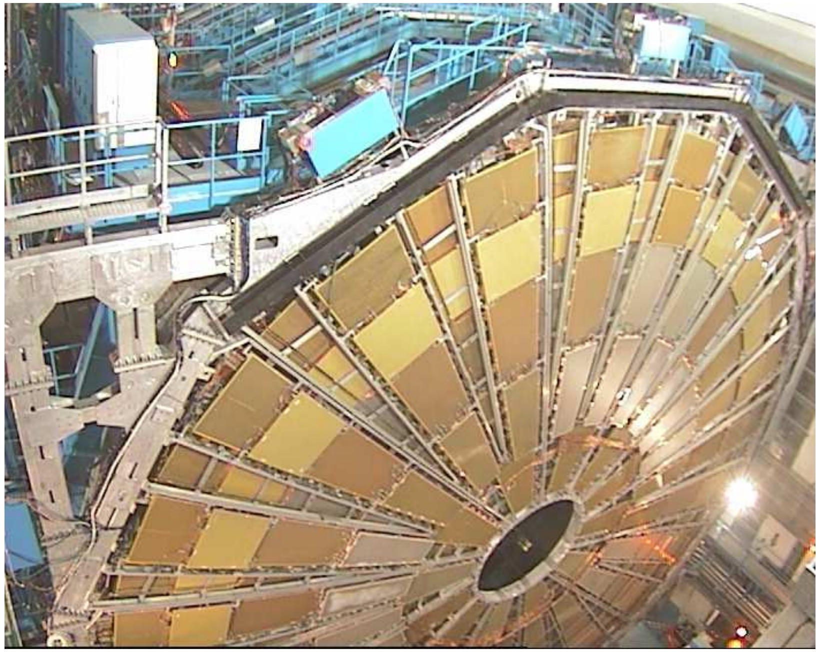
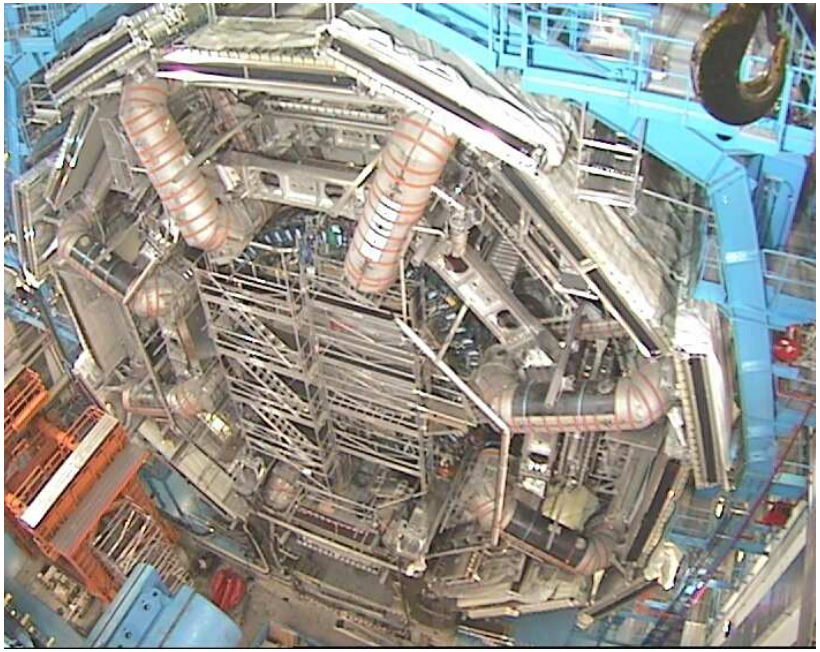
First Experience with the ATLAS Muon Spectrometer

VCI 2007, Vienna

20th February, 2007





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ATLAS Muon Collaboration

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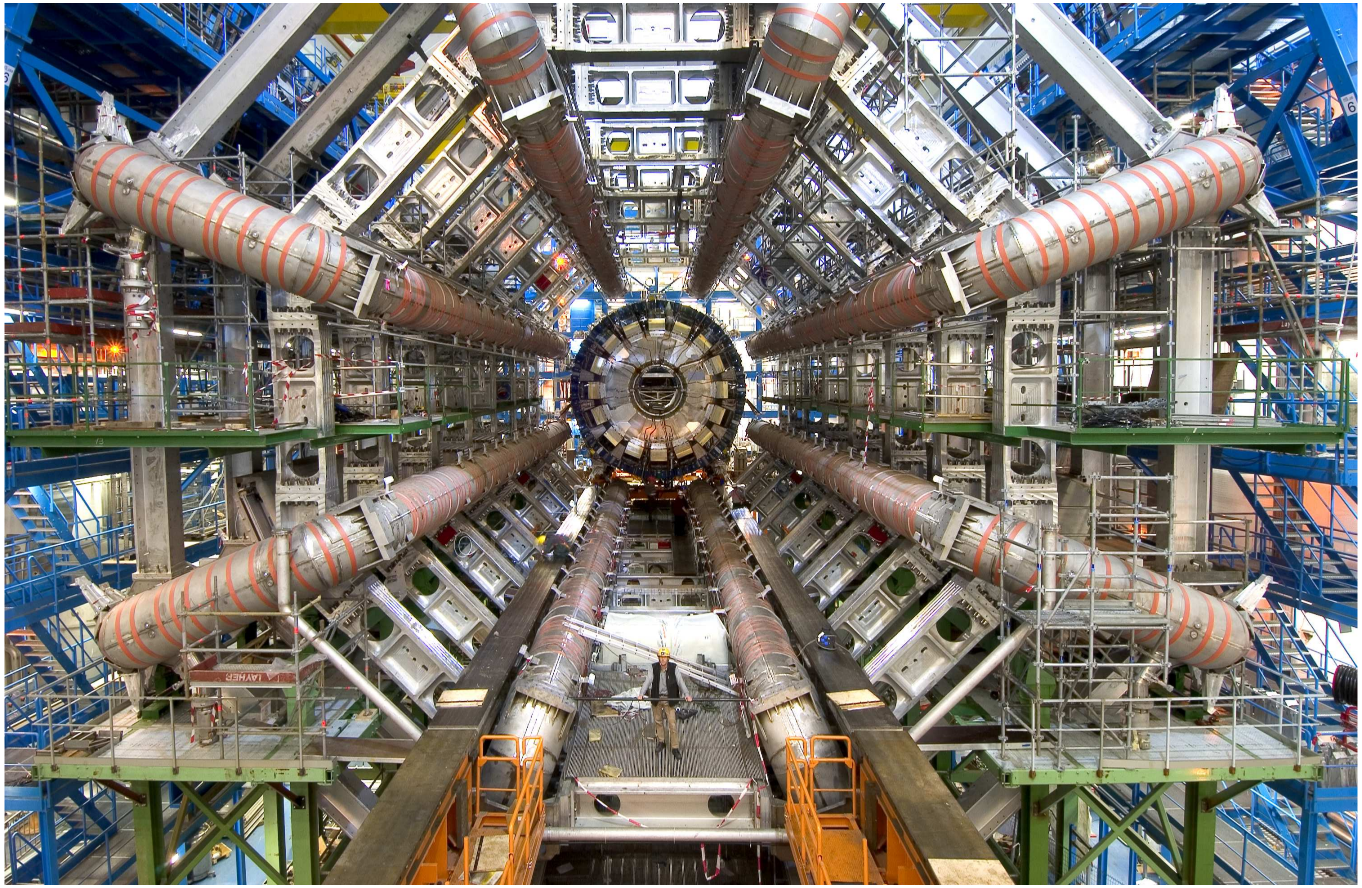
Outline

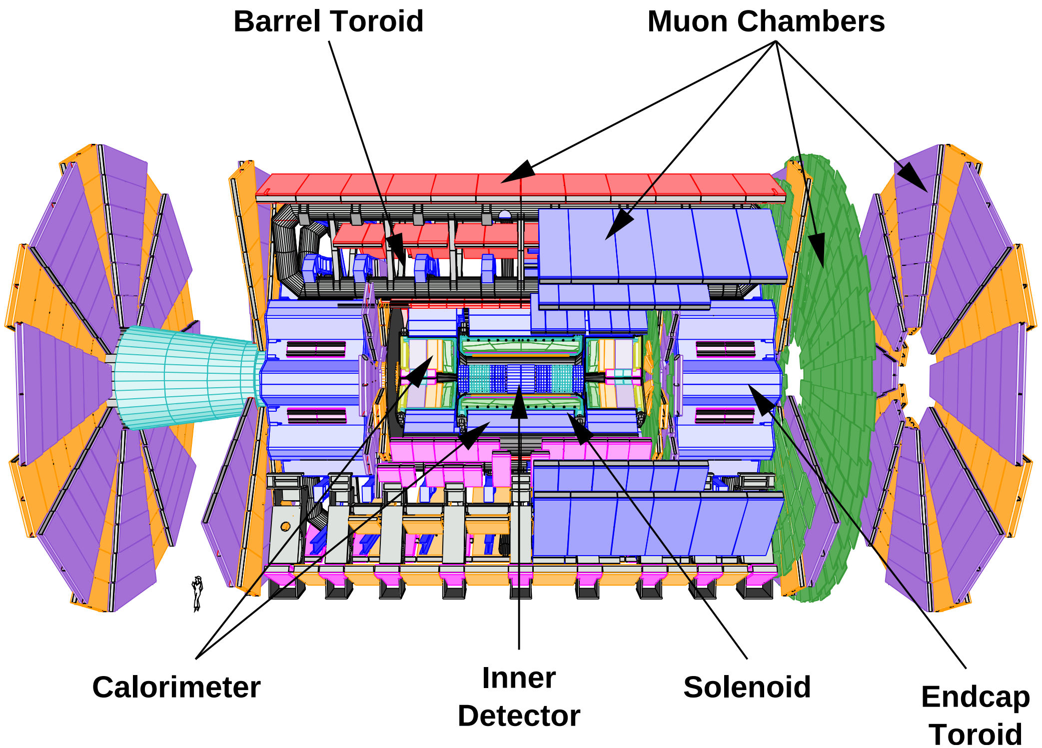
- Introduction
- The Barrel Muon Spectrometer
- The Endcap Muon Spectrometer
- The Alignment System
- First Results from the November 2006 Barrel Cosmic Run
- Summary

Introduction



The ATLAS Muon Spectrometer

- Physics requirement: $\Delta p_T / p_T < 10\%$ up to 1 TeV
- Stand-alone operation possible



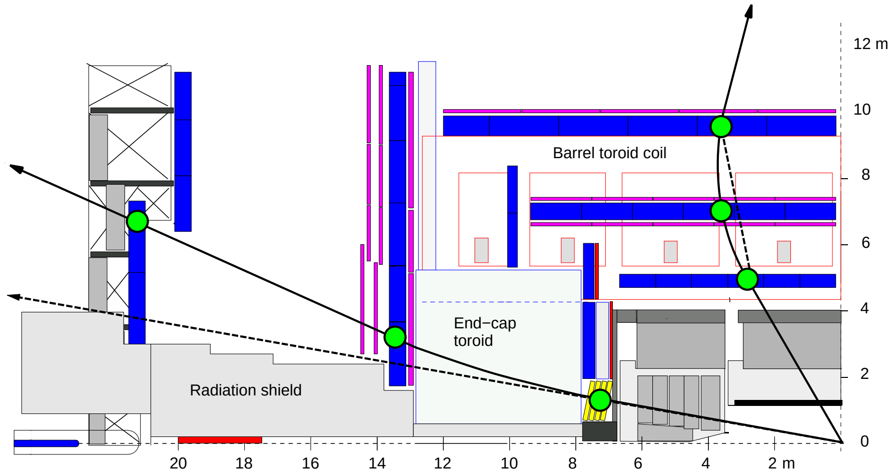
Realization

- Air core toroid magnet system
- Dimensions: 44 m $\times$ 22 m
- Active area: > 5500 m^2
- 2264 trigger chambers
- 1194 precision chambers
- 12232 alignment sensors

Introduction (2)

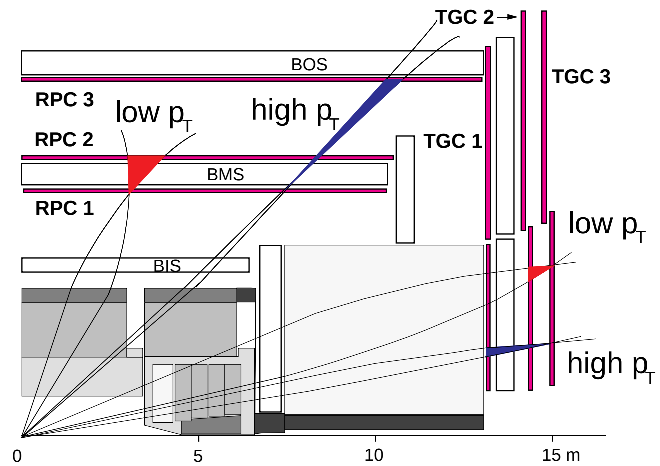
Principle of the ATLAS Muon Spectrometer

Momentum Measurement



- 3 planes of precision chambers
- Barrel: 3 point sagitta measurement
- Endcap: Point-Angle measurement
- 50 μm point resolution needed (including alignment across 5–10 m)

Level 1 Muon Trigger

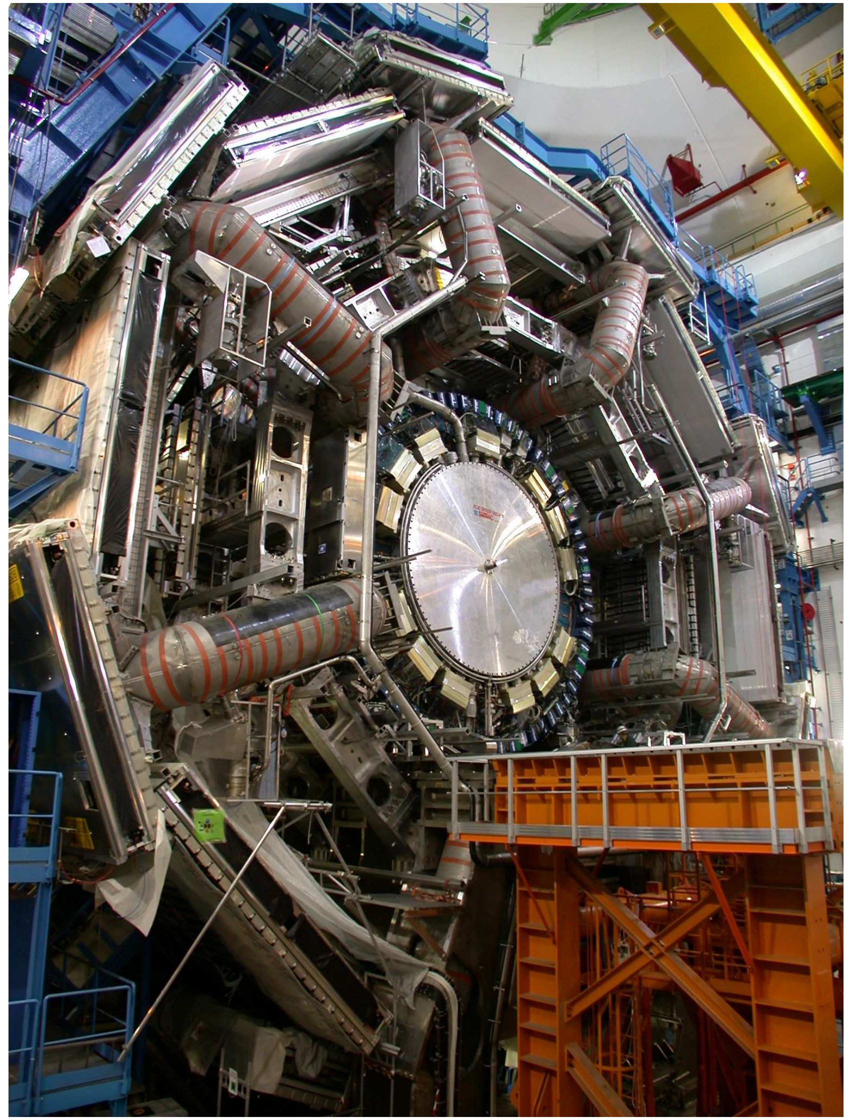


- Bunch crossing ID (40 MHz @ LHC)
- Low p_T trigger: 2 neighboring planes
- High p_T trigger: 1 additional plane
- Hits define Regions of Interest for LVL2

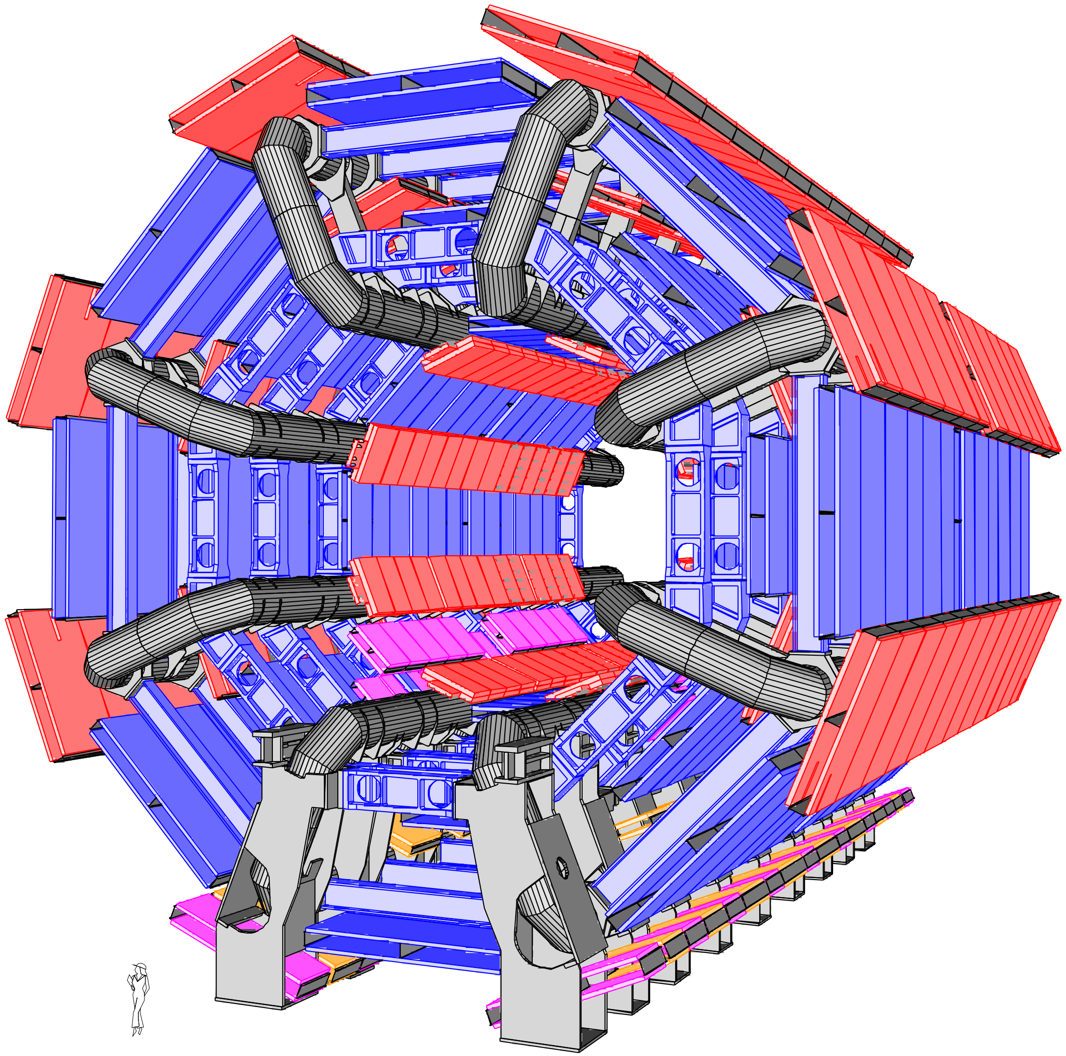
Introduction (3)

At VCI 2004

Today



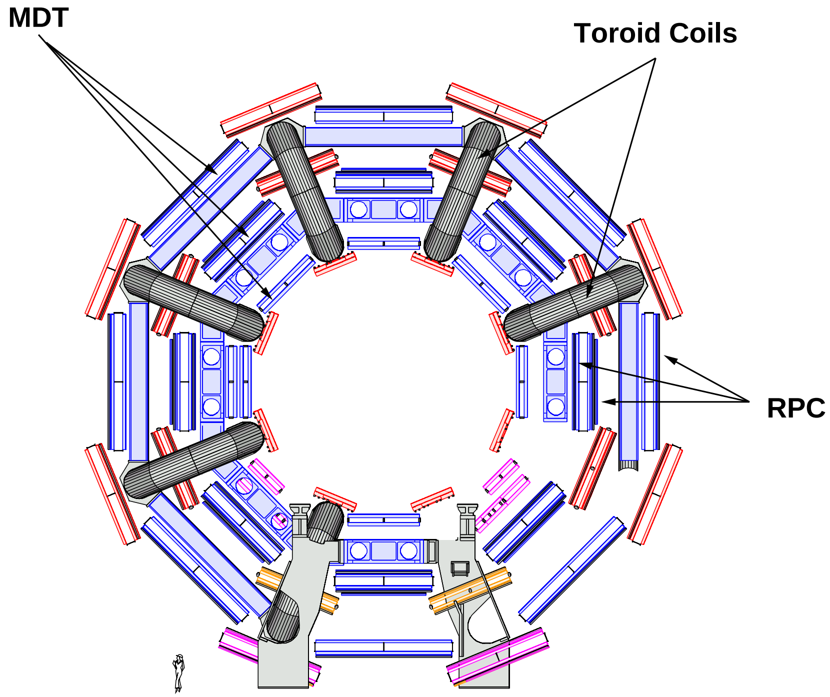
The ATLAS Barrel Muon Spectrometer



Barrel Muon Spectrometer

640 muon stations

3 layers, 16 sectors



Coverage: $\eta < 1$

Instrumentation

- 640 **precision chambers**
  Monitored Drift Tube (MDT) Chambers
- 686 **trigger chambers**
  Resistive Plate Chambers (RPCs)
  - **2 planes** on middle MDT layer **(low-p_T)**
  - **1 plane** on outer MDT layer **(high-p_T)**
- **Precision and trigger chambers combined** to **muon stations** to simplify installation

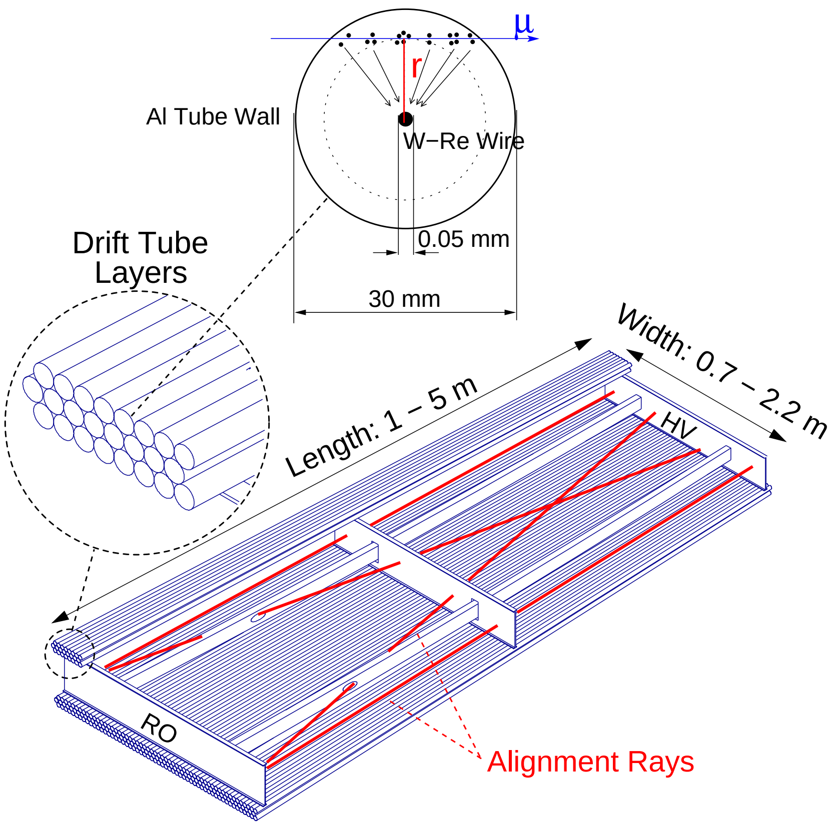
Toroid Magnet

- Inner diameter: 9.4 m
- Outer diameter: 20.1 m
- Length: 25.3 m
- **Field integral: 2–6 Tm**
- Stored Energy: 1080 MJ

Status: Surface station commissioning 100% complete
Installation 92% complete

Monitored Drift Tube Chambers

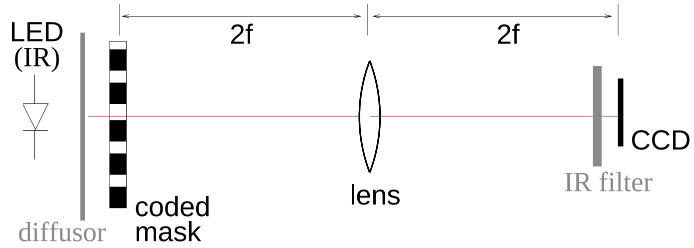
- Chamber size: 0.5–11 m^2
- **2 multilayer** of 3 (or 4) layers
- 48–432 **drift tubes**
- Support frame of aluminum



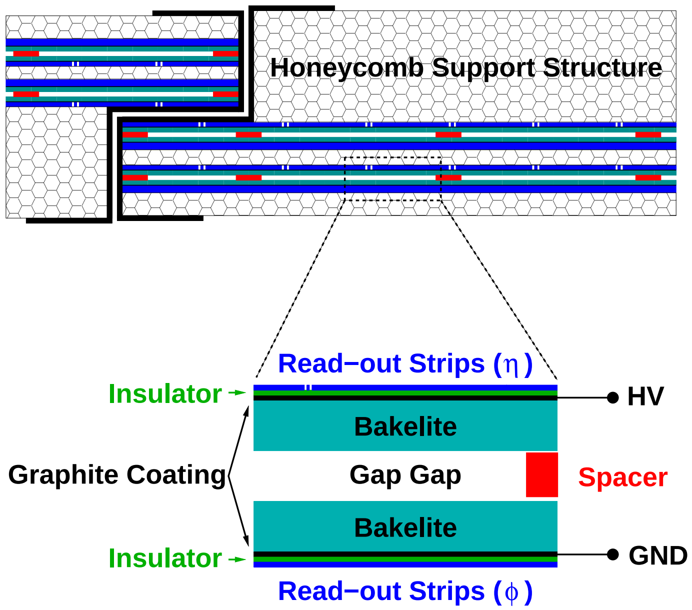
- Drift Tube Parameter
  - Gas mixture: Ar/CO_2 = 93/7
  - Pressure: 3 bar
  - Gas gain: 2×10^4
  - **Max. drift time: $\approx$ 700 ns**
  - **Resolution: 80 μm**

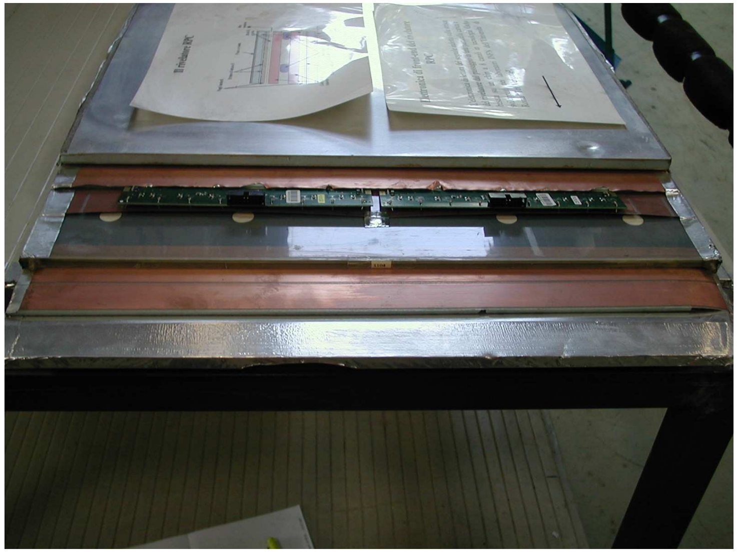
Monitored. . .

- **Optical systems** to **monitor chamber deformations** at the μm level



Resistive Plate Trigger Chambers





- Chamber size: as MDT chamber
- **2 gas gaps per RPC**
- Aluminum/honeycomb support
- RPC Parameters
  - 2 mm Bakelite plates
  - 2 mm gas gap
  - **2-dimensional read-out** (η and ϕ)
  - Gas mixture: $C_2H_2F_4$/i-C_4H_{10}/SF_6 = 94.7/5/0.3
  - Pressure: atmospheric
  - High voltage: 9600 V (adj. to pressure/humid.)
  - **Avalanche mode**
  - **Time resolution: few ns**
  - **Space resolution: 1 cm**

ATLAS Muon

Commissioning & Integration (1)

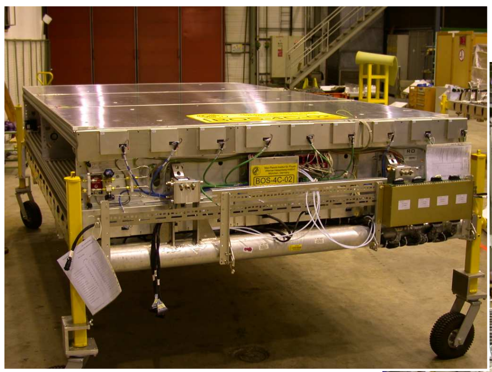
- Commission Monitored Drift Tube Chambers

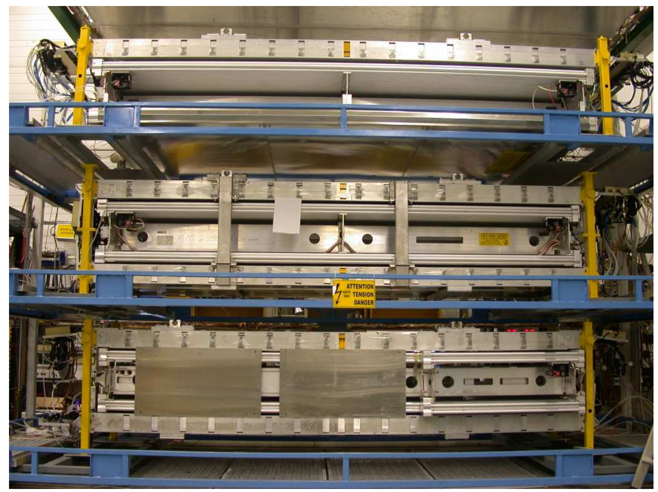
For middle and outer layers:

- Test Resistive Plate Chambers
- Combine to muon station (weight: 1 t)
- Sag compensation (MDT chamber bent to follow wire sag)

All stations:

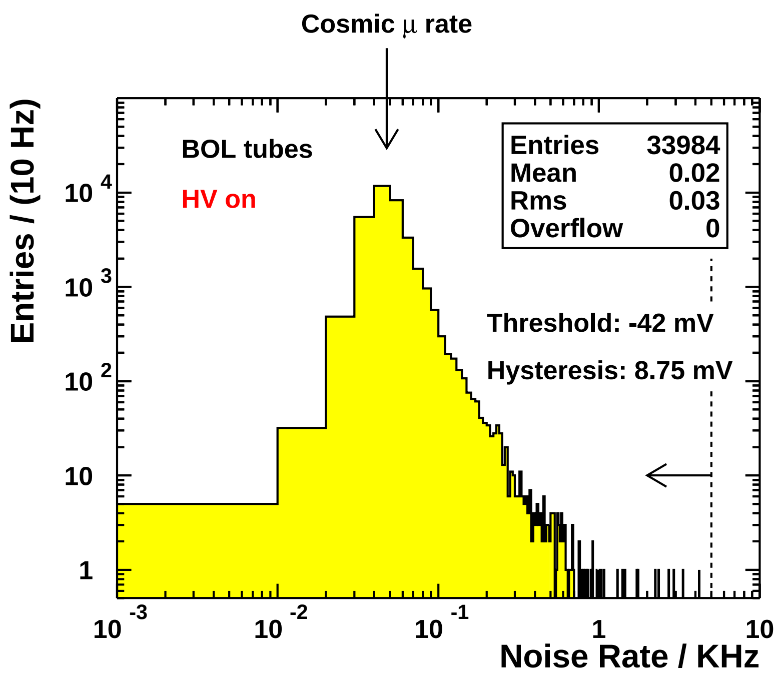
- Cosmic Ray certification



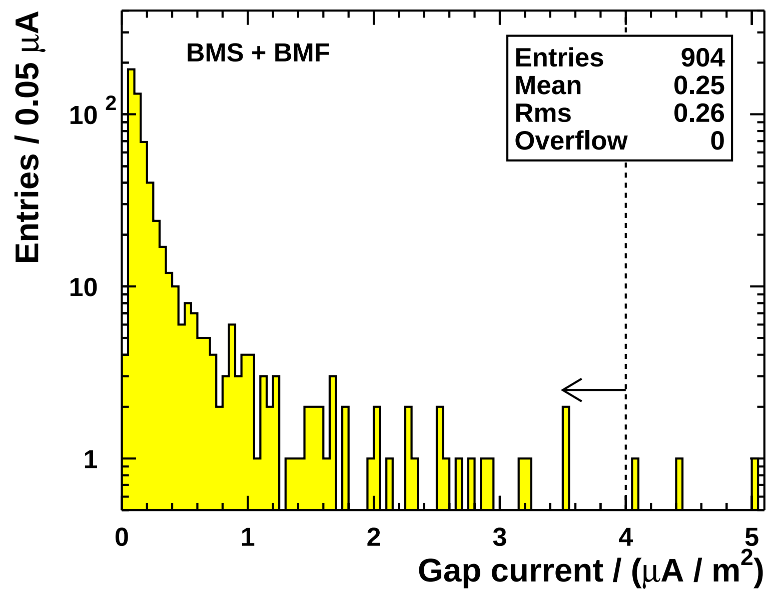


Results from Commissioning

MDT Noise Test



RPC Gap Currents



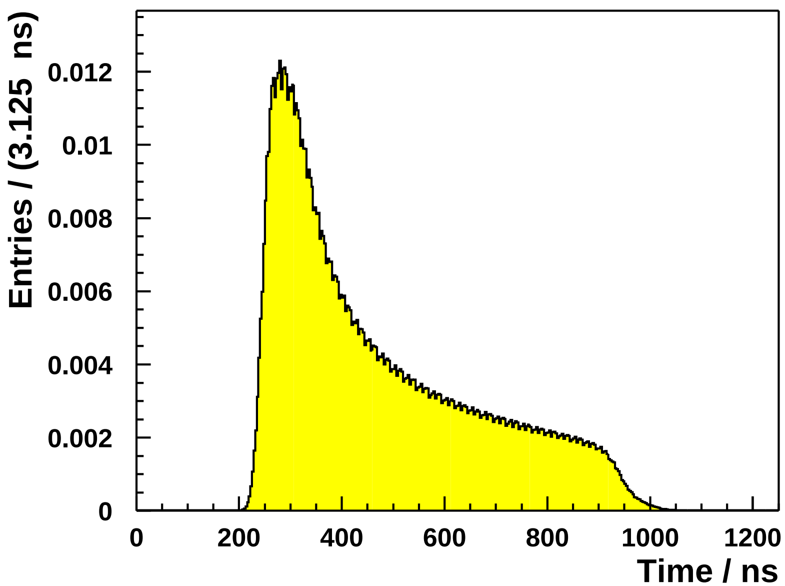
Very low failure rate of all components:

- **Electronics, alignment, HV etc. at 1% level**
- **Dead channels below 0.1%**

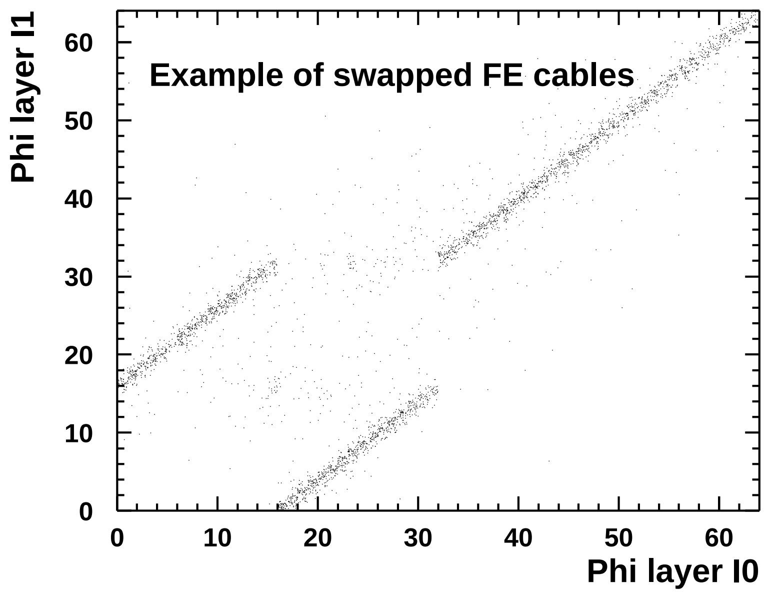
Cosmic Ray Certification

Complete system test, response and homogeneity

MDT Drift Time Spectra



RPC Gap Correlation

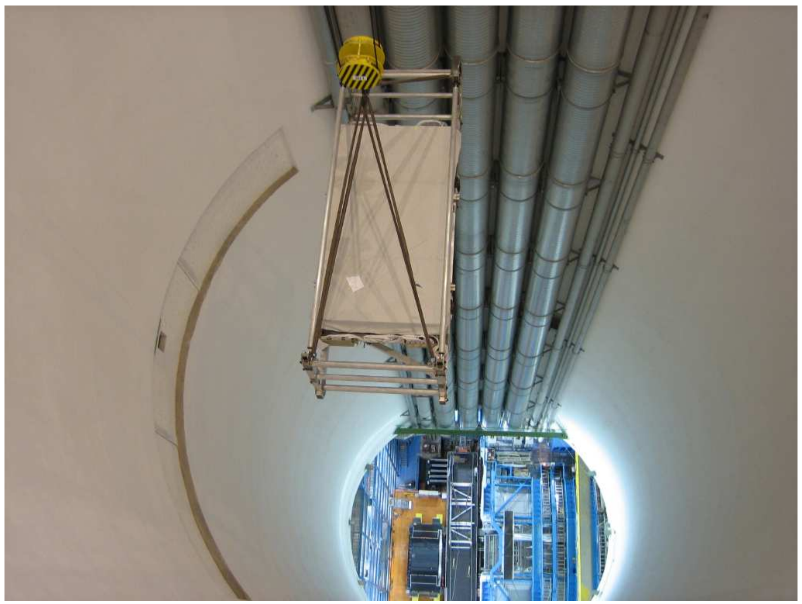


All barrel muon stations successfully certified

Barrel Installation (1)

At the Surface

On the way down to the Cavern. . .



Installation

Barrel Installation (2)

Commissioning of the Barrel Muon Spectrometer

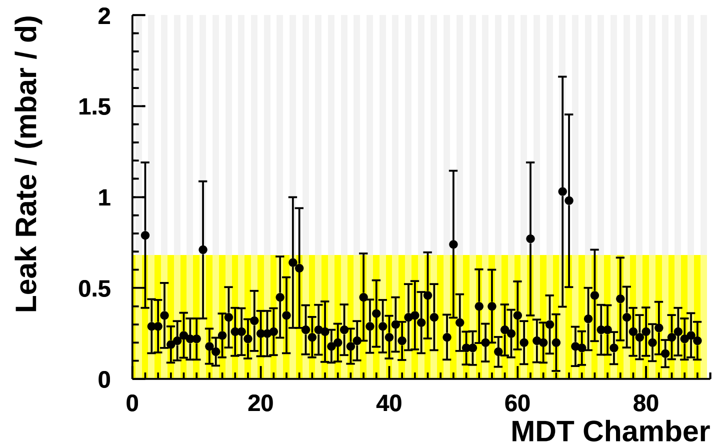
Muon Station Commissioning

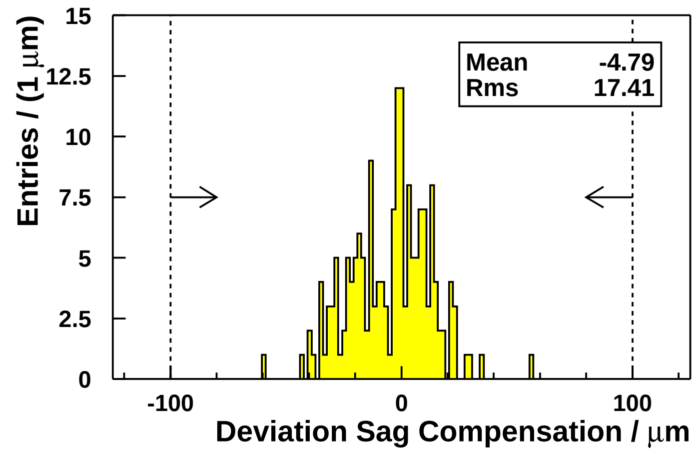
- Immediately after Installation
- MDT gas leak test
- MDT HV test
- Chamber initialization
- Alignment test
- RPC gas leak test

Full Sector Commissioning

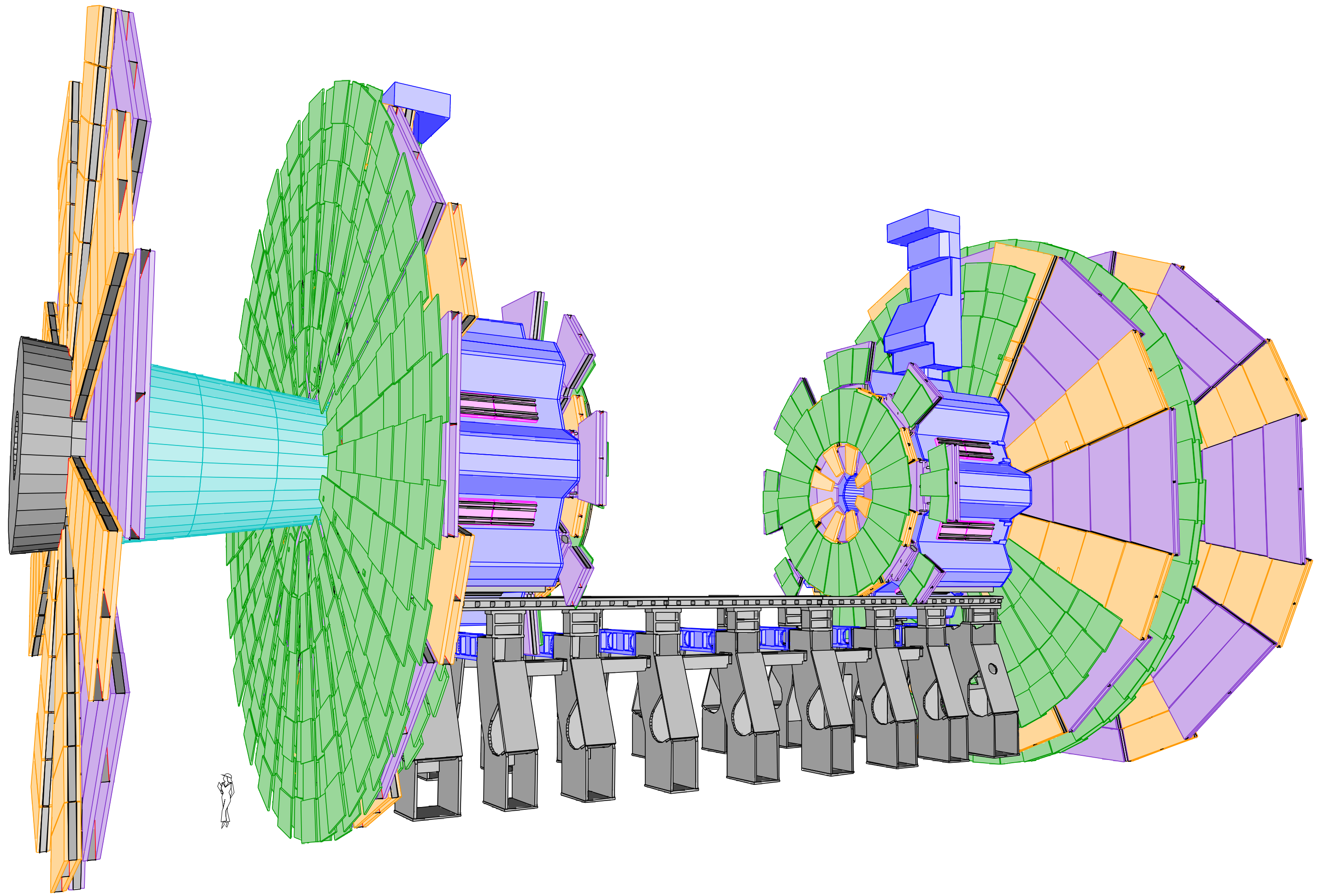
- **March – November 2007**
- 2 sectors / month
- **Cosmic ray data**

Examples of MDT Chamber Commissioning





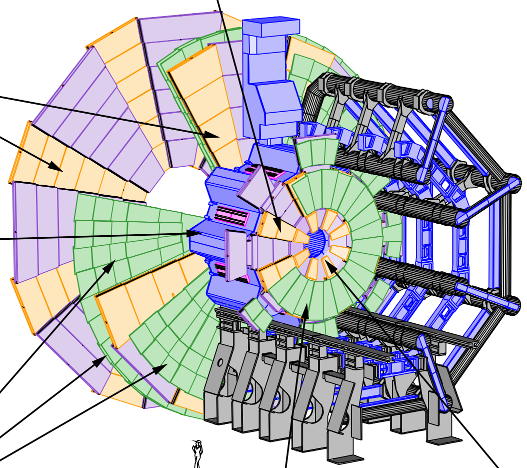
The ATLAS Endcap Muon Spectrometer



Endcap Muon Spectrometer

2112 muon chambers

2 Small Wheels, 10 Big Wheels



Coverage: 1 < $\eta < 2.7$

Instrumentation

- 534 **precision chambers**
  470 Monitored Drift Tube (MDT) Chambers
  64 Cathode Strip Chambers (CSCs)
- 1578 **trigger chambers**
  Thin Gap Chambers (TGCs)
  - **2 layer** outside 1st MDT BW **(low-p_T)**
  - **1 layer** inside 1st MDT BW **(high-p_T)**
  - 2nd coord.: 1 layer on MDT Small Wheel

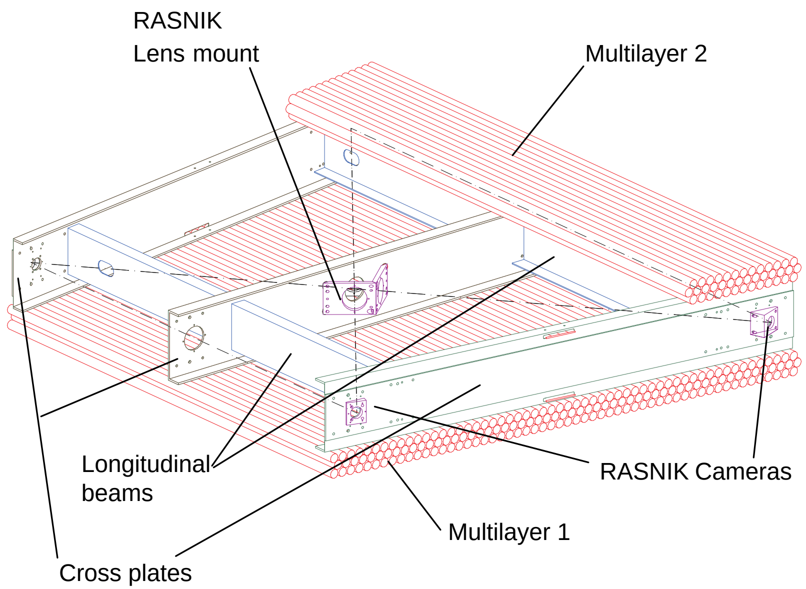
Toroid Magnets

- Inner diameter: 1.7 m
- Outer diameter: 10.7 m
- Length: 5 m
- **Field integral: 4–8 Tm**
- Stored Energy: 2×250 MJ

Status: MDT/TGC sectors 75% assembled
Installation of 1 MDT & 1 TGC Big Wheel completed

Precision Detectors

Monitored Drift Tube Chambers

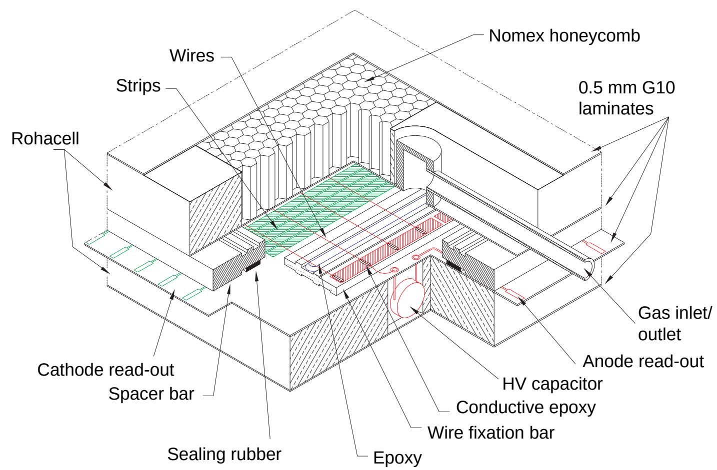


Same as barrel MDT chambers, but. . .

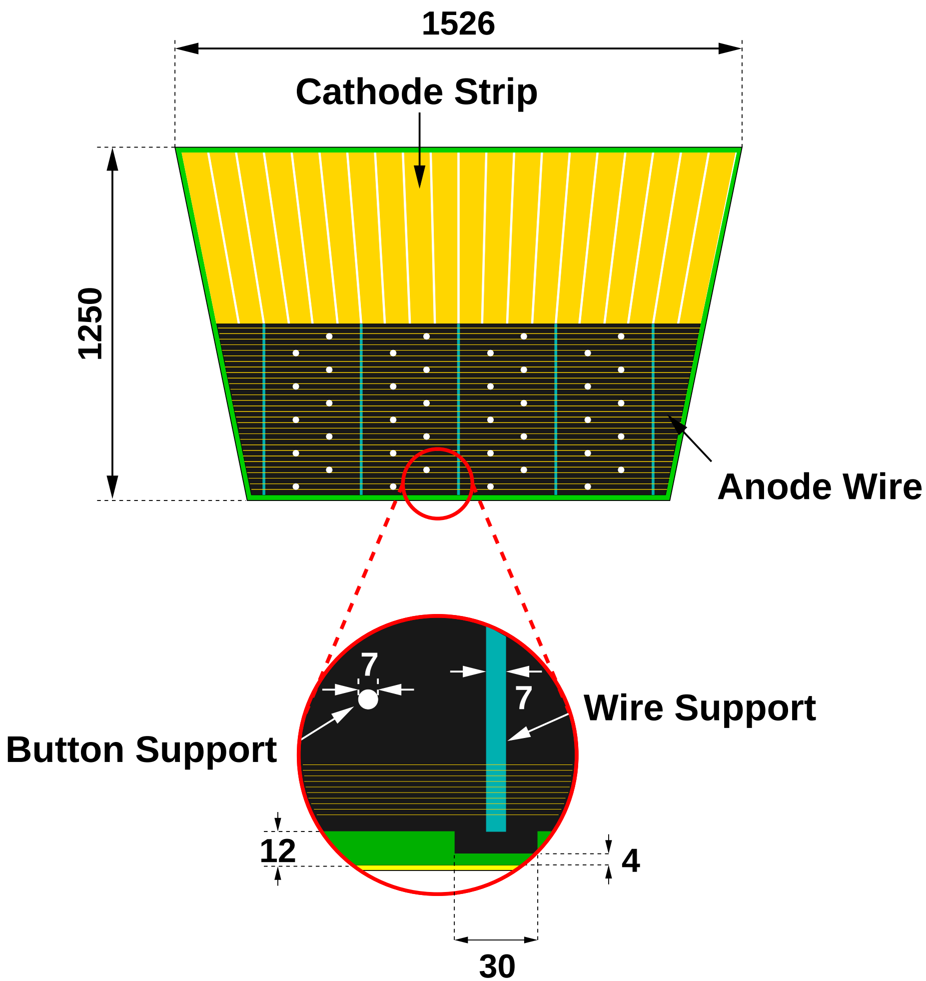
- **Trapezoidal shape**
- Chamber size: 2–10 m^2

Cathode Strip Chambers

- Trapezoidal shape
- Chamber size: 1 m^2
- 2×4 layer units
- Low mass honeycomb support panels
- Wire spacing, anode-cathode gap: 2.54 mm
- 30 μm WRe anode wires
- **2-D cathode strip read-out** with charge interpolation
- **Resolution: 60 μm**



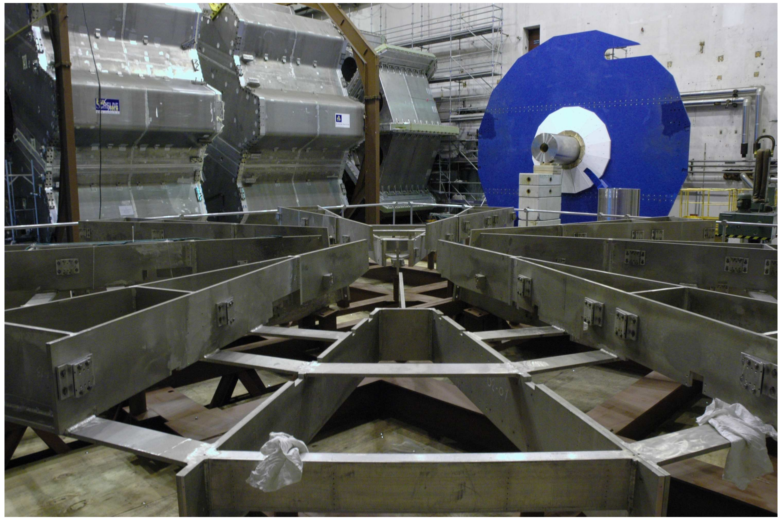
Thin Gap Trigger Chambers



- **Multiwire Proportional Chamber**
- Chamber size: 1–3 m^2
- Combined to **doublets or triplets**
- Low mass honeycomb support panels
- Wire spacing: 1.8 mm
- Anode-cathode gap: 1.4 mm
- 50 μm W anode wires
- Gas mixture: CO_2/n-Pentane = 55/45
- Operated in saturated mode
- **2-D read-out** (wires and cathode strips)
- **Wires (4–20) grouped in dep. of η**

Commissioning & Sector Assembly

MDT Small Wheel Support



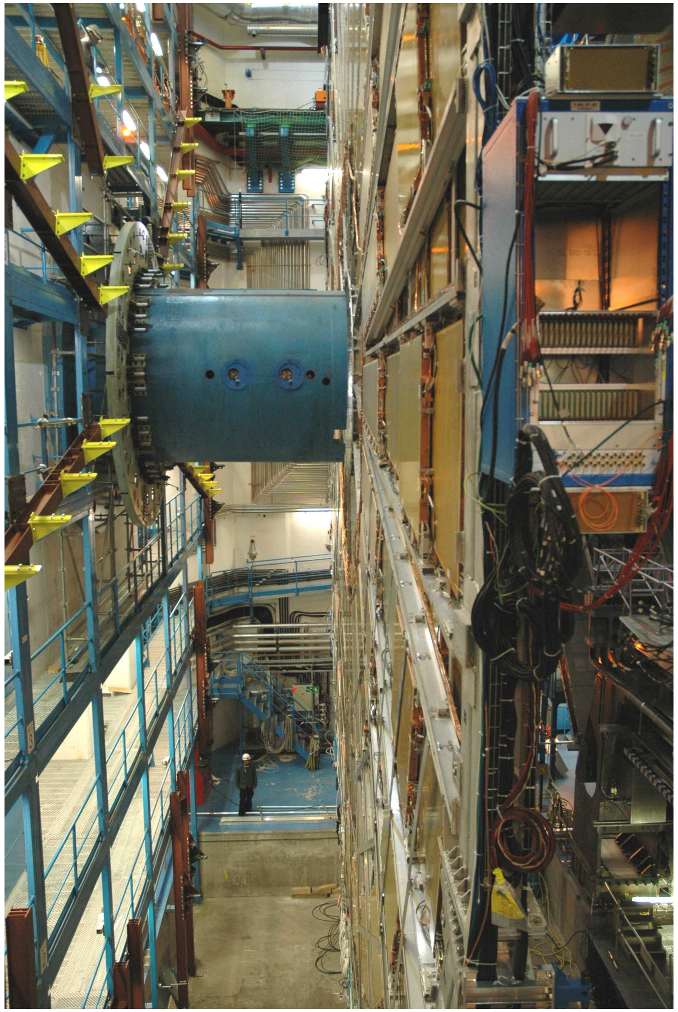
TGC Commissioning

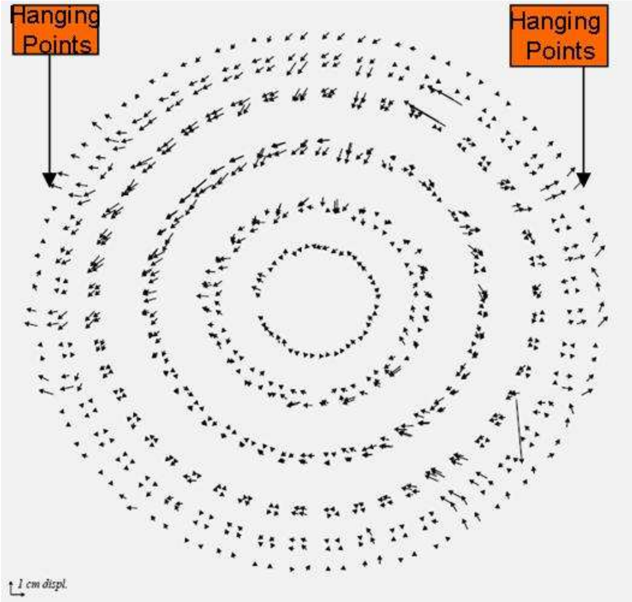
MDT Sector

TGC Sector Assembly

Endcap Installation (2)

Release of First TGC Big Wheel, Nov. 2006

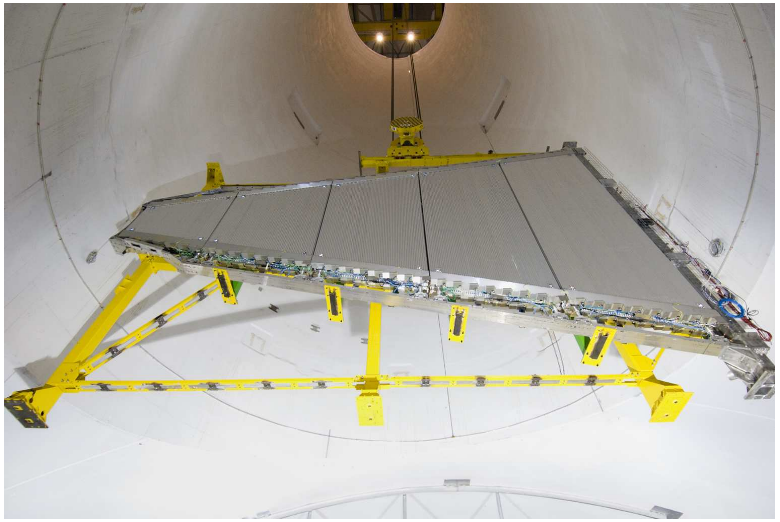




- Chamber **positions measured** with internal sensors **during load transfer**
- Optical Chamber **survey after movement**
  - Movement **in wheel plane: few mm**
  - Movement **out of wheel plane: +/- 7 mm**

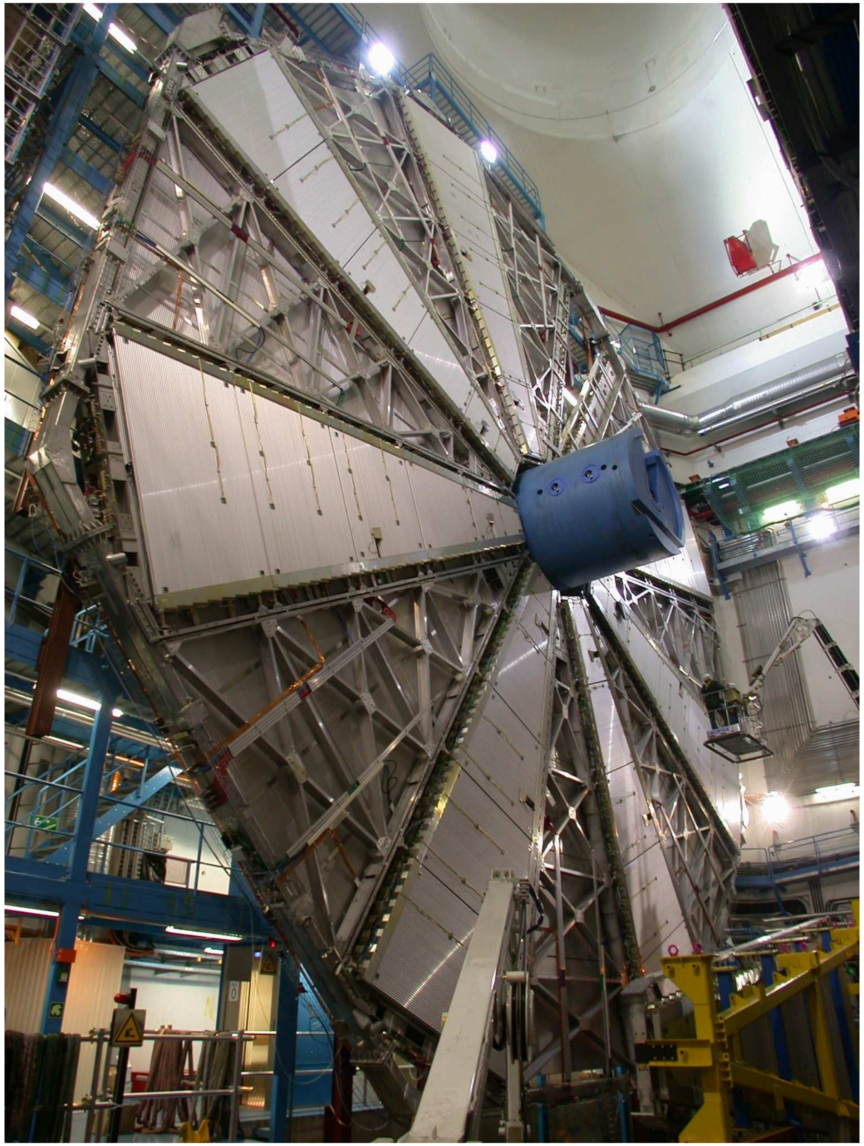
No negative effect on detector integrity
Geometrical accuracy satisfactory

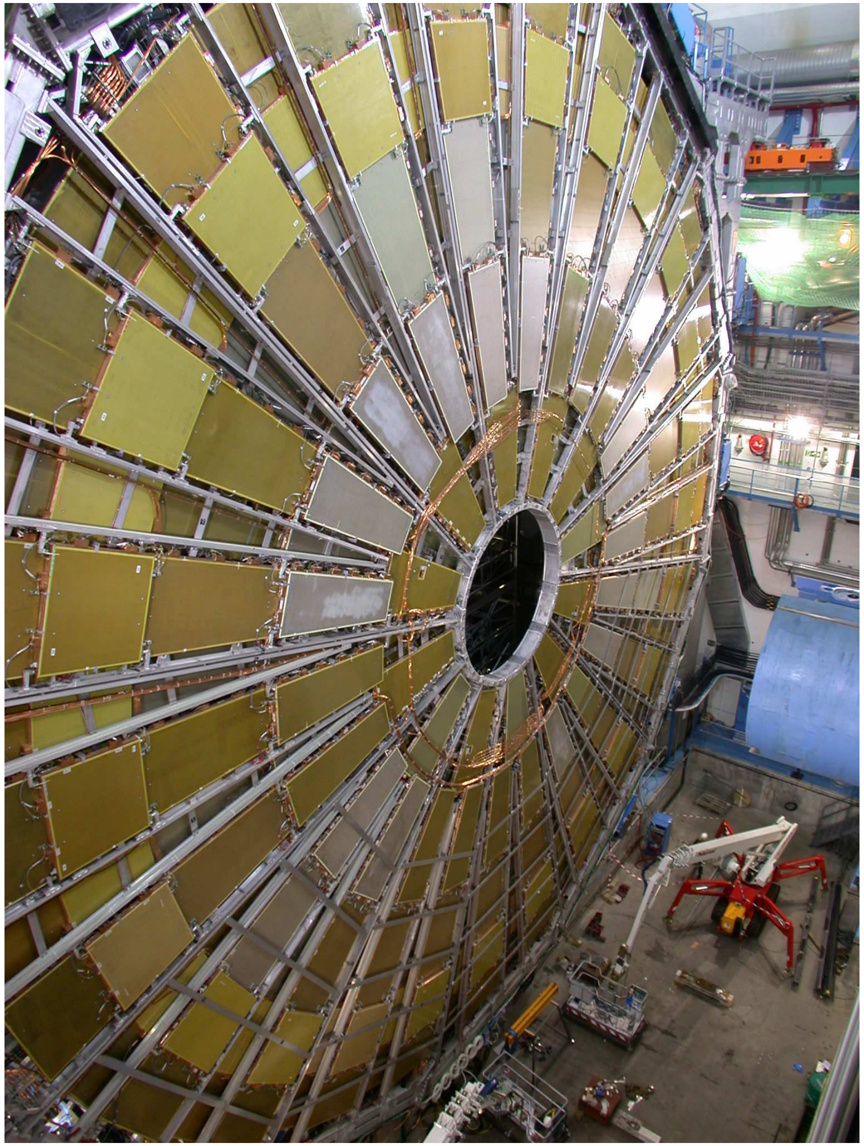
Endcap Installation (2)



First MDT Big Wheel completed last week

Endcap Installation (3)

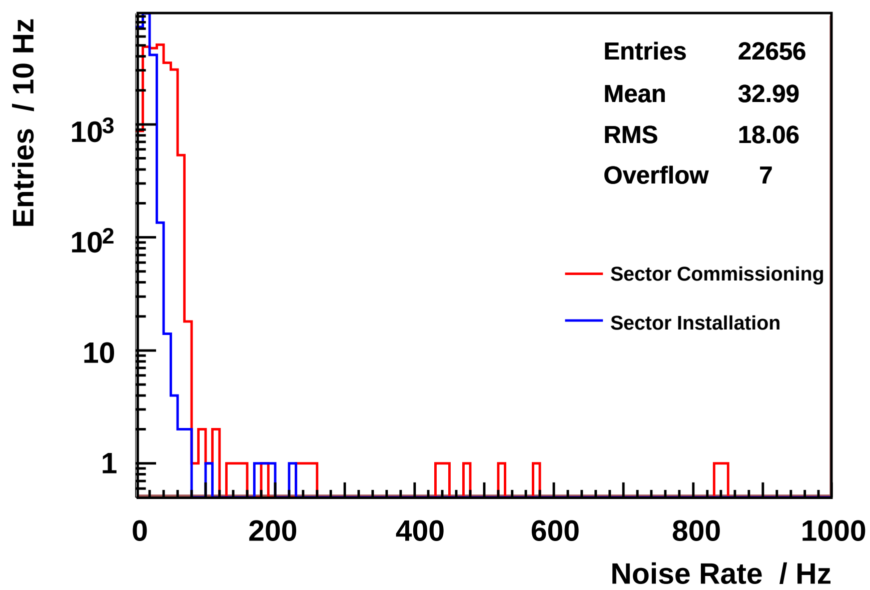




Endcap Installation (4)

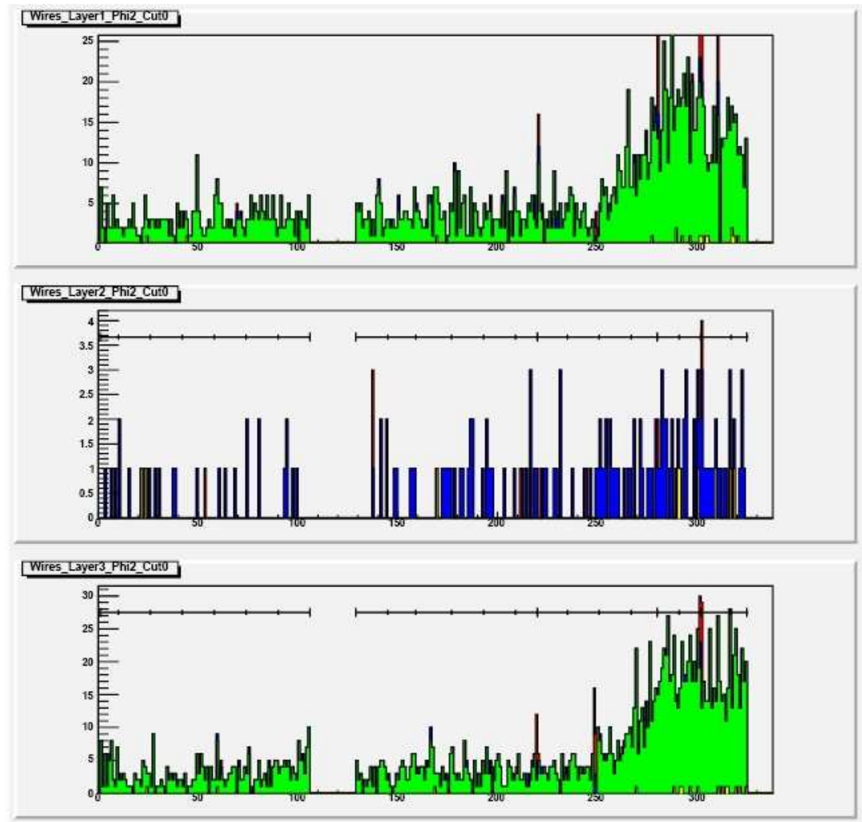
Commissioning of the First MDT and TGC Big Wheels

MDT Noise Rates



- **No change** compared to commissioning
- **Lower noise rate consistent** with **reduction** of cosmic **muons**

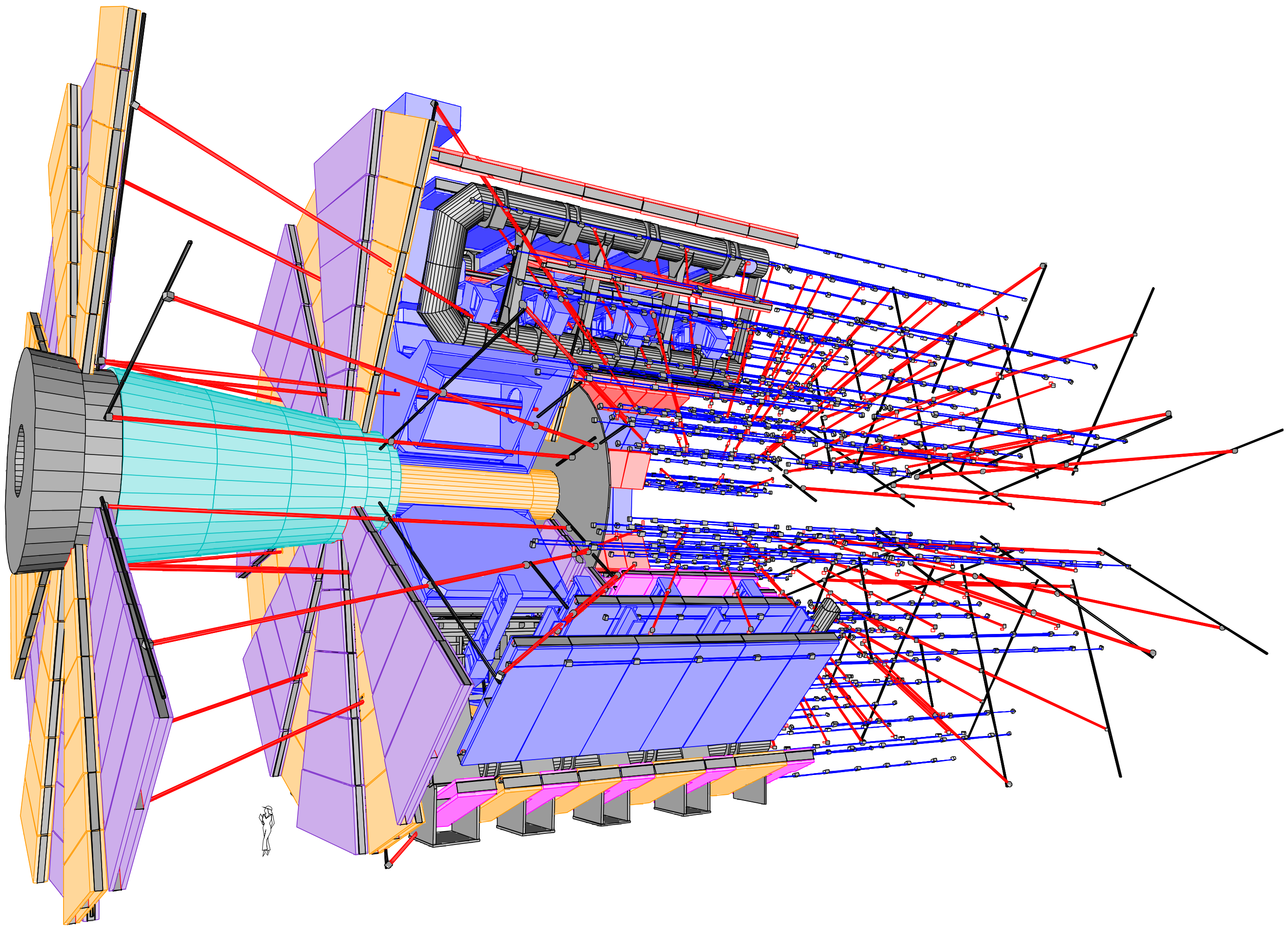
TGC Hit Map



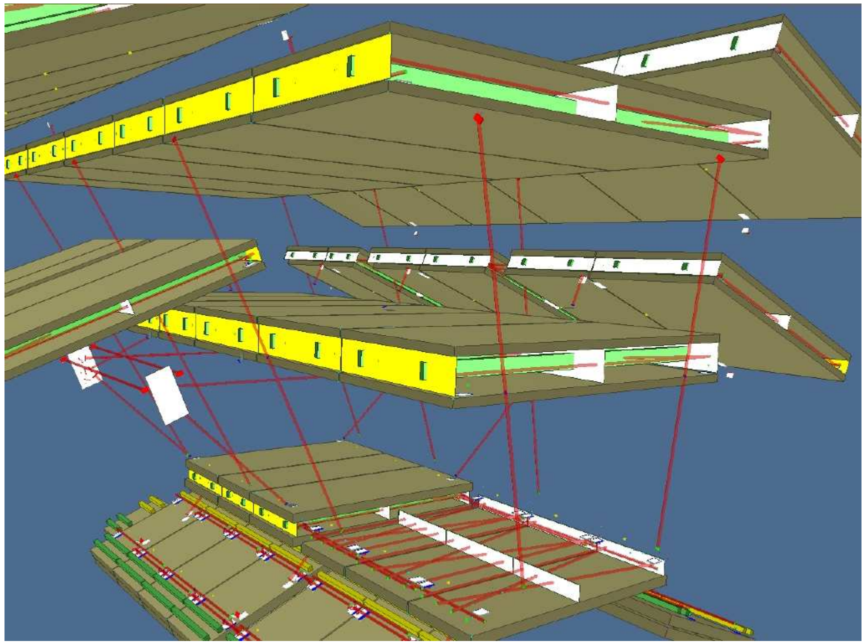
- Hit profiles **as expected**

Very promising results

The Alignment System



Barrel Alignment System (1)



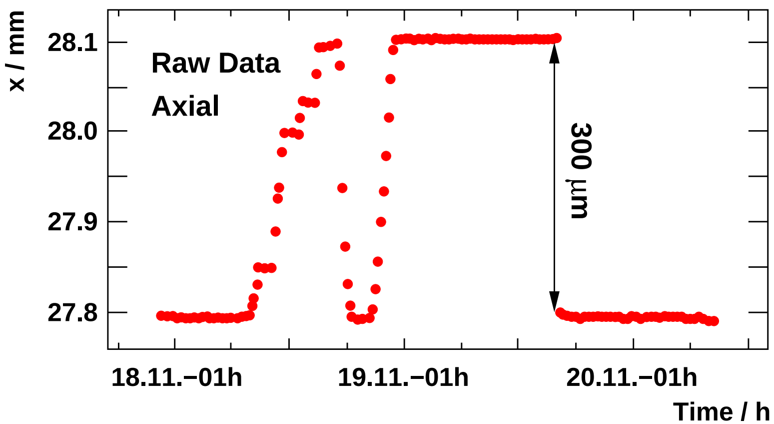
5817 sensors in total

- MDT inplane system
  monitor chamber deformations
  $\mathcal{O}(1)\ \mu$m precision
- Proximity and Axial system
  align chambers within layer
  10 μm precision
- Projective system
  align chambers within sector
  30 μm precision
- Chamber-Chamber-Connect. system
  align small sectors to large
  200 μm precision
- Reference system
  absolute alignment
  500 μm precision

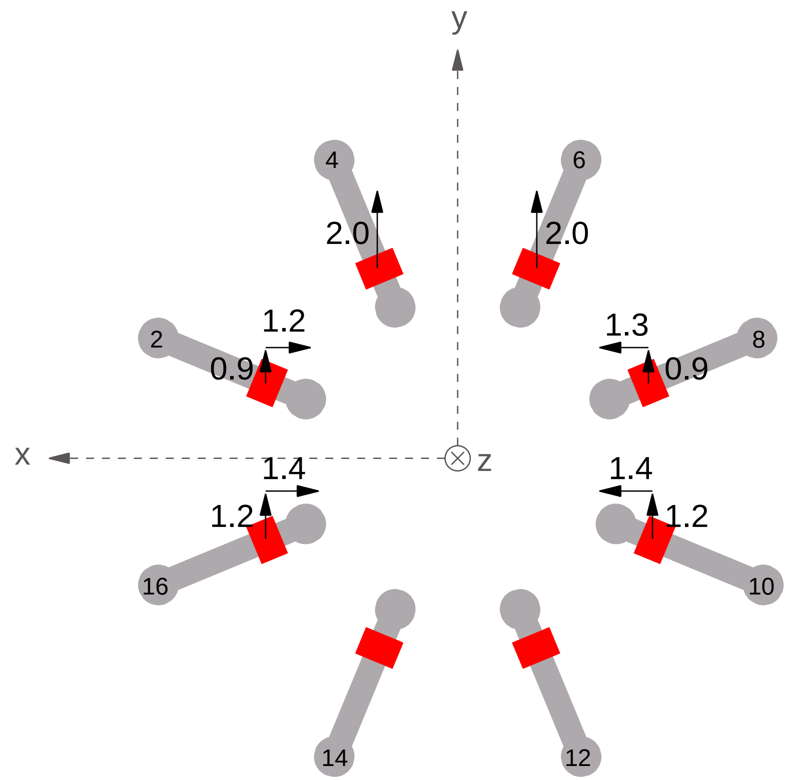
Barrel Alignment System (2)

Results from Barrel Toroid Test, Nov. 2006

- **15% of alignment system tested**
  (875 lines, all subsystems)
- **Deformation** of **barrel toroid as expected** (no field $\longrightarrow$ full field)
- **Chamber deformations: 100 μm**
- Axial **movements: 300 μm**
- **Projective** tower **movements: 500 μm**



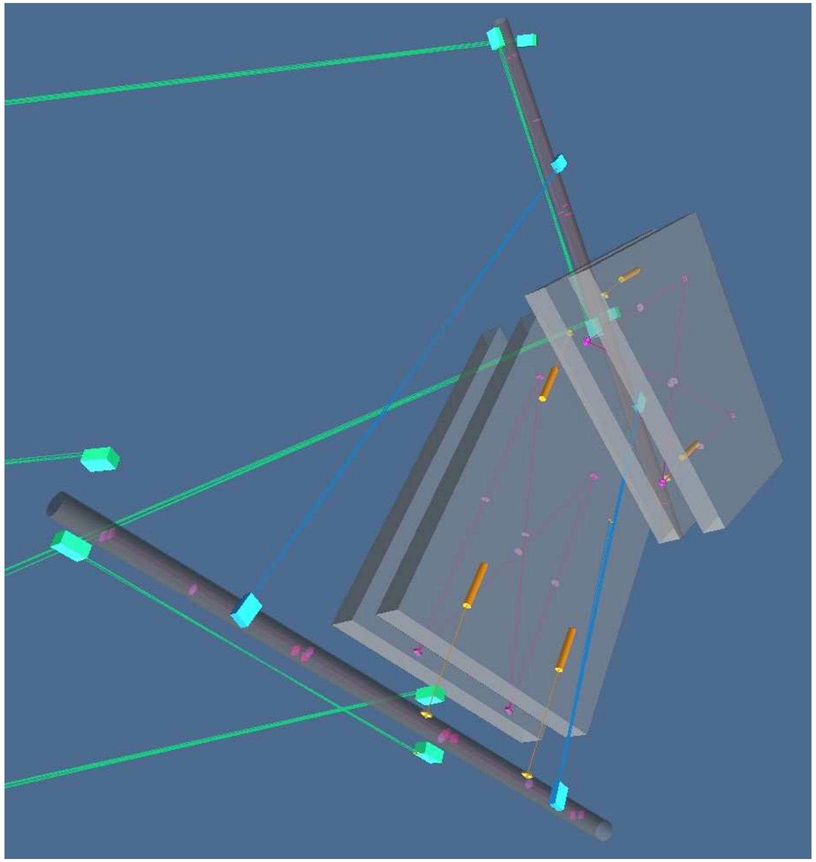
Barrel Toroid Deformation at Full Field



Alignment system working and indispensable

Endcap Alignment System (1)

- 2 × 4 wheels of precision chambers
- Direct projective system not possible



6416 sensors in total

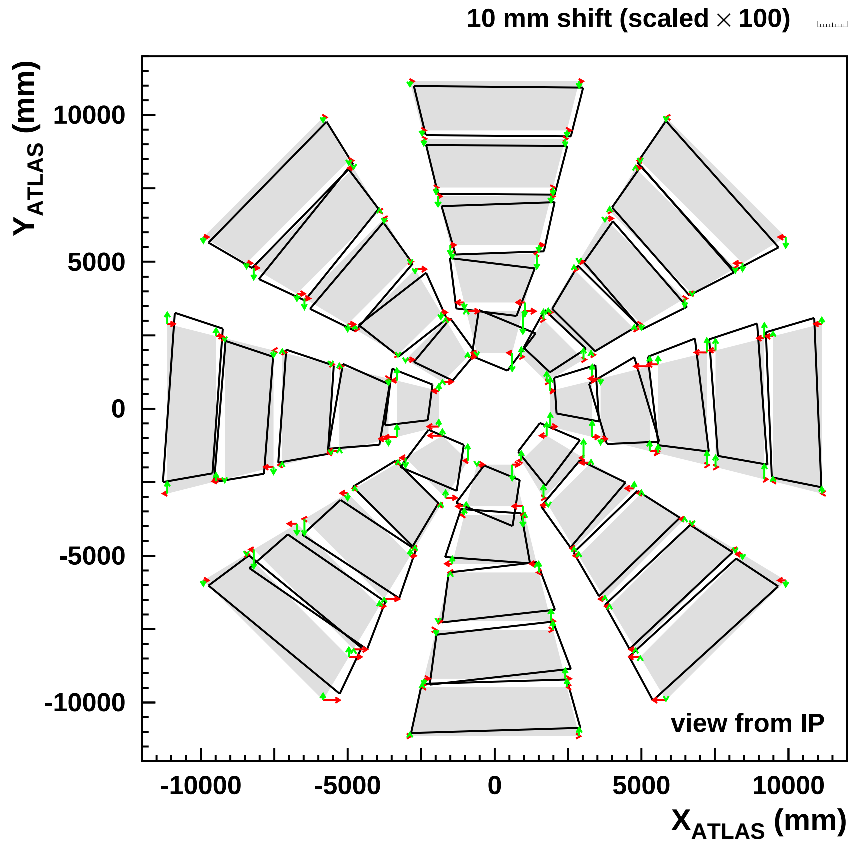
- Reference grid of monitored alignment bars
  - Internal optical straightness sensors
  - Temperature sensors
- Polar sensors
  align bar to other wheel
- Azimuthal sensors
  align bars within wheel
- Planarity sensors
  align chamber to chamber
- Proximity sensors
  align chamber to bar
  align chamber to chamber
- Inplane sensors
  MDT chamber deformations

Endcap Alignment System (2)

First Results — MDT Big Wheel C during Construction

- Gray Area: nominal position
- Black Lines: actual position (scaled × 100)
- Red Arrows: shift in X-direction
- Green Arrows: Shift in Y-direction

Displacement in Big Wheel plane

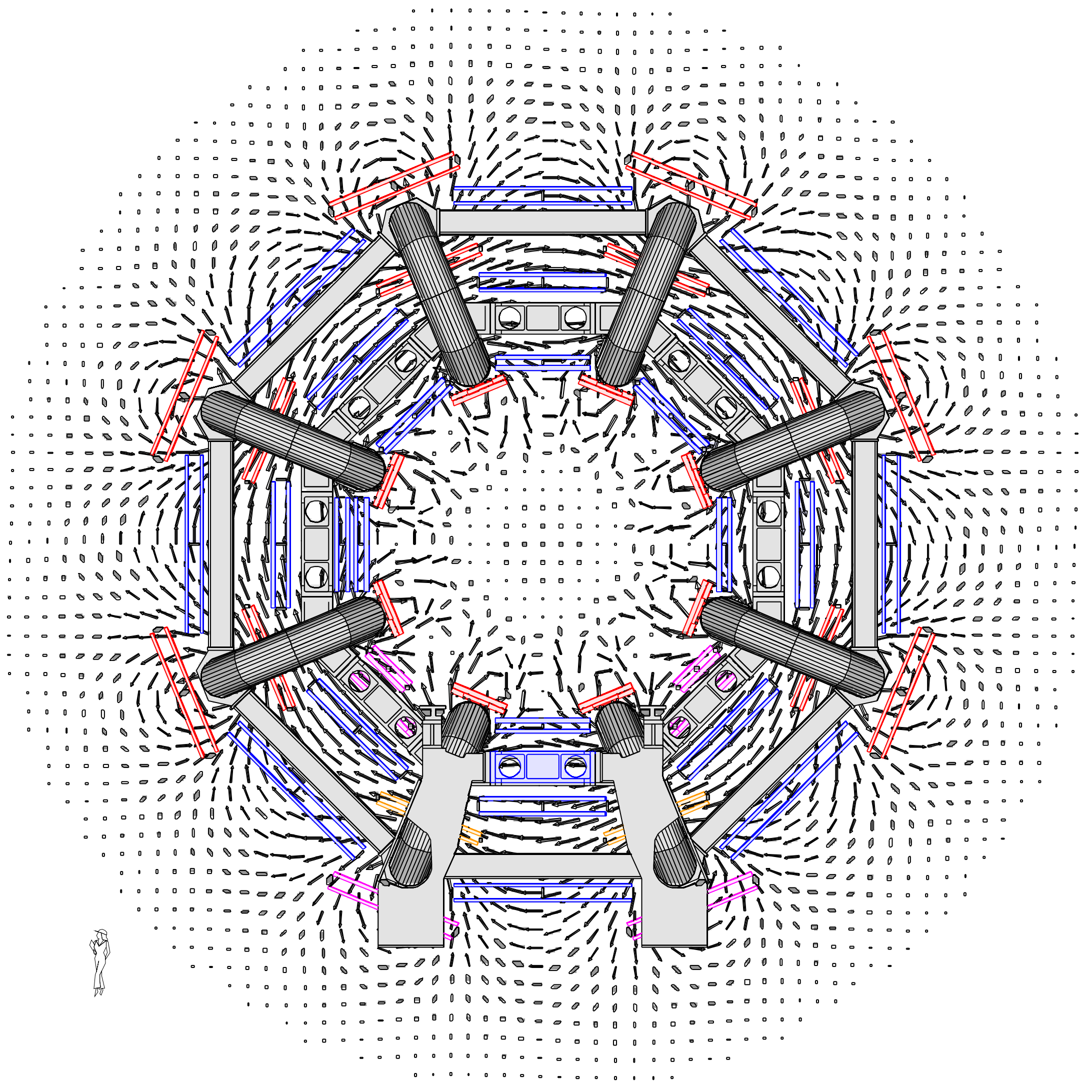


Results for lower 5 sectors

- ΔX: 2 mm RMS (max. 6 mm)
- ΔY: 3 mm RMS (max. 8 mm)

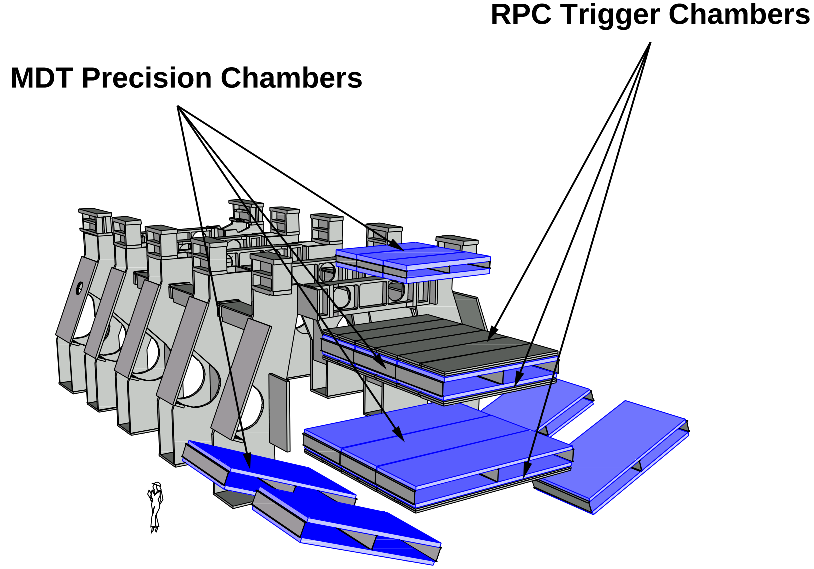
Sector / chamber positioning better than expectation

First Results from the November 2006 Barrel Cosmic Run with Magnetic Field

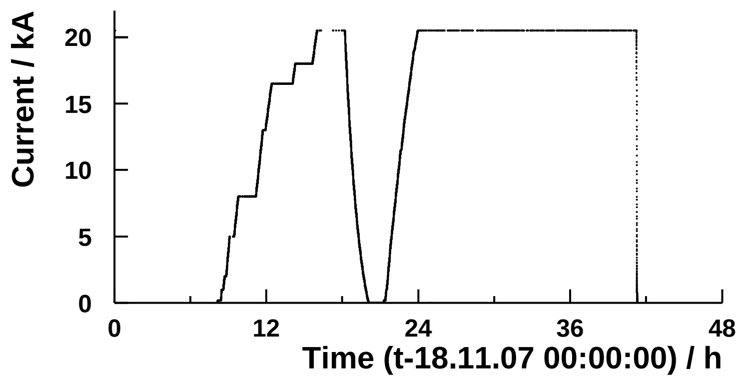


Nov. 2006 Cosmic Barrel Run

Setup



Magnet Current



- 18–19th November 2006
- Barrel Toroid at full field
  Current: 20.5 kA

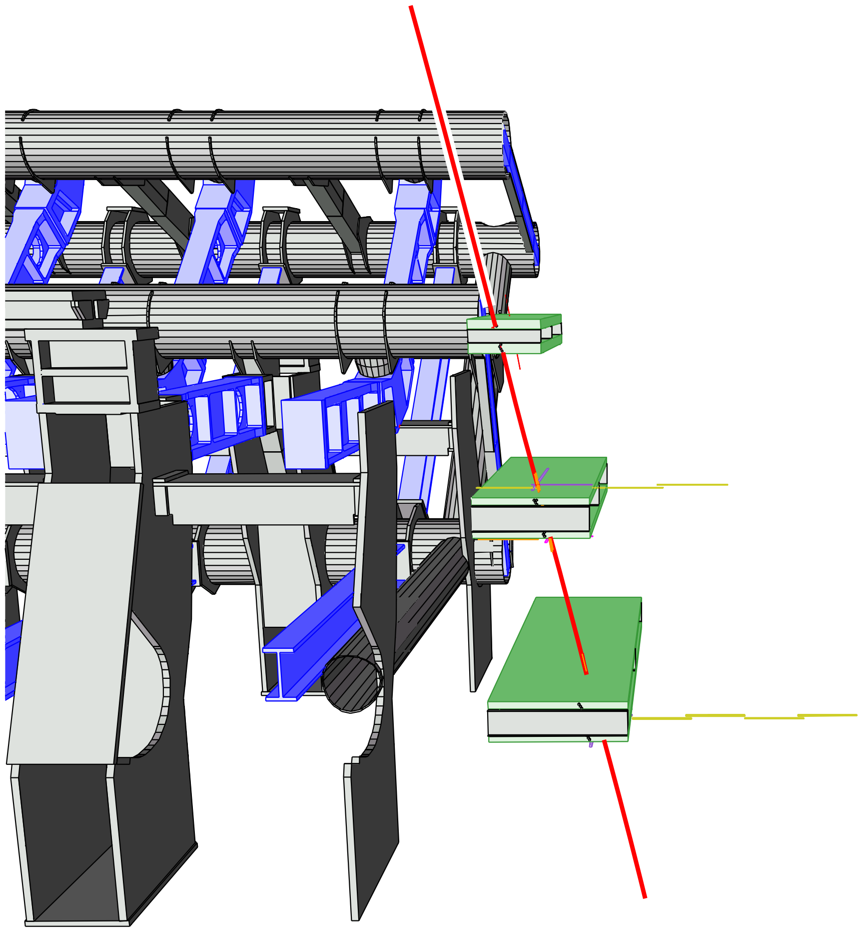
Muon Instrumentation

- **13 Muon Stations** (2% of barrel)
  - 1/4 sector
  - 2 stations in each neighboring sector
- Low- and high-p_T **trigger**
- Muon barrel **alignment** (15% of barrel)
- Use of **Central Trigger Processor**
- DAQ & Online Monitoring

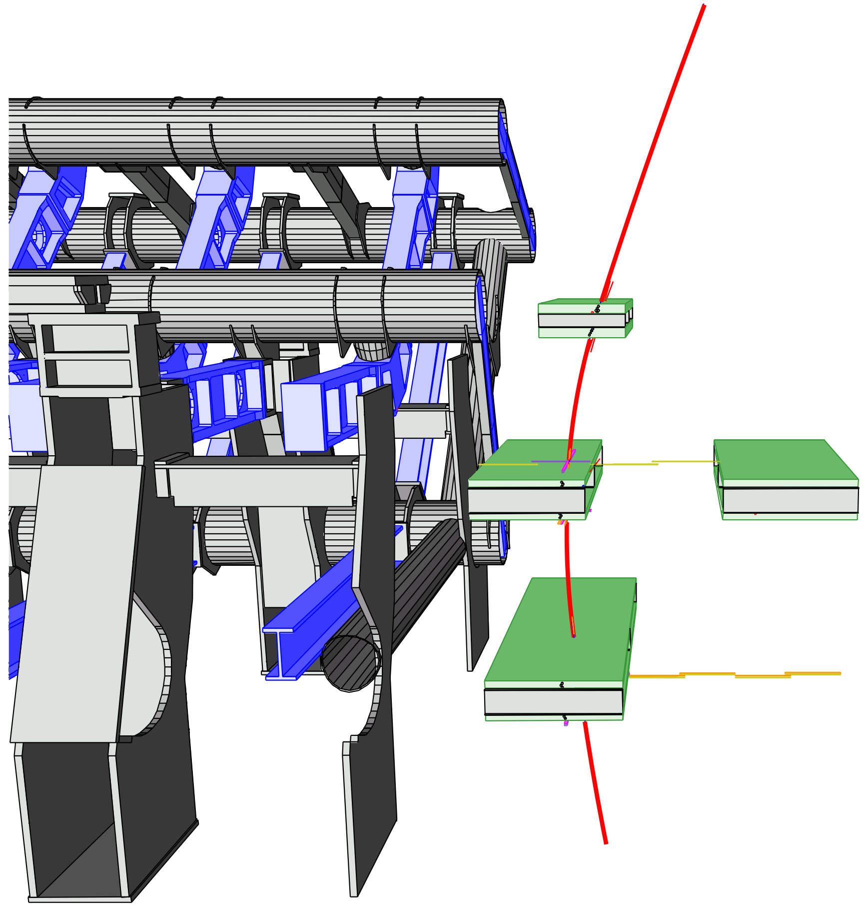
First complete system test for barrel spectrometer
Up to now only components in magnetic field

Some Events

High-p_T Track



Low-p_T Track



Run 1000372 with full magnetic field

Topics Covered Elsewhere

Please Note the Following ATLAS Muon Talks and Poster

- **Level 1 Trigger**
  David Berge (CERN)
  The ATLAS Level-1 Trigger: Status of the System and First Results from Cosmic-Ray Data
  Poster B149

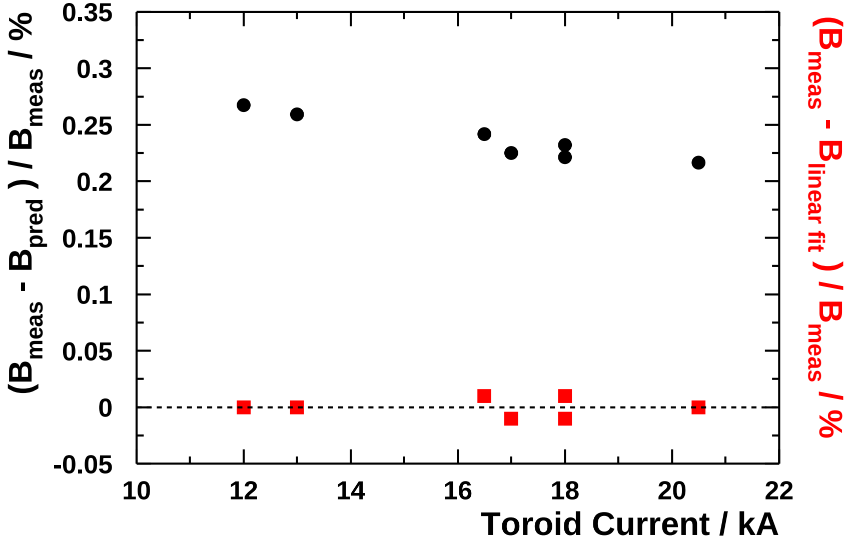
- **Resistive Plate Chambers**
  Gabriele Chiodini (INFN Lecce)
  RPC trigger counter cosmic ray tests in the ATLAS experiment
  Talk Session 3

- **Monitored Drift Tube Chambers**
  Oliver Kortner (MPI Munich)
  Alignment of the ATLAS Muon Spectrometer with Tracks and Muon Identification at High Luminosities
  Poster B183

Magnetic Field Measurements

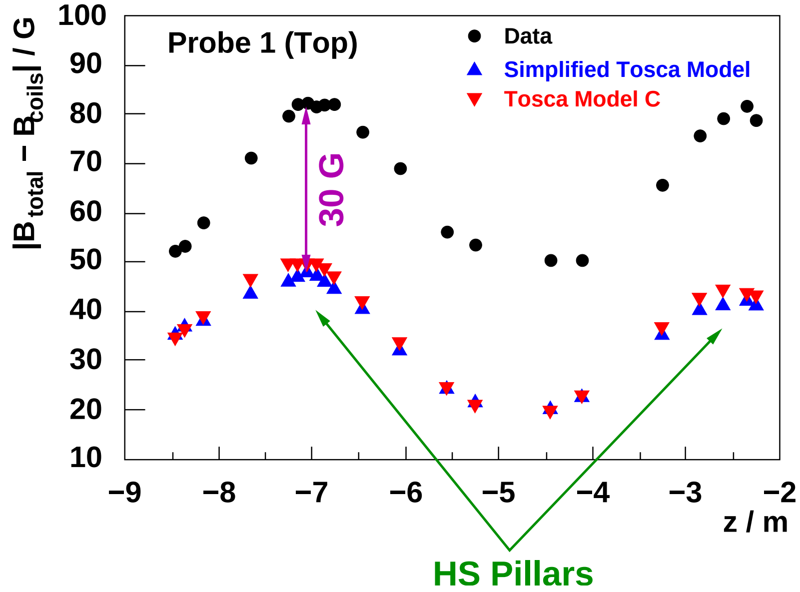
Predicted Field vs. Measurement

NMR Probe



- Predicted field scaled from calculation at 10 kA
- Measurement at point with no gradient and very little magnetic pollution (middle MDT layer)
- **Very good agreement**

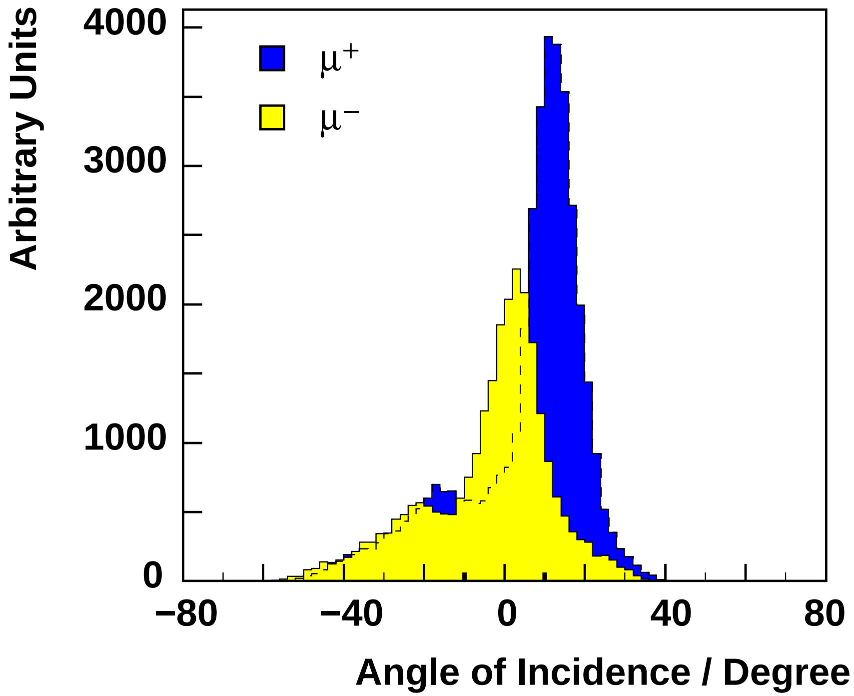
Influence of the Surrounding Service Structure



- Service structure of steel
- **Perturbations well simulated**, can reach 500 G in some areas
- Model parameters will be further refined

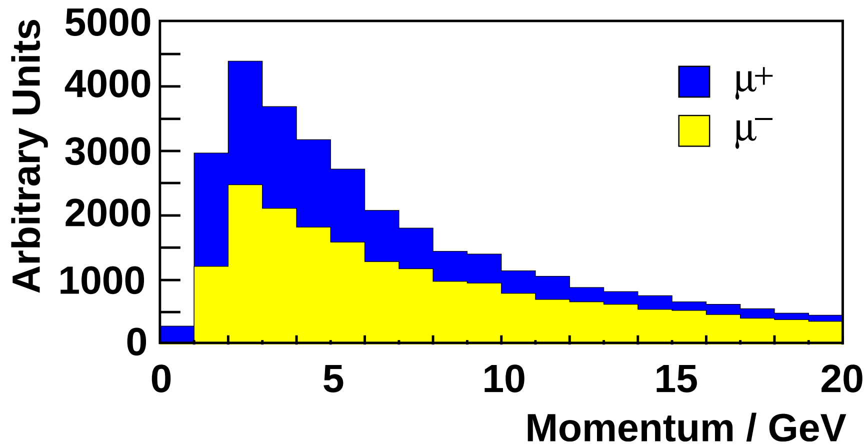
Muon Spectra

Angular Distribution



- **Clear separation** of μ^+ and μ^-
- **Angular distribution consistent with geometry** (two peaks correspond to near and far access shafts)

Muon Momenta



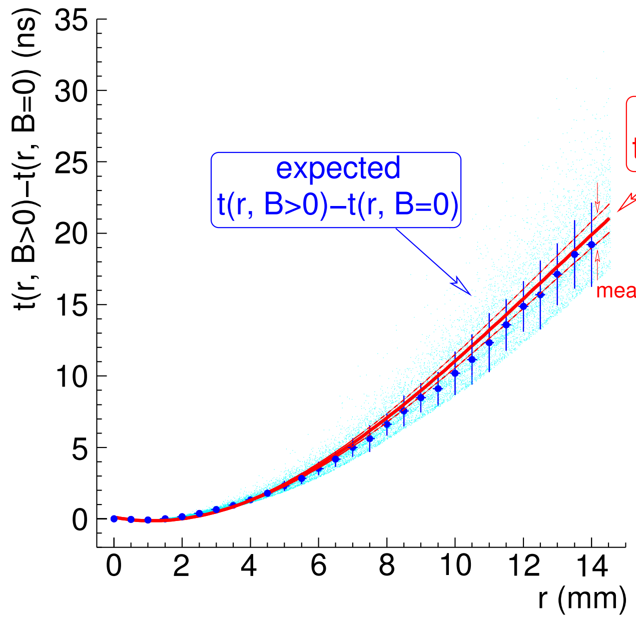
- **Momentum spectra** fall-off **consistent with expectations**
- **Ratio** $\mu^+ / \mu^- = 1.48 \pm 0.27$ **in agreement with PDG value** (1.25–1.30)
- Further Monte-Carlo studies in progress

MDT Space-Drift Time Relation

Autocalibration in Magnetic Field

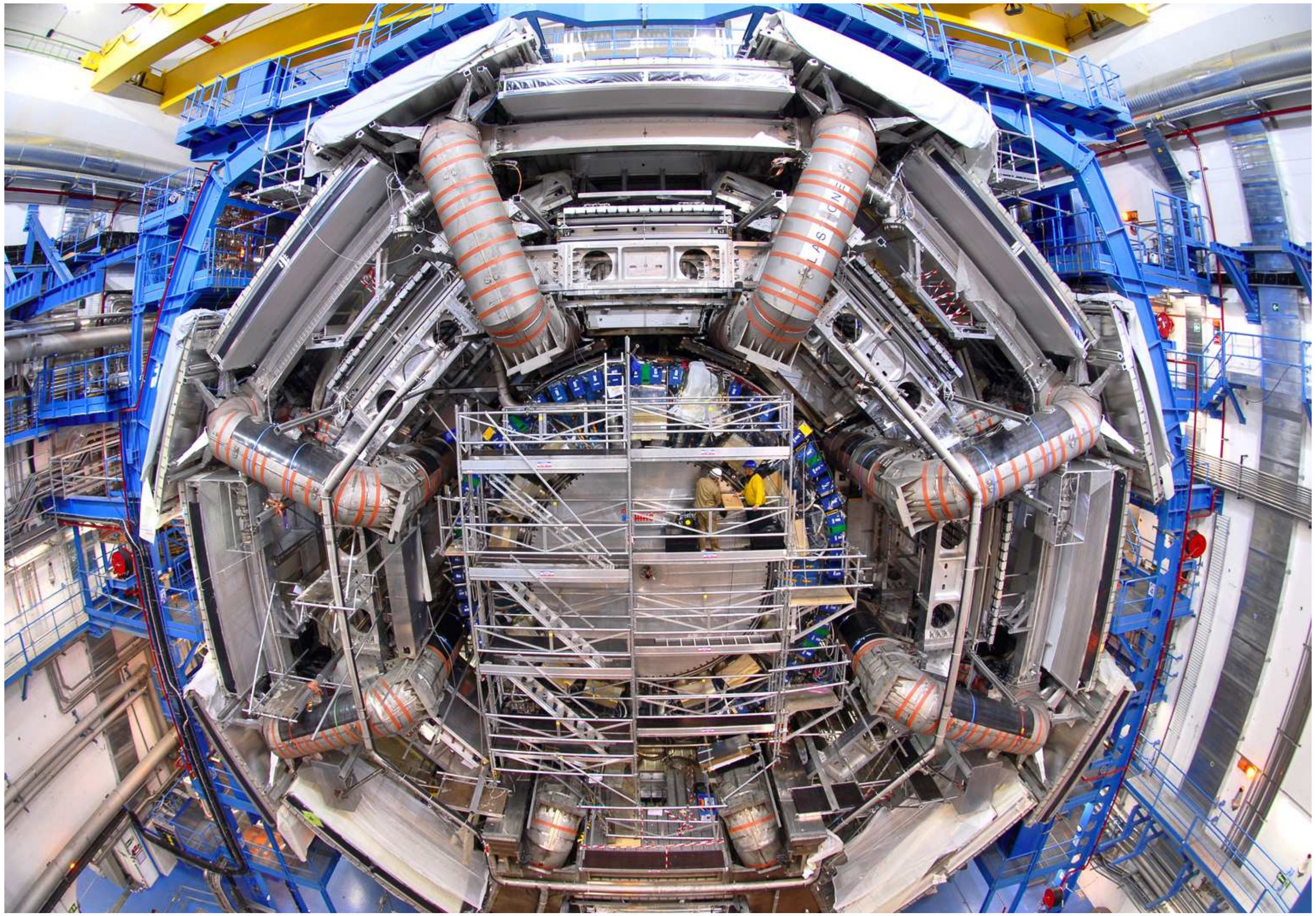
- r(t) determined from track residuals by **iterative algorithm** (autocalibration)
- Required accuracy: 20 μm
- **Autocalibration zones** are **chamber sized** (limited by angular acceptance)
- **Change** of maximum **drift time** from testbeam measurements: 70 ns$/\mathbf{B}_\perp^2 \rightarrow$ 500 μm
- Algorithm must **correct for inhomogeneous magnetic field**

- **Model**:
  $t(r, \mathbf{B}) \approx t(r, 0) + \mathbf{B}_\perp^2 \cdot f(v_{\mathbf{B}=0}, \mathbf{E})$
  (fit to testbeam data $\rightarrow$ accuracy of 1 ns)



Excellent agreement between measurement and expectation

Summary



Summary (1)

- Barrel muon spectrometer installation almost finished
  - Sector commissioning with cosmics will start in March
  - Preliminary commissioning showed no major problems
- Endcap muon spectrometer well advanced
  - All chambers at CERN and tested
  - 2 of 10 Big Wheels installed
  - Preliminary commissioning showed very good results
  - Toroids to be lowered in June / July

ATLAS Muon

Summary (2)

- System test of barrel muon spectrometer successful
  - Toroid at full field
  - Toroid Fast-Quench test
  - 1/4 sector of muon station tested
  - Trigger test (muon LVL1 with CPT, LVL2)
  - Very useful to study calibration of precision chambers
- Combined system test (with calorimeter) planned for March/April
- Beamline to be closed in August

ATLAS Muon spectrometer will be ready

to take data in November 2007

Thank you. . .

Giulio Aielli (INFN Roma II)

Christoph Amelung, Stephanie Zimmermann (CERN)

Gerjan Bobbink, Egge van der Poel, Jochem Snuverink (Nikhef)

Gabriella Gaudio (INFN Pavia)

Claudio Ferretti (University of Michigan)

Mauro Iodice, Fabrizio Petrucci (INFN Roma III)

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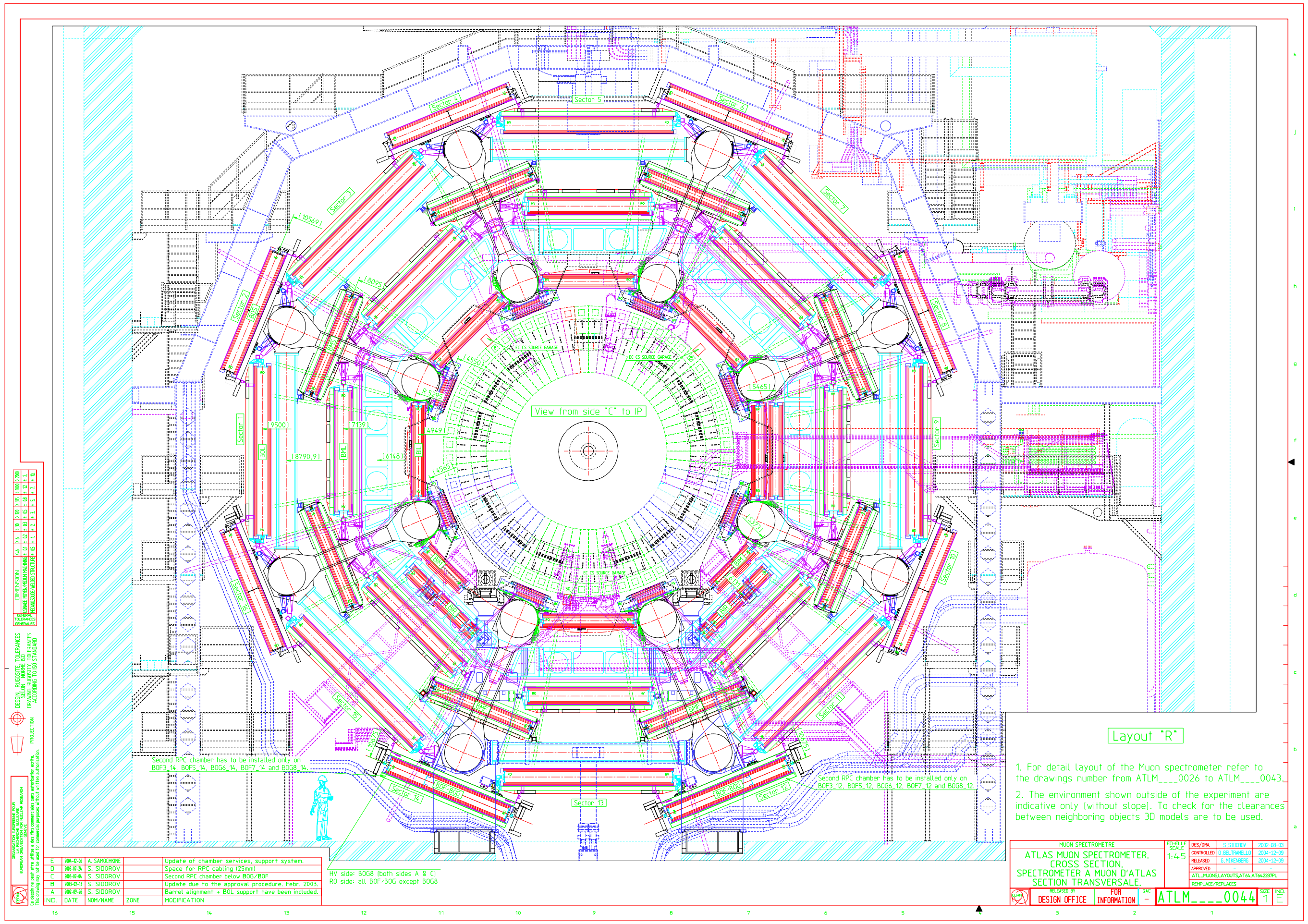
Oliver Kortner, Jörg v. Loeben (MPI Munich)

Witold Kozanecki, Rosy Nikolaidou (DAPNIA - CEN Saclay)

Giora Mikenberg (Weizmann Institute of Science)

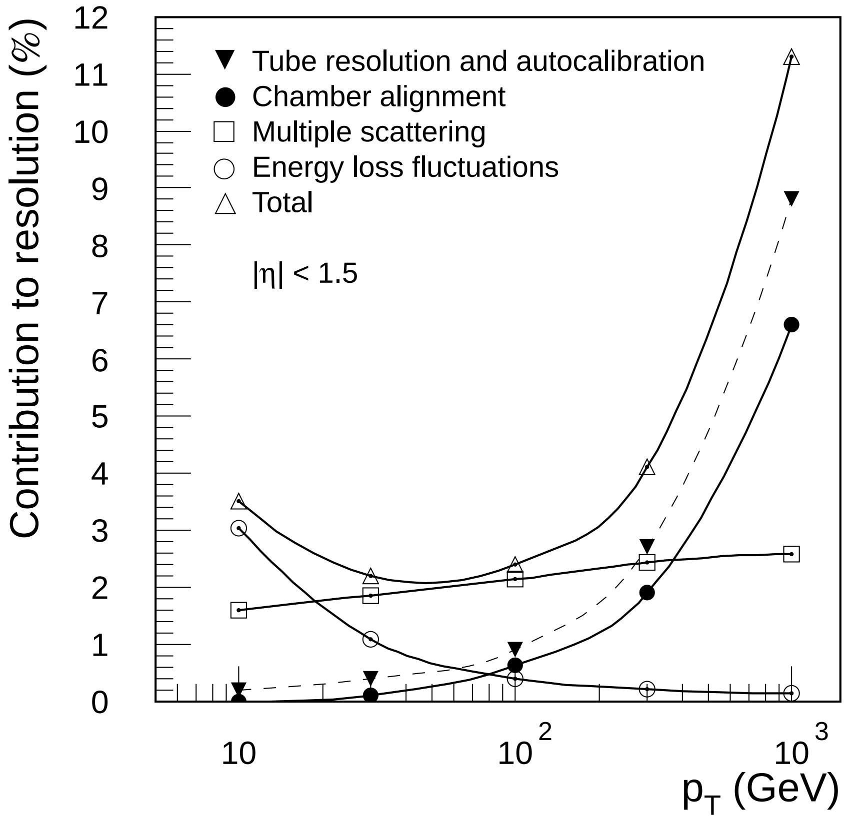
Sotirios Vlachos (National Technical University of Athens)

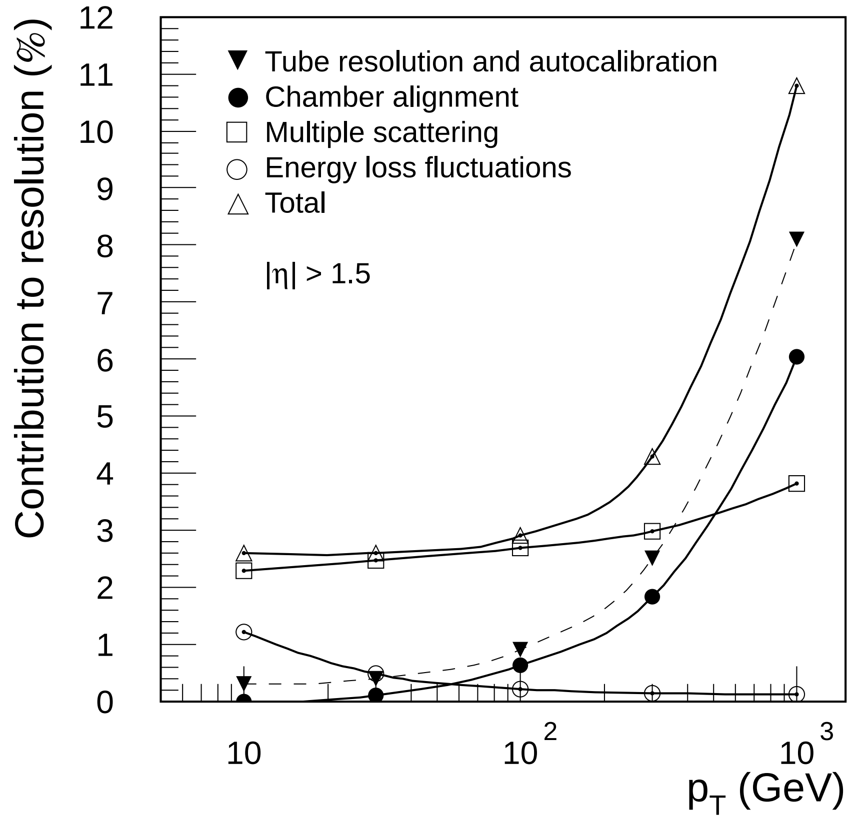
Additional Slides



ATLAS Muon Spectrometer (1)

Momentum Resolution





Calibration and alignment dominate for $p_T > 300$ GeV

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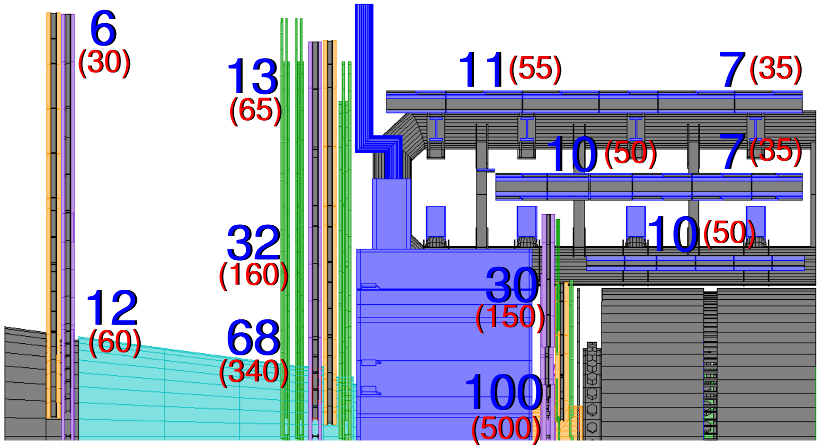
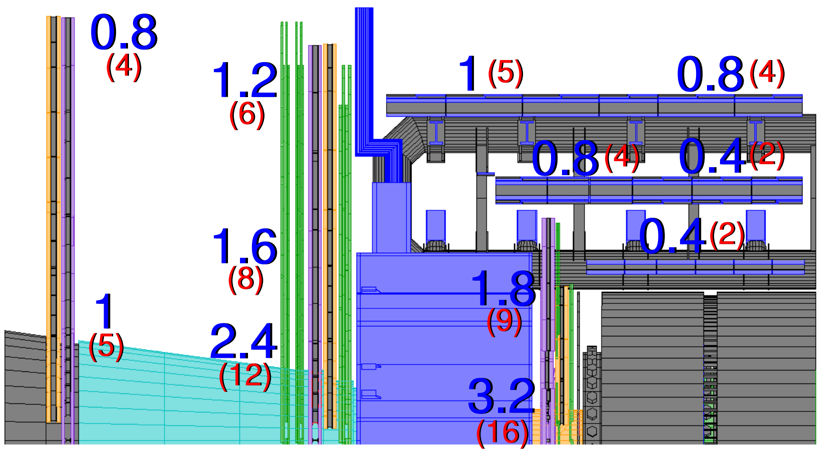
ATLAS Muon Spectrometer (2)

Radiation Levels at $10^{34}/(cm^2\ s)$

Rate (Hz/cm^2)



Occupancy (%)



Consequences

- High occupancy
  - Lower efficiency
  - Large read-out bandwidth required
- Degradation of resolution due to space charge fluctuations
- Aging
- Radiation damage to electronics

All systems designed to work at expected bgd $\times$ 5

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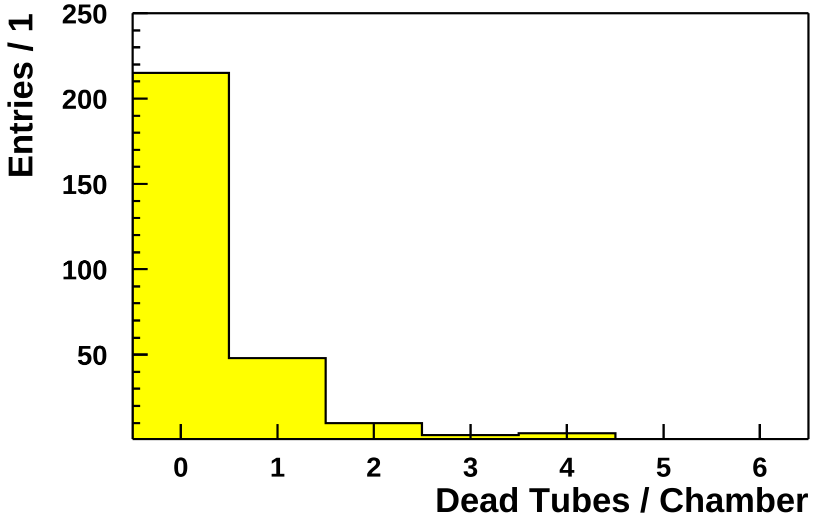
Results from Commissioning (2)

Number of Dead Channels

Type	Channels	Dead Channels	Percentage / %
Barrel MDT	184944	123	0.07
Barrel RPC η-strips	119904	884	0.74
Barrel RPC ϕ-strips	253440	842	0.33
Endcap MDT Big Wheel 1 A+C	147072	61	0.04
Endcap TGC Big Wheel 1 C	30000	5	0.06

Distribution of Dead Tubes in Middle and Outer Layer Barrel MDT Chambers



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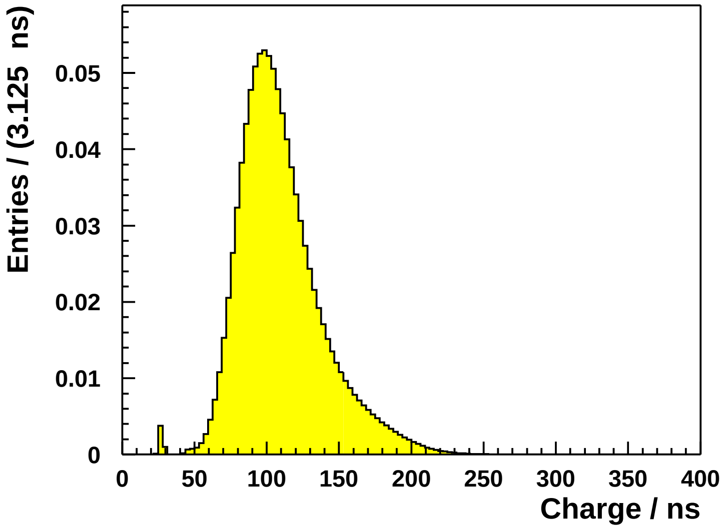
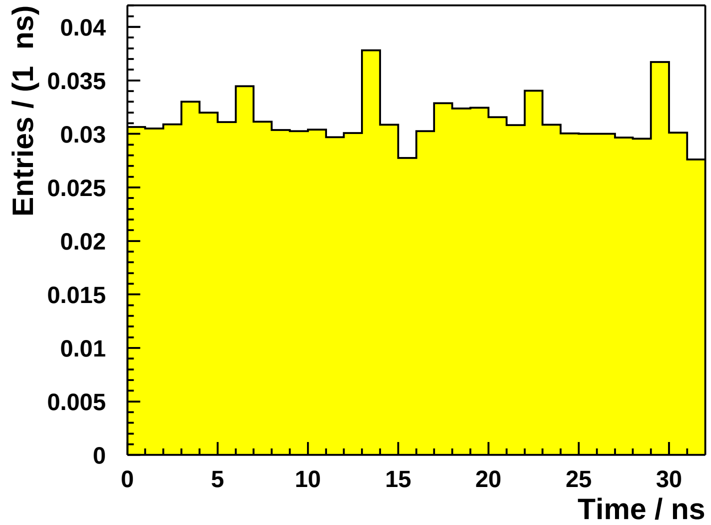
Cosmic Ray Certification (2)

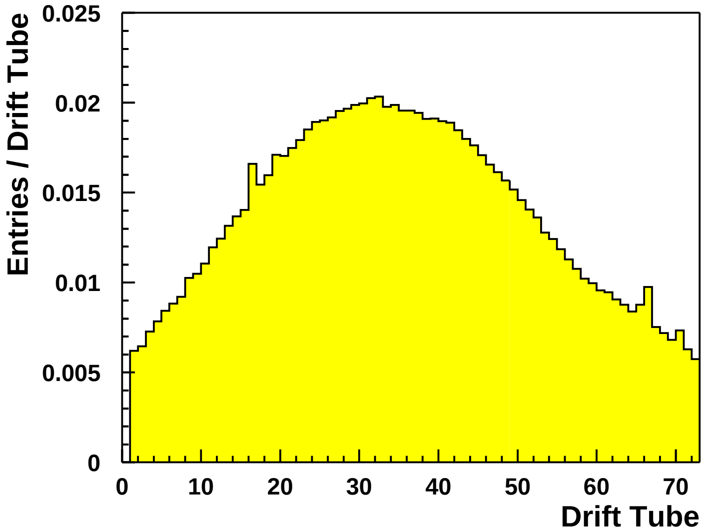
MDT ADC Spectra



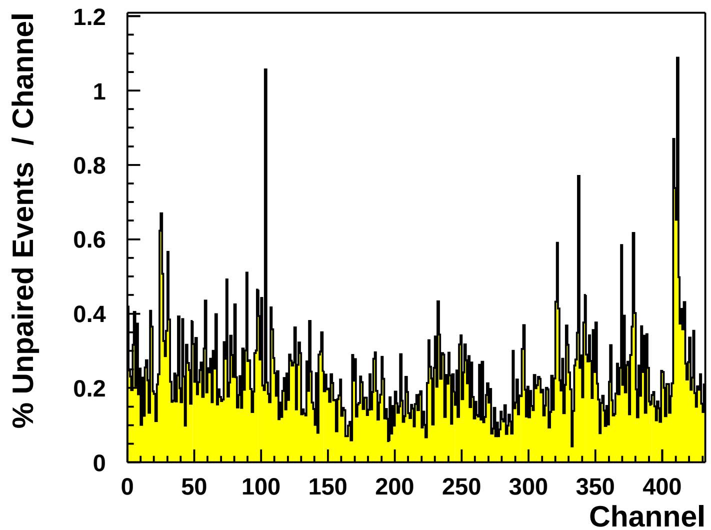
MDT TDC Fine Time Spectra



MDT Hit maps



MDT Unpaired Events



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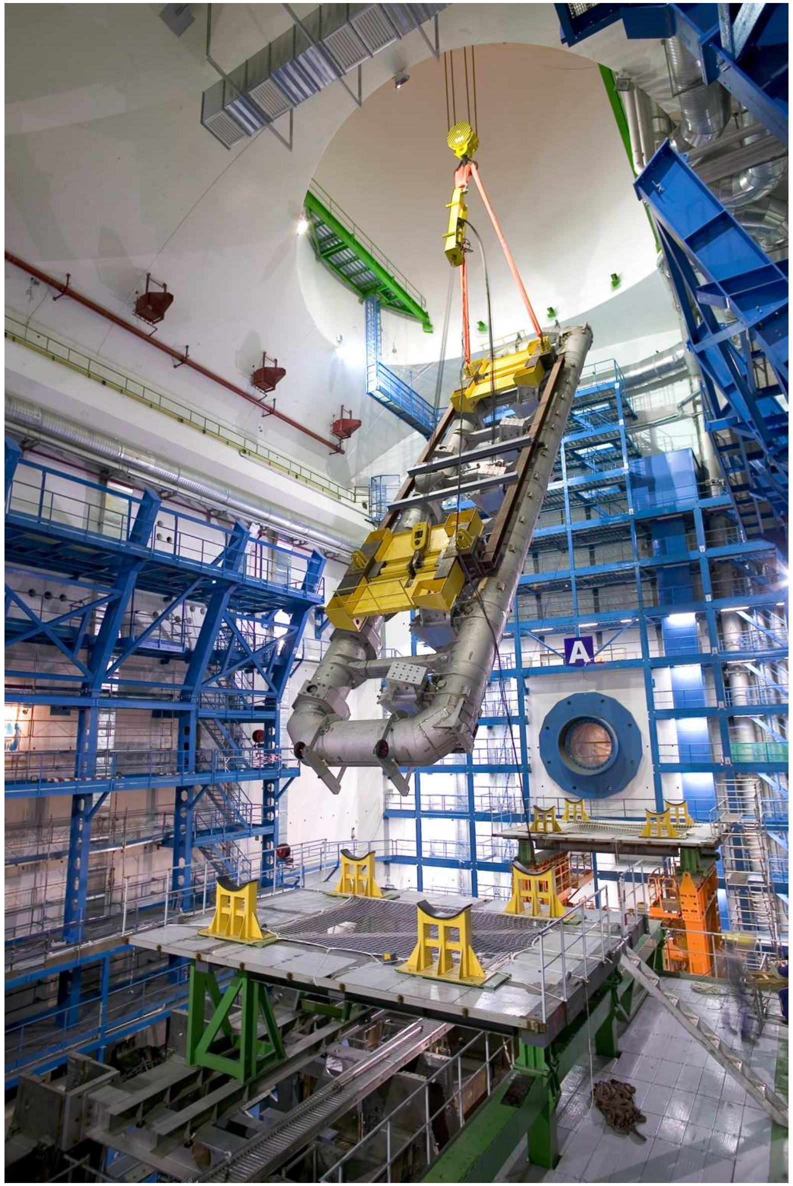
Barrel Toroid Installation



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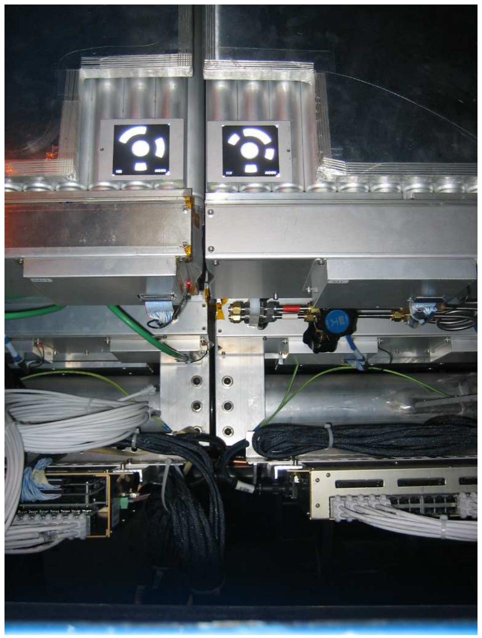
Barrel Installation (3)

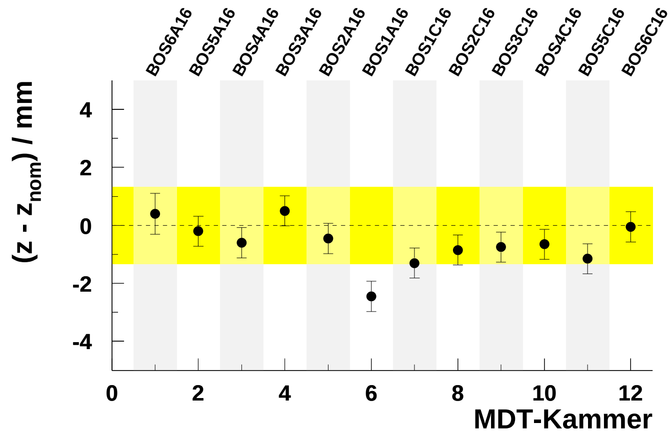
Station Positioning and Survey Results — An Example

- 2 of 4 bearings adjustable
- Final position fixed by 1 adjustable rail clamp
- Gap between stations: 8 mm

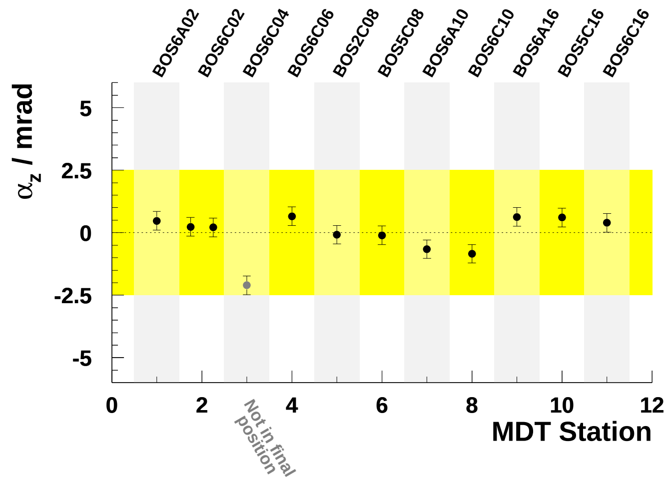


Positioning Rate:
Up to 4 stations / day

MDT Positions Sector 16



MDT Angle α_y



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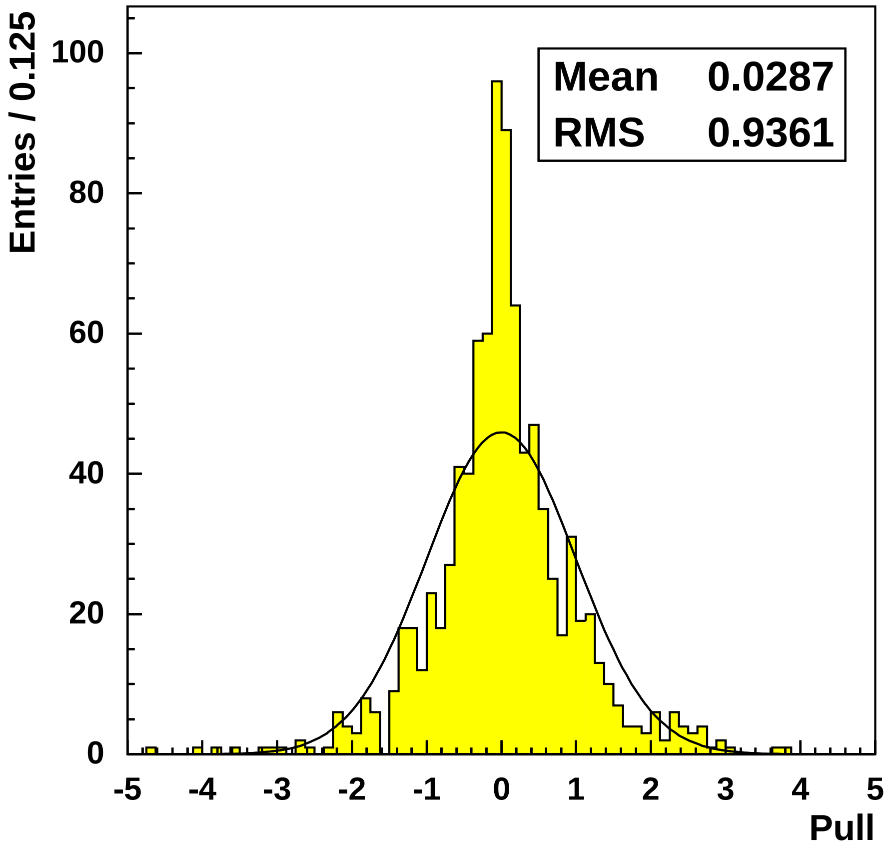
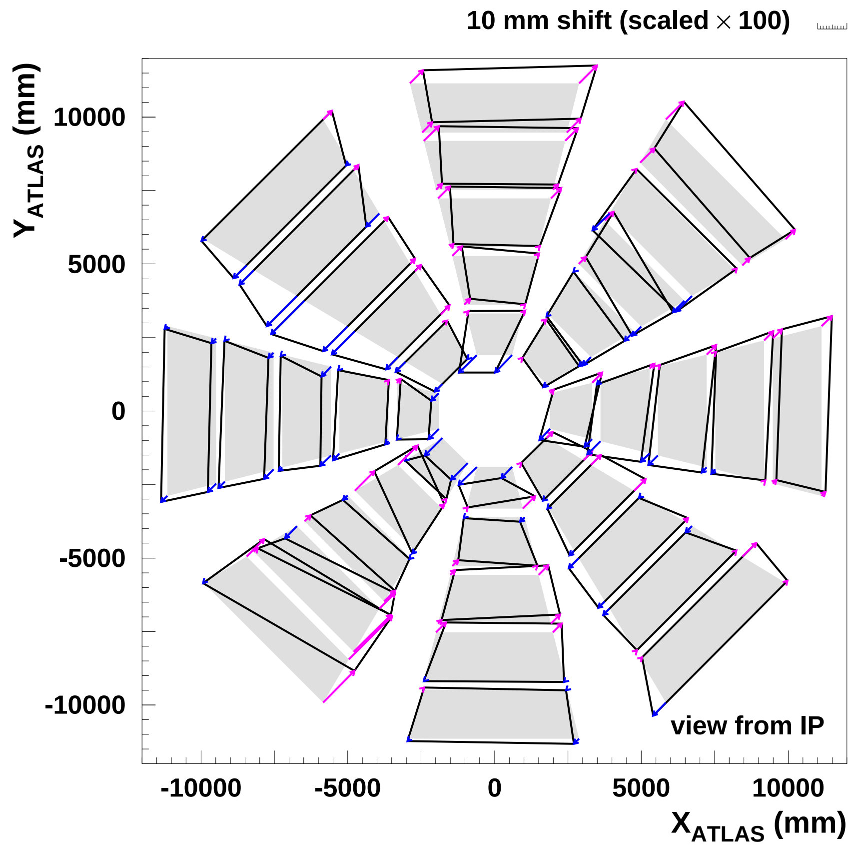
Endcap Alignment System (3)

Pull Distribution (lower 5 sectors)



Displacement perpendicular to Big Wheel plane



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Barrel Toroid Fast Quench Test

- Initiated if local loss of superconductivity in coils
- Energy dump / field breakdown in 60 s (normal ramp down: 3 h)
- Expected rate: 1 / year

Results

- Toroid OK
- Detector Safety System successfully used to cut low voltage power supplies, ramp down high voltage power supplies
- No dangerous chamber deformations measured
- Induced currents in cable loops negligible (due to routing)

Fast quench test successful
No damage to magnet or detector

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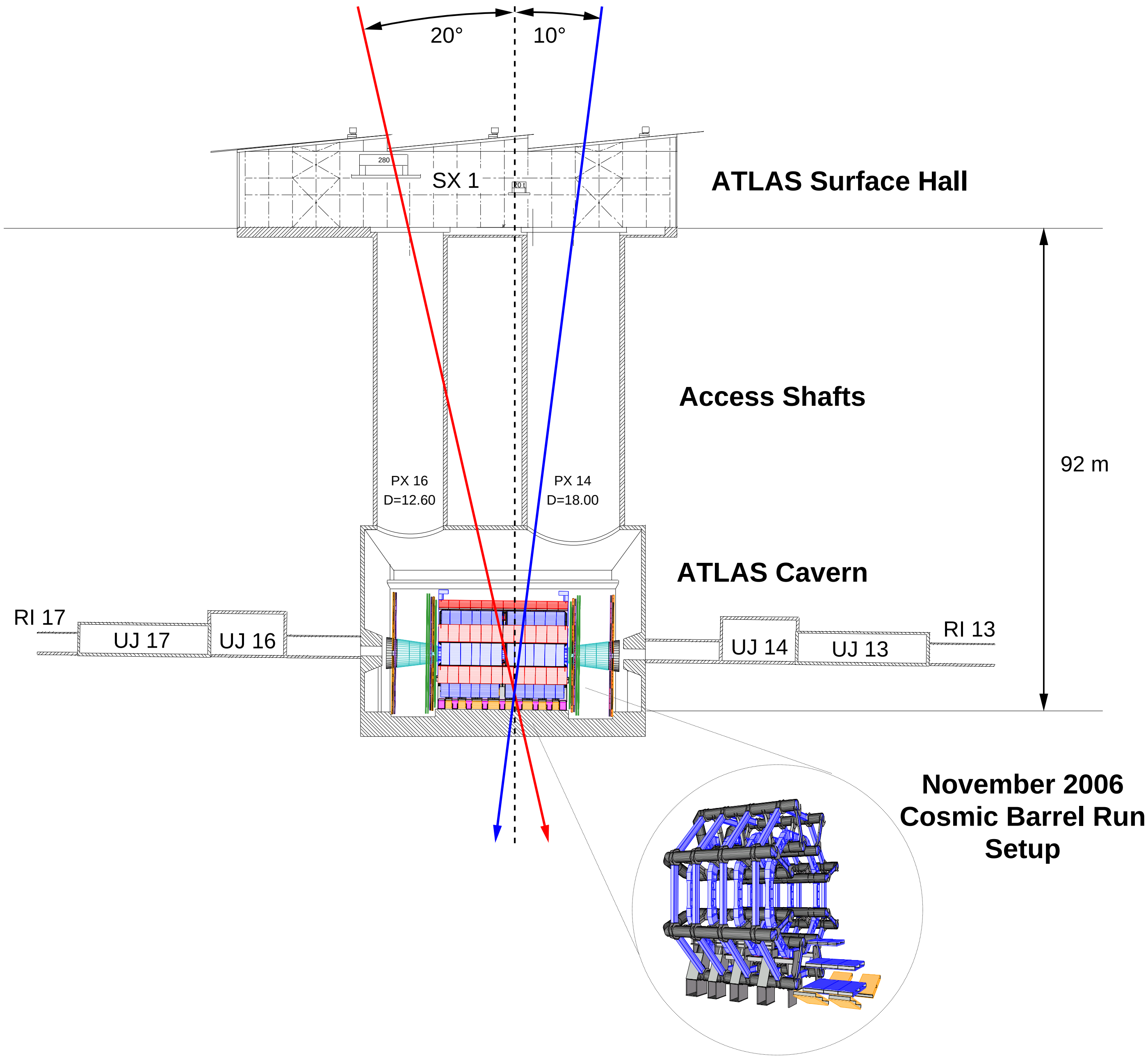
Geometry



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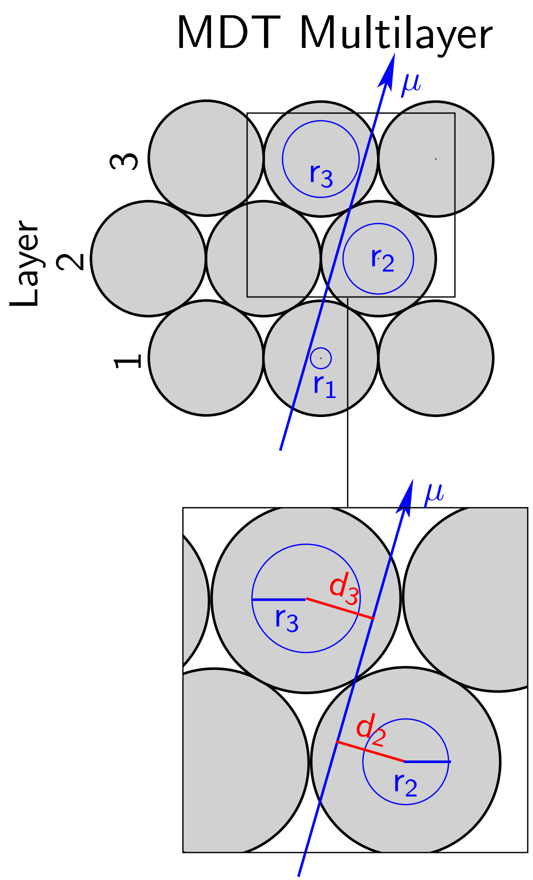
Autocalibration (1)

Autocalibration: Determination of the space-drift time relation r(t) without an external tracking reference

Needs: Initial space-drift time relation $r(t)_{init}$



Idea:

Use $r(t)_{init}$ to reconstruct straight segments in multilayers

Principle of the Autocalibration:

- d_k:= distance k-th anode wire $\leftrightarrow$ track
- $r(t_k)$:= drift radius of the the k-th hit
- Residual $\Delta(t_k) := r(t_k) - d_k$
- Use $\Delta(t)$ to improve $r(t)_{initial}$

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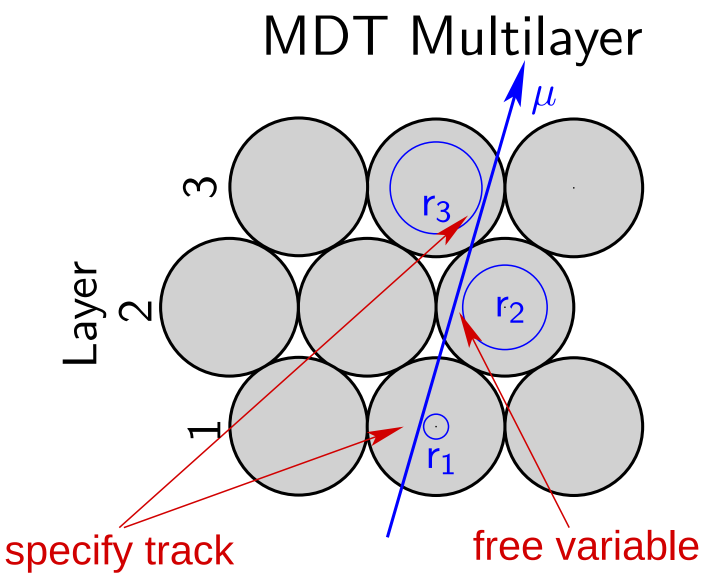
Autocalibration (2)

Semi-analytic Autocalibration

Residuals $\Delta(t)$ can be calculated analytically: $\Delta(\delta r(t_1), \delta r(t_2), \delta r(t_3))$

Problem:

For a chamber with three layers it is in general impossible to define all three variables $\delta r(t_k)$, for $k = 1..3$



Solution:

- Parametrize $r(t)$
- Take n tracks of different angles of incidence and obtain the parameters by minimizing:

$$\chi^2 = \sum_n \frac{[\Delta_{measured} - \Delta(\delta r(t_1), \delta r(t_2), \delta r(t_3))]^2}{\sigma^2}$$

- $r(t)_{new} = r(t)_{initial} - \delta r(t)$

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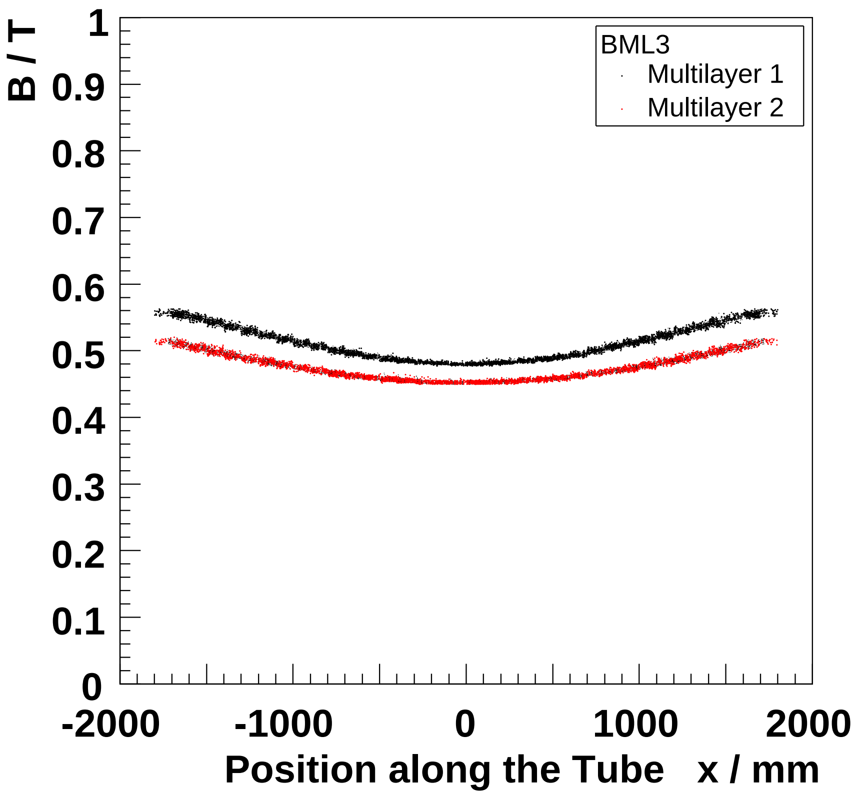
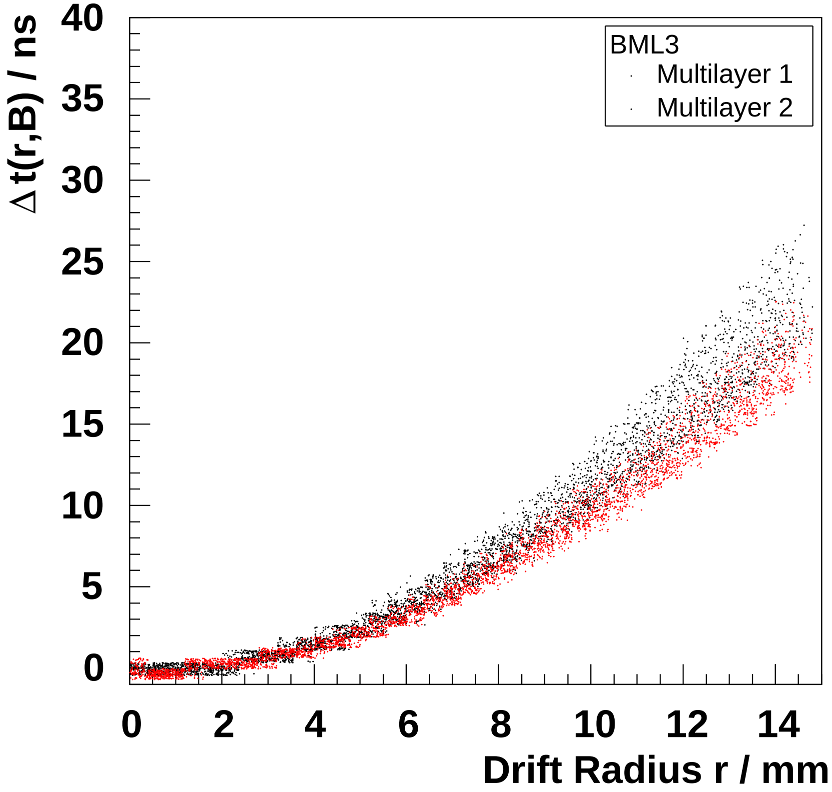
MDT Space-Drift Time Relation (2)

Magnetic Field



Influence on r(t)-Relation



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