Muon Detectors for High-Energy Hadron Colliders

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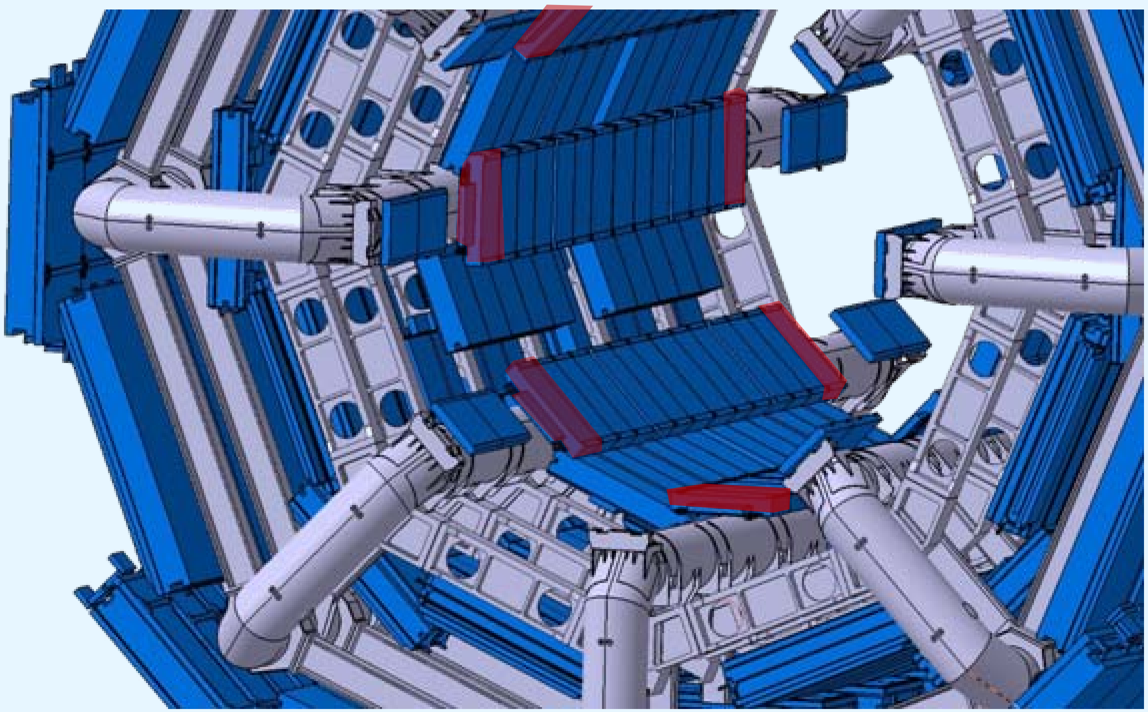
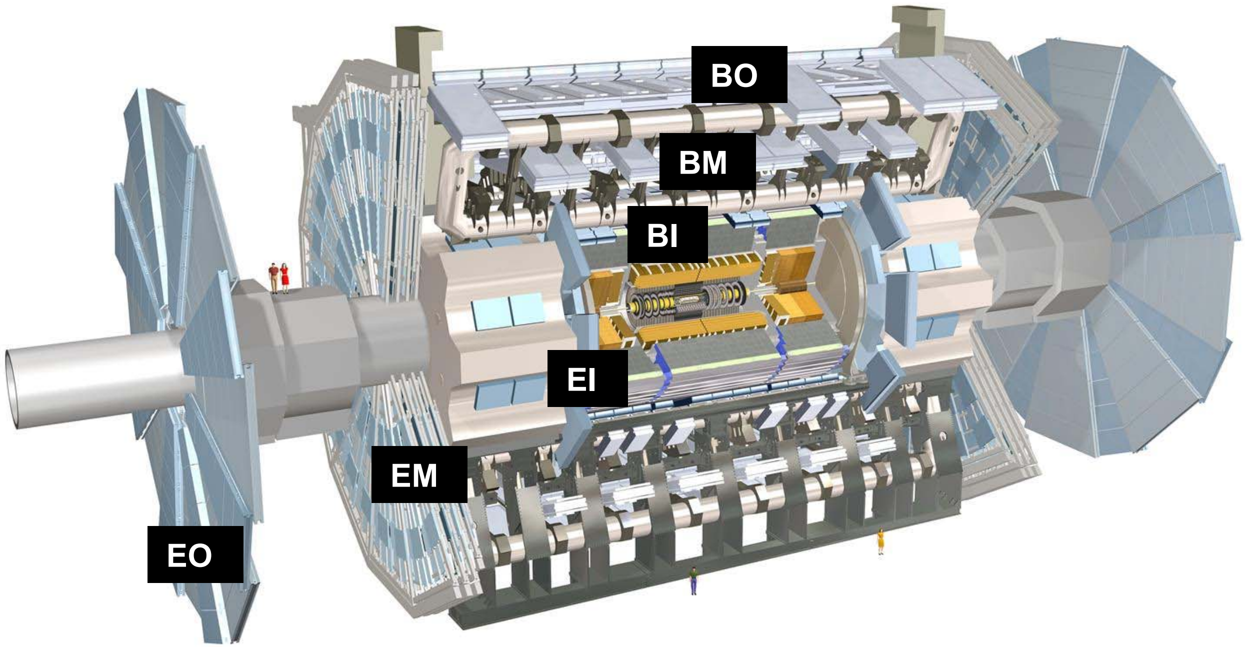


- Example:
  ATLAS muon spectrometer, upgrades for HL-LHC
- Applications for FCC-hh

Typical example: ATLAS Muon Spectrometer



- About 1200 Monitored Drift Tube (MDT) precision tracking chambers with in total 350k drift tubes: sense wire positioning accuracy of 20 μm and chamber spatial resolution of 35 μm.

  Track sagitta measurement in 3 detector layers.
  Optical alignment system with 30 μm sagitta correction accuracy.

- Combined with 600 RPC (double gas gaps, barrel BM, BO) and 3600 TGC (endcaps) trigger chambers for L1 muon trigger, BCID and 2nd coord.measurement (< 10 ns time and order cm spatial resolution).

- High neutron and gamma background rates: up to 400 Hz/cm^2 in EI MDTs at LHC design luminosity.

ATLAS Muon System Upgrade for HL-LHC

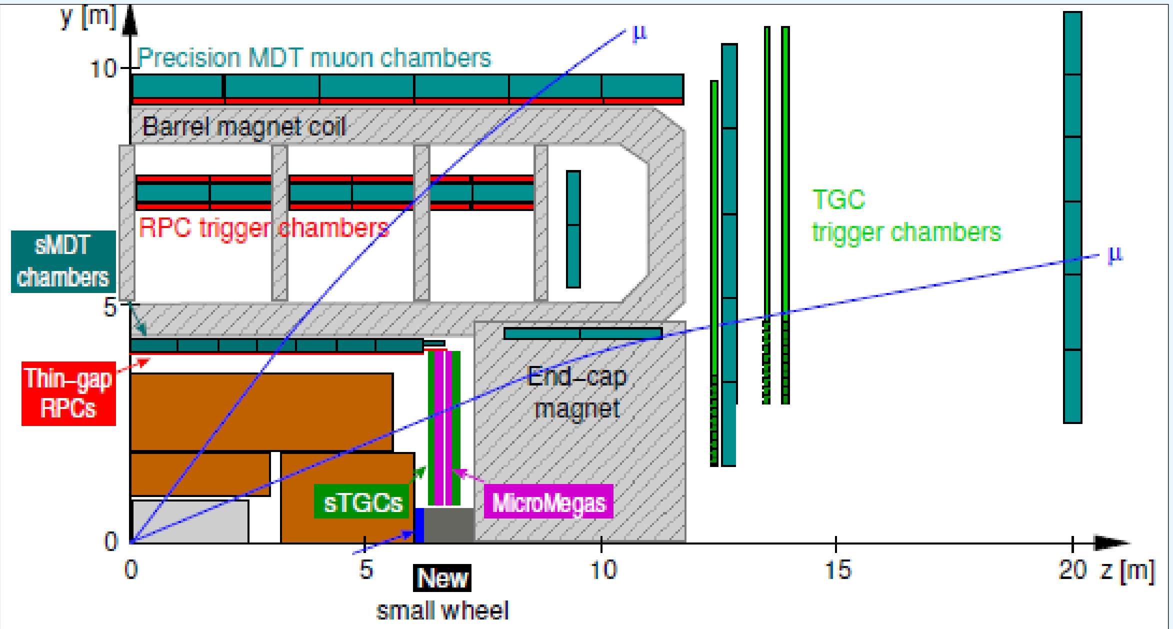
At HL-LHC: about 7 times higher background rates:

1 Rate capability of the MDT detectors in the inner endcap layer (EI)

2 Lifetime of the RPC chambers in the barrel spectrometer

3 Higher momentum resolution of the 1st level muon trigger (close to offline)

4 Increased barrel trigger coverage



→ Replacement of EI layer with tracking detectors with higher rate capability (Micromegas) and with trigger chambers with higher spatial resolution (sTGCs), planned already for 2019-20 shutdown.

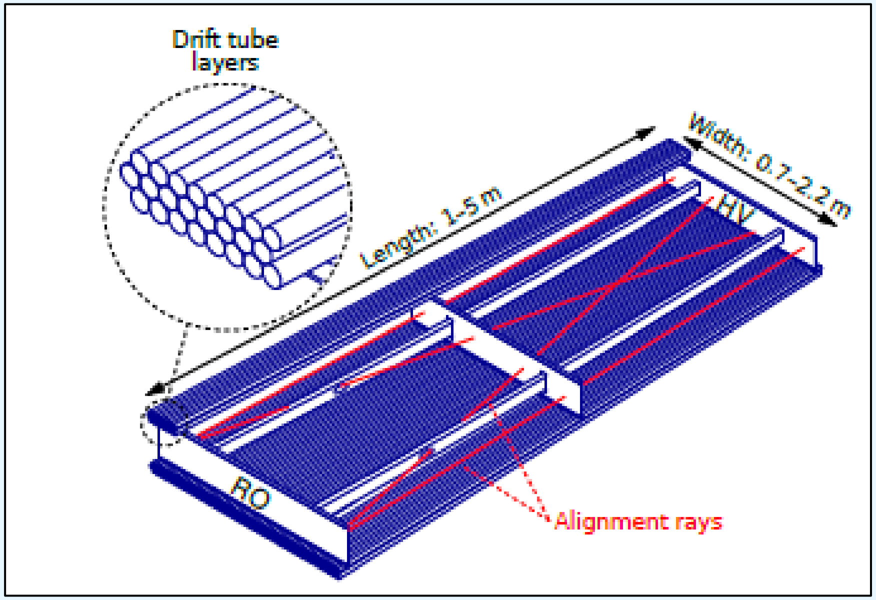
HL-LHC upgrades 2024-2026 shutdown:

→ Additional trigger chambers in the inner barrel layer with increased lifetime (thin-gap RPCs), combined with new small-diameter MDT chambers (sMDT).

→ Use of the MDT chambers in the 1st level trigger: muon track trigger within 6 μs available latency.

Developments at MPP

Monitored Drift Tube (MDT) Chambers



- Aluminum tube diameter: 30 mm
- Drift gas: Ar:CO_2 (93:7) at 3 bar
- Gas gain: 20000
- Drift tube resolution: 80 μm
- Wire positioning accuracy: 20 μm
- 2 x 3 tube layers
- Chamber resolution: 35 μm

Small-Diameter Muon Drift Tube (sMDT) Chambers

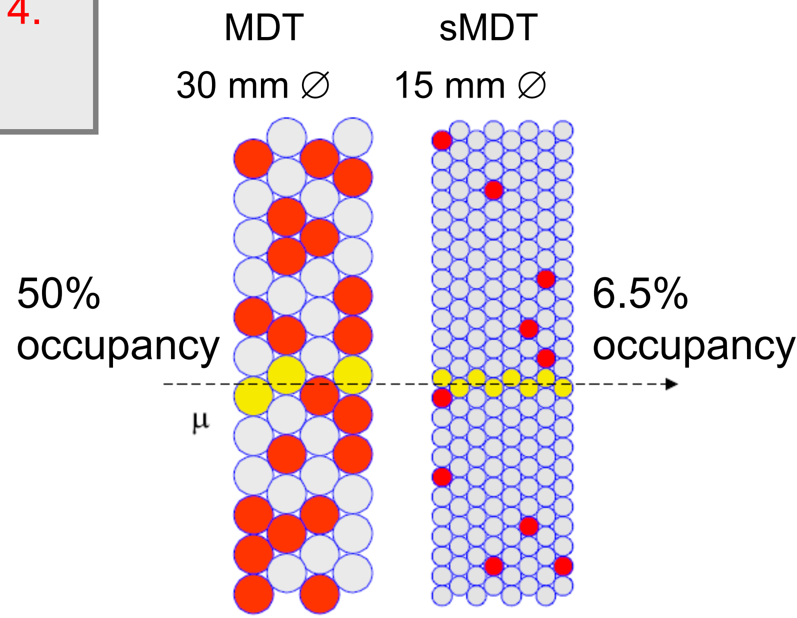
By reducing the tube diameter from 30 mm (MDT) to 15 mm (sMDT) at otherwise the unchanged operating conditions ($Ar:CO_2$ (93:7) at 3 bar, gas gain 20k, i.e. voltage 3070 V):

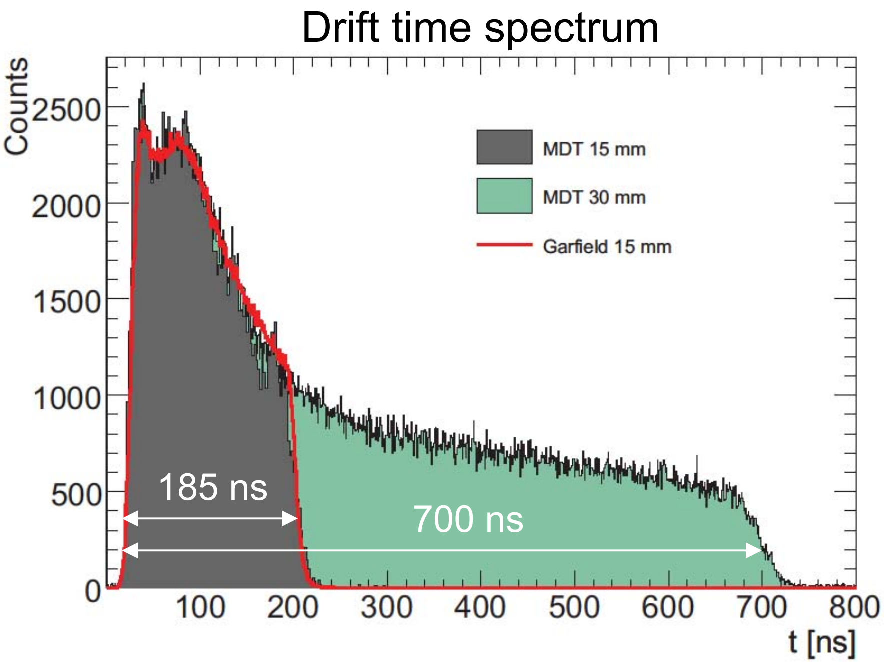
- 8 x lower background occupancy

  (4 x shorter maximum drift time, 2 x smaller tube cross section).

- reduce electronics deadtime (≈ max. drift time) by at least factor 4.

⇒ 10 x higher rate capability of sMDTs compared to MDTs.





Also:

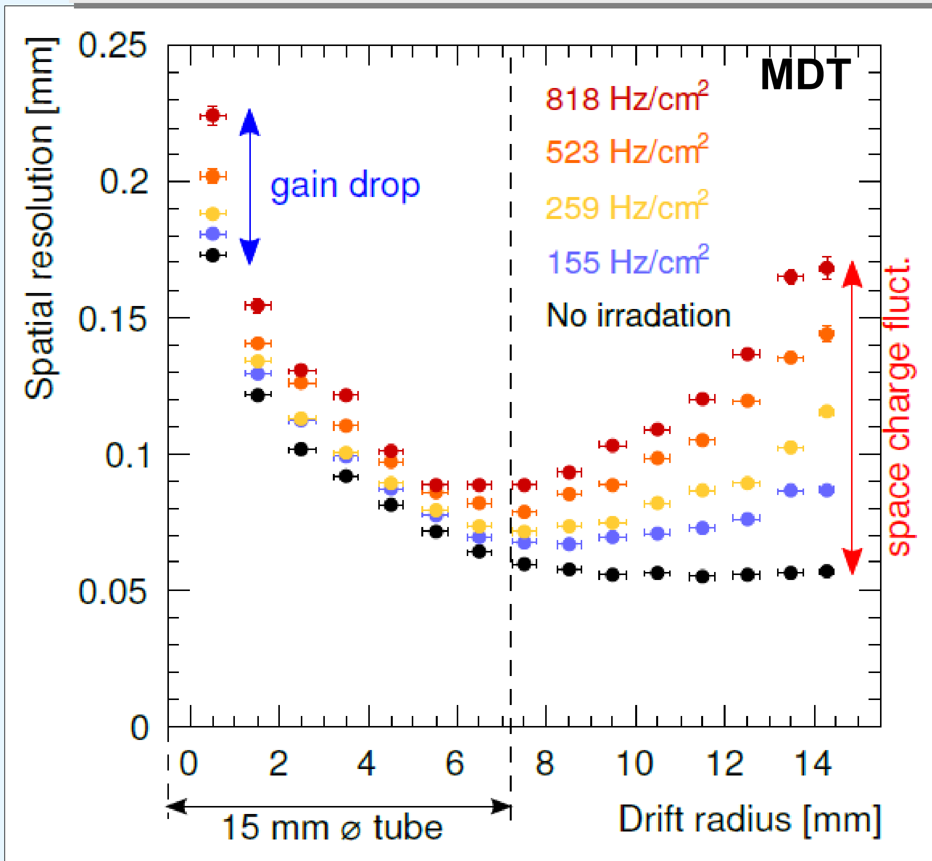
twice as many tube layers fit into the same available detector volume.

Space Charge Effects

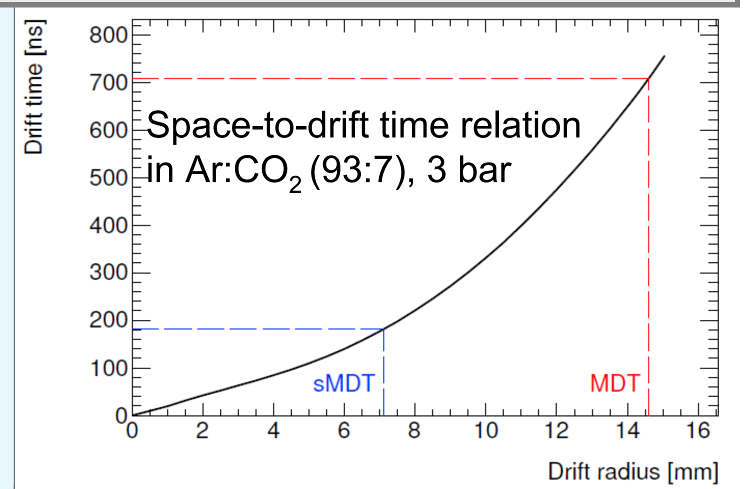
Why 15 mm tube diameter?

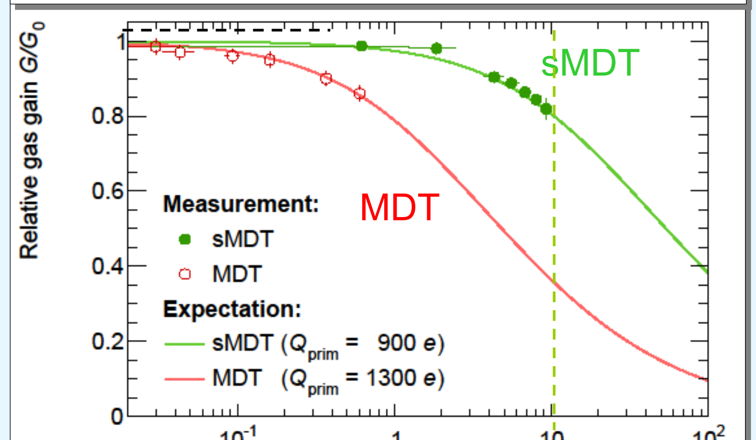
Space charge effects due to background radiation are strongly reduced in sMDT tubes:

- Effect of space charge fluctuations eliminated for r < 7.5 mm (almost linear r-t relation).
- Gain loss suppressed proportional to r^3.



Measurements performed at the CERN Gamma Irradiation Facility



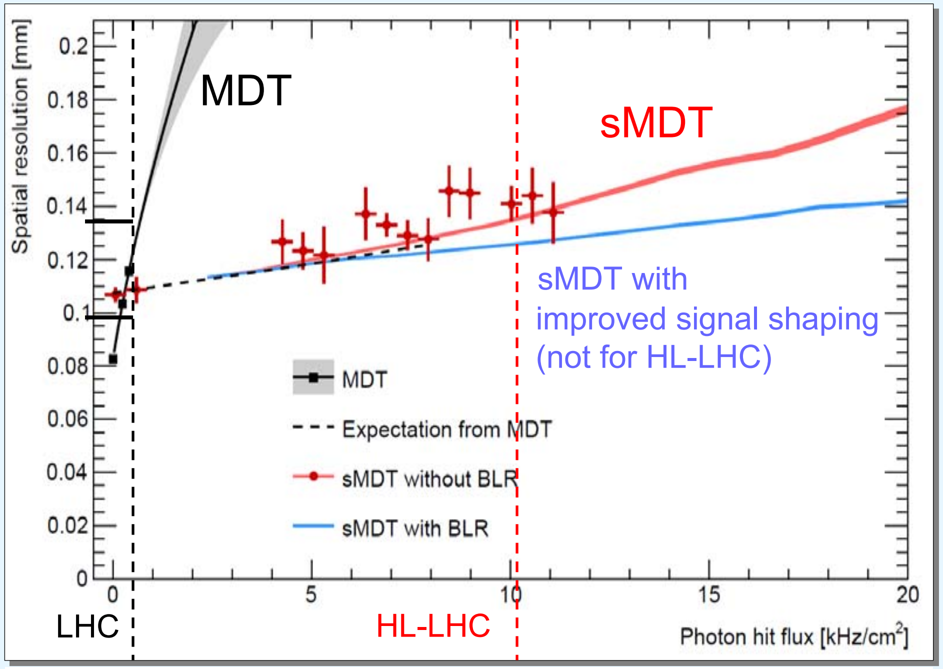


Max. rates in EI at HL-LHC

Rate Capability of sMDT Drift Tubes

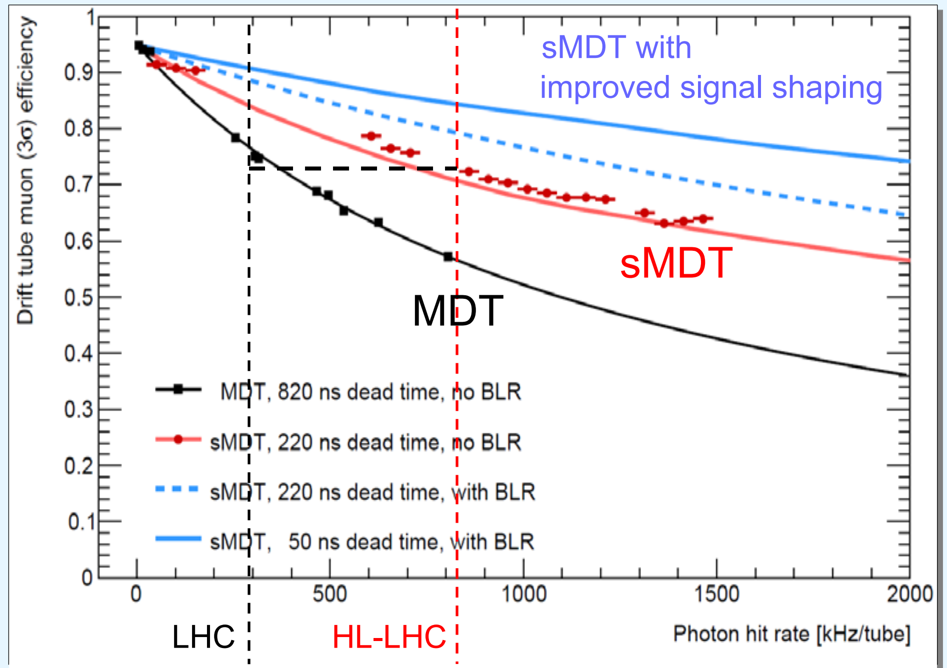
Test under γ irradiation in a muon beam at CERN with standard ATLAS readout electronics

Average spatial resolution of drift tube



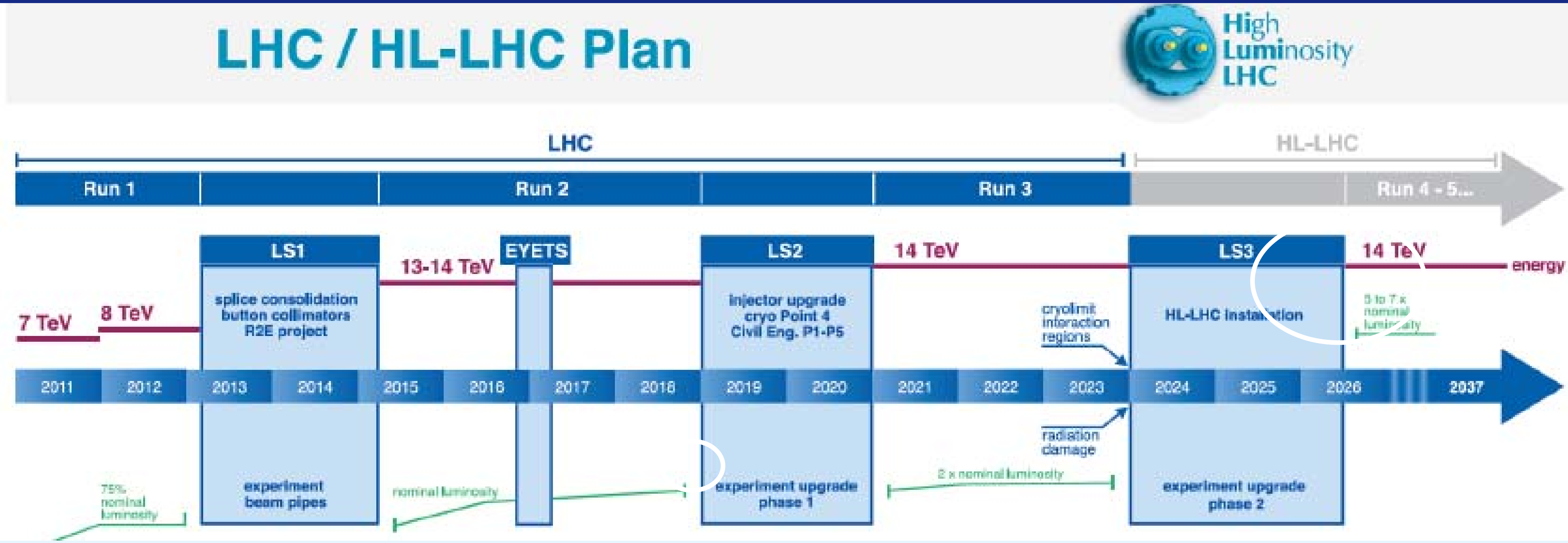
max. background flux: in EI layer

Muon efficiency of drift tube



max. background hit rates: in EI layer

ATLAS Barrel Muon Chamber Upgrades



April 2014:
2 sMDT + RPC chambers
to improve acceptance and momentum resolution in the bottom barrel sector.
In operation since Run 2.

Jan. 2017:
12 sMDT chambers
to improve the momentum resolution (by factor of 2 at 1 TeV) in the detector feet.

2019-20: BI 7-8
16 sMDT + 32 RPC chambers
to improve the trigger selectivity and the rate capability in the barrel inner layer.
Pilot project for phase 2 upgrade.

New Small Wheels
to increase rate capability of tracking and trigger detectors and trigger p_T resolution together with MDT-based trigger.

2024-26: BI 1-6
96 sMDT + 276 RPC chambers
for the barrel inner layer to increase the robustness of the barrel muon trigger system.

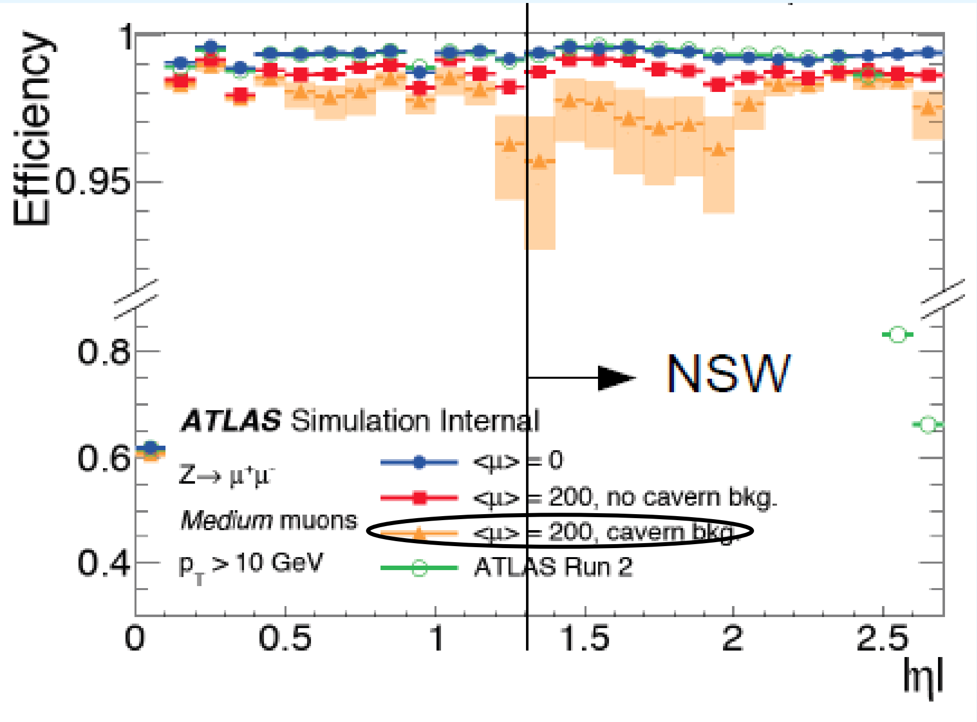
Use of (s)MDT chambers for the 1st level muon trigger
to increase p_T resol. and selectivity.

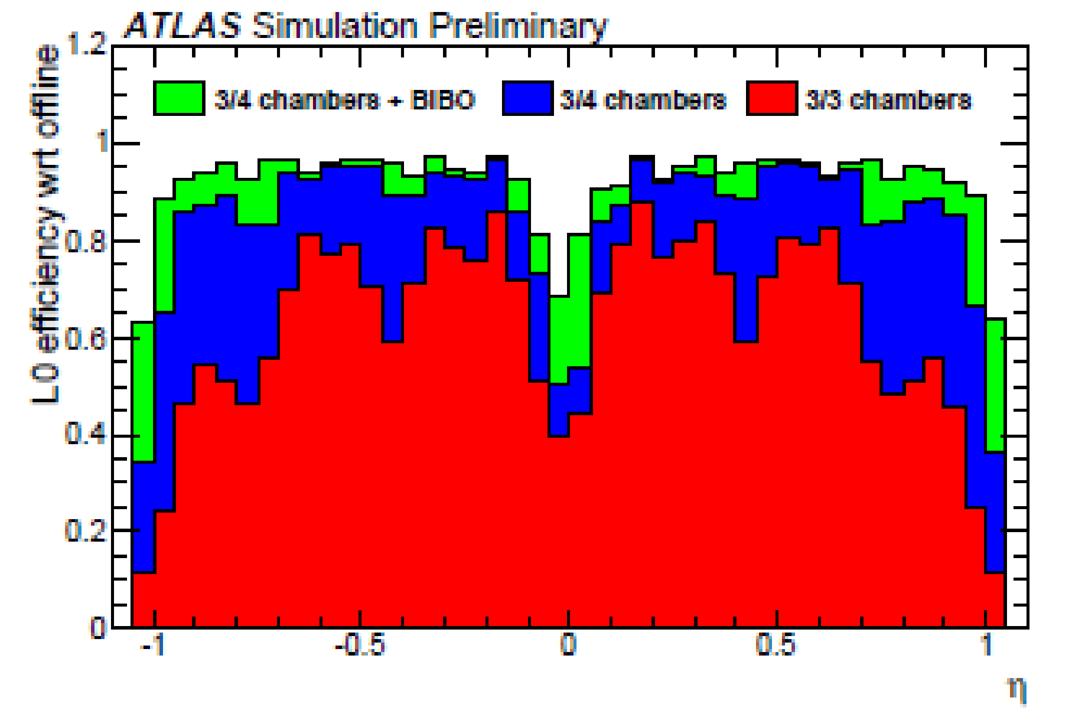
New MDT on-chamber electronics
because of 10 x higher trigger rate and MDT-based trigger.

Improvement of the Muon Trigger Efficiency

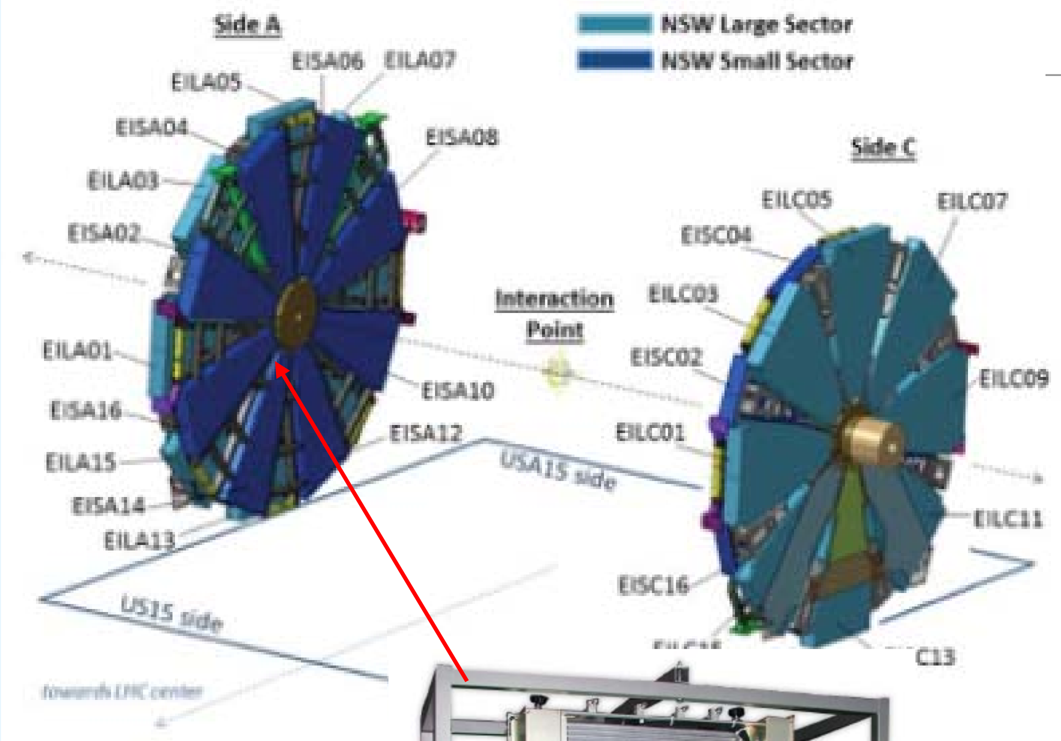
Endcaps: recovery of MDT efficiency loss due to cavern background radiation by new EI layer (New Small Wheel NSW)

Barrel: improved coverage and efficiency and redundancy w.r.t. aging of present RPCs

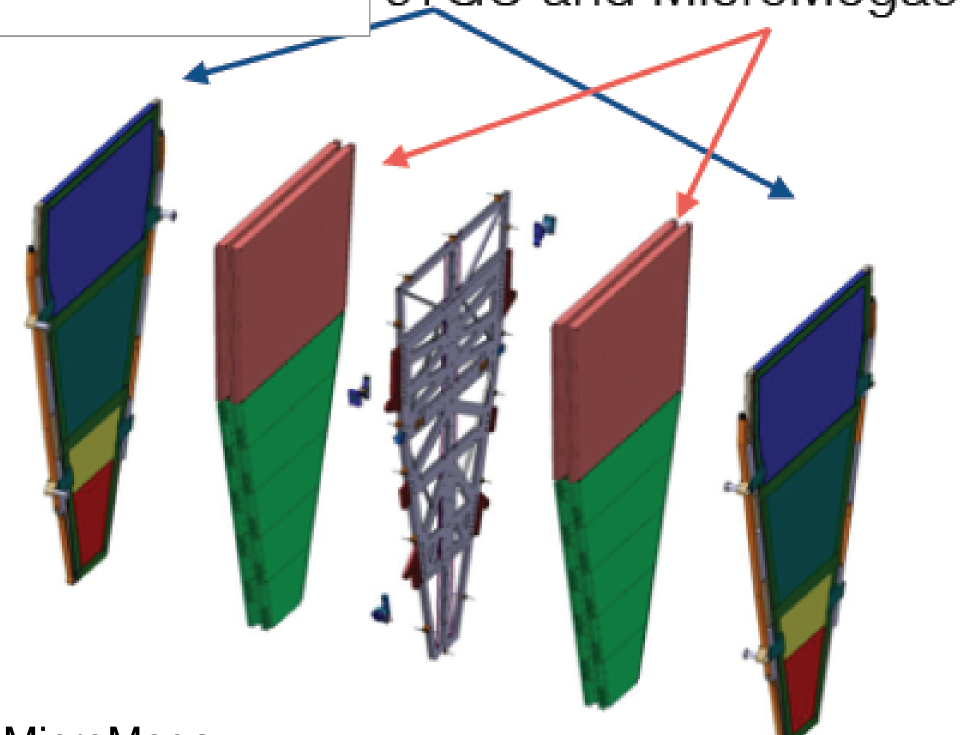




New Small Wheels (EI Layer)

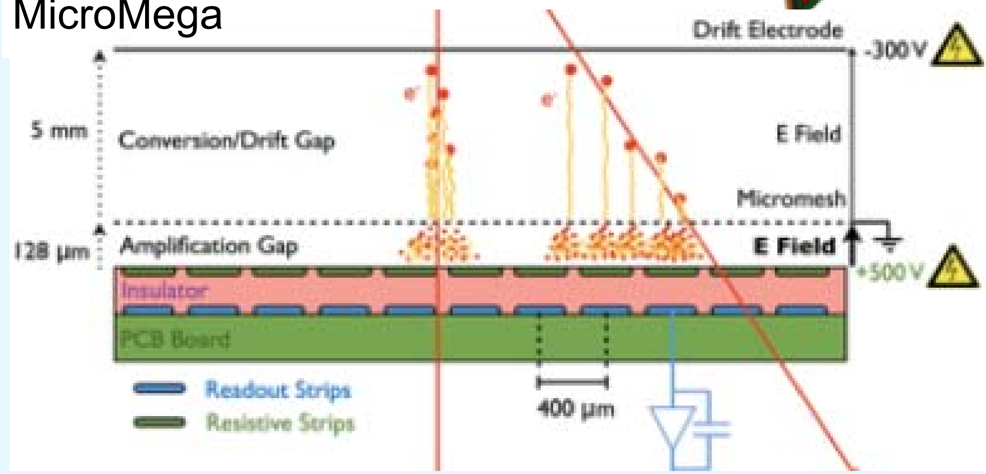


sTGC and MicroMegas



Full-scale sMDT prototype 2010

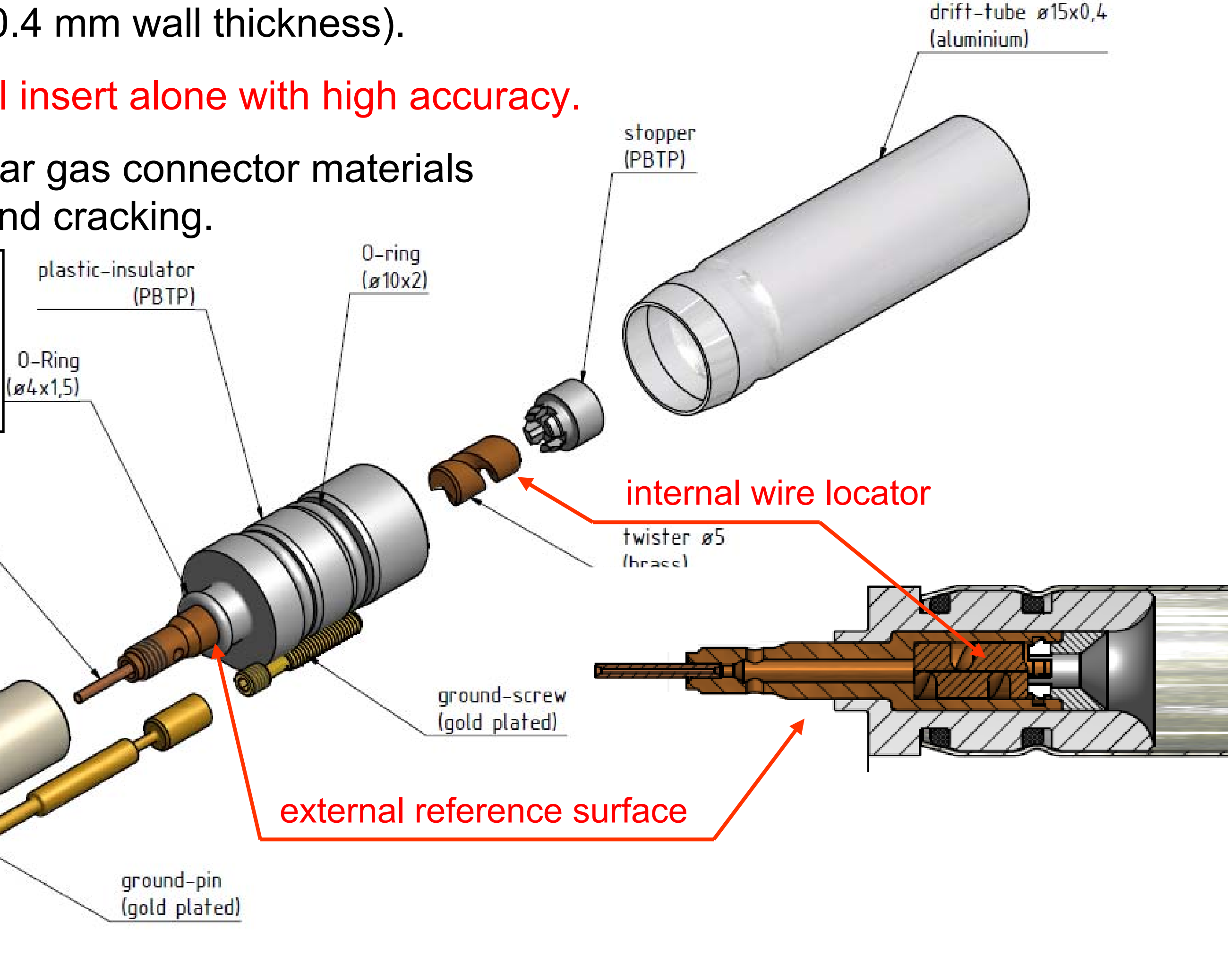
MicroMega

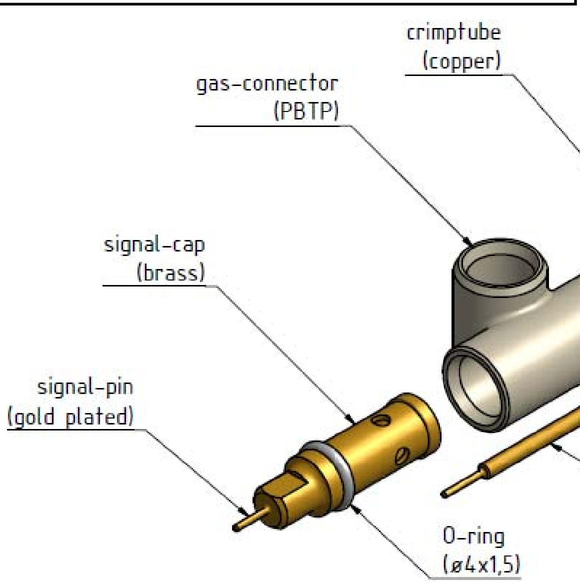


sMDT Chamber Design

- Design and assembly procedures optimized for mass production: assembly of a chamber/day.
- Simple, low-cost drift tube design ensuring high reliability.
- Industry-standard aluminum tubes (0.4 mm wall thickness).
- Sense wire position defined by metal insert alone with high accuracy.
- Injection molded endplug and modular gas connector materials selected to prevent outgassing and cracking.

- No aging observed up to 9 C/cm charge accumulated on the wire (MDT requirement: 0.6 C/cm).



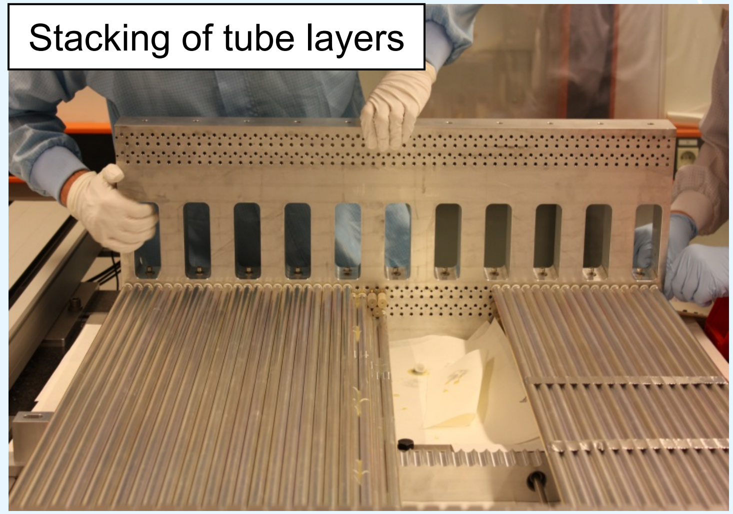


Automated Drift Tube Assembly

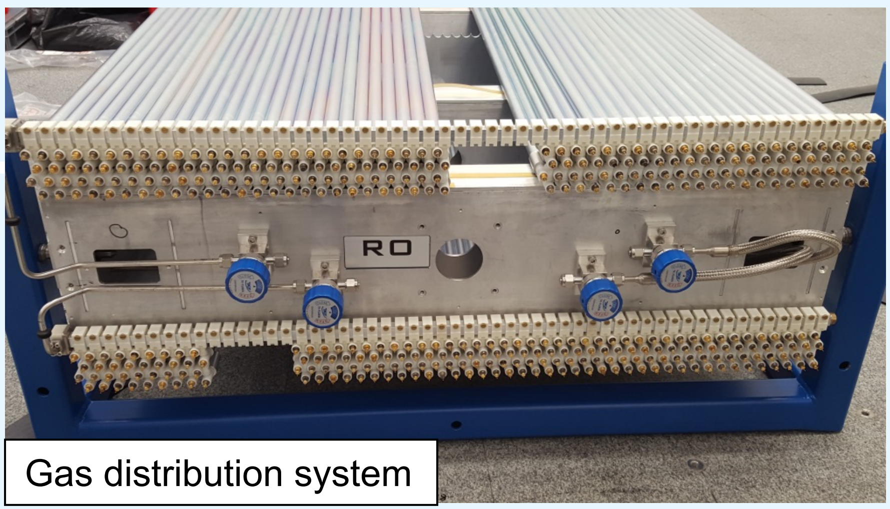
Design for mass production of chambers large numbers of tube layers:

Assembly within one working day independent of the number of layers.

Endplug insertion in jigging holes



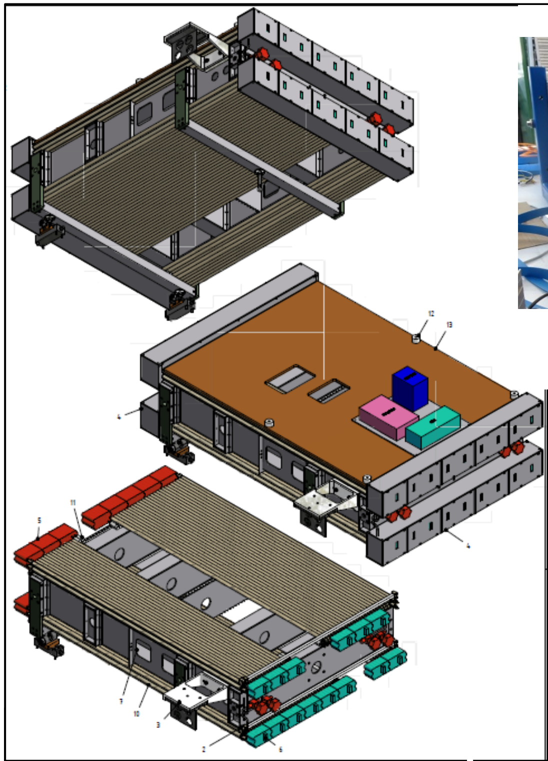
Stacking of tube layers

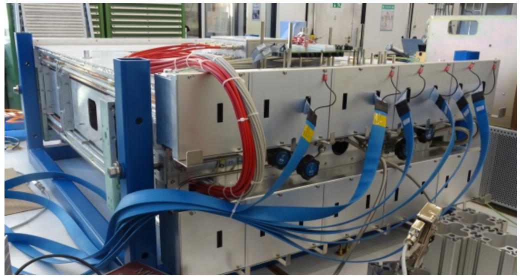


Gas distribution system

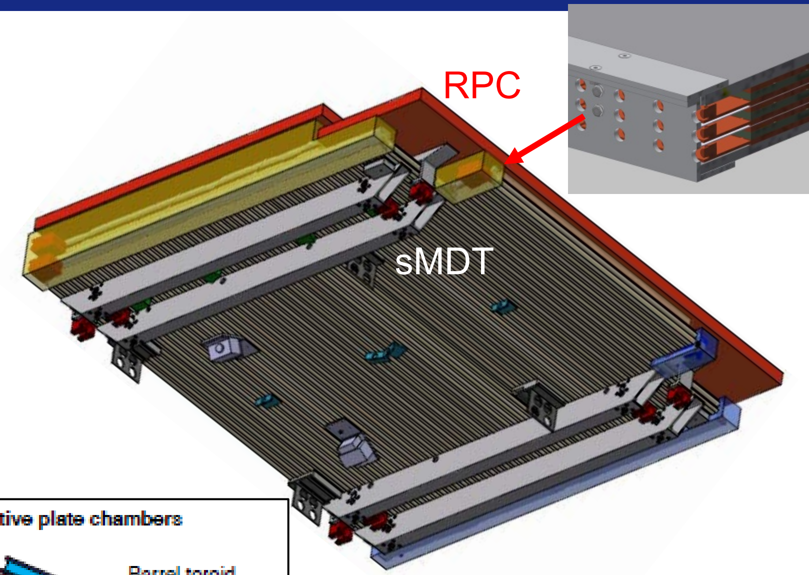
Completed BMG chambers

New sMDT and RPC Chambers for ATLAS

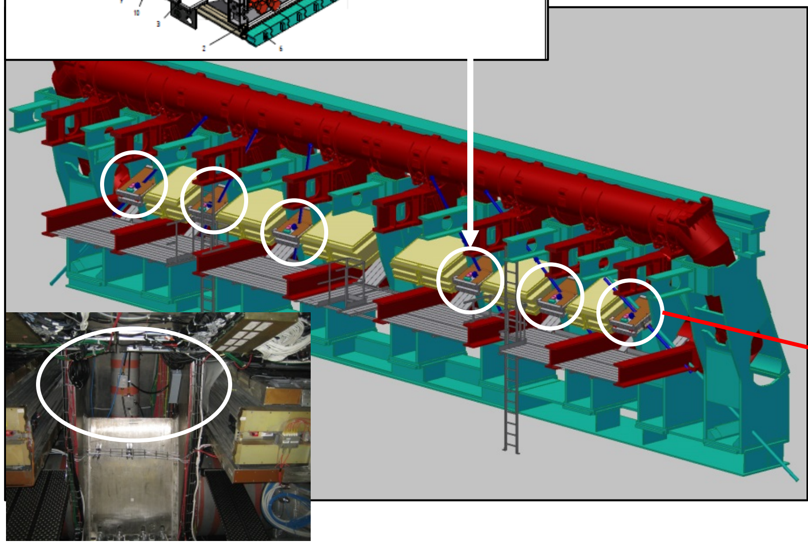


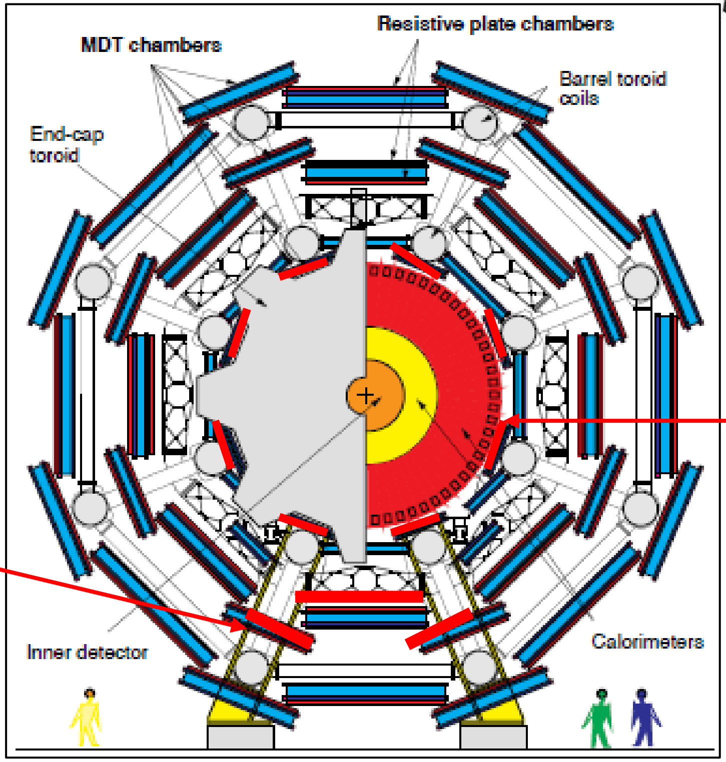


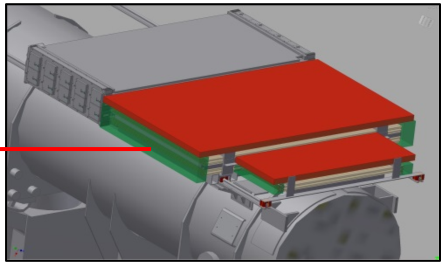
Construction of 12 chambers 2016.
for Installation in the detector feet
in the winter shutdown 2016/17



16 sMDT + triple thin-gap RPC for ends of the BI layer

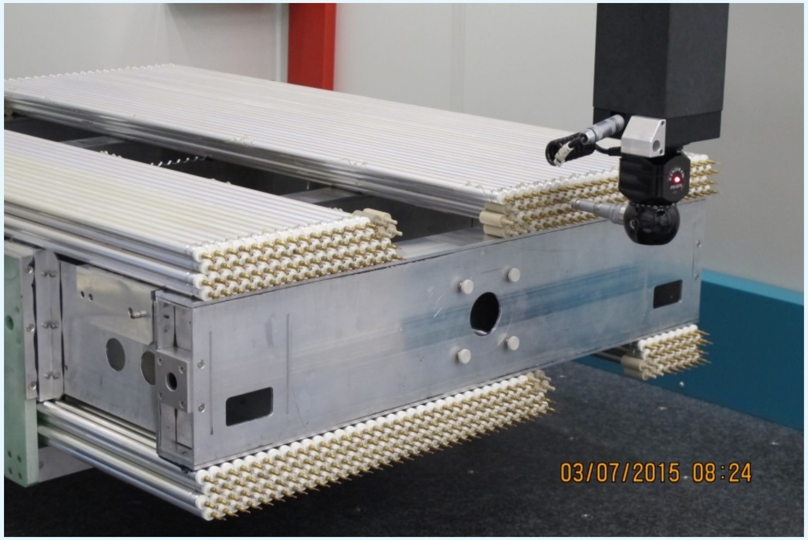






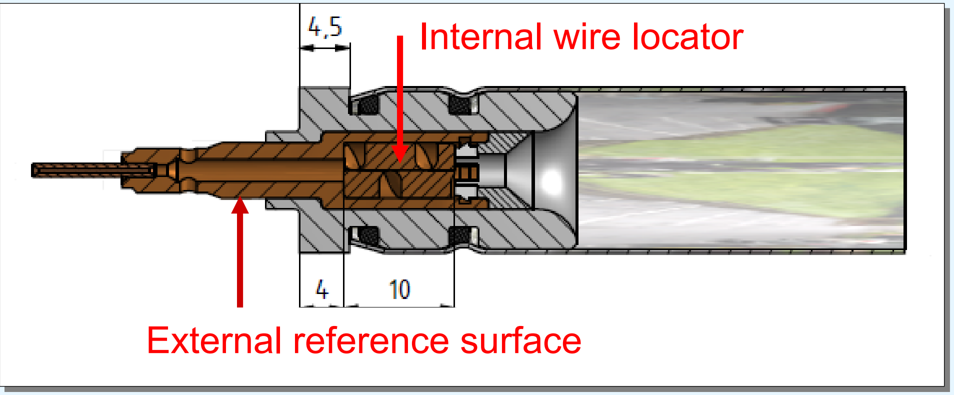
Installation in 2016-17.
Pilot project for replacement of the BI layer for HL-LHC.

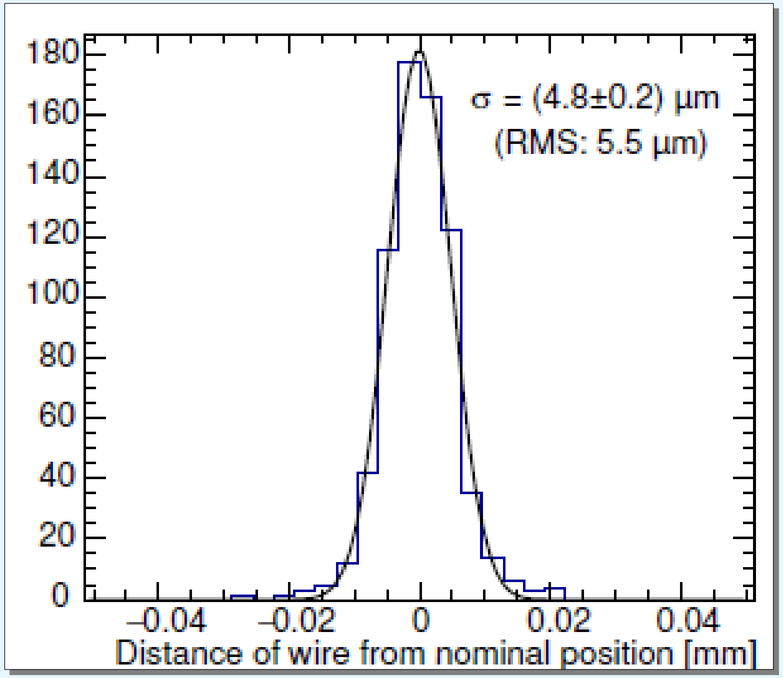
Quality Control: Mechanical Wire Position Measurement



- Measurement of individual sense wire and alignment sensor positions with with 3D coordinate measuring machine (2 µm precision).

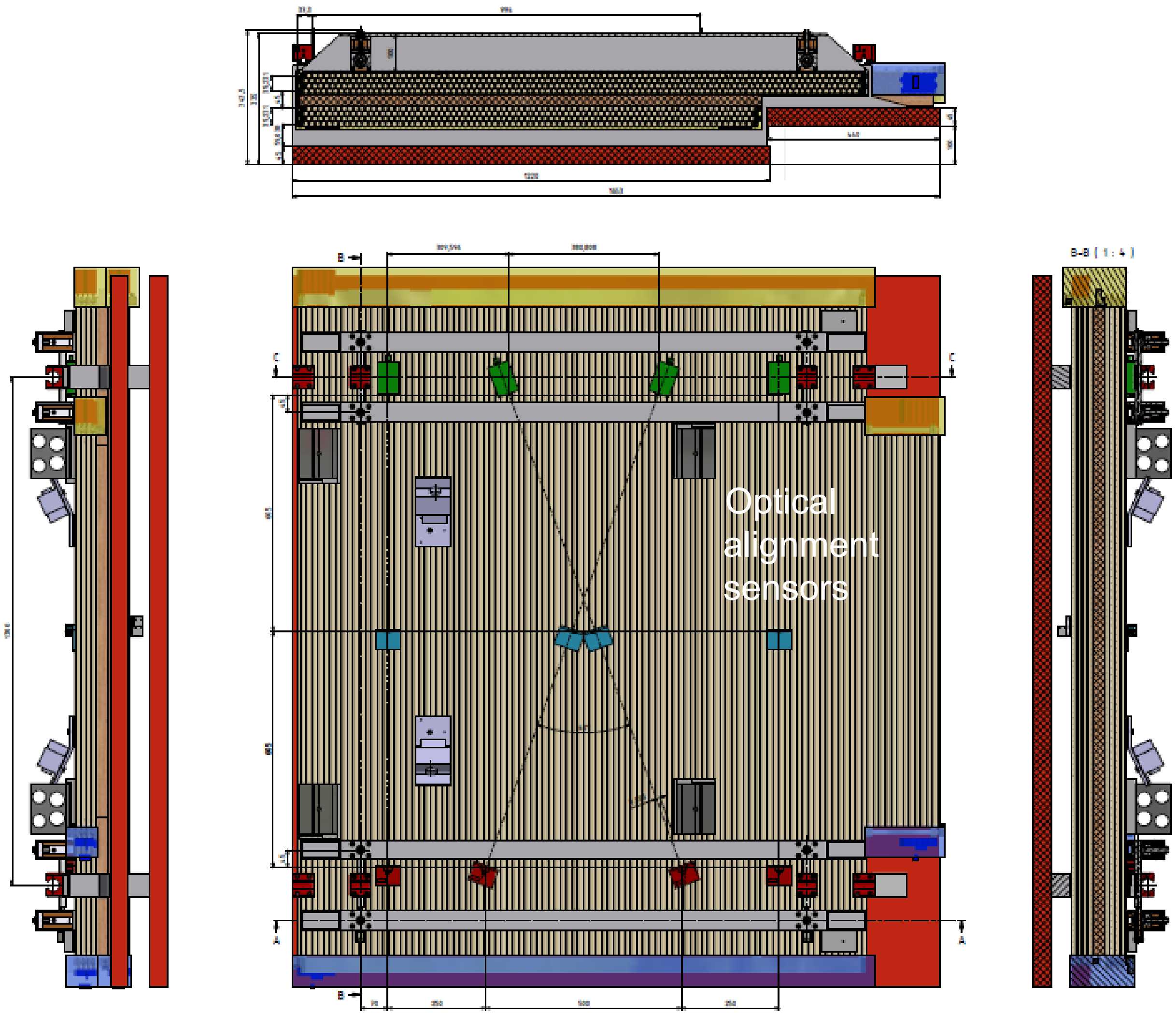
- ⇒ Wire positioning accuracy of better than 5 µm, (MDTs: 20 µm).

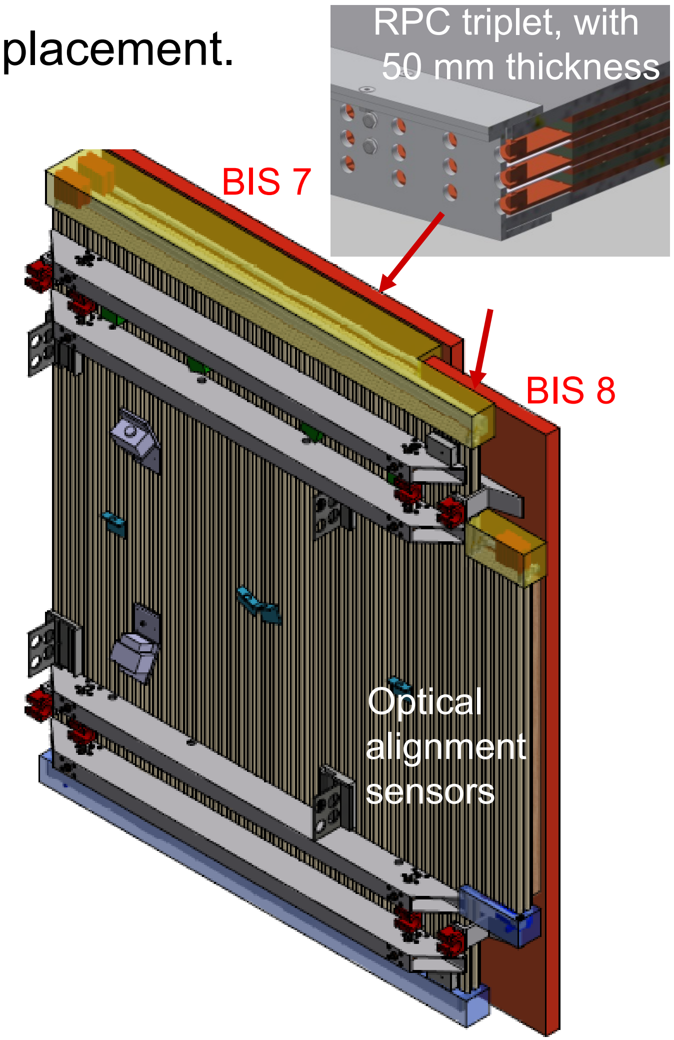




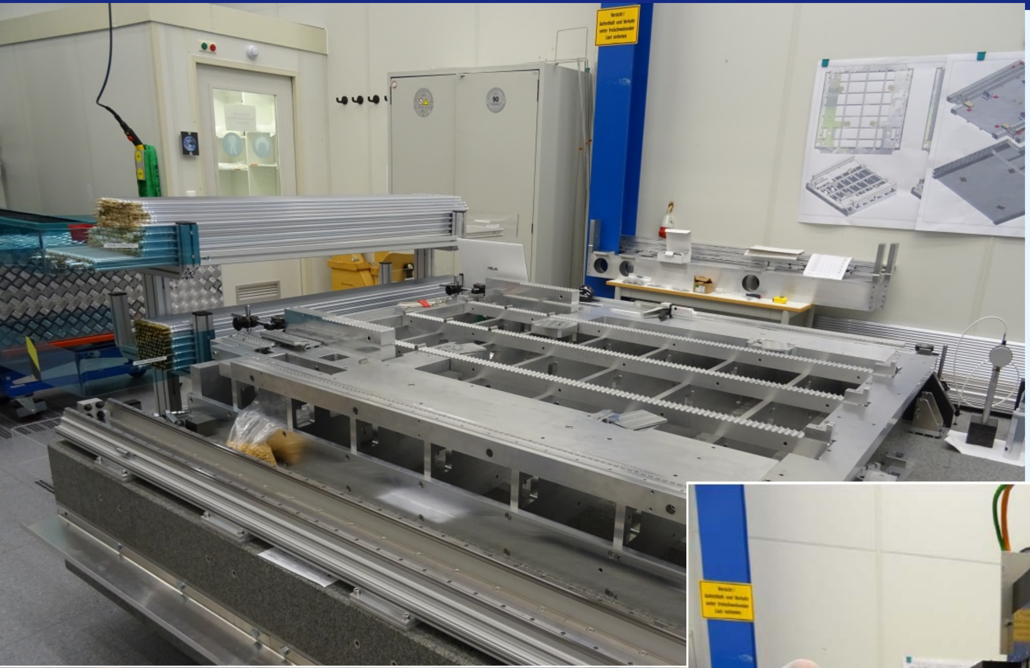
Integrated BI Chamber Design

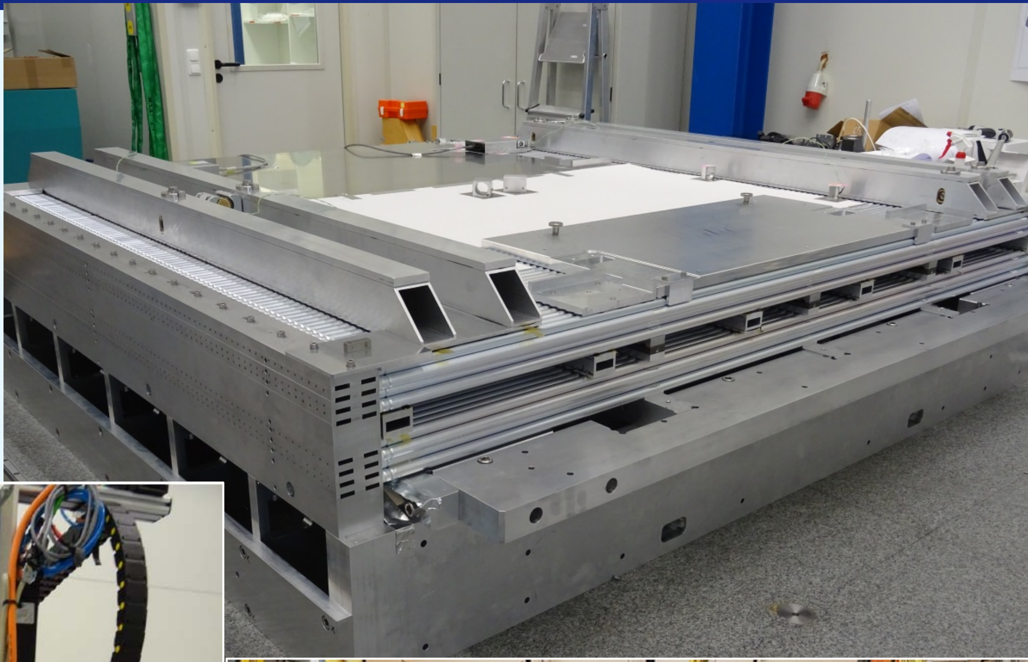
Integrated design of sMDT + new RPC chambers for BI layer replacement.





BI sMDT Chamber Construction Start 2018



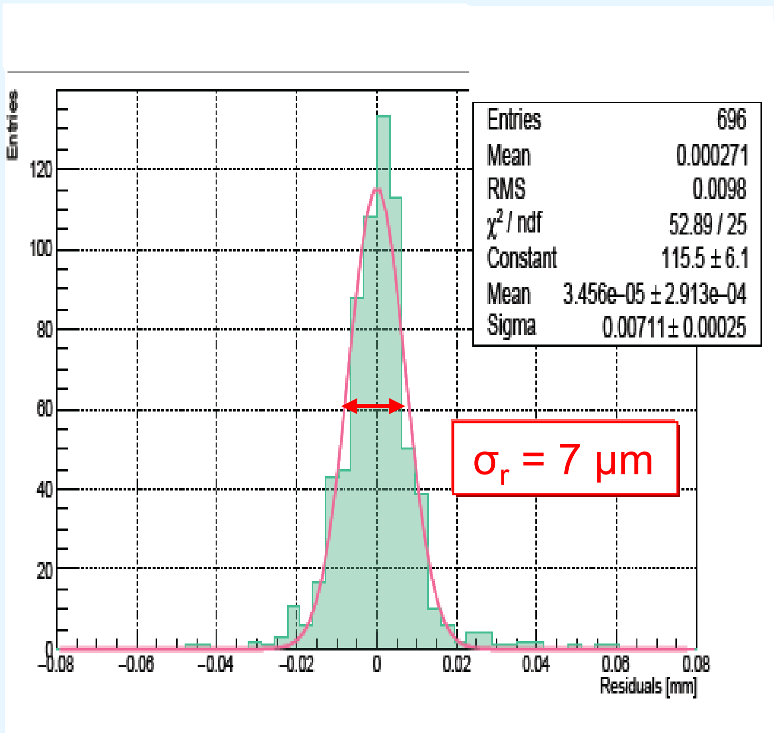


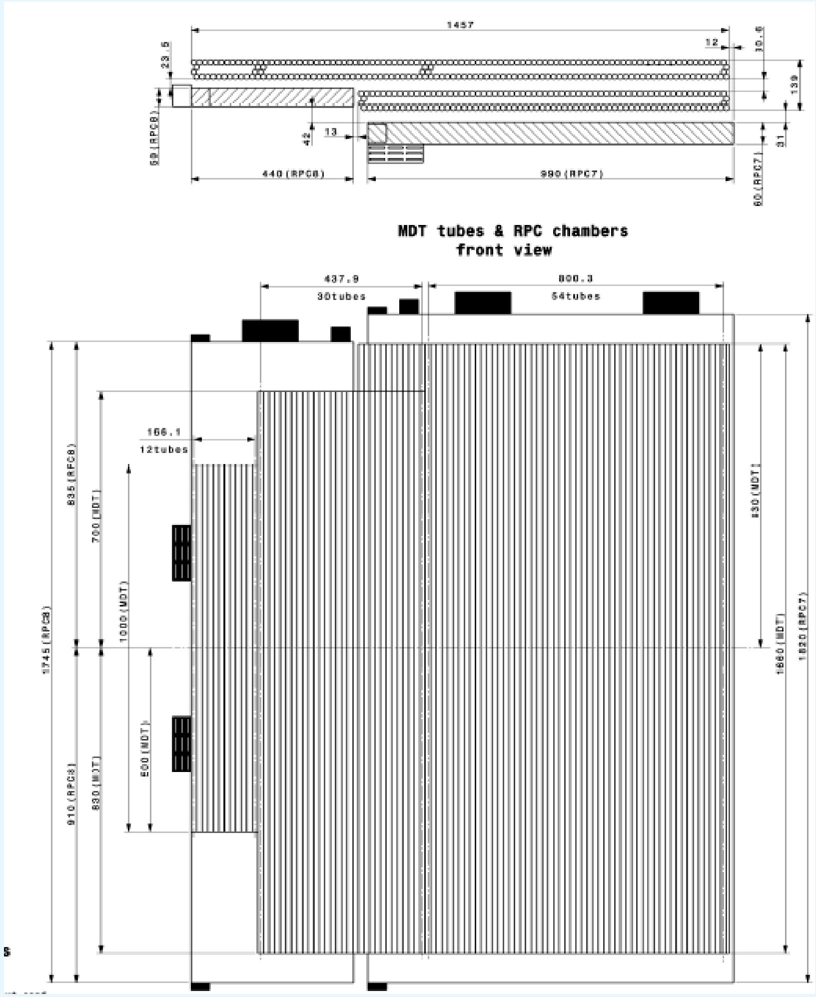
Mechanical Accuracy

3D CMM measurement of wires, alignment sensor platforms and global deformations:

Wire positioning accuracy of better than 10 μm confirmed in spite of complex shape and low stiffness

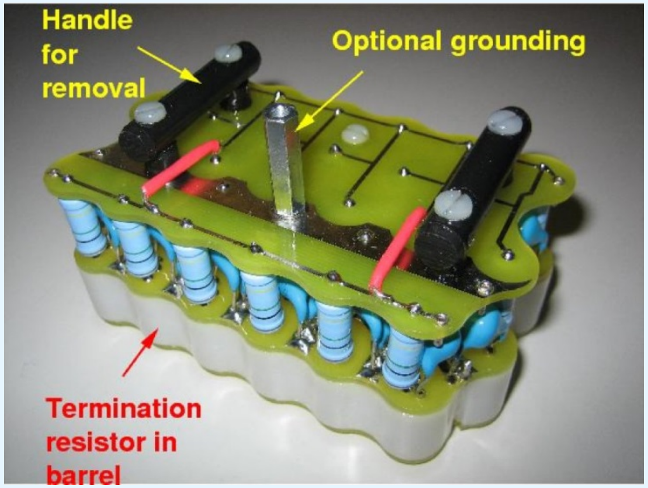
Wire pos. residuals





sMDT Readout Electronics

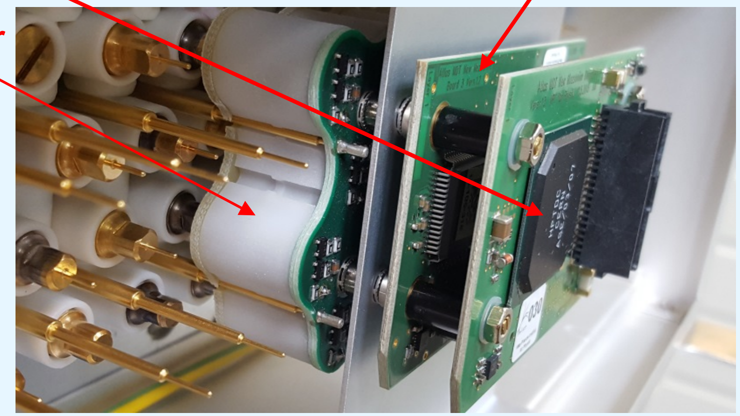
High-voltage distribution boards (24 channels)



Signal distribution and readout boards (24 channels)

with three 8-channel amplifier-shaper-discriminator (ASD) chips and one TDC chip (here: CERN HPTDC for Phase 1 upgrades)

Coupling capacitor in barrel

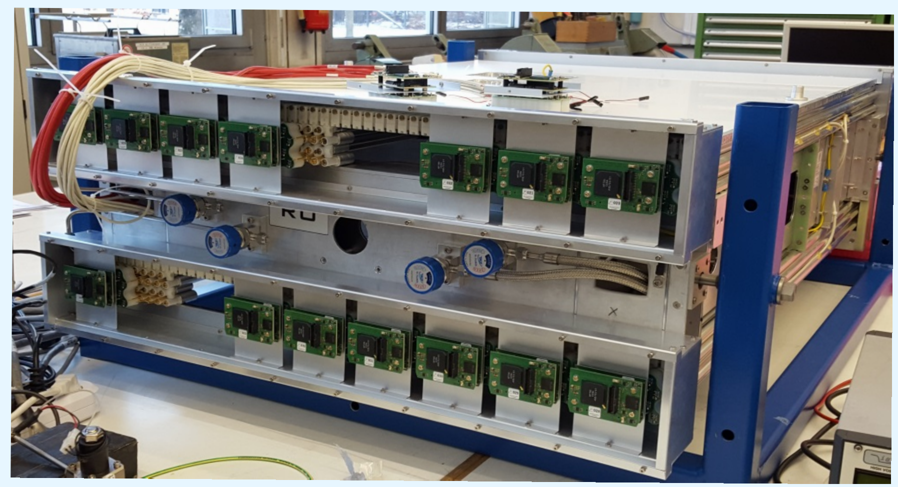


Challenge of 4 x denser tube grid:

Direct connection to endplug signal pins.

HV protection of termination resistors and coupling capacitors.

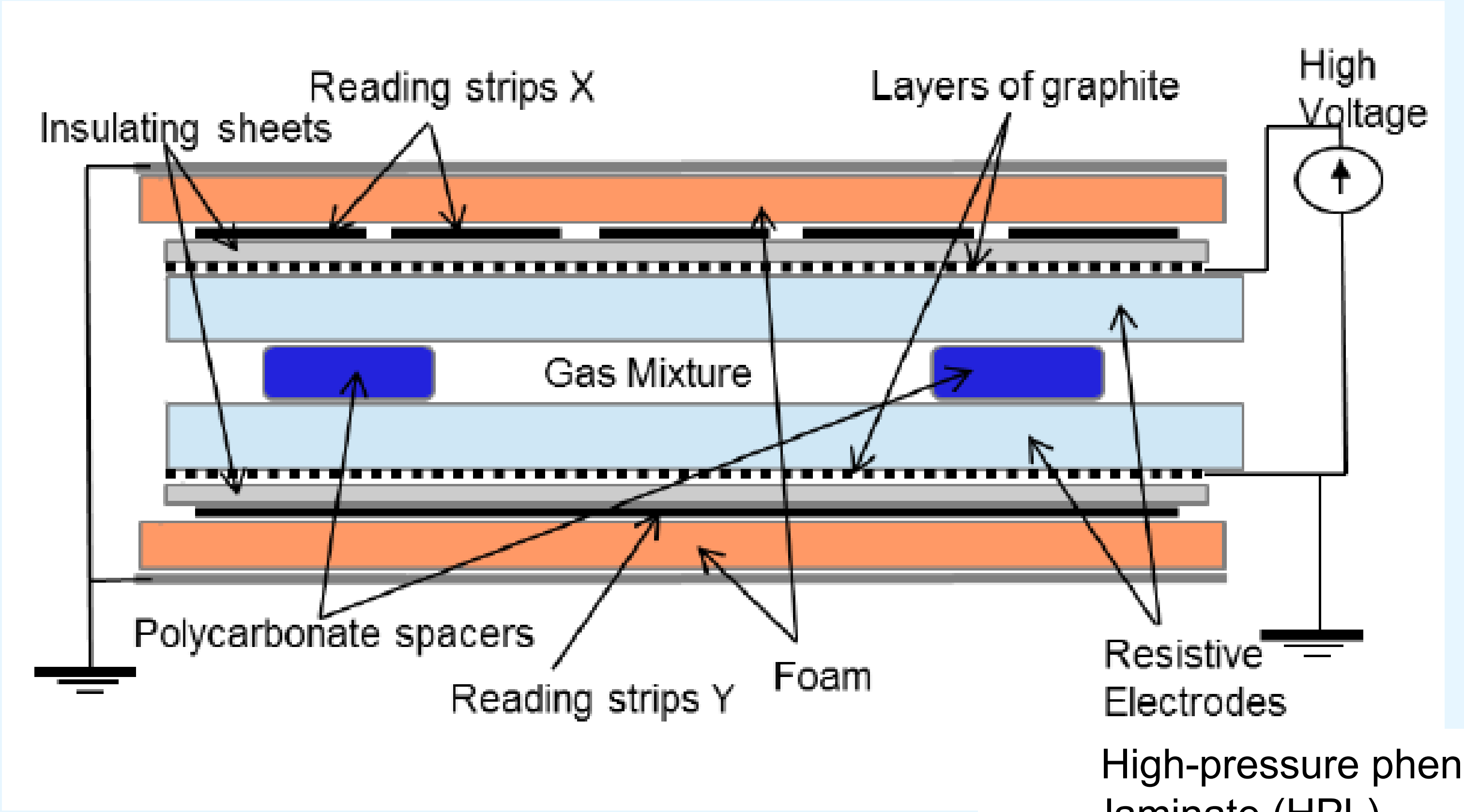
⇒ Stacked passive and active boards.



Thin-gap RPCs for HL-LHC

Present RPCs are certified up to rates of 100 Hz/cm^2 over 10 years of LHC operation w/o efficiency loss.
Both counting rates and total operation time will be exceeded at HL-LHC.

$\Rightarrow$ Reduce HV and accumulated charge (but also efficiency). Backup with new BI RPCs.
Backround rates of up to 600 Hz/cm^2 expected in the new RPCs in BI layer at HL-LHC.



High-pressure phenolic laminate (HPL)

Thin-gap RPCs for HL-LHC

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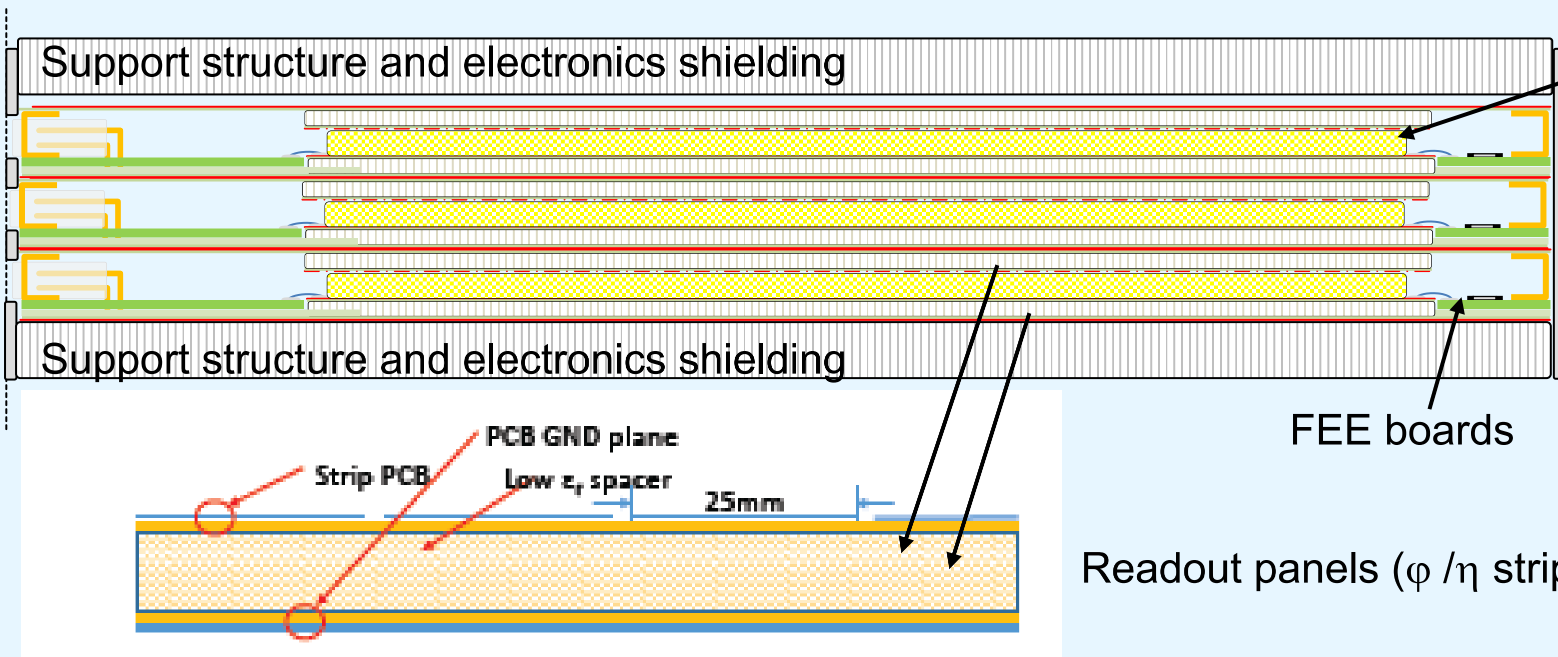
$\Rightarrow$ Reduce HV and accumulated charge (but also efficiency). Backup with new BI RPCs.
Backround rates of up to 600 Hz/cm^2 expected in the new RPCs in BI layer at HL-LHC.

$\Rightarrow$ Development of new thin-gap RPCs
with 1/2 gas gap and 2/3 electrode thickness and new highly sensitive, low-noise amplifiers which can be operated at much lower voltage and, therefore, much lower signal charge such that their lifetime under irradiation becomes substantially longer.



Triplet of gas gaps, required minimum, maximum fitting into the BI layer (only 50 mm thickness). Challenging mechanics and elx. shielding.

Readout panels (φ /η strips on top/bottom)

Thin-Gap RPC Specifications

- Smaller gas gap (1 mm instead of 2 mm) between two HPL electrodes
  - reduces chamber thickness,
  - gives twice better time resolution (0.4 ns instead of 1 ns),
  - can be operated with same gas gain and efficiency at much lower voltage (6 kV instead of 9.6 kV).

- Thinner HPL electrodes (1.2 mm instead of 1.8 mm)
  - further reduction of chamber thickness and weight,
  - increased signal charge induced on the strips.

- Possible with new low-noise (BJT) charge amplifiers
  - further reduction of the operating voltage to about 5.8 kV leading to in total 15 x lower gain and avalanche charge at the same efficiency.

	Standard RPC	BIS78 RPC
Effective threshold	1 mV	0.3 mV
Power Consumption	30 mW	6 mW
Technology	GaAs	BJT Si + SiGe
Gap Width	2 mm	1 mm
Operating Voltage	9600 V	5800 V
Charge x hit	30 pC	5-7 down to 3 pC
Electrode thickness	1.8 mm	1.2 mm
Time resolution	1 ns	0.4 ns
Gaps per chamber	2	3

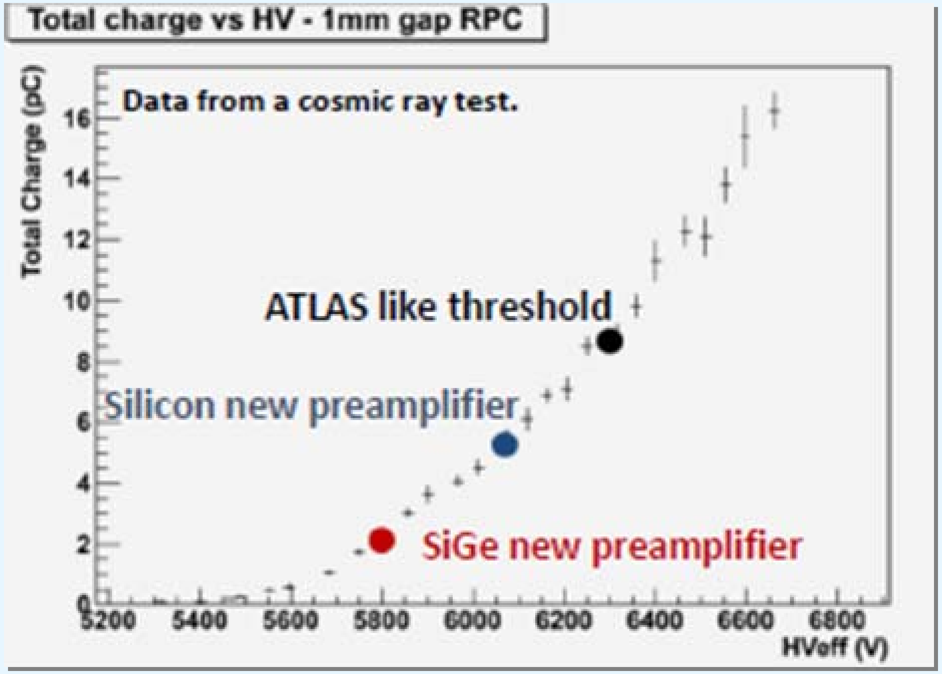
$\Rightarrow$ More than sufficient for operation at 7 x higher rates than present limit (100 Hz/cm^2) over 10 years at HL-LHC (safety factor of 2.5).

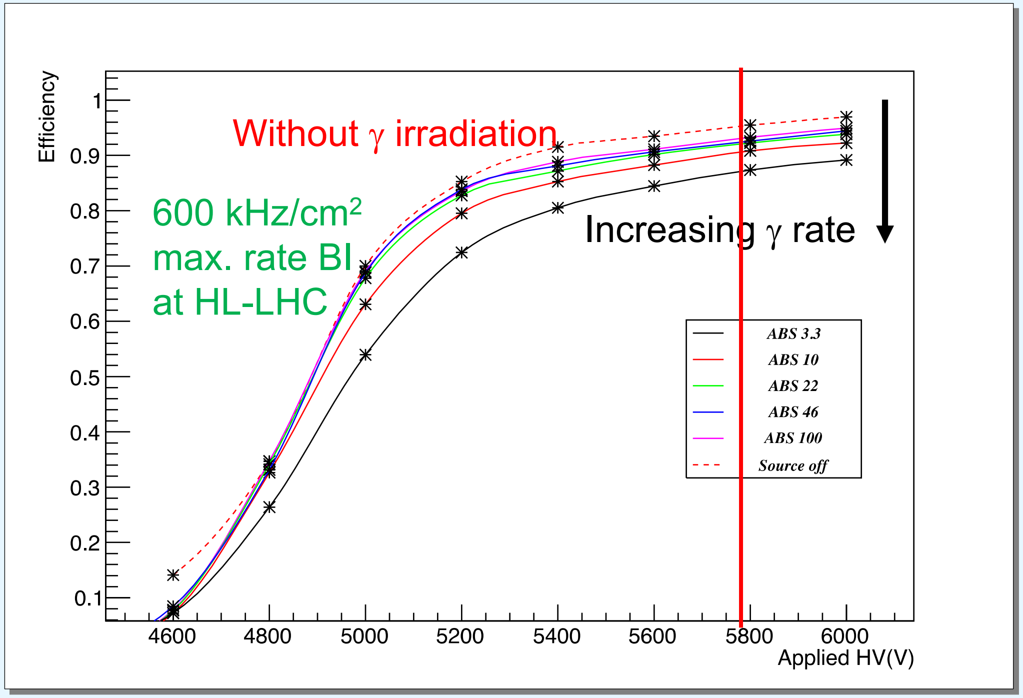
RPC Front-End Electronics Development

New fast low-noise charge amplifier (Univ. Rome II)

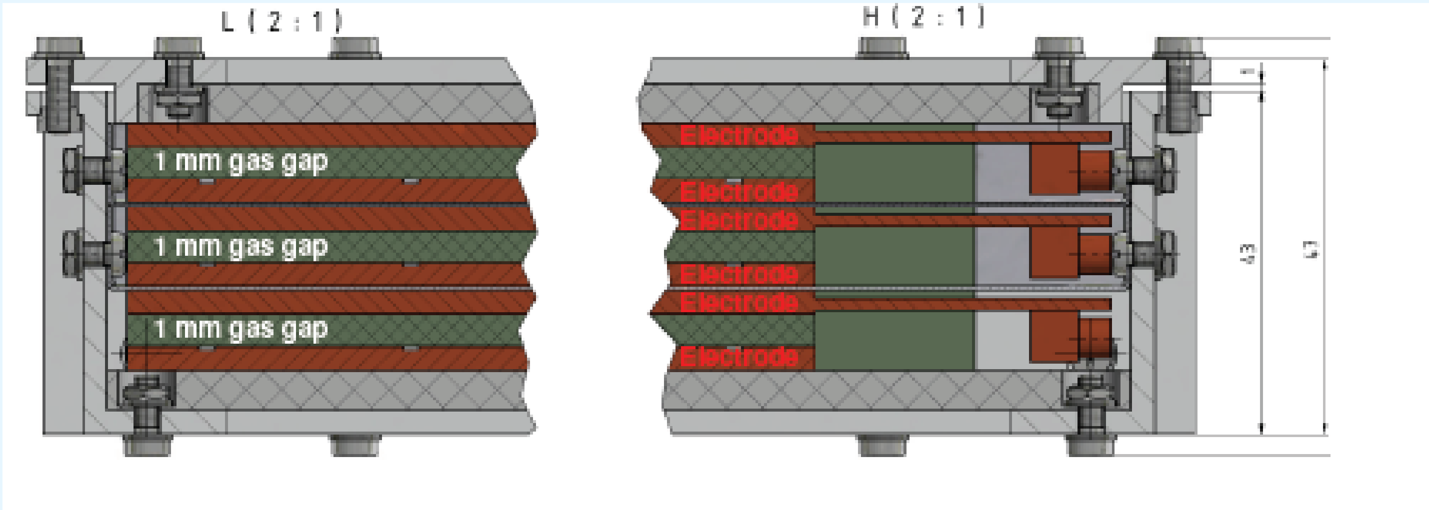
for much smaller signals at the reduced gas gain

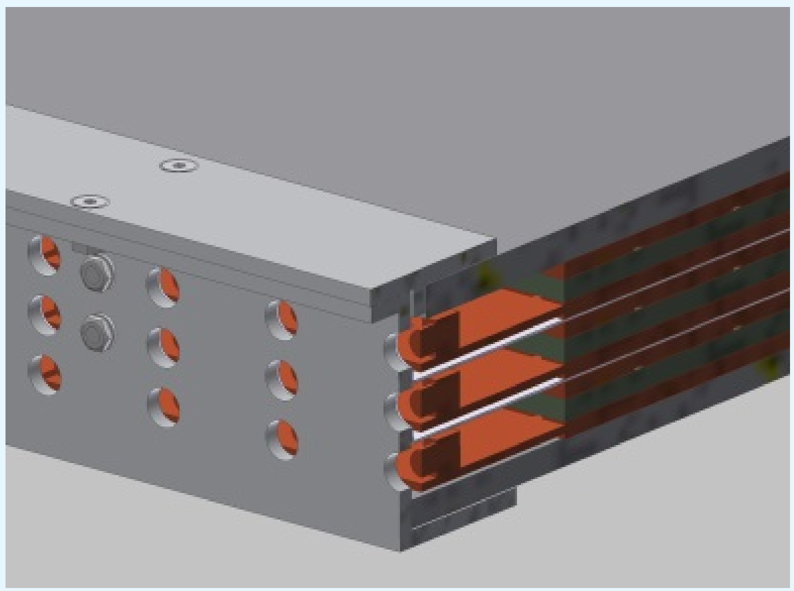
Voltage supply	3-5 Volt
Sensitivity	2-4 mV/fC
Noise (up to 20 pF input capacitance)	1500 e⁻ RMS
Input impedance	100-50 Ohm
B.W.	10-100 MHz
Power consumption	10 mW/ch
Rise time $\delta(t)$ input	300 – 600 ps
Radiation hardness	1 Mrad, 10^{13} n cm^{-2}



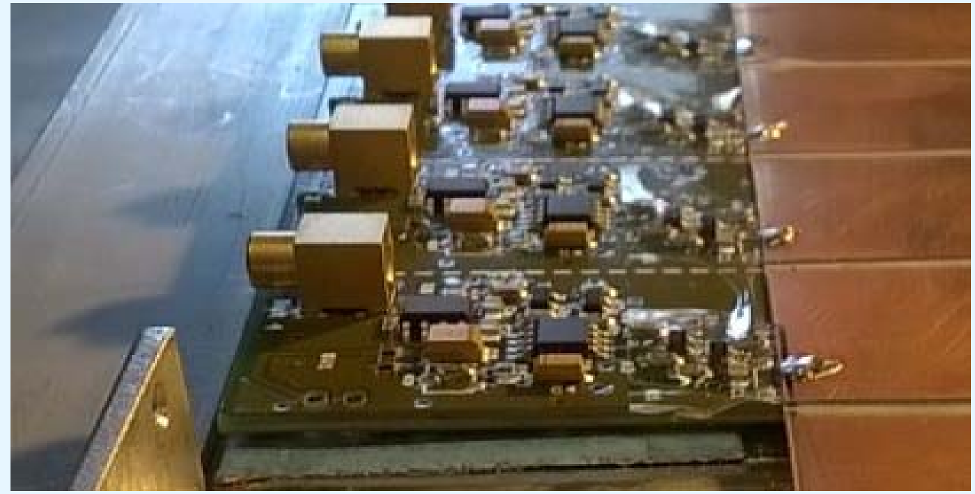


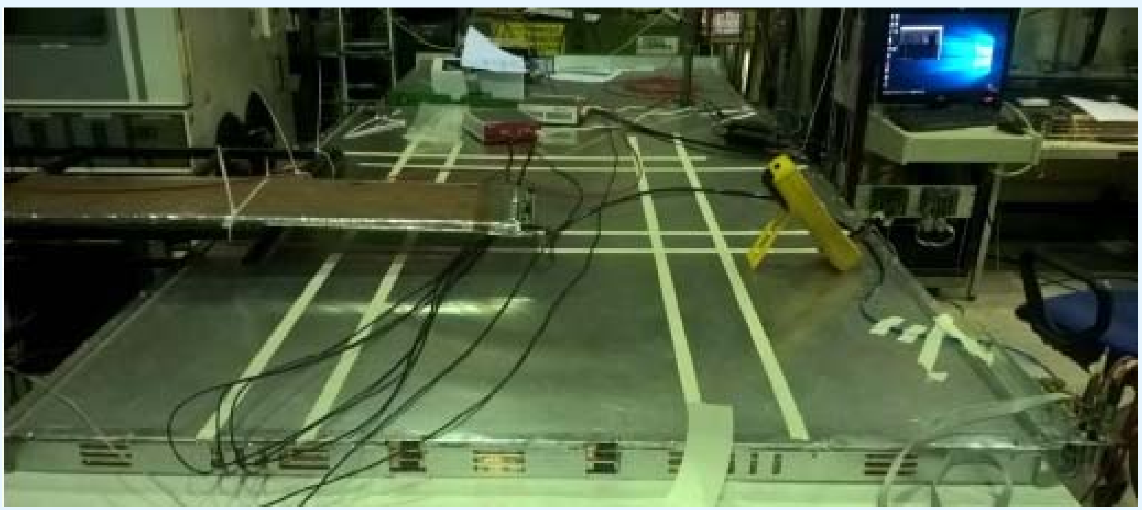
BI Thin-Gap RPC BI Triplet Prototype



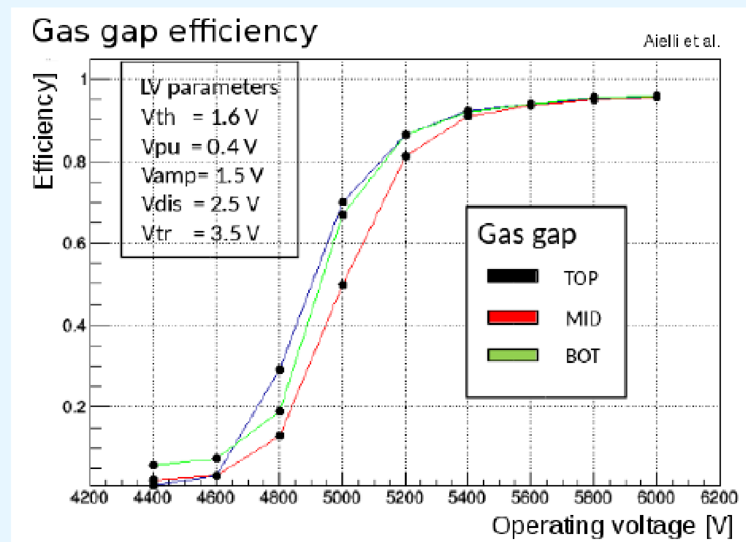


BI Thin-Gap RPC Triplet Prototype Construction





Thin-gap RPC triplet construction by MPP and Rome II and test at CERN in October-November 2017:



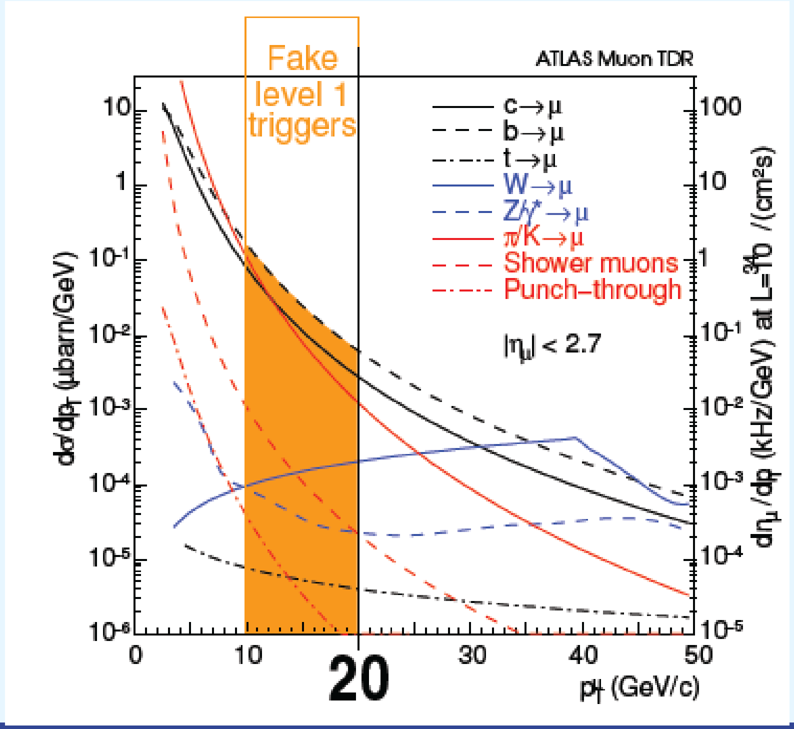
Improvement of the 1st level muon trigger selectivity

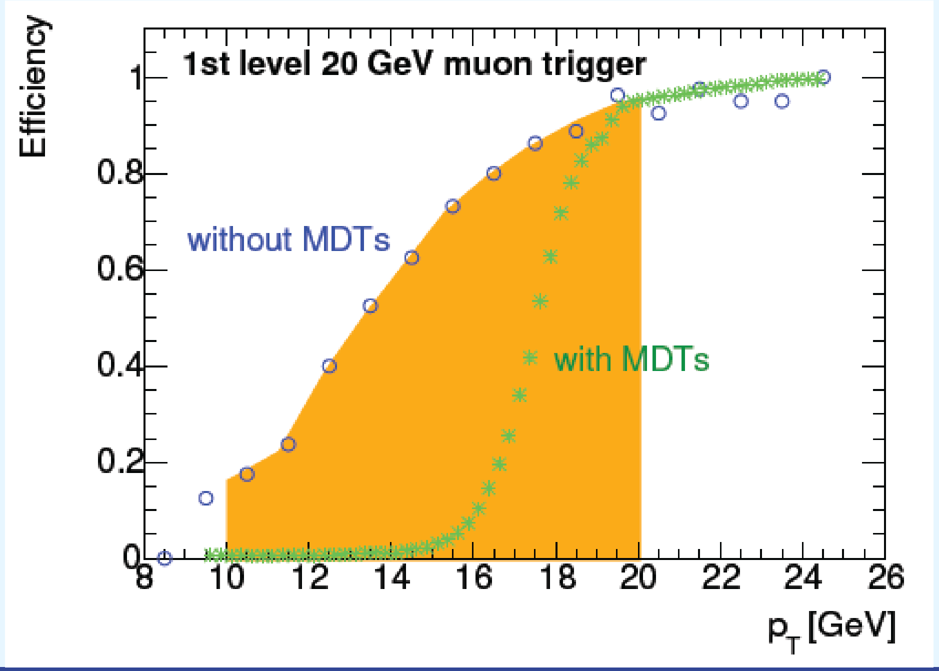
by including the MDT precision tracking chambers in the trigger to achieve the highest possible momentum resolution.

Requires implementation of fast, triggerless readout of the MDT chambers, therefore replacement of the MDT on-chamber electronics.

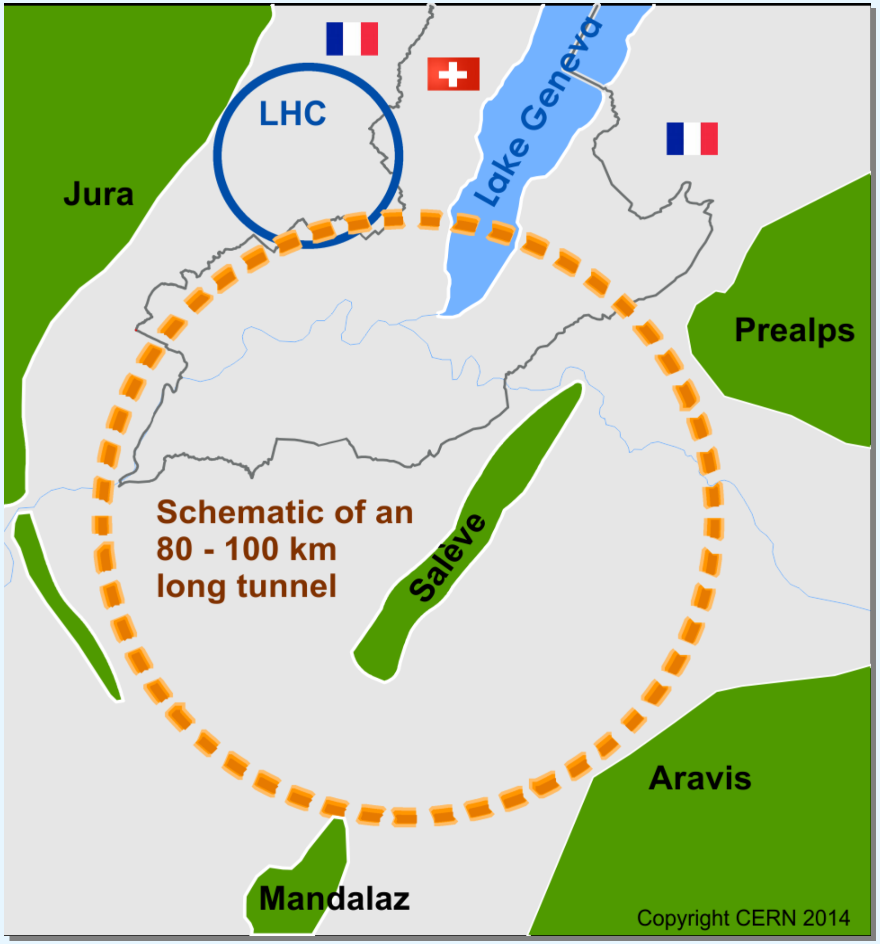
MDT-trigger concept and new trigger and FE electronics developed at MPP.

New MDT front-end and RPC trigger electronics also needs to cope with the increased 1st leve trigger rate (1 MHz) for HL-LHC.





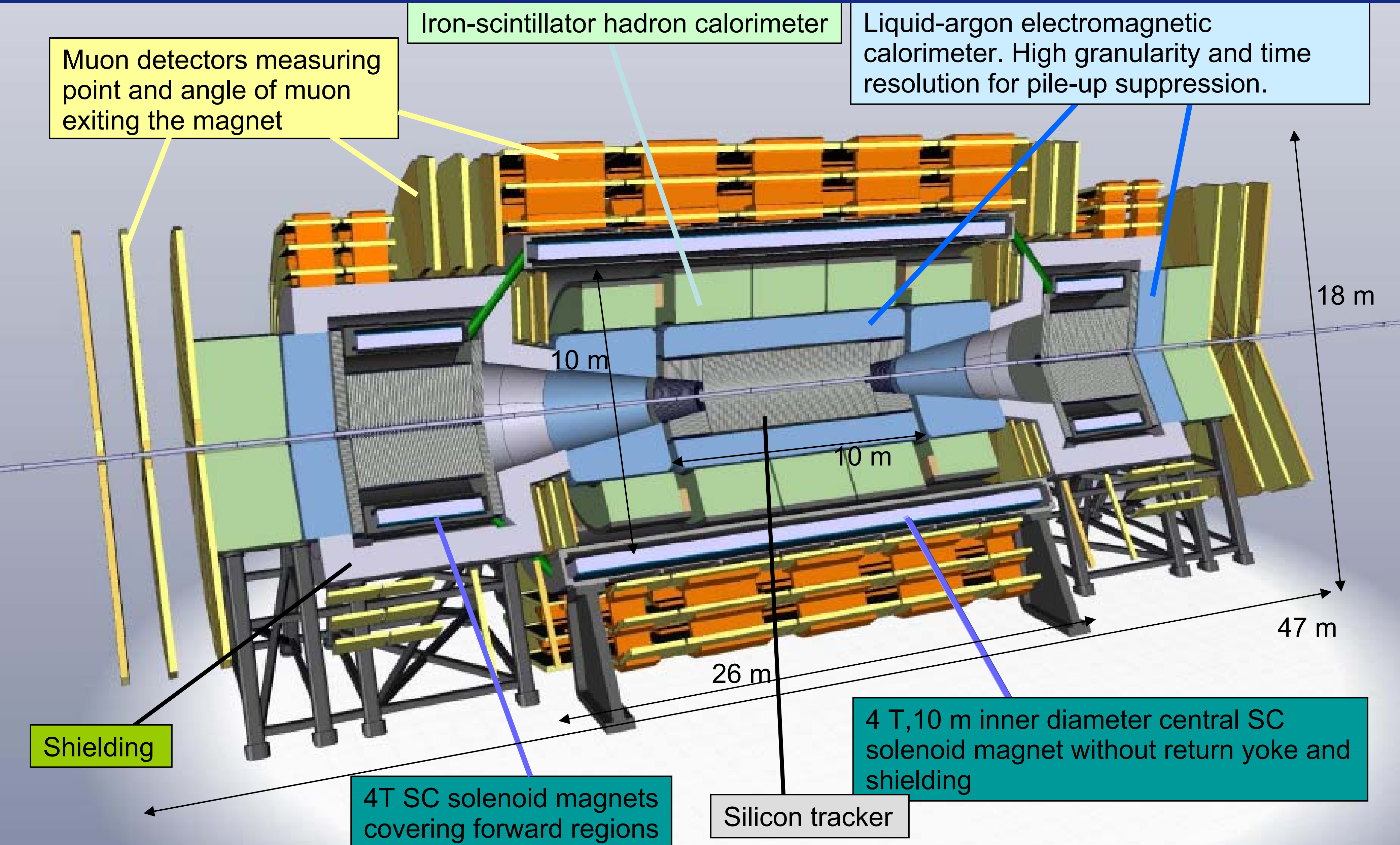
Future Circular Hadron Collider (FCC-hh) Study



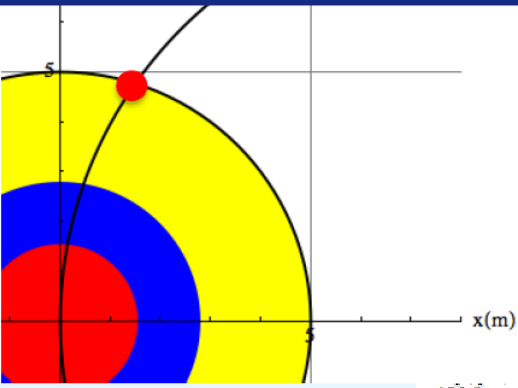
- 100 TeV proton-proton collision energy.
- 16-20 T Nb_3Sn superconducting dipole magnets.
- Start with HL-LHC luminosity, parameters and pile-up level.
- Then increase luminosity up to 3 x 10^{35} /cm^2 s luminosity.

  1000 (200) pile-up events for 25 (5) ns bunch interval.

Baseline Detector for FCC-hh

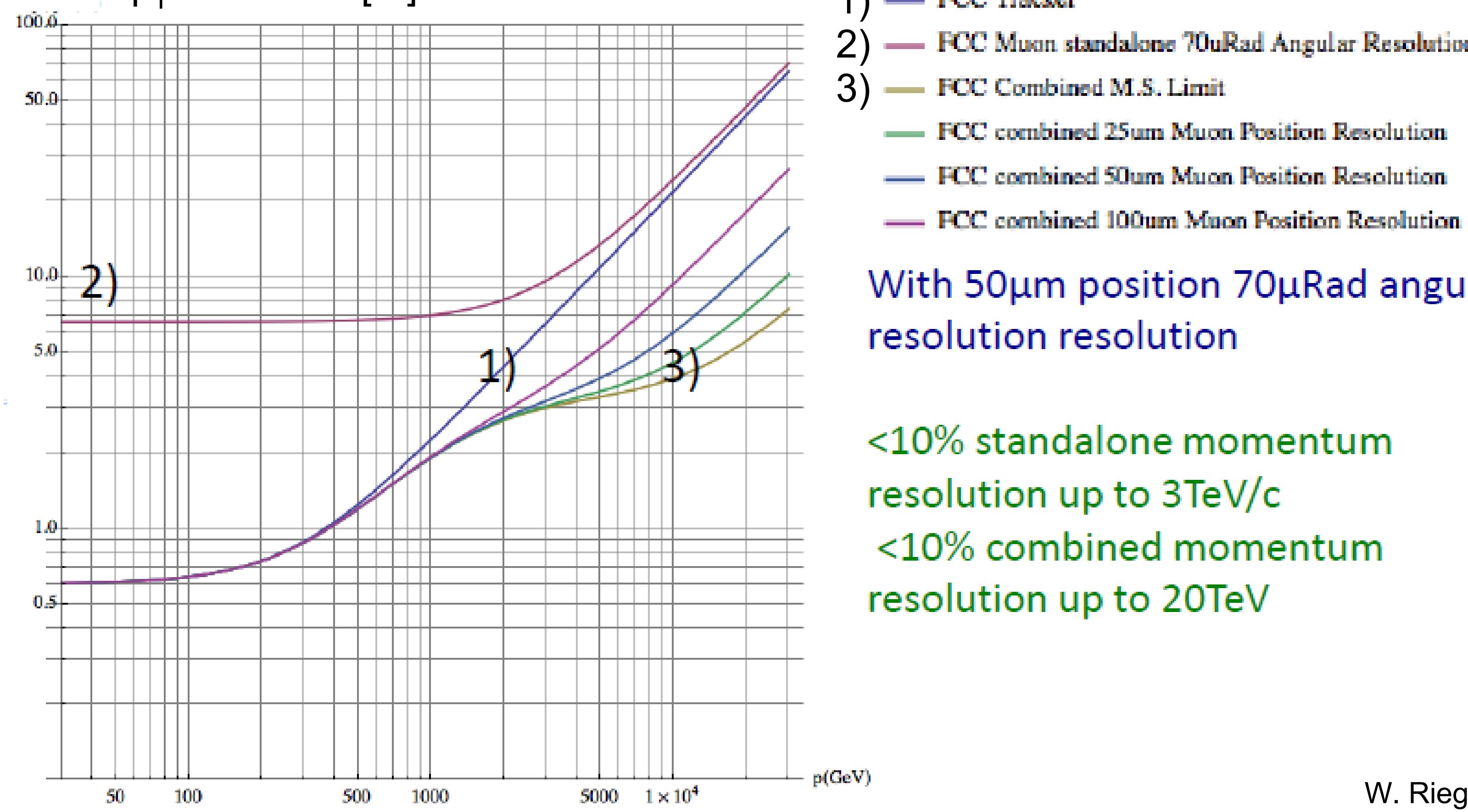


Muon Momentum Measurement



Three ways to measure the muon momentum

1) Tracker only with identification in the muon system
2) Muon system only by measuring the muon angle where it exits the coil
3) Tracker combined with the position of the muon where it exists the coil



With 50μm position 70μRad angular resolution resolution

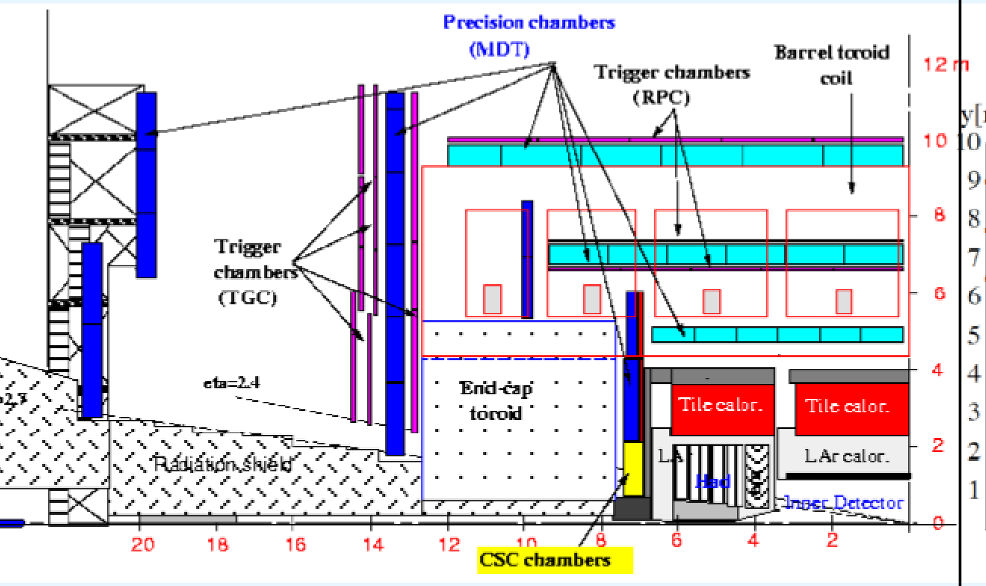
<10% standalone momentum resolution up to 3TeV/c

<10% combined momentum resolution up to 20TeV

W. Riegler

Layout and Shielding

ATLAS



Track sagitta measurement with 3 layers in the toroidal magnetic field of the muon spectrometer (MS).

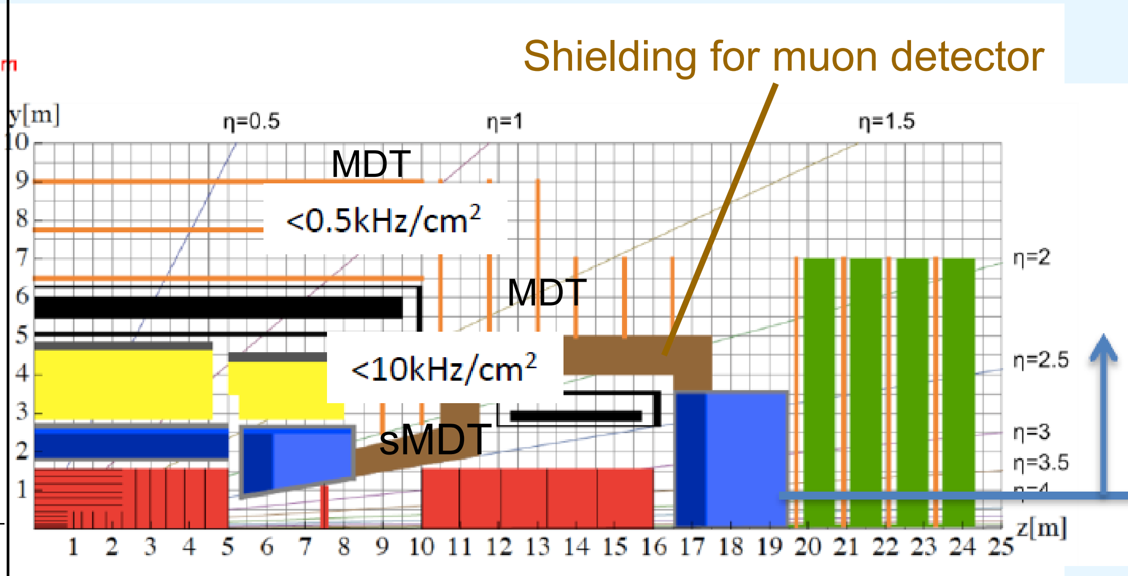
Standalone and ID + MS combined muon track reconstruction.

5000 m^2 precision tracking area,

1200 chambers with 350k channels.

Optical alignment monitoring system needed.

FCC-hh baseline



Barrel and endcaps (up to |η| ≈ 1.8):
background rates at max. FCC-hh luminosity not higher than in the ATLAS muon spectrometer now:

30 mm diameter drift tube chambers (MDT-like).

Forward up to |η| ≈ 2:
15 mm diameter drift tube chambers (sMDTs).

1000 m^2 precision tracking area,

200 chambers with 130k channels.

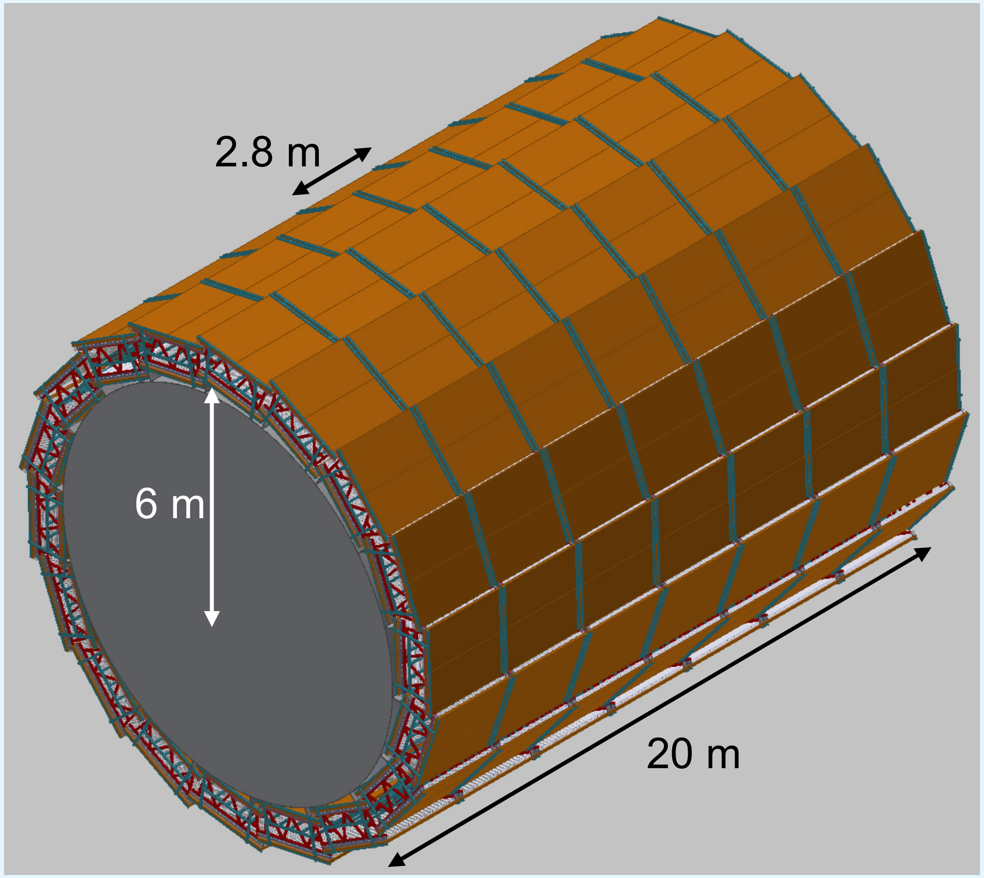
Optical alignment system not needed.

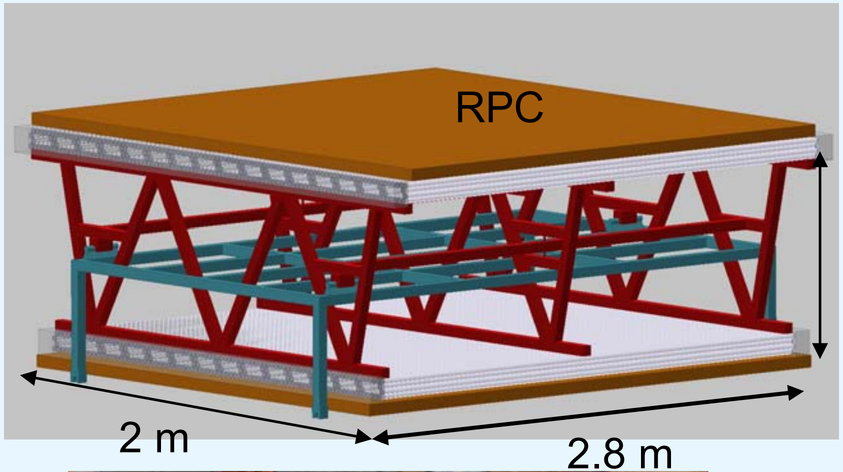
(s)MDT + Thin-Gap RPC Chambers for FCC-hh Muon Detector

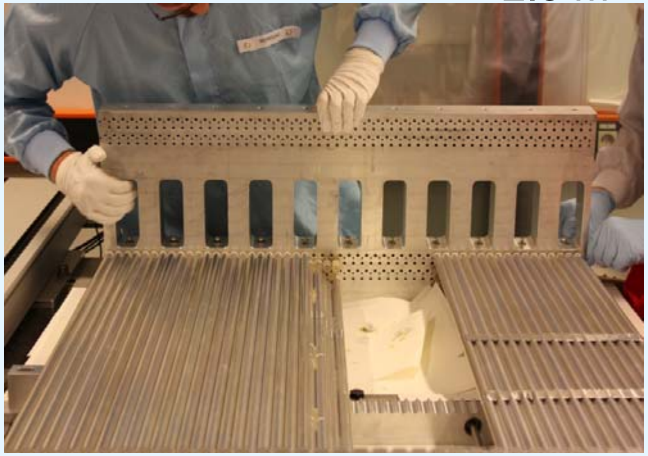
Drift tube chambers robust, cost-effective solution for high-precision tracking over large areas (cf. ATLAS).

Fast and precise assembly method developed for sMDTs,
allows for precise relative positioning of the two tube multilayers over 1 m distance.

2 x 4 layers of drift tubes at a distance of 1m with wire positioning accuracy of 20 μm provide
< 50 μm spatial resolution, 70 μrad angular resolution, 100% efficiency.







MDT-Based 1st Level Muon Trigger

MDTs also used for highly selective MDT based 1st level muon track trigger with streamed MDT readout like for ATLAS at HL-LHC.

Combined with RPCs for BCID, seeds for MDT trigger, 2nd coordinate.

Muon detector technologies for FCC-hh already available now.