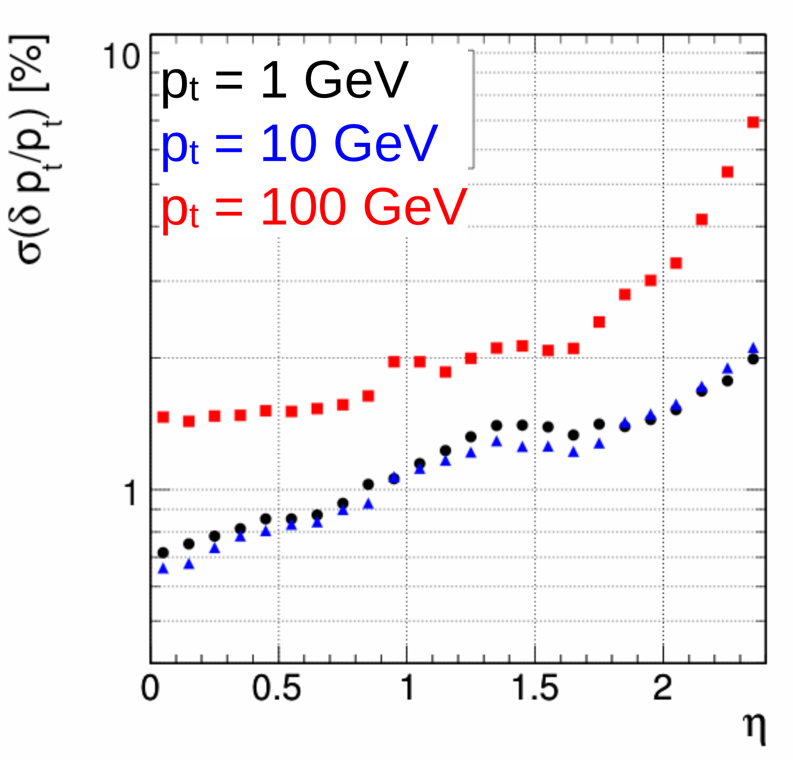
back-to-back with stereo angle of 100 mrad



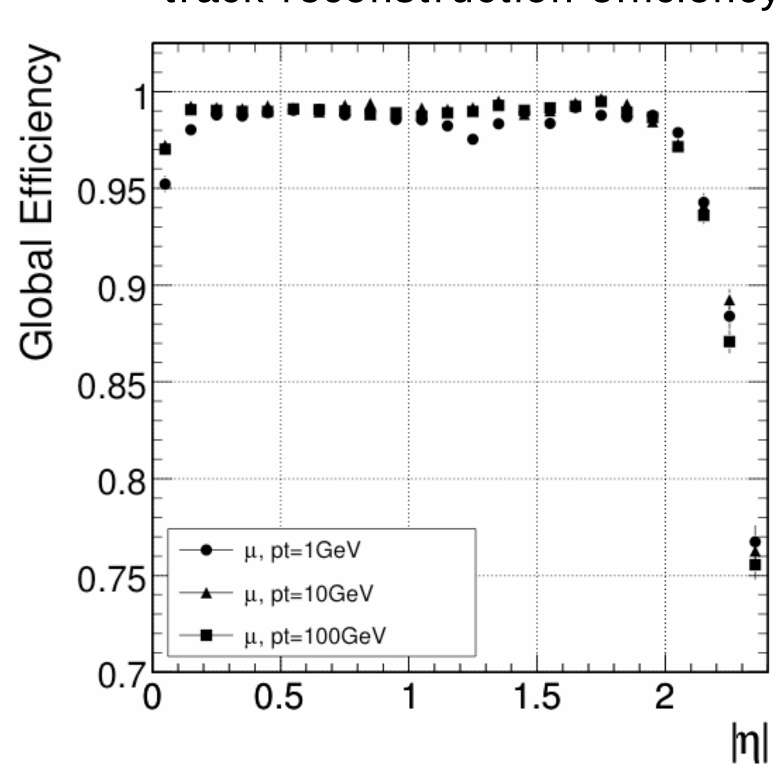
Expected Performance of CMS Tracker

for single muons

transverse momentum resolution



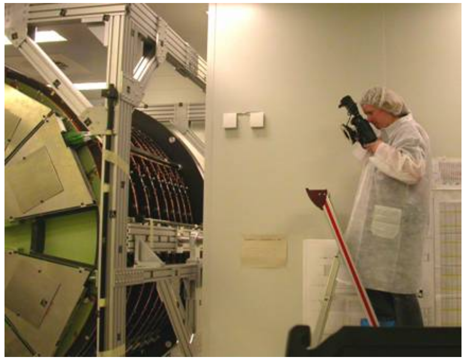
track reconstruction efficiency



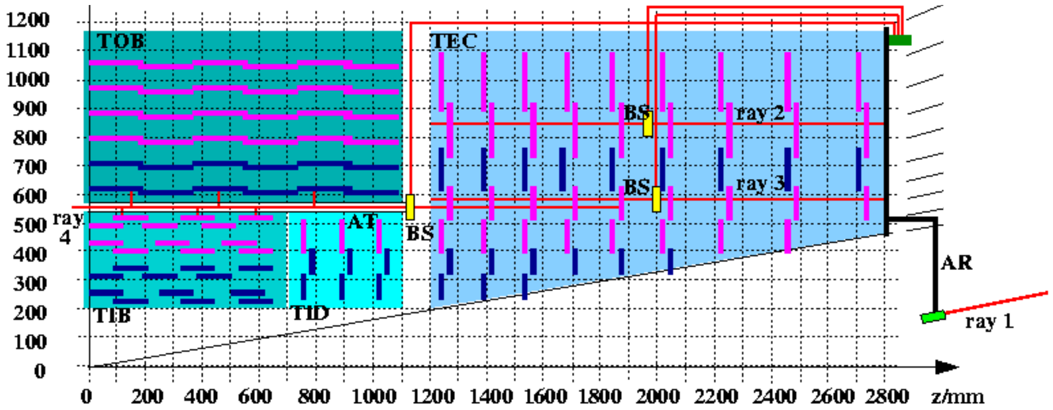
...requires a well aligned tracker

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

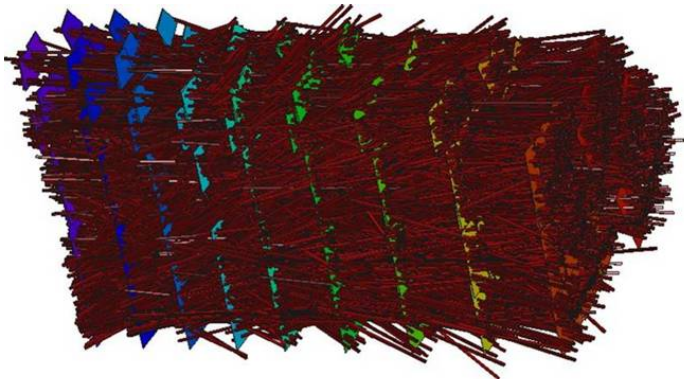
- survey measurements at all stages of detector assembly



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

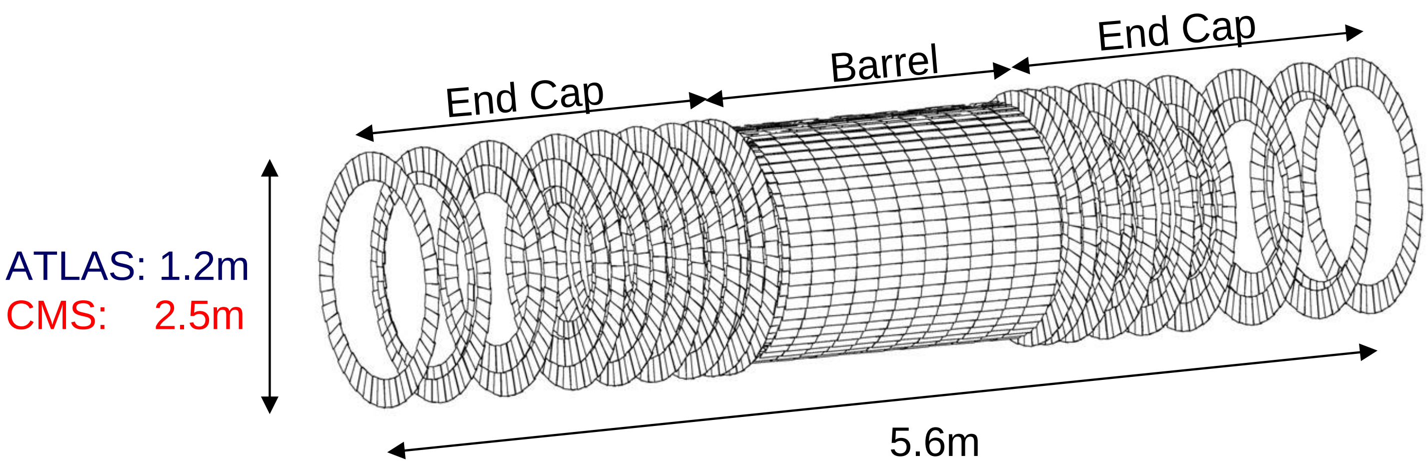


- alignment with particle tracks will provide the best precision

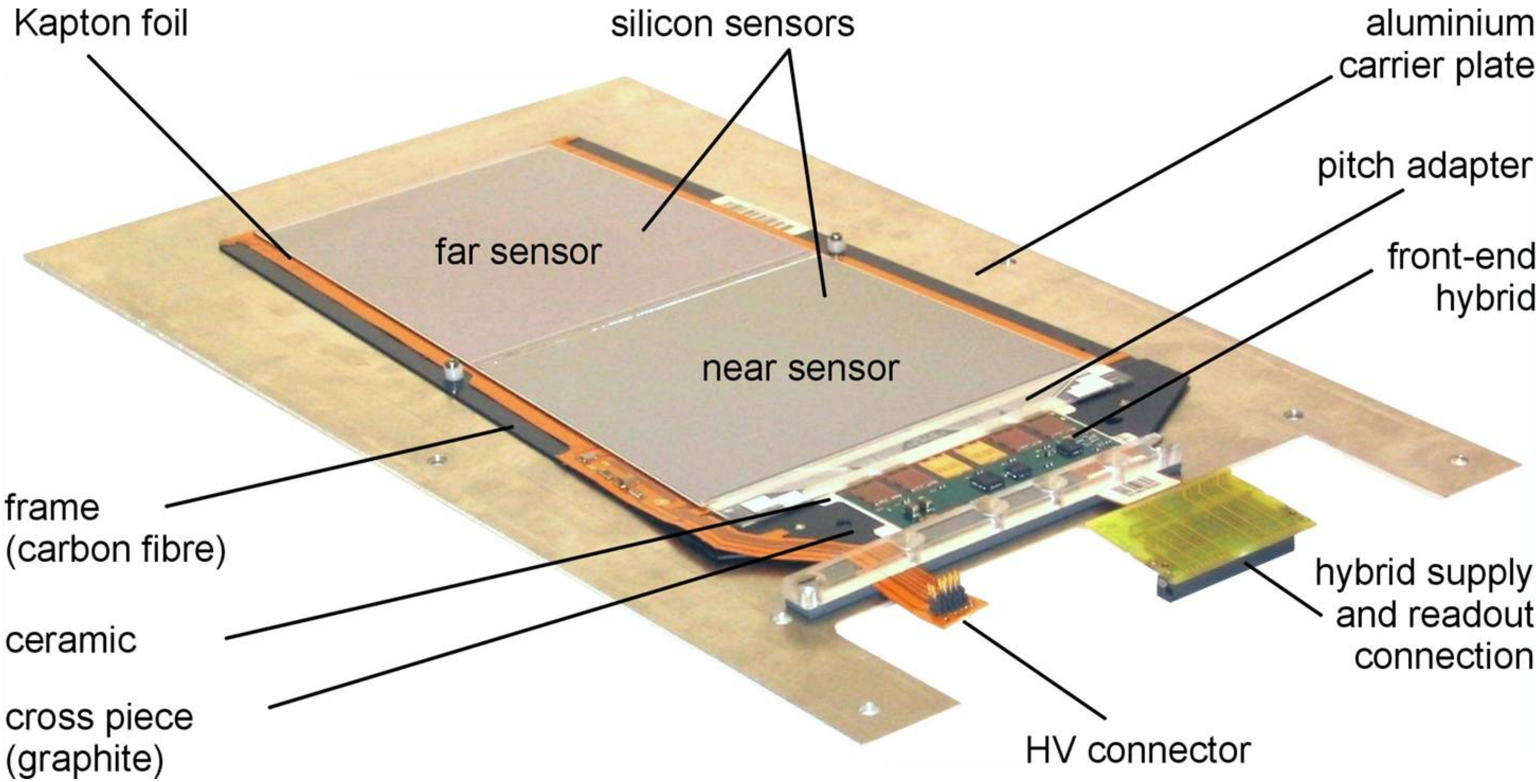


Silicon Microstrip Detectors in ATLAS and CMS

	ATLAS	CMS
Barrel	4 layers	10 layers
End Caps	2 x 9 disks with up to 3 rings	2 x 9 disks with up to 7 rings
Modules	4,088, double sided	15,148, single sided
Silicon Sensors	15,392	24,244
Silicon Area	61,1m²	198 m²
Read-out ASICs	49.056	75,376
Channels	6,3 Mio.	9,6 Mio.
Optical data transmission	digital	analog
Cooling	evaporative C_3F_8	mono-phase C_6F_{14}
Cost	45 MCHF	80 MCHF

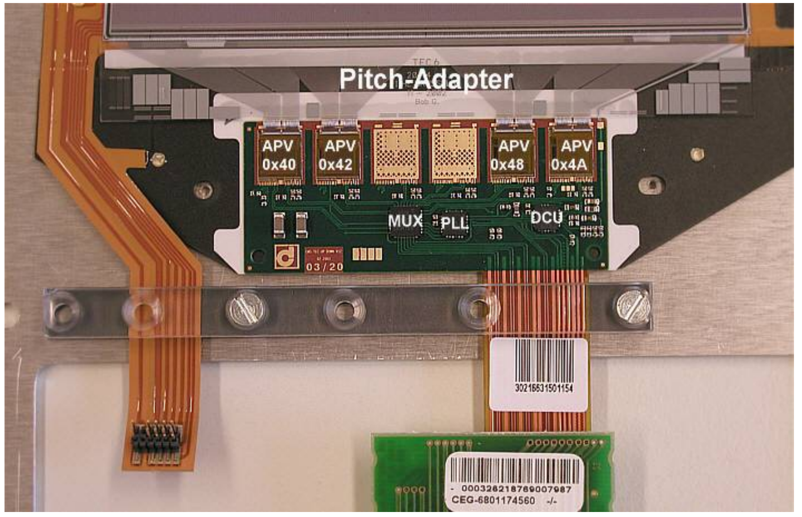


CMS Silicon Detector Module



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

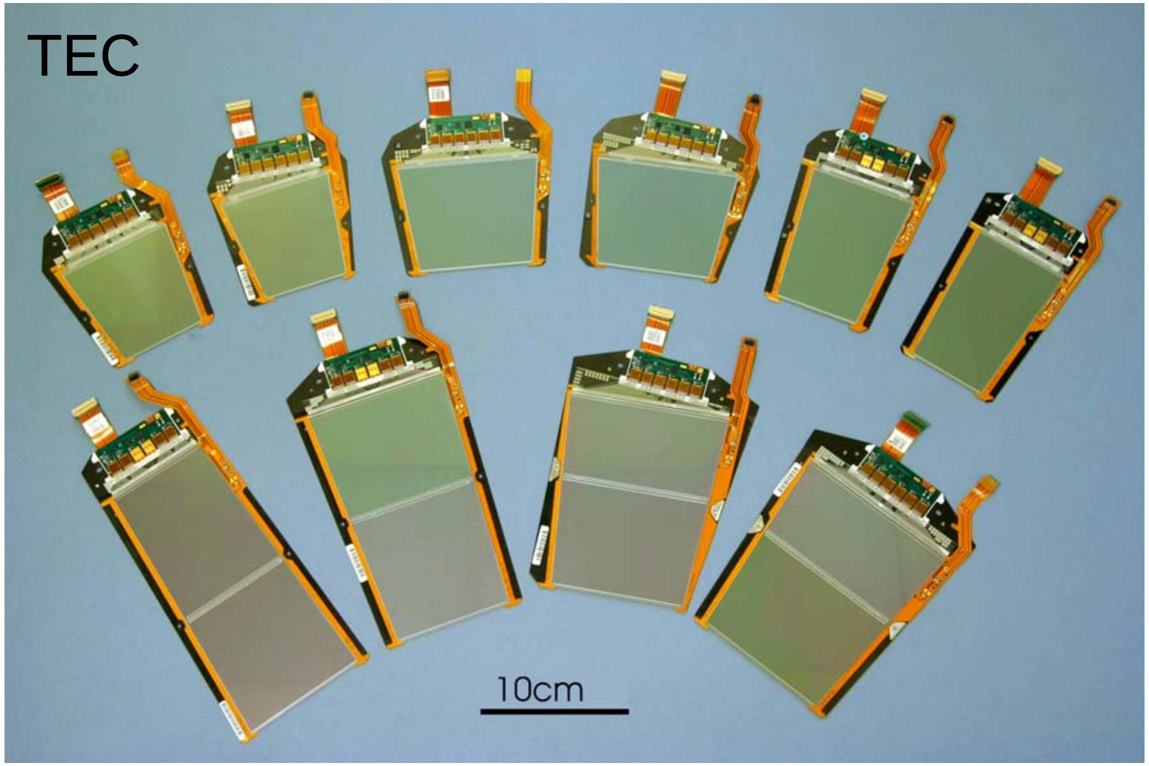
read-out ASIC

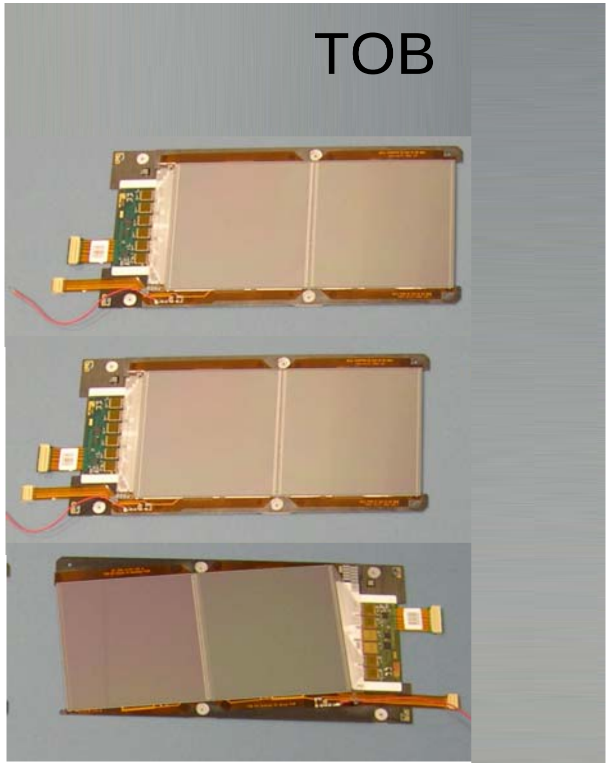
APV25
128 channels of charge sensitive amplifier, 50 ns shaper,
analogue pipeline (4 µs), deconvolution (50ns → 25ns)

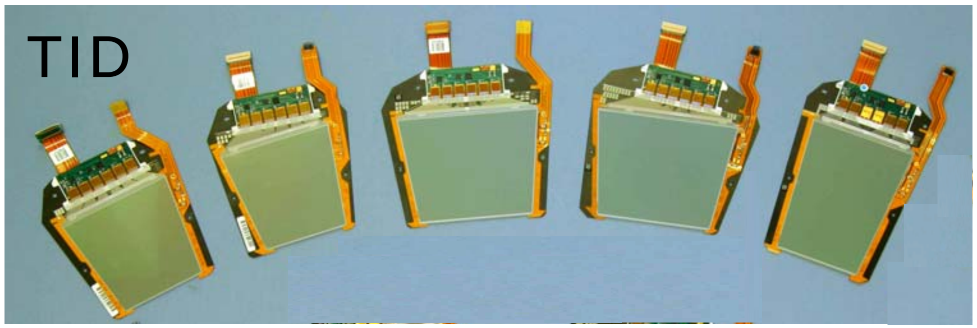
full **analogue** information is sent to ADCs in the service cavern

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

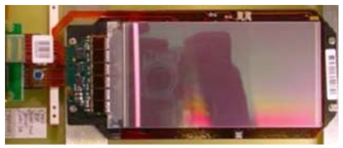
...29 different module types are needed





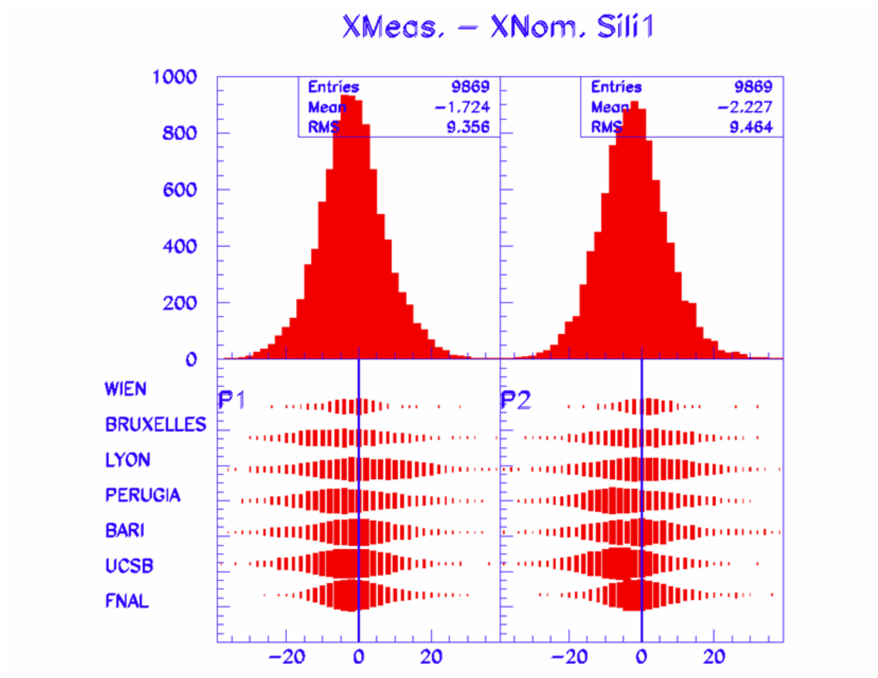


TIB



Module Production

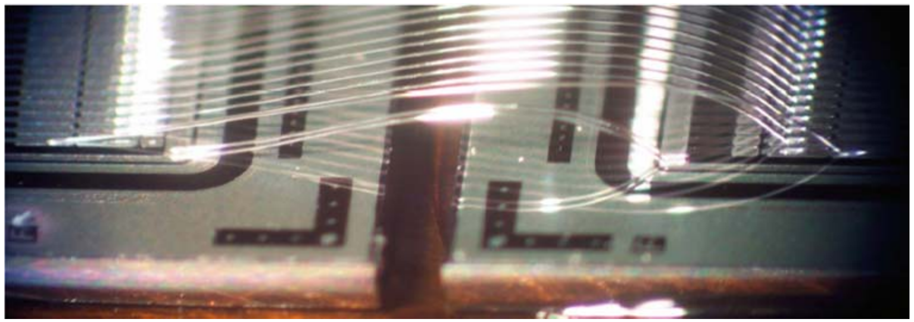
automated module assembly
and wire bonding



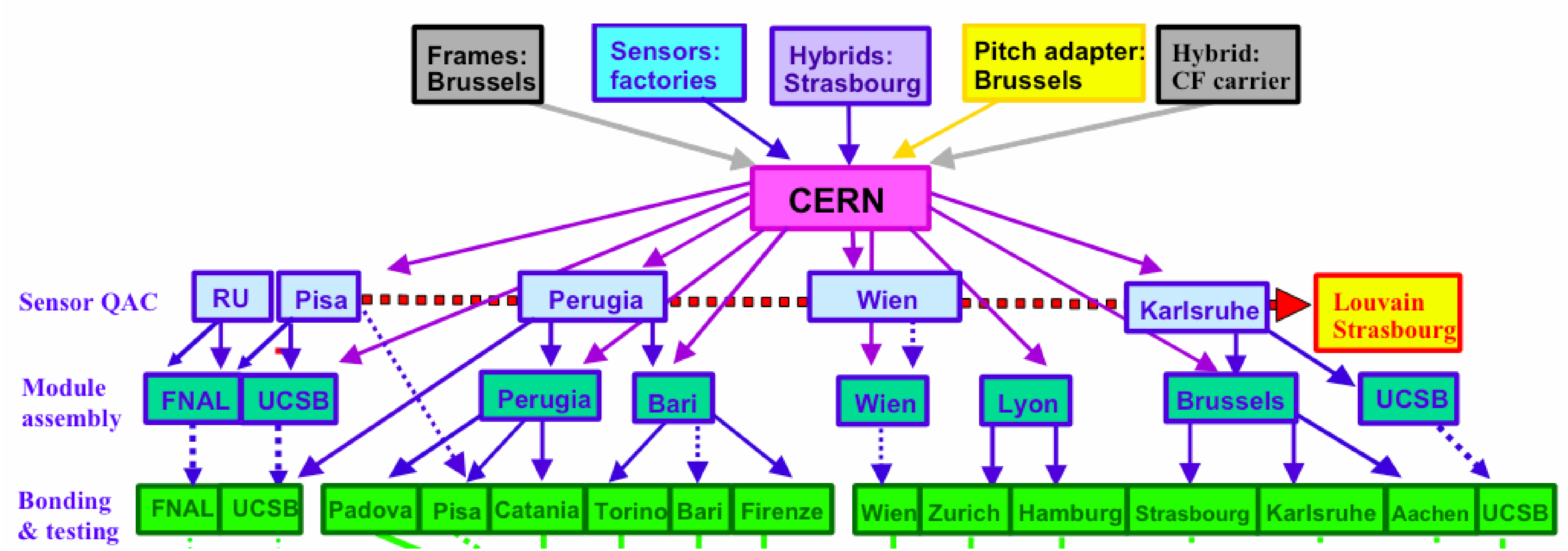
6 gantry (module assembly) centers
20 modules per gantry per day

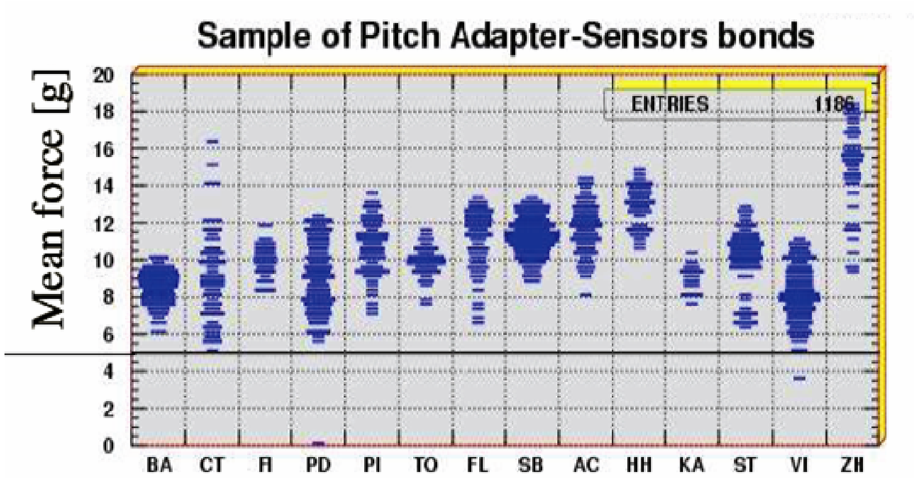
typical RMS of placement 10 µm

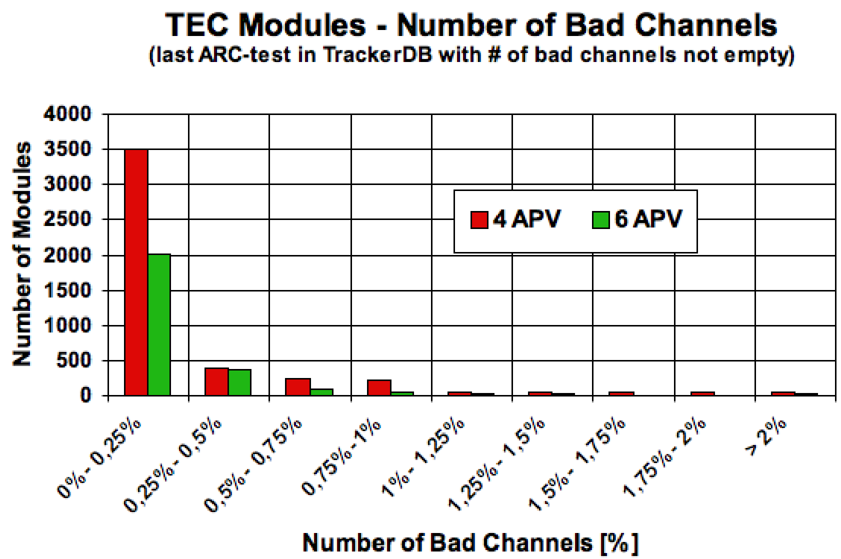
wire bonding rate ~ 1 Hz



Module Production … an Industry of its own

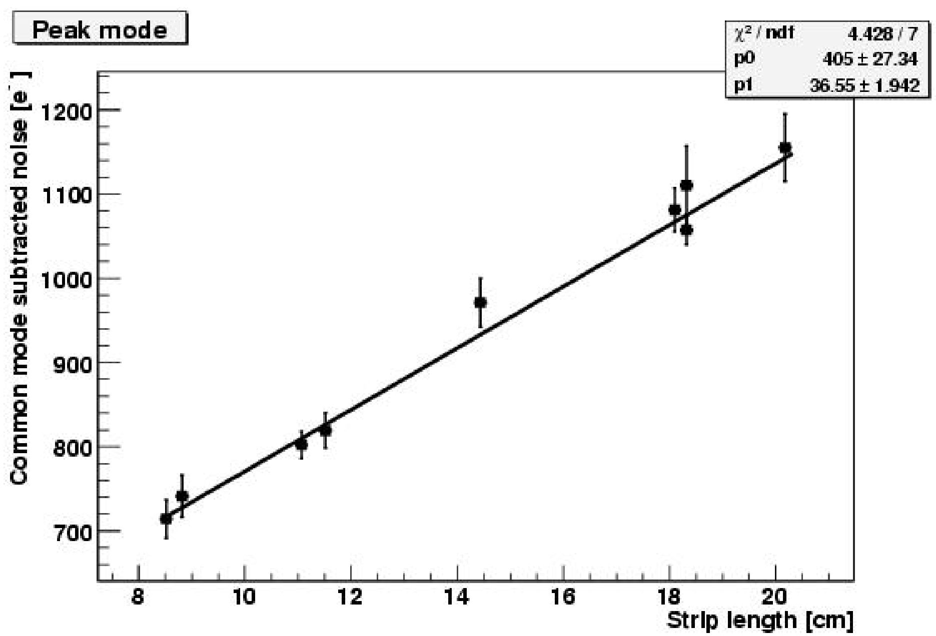


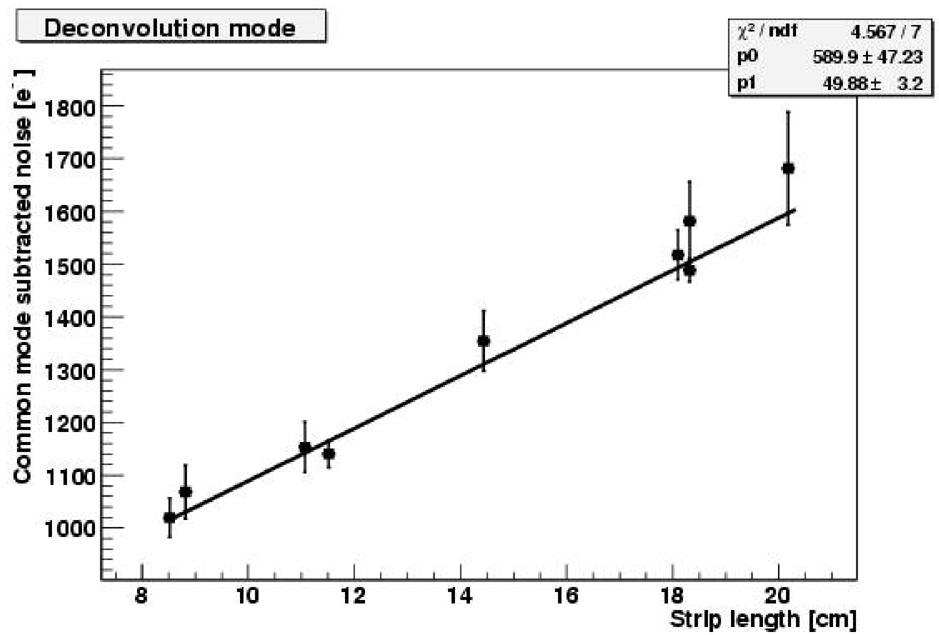




Module Performance: Testbeam Data

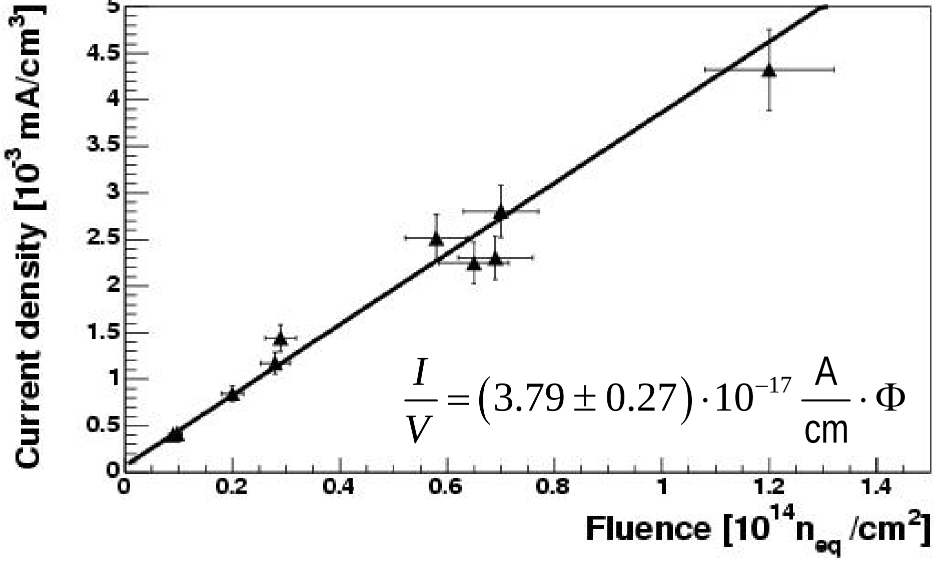
Module type	Pitch [μm]	Strip length [mm]	S/N Peak mode	S/N Dec. mode	ENC [e^-] Peak mode	ENC [e^-] Dec. mode
IB1	80	116.9	25.8 ± 1.3	18.3 ± 0.5	931 ± 48	1315 ± 37
IB2	120	116.9	29.5 ± 1.4	20.3 ± 0.6	815 ± 37	1182 ± 31
OB1	122	183.2	36	25	1110 ± 47	1581 ± 75
OB2	183	183.2	38	27	1057 ± 17	1488 ± 22
W1TEC	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



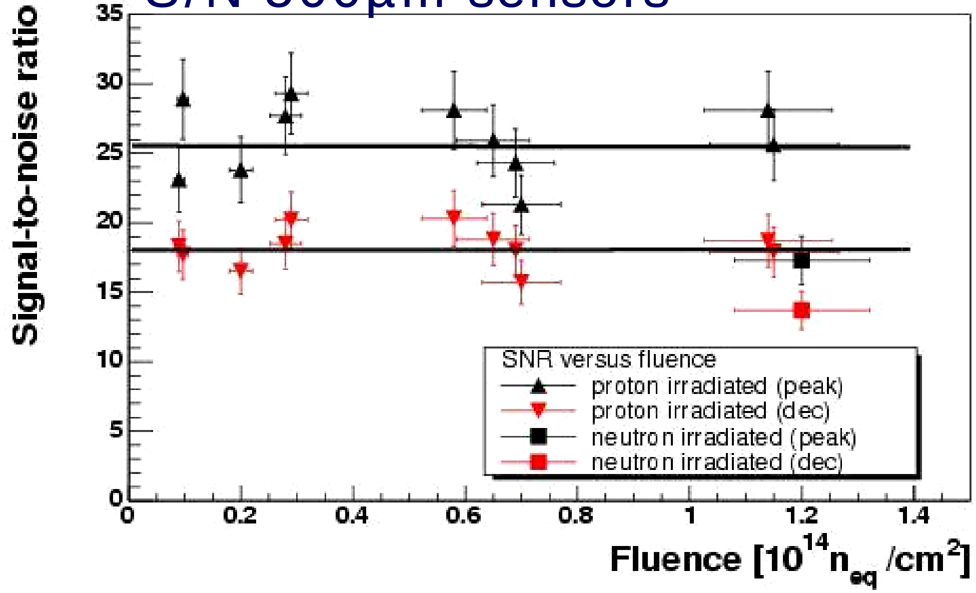


Module Performance after Irradiation

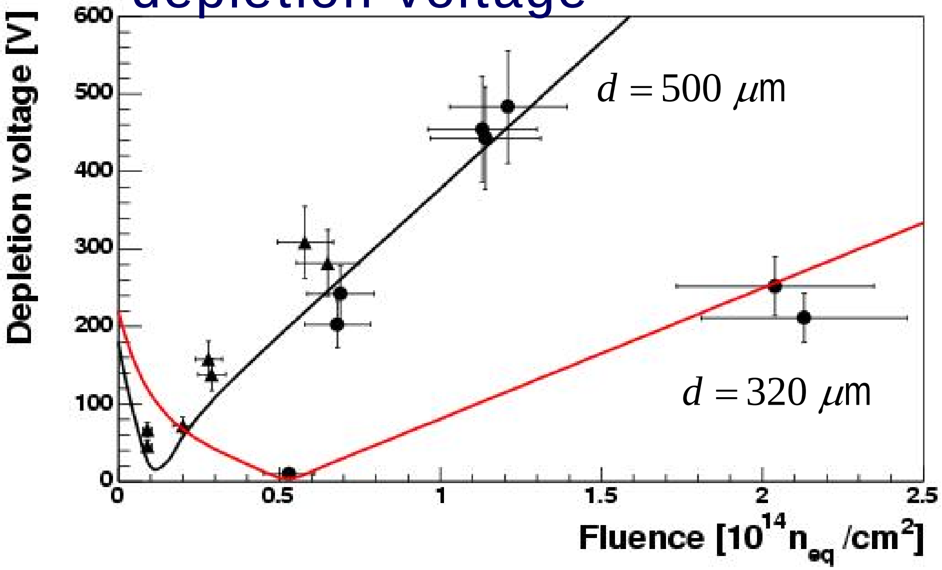
dark current



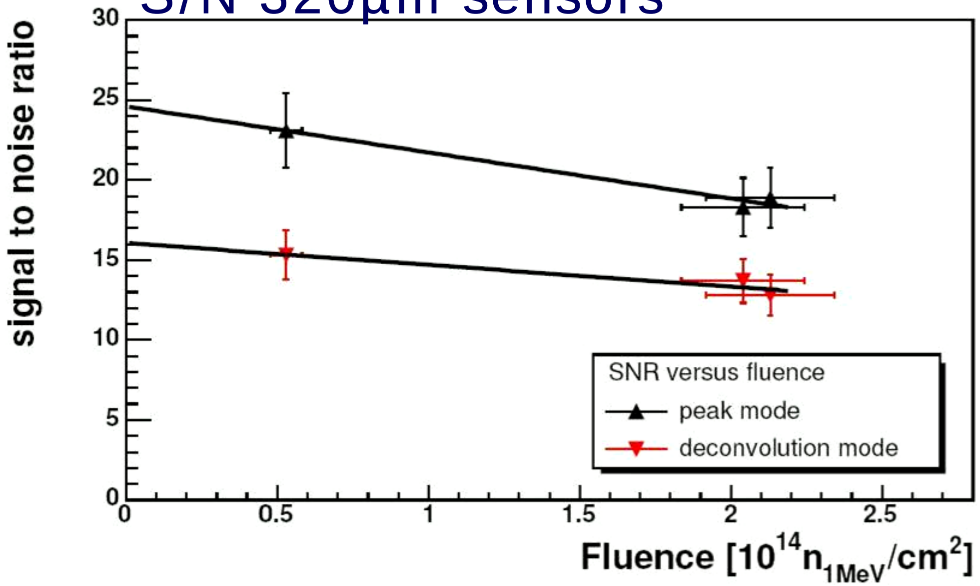
S/N 500µm sensors



depletion voltage



S/N 320µm sensors

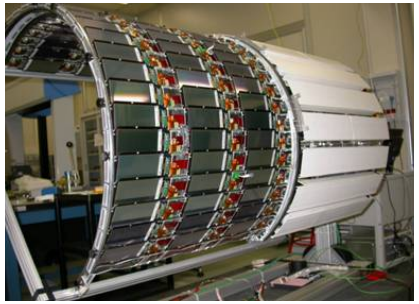


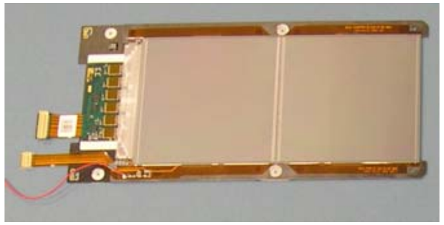
Integration of Modules into Subsystems

modules

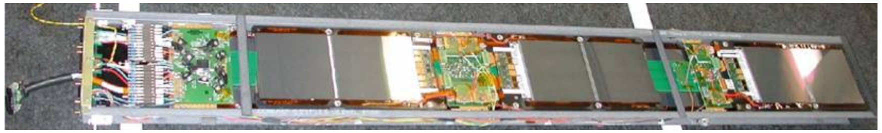
2724+816

TIB





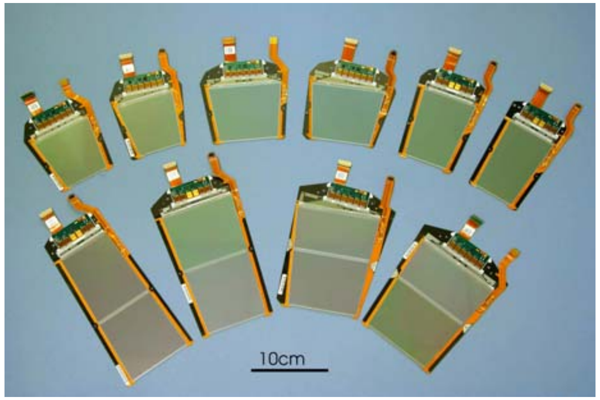
rod



5208

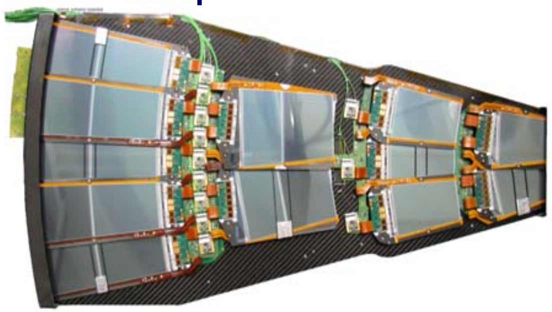
688

TOB



6400

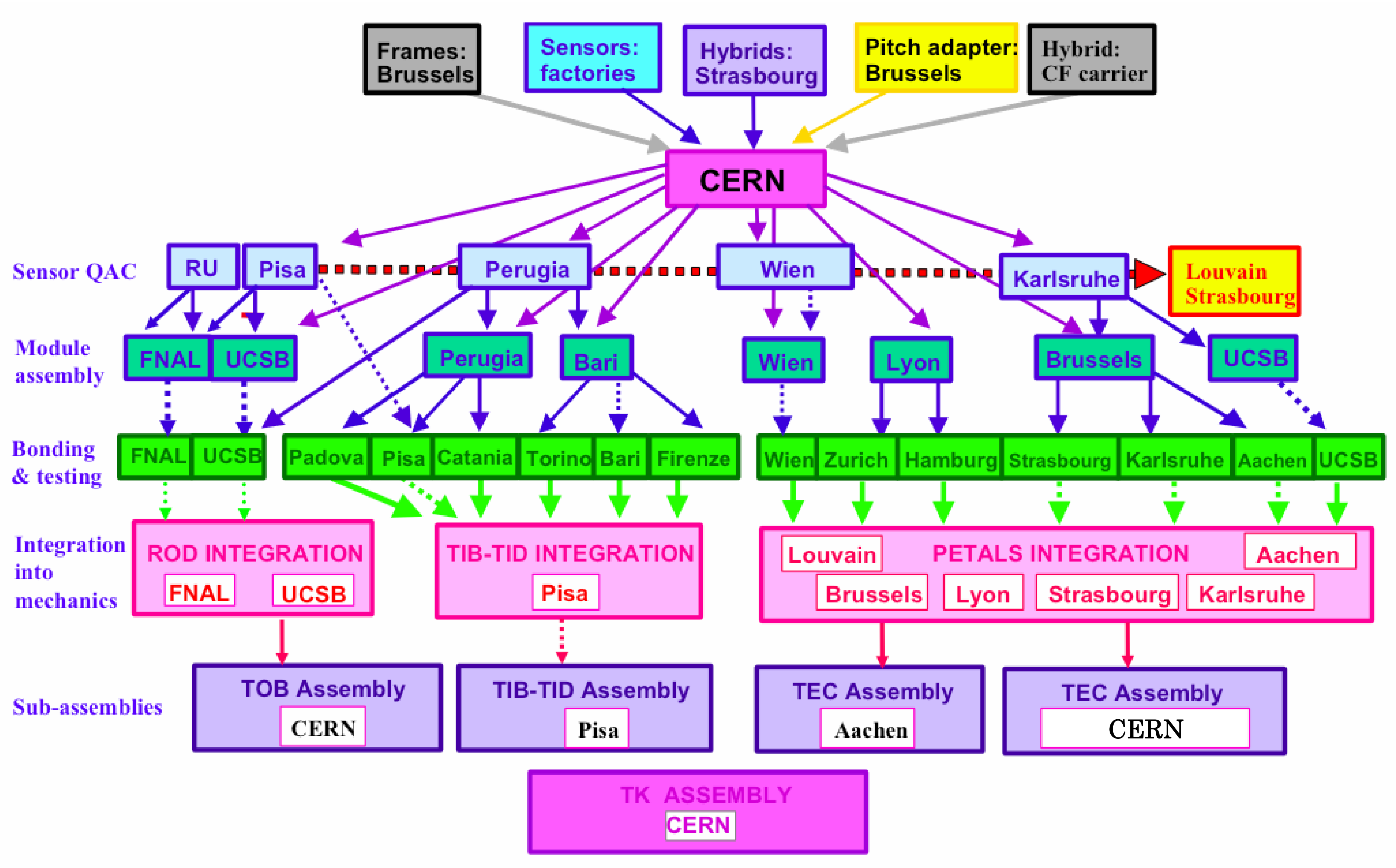
petal



288

TEC (x2)

CMS Tracker Logistics



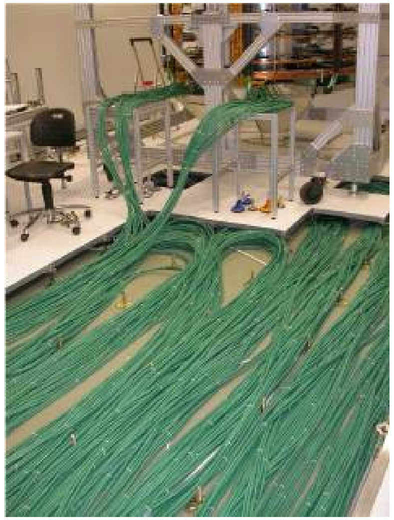
TEC Integration: what is needed

144 petals

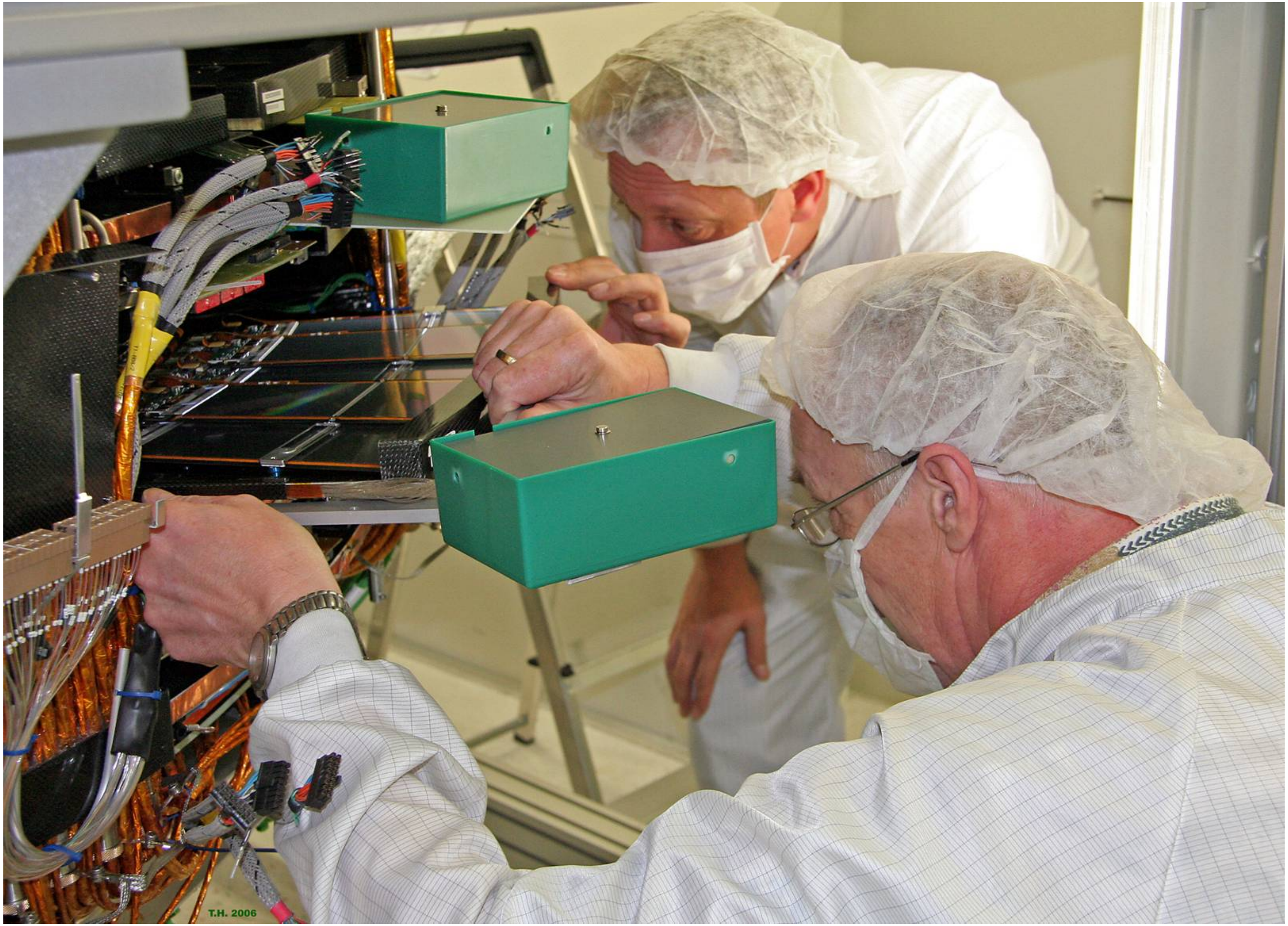
a large clean room

an empty TEC

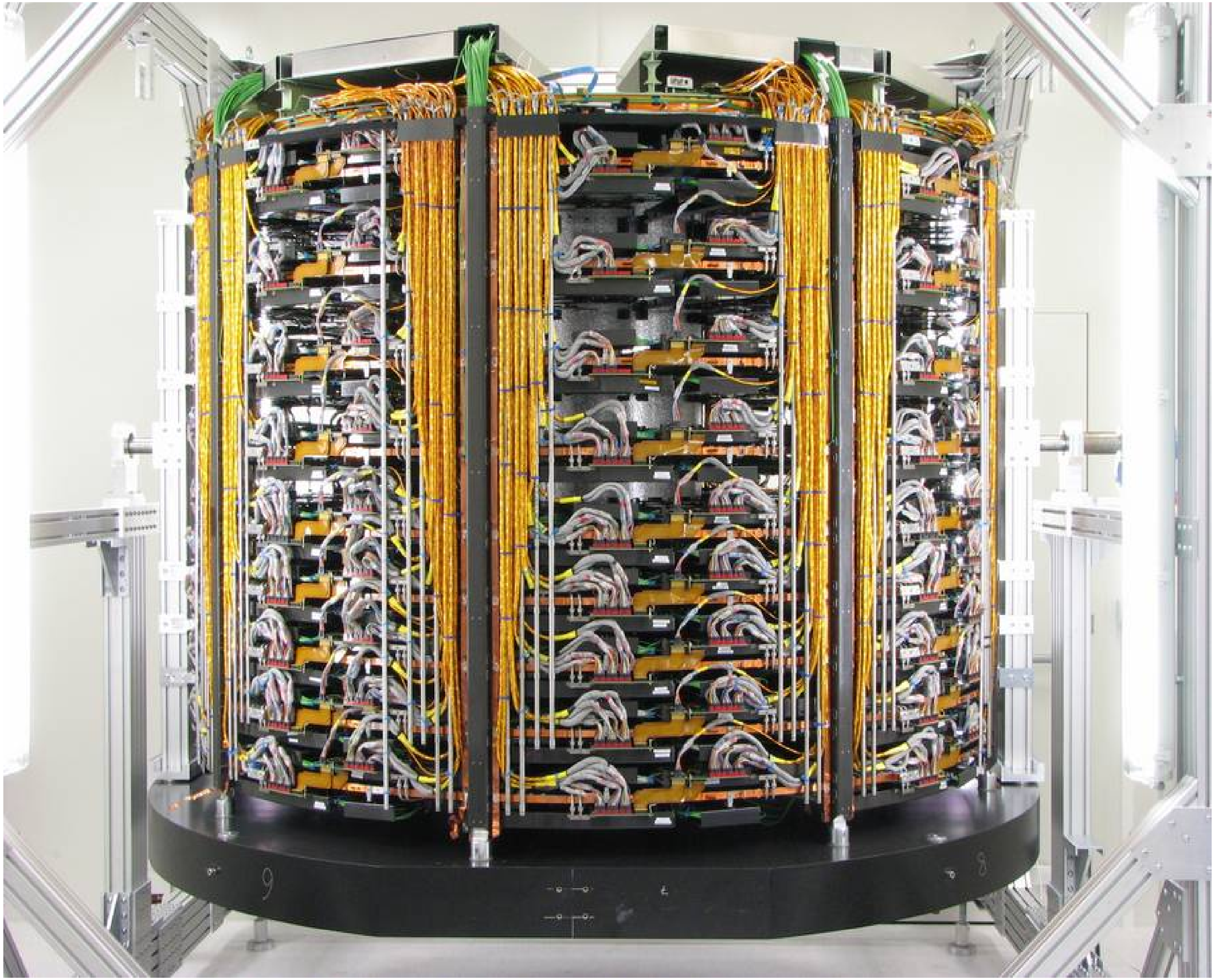
and a huge test system: read-out for 400 modules, 2.5 km final cables, cooling ...



...and skilled people



Finished TEC+ in Aachen



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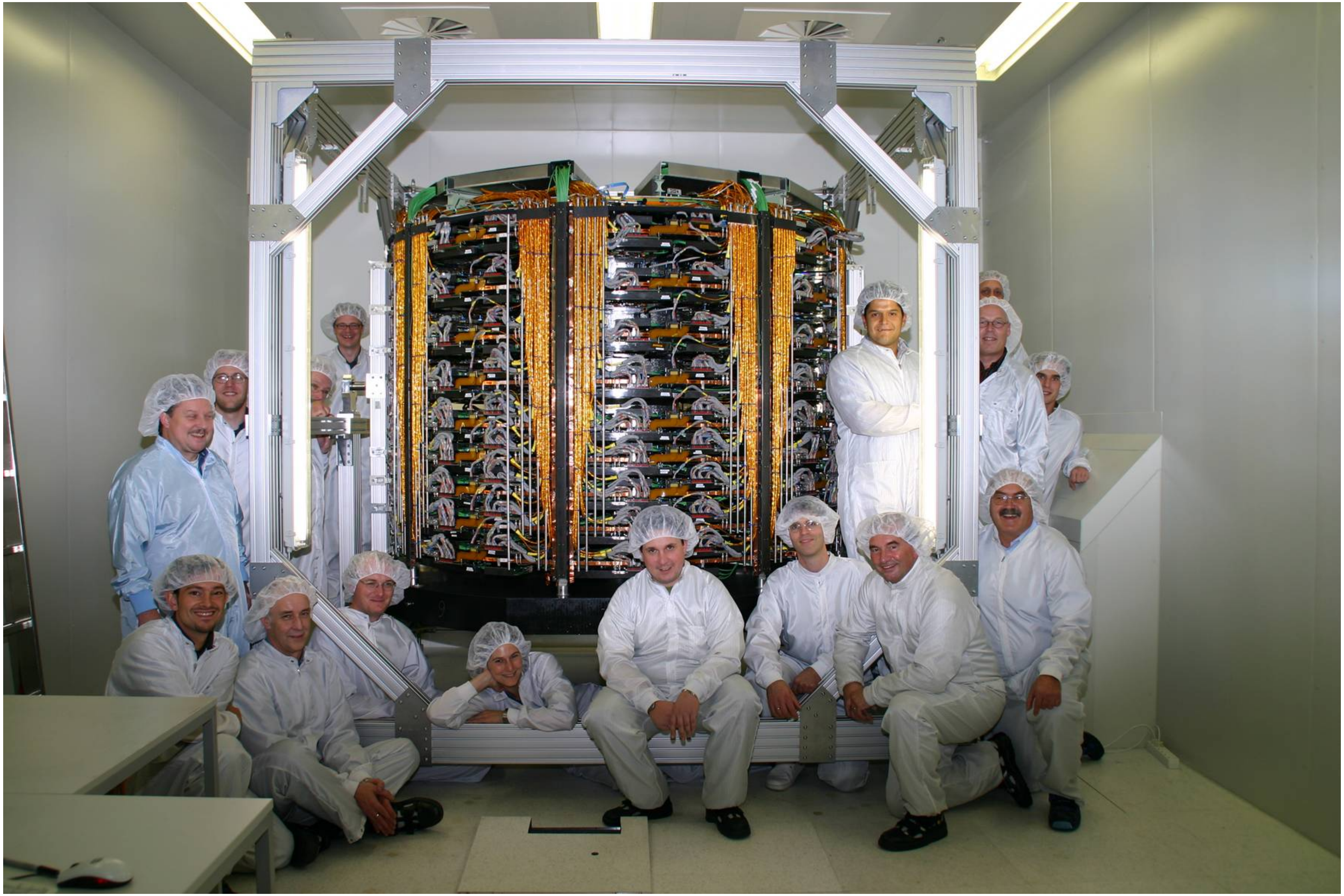
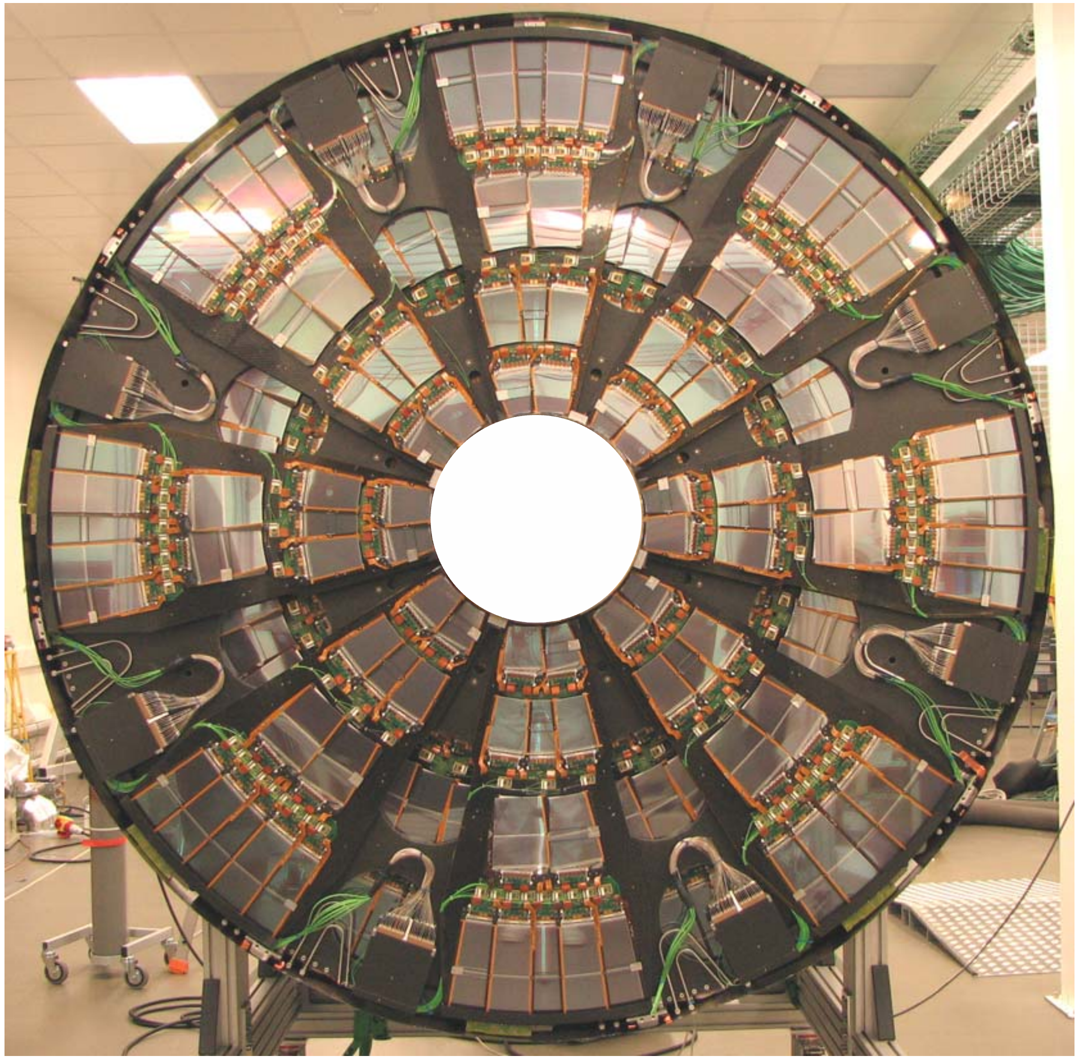
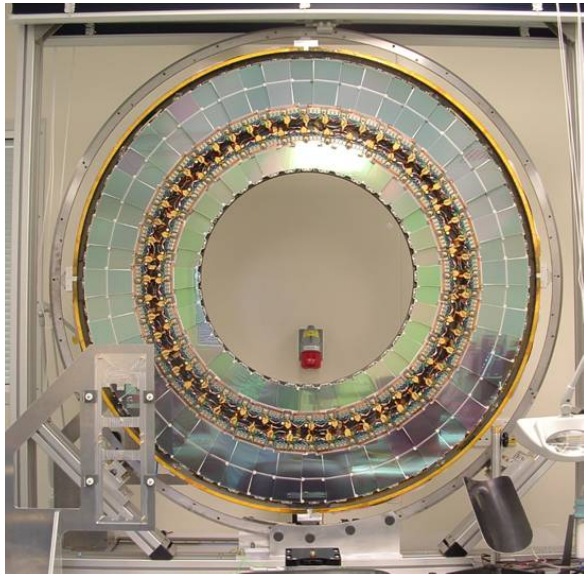


...and at CERN



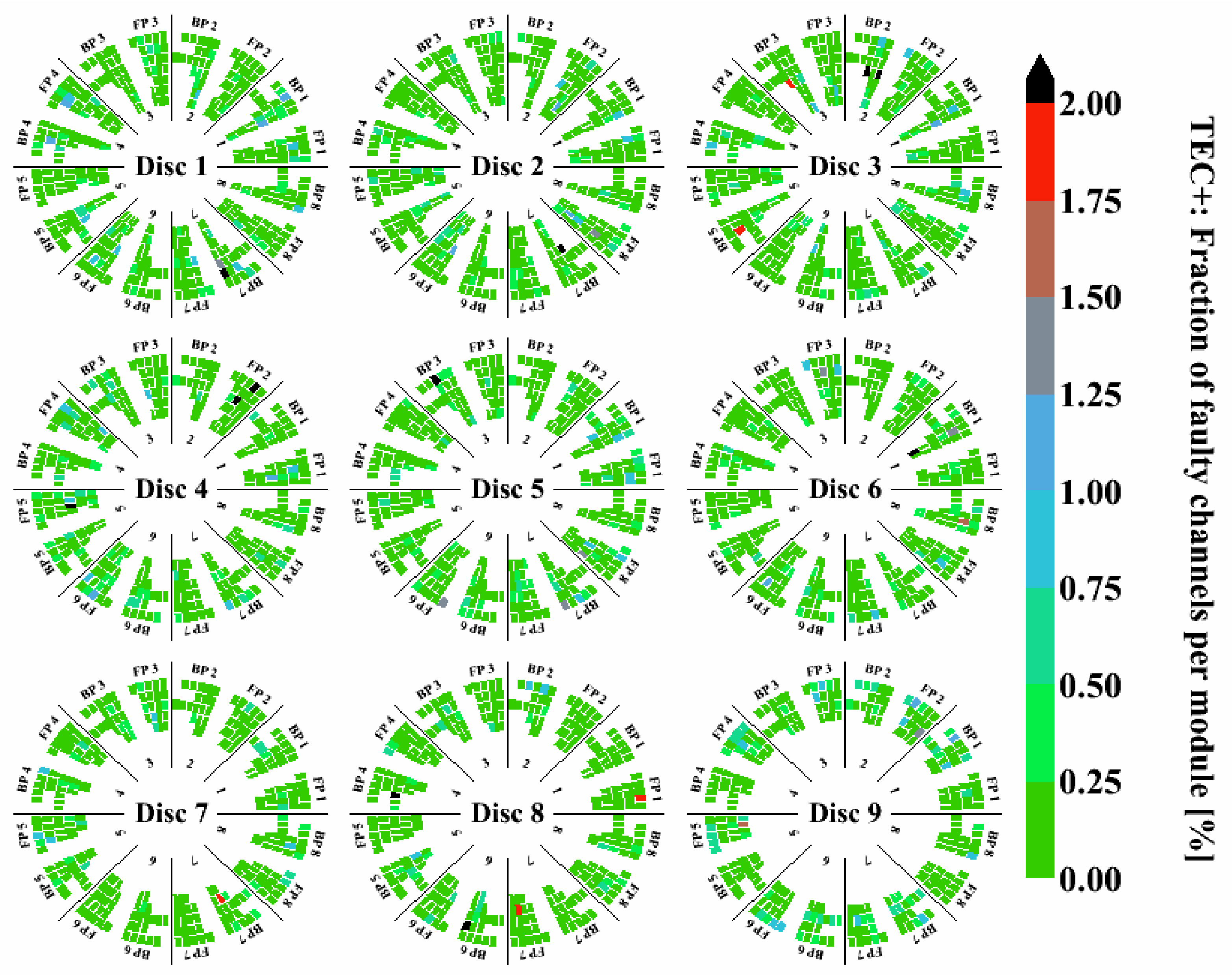
modular structure:
petals as self-contained, pre-tested units



“monolithic” structure:
modules mounted onto disks

Performance of integrated Structures

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

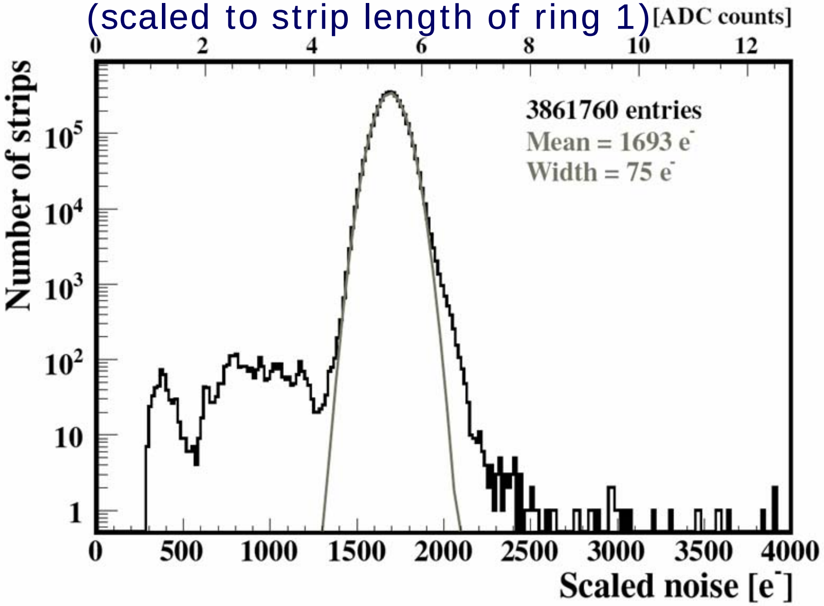


Performance of integrated Structures

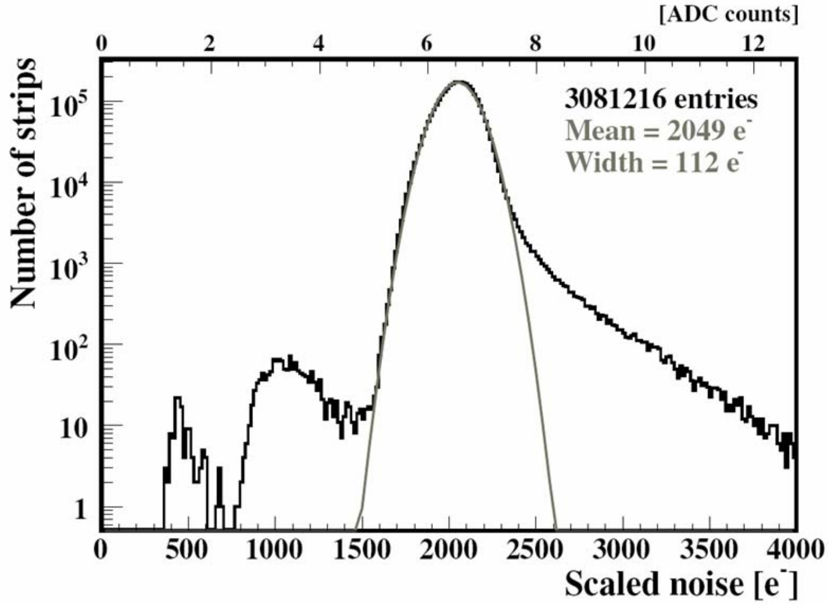
noise of (almost) all channels in the CMS tracker (25 ns mode)

TEC

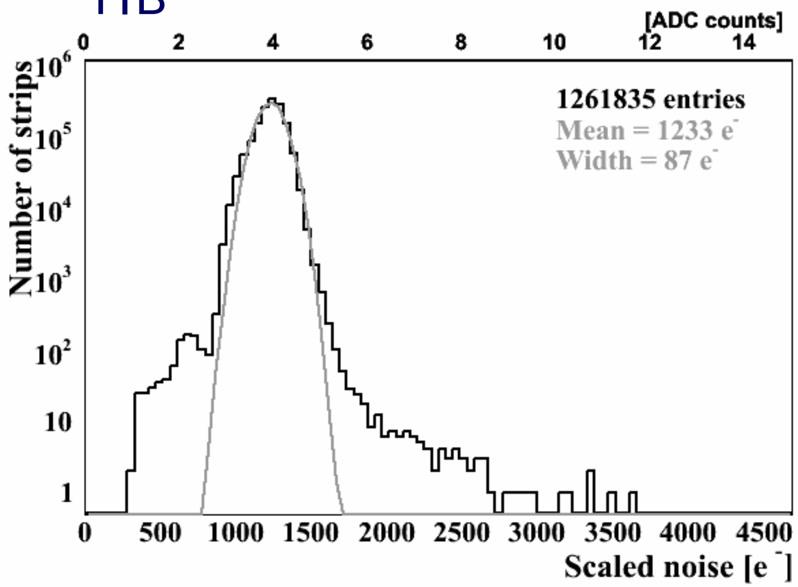
(scaled to strip length of ring 1)



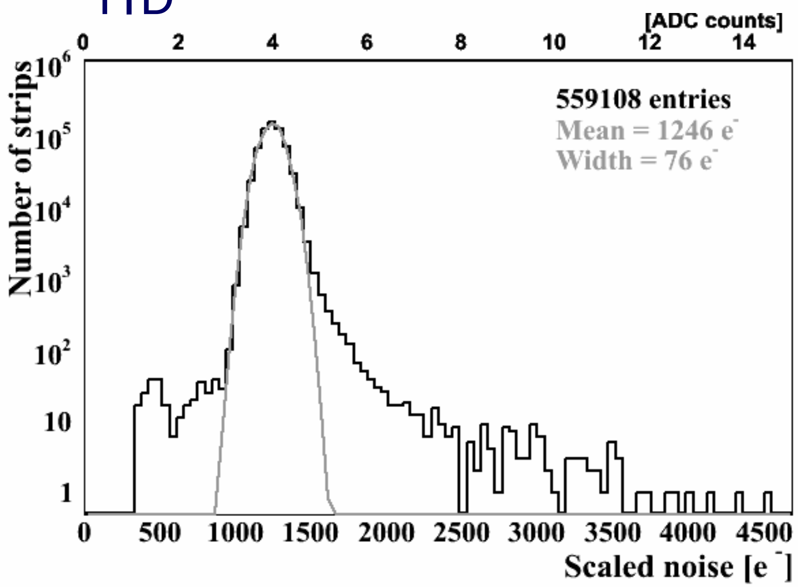
TOB



TIB

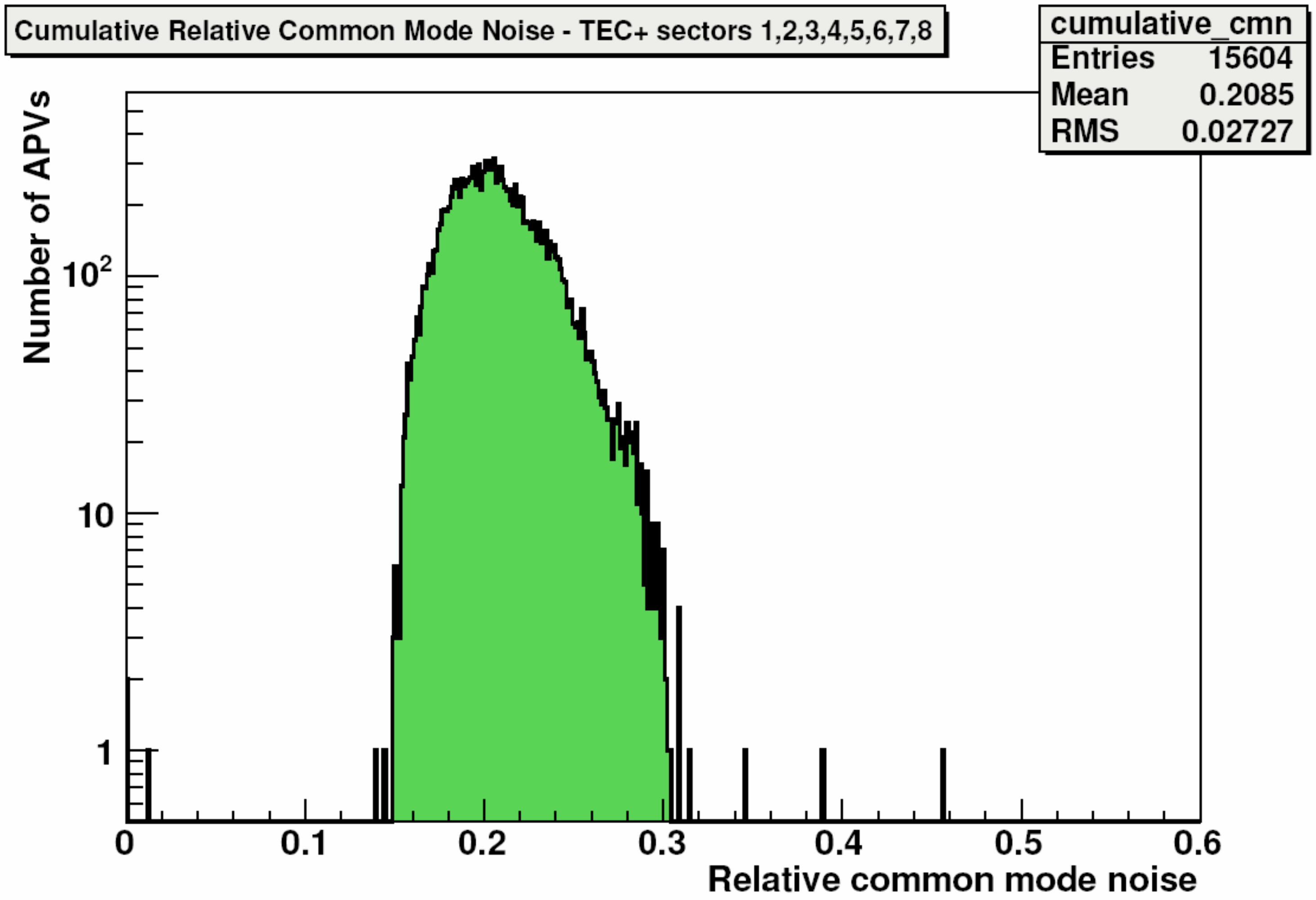


TID



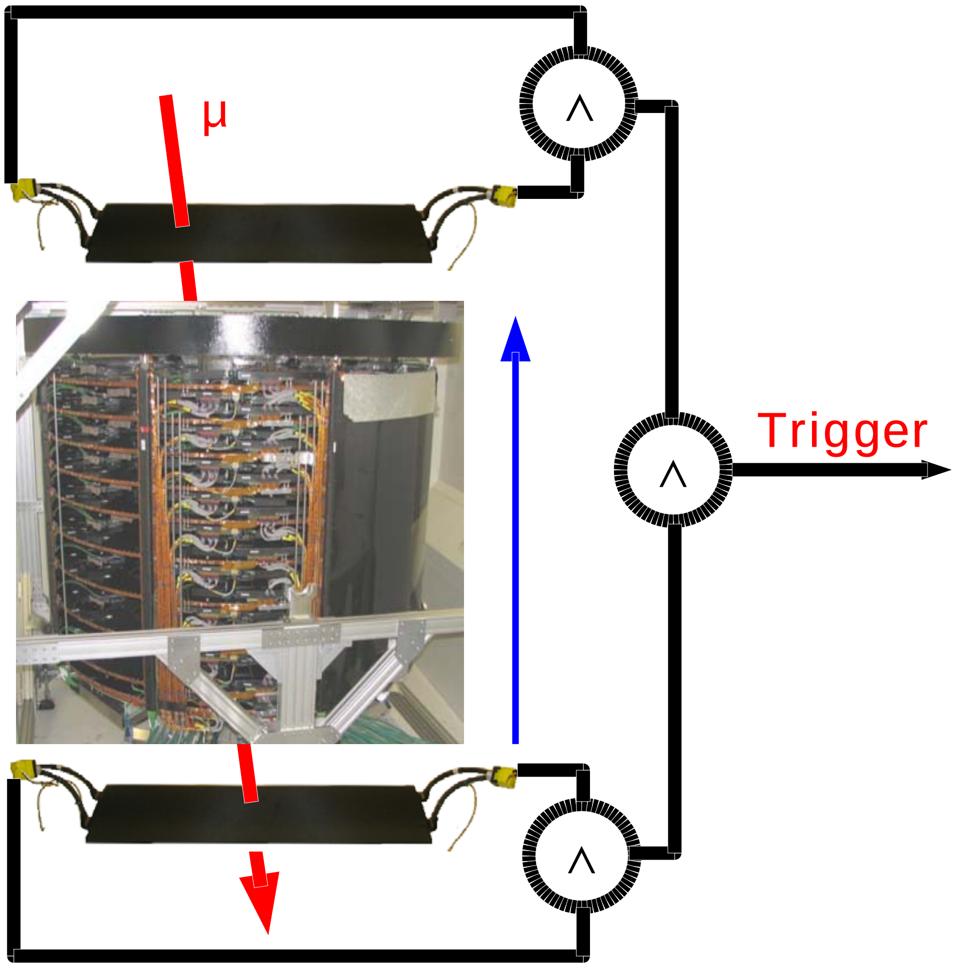
Performance of integrated Structures

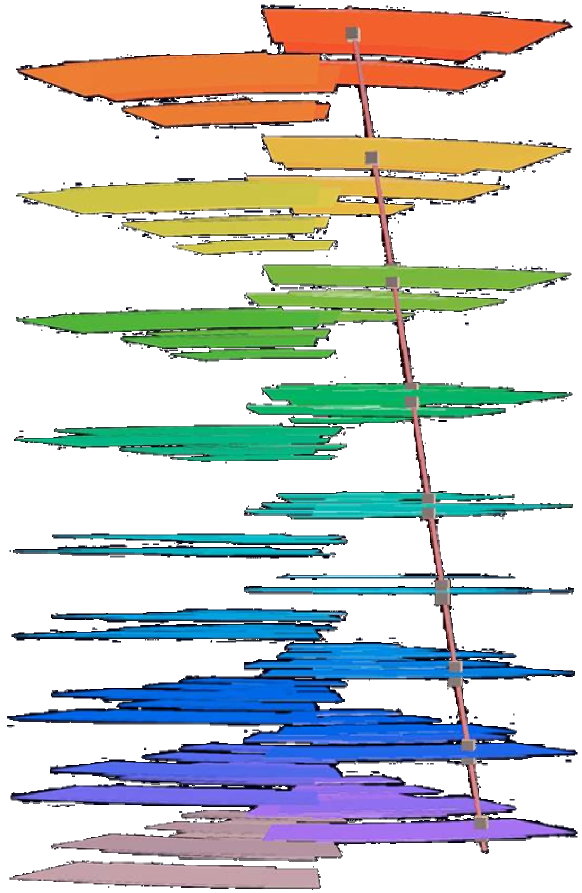
common mode noise relative to intrinsic noise: less than 30%



Performance of integrated Structures

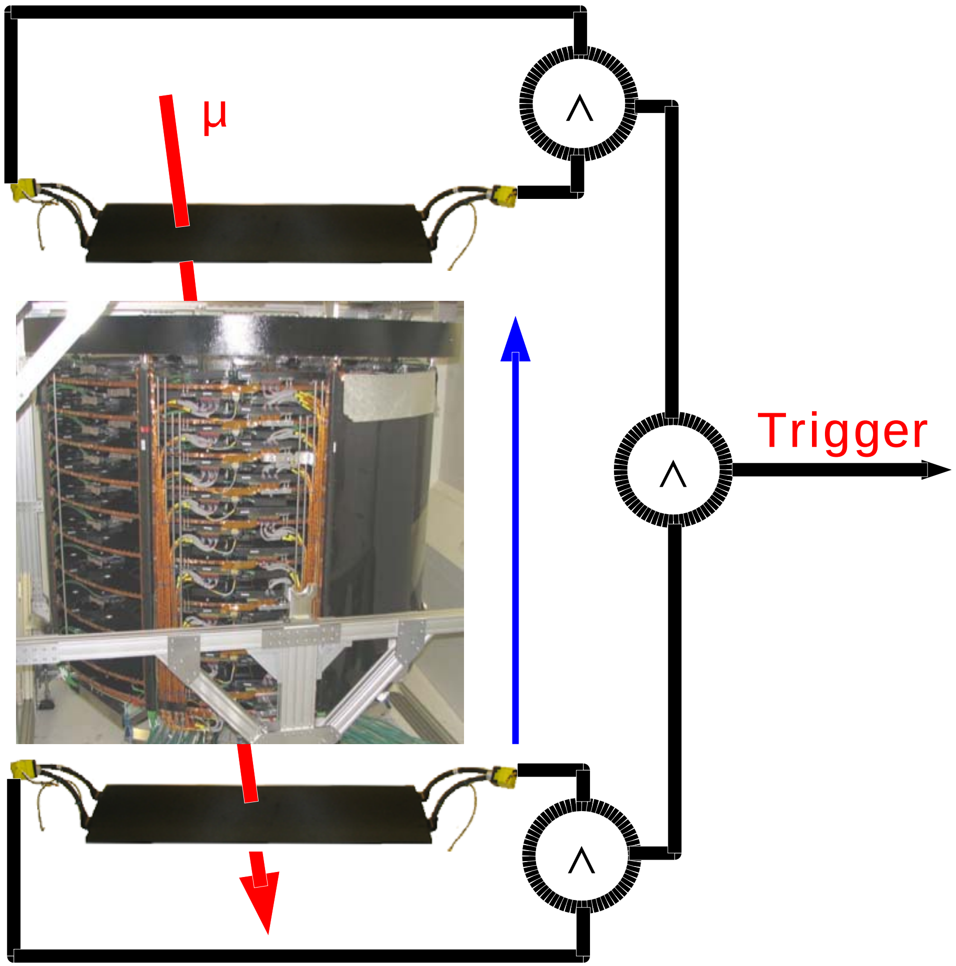
cosmic muons recorded in one end cap

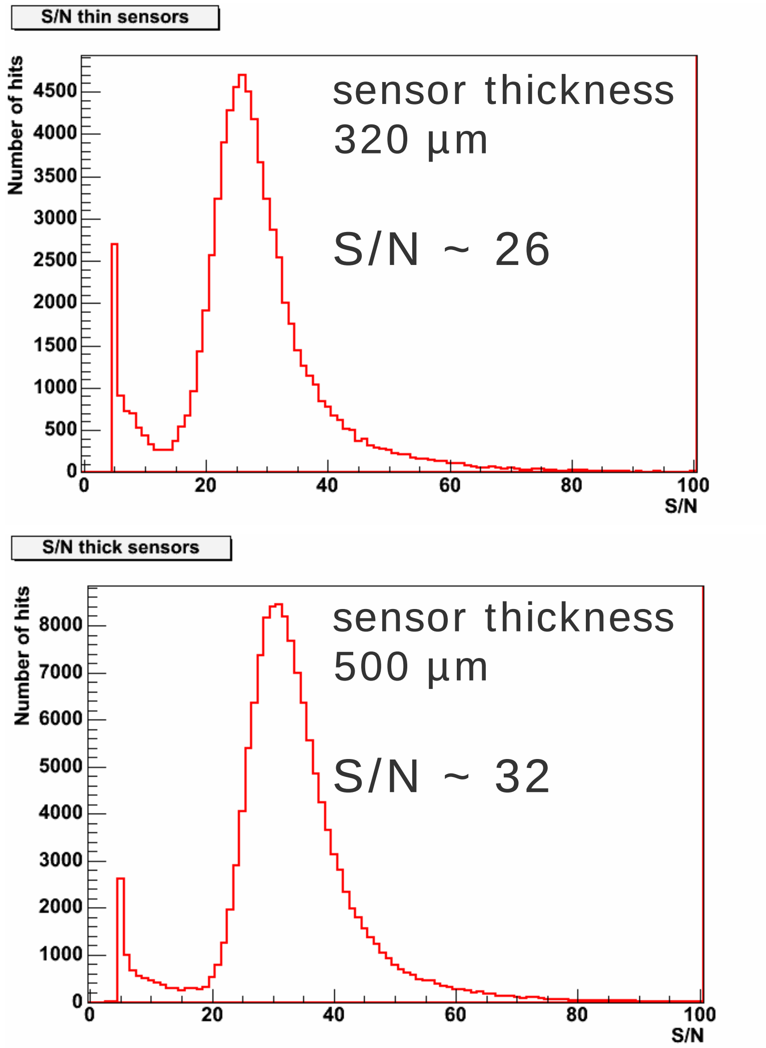




Performance of integrated Structures

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

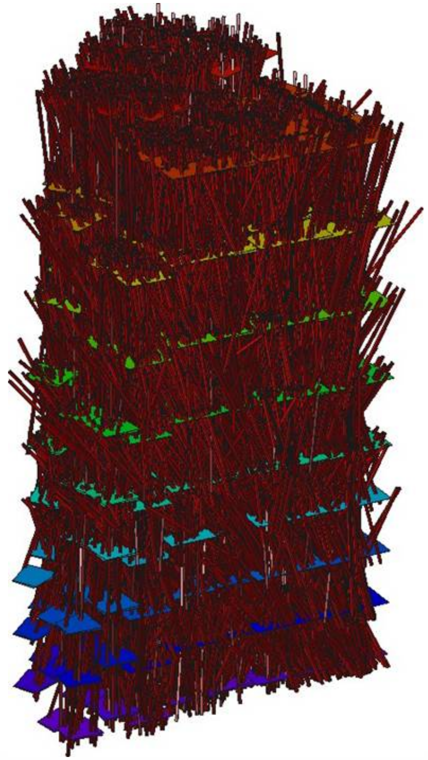




caveats: muons are not exactly MIPs
rough timing adjustment

Tracker Alignment

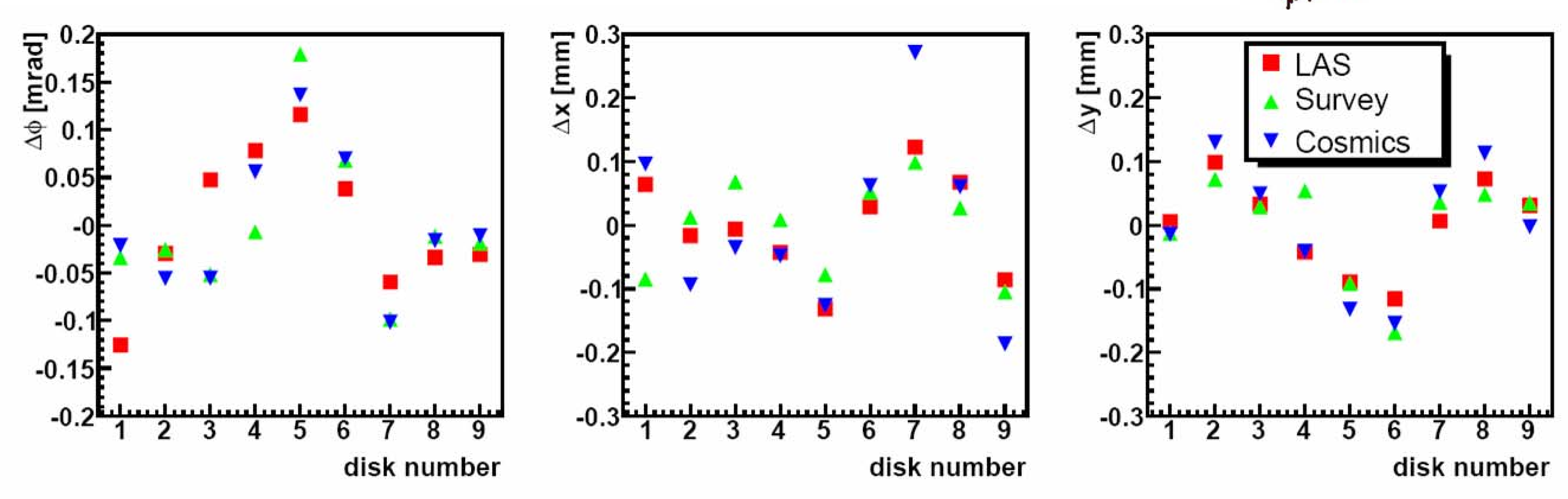
cosmic muon tracks in TEC+ can be used to align this part of the CMS tracker before installation into the tracker



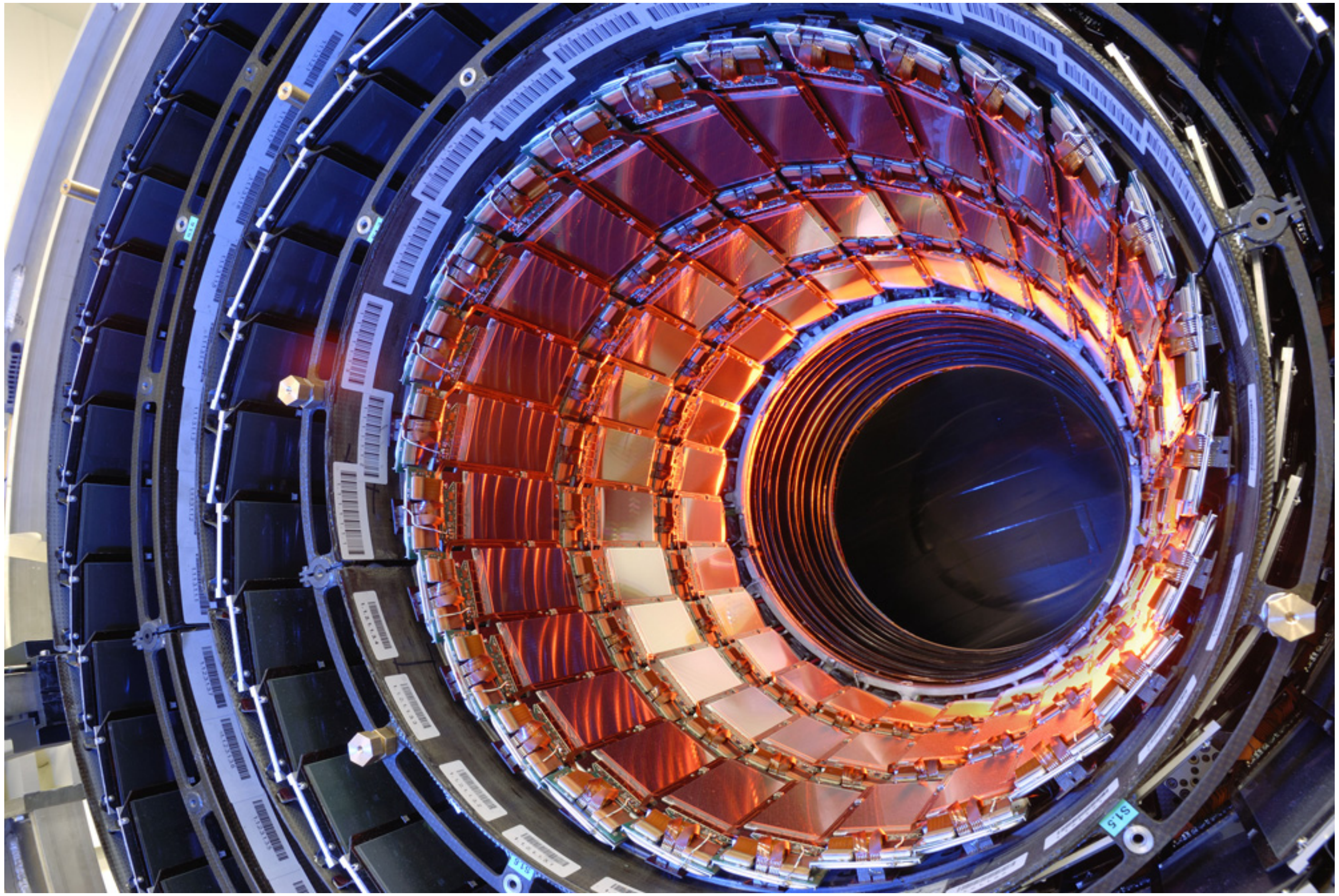
comparison to

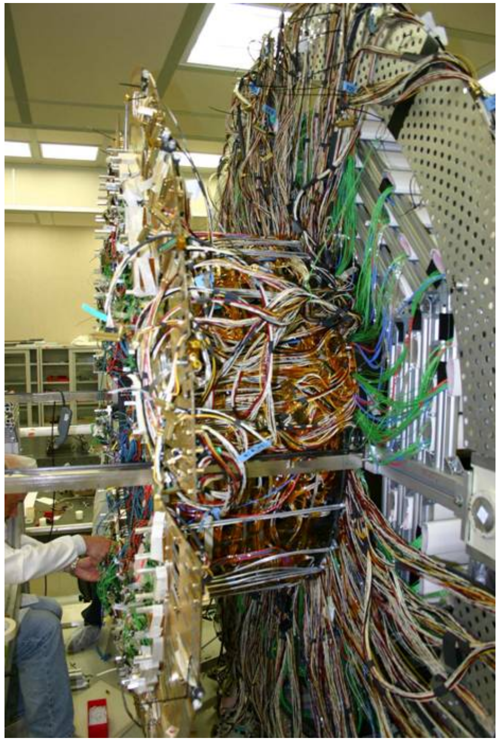
survey measurements and

laser alignment system

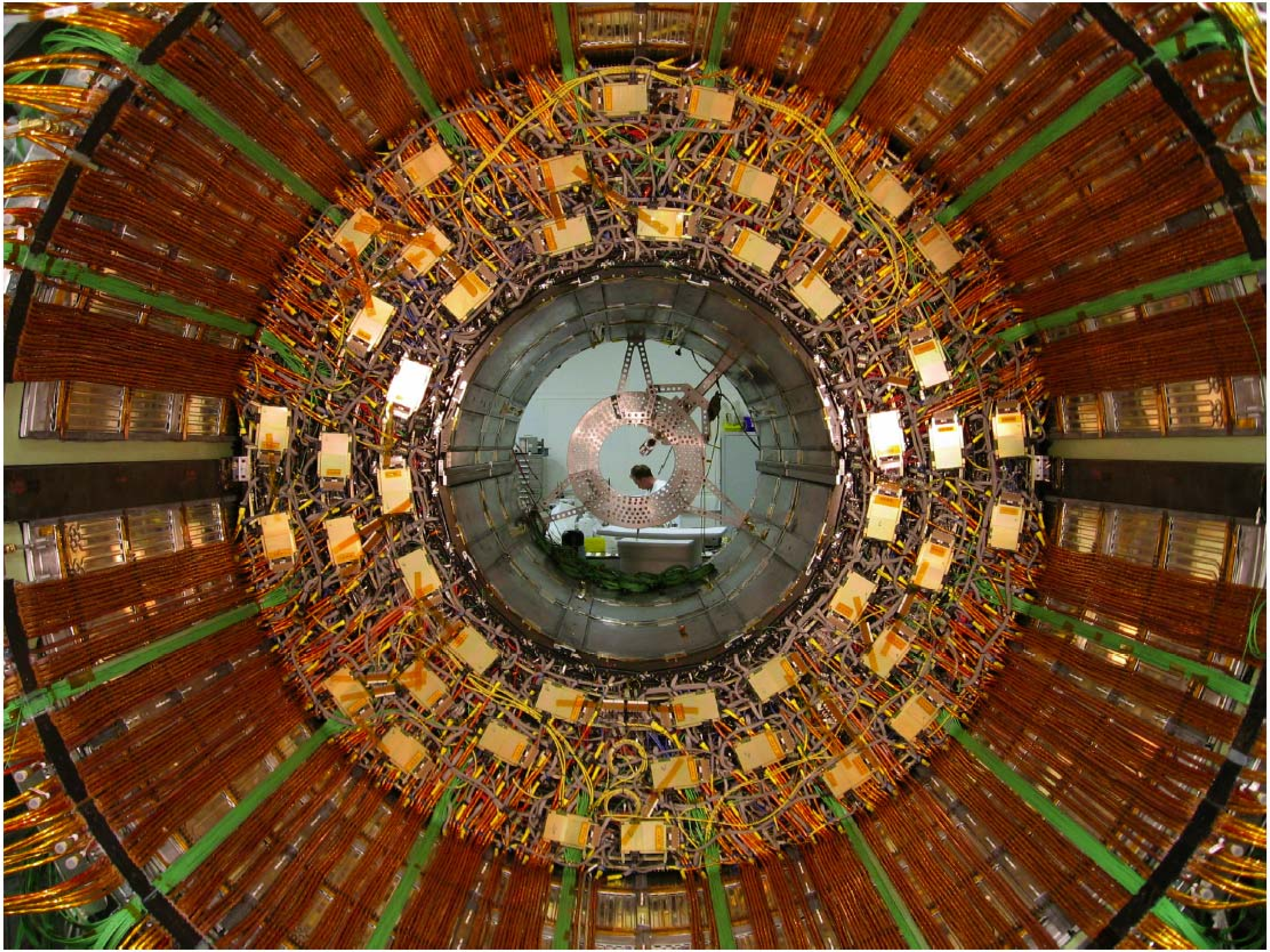


Finished TIB

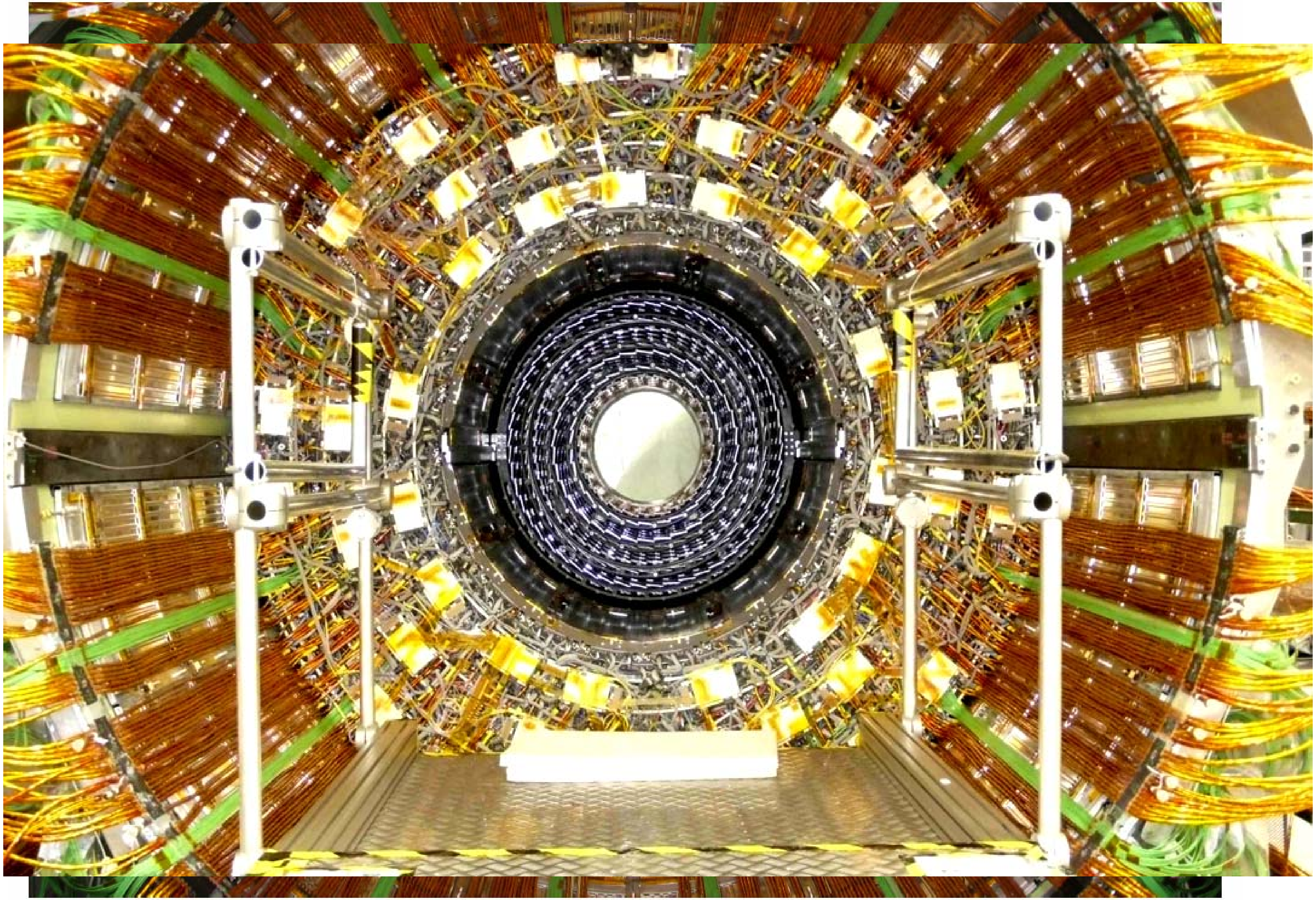




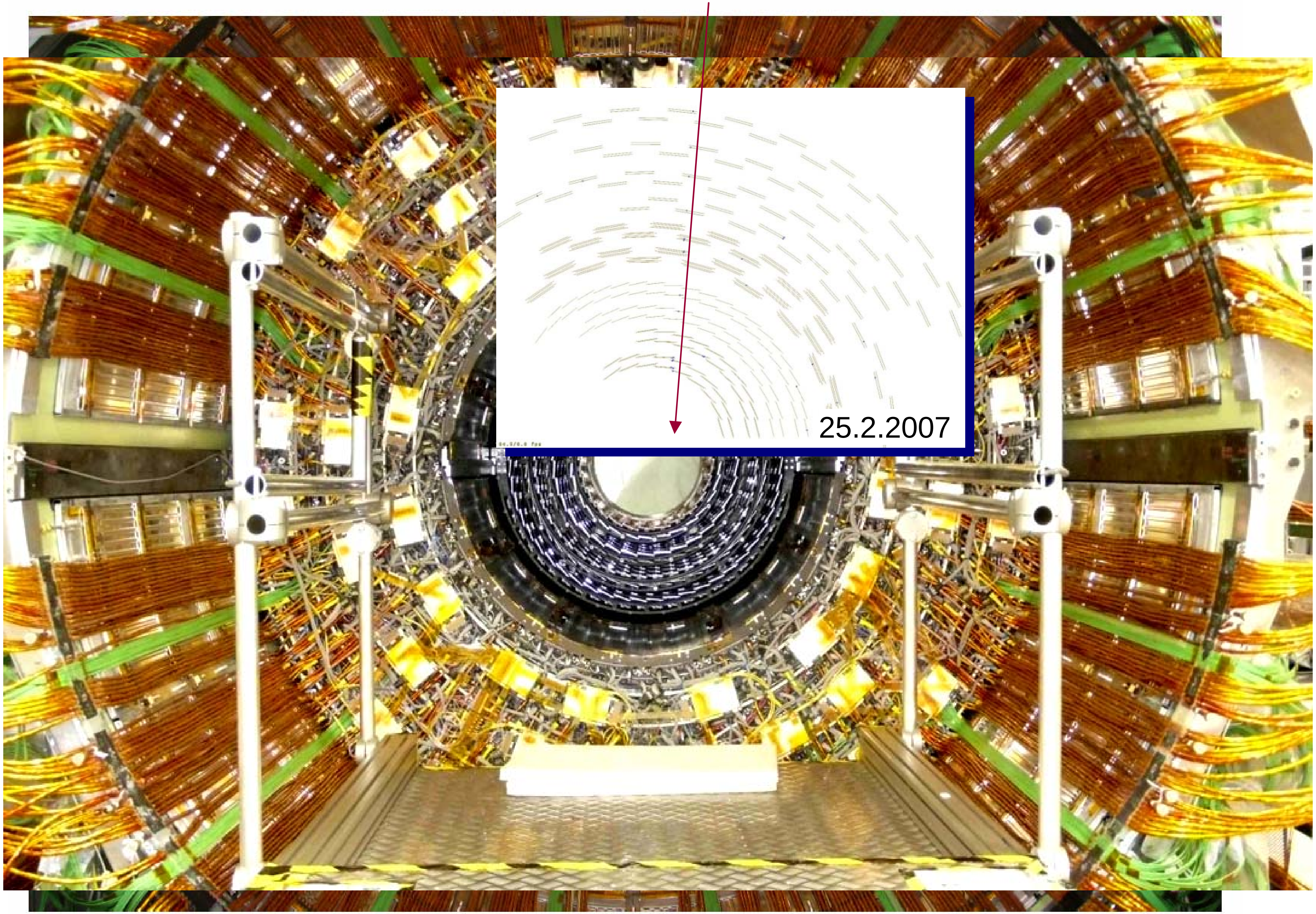
Finished TOB



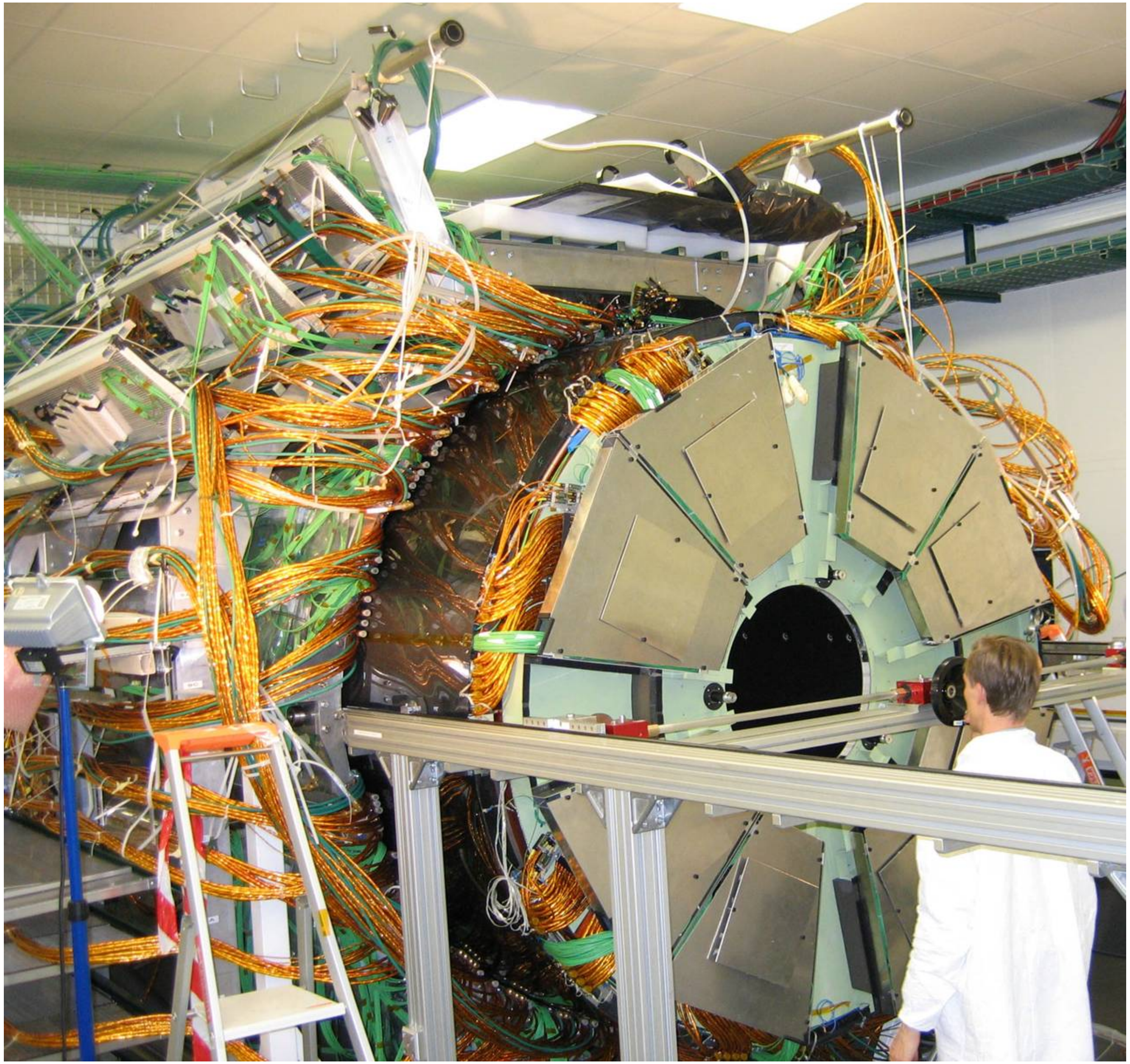
Finished TOB with TIB inside



Finished TOB with TIB inside and cosmic muon signals

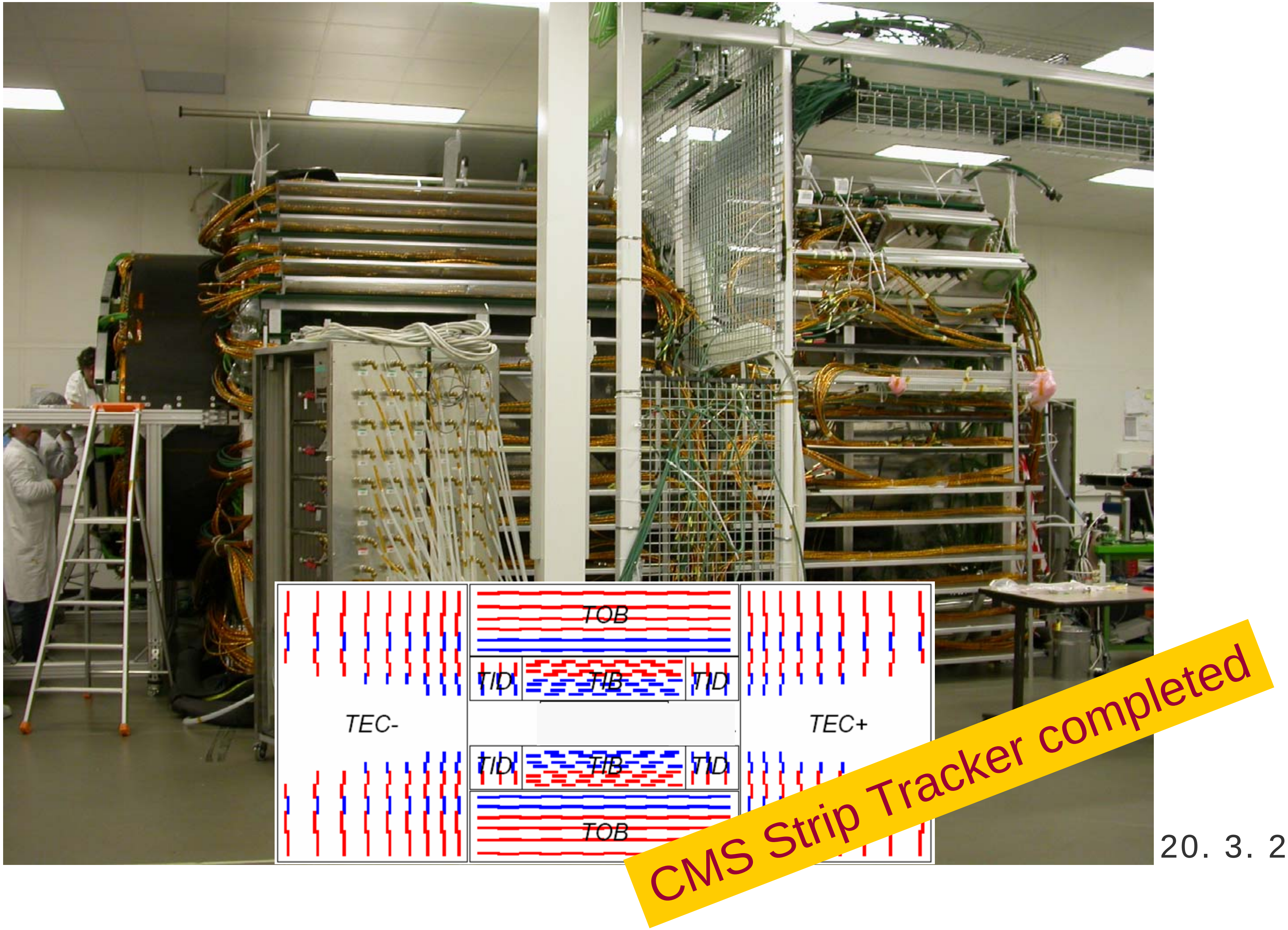


Insertion of TEC+ into the CMS Tracker



28. 2. 2007

Insertion of TEC- into the CMS Tracker



20. 3. 2007

...the CMS tracker is approaching its final destination

What have we learned?

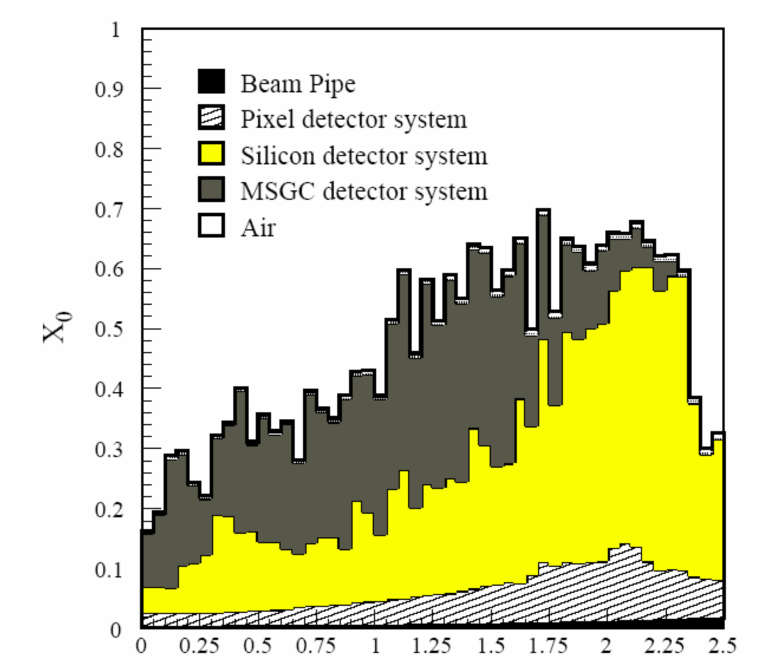
- it took about 5 years of R&D before we knew which tracker to build
- after we knew rather precisely what we wanted to build
  it took again more than 5 years to actually do it
- decisions which at the time seemed rather late and risky (move to all silicon tracker, change of ASIC to deep sub-micron 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 seemed to be a never ending story actually came to an end

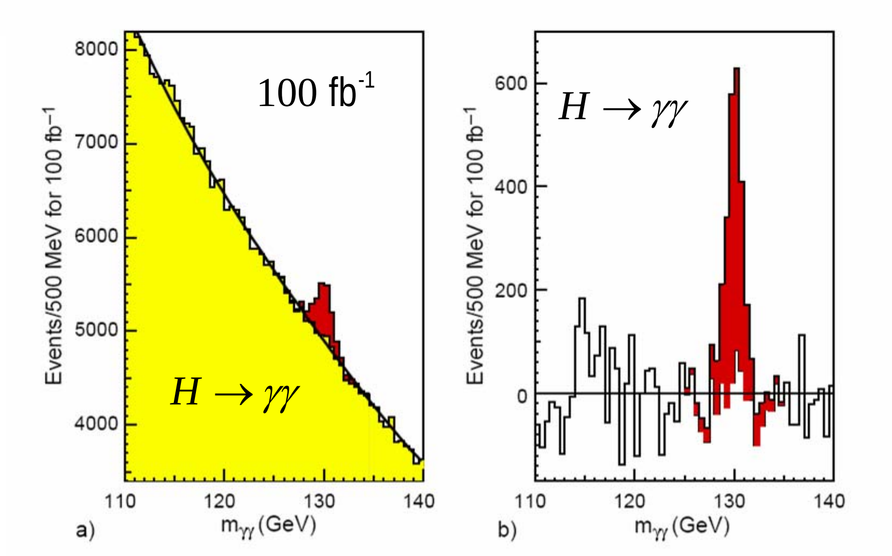
What went wrong?

- 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
- cable management in inner barrel part
- noise susceptibility of certain module positions in the outer barrel
- logistics was really difficult (partly unavoidable)

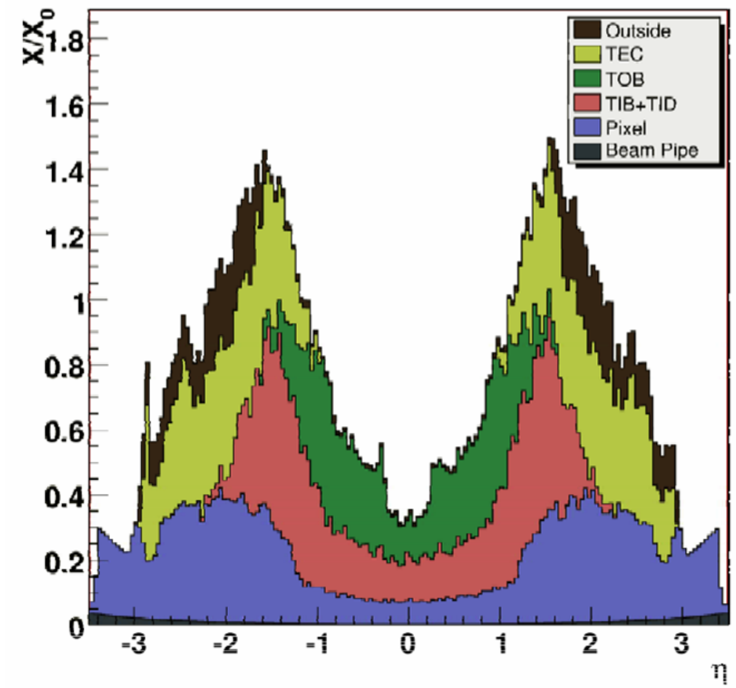
What went fundamentally wrong: Material Budget

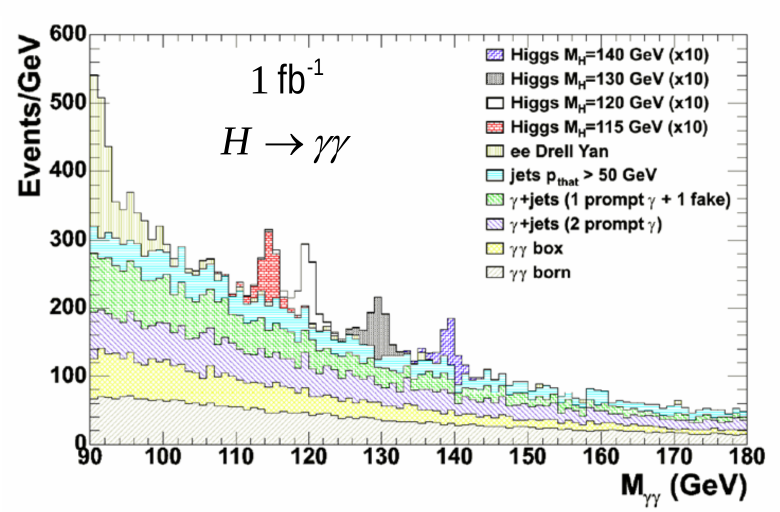
1997





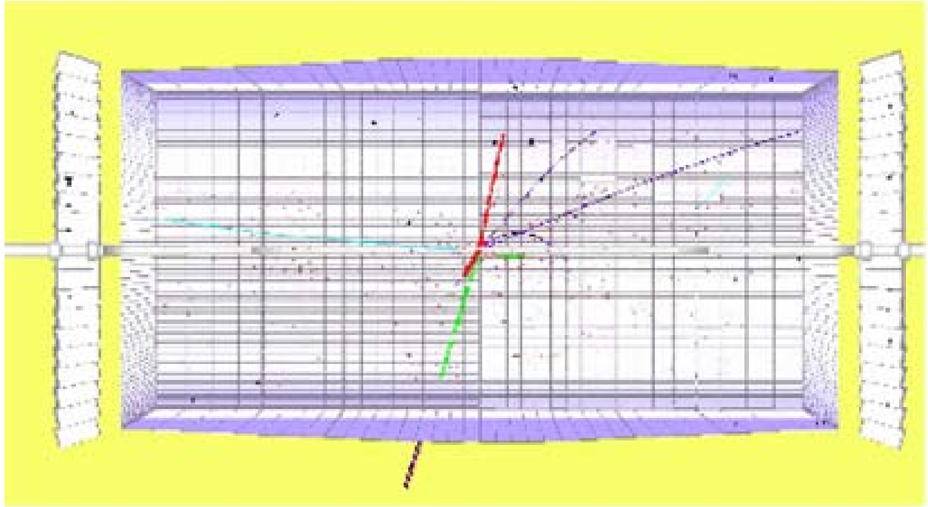
2006



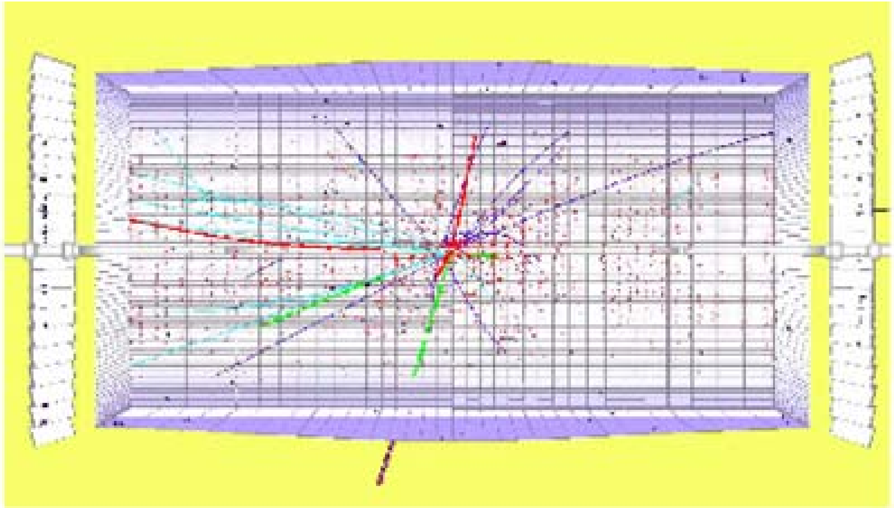


What comes next? SLHC!

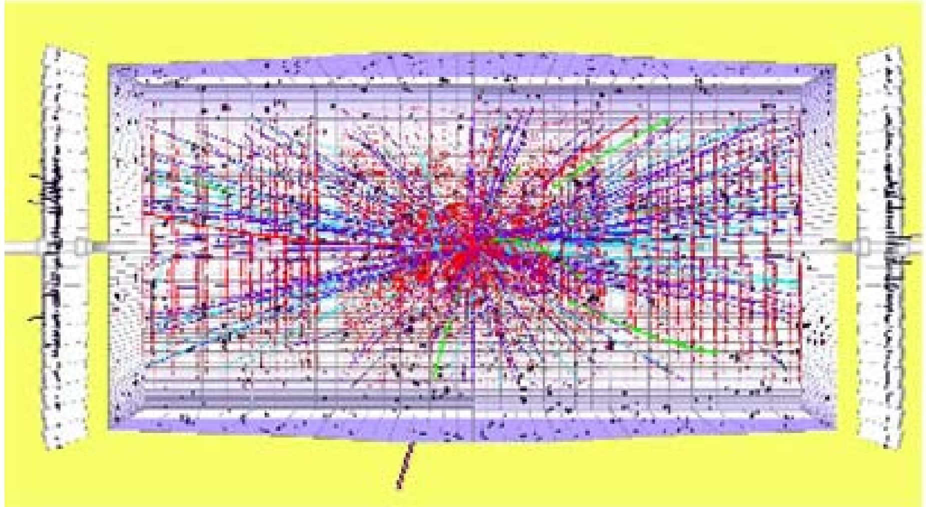
LHC start-up: 10^{32} cm^{-2} s^{-1}



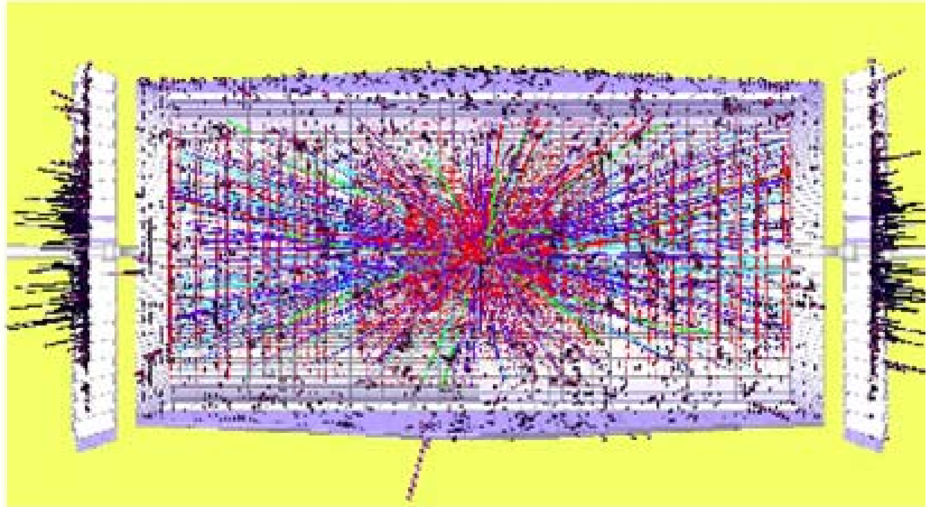
LHC first year: 10^{33} cm^{-2} s^{-1}



LHC design luminosity: 10^{34} cm^{-2} s^{-1}



SLHC design luminosity: 10^{35} cm^{-2} s^{-1}



~20 soft interactions superimposed on interesting event

~200 soft interactions superimposed on interesting event

Upgrades to SLHC Trackers

SLHC trackers need to be 10 times

- more radiation hard
- finer segmented

...many ideas (strixels, n-on-p, 3D, thinned sensors, ...)

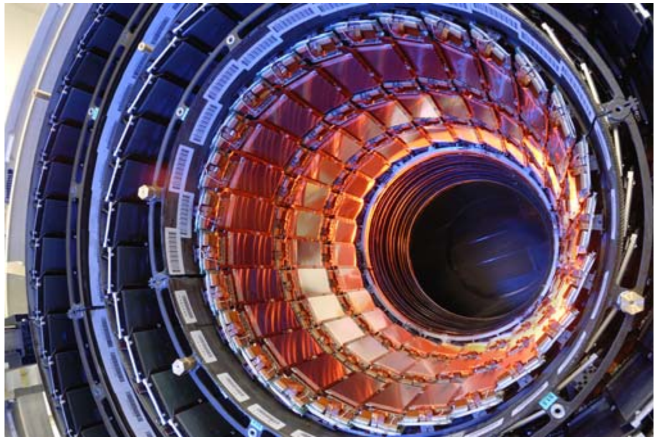
SLHC trackers need to deliver first level trigger information.

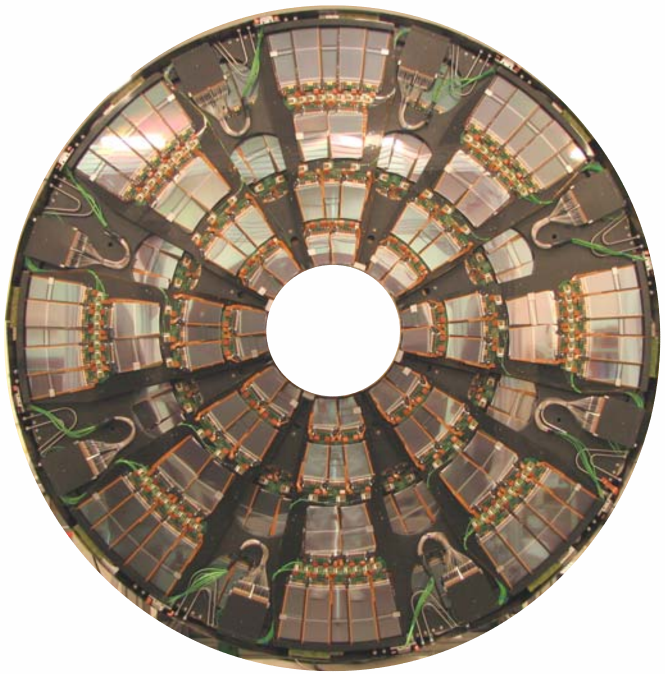
SLHC trackers will use ASICs in 0.13µm technology (or less)
→power distribution will become even more problematic

Sounds like even higher material budget, but we actually need to reduce it.

Its time to start serious R&D in order to be ready in less than 10 years.

Summary





- 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 July 2007