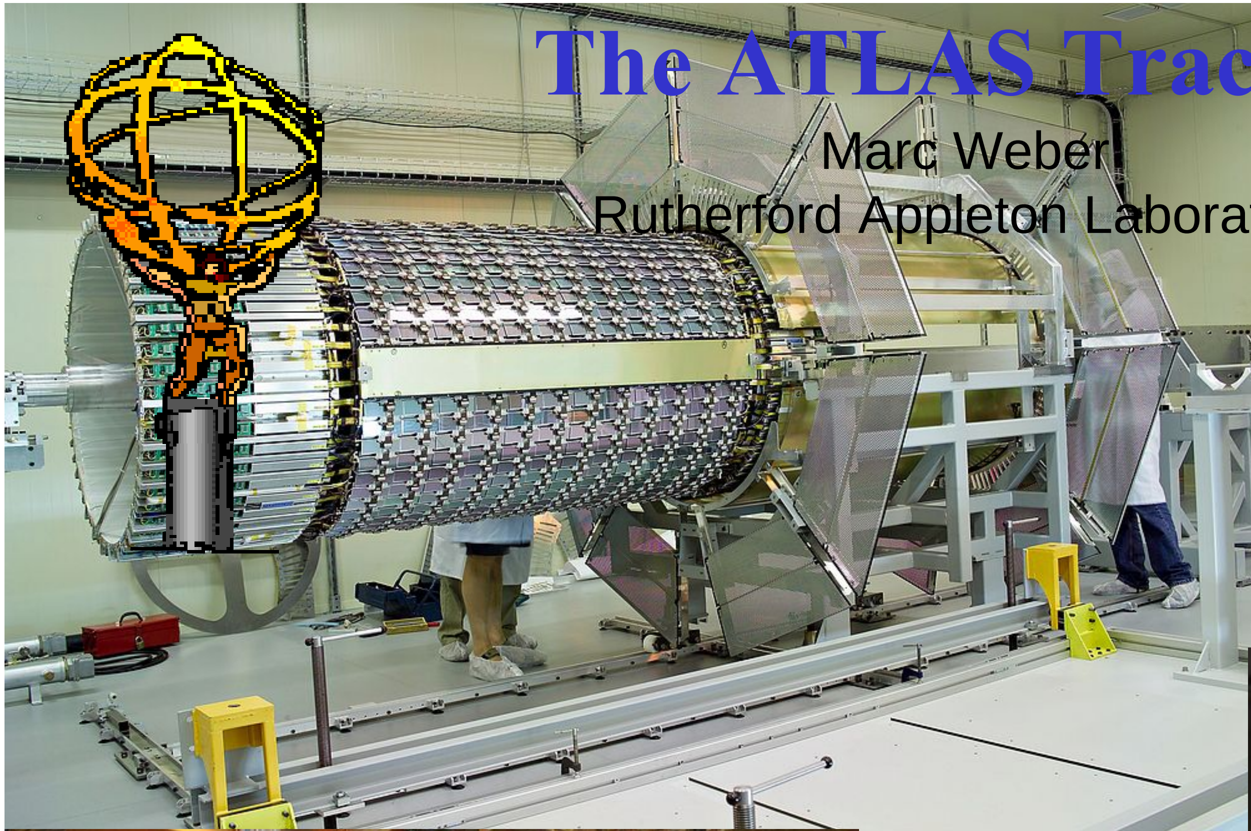
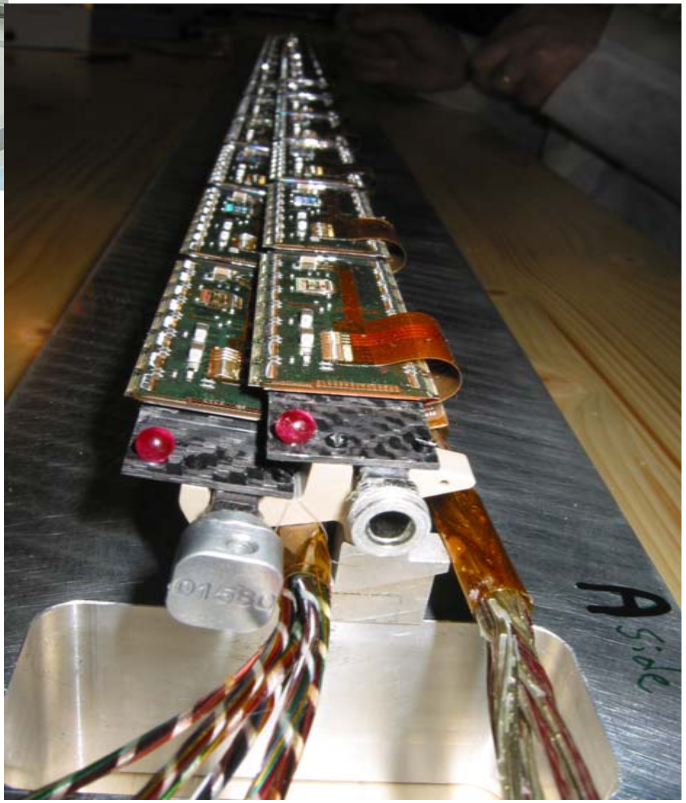


The ATLAS Tracker

Marc Weber
Rutherford Appleton Laboratory

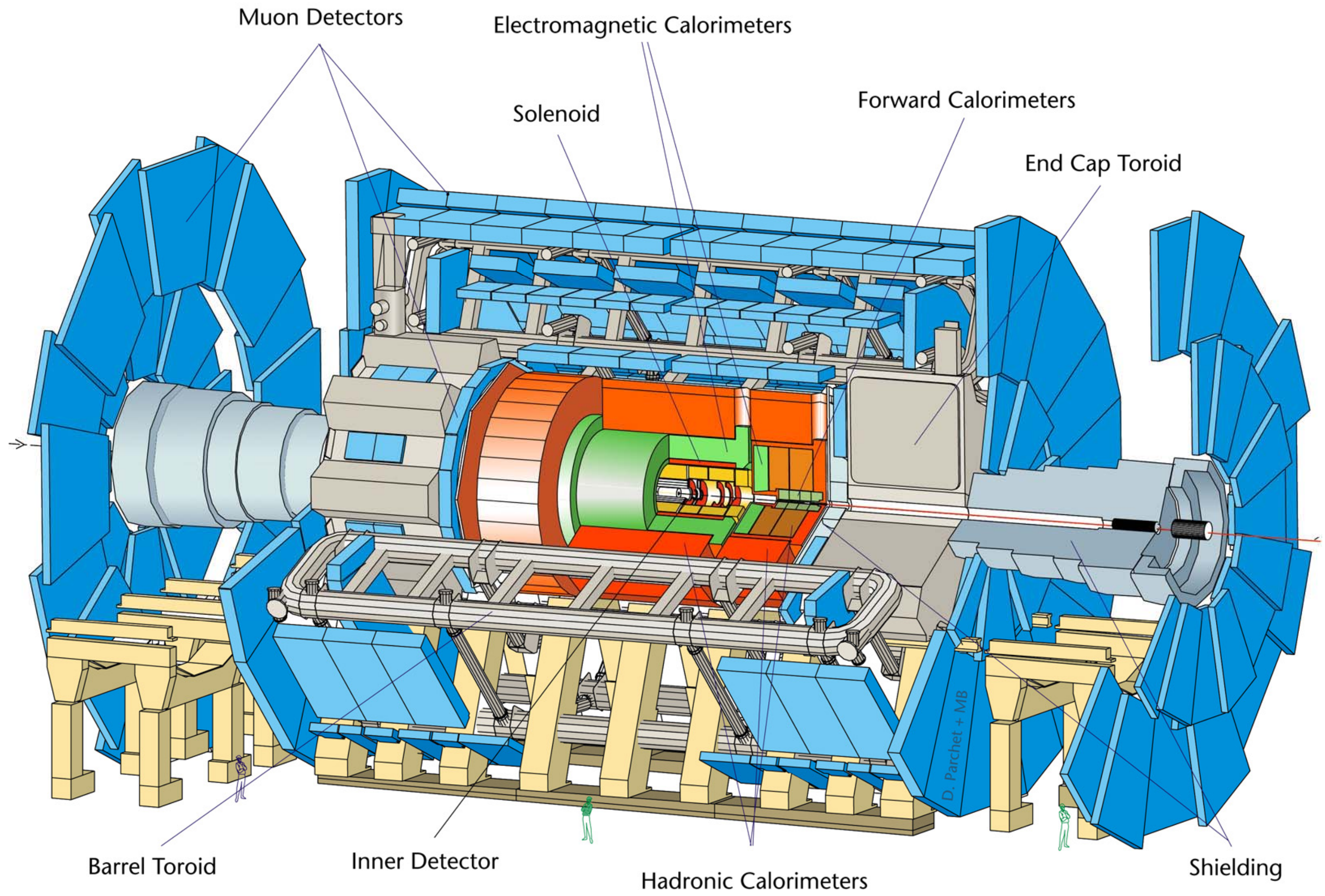
- Requirements
- Layout
- Expected performance
- Status
- Upgrade



New Frontiers in Subnuclear Physics

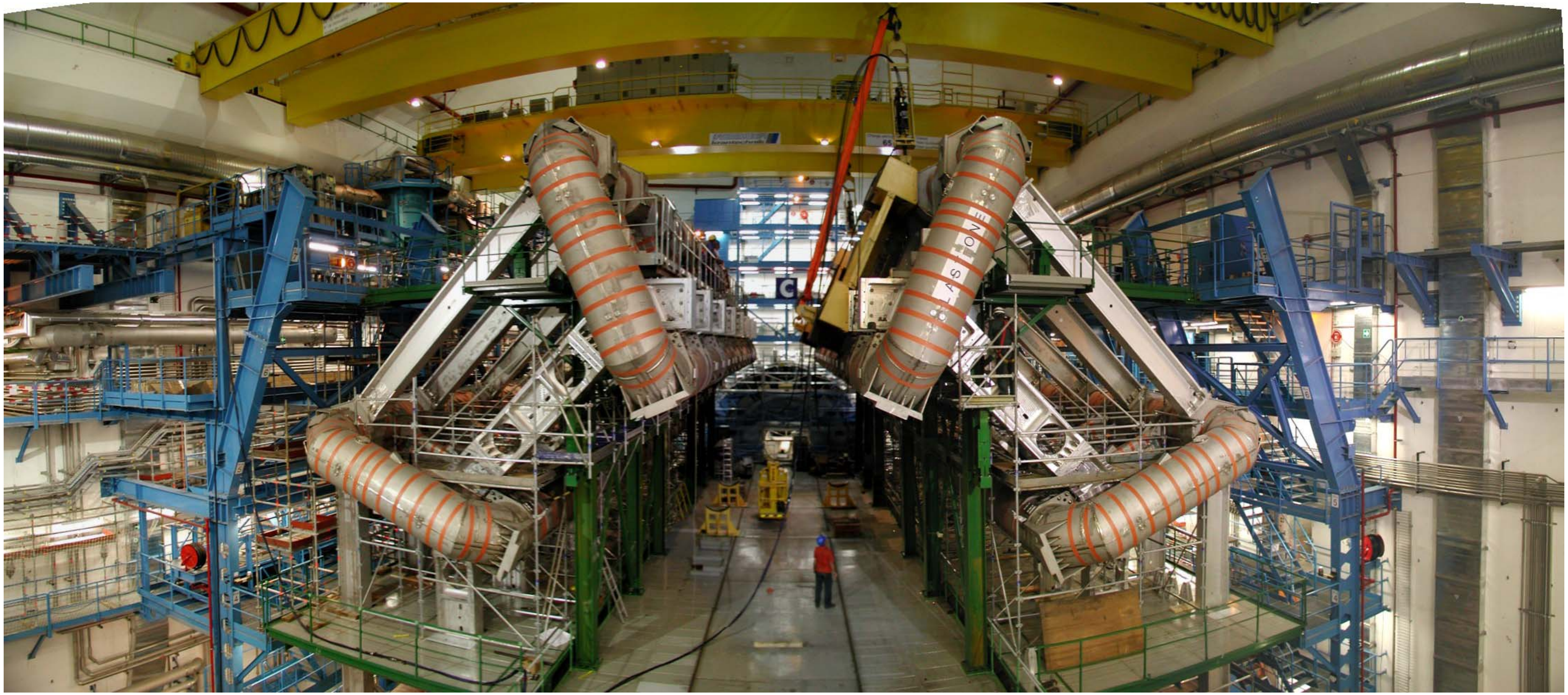
Milano, Sept. 12-17, 2005

ATLAS detector



- Huge multi-purpose detector; 46 m long; diameter 22 m; weight 7000 t
- Tracking system much smaller; 7 m long; diameter 2.3 m; 2 T field

The ATLAS cavern



- Huge multi-purpose detector; 46 m long; diameter 22 m; weight 7000 t
- Toroid magnets and muon detectors dominate size
- Note that the lower part of the detector is not visible in the picture

Why tracking at LHC is tough ?

- Too many particles in too short a time
  - 1000 particles / bunch collision
  - too short: collisions every 25 ns

- Too short ⇔ need fast detectors and electronics; power!

- Too many particles ⇔
  - need high resolution detectors with millions of channels
  - detectors suffer from radiation damage

  to date this requires silicon detectors

Extreme radiation levels !

- Radiation levels vary from 1 to 50 MRad in tracker volume

  - less radiation at larger radii; more close to beam pipe

  - more radiation in forward regions

- Fluences vary from to 10^{13} to 10^{15} particles/cm^2

- **Vicious circle:** need silicon sensors for resolution and radiation hardness ⇔ cooling (sensors and electronics) ⇔ more material ⇔ even more secondary particles etc.

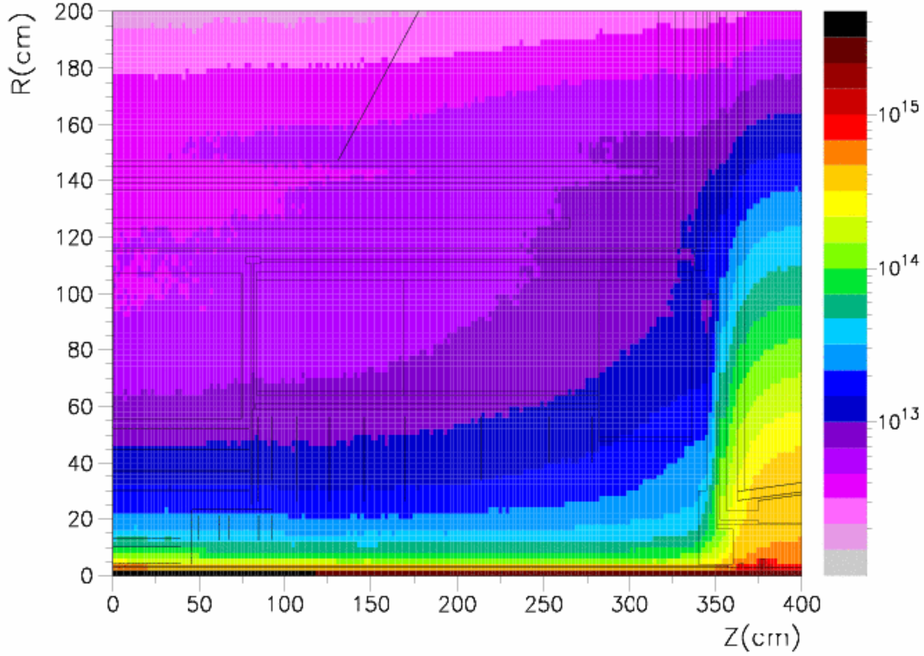
Don’t win a beauty contest in this environment, but detectors are still very good !

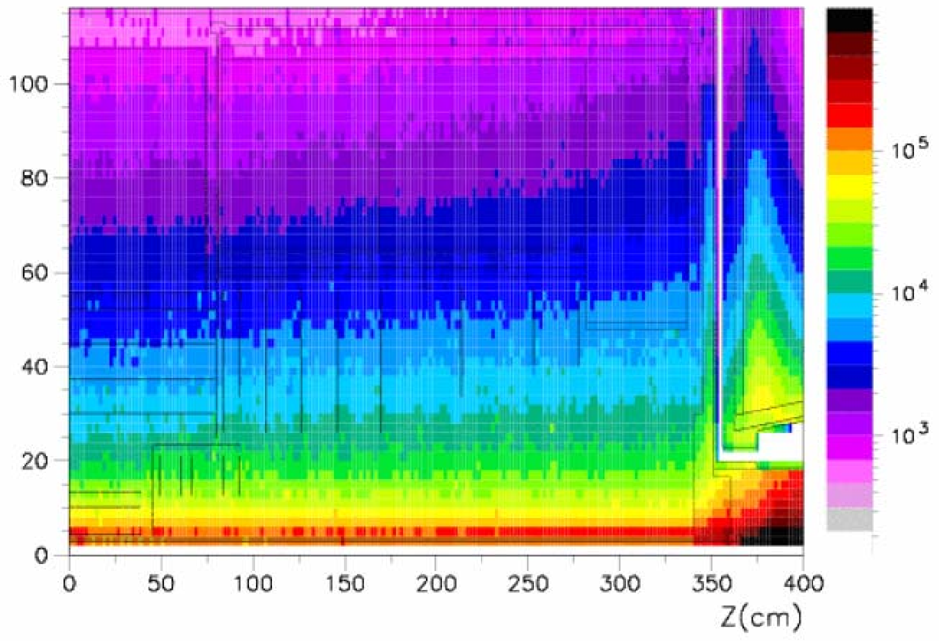
Extreme radiation levels !

Plots show radiation dose and fluence per high luminosity LHC year for ATLAS (assuming 10^7 s of collisions; source: ATL-Gen-2005-001)

Fluence [1 MeV eq. neutrons/cm^2]

Radiation dose [Gray/year]





"Uniform thermal neutron gas"

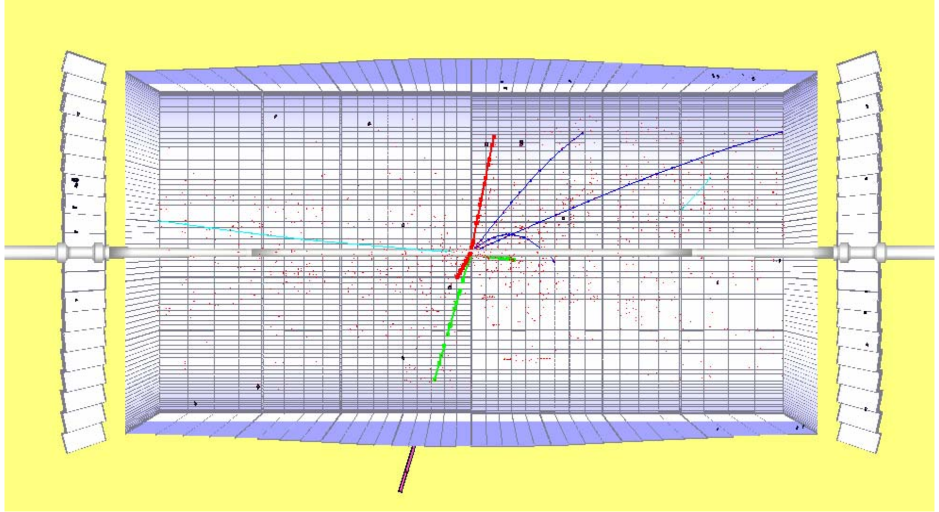
Put your cell phone into ATLAS !
It stops working after 1 s to 1 min.

- Neutrons are everywhere and cannot easily be suppressed

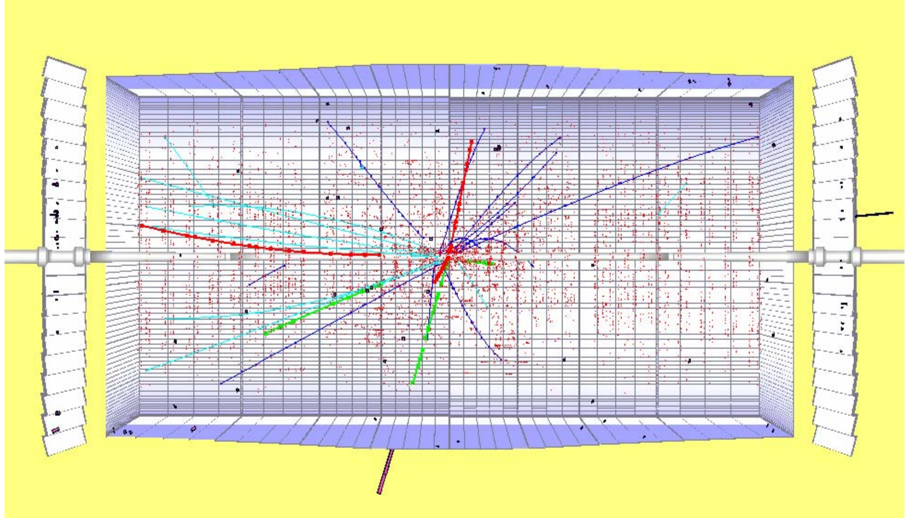
The Boring masks the Interesting

H→ZZ → μμee + minimum bias events (M$_H$= 300 GeV)

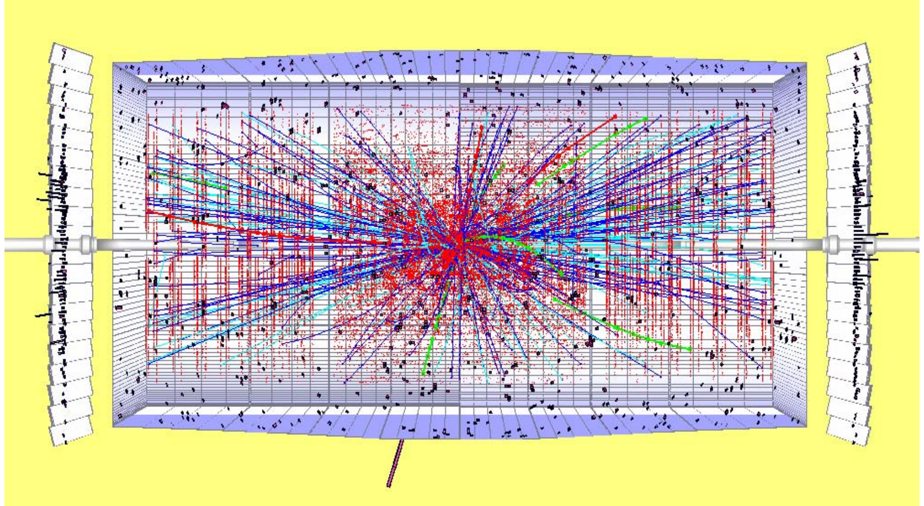
LHC in 2008 ?? : 10^{32} cm^{-2}s^{-1}



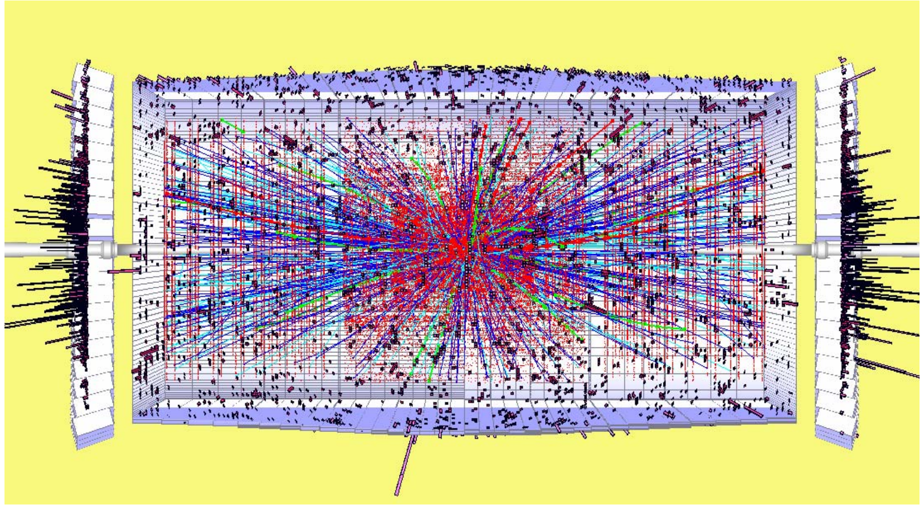
LHC first years: 10^{33} cm^{-2}s^{-1}



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



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



ATLAS Tracker Strategy

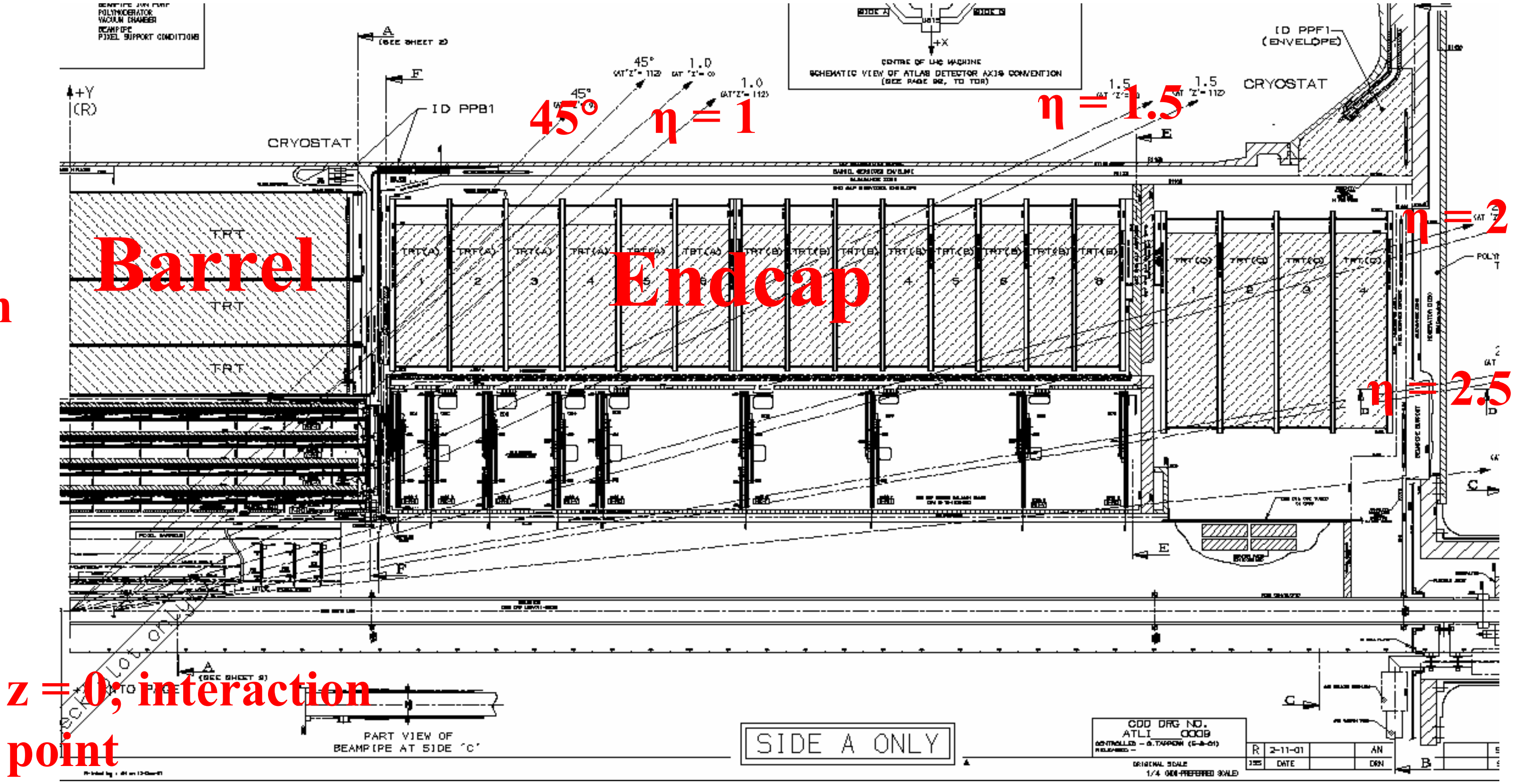
- High-resolution **silicon pixel detector** near beam pipe to detect event vertices
  - many channels; many chips; much power; cooling; etc.
- Cannot do this at all radii:
  - too much passive material
  - too expensive
- **Silicon strip detector (SCT)** at medium radii
  - still high resolution, but less material and “cheaper”
- No money left at outer radii; build **gas detector (TRT)**
  - don’t need ultimate resolution; less tracks/area
  - use transition radiation threshold for e/π separation

How does tracker look like ?

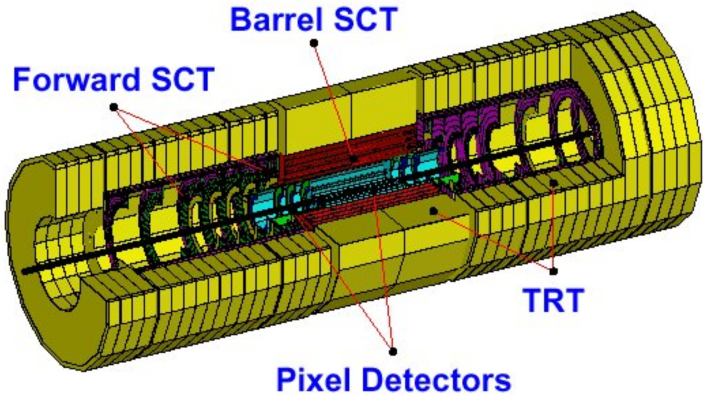
TRT
r=55-105 cm

SCT
r=25-50 cm

Pixels
r=5-25 cm

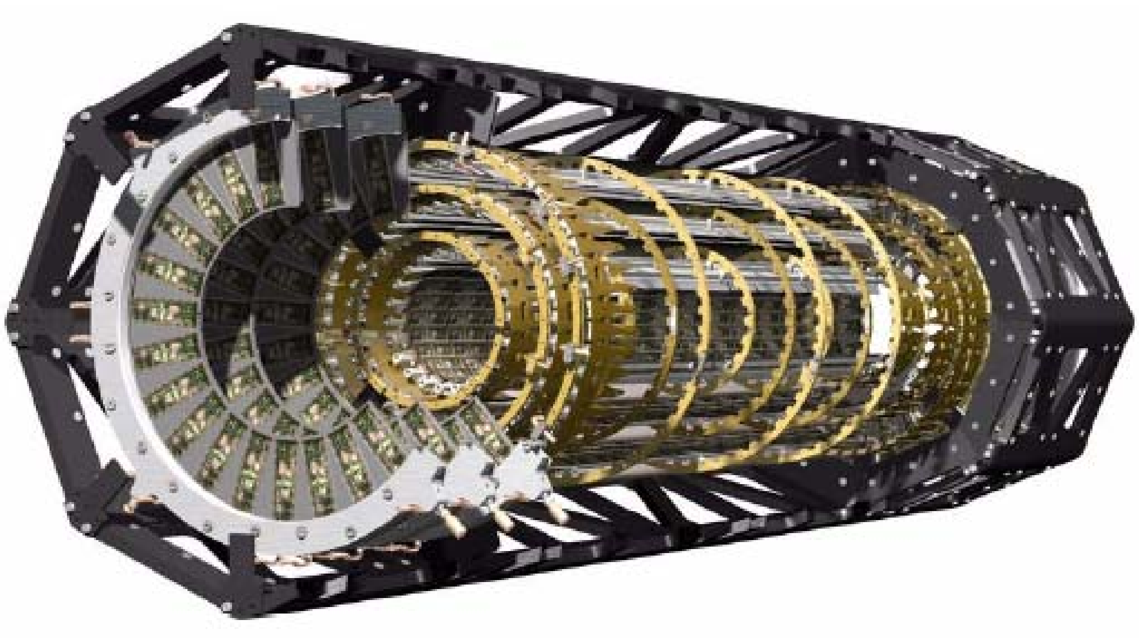


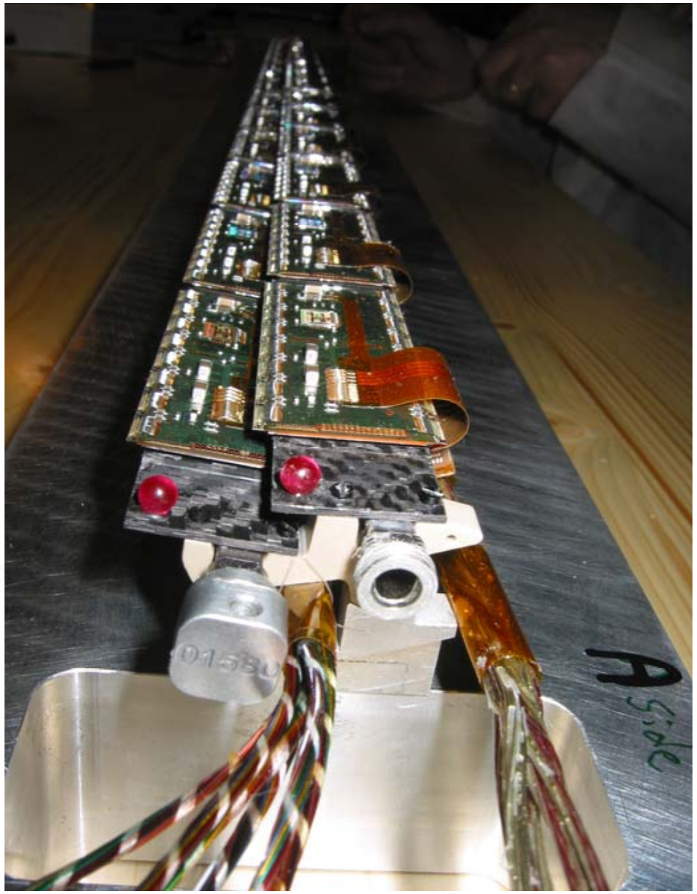
- the beast is still big; 7 m long
- barrels and discs; transition near η = 1
- routing of cables and cooling tubes is important (but not emphasis of this talk)



How does it look in real life ? Pixel detector

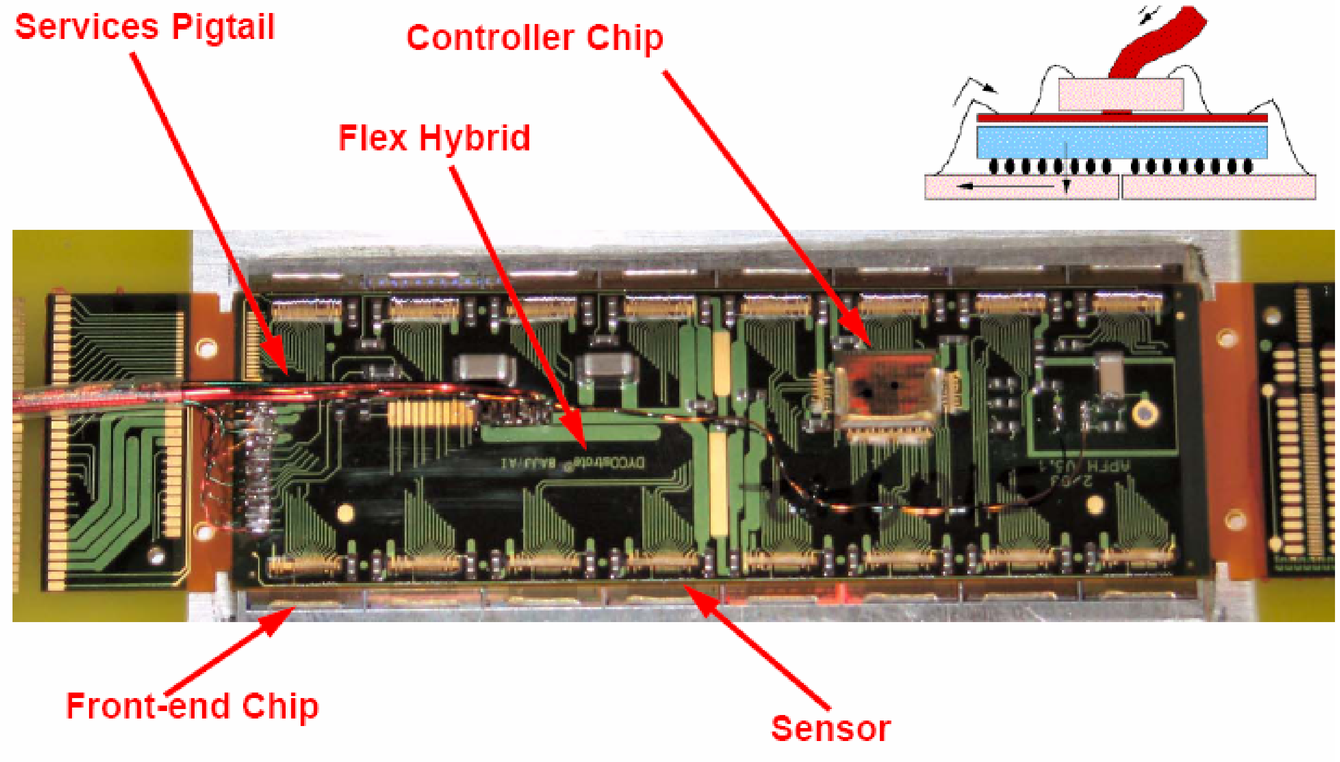
- 3 barrel layers at 5, 9, 12 cm radius and 3 discs (each end)
- 1.8 m^2 of silicon; 80 M pixels; typical power consumption 7 kW
- Pixel support structure: sophisticated carbon composite design
- Bi-stave: 2x13 modules; stave length: ≈80 cm





How does it look in real life ? Pixel detector

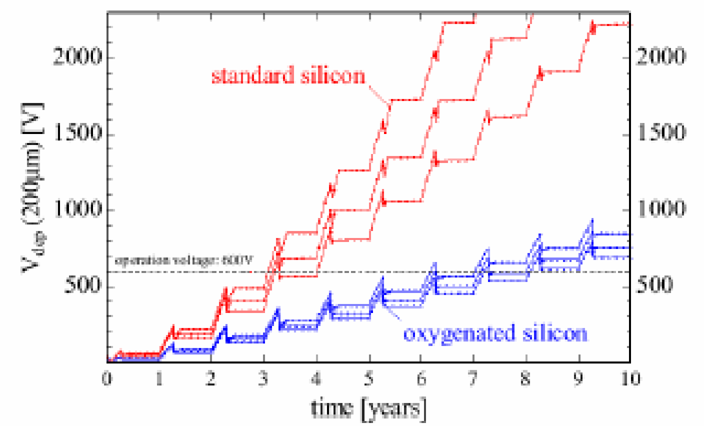
- Pixel module: composed of sensor; readout-chip; flex hybrid; cable
- module size: 16.4 mm x 60.8 mm; 46K channels per module; pixel size: 50 x 400 μm^2
- very dense packaging; 10% R.L. at normal incidence (all layers, including support and services)



Technological challenges: Pixel detector

Pioneering project: first pixel detector in hadron colliders

- **Sensors:** n+ on n-bulk, oxygenated silicon; max. voltage 700 V; multi-guard ring structure; operates up to 10^{15} 1-MeV neq/cm^2; total input capacitance: <400 fF; signal after irradiation: > 10Ke$^-$

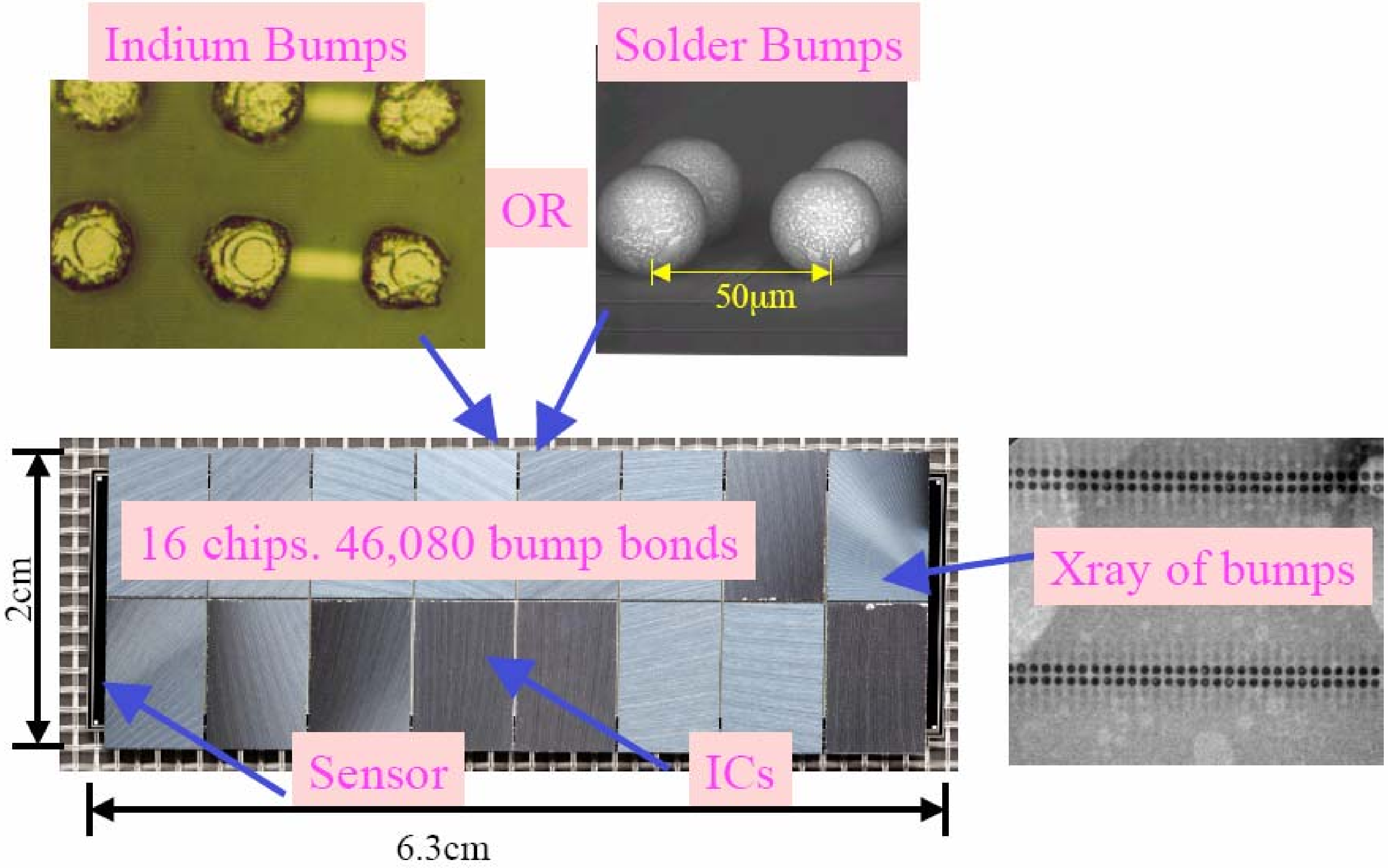


- **Readout chip:** complex; fast; low-noise (<400 e$^-$); radiation-hard to ≈50 MRad; sensitive to small signals (6K e$^-$); 3.5 M transistors in 80 mm^2; 0.25 m CMOS process; 2880 pixels/chip; various attractive novel features

Technological challenges: Pixel detector

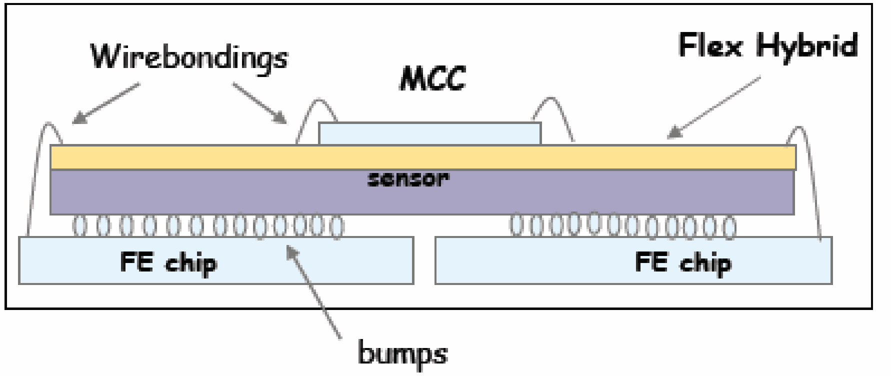
- **Bump-bonding of chips to sensors:**

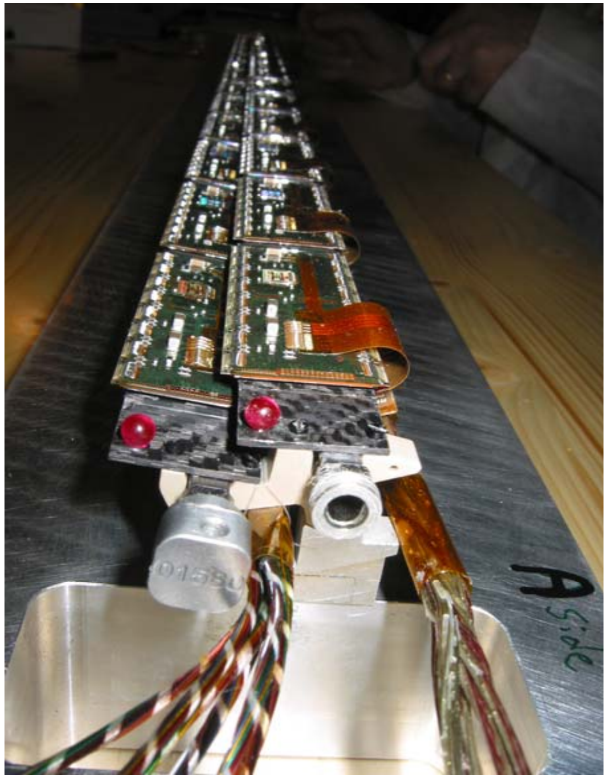
  pitch of only 50 µm (commercial pitches ≈200 µm)



Technological challenges: Pixel detector

- **innovative packaging of sensor/chips/support structure/cooling**
  - sophisticated, crowded flex-hybrid
  - carbon-carbon support structures
  - bump-bonding of chips to sensors
  - direct cooling of chips

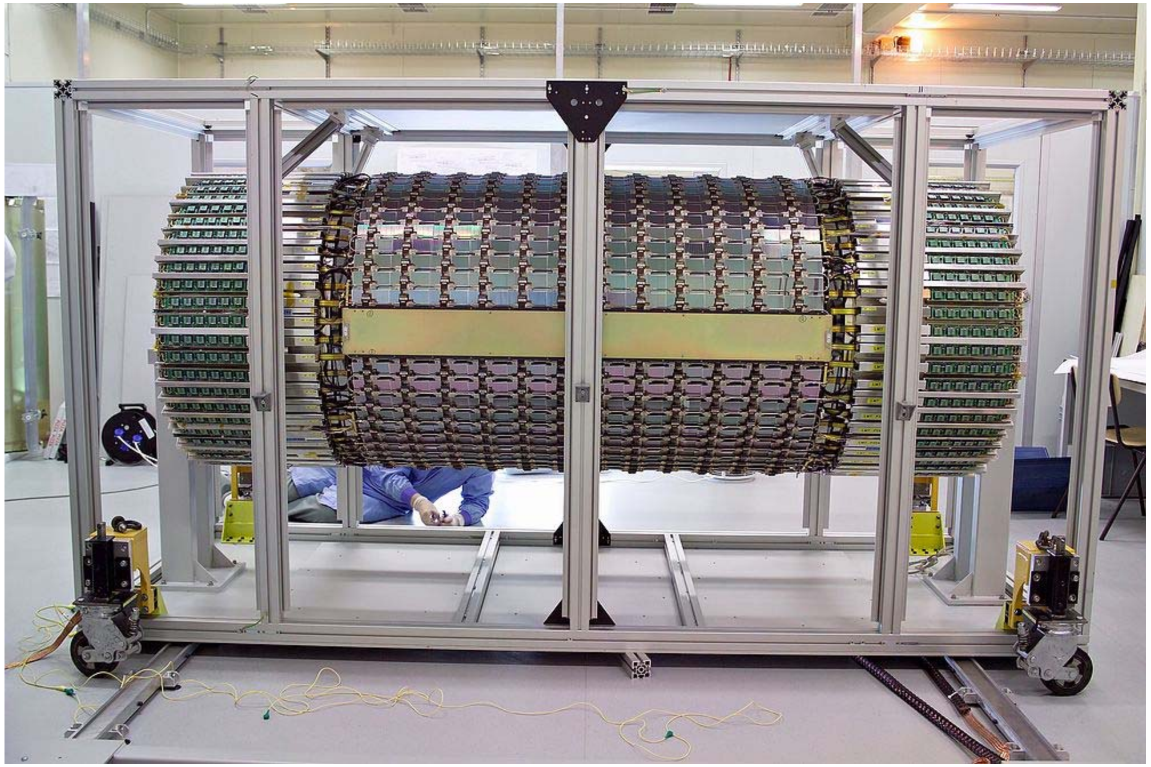




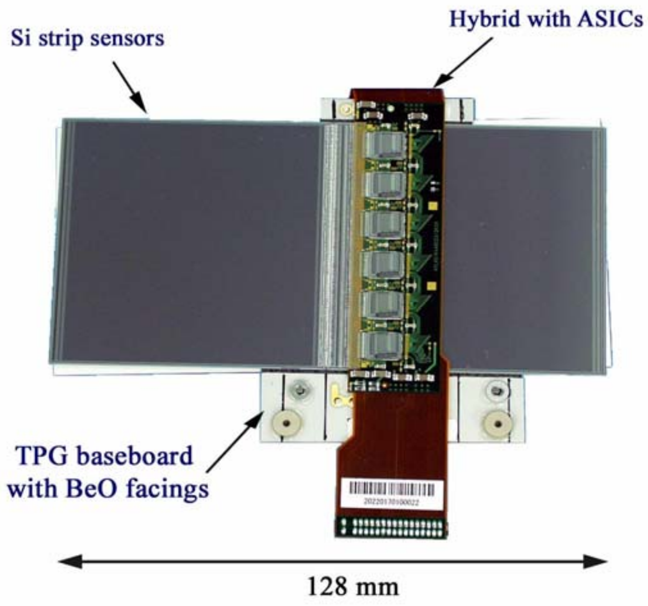
- **Global and local support structures:** stiff; lightweight; precise; “zero” thermal expansion

How does it look in real life ? SCT Detector

- 4 barrel layers at 30, 37, 45, 52 cm radius and 9 discs (each end)
- 60 m^2 of silicon; 6 M strips; typical power consumption ≈50 kW
- Precision carbon fiber support cylinder carries modules, cables, optical fiber, and cooling tubes
- Evaporative cooling system based on C_3F_8 (same for pixel detector)



Barrel 6 at CERN



Technological challenges: SCT detector

- big challenge to develop radiation-hard sensors and chips but less severe than for pixels

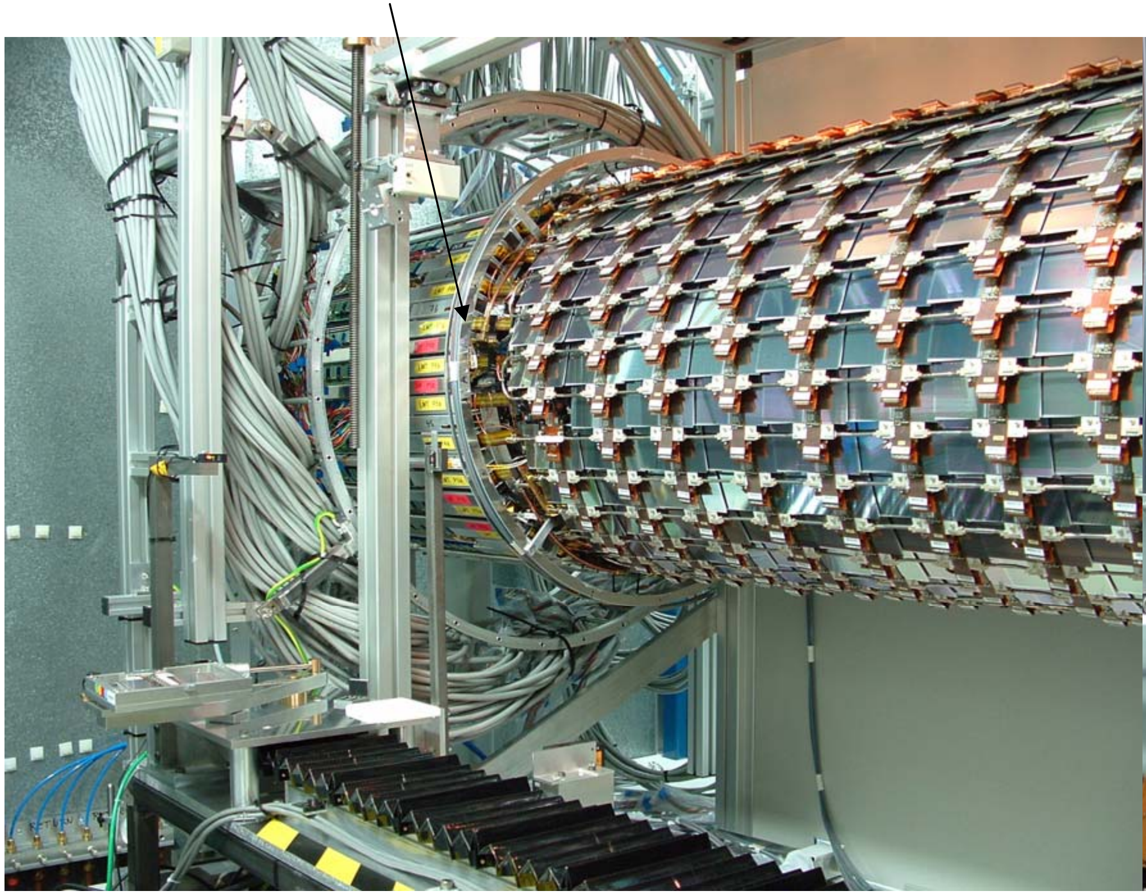
detector area is two orders of magnitude bigger than other systems, however

- precise modules and support structures
- mass production, logistics and testing of 4000 modules and much more their sensors, hybrids, and chips in world-wide collaboration
- System design and assembly of macrostructures

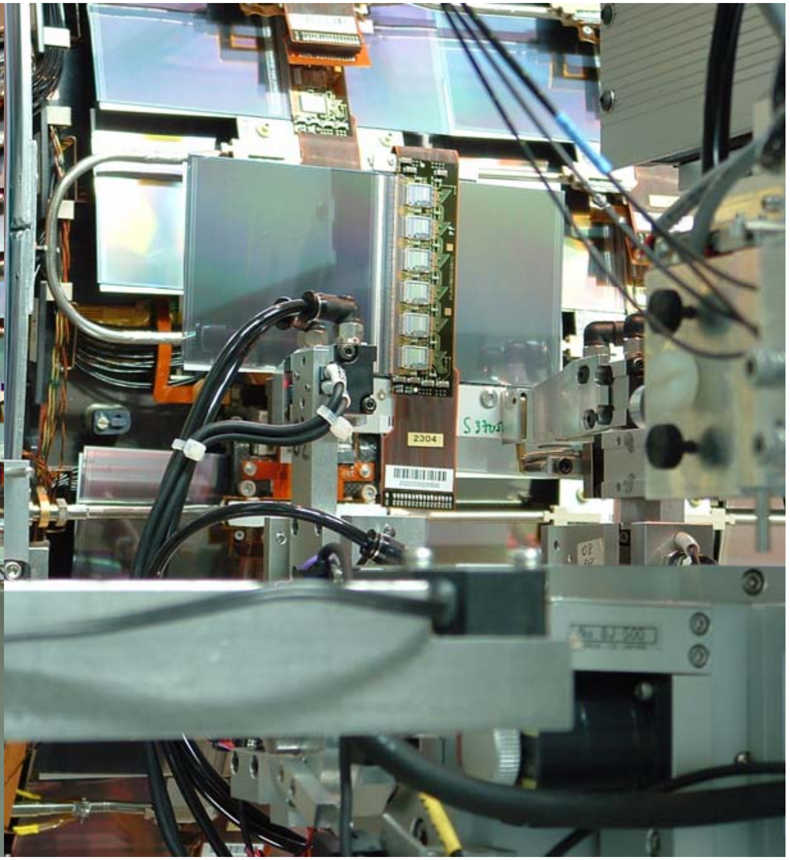
Technological challenges: SCT detector

- large number of modules to be mounted on crowded cylindrical carbon fiber structure ⬄ very successful use of robot
- Clearance between adjacent rows is 1 mm

Empty spot for last module on Barrel 3 (Oxford)

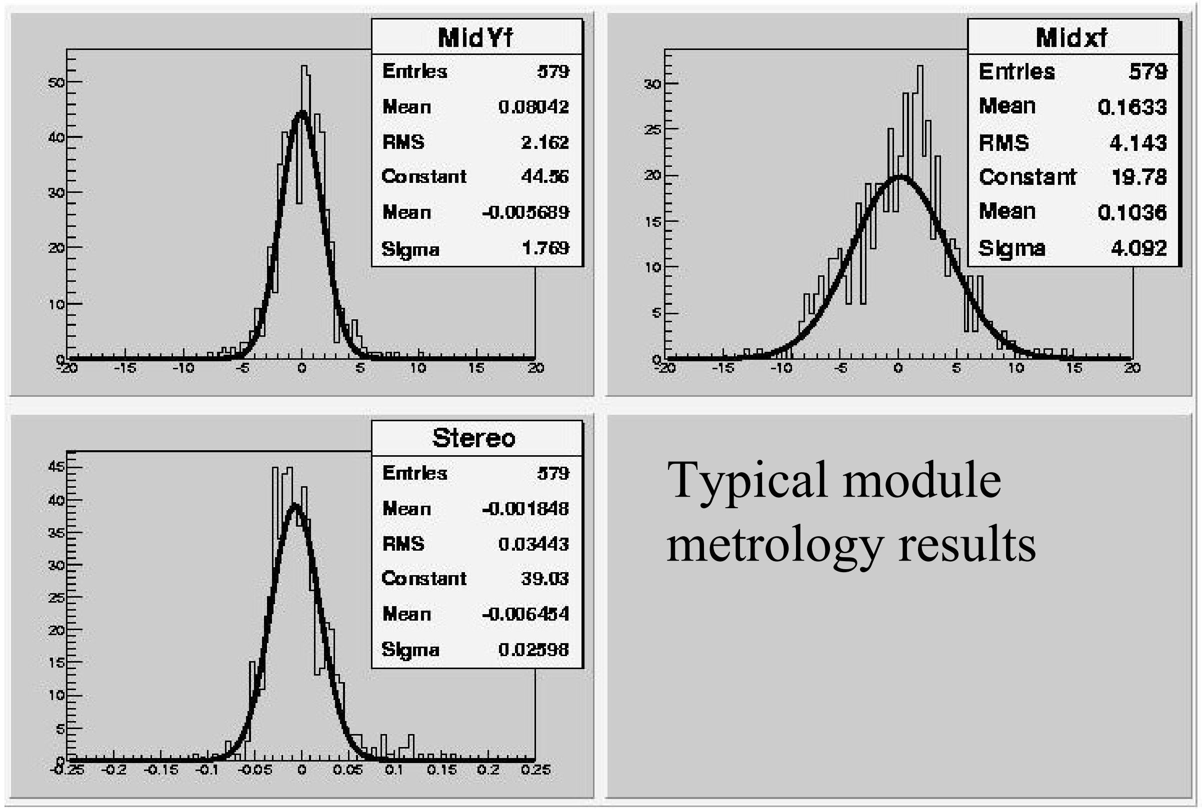


The robot in action

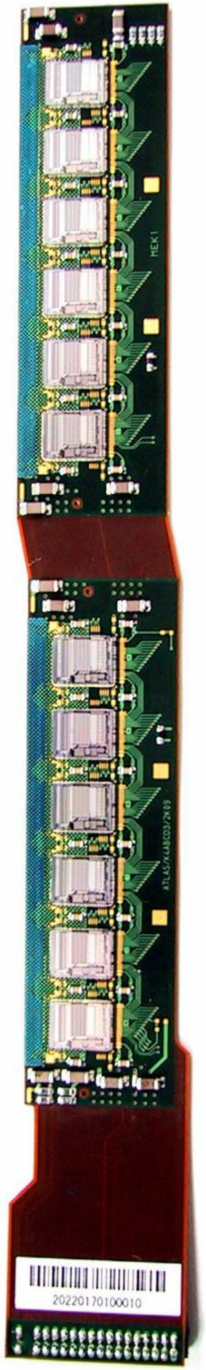


Technological challenges: SCT detector

- Only 1 module type for barrel detector; got hybrids, sensors, and modules right; ABCD chip design excellent, but had to overcome severe yield problems
- Mechanical precision of key module parameters better than 5 µm (to simplify alignment); required extensive metrology



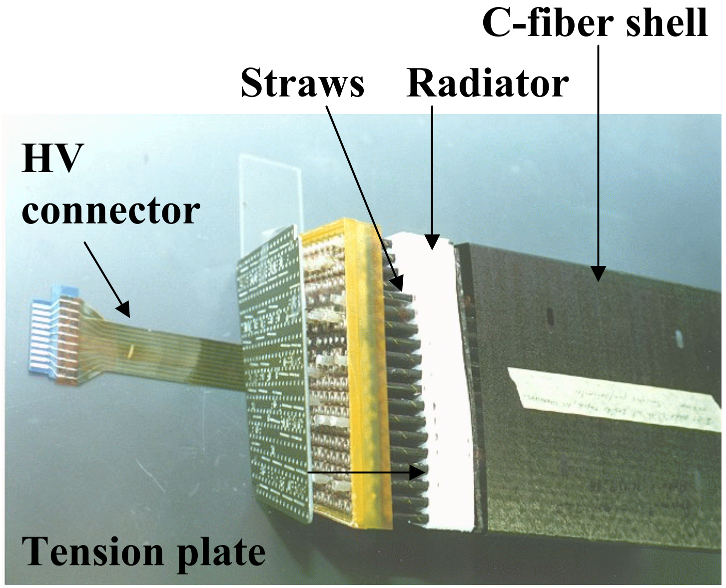
Typical module metrology results



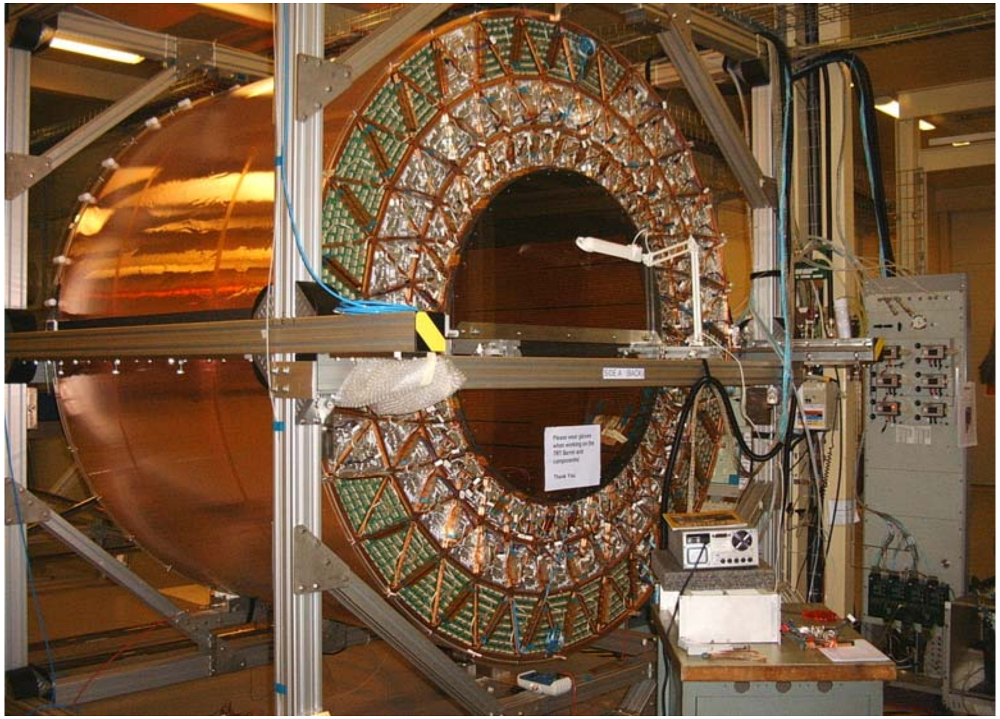
Same hybrid serves module top and bottom sensors

How does it look in real life ? TRT

- One barrel and 3 end caps (initially 2) at each end; up to 36 hits
- 4 mm diameter straw tubes, 30 µm W/Au wires; 420 K channels
- signal is due to both charged particles ionization and transition radiation photon absorption; 2 adjustable thresholds, low one for drift time determination, high one for TR photon
- gas mixture: Xe(70%)/ CO_2(27%)/O_2(3%); gas gain 2.5 K;
- positioning of wires precise to ≈ 20 µm



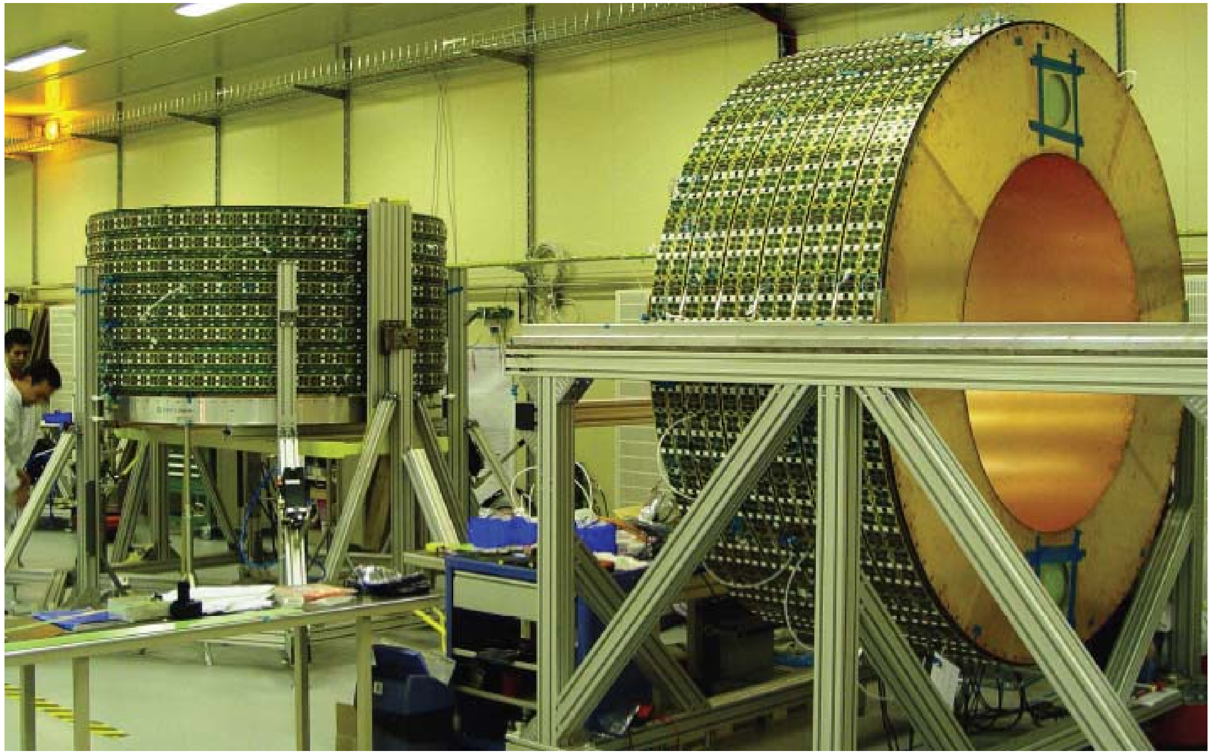
TRT barrel at CERN SR building

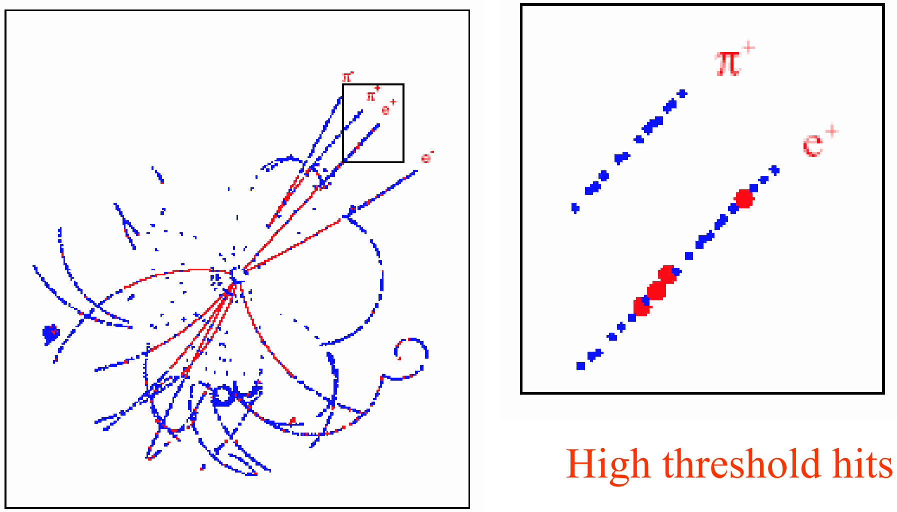


Technological challenges: TRT

- Scale of detector
- Radiation-hardness/ LHC rates
- Gas composition/radiator

TRT endcaps at CERN SR building





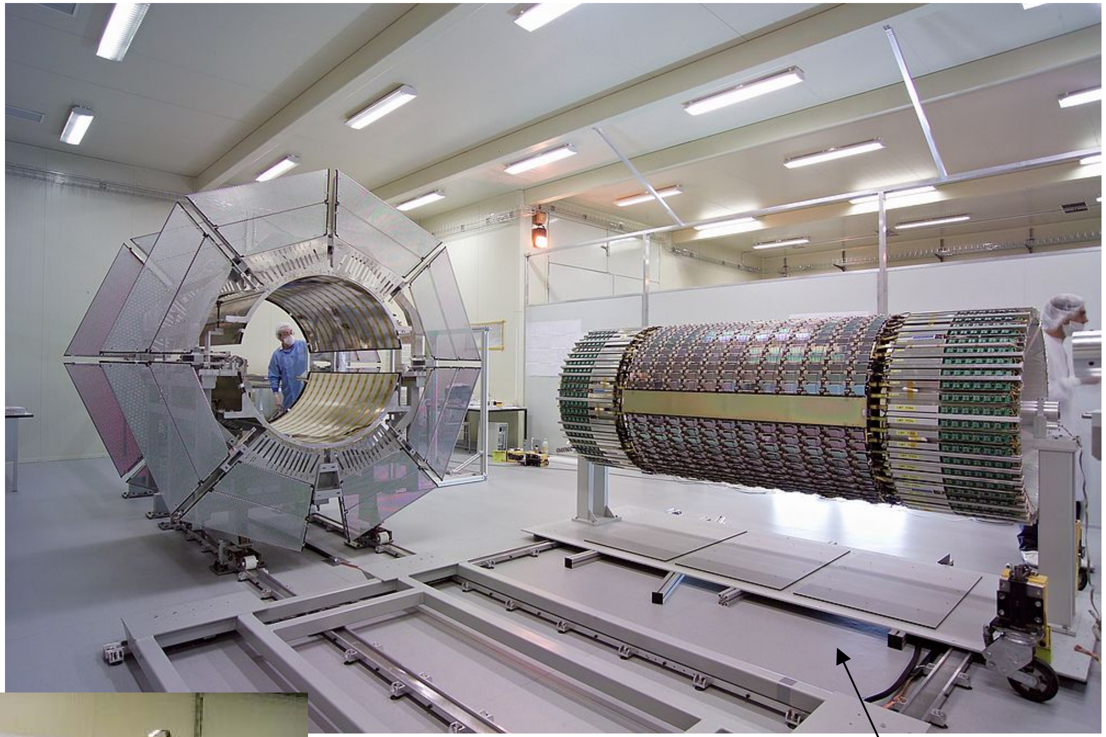
High threshold hits

Particle ID with the TRT

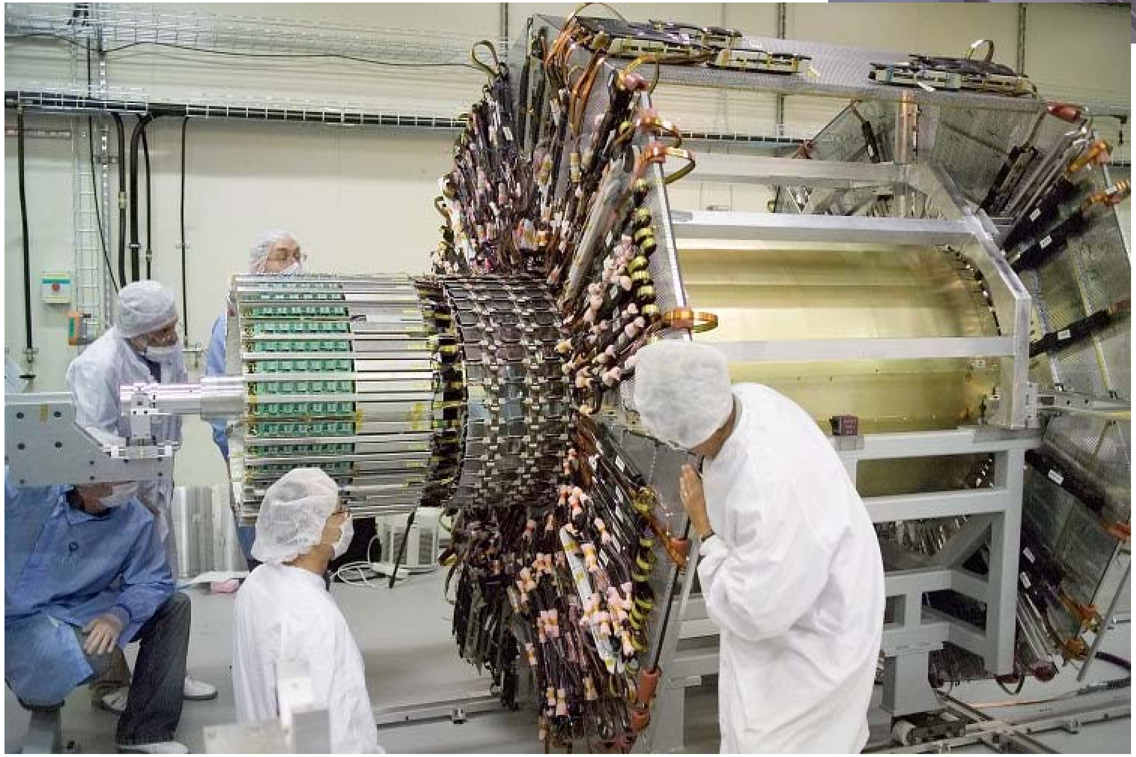
ATLAS Tracker Status

Huge progress everywhere

Example SCT barrel assembly at CERN

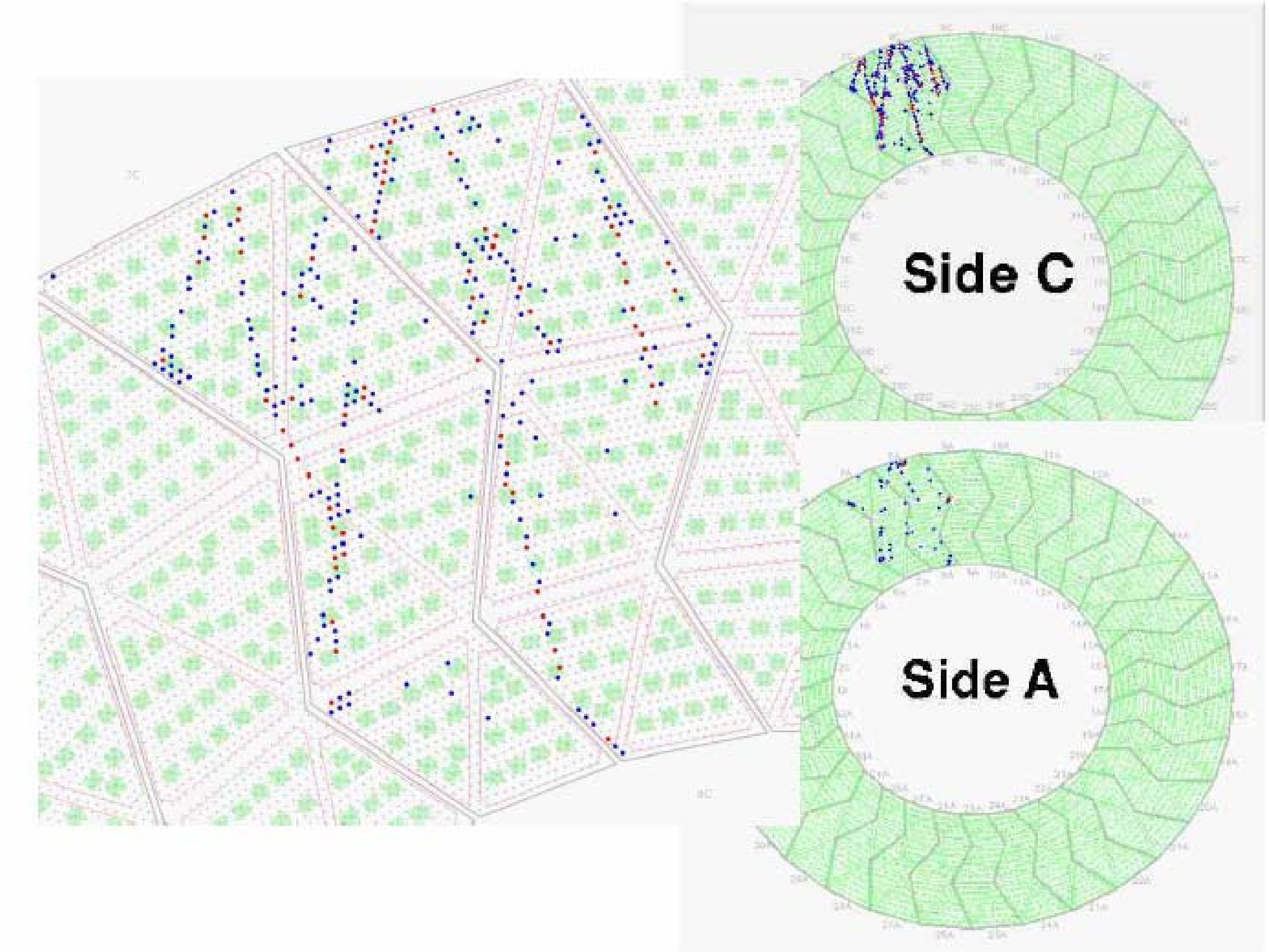


Heavy tooling for insertion of Barrel 6 into mechanical/thermal and electrical shield (Thermal enclosure)



Last barrel (B4) is inserted into Thermal enclosure and the 3 outer barrels

TRT cosmic ray events



Taking cosmics since July 2005 with 3% of detector; beautiful events; excellent training ground; debugging and developing aid

ATLAS Tracker Status

After so many years of struggle, overall picture is very encouraging!

SCT: barrel detectors are at CERN and almost completed;

endcap detectors to be shipped to CERN early 2006;

TRT: detector at CERN and essentially finished

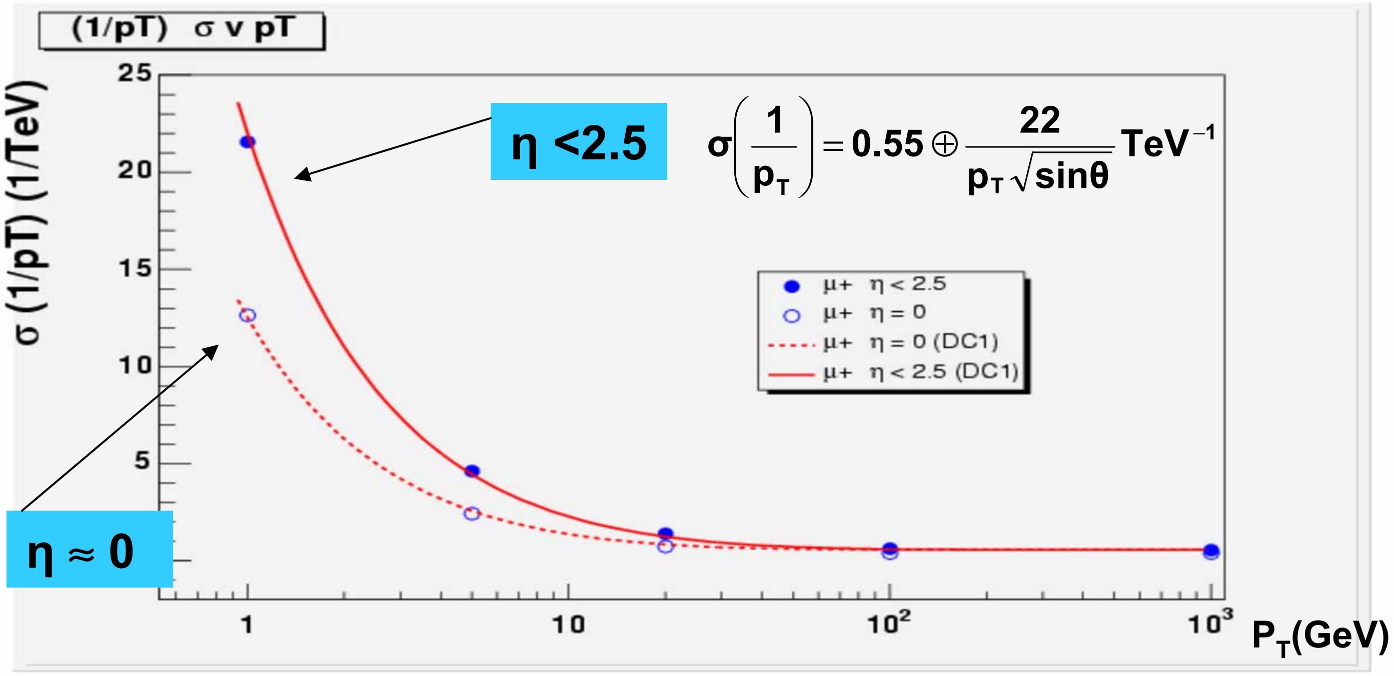
Pixel: module production 60% done; disc and stave population advanced

Installation underground: SCT and TRT barrel: 1/3/06; SCT and TRT end caps: 25/5/2006 and 30/6/2006; Pixels: 5/10/2006

Expect the ATLAS tracker to be ready for first data taking in summer 2007

If it all works, what will it do for us ?

Tracker performance



η <2.5

$$\sigma\left(\frac{1}{p_T}\right) = 0.55 \oplus \frac{22}{p_T\sqrt{\sin\theta}}\,\mathrm{TeV}^{-1}$$

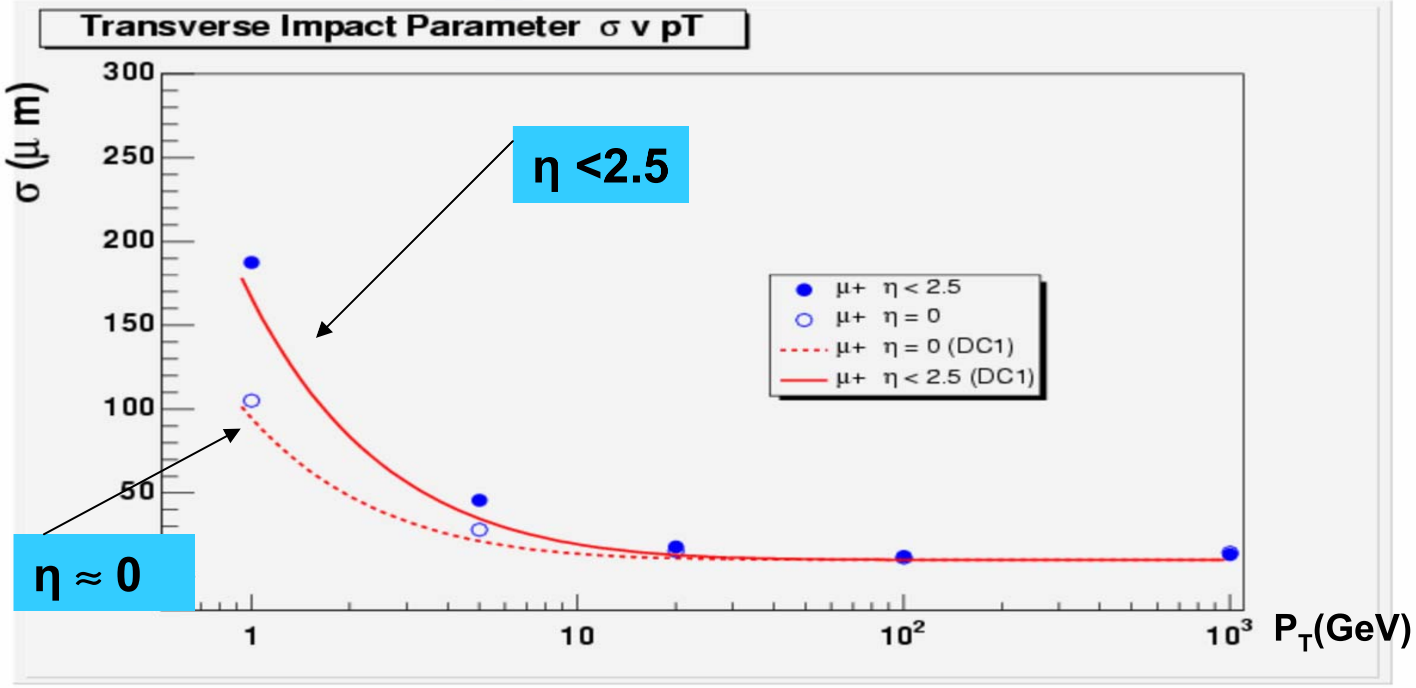
η ≈ 0

$$\sigma\left(\frac{1}{p_T}\right) = 0.55 \oplus \frac{12.5}{p_T\sqrt{\sin\theta}}\,\mathrm{TeV}^{-1}$$

Inverse transverse momentum resolution (1/p_T) based on latest simulation (Geant 4) and reconstruction software

- Increased resolution for all η average reflects increase of material at large η
- performance exceeds expectation of Technical Design Report

If it all works, what will it do for us ? Tracker performance



η <2.5

η ≈ 0

Transverse momentum resolution (d_0) based on latest simulation (Geant 4) and reconstruction software; curves are not a fit but an earlier simulation

- Asymptotic resolution is close to 10 μm
- at lower momenta, resolution depends on η and increases with η

ATLAS tracker for SLHC

- **Super LHC (SLHC):** upgrade of accelerator to deliver 10-fold increase of luminosity by ≈2015
- **Why is SLHC so attractive ? Rationale:**

- must fully exploit discovery potential of LHC (increased mass reach, precision, new and rare channels, the unknown !)

- Tevatron experience shows that hadron colliders at energy frontier can be competitive for 20 years

- time to decrease stat. errors becomes too long; upgrade is more efficient

- LHC tracking detectors are designed for ≈8 years lifetime (would not have known how to do it better !)

⇔ **Inner tracker must be replaced**

ATLAS SLHC Tracker

- **Most urgent priority is finishing current tracker !**
- First SLHC initiatives have emerged, however
  - 2 US, 1 UK, 2 ATLAS SLHC work shops
  - generic R&D projects
  - thinking and understanding !

- **SLHC tracker specifications are simple:**

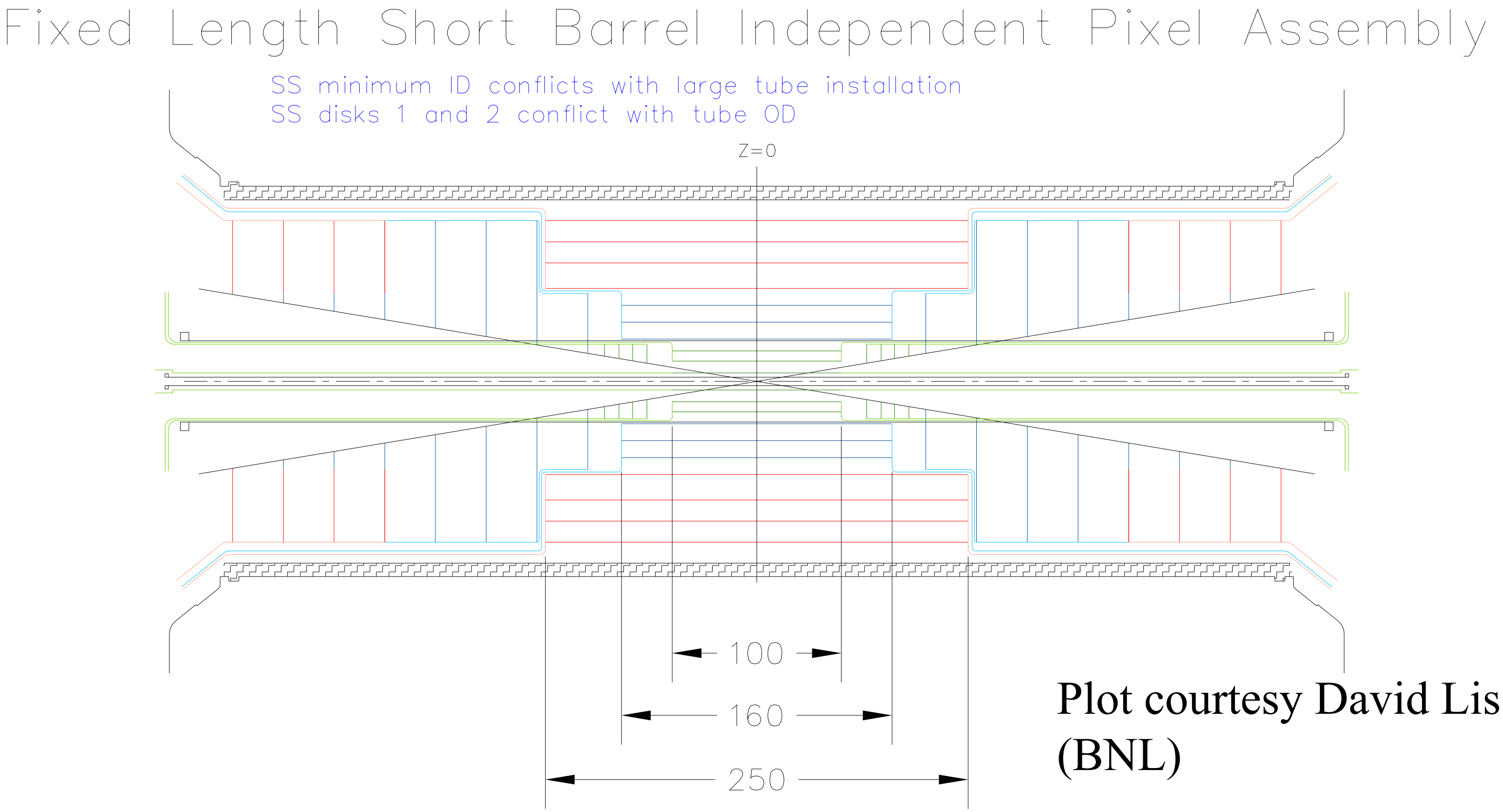
1. Tracker must maintain LHC tracking resolution/performance
2. Tracker must be 10 times more radiation hard
3. Must cope with 5 or 10 times more particles per bunch crossing

   (depending on bunch distance, which will not be known too soon)

Have learnt enormously from the LHC tracker R&D

Believe, but don't know yet, that this can be done !

An ATLAS SLHC Tracker could look like this



Plot courtesy David Lissauer (BNL)

- **all silicon: rates too high for TRT**
- 3 different radial regions with different detector types
  - innermost: 3-4 pixel layers
  - medium radius (current SCT): 3-4 short strip layers
  - outermost (current SCT): 2-4 long strip layers

Main challenges: power and material budget

- **Power consumption**

  SCT alone requires ≈50 kW of power, half of it wasted in cables; power consumption scales with channel number ⇔ naively get 10 times more power !

- **Space for cables**

  power cables are bulky; no space for more than the current number of cables

- **Cooling system**

  Effective cooling of electronics; increased radiation and leakage current require sensors temperatures below the current -7°C; no space for new cooling pipes

- **Hybrid material**

  More channels ⇔ more hybrids ⇔ more material ⇔ poorer resolution

Innovation needed in all these area

Other challenges radiation-hard silicon and power efficient chips

A look at material issues

- naively extrapolating from an SCT to an SLHC layer assuming 5 times more channels, we get (one layer, barrel, normal impact):

Component	**R.L. for SCT**	**Scaling factor***	**R.L. for SLHC**
Cable	**0.2 %**	**x 5**	**1 %**
Hybrid	0.3 %	**x 5**	1.5 %
Sensor	0.6 %	x 1	0.6 %
Cooling; CF cylinders; module baseboard; etc.	0.4; 0.3; 0.2 %	**x ≈3;** x 1; x 1	1.7 %
Total	**2 %**		**5 %**
Silicon fraction	30 %		12 %

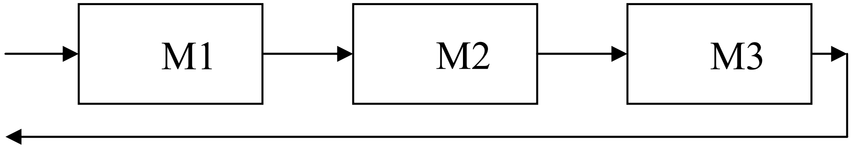
*crude estimate; no innovation

too big !

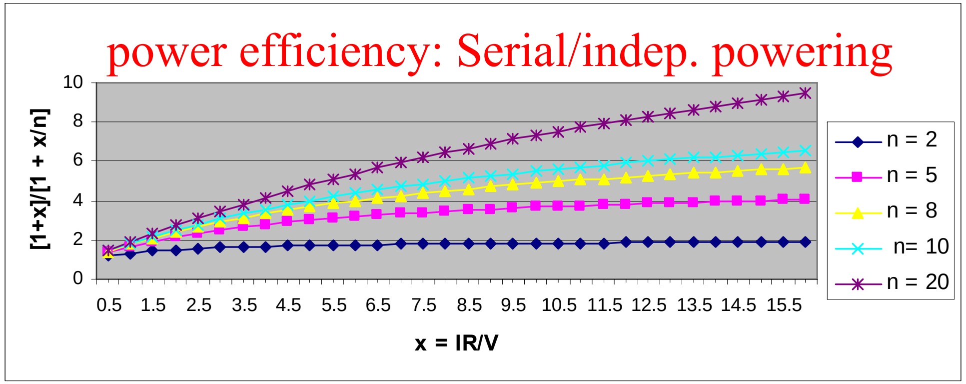
Material budget will explode at SLHC without innovations in powering, packaging, and cooling

Selected R&D initiatives

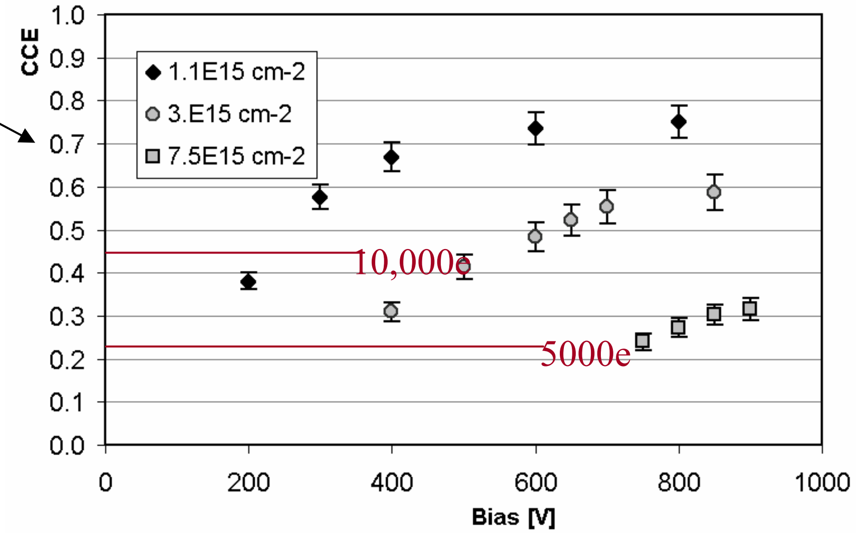
- **Serial powering of modules** pioneered by Bonn group for ATLAS Pixels see T. Stockmanns et al., Instr. and Meth. A 511, 174-179 (2003)



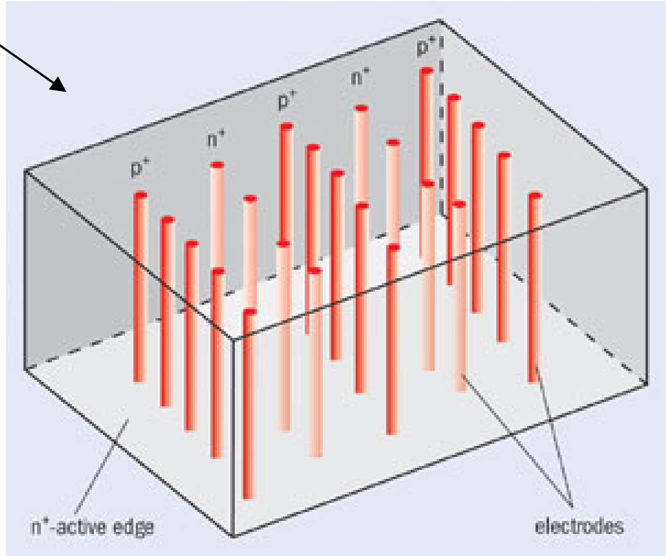
Much less cables and higher power efficiency



- **Radiation-hard n-on-p strip sensors**



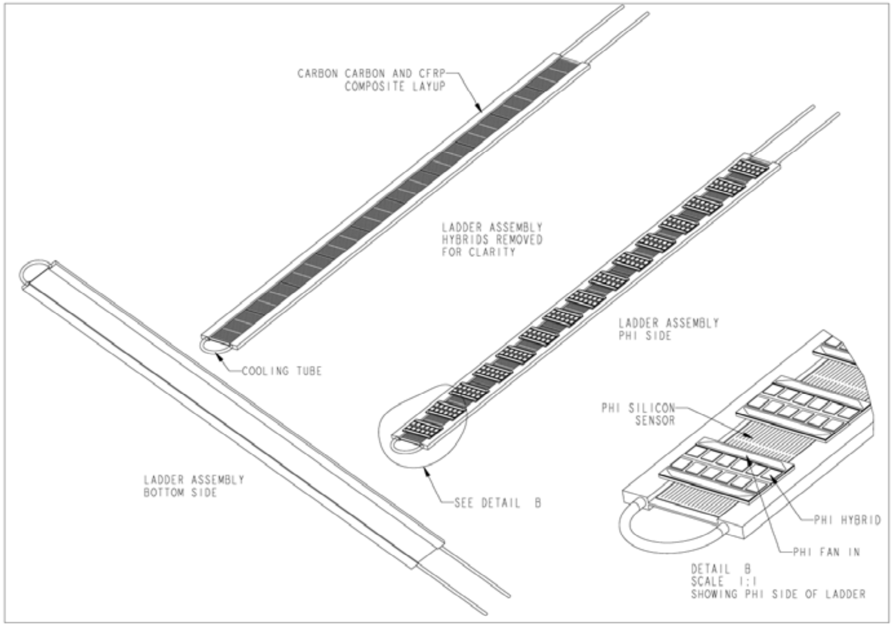
- **3-d pixel** (Sherwood Parker)

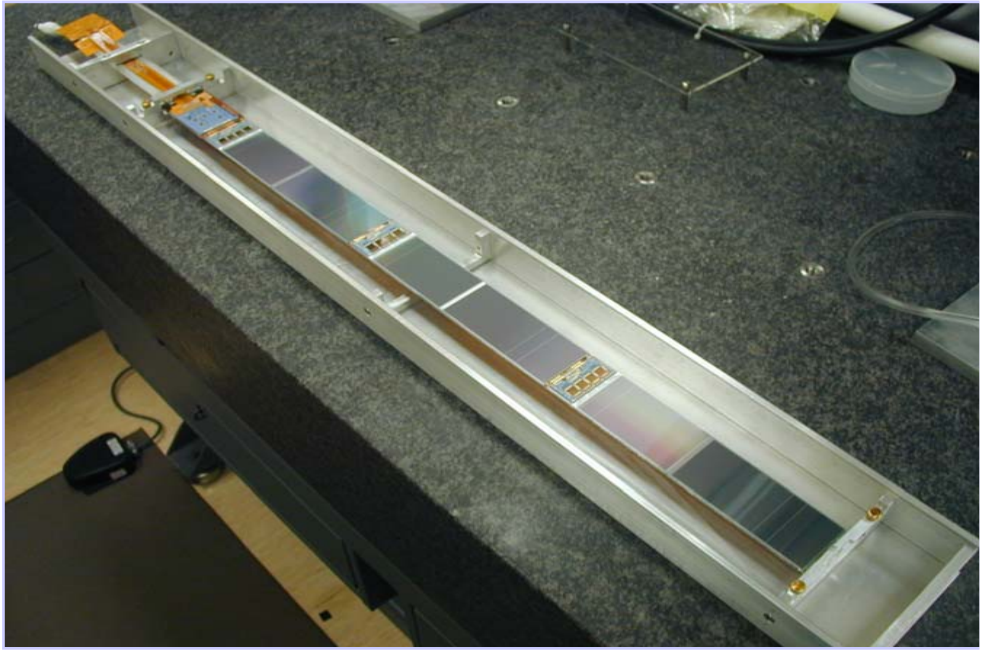


Selected R&D initiatives

- “Revival” of staves or supermodule concept

Idea for a medium radius stave with short strips (courtesy Phil Allport)





CDF Run IIb stave as starting point for outer layer stave at SLHC

Summary

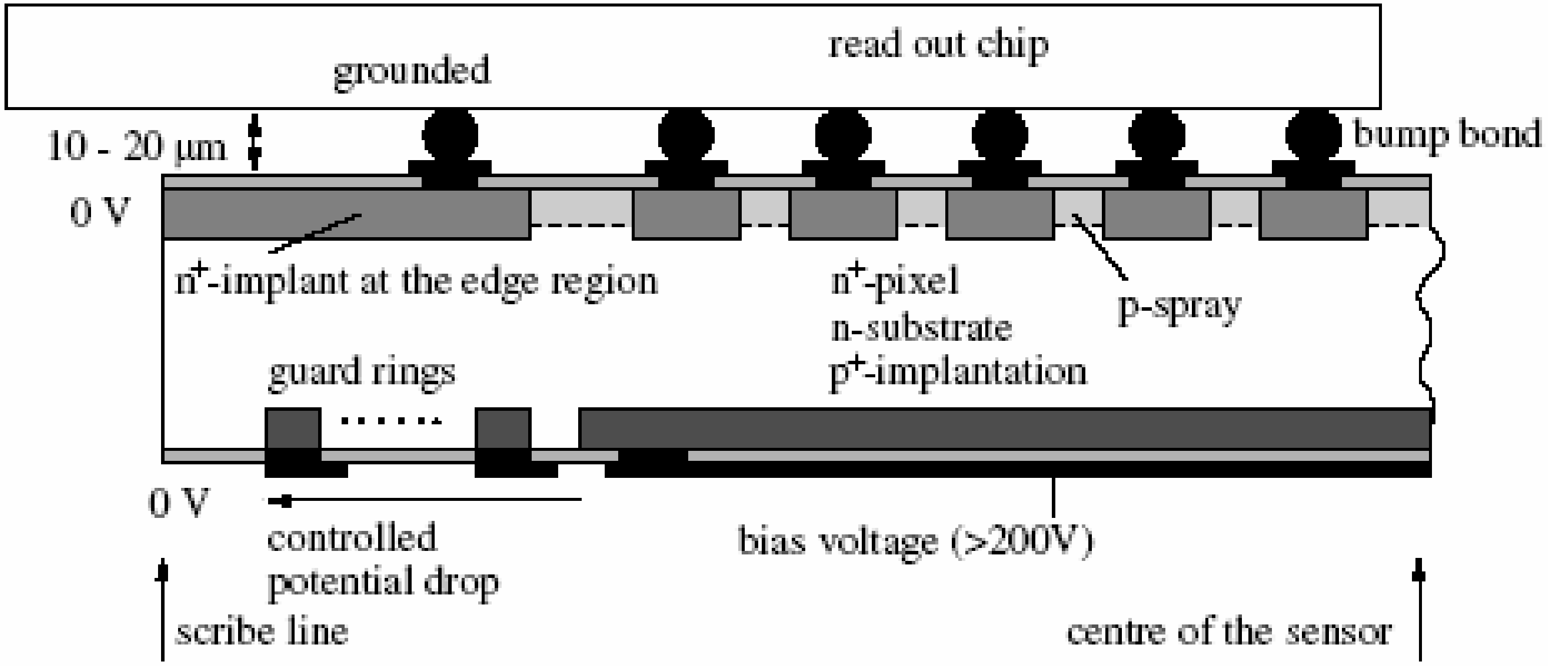
- Tracking at LHC is tough, but immensely important for physics
- Scale of detectors and technological challenge are huge
- After more than a decade of R&D and years of mass production, the final devices are taking shape

- Large fraction of ATLAS tracker available
- Shift from module production, to assembly and integration
- Will go underground next year and expect ATLAS tracker to be available in time for data taking

Appendix

Pixel sensor

- High bias voltage due to:
  - oxygenation
  - multi-guard ring structure
- For unirradiated sensors depletion begins at the back side (n-p junction); n+ pixels are only isolated when the bulk is fully depleted
- After irradiation and n to p type conversion; depletion starts from top side, and pixels are separated even when not fully depleted



SLHC Physics Motivation

- **Extend LHC discovery mass reach by ≈ 30%**
  - increased reach for squark and gluino by ≈500 GeV to 3 TeV
  - increased reach for add. heavy gauge bosons from ≈5.3 to 6.5 TeV
  - extended sensitivity (100 GeV) to heavy MSSM Higgses (important for distinction of MSSM and SM)
  - increased quark compositeness limit (indirect) from 40 to 60 TeV
- **Increased precision in SM and Higgs physics**
  - triple gauge boson and Higgs couplings improved by ≈ 2
- **Increased sensitivity to rare processes/decays**
  - FNC top decays: e.g. limit for t->qZ increased from 1.1 to 0.1 x 10^{-5}
  - some sensitivity to Higgs self-coupling in gg->HH channel (hopeless at LHC !)
  - some sensitivity to strongly coupled vector boson systems, if no Higgs (hopeless at LHC!)