The CMS All Silicon Tracker

A Detector for the Exploration of the Terascale

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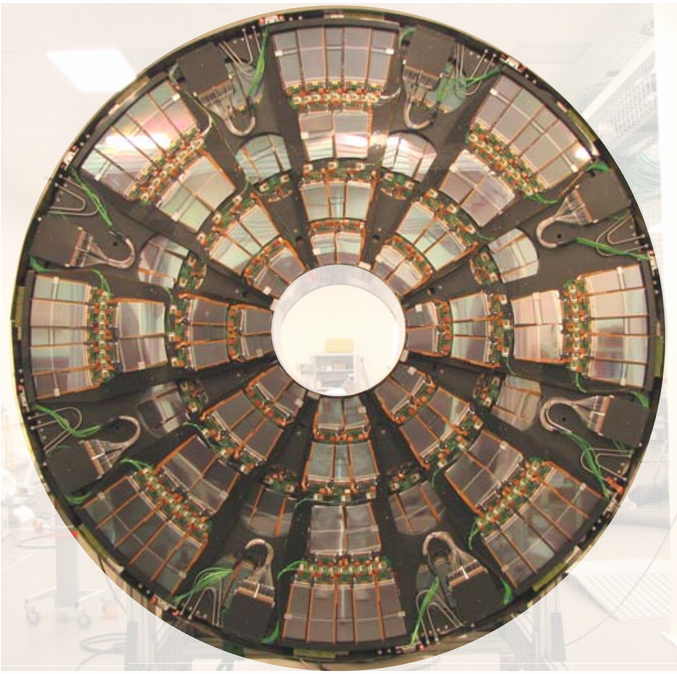
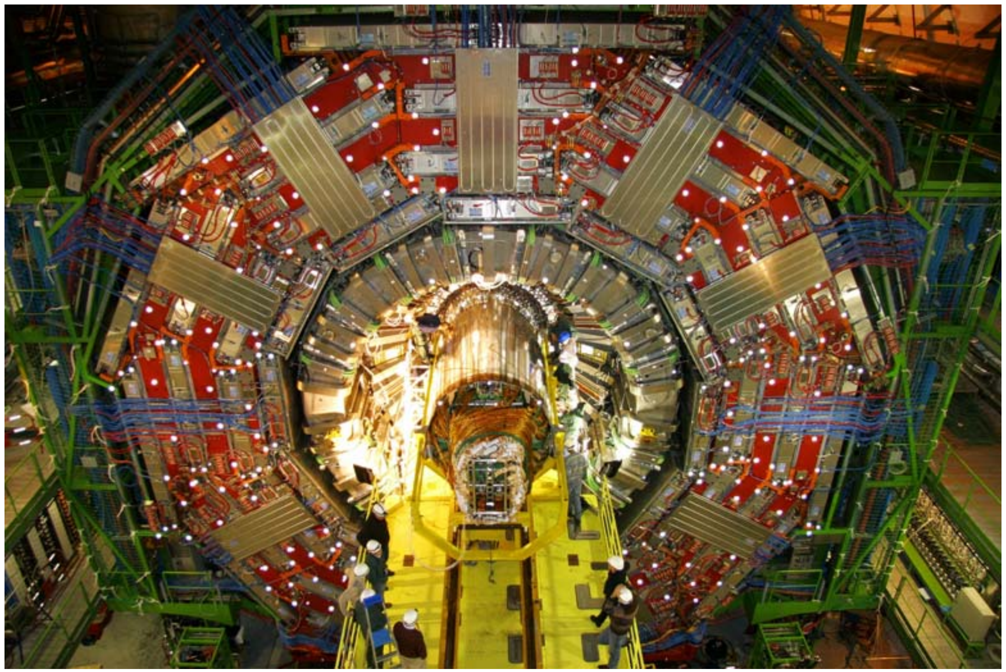
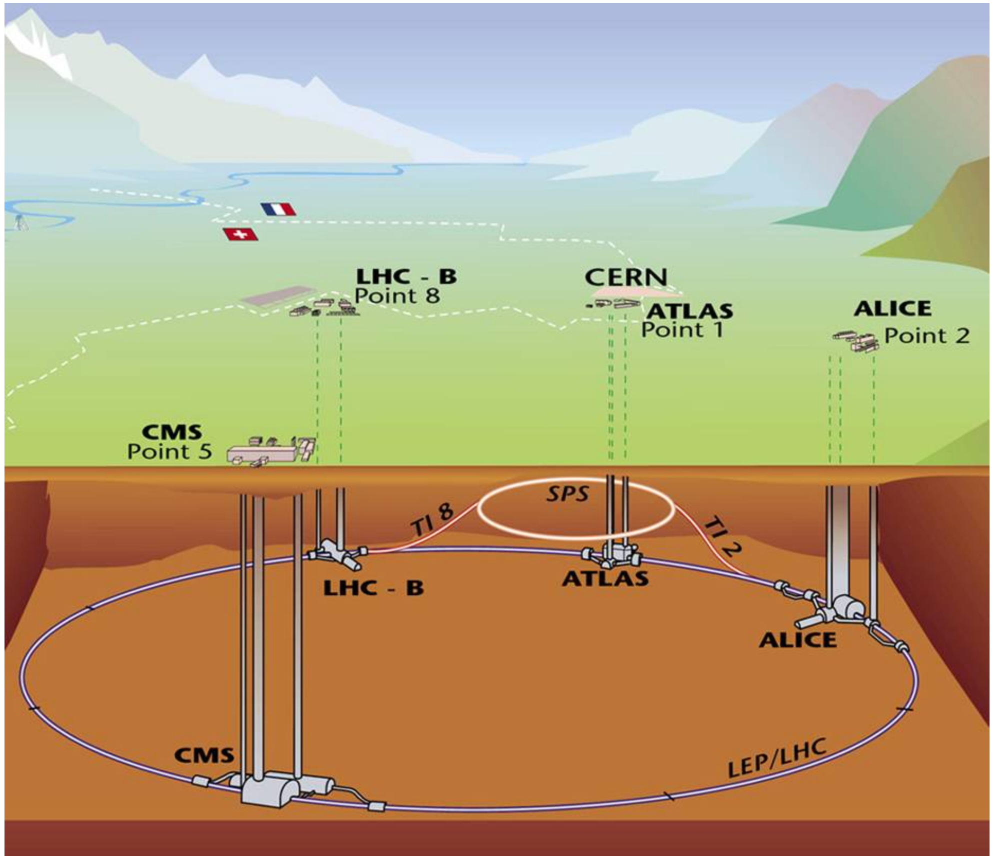
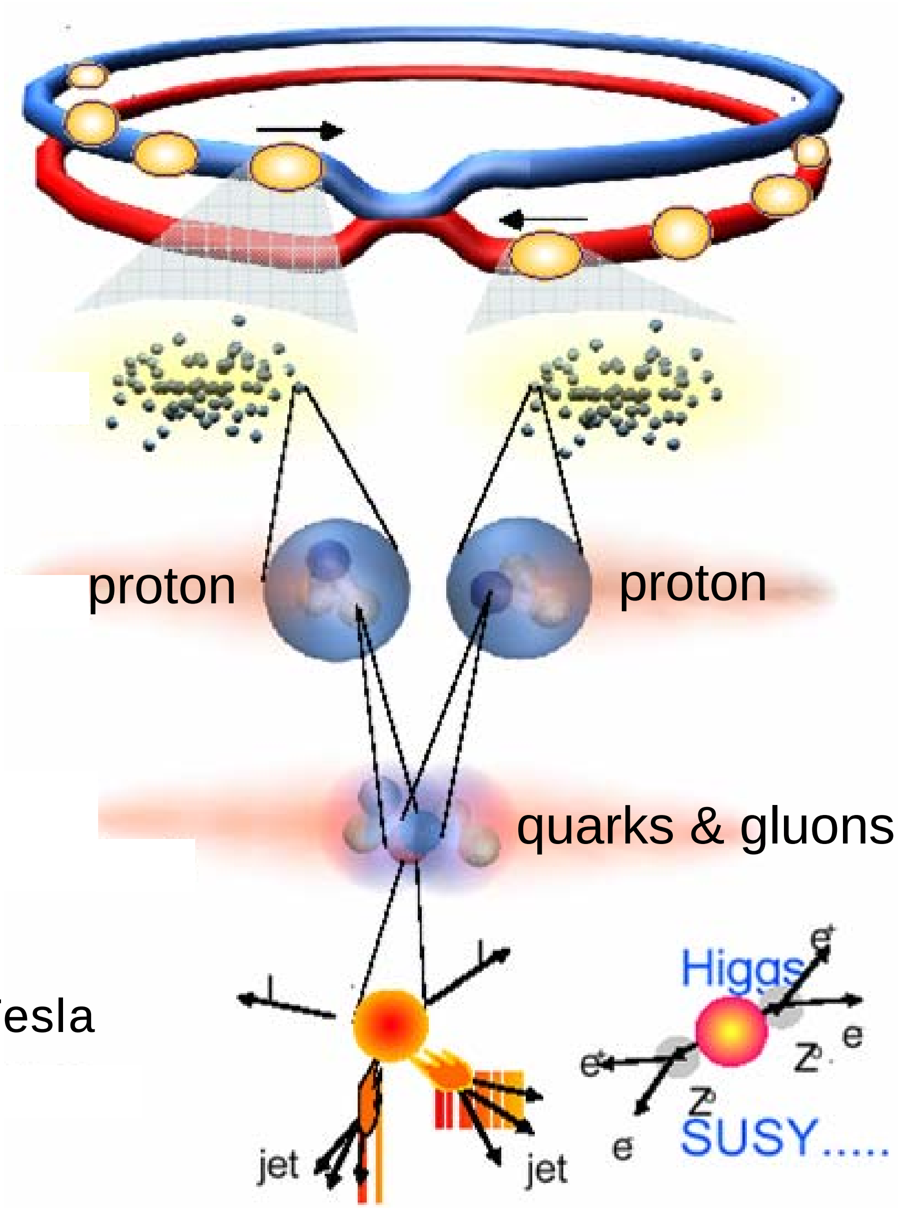
Göttingen, 25. 1. 2008





Large Hadron Collider at CERN





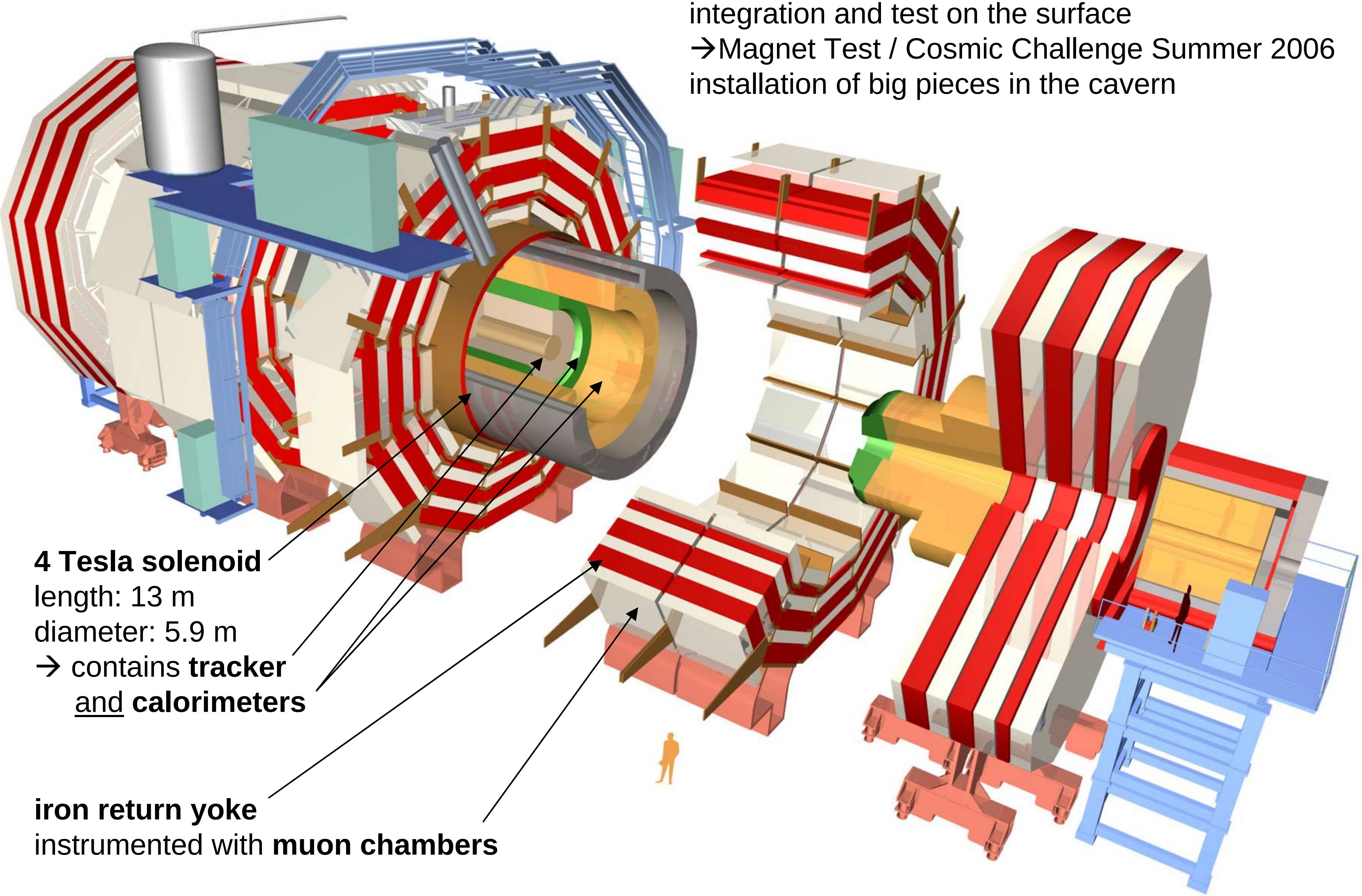
- circumference 27 km
- 1200 superconducting dipoles of 8.4 Tesla

→ 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

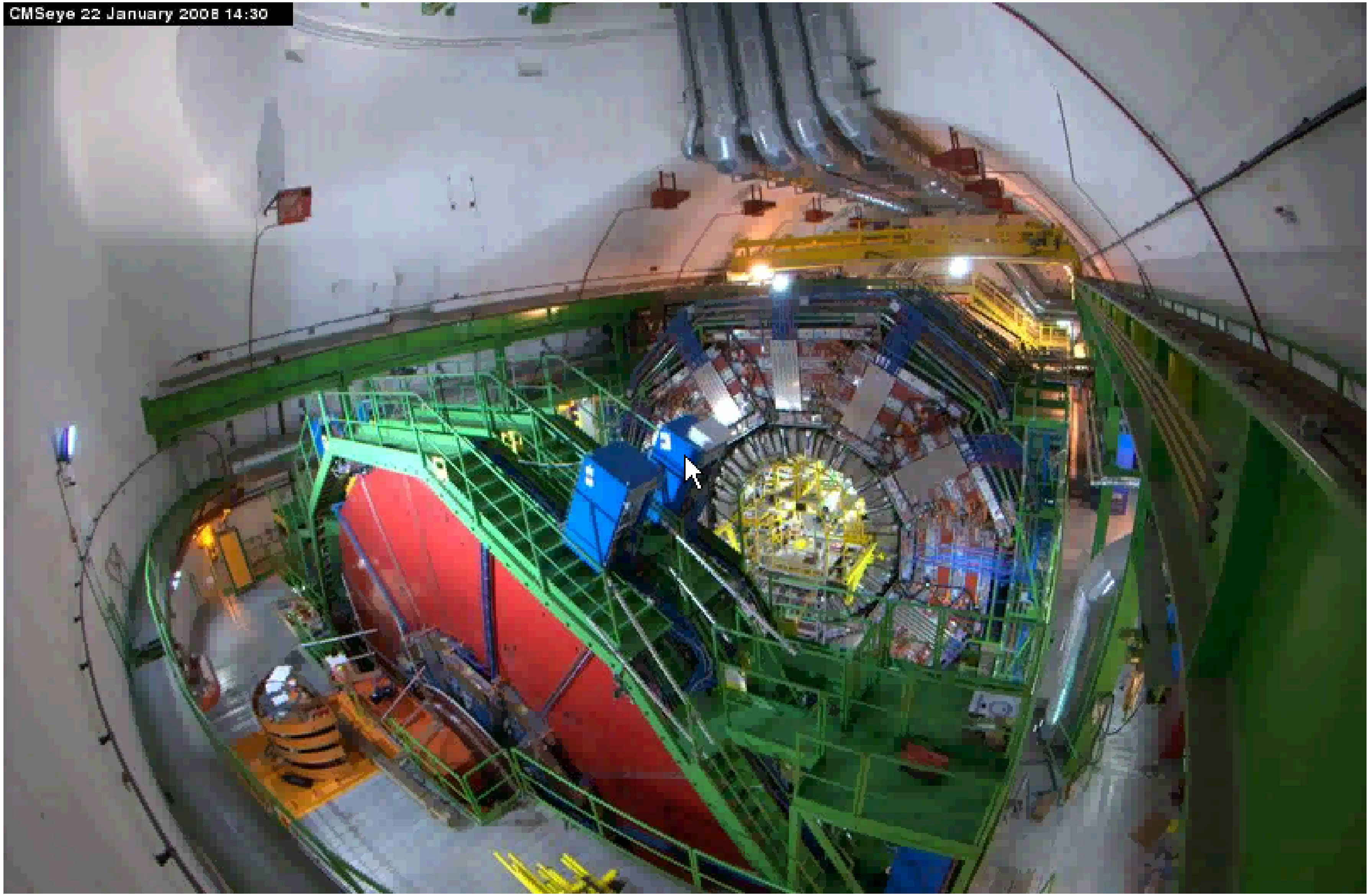


4 Tesla solenoid
length: 13 m
diameter: 5.9 m
→ contains **tracker** and **calorimeters**

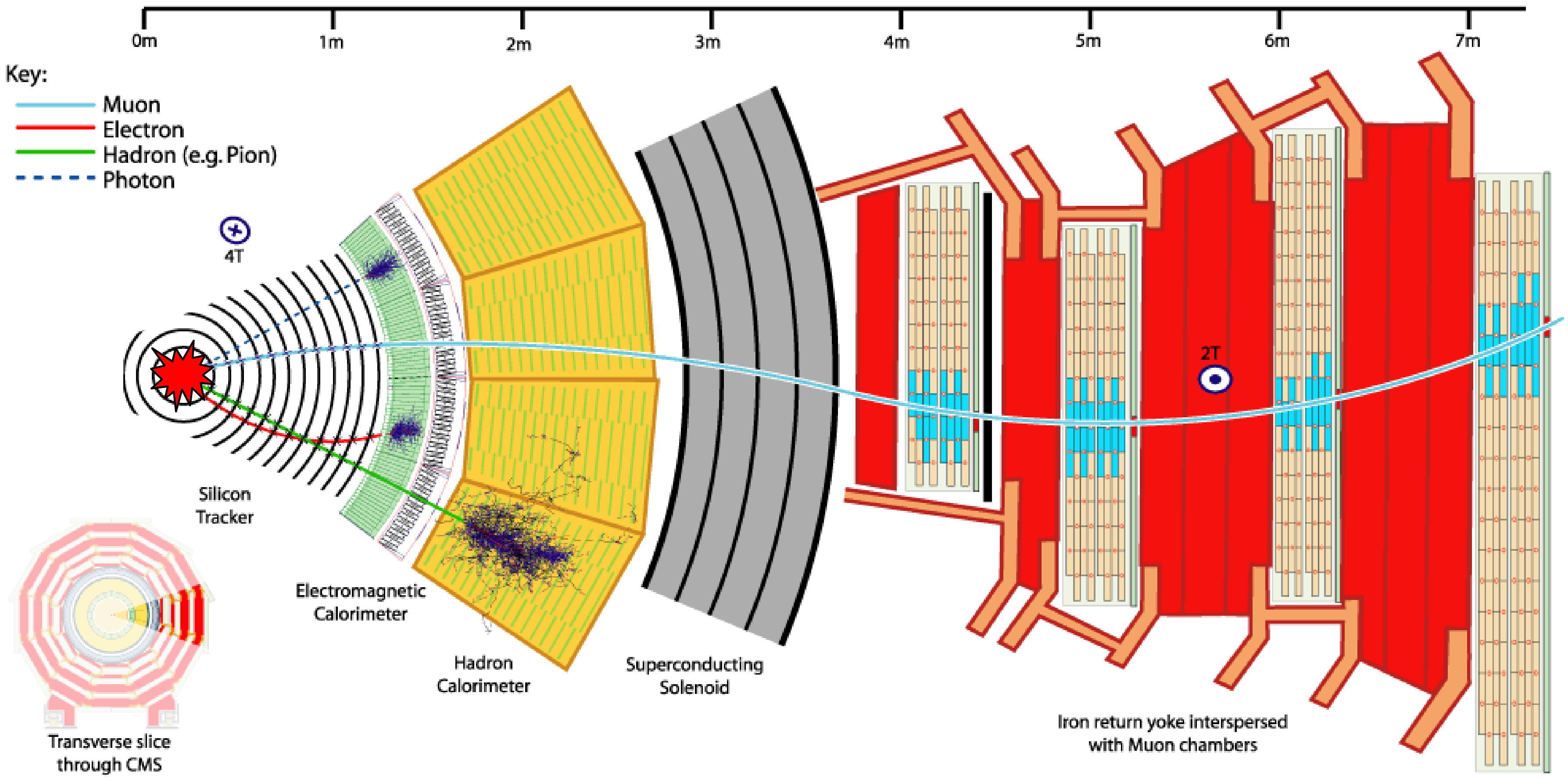
iron return yoke
instrumented with **muon chambers**

CMS Central Section arriving Underground

Lowering of last heavy part of CMS 22. 1. 2008



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

→ 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

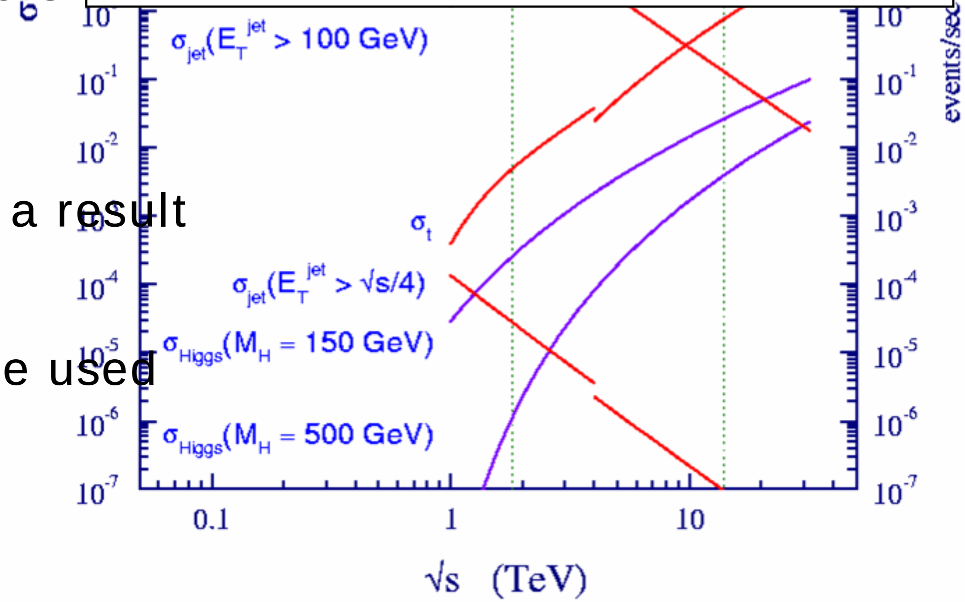
→ novel requirements on tracking detectors
  → **~25 ns** readout time
  → **high granularity**
  → **radiation hardness**
  high spatial resolution (typ. 10μm) is a result of these requirements

→ traditional tracking chambers cannot be used

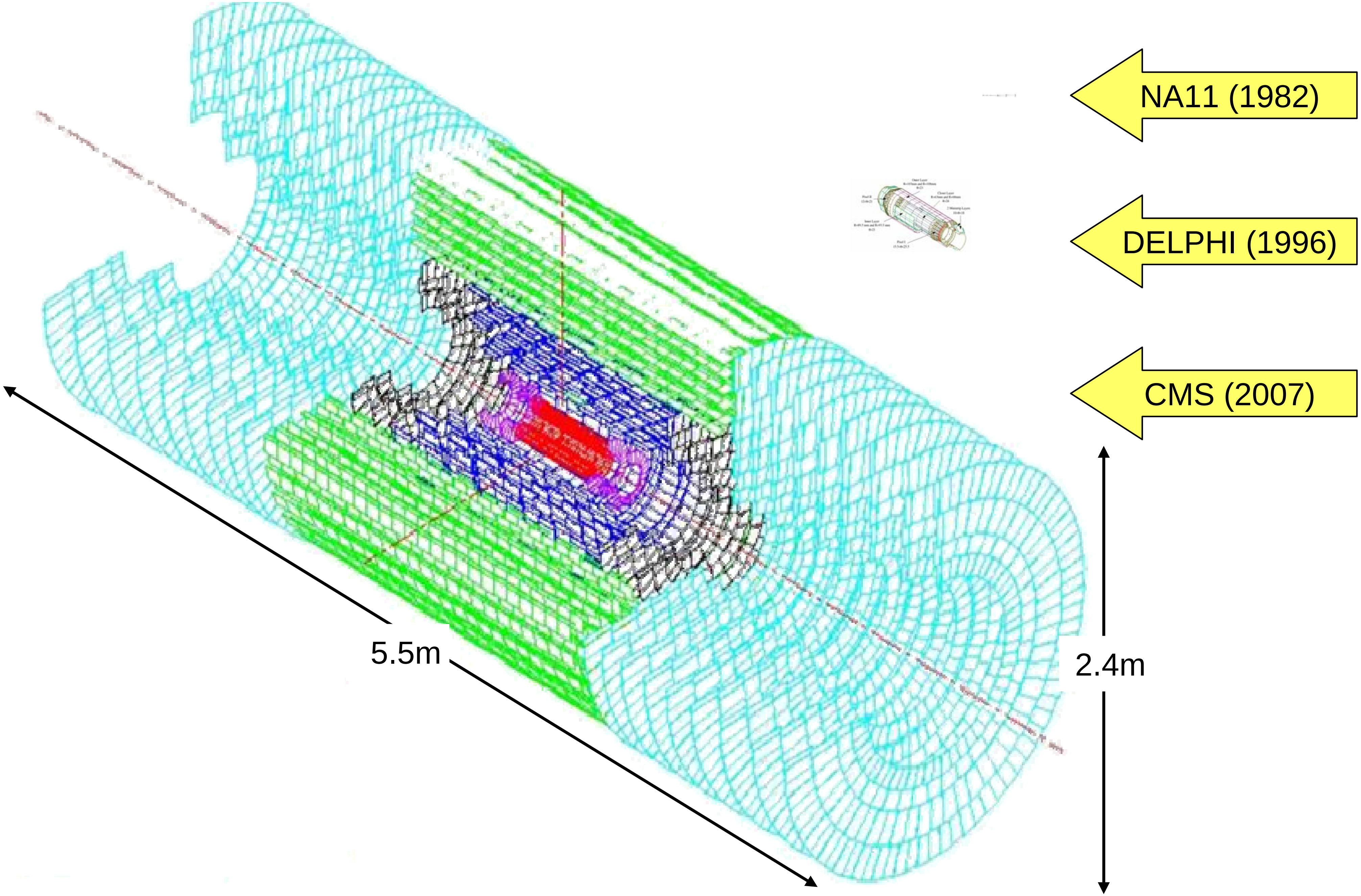
→ **Silicon Tracker**

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

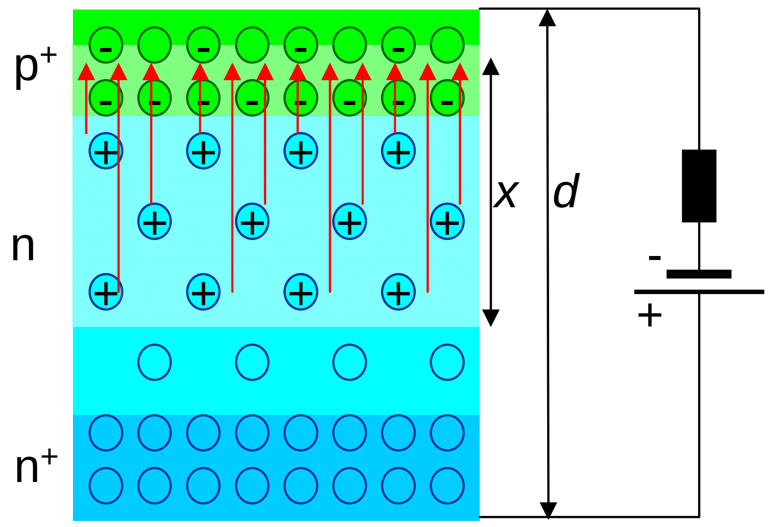


A new domain for Silicon Detectors

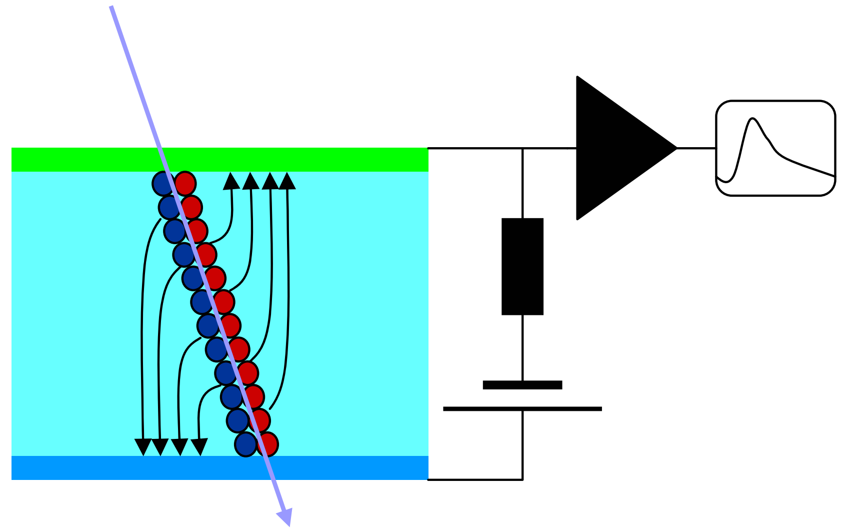


Working Principle of a Silicon Detector

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

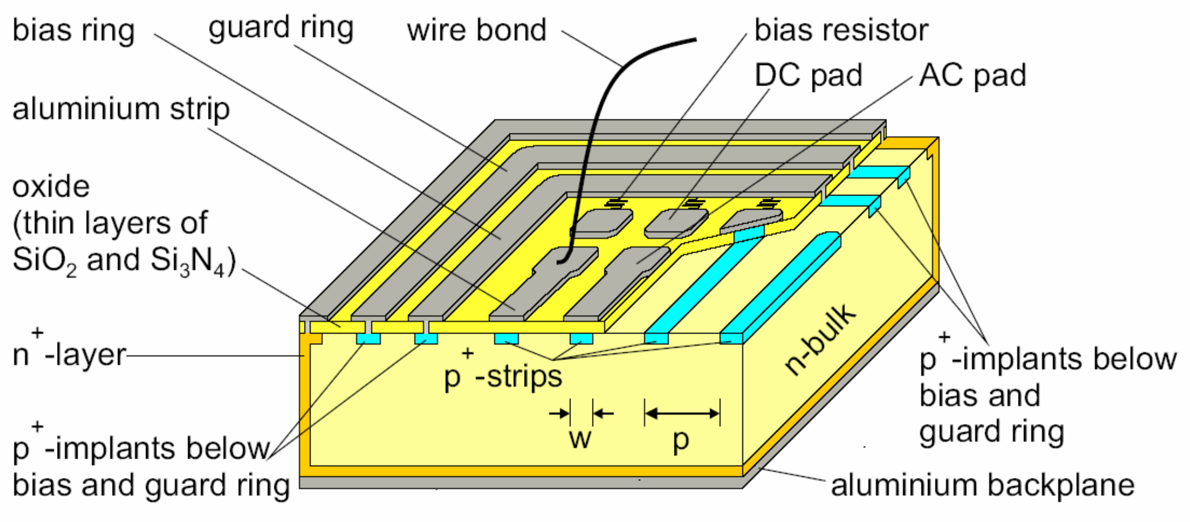


3. **ionizing particles create electron hole pairs**

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:**

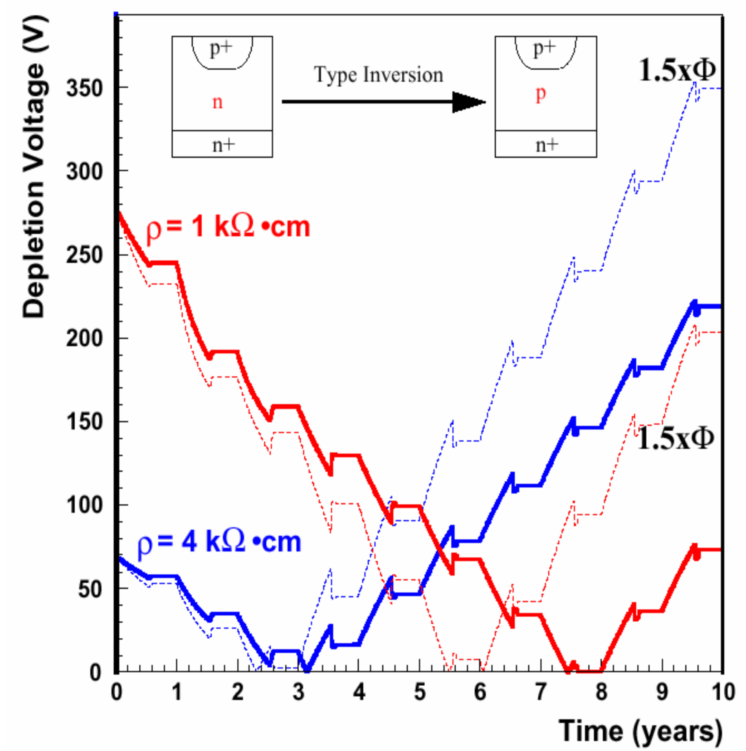
- **radiation hardness** ...requires high voltage operation and efficient cooling

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 crystal lattice**
  → new energy levels



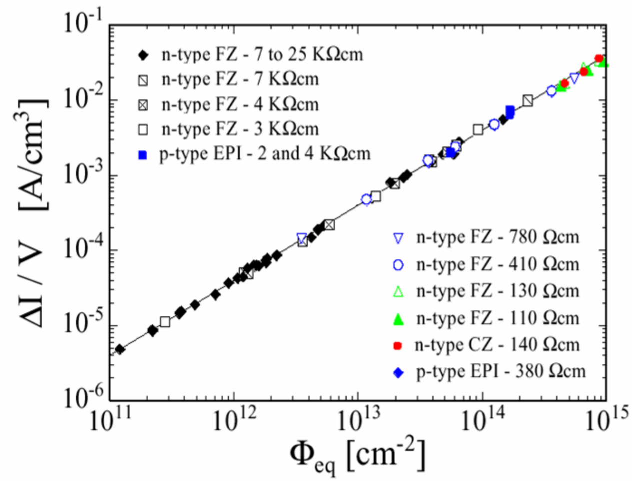
Sensors

- 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.

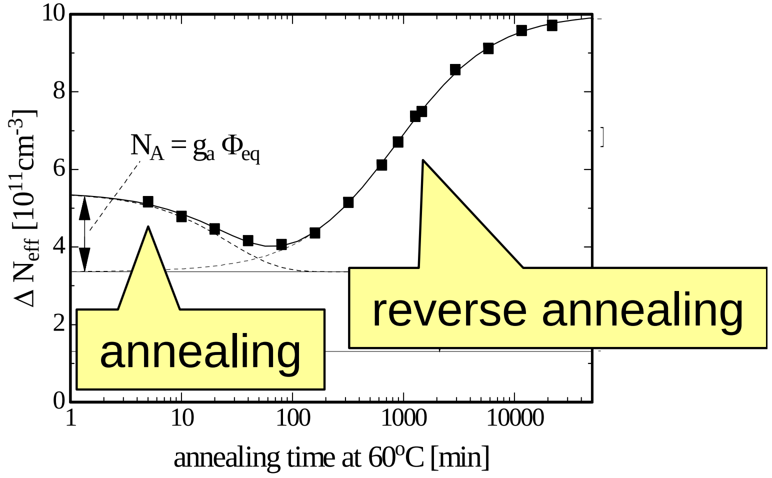


Measures to achieve radiation hardness

- 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')

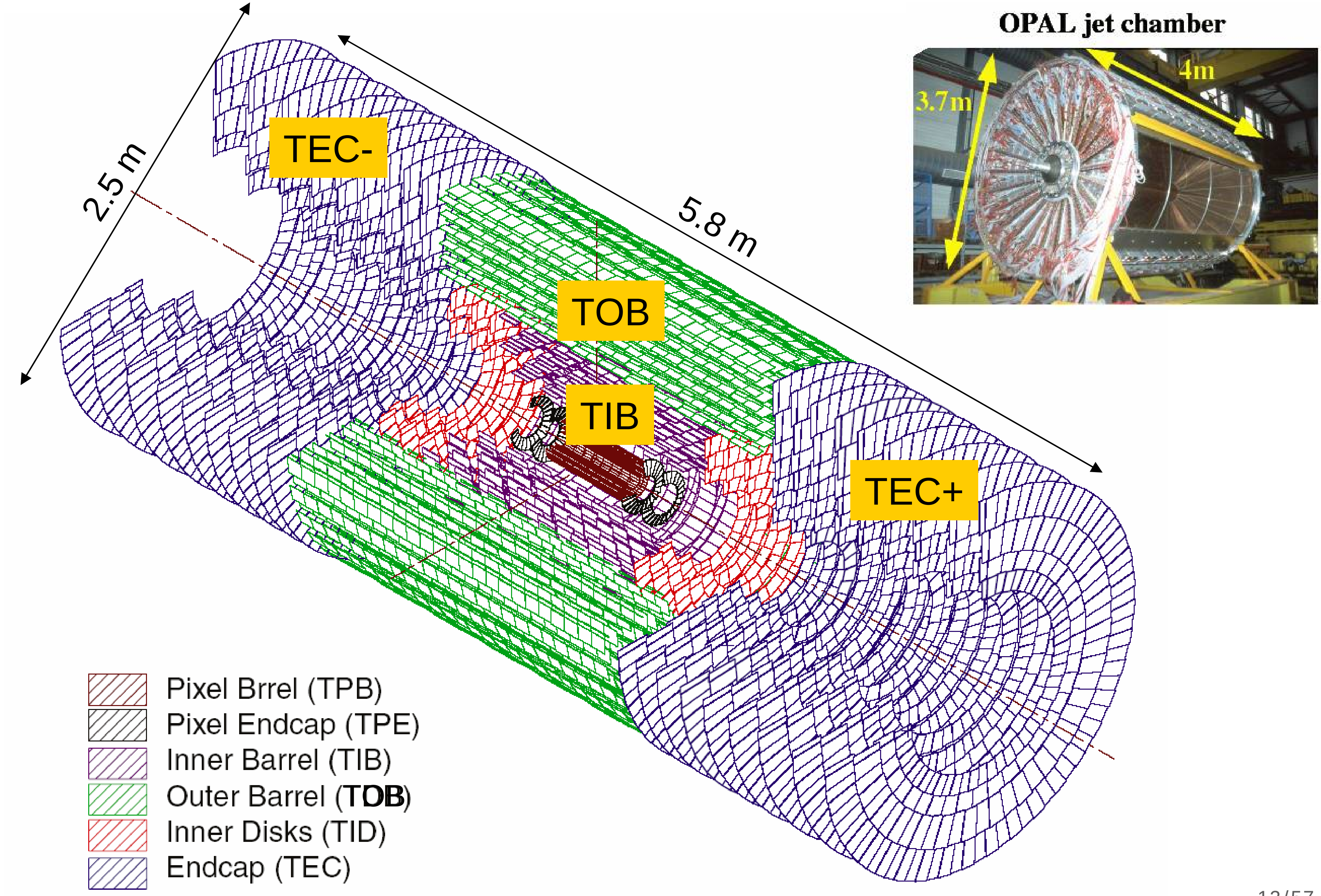
  dark current x bias voltage after 10 years:
  2 mA x 500 V = 1 W !

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

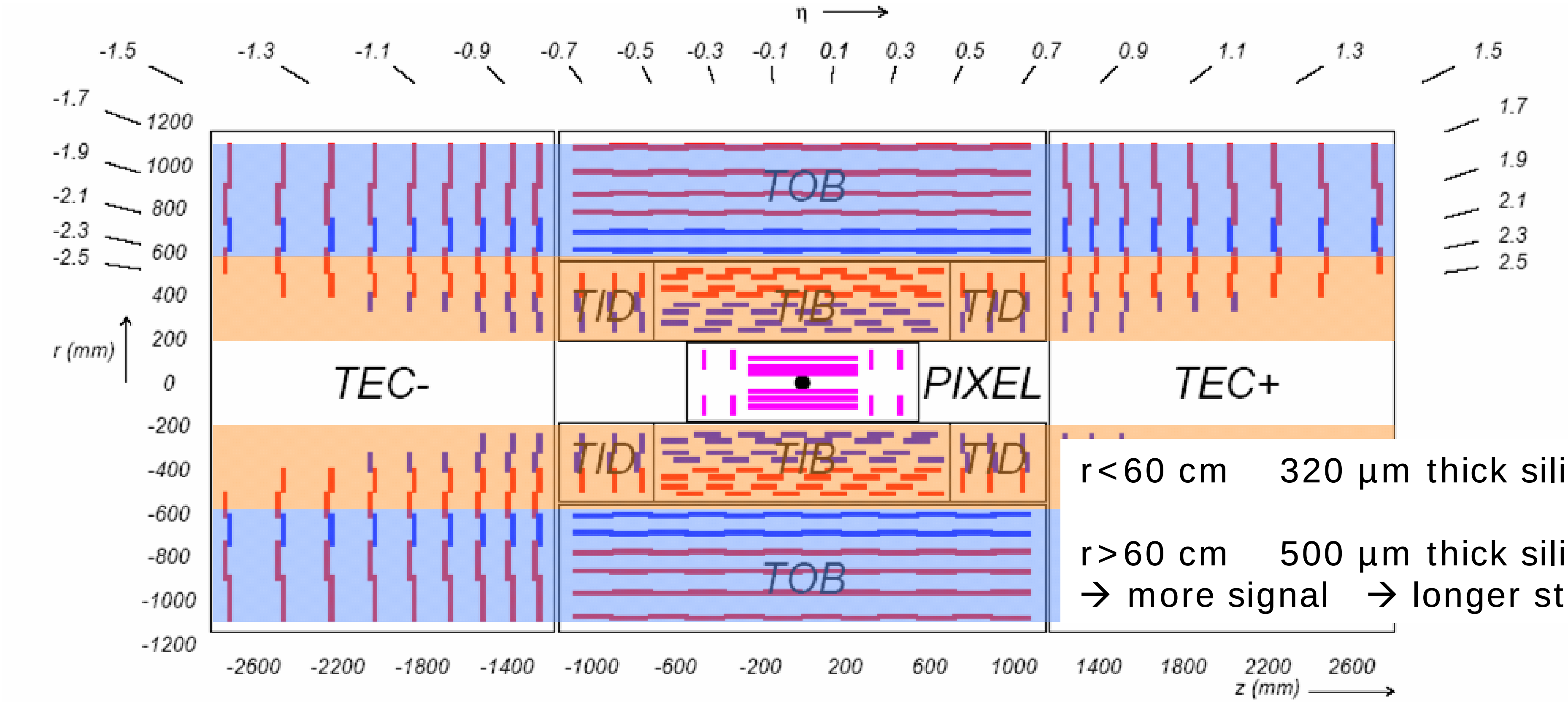
  by
  - operation at around –10°C
  - efficient cooling with small temperature gradients
  - thermal separation of sensors and electronics

→ radiation hardness can be achieved

CMS All Silicon Tracker



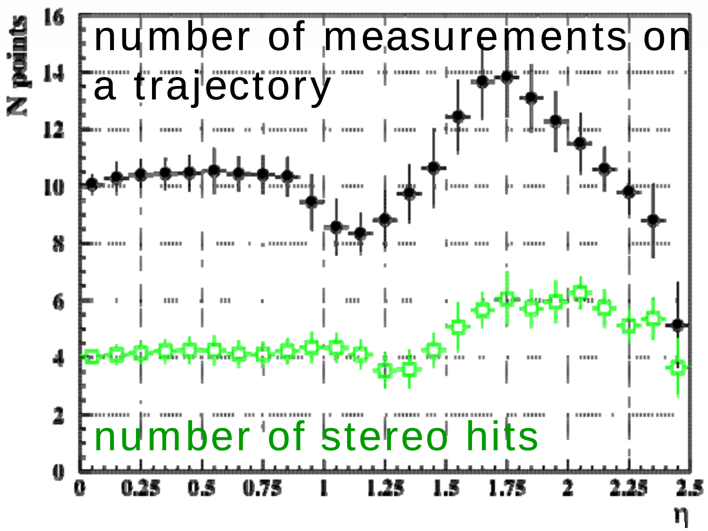
CMS All Silicon Tracker



r<60 cm 320 μm thick silicon

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

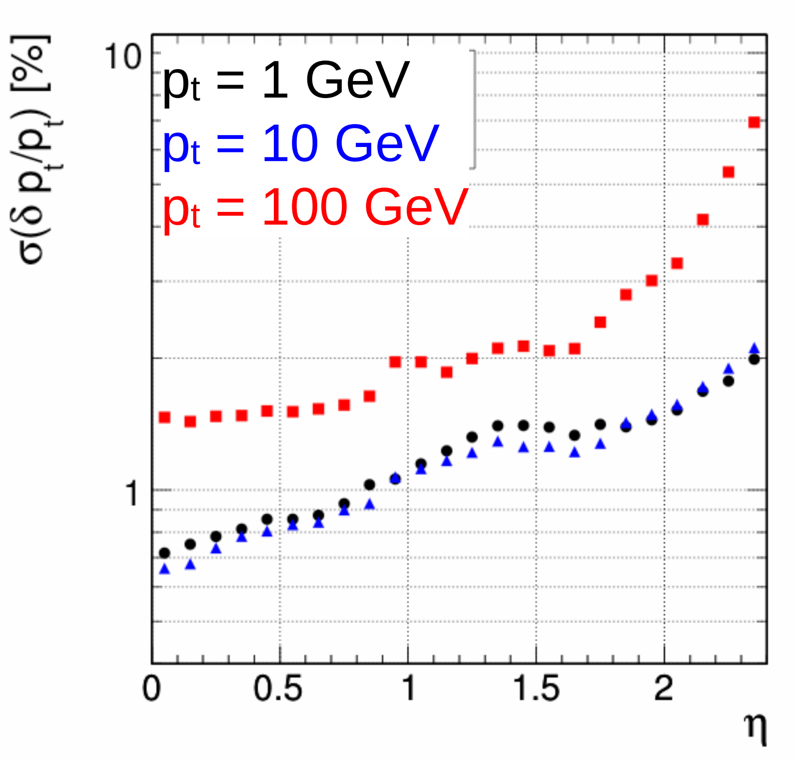
15,148 silicon strip detector modules
single sided or mounted
back-to-back with stereo angle of 100 mrad



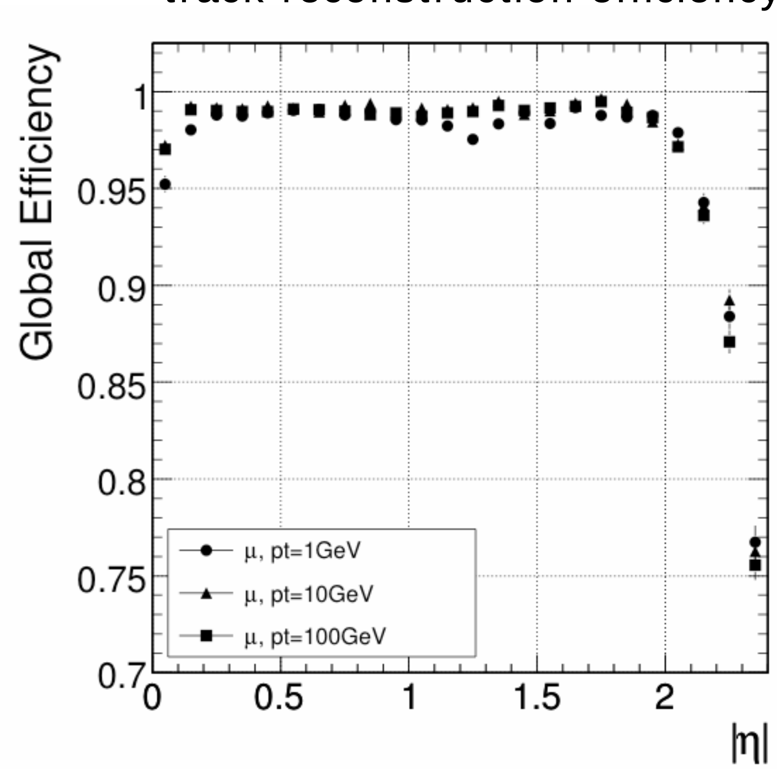
Expected Performance of CMS Tracker

for single muons

transverse momentum resolution



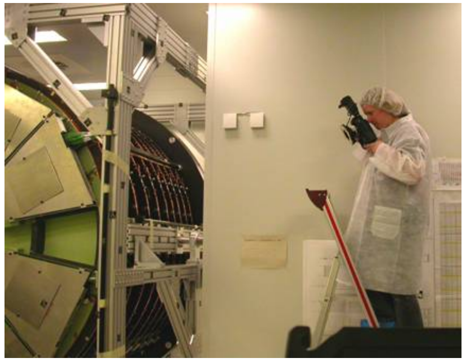
track reconstruction efficiency



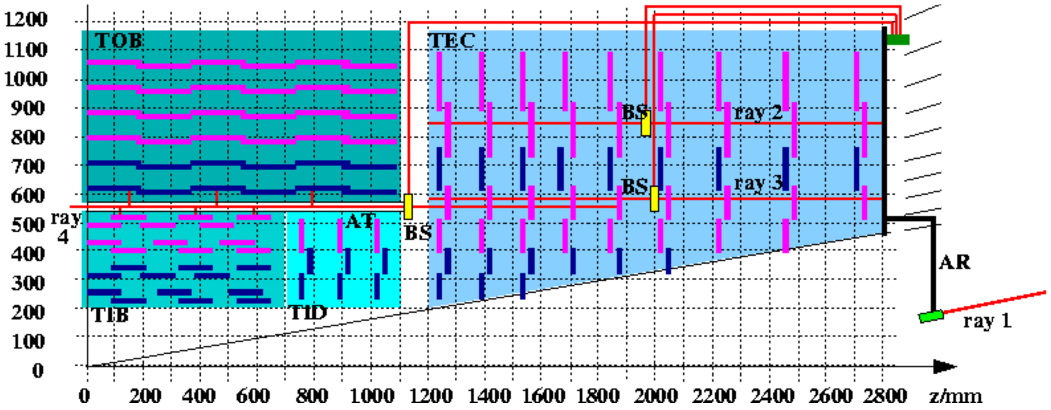
...requires a well aligned tracker

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

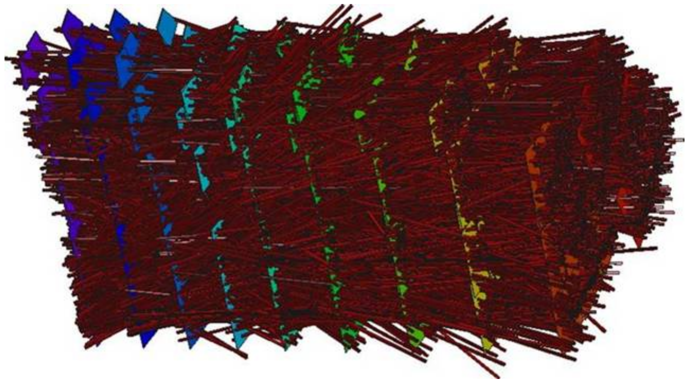
- survey measurements at all stages of detector assembly



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

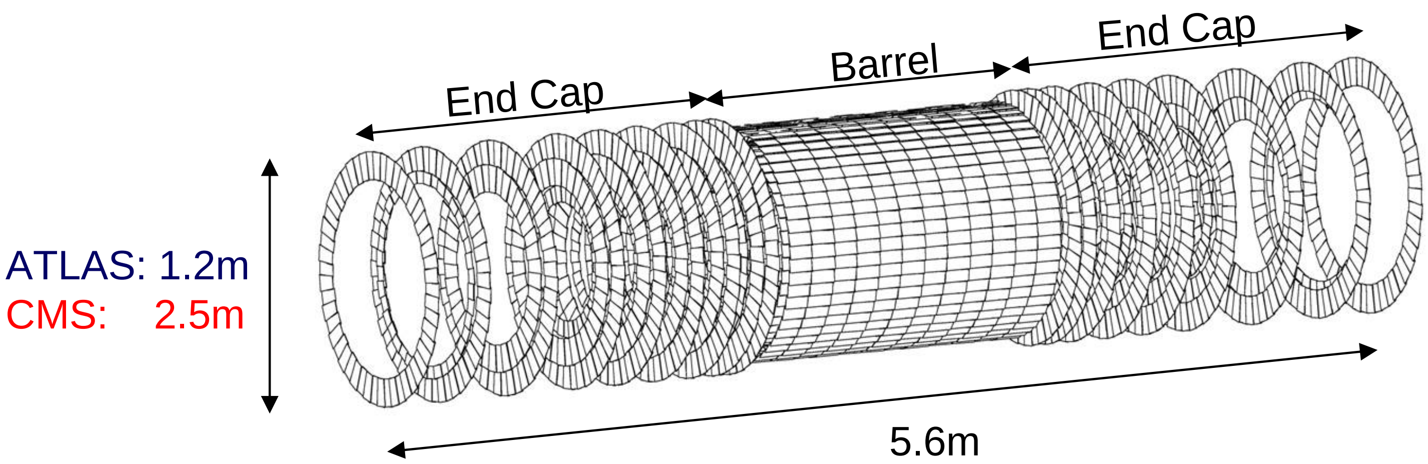


- alignment with particle tracks will provide the best precision

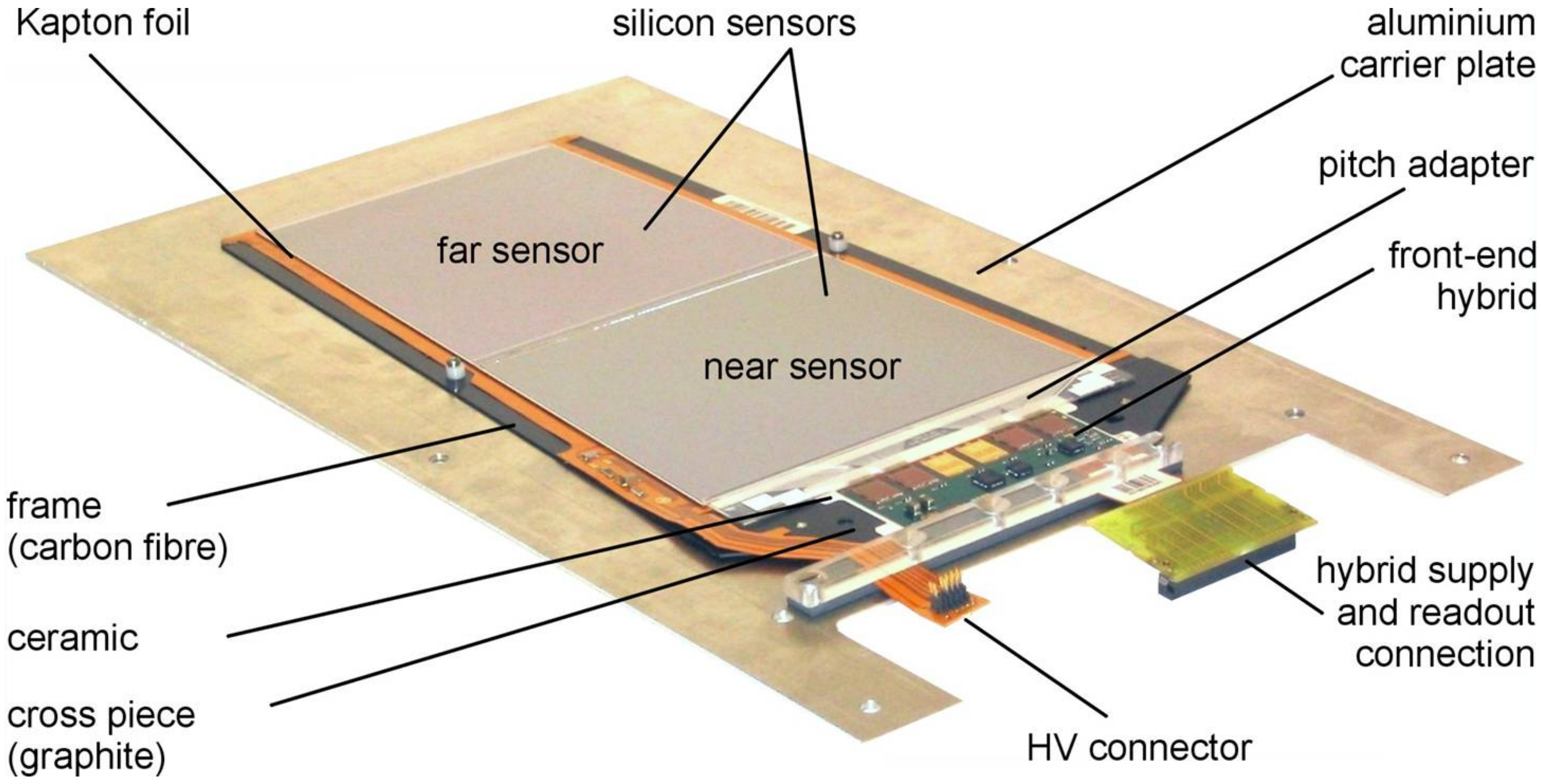


Silicon Microstrip Detectors in ATLAS and CMS

	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

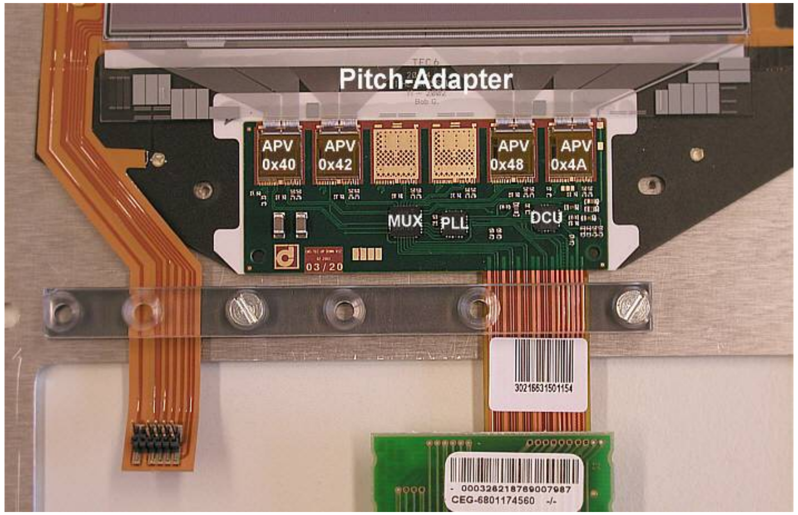


CMS Silicon Detector Module



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

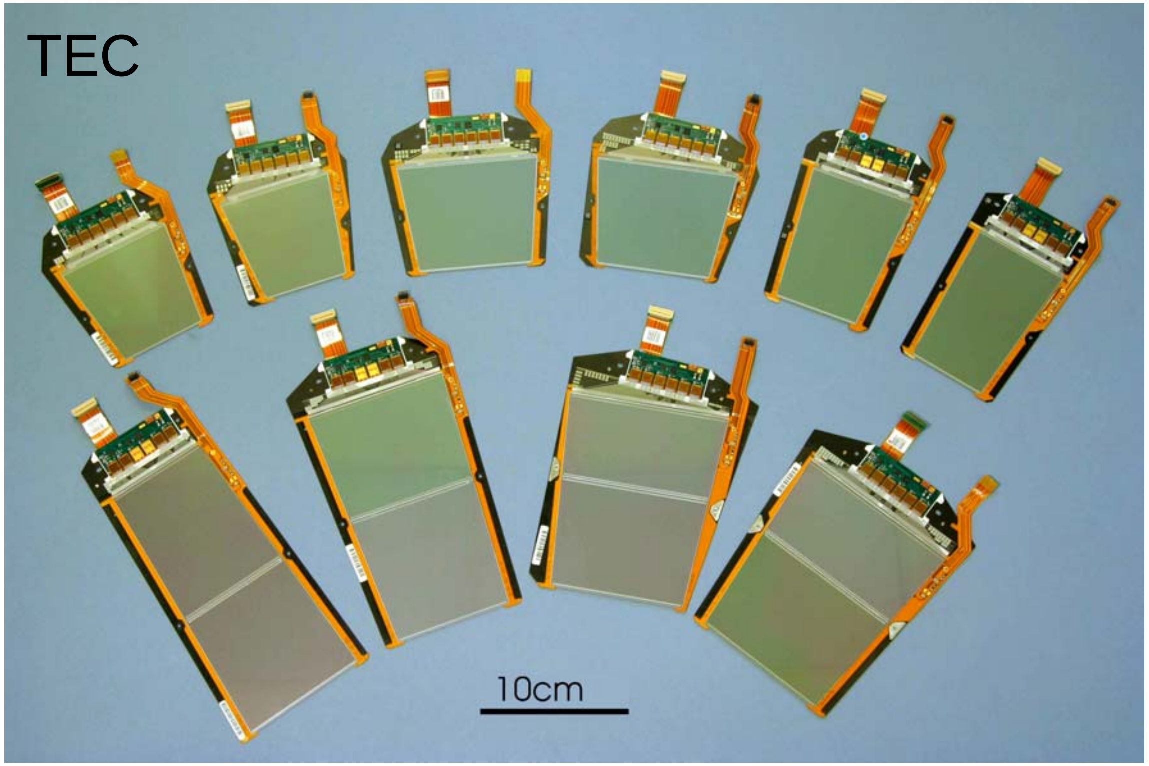
read-out ASIC

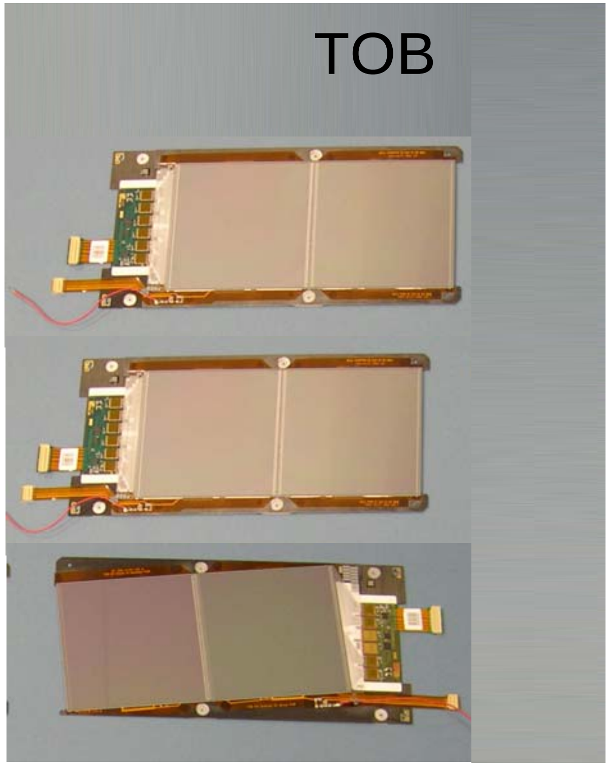
APV25
128 channels of charge sensitive amplifier, 50 ns shaper,
analogue pipeline (4 µs), deconvolution (50ns → 25ns)

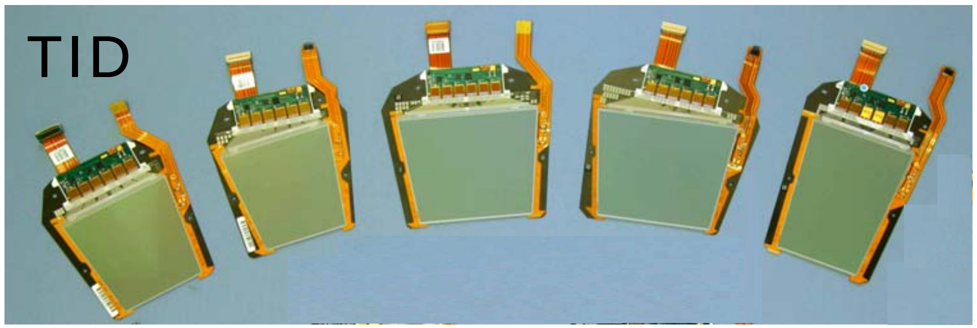
full **analogue** information is sent to ADCs in the service cavern

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

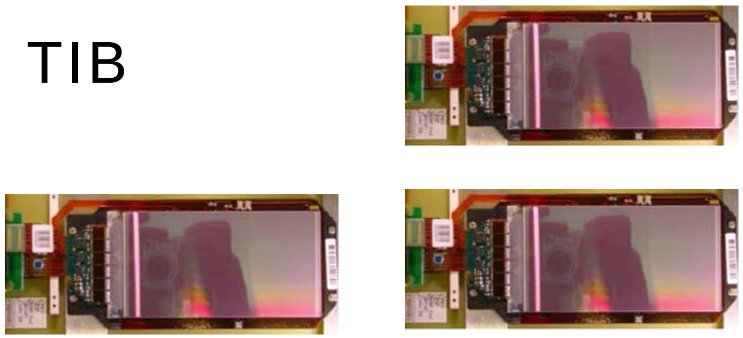
...29 different module types are needed





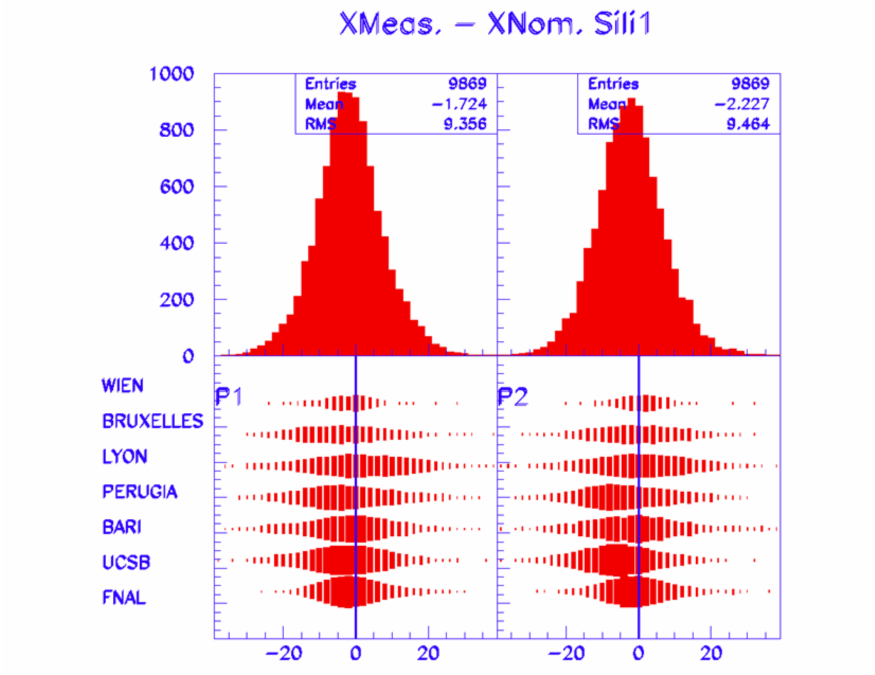


TIB



Module Production

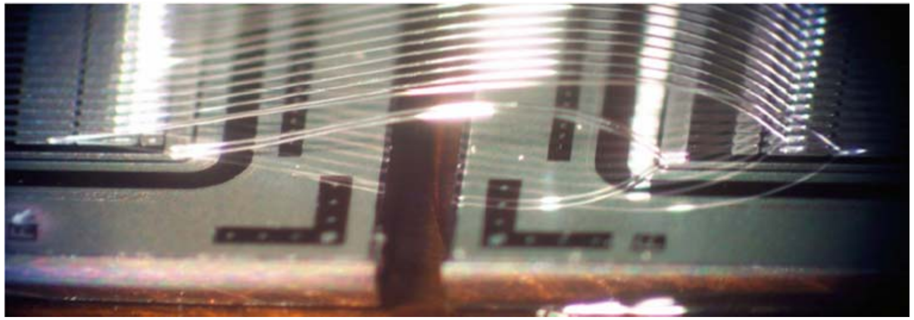
automated module assembly
and wire bonding



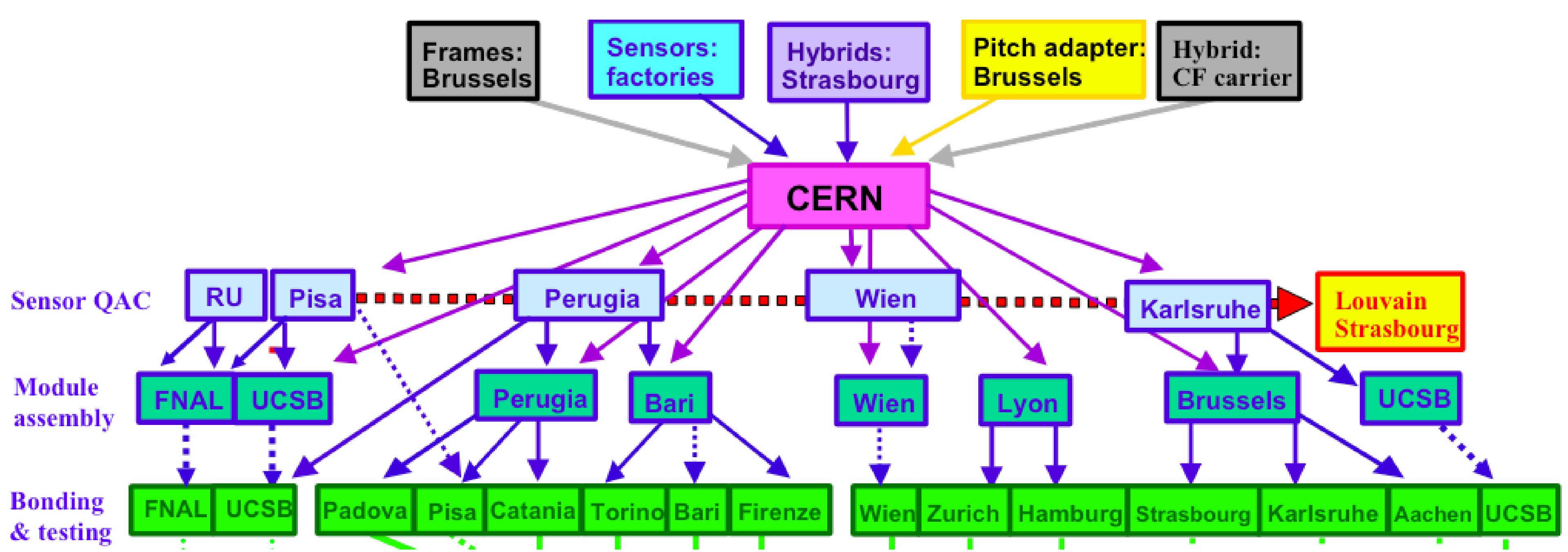
6 gantry (module assembly) centers
20 modules per gantry per day

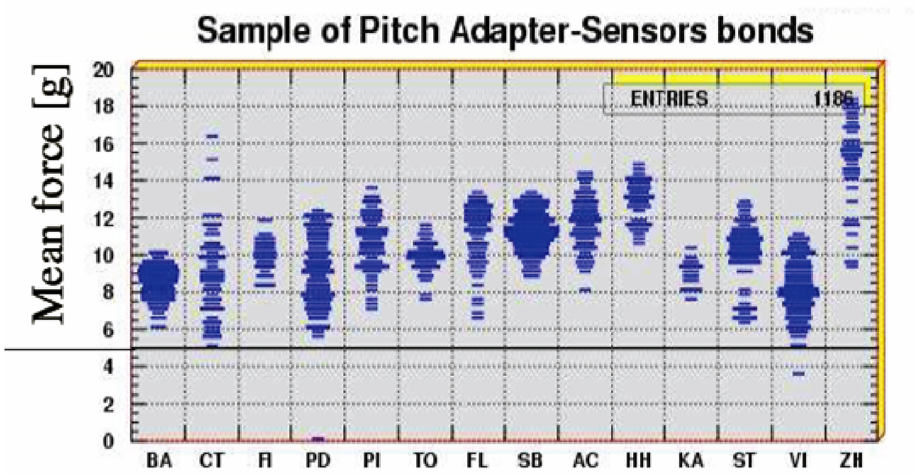
typical RMS of placement 10 µm

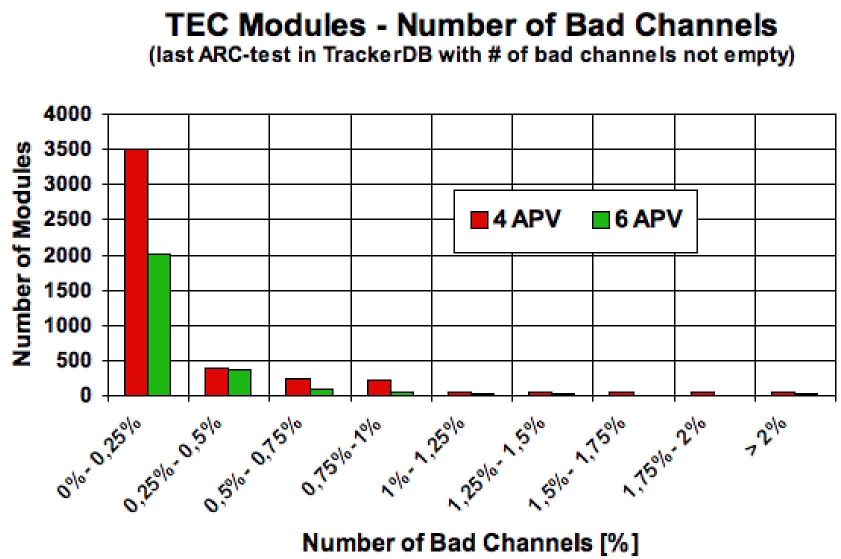
wire bonding rate ~ 1 Hz



Module Production ... an Industry of its own

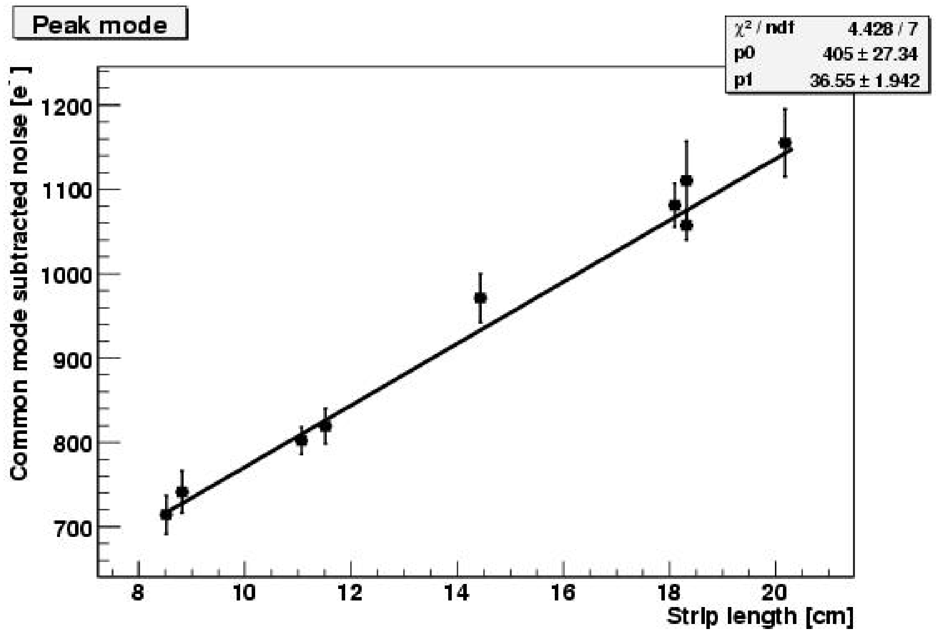


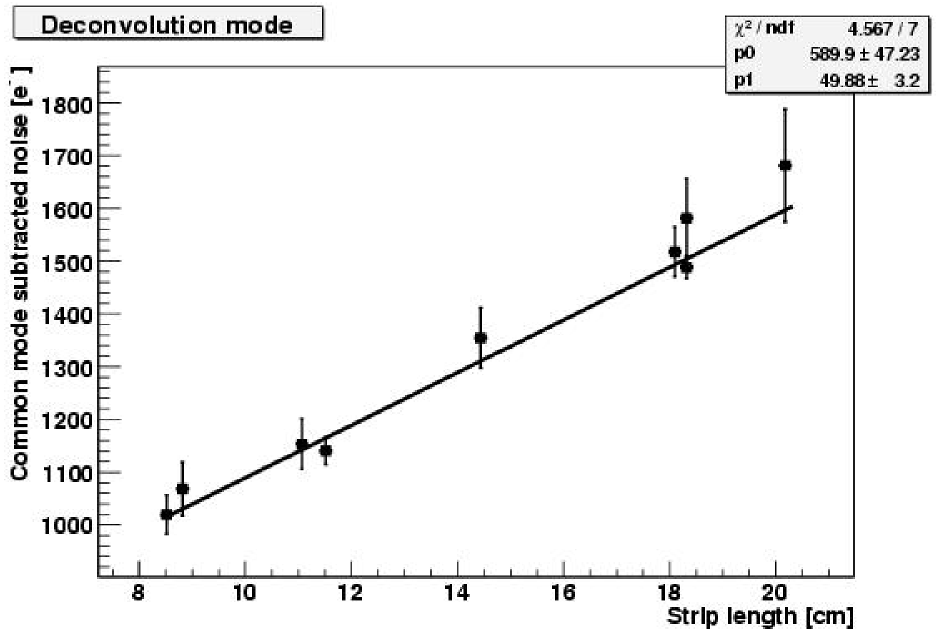




Module Performance: Testbeam Data

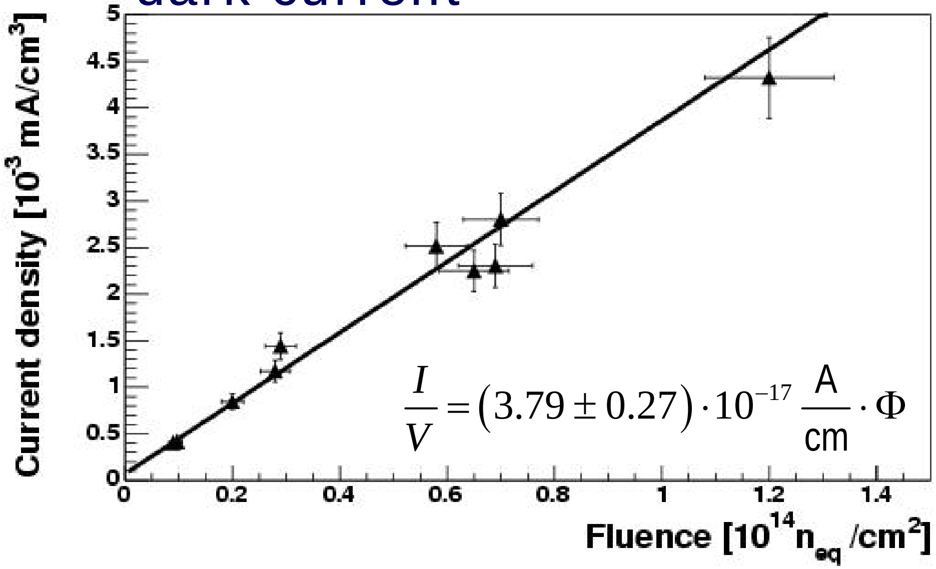
Module type	Pitch [μm]	Strip length [mm]	S/N Peak mode	S/N Dec. mode	ENC [e^-] Peak mode	ENC [e^-] Dec. mode
IB1	80	116.9	25.8 ± 1.3	18.3 ± 0.5	931 ± 48	1315 ± 37
IB2	120	116.9	29.5 ± 1.4	20.3 ± 0.6	815 ± 37	1182 ± 31
OB1	122	183.2	36	25	1110 ± 47	1581 ± 75
OB2	183	183.2	38	27	1057 ± 17	1488 ± 22
W1TEC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



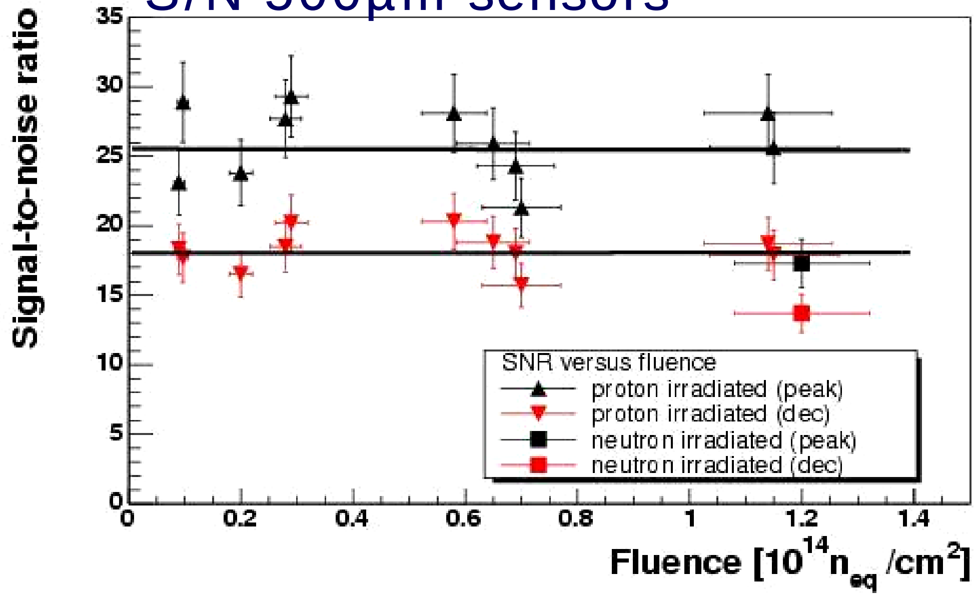


Module Performance after Irradiation

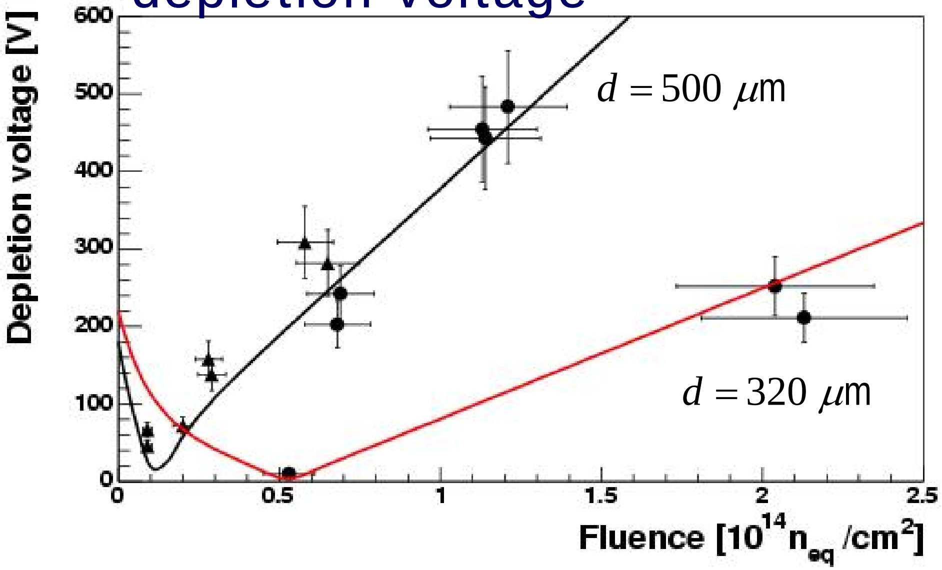
dark current



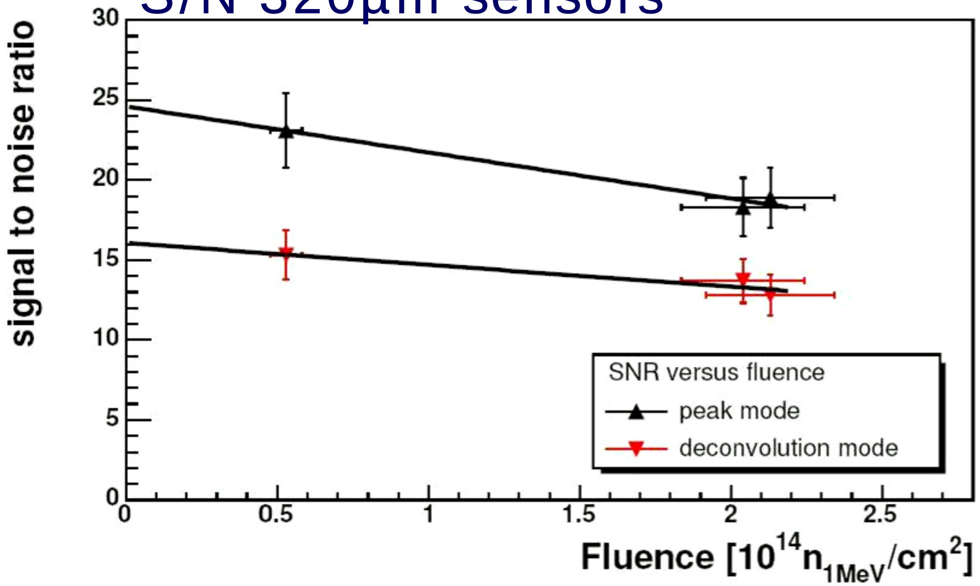
S/N 500µm sensors



depletion voltage



S/N 320µm sensors

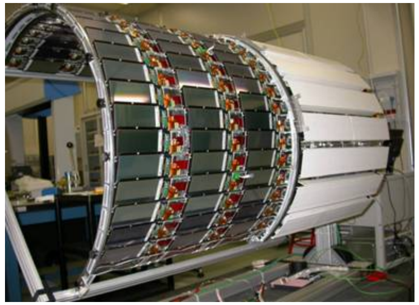


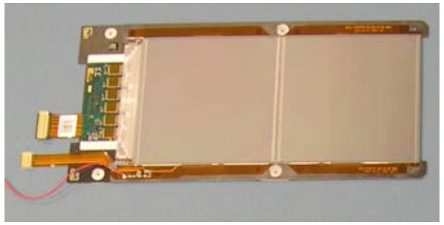
Integration of Modules into Subsystems

modules

2724+816

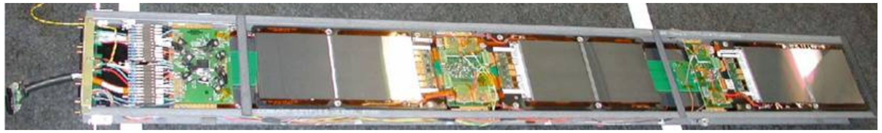
TIB





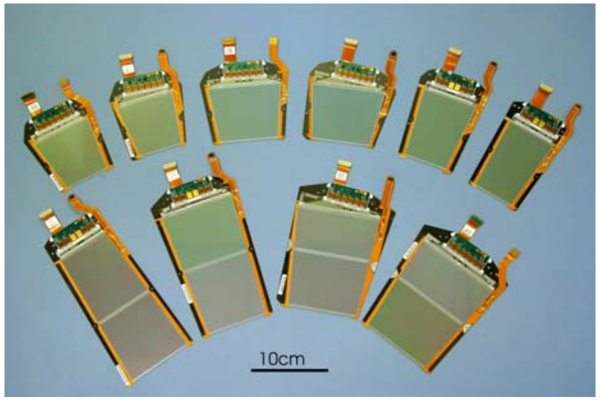
5208

rod



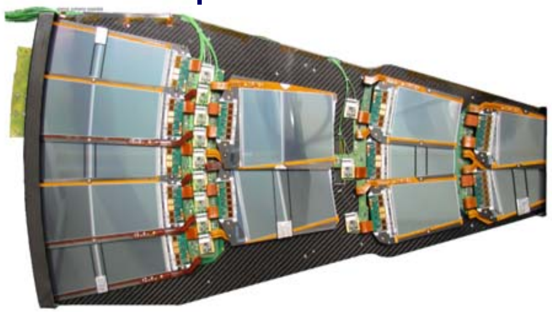
688

TOB



6400

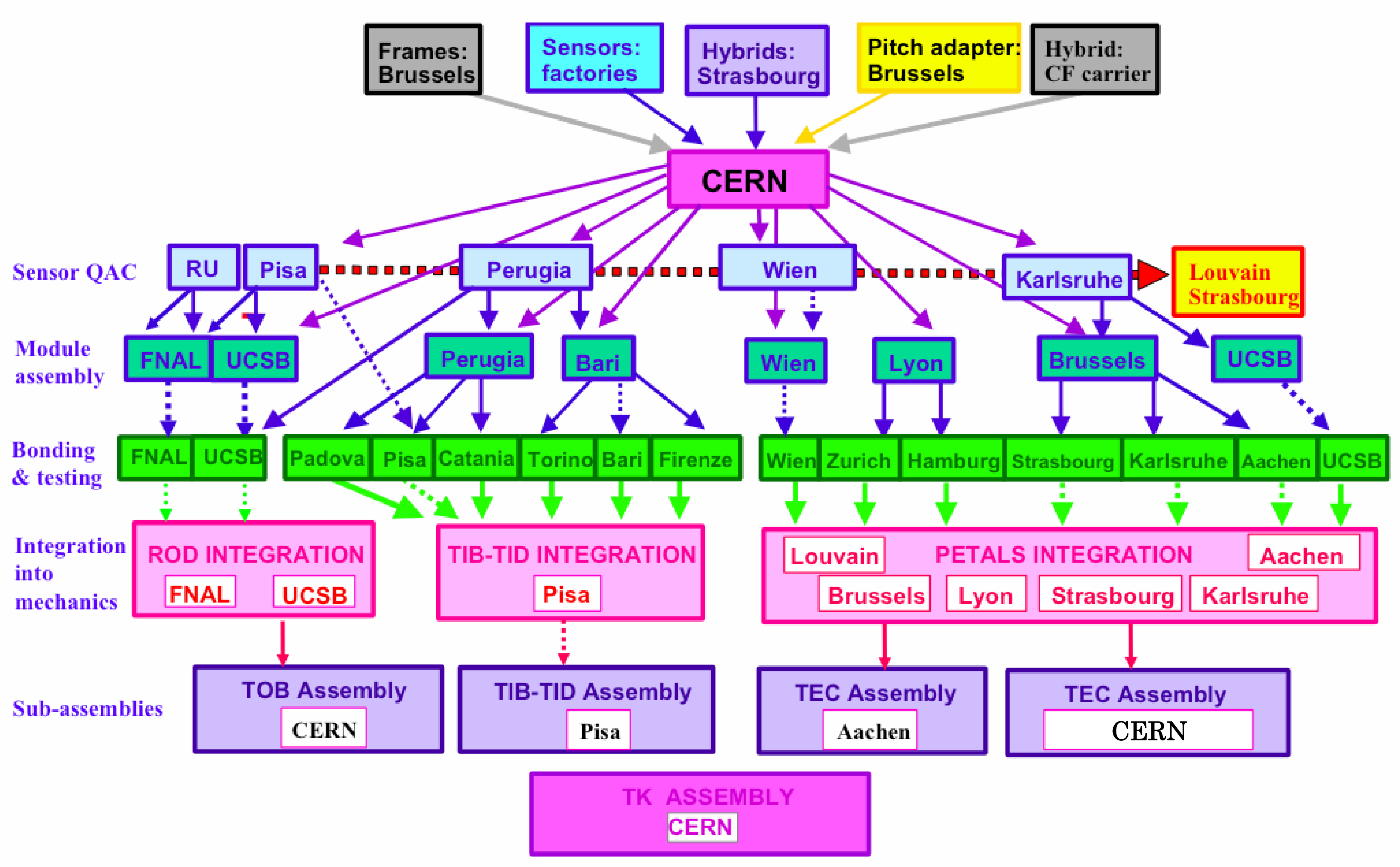
petal



288

TEC (x2)

CMS Tracker Logistics



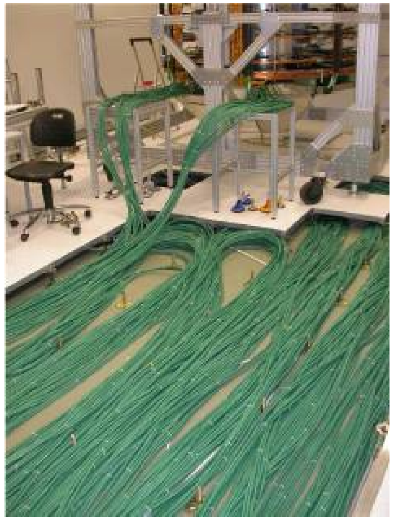
TEC Integration: what is needed

144 petals

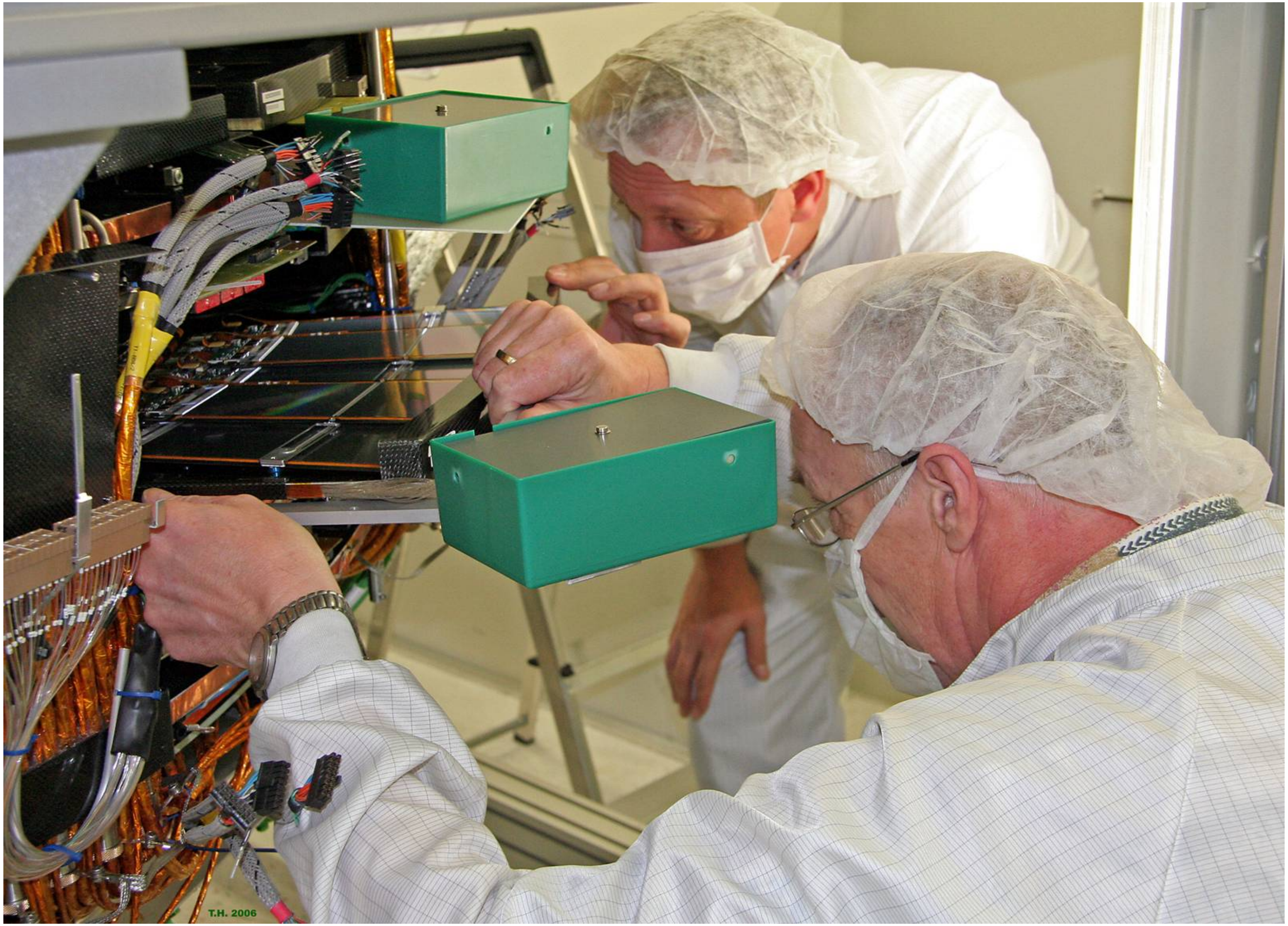
a large clean room

an empty TEC

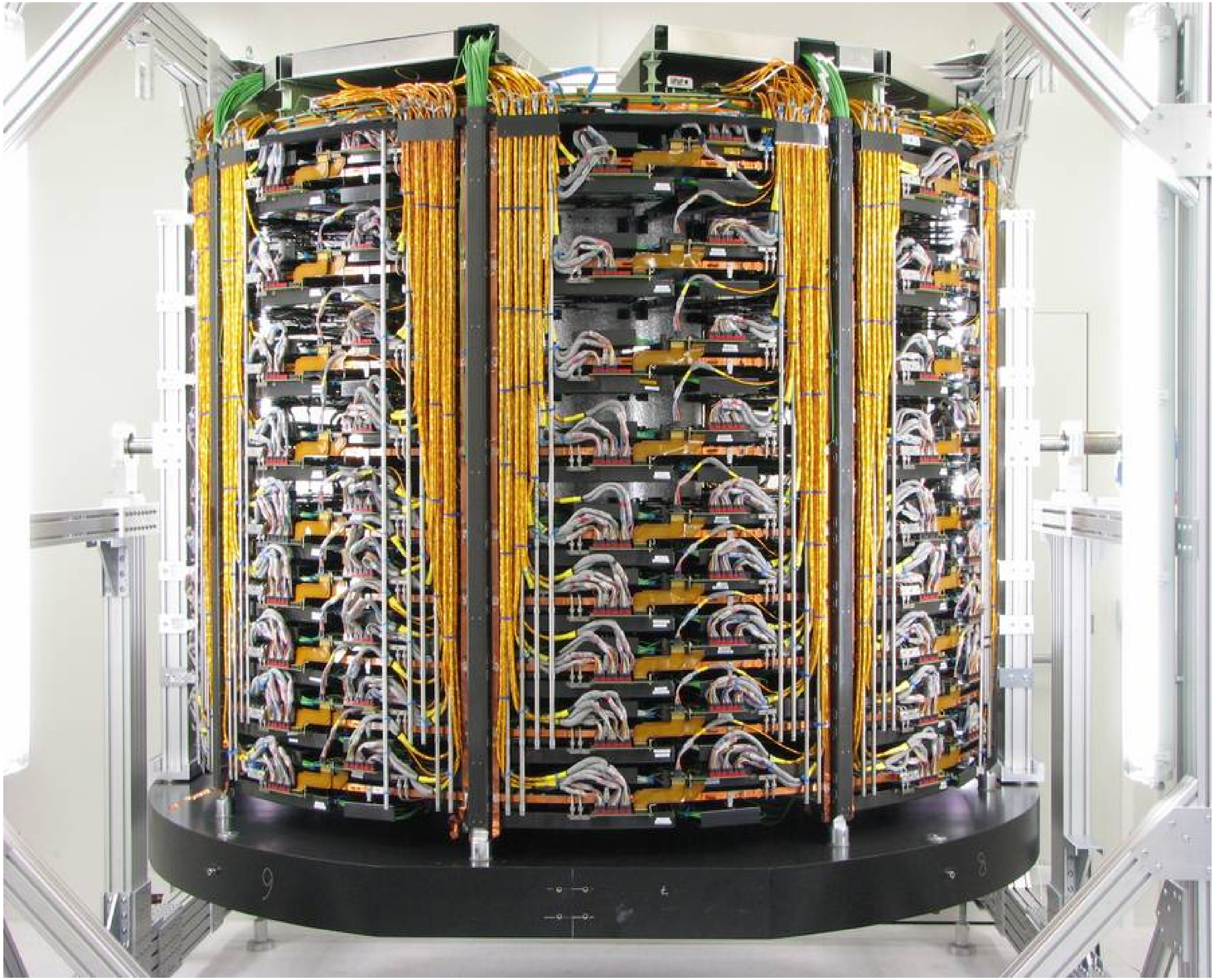
and a huge test system: read-out for 400 modules, 2.5 km final cables, cooling ...



...and skilled people



Finished TEC+ in Aachen



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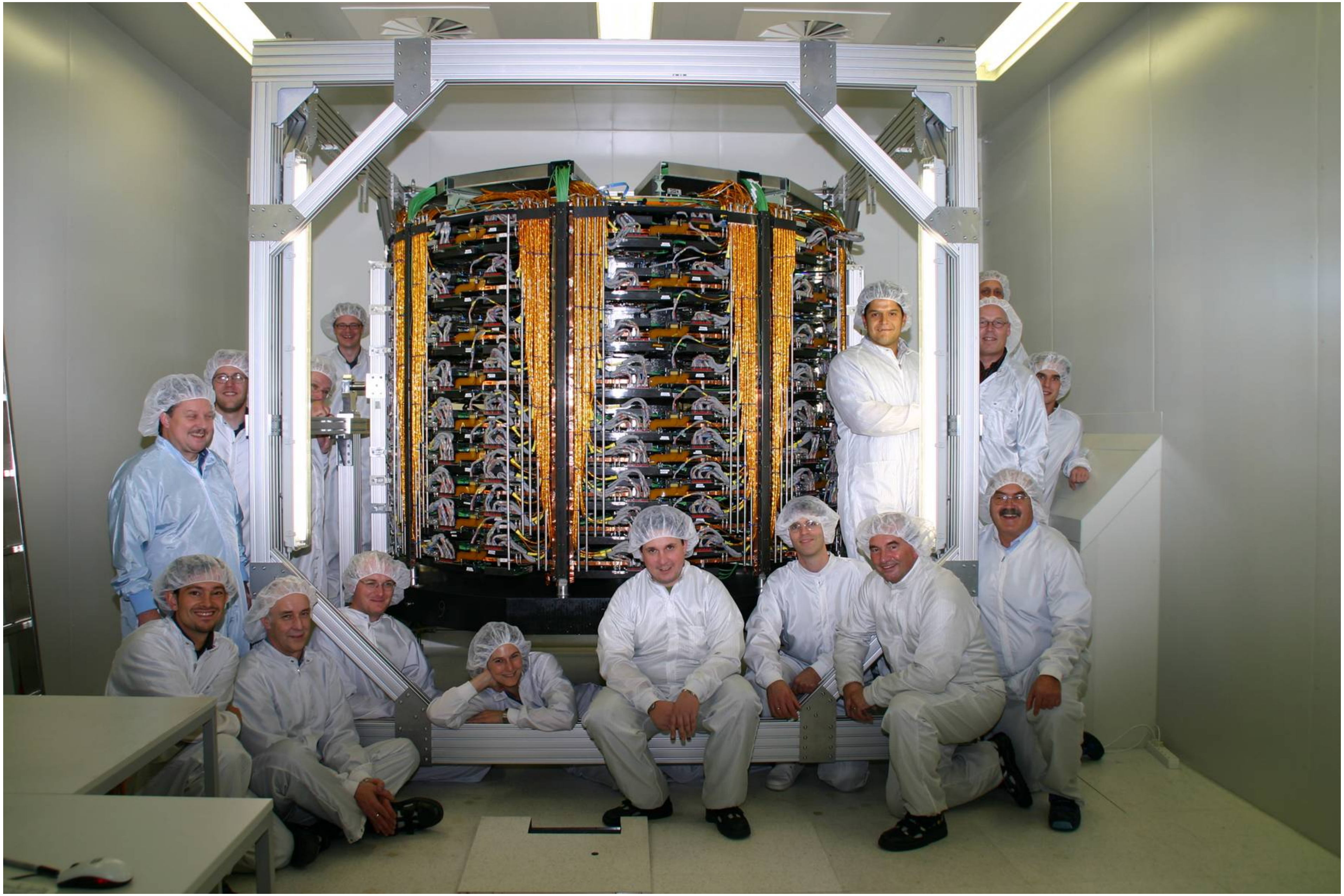
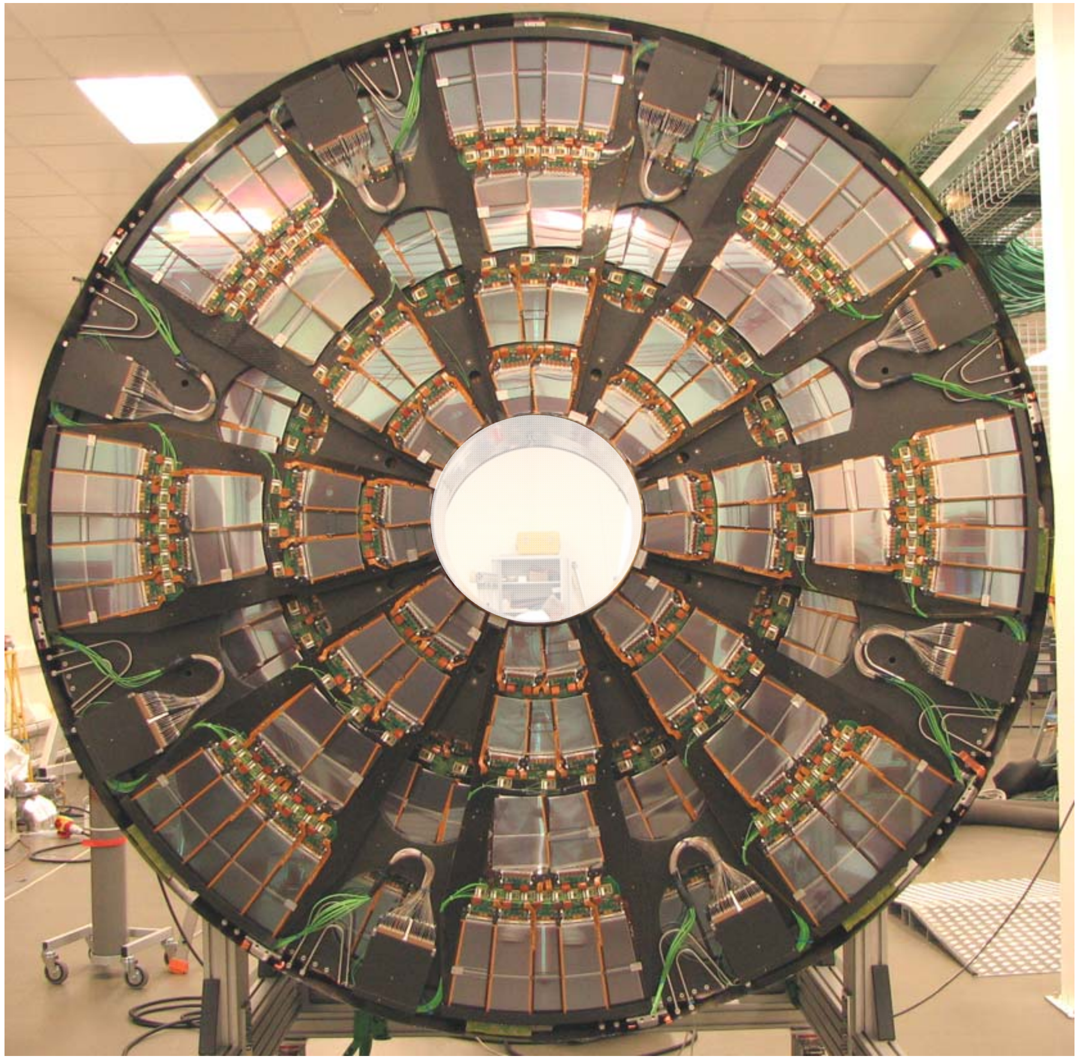
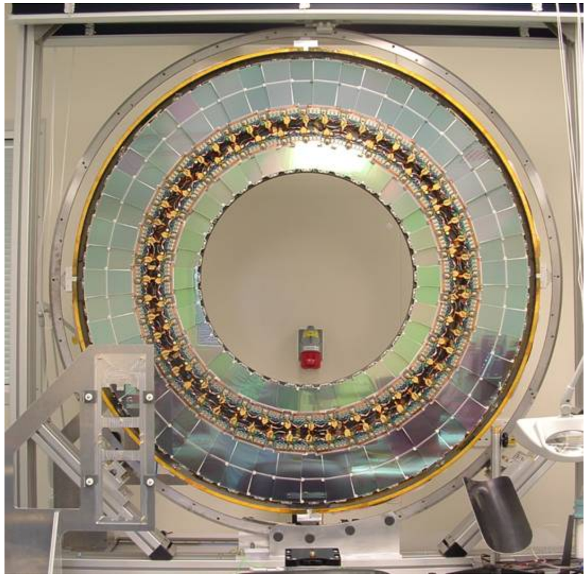


...and at CERN



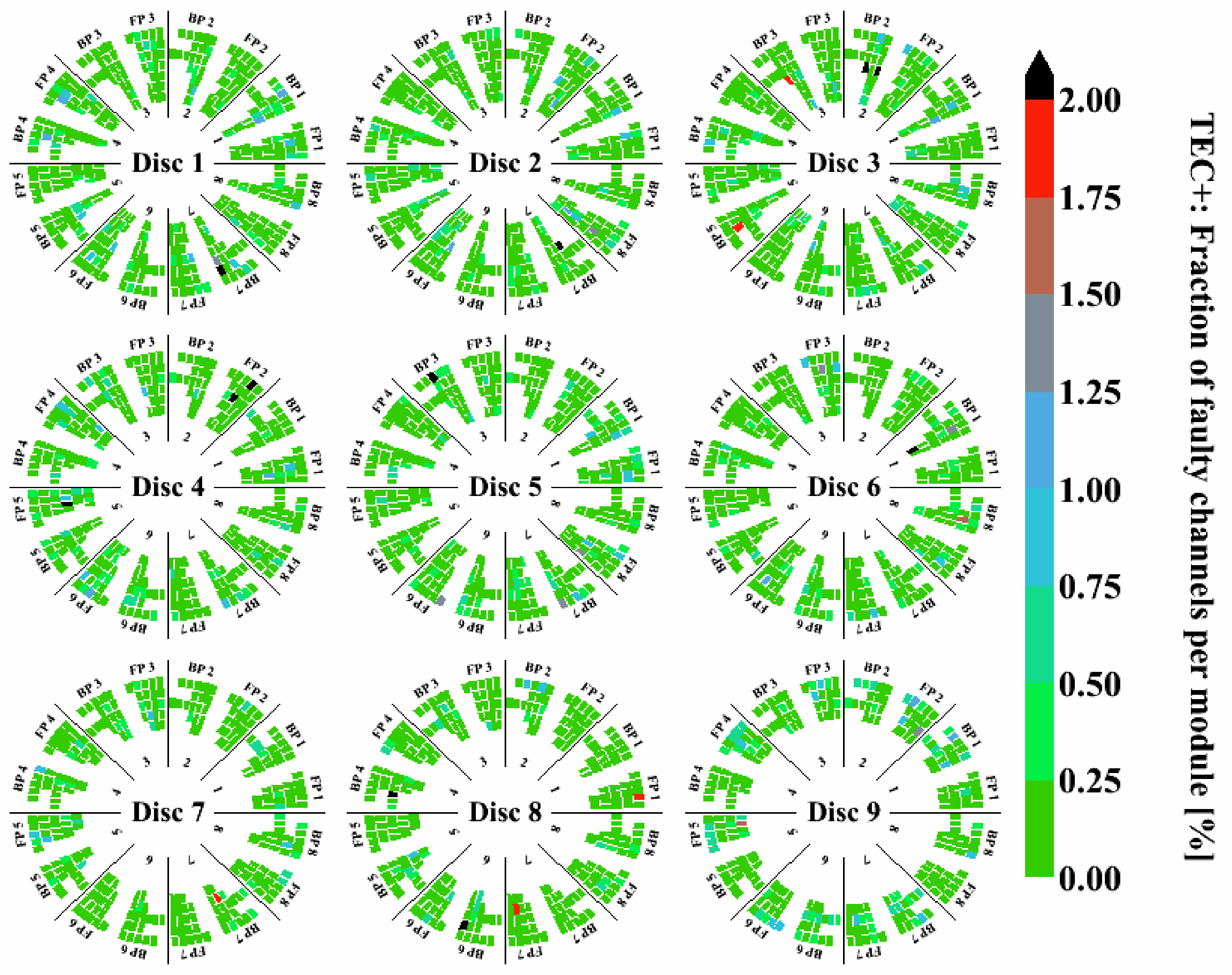


modular structure:
petals as self-contained, pre-tested units

“monolithic” structure:
modules mounted onto disks

Performance of integrated Structures

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

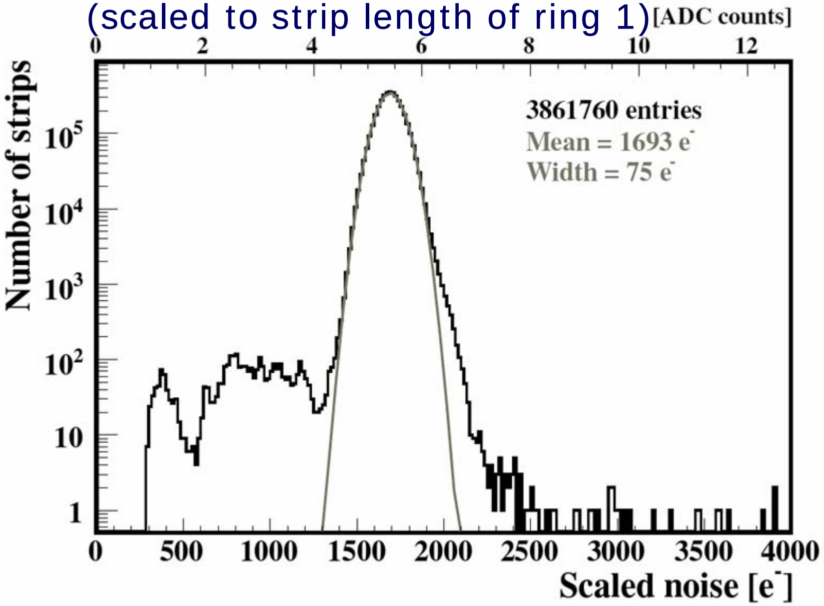


Performance of integrated Structures

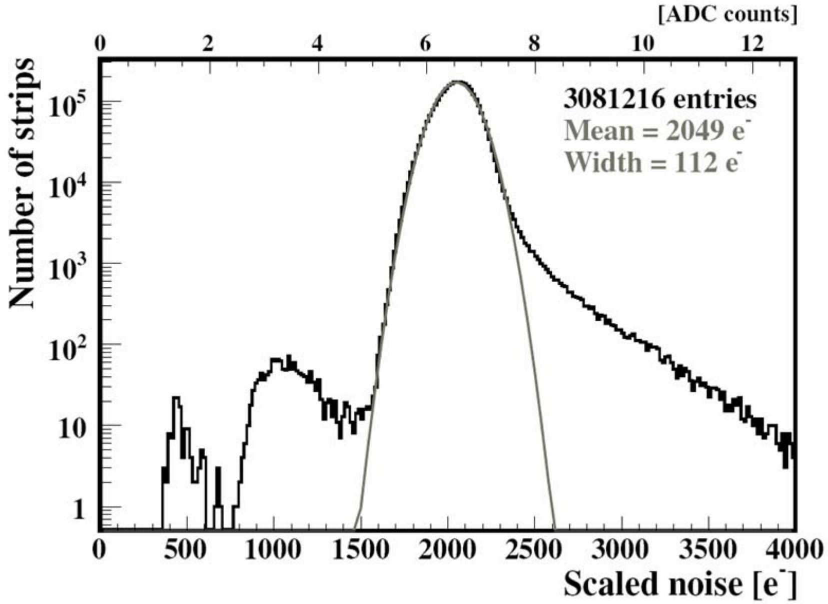
noise of (almost) all channels in the CMS tracker (25 ns mode)

TEC

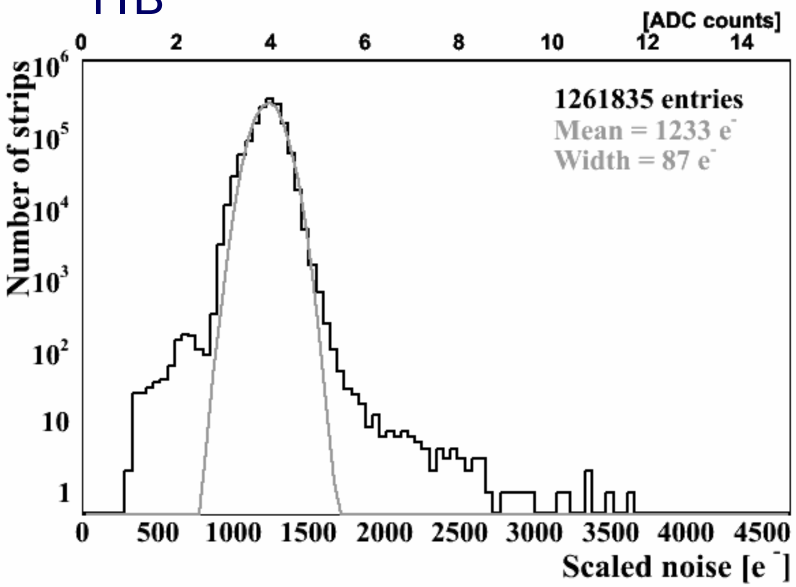
(scaled to strip length of ring 1)



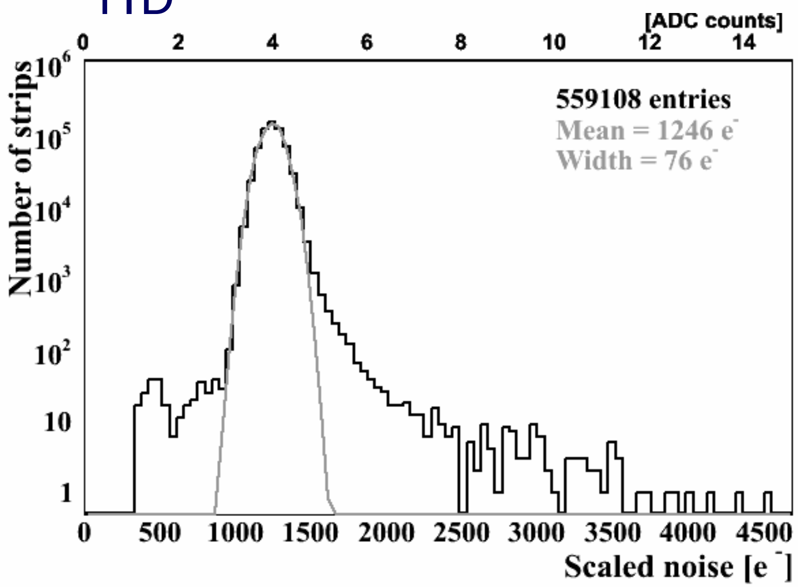
TOB



TIB

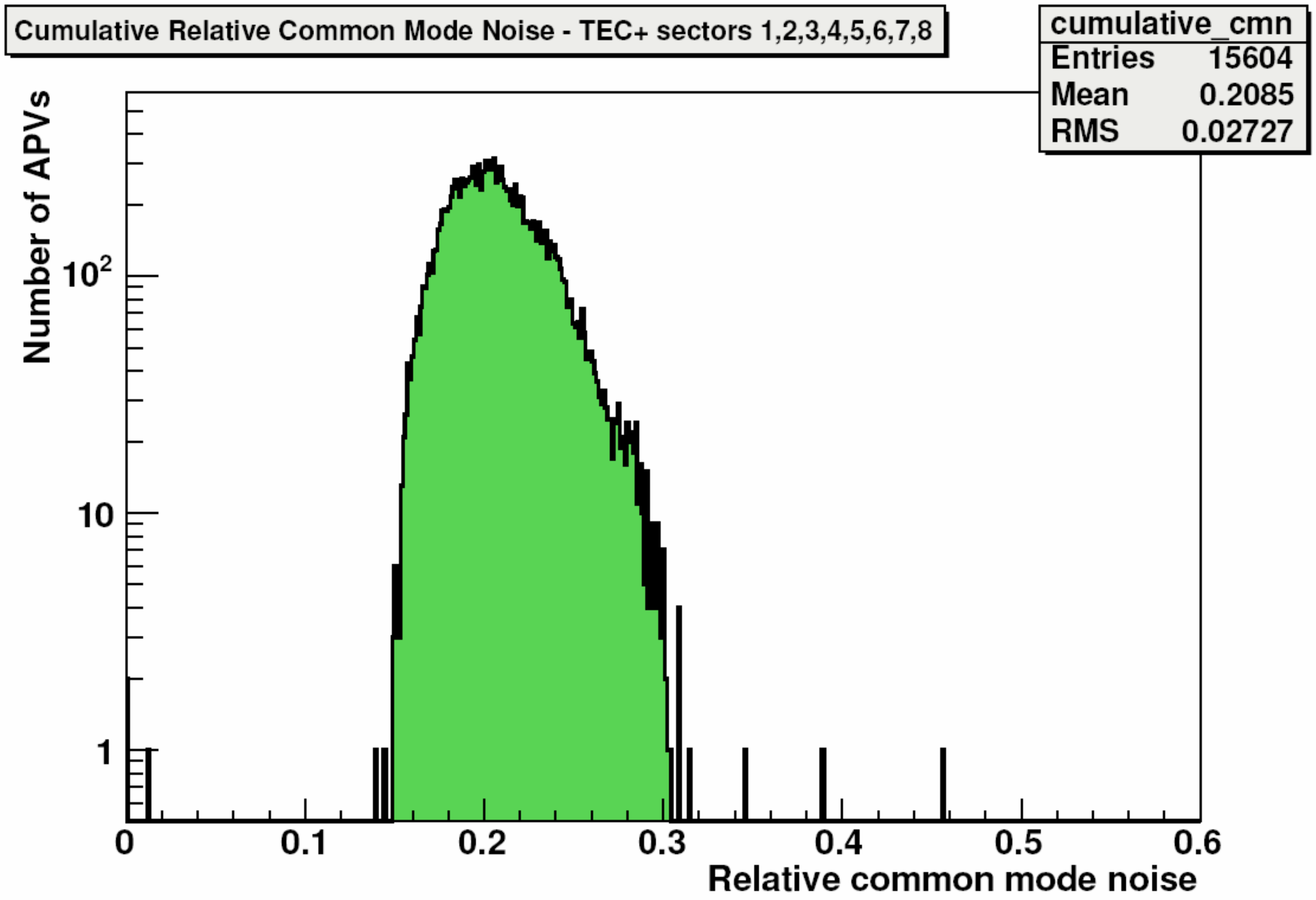


TID



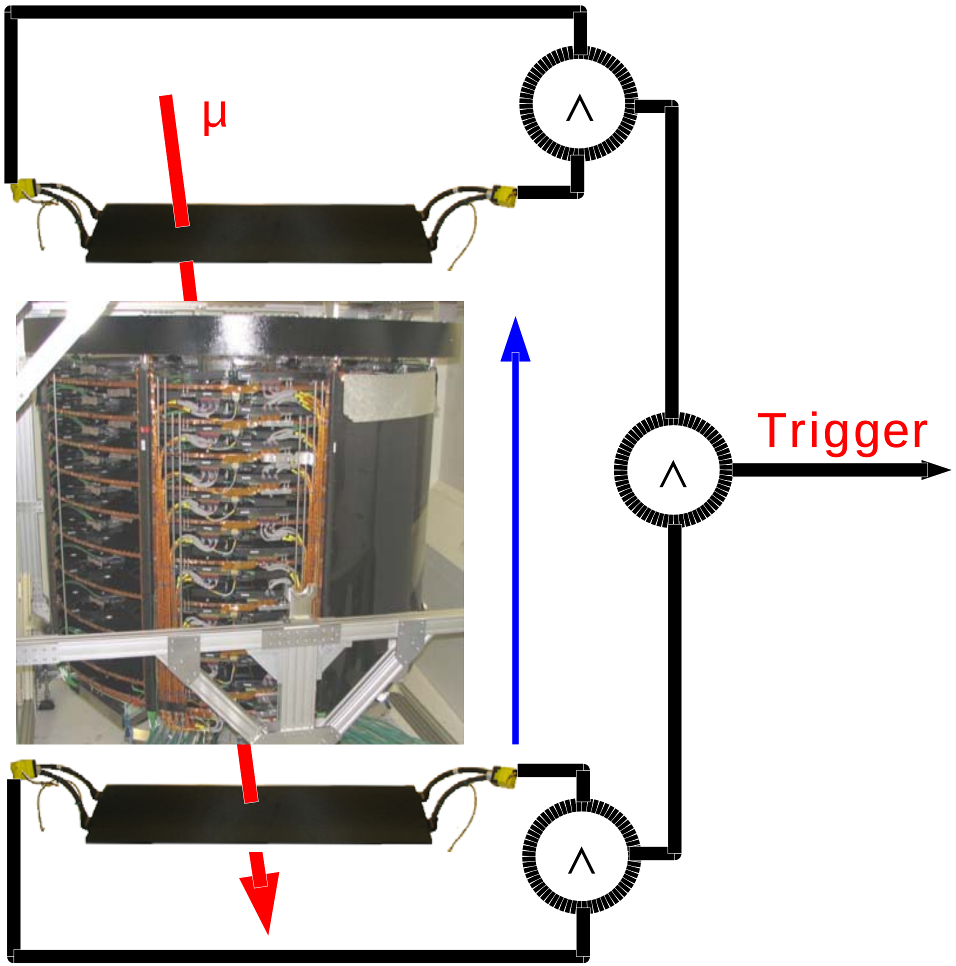
Performance of integrated Structures

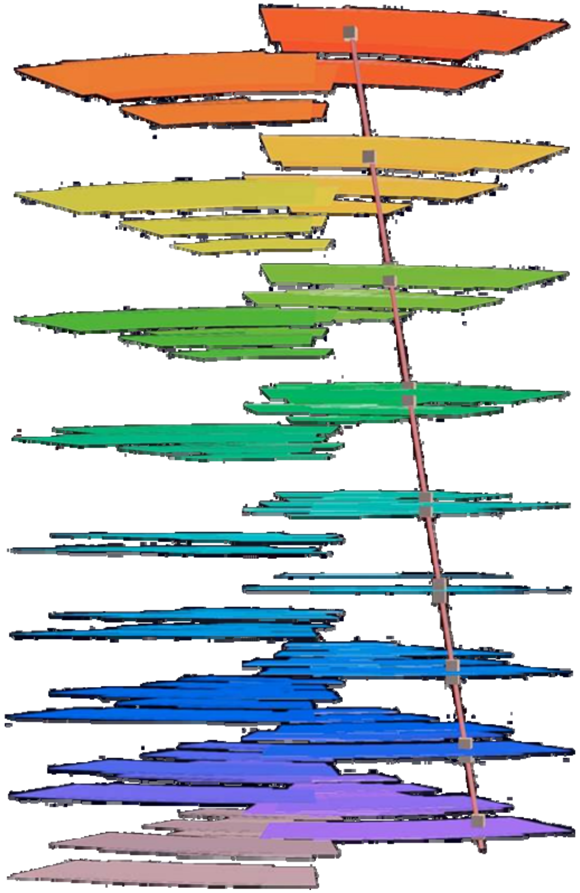
common mode noise relative to intrinsic noise: less than 30%



Performance of integrated Structures

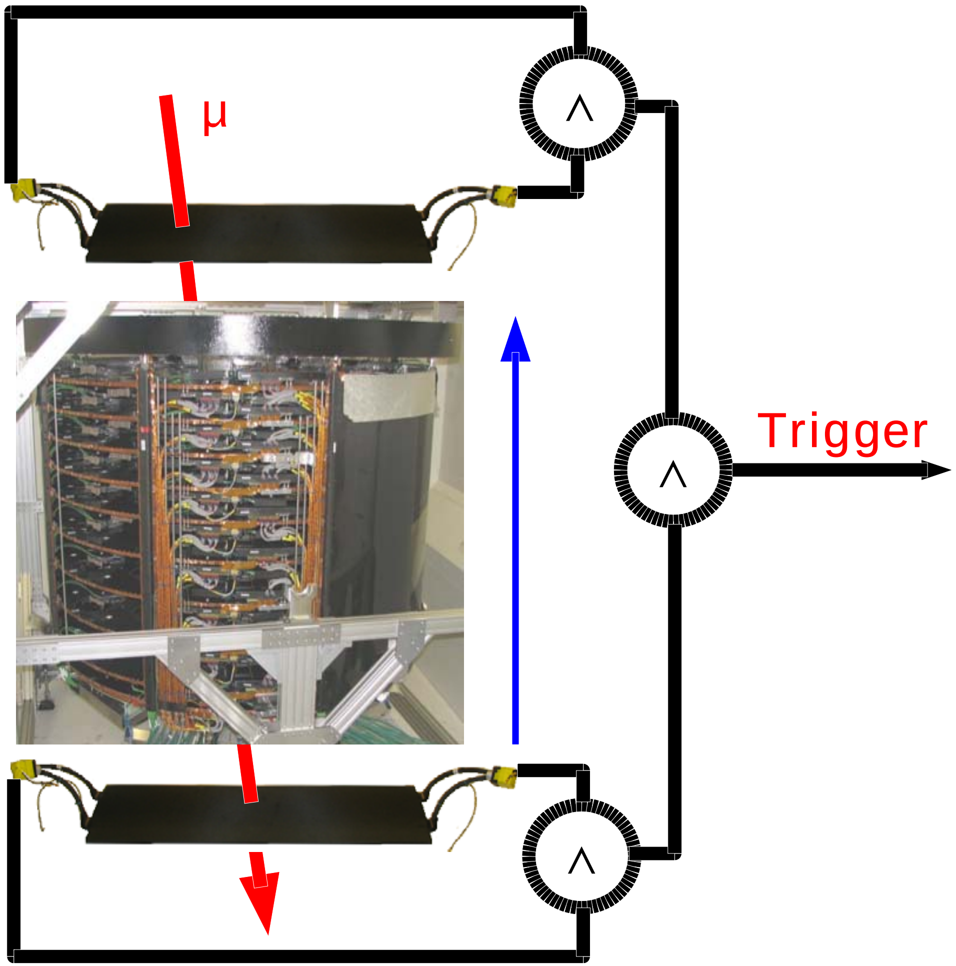
cosmic muons recorded in one end cap

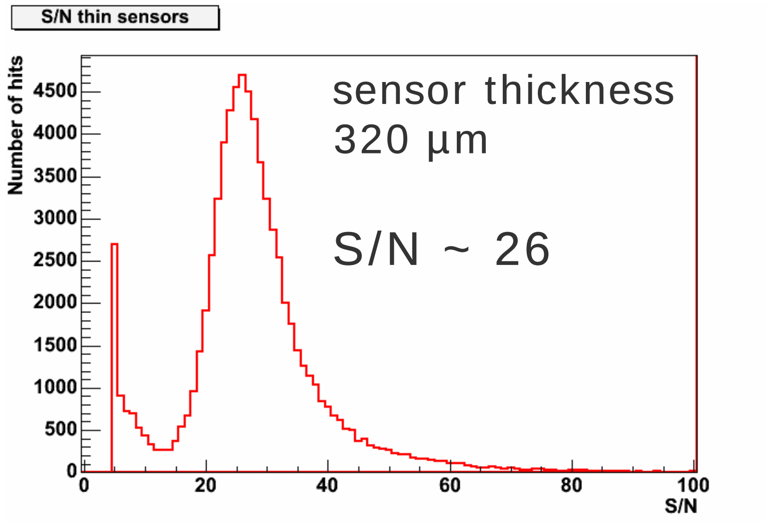


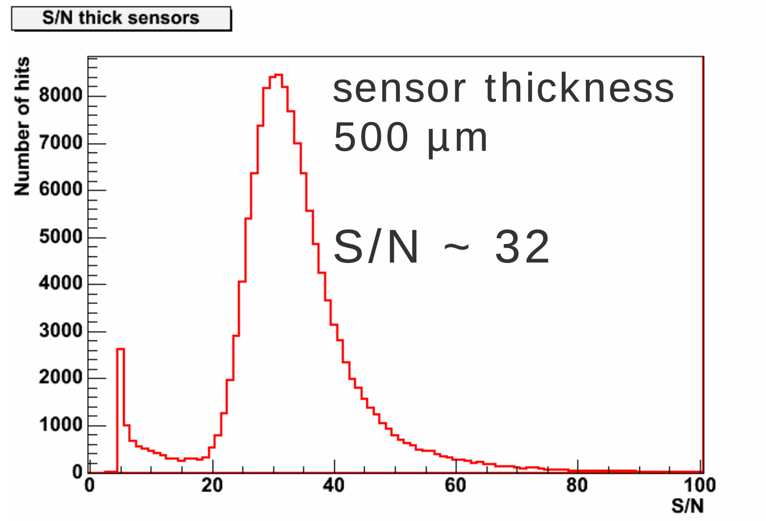


Performance of integrated Structures

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



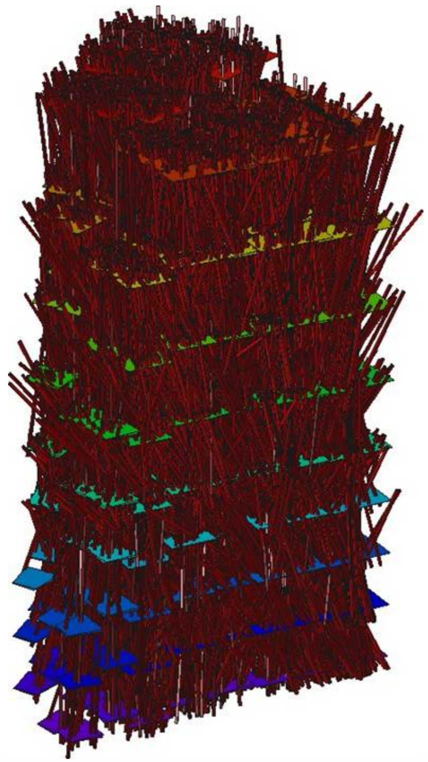




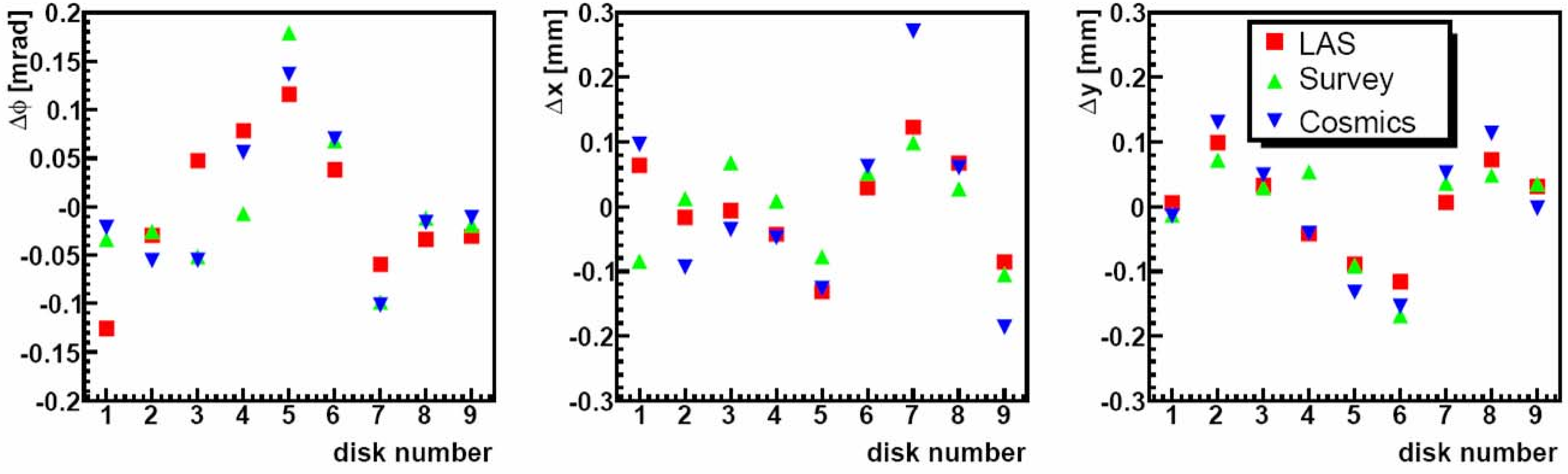
caveats: muons are not exactly MIPs
rough timing adjustment

Tracker Alignment

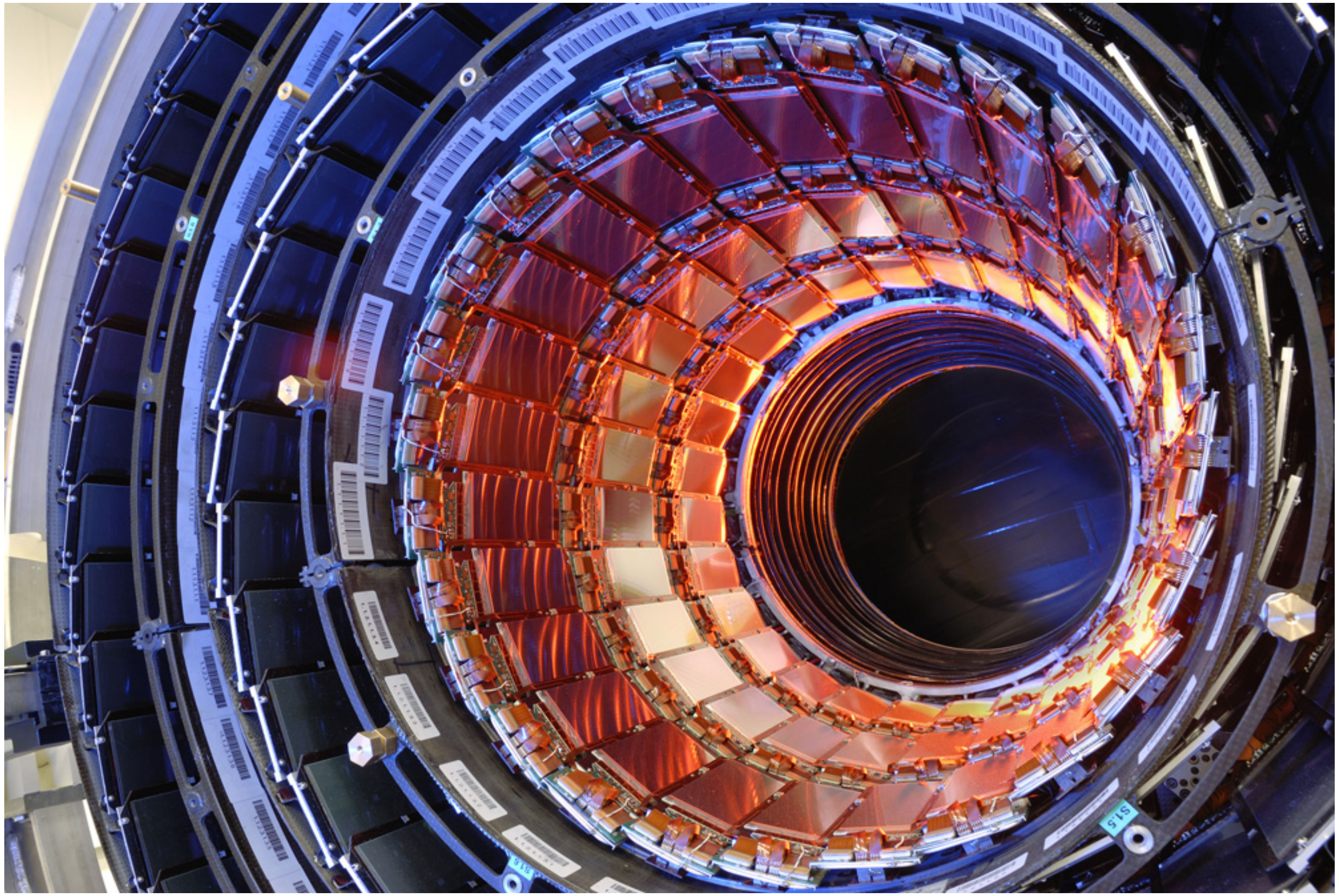
cosmic muon tracks in TEC+ can be used to align this part of the CMS tracker before installation into the tracker

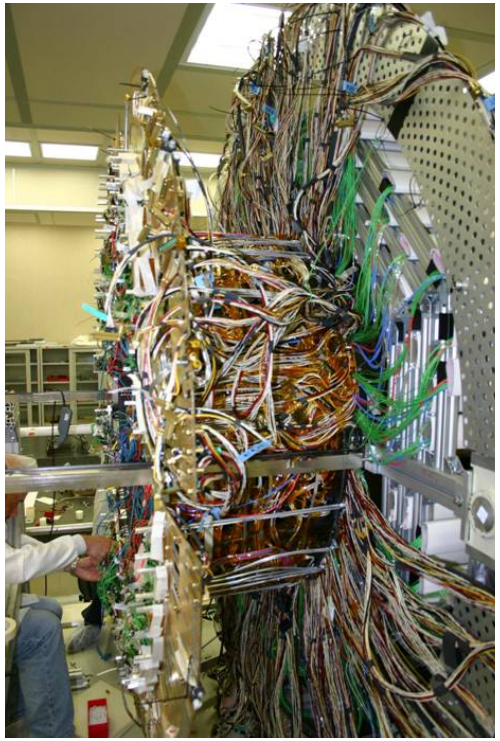


comparison to
- survey measurements and
- laser alignment system

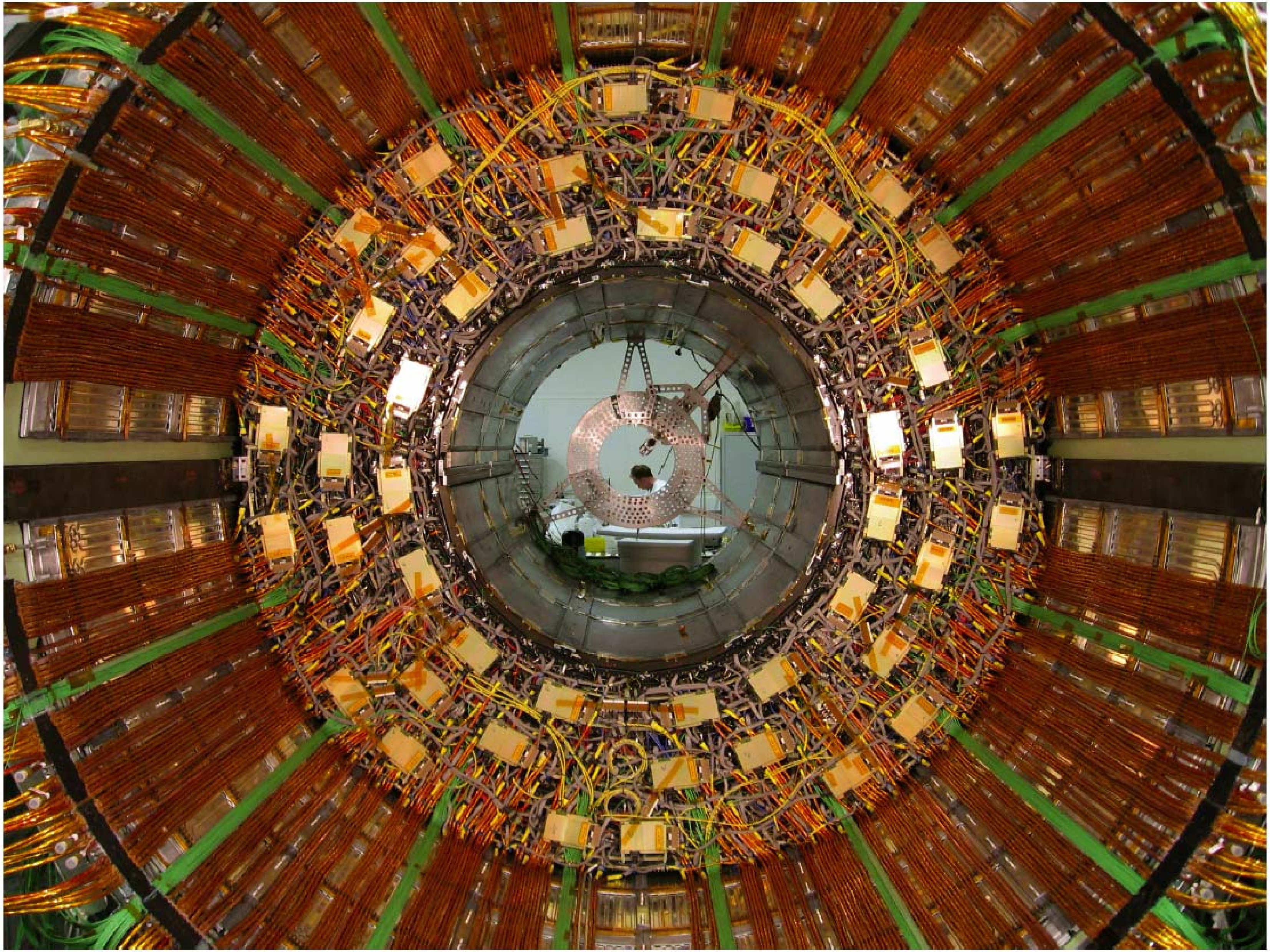


Finished TIB

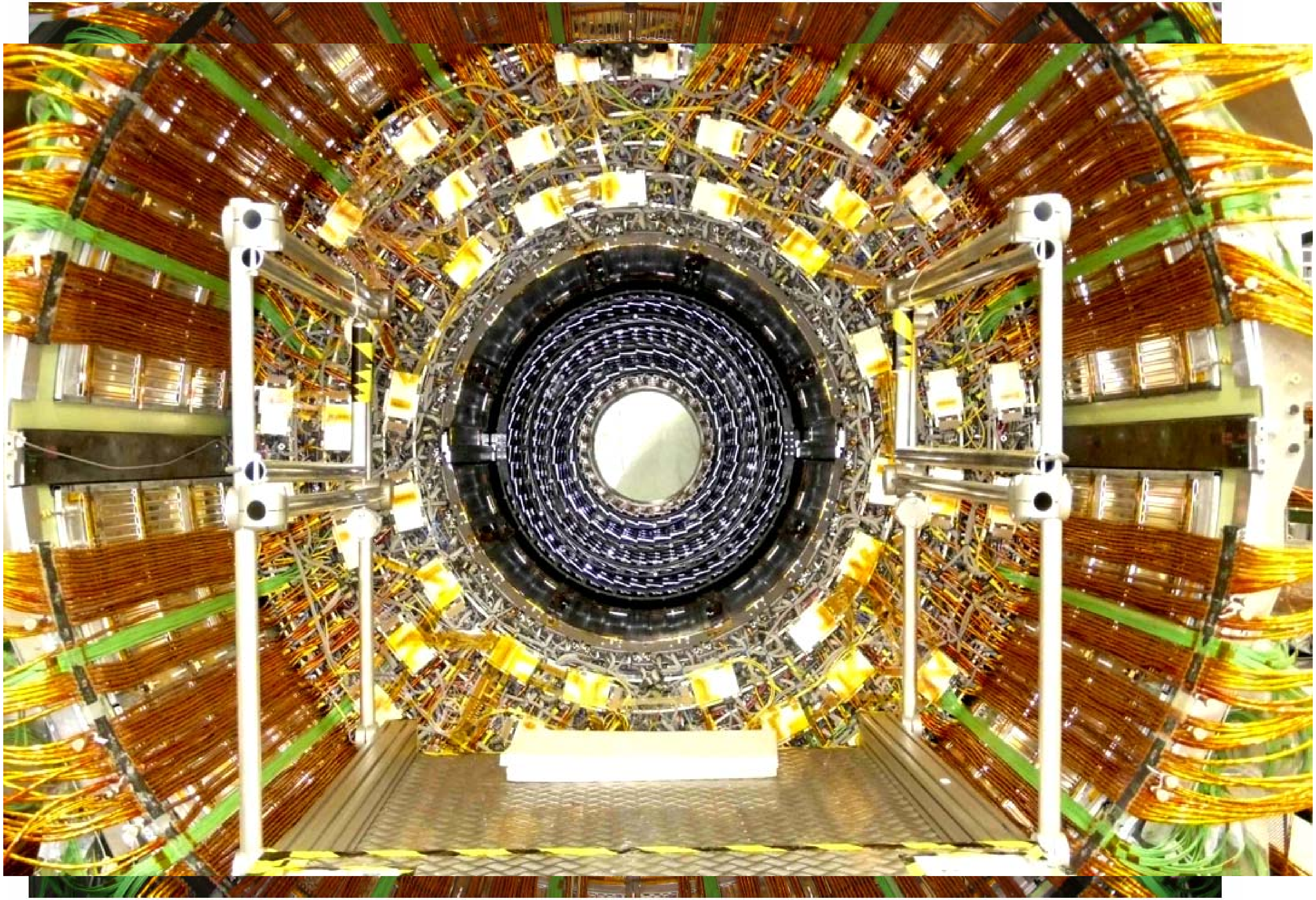




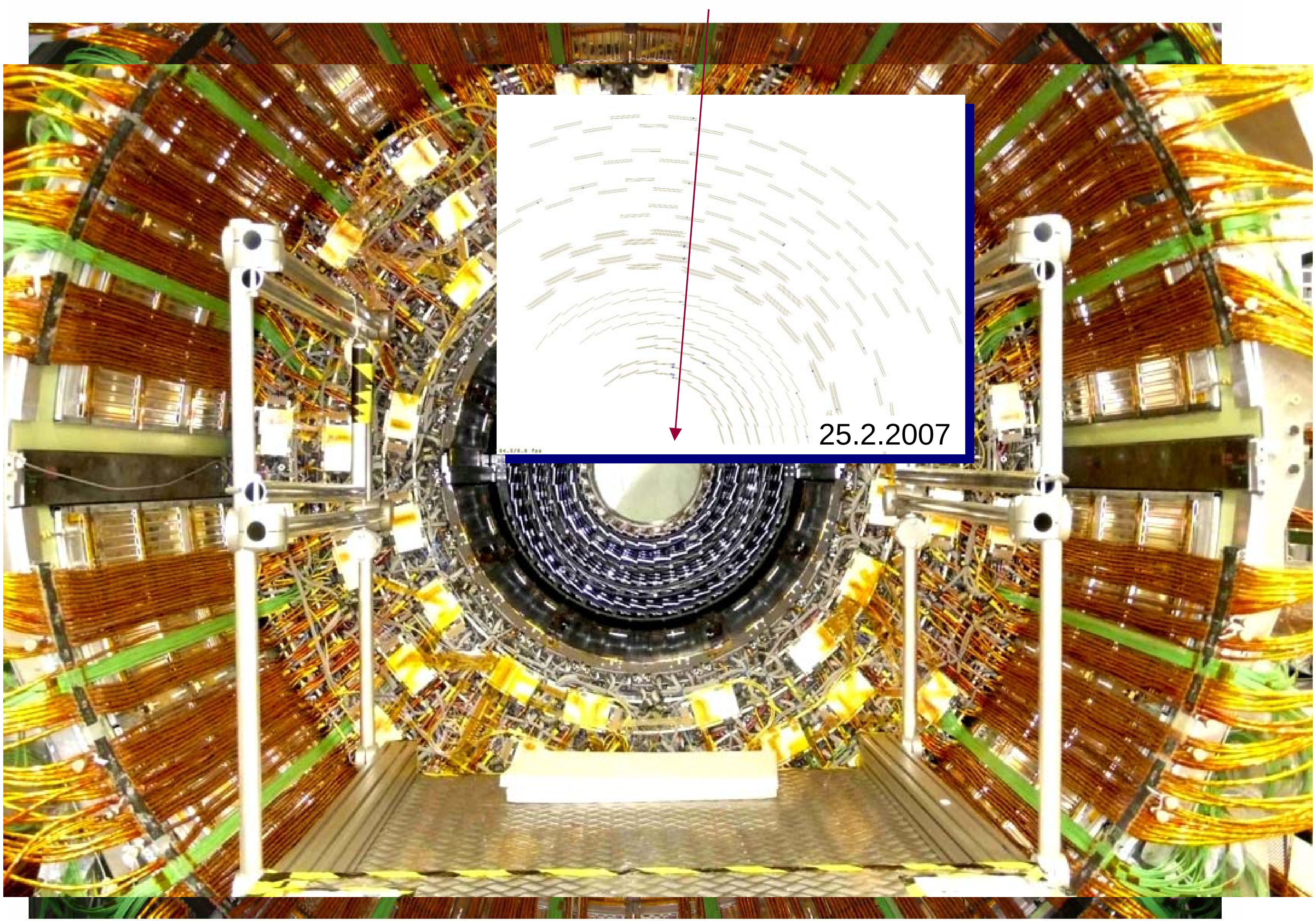
Finished TOB



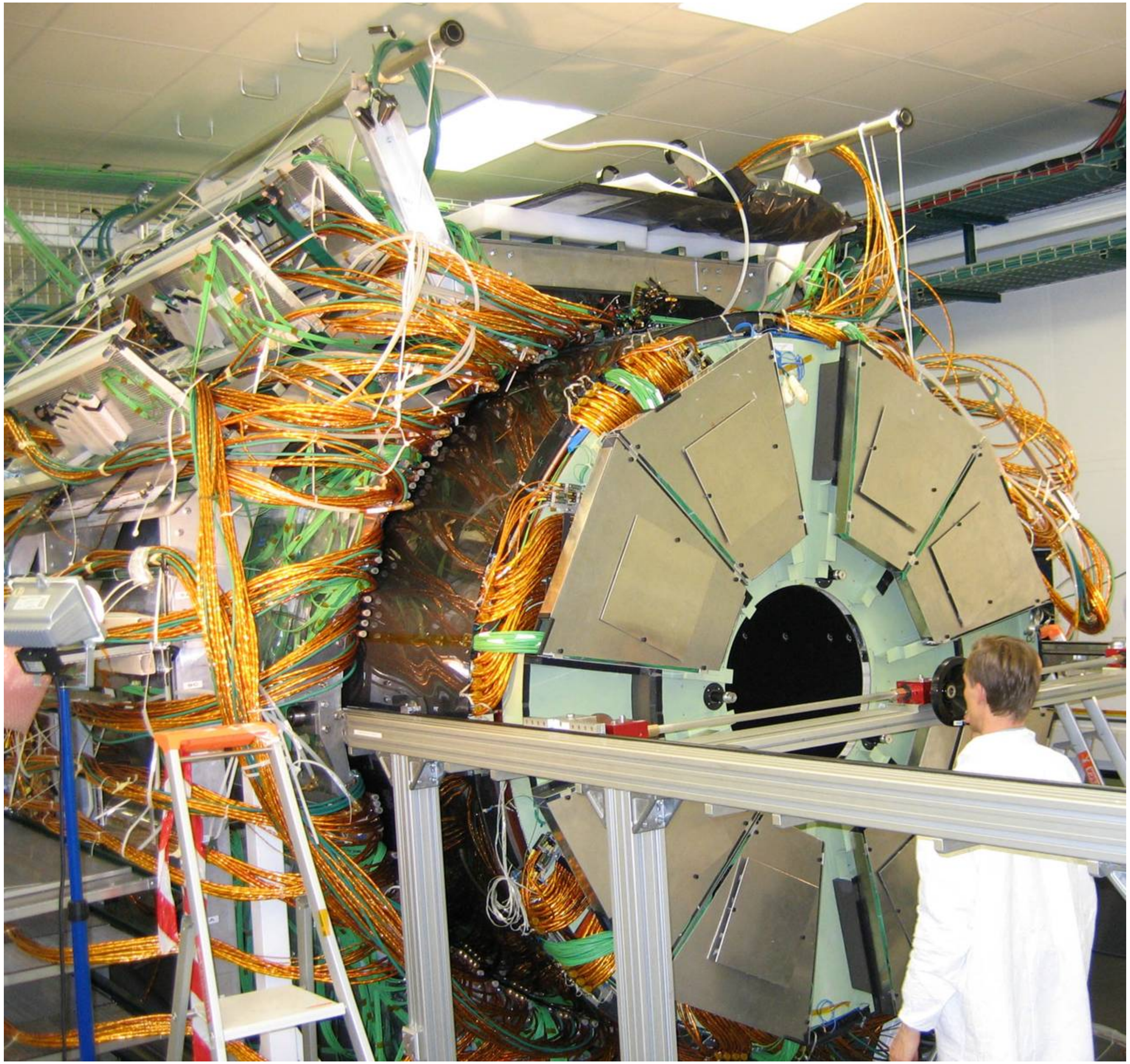
Finished TOB with TIB inside



Finished TOB with TIB inside and cosmic muon signals

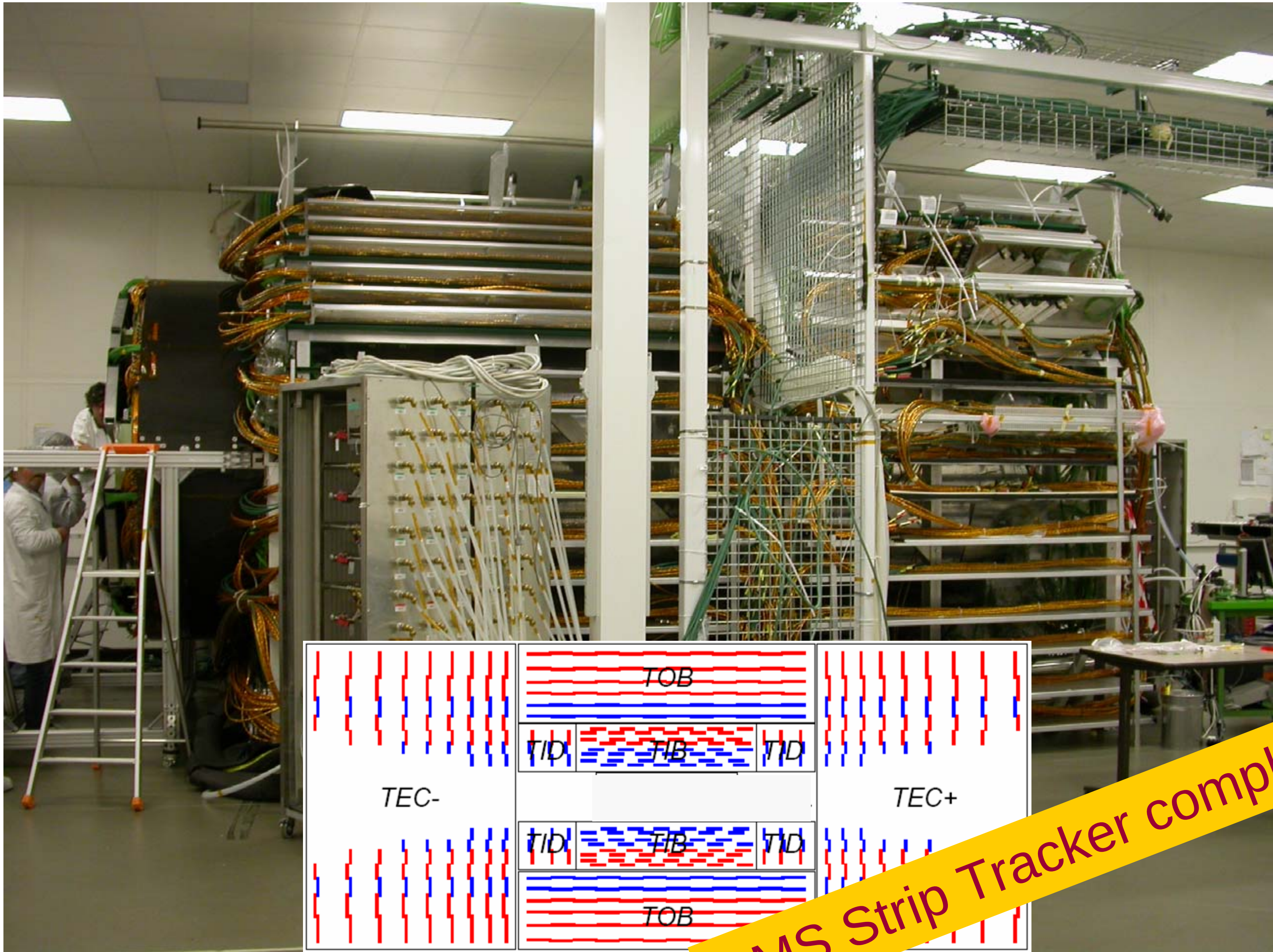


Insertion of TEC+ into the CMS Tracker



28. 2. 2007

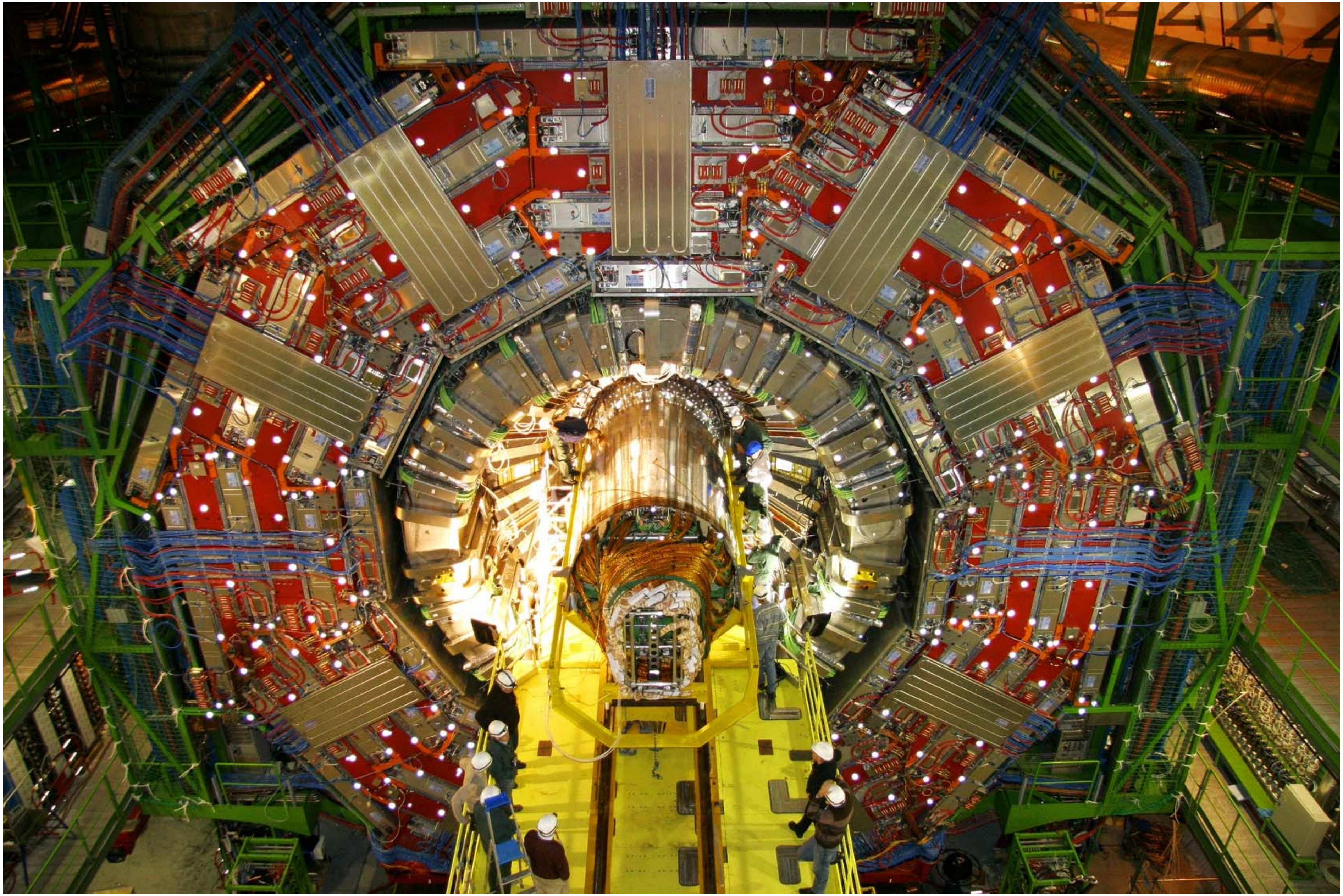
Insertion of TEC- into the CMS Tracker



CMS Strip Tracker completed

20. 3. 2007

Insertion of Tracker into CMS on Dec 18, 2007



What comes next?

Data Taking, Measurements, Discoveries!

However, we should plan beyond the current LHC program:

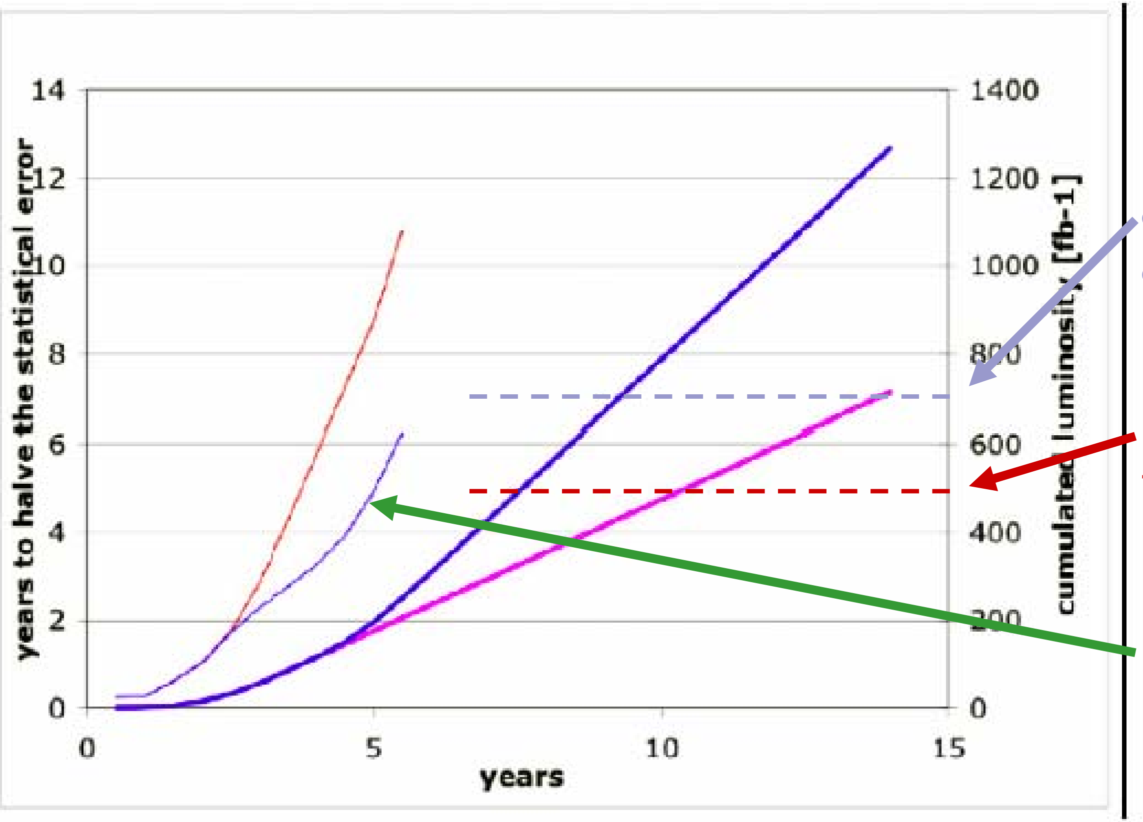
- LHC discoveries will need to be confirmed and studied with higher statistics
- discovery potential can be extended with higher statistics
- many Standard Model processes which will profit from or will only be visible with higher statistcs

→ luminosity upgrade of LHC

LHC

Why do we need an Upgrade?

- LHC machine and detectors were designed to deliver 500 fb^{-1} at $L=10^{34}$ cm^{-2} s^{-1}



lifetime of quadrupole triplets around interaction region about 700 fb^{-1}

lifetime of central trackers ~500 fb^{-1}

time to significantly decrease the statistical uncertainty gets very long

Figure 1.1: The thick lines on the right show integrated delivered luminosity (right hand scale) for two potential LHC running scenarios as a function of years from startup. The thin lines on the left (left hand scale) show the run-time required to halve statistical errors. [7].

- beyond 500 fb^{-1} an extension of LHC operation will be difficult and not profitable

→ Super-LHC: 10x instantaneous luminosity leading to 3000 fb^{-1}

What will change from LHC to SLHC?

- peak luminosity $L=10^{34}\ cm^{-2}\ s^{-1}$ → $L=10^{35}\ cm^{-2}\ s^{-1}$
- integrated luminosity 100 fb^{-1}/year → 1000 fb^{-1}/year
- replaced/new machine elements, also close to interaction regions
  → lower beta*
- modified bunch structure: no final decision yet, currently preference for 50 ns crossing rate of slightly longer bunches with more protons
  - 10, 12.5, 15 ns: heat load in LHC beam screen due to electron cloud too high (last resort if bunch charge or pile-up at 50 ns lead to unexpected problems
  - 25 ns: beam separation magnets inside the experiments much closer to IP than for 50 ns option
    → this is the fall-back

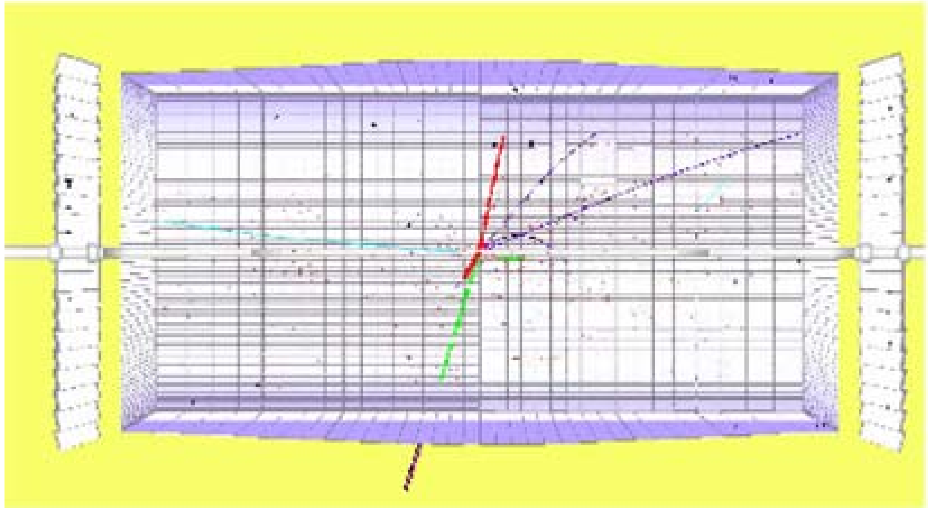
→ about 400 pp interactions on average in each bunch crossing

→ about 20,000 particles in the tracker per bunch crossing

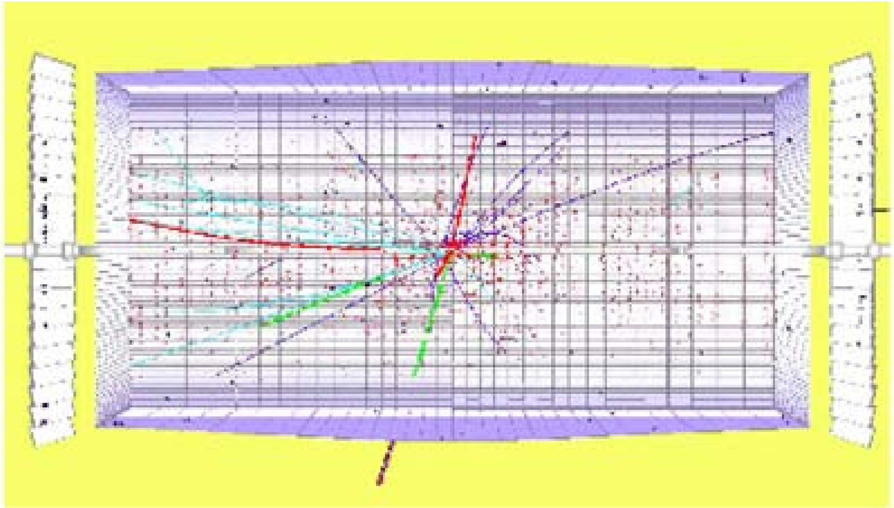
- c.m. energy will remain at 14 TeV (increase to 28 TeV would require complete rebuilt of machine including s.c. dipoles with B=16T which do not exist)

A Pictorial Preview

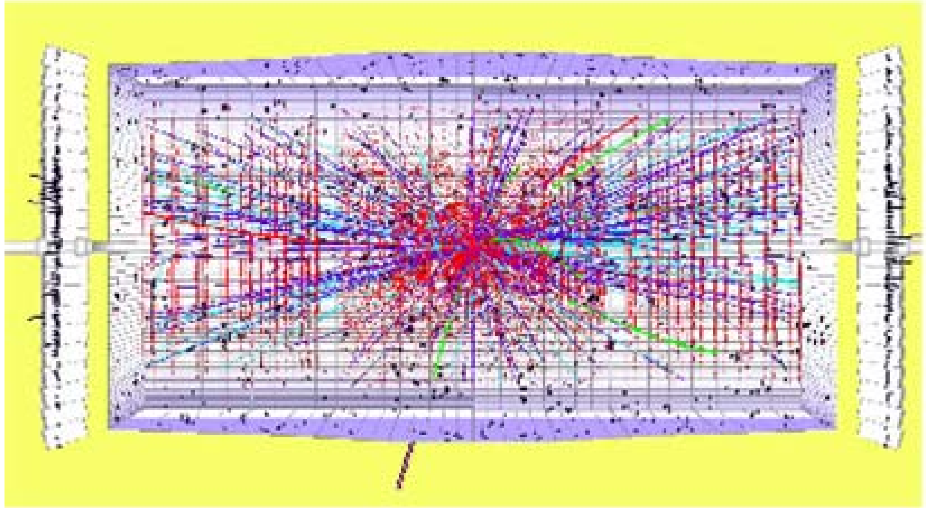
LHC start-up: 10^{32} cm^{-2} s^{-1}



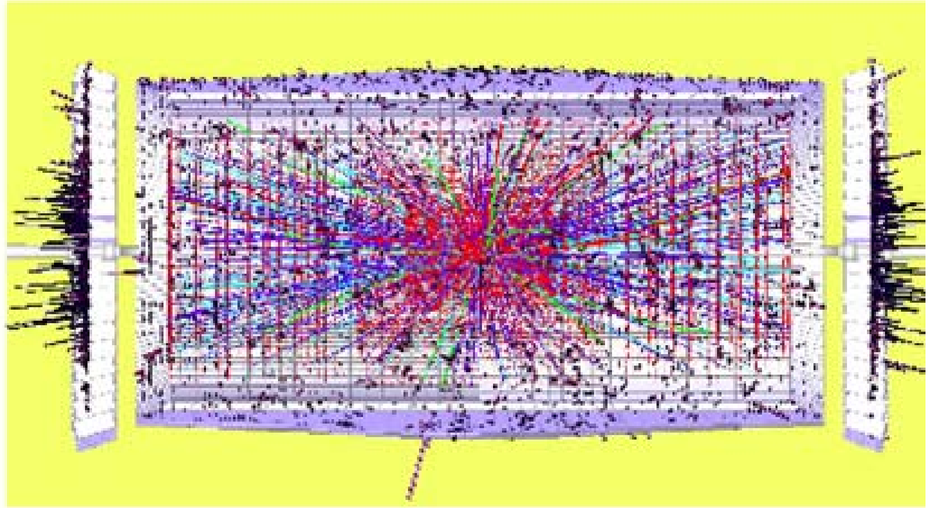
LHC first year: 10^{33} cm^{-2} s^{-1}



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

Implications for CMS

- occupancies increase roughly by a factor of 20
- data rates increase roughly by a factor of 20
- radiation dose and fluence increase roughly by a factor of 20

Aim: preserve performance of CMS
(otherwise a factor of 10 in statistics would be rather useless)

- **Tracker** (pixel and strips): needs to be rebuilt
- **ECAL**: crystals and on-detector electronics should work at SLHC
- **HCAL**: HB ok, HE need replacement of scintillators, HF may be in conflict with new machine elements
- **Muon**: chambers ok, on-detector electronics may need upgrade
- **Trigger**: needs to be rebuilt

Since R&D and detector construction will take ~10 years
work on upgrade has to start **now**!

Implications for the Tracker

- current CMS Tracker is highly efficient and precise
  → keep specifications for momentum and spatial resolution

- only one way to make it significantly better: **reduce material budget**

- operation of Tracker at the SLHC with equal or better performance requires

  - higher granularity to cope with 20 times increased occupancy
    → smaller strip/pixel sizes ... but watch cost and power

  - improved radiation hardness to survive 5-6 times higher radiation levels
    → new sensor concepts for inner layers, improved cooling

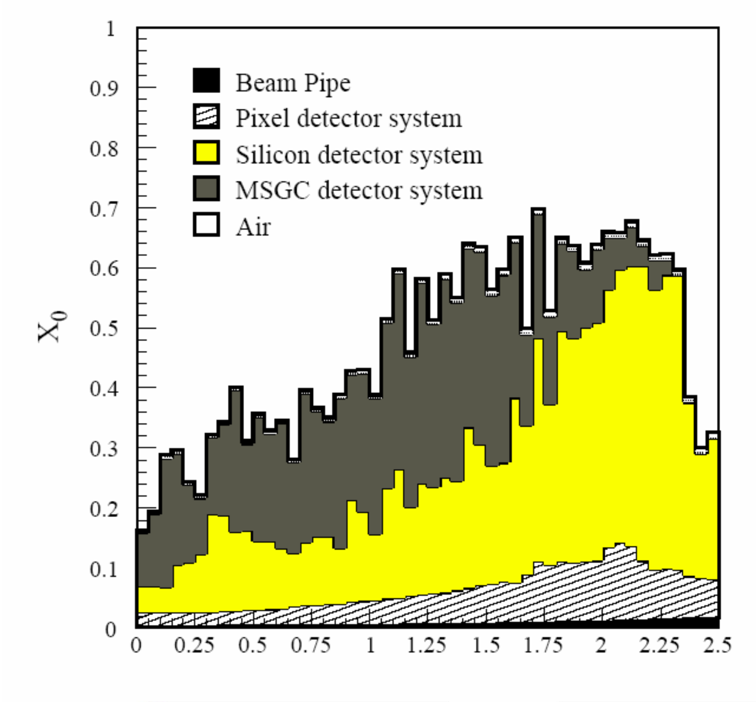
  - improved read-out system to cope with increased hit rates and data volume, and to contribute to the L1 trigger

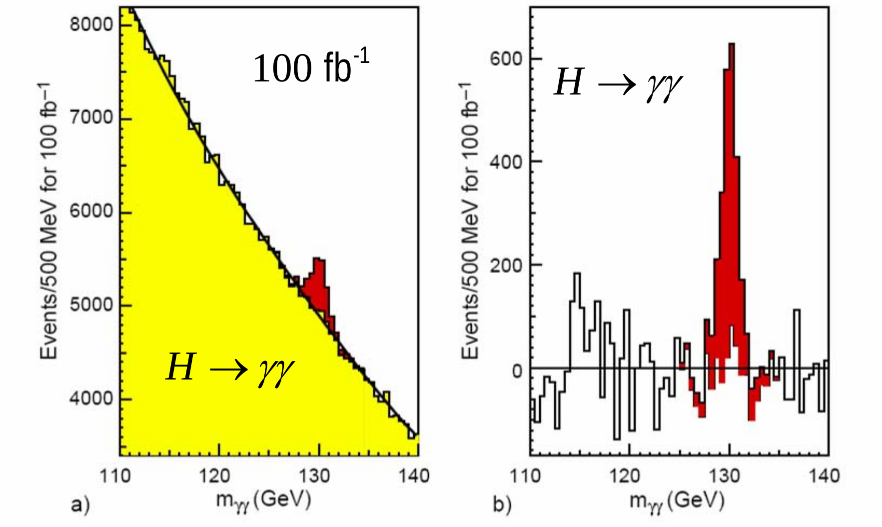
  - improved power distribution to supply more detector channels and allow usage of 0.13µm (or smaller) ASIC technology

  - reduced material budget: fewer layers, less copper (powering scheme), improved services lay-out, ...

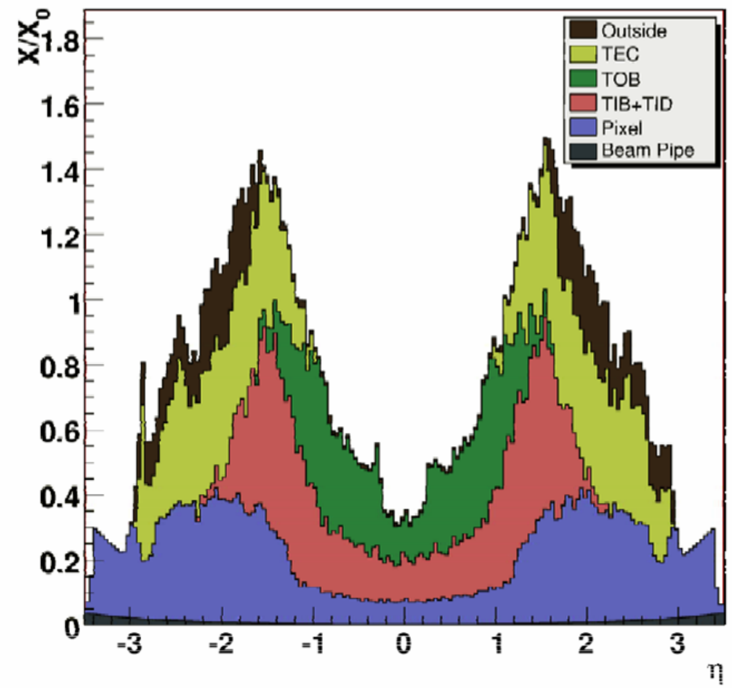
To be Improved: Material Budget

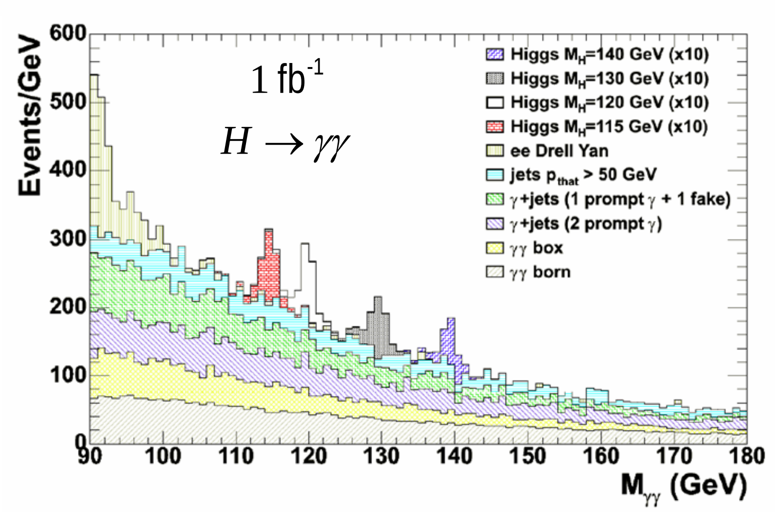
1997





2006





Material Budget in the current Tracker

Element	Index	Total Mass		Mass Fraction
Nitrogen	0	3.87108 kg	0.00107488	
Oxygen	1	365.756 kg	0.10156	
Argon	2	51.9506 g	1.44251e-05	
Hydrogen	3	114.589 kg	0.031818	
Iron	4	49.7929 kg	0.013826	
Carbon	5	1412.52 kg	0.392215	
Manganese	6	331.092 g	9.19346e-05	
Chromium	7	2.67785 kg	0.00074356	
Nickel	8	10.4754 kg	0.0029087	
Aluminium	10	585.763 kg	0.162649	
Beryllium	11	760.09 g	0.000211055	
Copper	13	494.673 kg	0.137356	
Gold	14	442.466 g	0.00012286	
Silicon	15	306.091 kg	0.0849924	
Sulfur	16	7.27642 g	2.02045e-06	
Phosphor	17	5.21479 g	1.44799e-06	
Indium	18	1.07669 g	2.98966e-07	
Lead	19	326.109 g	9.05509e-05	
Tin	20	4.67424 kg	0.0012979	
Barium	21	4.72014 kg	0.00131064	
Titanium	22	24.3486 kg	0.00676089	
Fluorine	23	192.615 kg	0.0534834	
Silver	24	11.204 kg	0.00311102	
Pix_Bar_Ring_HC25		45.2962 g	1.25774e-05	
Bor 10	26	64.9296 g	1.8029e-05	
Bor 11	27	285.69 g	7.93278e-05	
Chlorine	28	73.206 g	2.03272e-05	
Antimony	29	171.786 g	4.76999e-05	
Bromine	30	9.00321 kg	0.00249993	
Zinc	31	3.67327 kg	0.00101996	
Sodium	32	970.164 g	0.000269386	
Potassium	33	1.19481 kg	0.000331765	
Cobalt	34	211.631 g	5.87636e-05	

Total Weight without Air 3601.39 kg

[R. Ranieri, SLHC Upgrade Workshop 13.9.2007]

Material Budget in the current Tracker

	Support	Sensors	Cables	Cooling	Electronics
TIB/TID	18.2%	7.6%	46.0%	15.3%	12.9%
TEC	48.6%	11.9%	12.1%	19.5%	7.9%
TOB	30.9%	15.5%	17.8%	9.7%	26.1%
TST+TS+PP	15.8%	0	69.4%	14.8%	0.0%
STRIP	30.9%	10.7%	28.2%	15.3%	14.2%

[R. Ranieri, SLHC Upgrade Workshop 13.9.2007]

- sensors contribute only 10.7%
- big contribution by support structure, cables and cooling
- material budget obviously depends on system layout

Power Distribution

- power dissipation inside current tracker: about 60 kW
  at low voltage (2.5V) → high currrents
  → about half of power is dissipated in cables

- channel number will increase

- power per analogue channel will decrease, but probably not compensate increase in channel number

- increased logic (on chip data reduction, trigger logic) will increase power

- fast data links (GB/s or more) need power

- ASIC supply voltage will decrease (factor 2 for 0.25µm→0.13µm)
  → same power requires more current

- total power cable cross section is limited by cable channels in CMS
  cables are big contribution to material budget
  → can not increase currents, rather decrease them

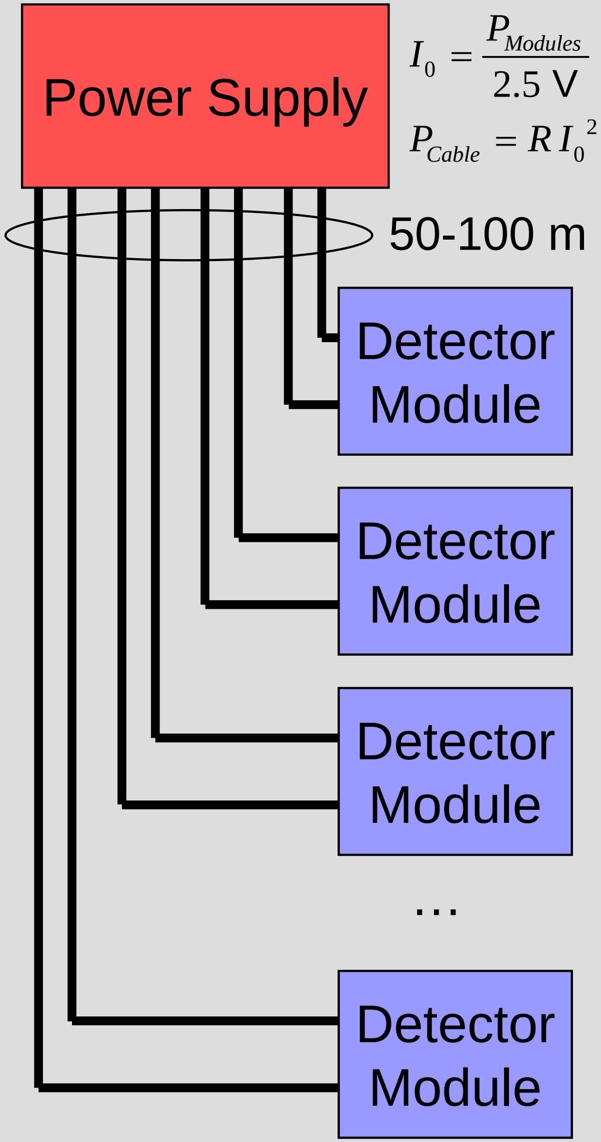
→ new powering scheme needed: supply power at high voltage (e.g. 48V) into tracker (at much reduced current) and convert locally (DC-DC or serial)

Now

Independent Powering

$$I_0 = \frac{P_{Modules}}{2.5\text{ V}}$$

$$P_{Cable} = R I_0^2$$



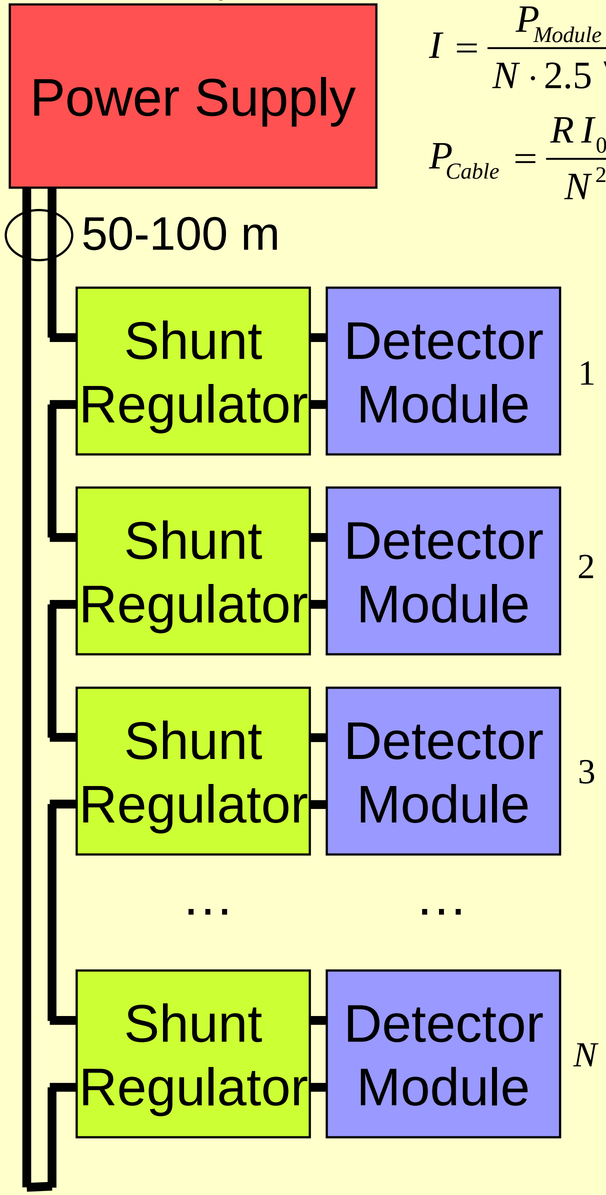
Novel Powering Schemes

Serial Powering

N modules powered in series

$$I = \frac{P_{Module}}{N \cdot 2.5\text{ V}}$$

$$P_{Cable} = \frac{R I_0^2}{N^2}$$

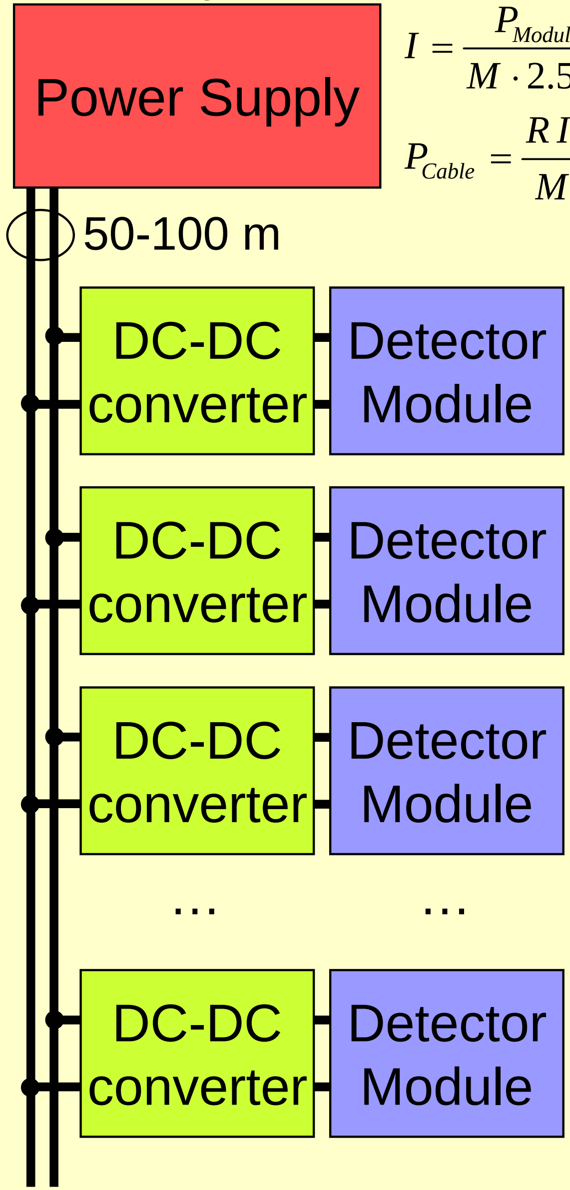


DC-DC Powering

M :1 voltage conversion

$$I = \frac{P_{Module}}{M \cdot 2.5\text{ V}}$$

$$P_{Cable} = \frac{R I_0^2}{M^2}$$



Tracker Contribution to L1 Trigger

- extraction of L1 trigger information from tracker requires a completely new approach

- data processing on the detector will be necessary

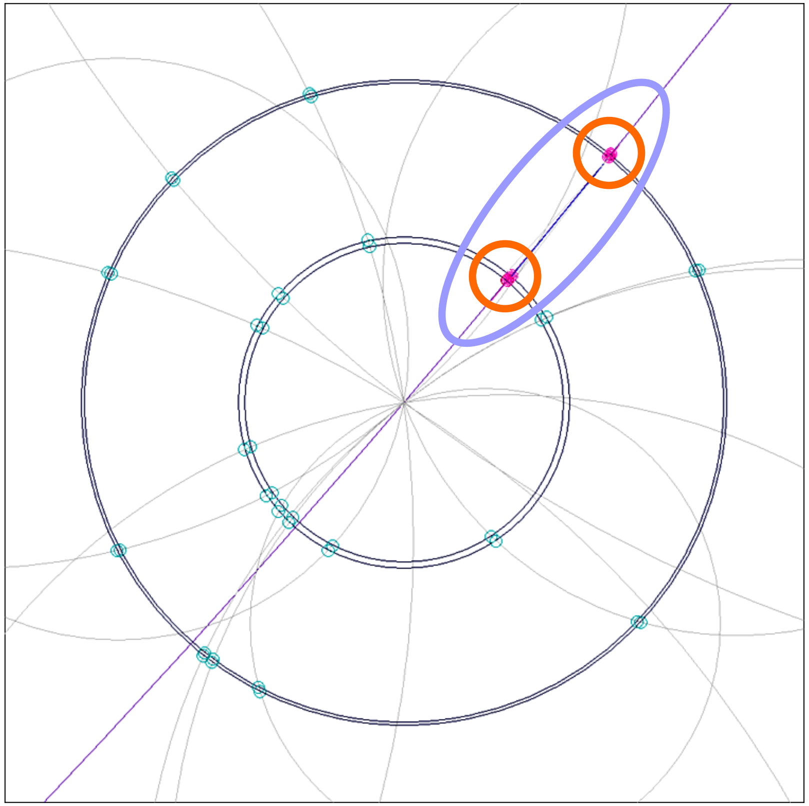
- track stubs pointing to ECAL clusters or MUON tracks would be sufficient

  → **double layer** of pixel detectors with hit correlation logic

  hit pairs of high p_t tracks point to IP

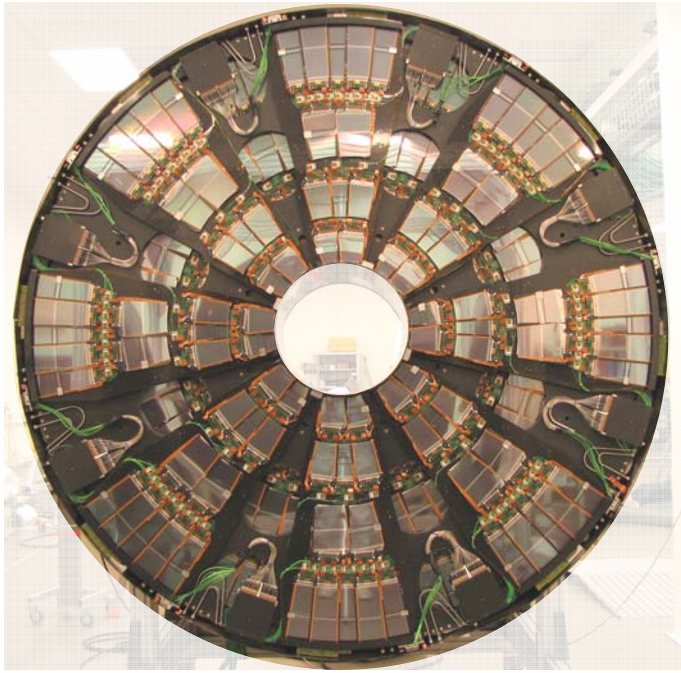
  correlation = p_t cut

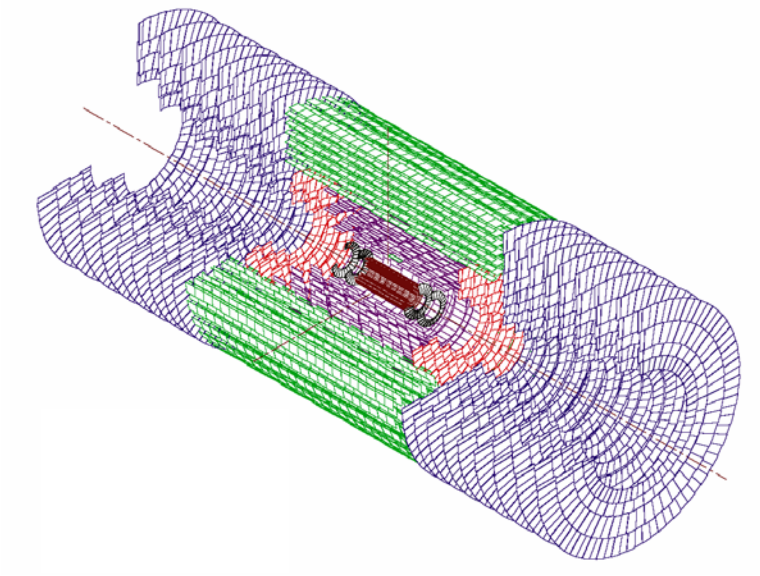
- binary read-out with off-detector processing could be an alternative



[J. Jones et al., http://www.imperial.ac.uk/research/hep/preprints/06-11.pdf]

Summary





- Silicon Strip Tracker completed and installed in CMS
- 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
- now: cabling, commissioning … data taking
- work on SLHC Upgrade has started