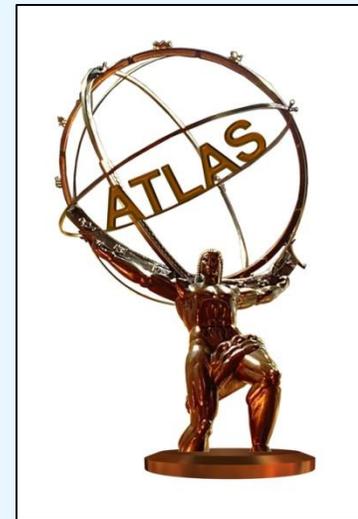
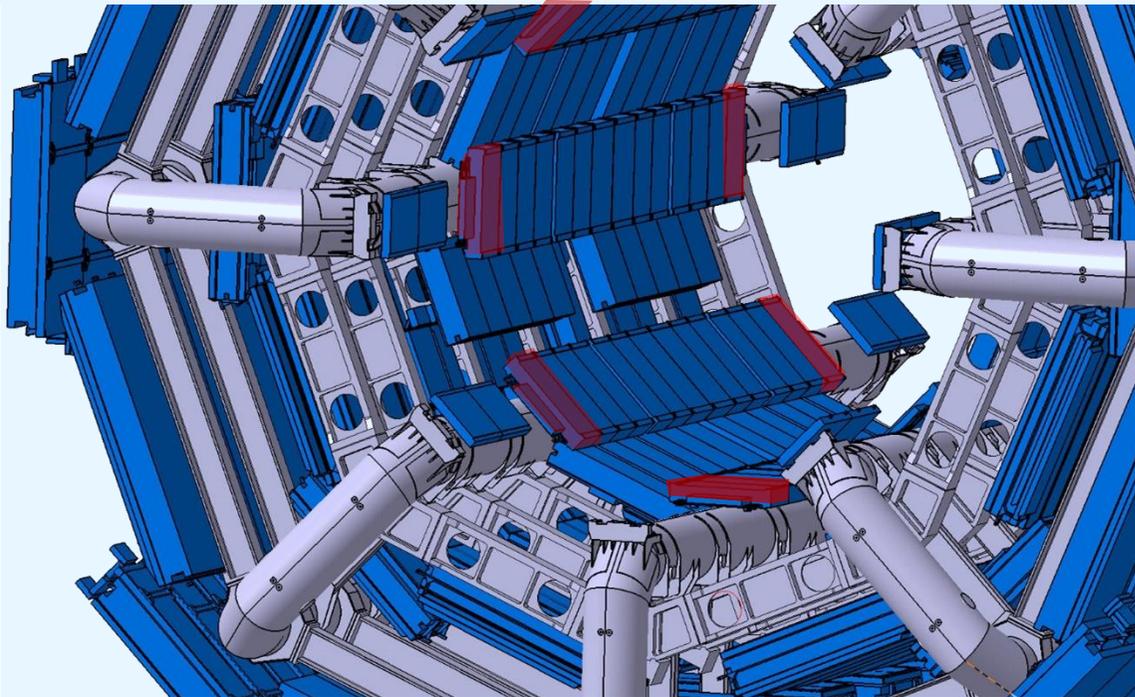


Muon Chambers and Electronics for ATLAS Phase 2 Upgrades

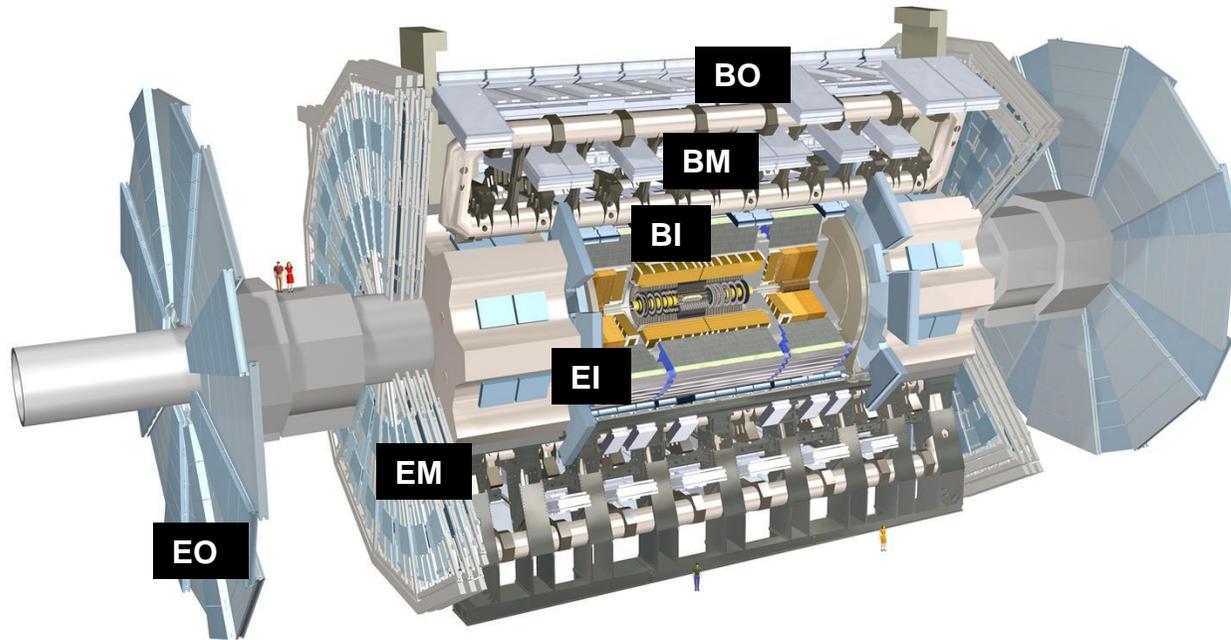
Hubert Kroha

Max-Planck-Institut für Physik, Munich

On behalf of the ATLAS Muon Collaboration



ATLAS Muon Spectrometer



- About 1200 Monitored Drift Tube (MDT) precision tracking chambers with in total 140k drift tubes: sense wire positioning accuracy of $20\ \mu\text{m}$ and chamber spatial resolution of $40\ \mu\text{m}$.

Track sagitta measurement in 3 detector layers.

Optical alignment system with $30\ \mu\text{m}$ 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 ($< 10\ \text{ns}$ time and order cm spatial resolution).

High neutron and gamma background rates:

up to $400\ \text{Hz}/\text{cm}^2$ in EI MDTs at LHC design luminosity.

About 7 x higher background rates expected at HL-LHC, as well as much increased muon trigger rate.

Muon System Upgrade Strategy for HL-LHC

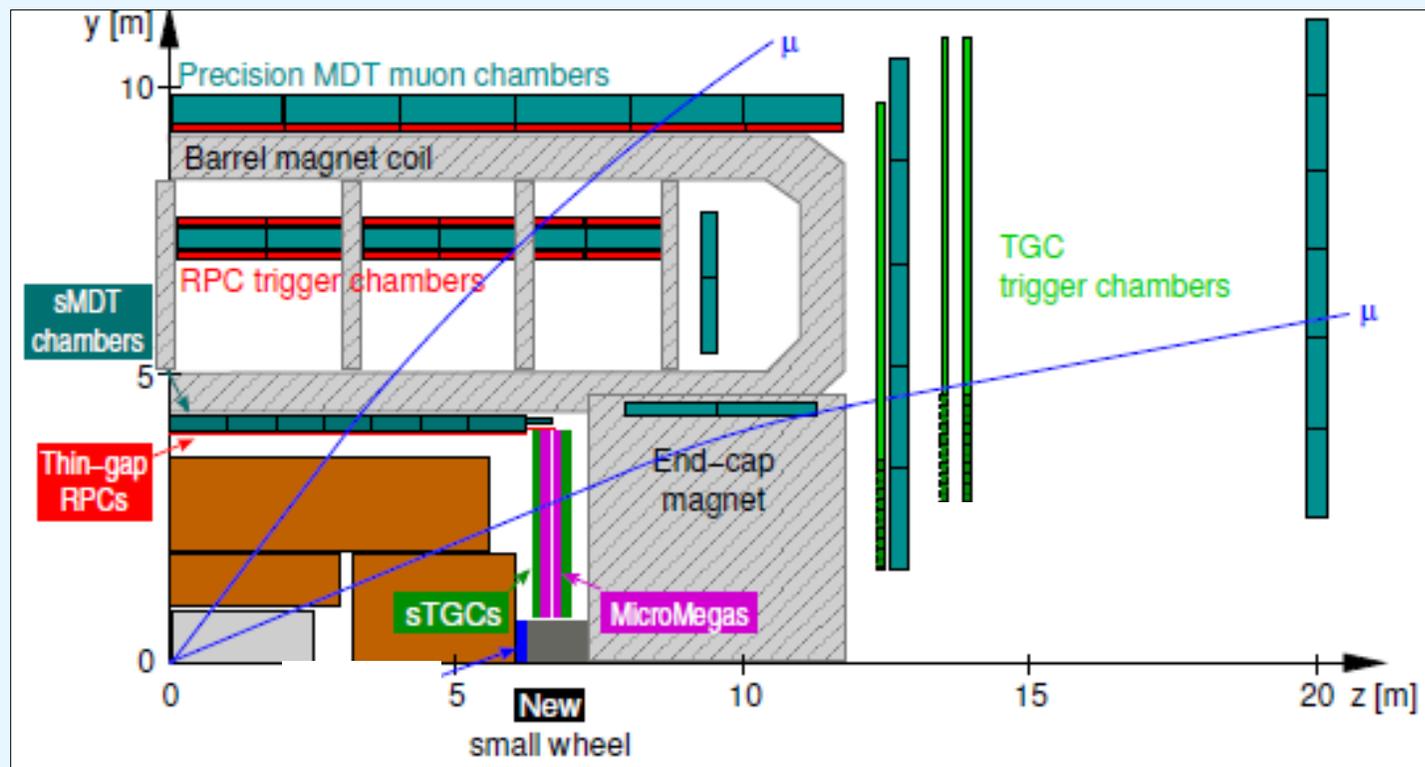
1 Strengthening of the endcap muon tracking and trigger

by installing new Small Wheels in the EI layer

with high-resolution small-strip sTGC trigger chambers and Micromegas tracking detectors with much increased rate capability already in LS2 (2019-20).

Extension of the EI sTGC trigger chamber layer to larger radii in LS3 (2024-26) under consideration.

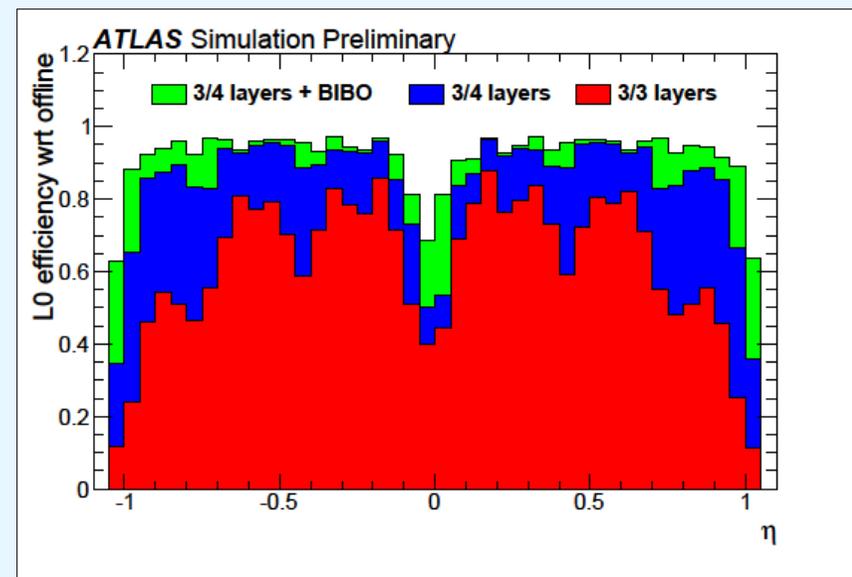
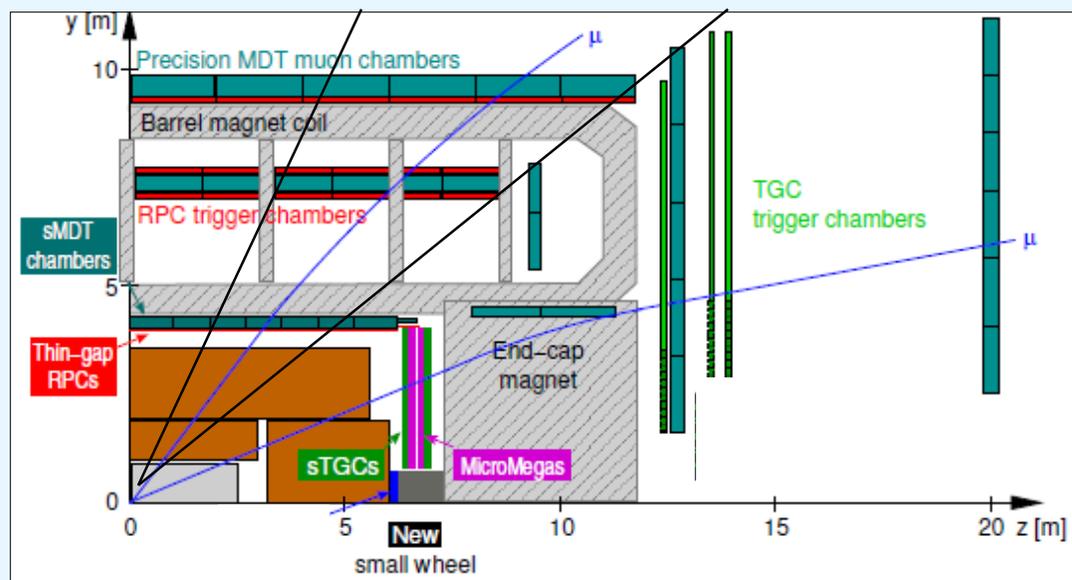
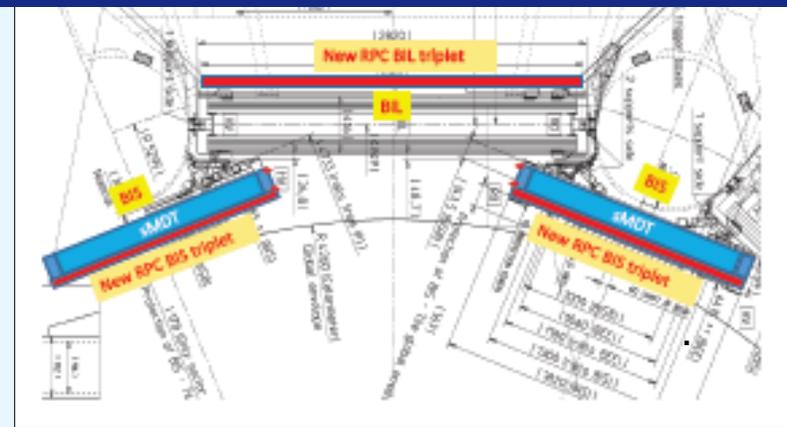
Overview of ATLAS muon system upgrades in one quadrant



Muon System Upgrade Strategy for HL-LHC

2 Strengthening of the barrel muon trigger

- by installing 276 additional RPC chambers in the BI layer
 - to close acceptance gaps and redundancy, in particular
 - to compensate for potential efficiency loss of the existing RPCs when operated beyond their anticipated lifetime.
- Requires also replacement of the 96 BIS MDTs by **small-diameter sMDT drift tube chambers** to make space for the new RPCs and increase the tracking rate capability (~ 10 x).
- Pilot project for Phase 1 upgrade: **16 new sMDTs with RPCs at the ends of the BIS layer (BIS7/8).**



3 Improvement of the 1st level muon trigger selectivity (see previous talk)

by including the (s)MDT chambers in the trigger to achieve at trigger level the highest possible muon momentum resolution and selectivity.

- Requires implementation of fast readout of the drift tubes, i.e. replacement of the MDT on-chamber electronics, esp. new TDC and data concentrator (CSM).
- New MDT front-end and RPC trigger electronics also required to cope with the increased rate (≥ 1 MHz) and longer latency ($\sim 6 - 10 \mu\text{s}$) of the new 1st level trigger at HL-LHC.

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.

⇒ Reduce HV and accumulated charge (but also efficiency).

Reduction of HV may also be necessary for the use of new eco gases (ongoing ATLAS/CMS efforts).

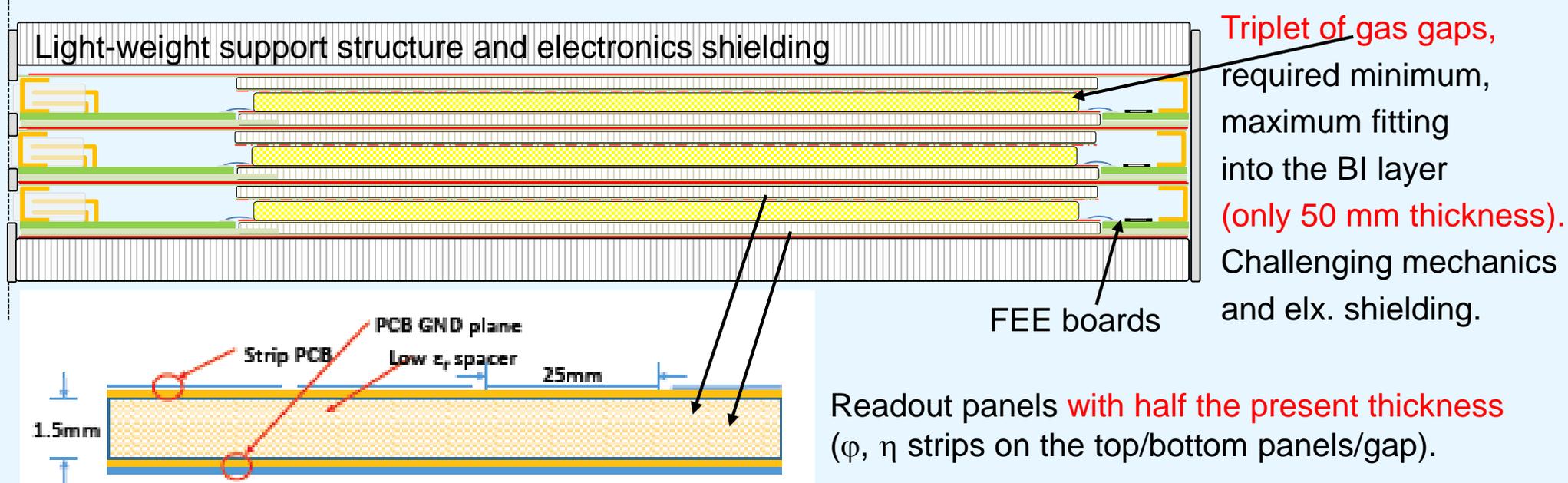
⇒ Backup with new BI RPCs.

Background rates of up to 600 Hz/cm^2 expected in the new RPCs in BI layer at HL-LHC.

⇒ **Development of new thin-gap RPCs**

with 1/2 gas gap and 2/3 electrode thickness and new highly sensitive amplifiers

which can be operated at much lower voltage and, therefore, much lower charge/hit such that their lifetime under irradiation becomes substantially longer.



Thin-Gap RPC Design Criteria

- **Smaller gas gap (1 mm instead of 2 mm)** between two bakelite electrodes
 - helps to reduce chamber thickness,
 - gives twice better time resolution (0.4 ns instead of 1 ns) and less charge fluctuations,
 - operatew with same gas gain and efficiency at substantially lower voltage (**~6 kV instead of 9.6 kV**).
- **Thinner bakelite electrodes (1.2 mm instead of 1.8 mm)**
 - allow for further reduction of chamber thickness and weight,
 - increase the signal charge induced on the strips.
- **Together with new low-noise charge amplifiers**
 - allows for further lowering of the operating voltage to **5.4 kV**,
corresponding to **15 x lower gas gain and avalanche charge** without efficiency loss;
also provides more room for new eco gas choice.

⇒ **More than sufficient for operation at 6 x higher rates than present limit over 10 years at HL-LHC (safety factor of 2.5).**

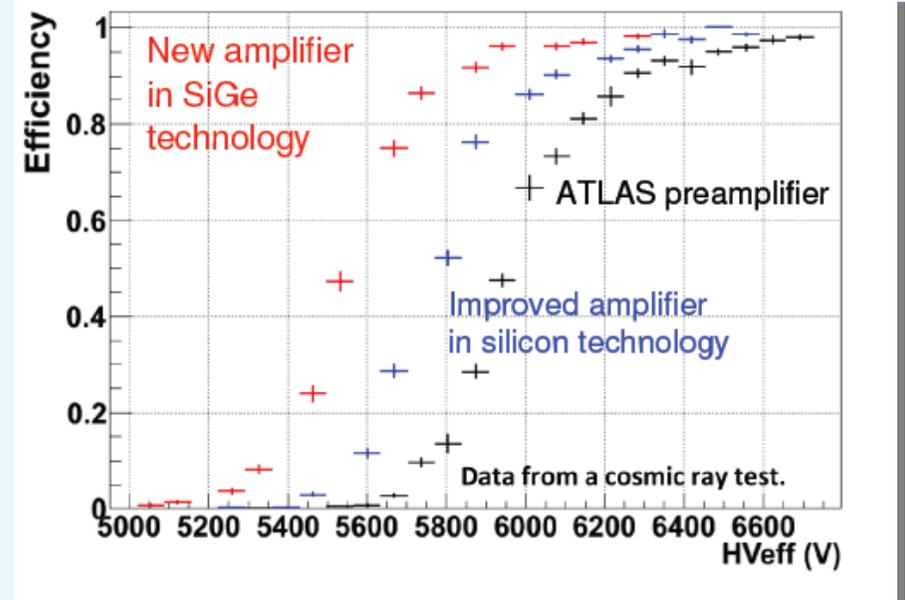
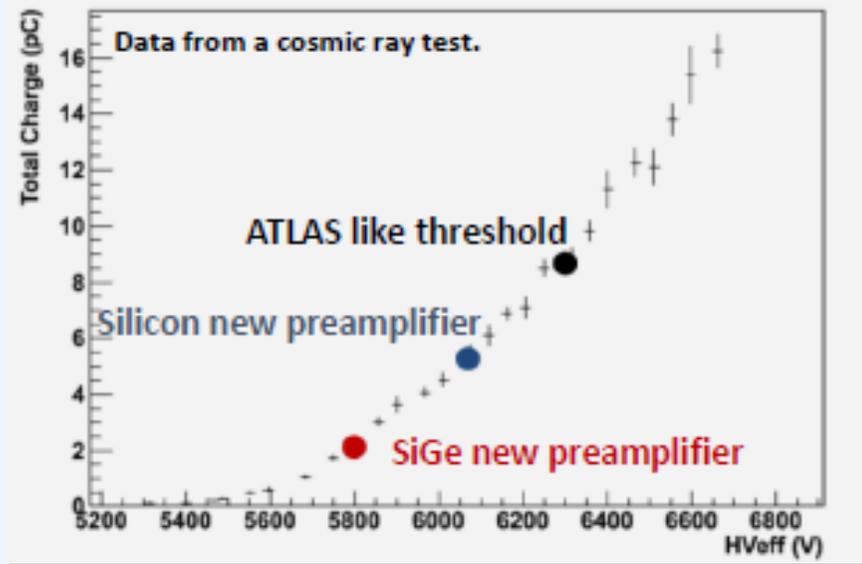
Thin-Gap RPC Front-End Electronics Development

New fast low-noise charge amplifier

for much smaller signals at the reduced gas gain

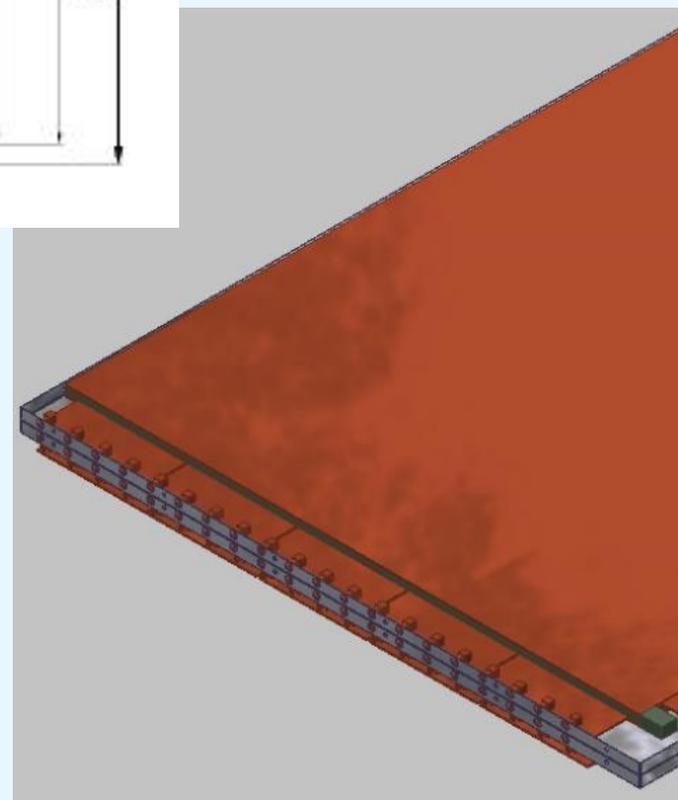
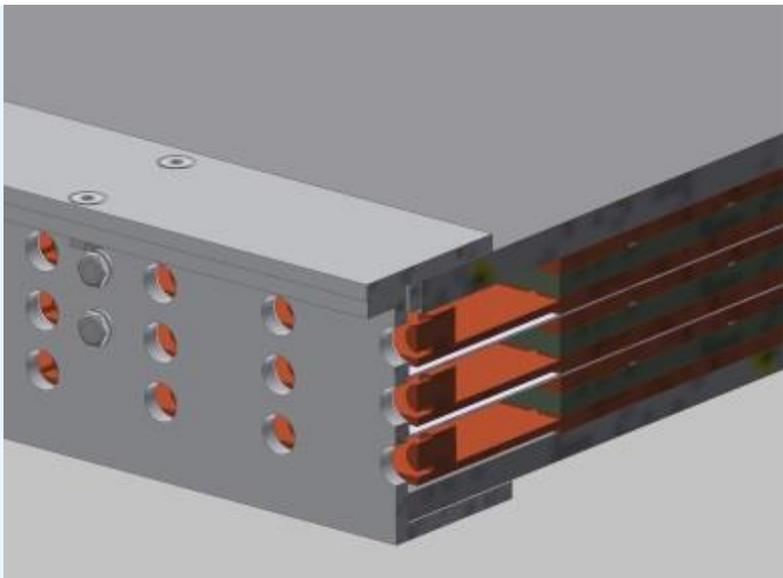
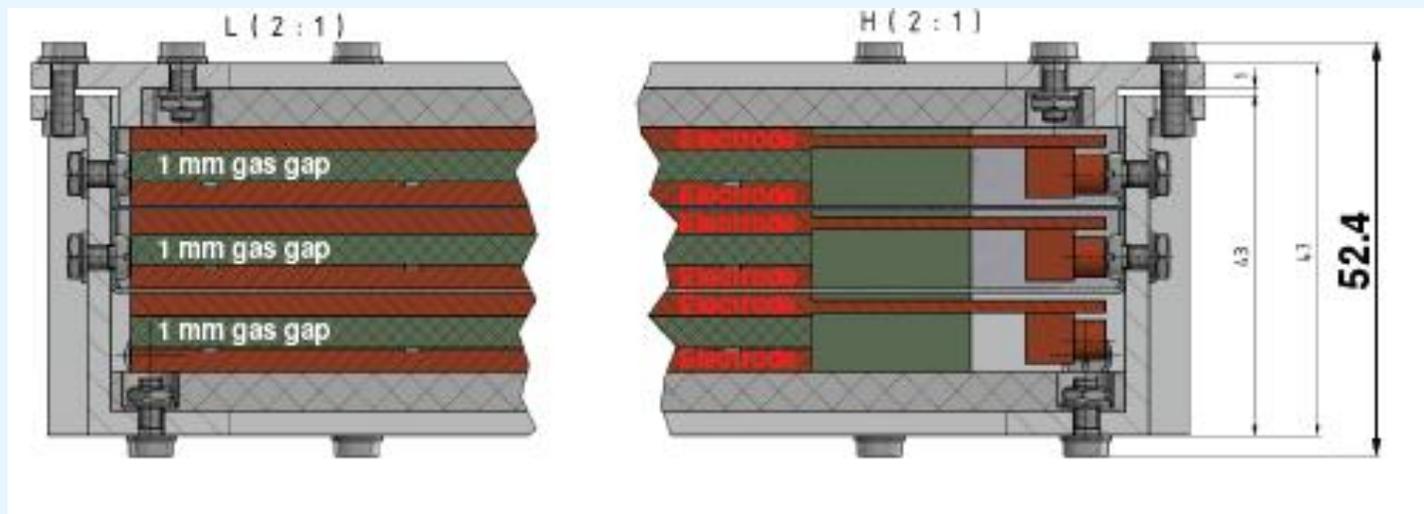
Voltage supply	3-5 Volt
Sensitivity	2-4 mV/fC
Noise (up to 20 pF input capacitance)	1500 e ⁻ RMS
Input impedance	100-50 Ohm
B.W.	10-100 MHz
Power consumption	10 mW/ch
Rise time $\delta(t)$ input	300 – 600 ps
Radiation hardness	1 Mrad, 10 ¹³ n cm ⁻²

Total charge vs HV - 1mm gap RPC

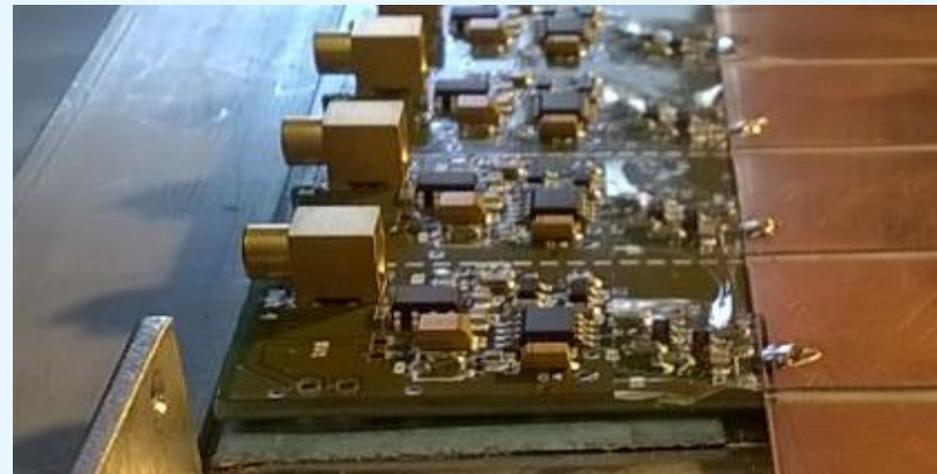


Thin-Gap RPC BI Triplet Mechanical Design

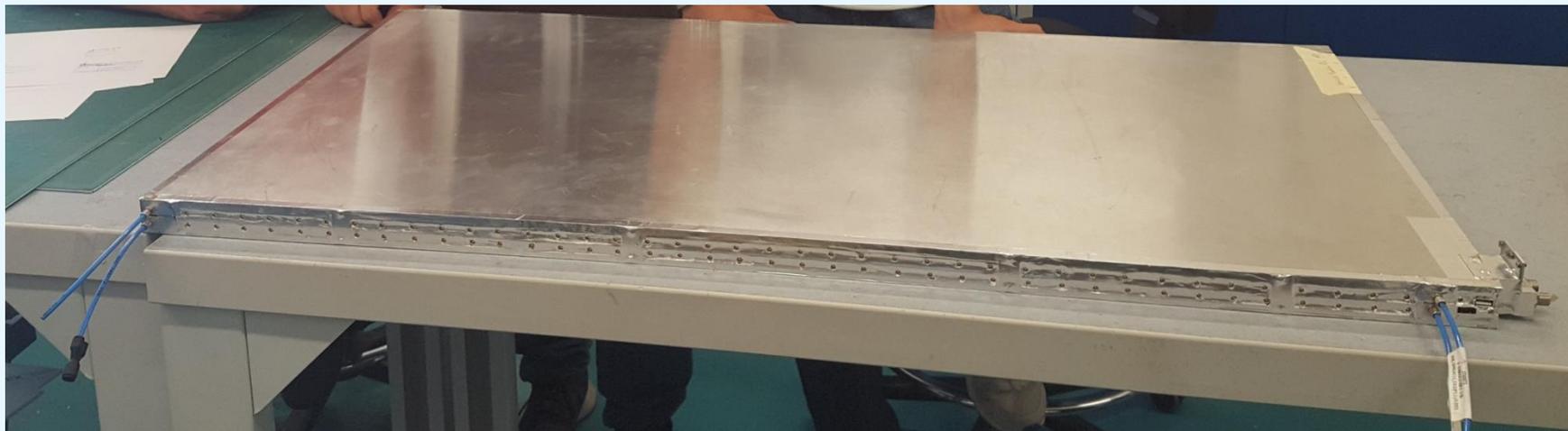
Very challenging space constraints: **only 50 mm available.**



BIS7/8 RPC Prototype Construction

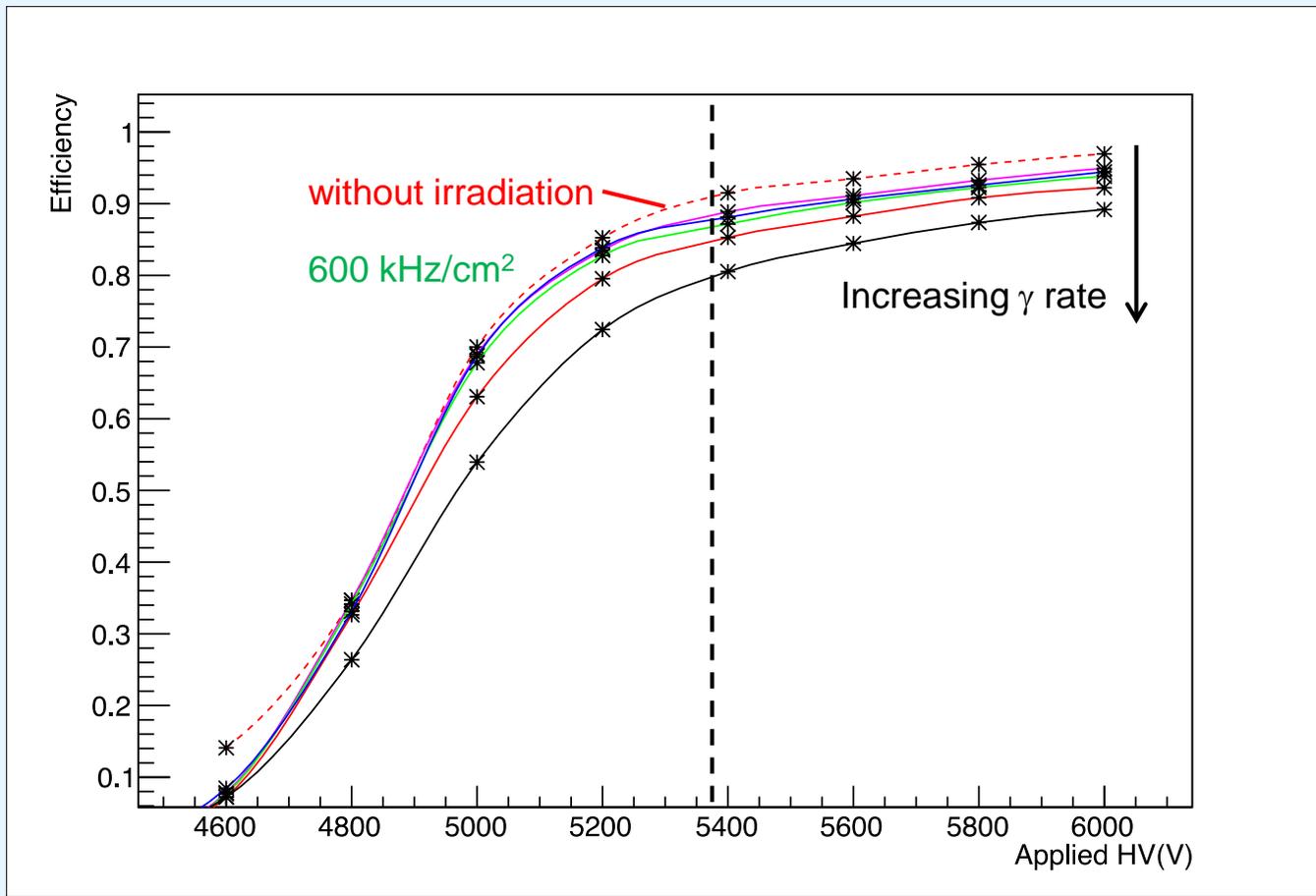


Optimisation of strip panel layout and electrical shielding.



BIS7/8 RPC Prototype Test

Test of single gas gaps in muon beam and under γ irradiation in GIF++ at CERN in May 2016



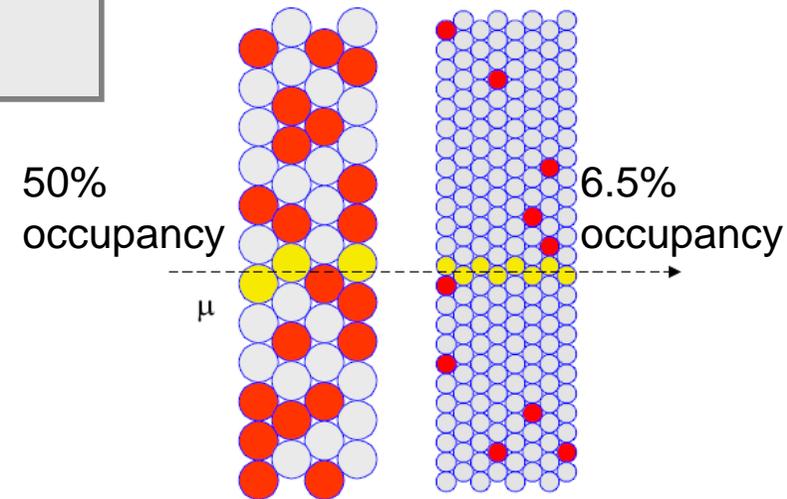
Small Diameter Drift Tube (sMDT) Chambers

By reducing the tube diameter from 30 mm (MDT) to 15 mm (sMDT) at otherwise the unchanged operating conditions (Ar:CO₂ (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 (\approx max. drift time) by a factor of 4, thus the masking of muon hits by preceding background hits.
- \Rightarrow 10 x higher rate capability of sMDTs compared to MDTs.

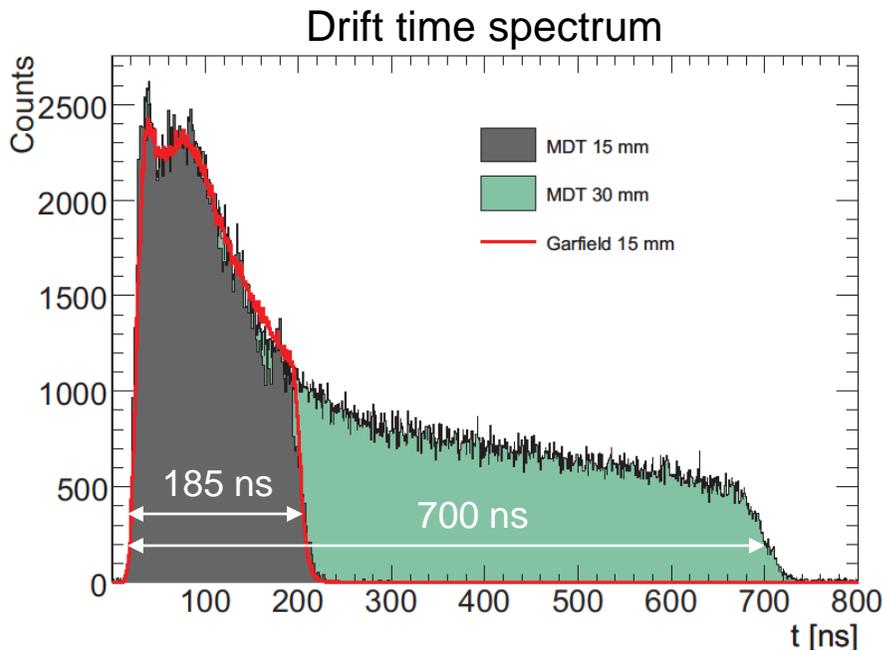


MDT 30 mm \varnothing sMDT 15 mm \varnothing



Also:

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

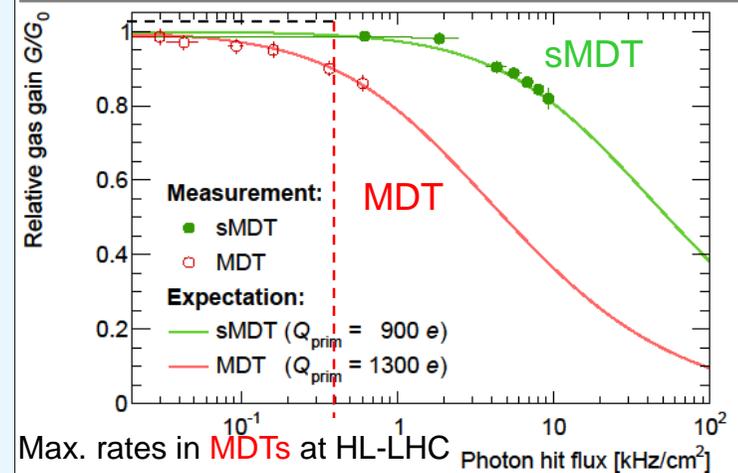
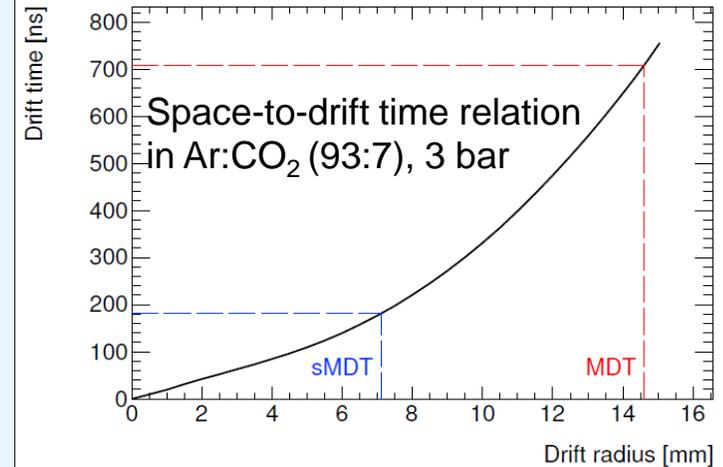
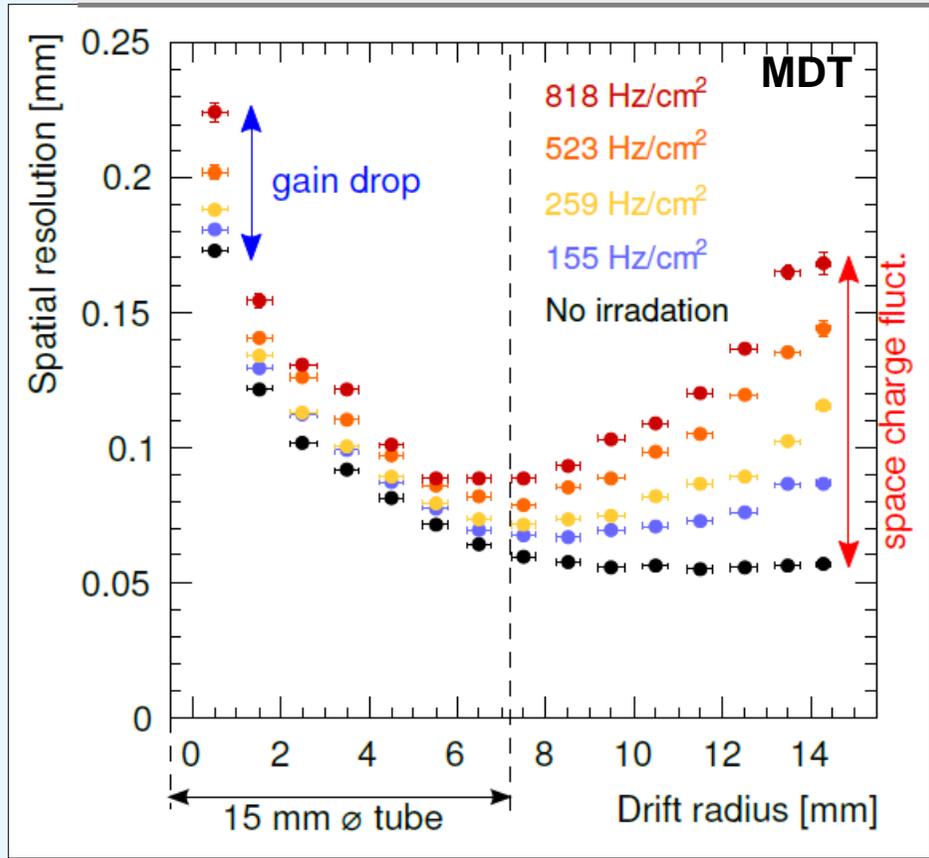


Space Charge Effects

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 due to almost linear r-t relation.
- Gain loss suppressed proportional to r^3 and less primary ionization.

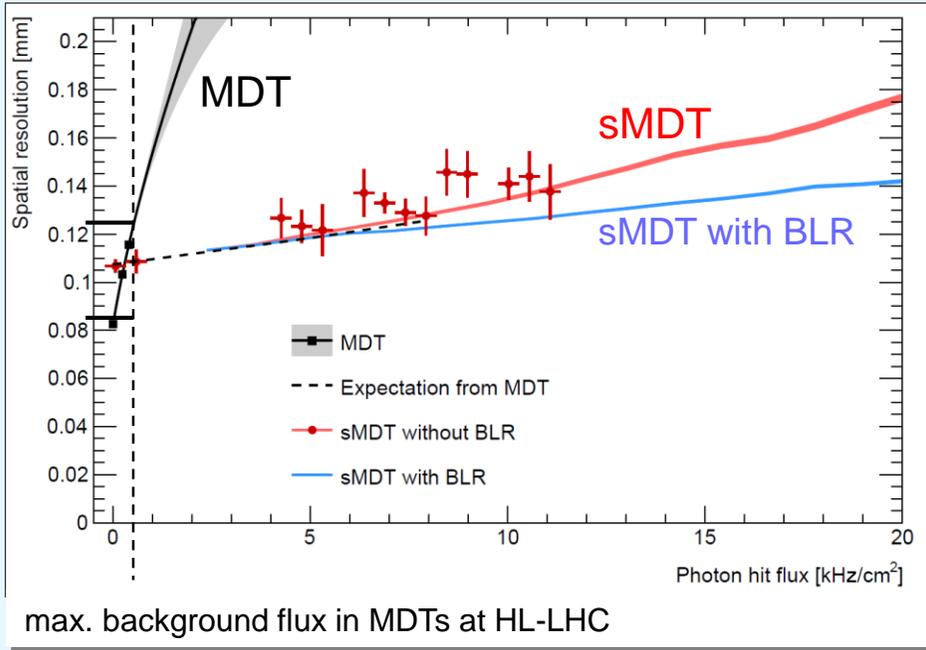


Measurements performed at the CERN Gamma Irradiation Facility

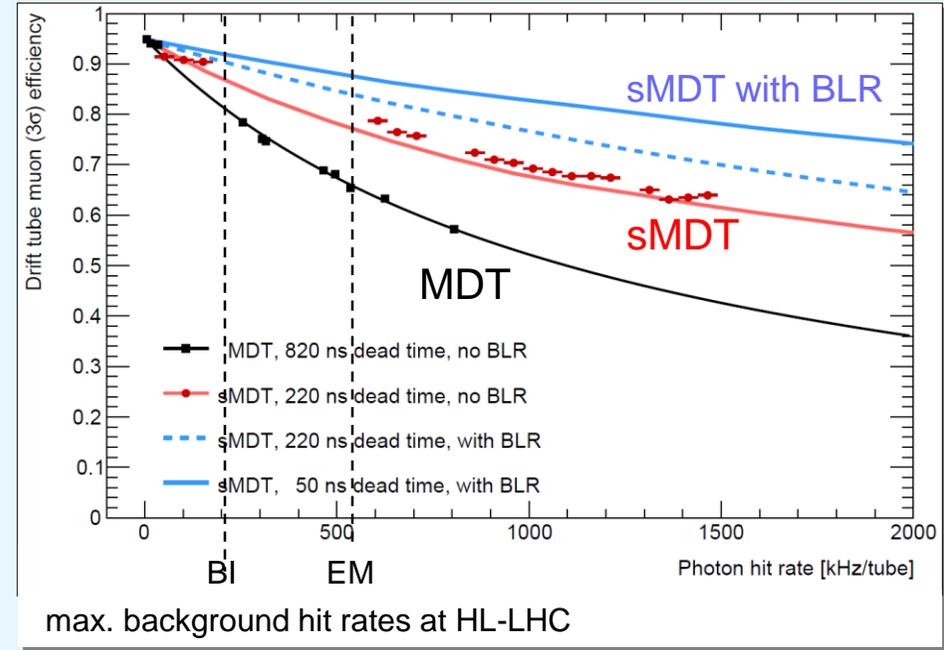
Rate Capability of sMDT Drift Tubes

Measurements at GIF with standard MDT readout electronics (bipolar shaping) and minimum adjustable deadtime of 220 ns for sMDTs (820 ns standard deadtime for MDTs).

Average spatial resolution

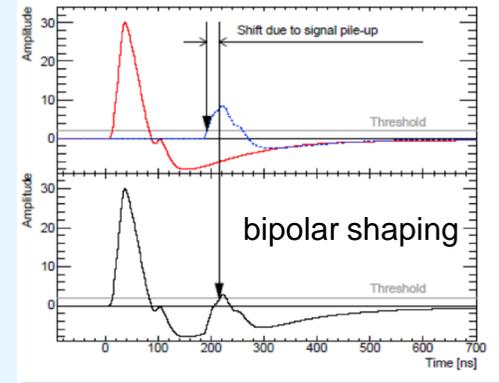


Muon efficiency



sMDT rate capability limited by current readout electronics due to signal pile-up effects (signal loss and additional time slewing).

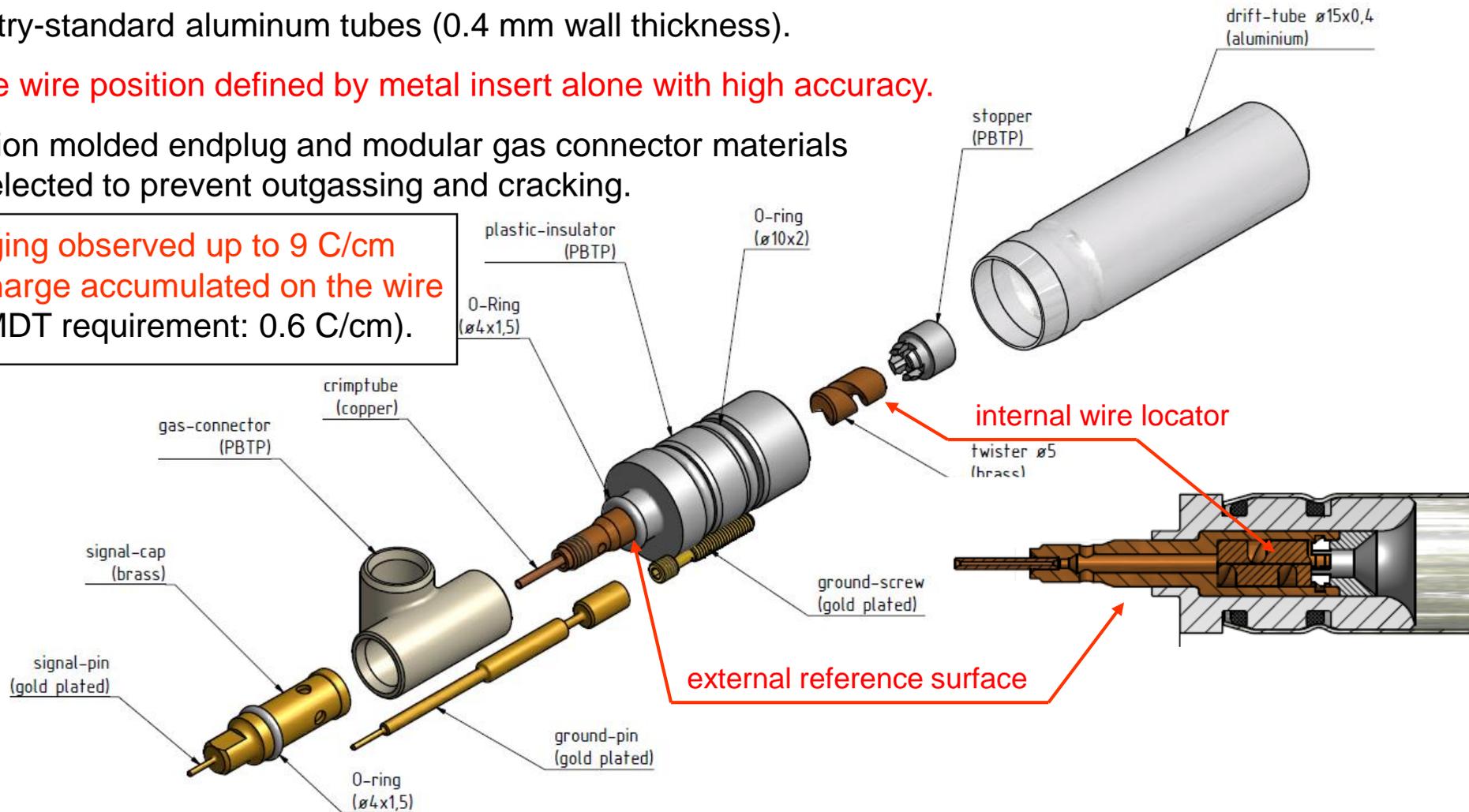
Can be suppressed using baseline restoration (BLR) like in ATLAS TRT, not needed for muon system at HL-LHC.



sMDT Chamber Design

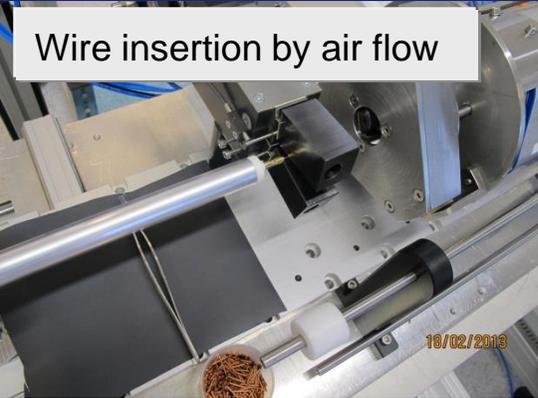
- Design and assembly procedures **optimized for mass production.**
- Simple, low-cost drift tube design ensuring high reliability.
- Industry-standard aluminum tubes (0.4 mm wall thickness).
- **Sense wire position defined by metal insert alone with high accuracy.**
- Injection molded endplug and modular 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).**

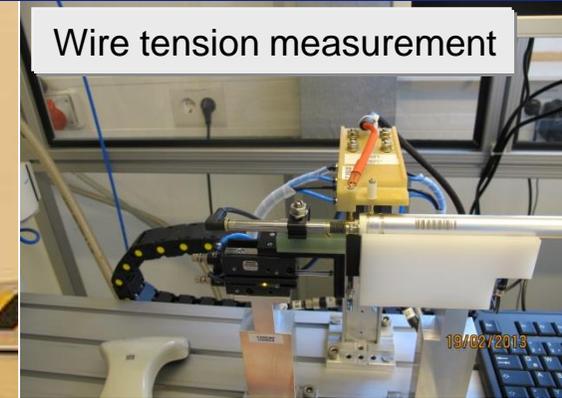


Automated Drift Tube Assembly

Wire insertion by air flow



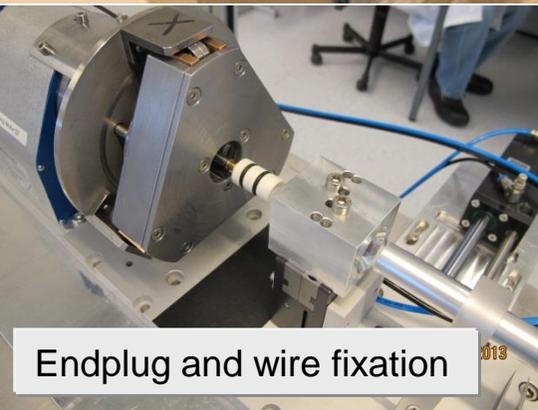
Wire tension measurement



Wire tensioning: $350 \text{ g} \pm 4\%$

Temperature controlled clean room.
Assembly of 100 tubes/day per station.
Failure rate below 1%.

Endplug and wire fixation



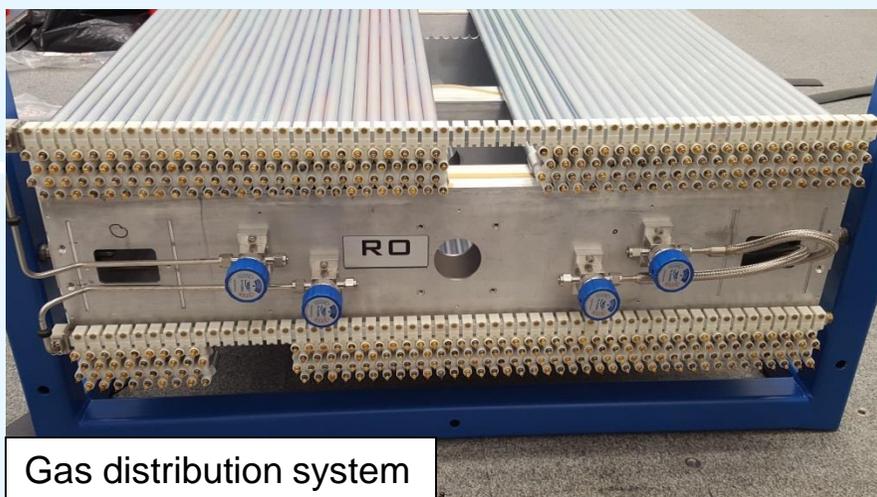
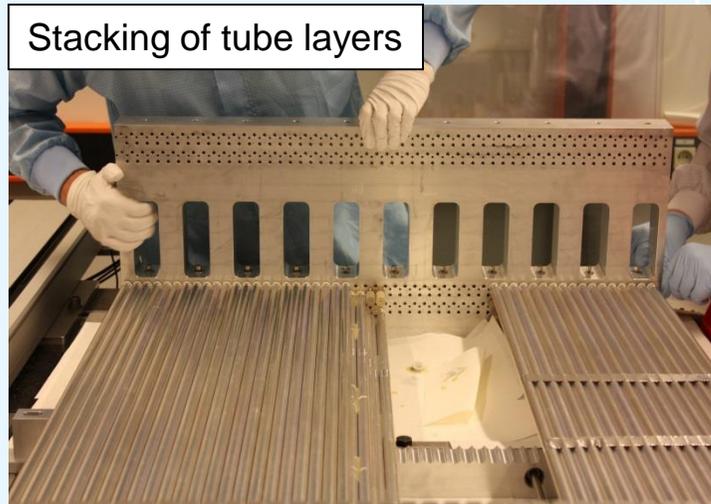
sMDT Chamber Construction

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

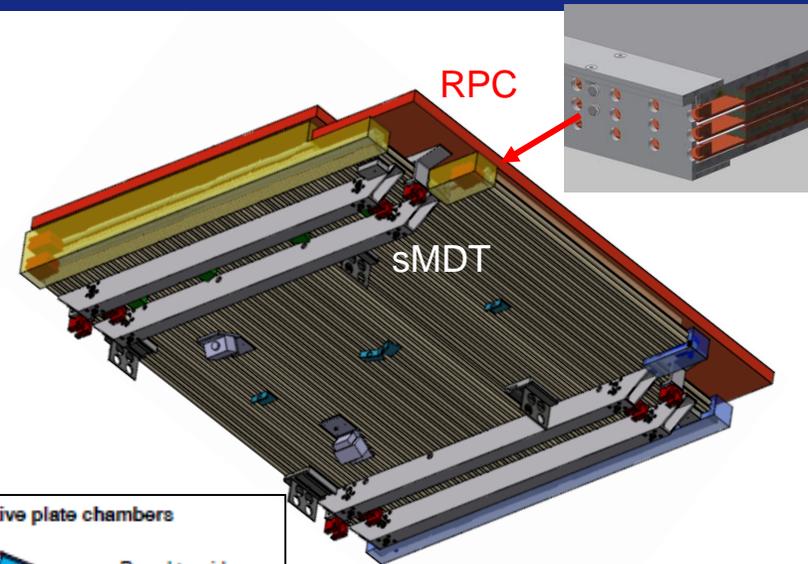


Completed BMG chambers

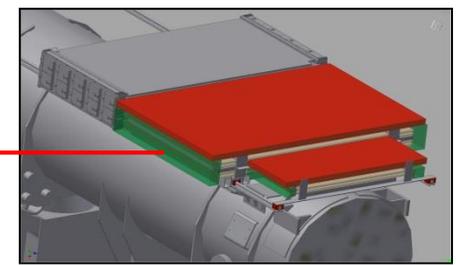
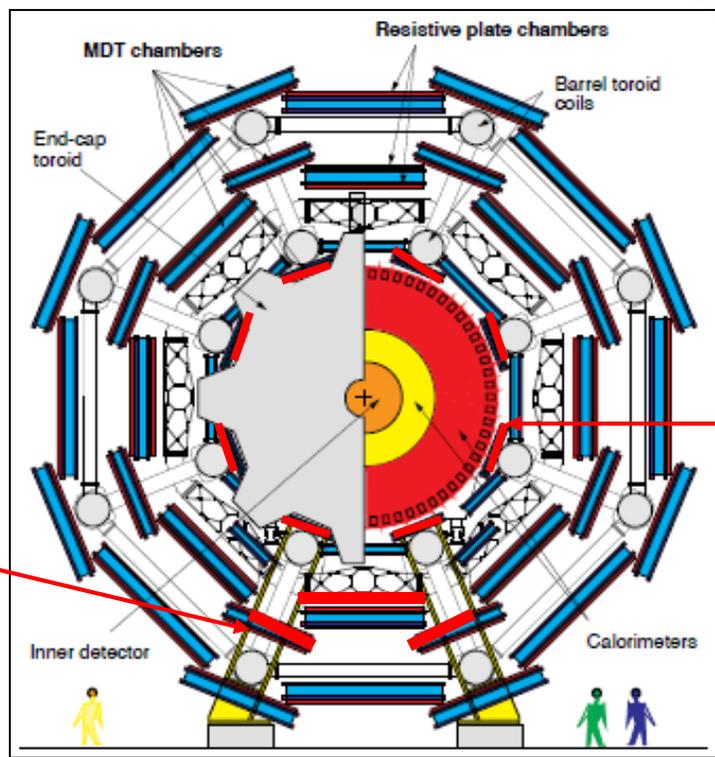
New sMDT and RPC Chambers for ATLAS



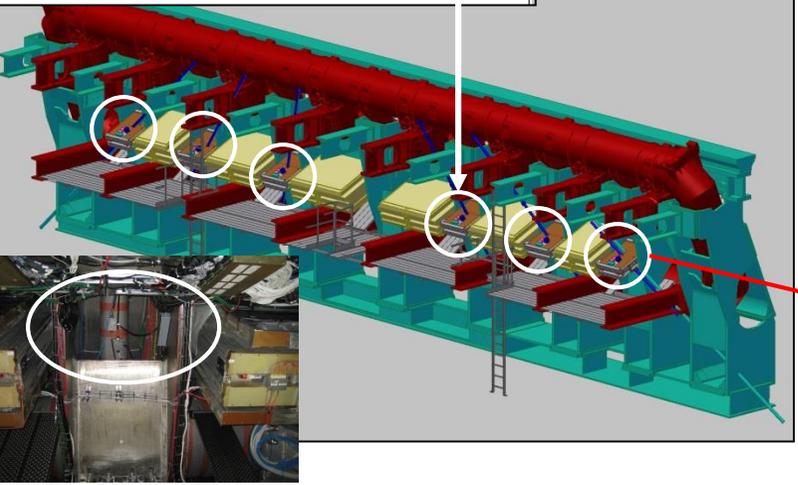
Construction 2015/16, completed.
Installation in the detector feet in
EYETS 2016/17



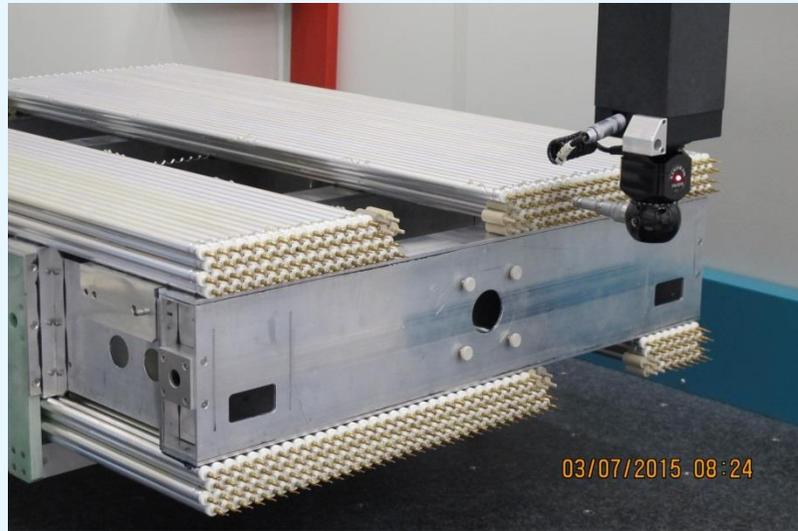
sMDT + triple thin-gap
RPC for ends of the
BIS layer



Installation in LS2.
Pilot project for
replacement of BIS
layer in Phase 2

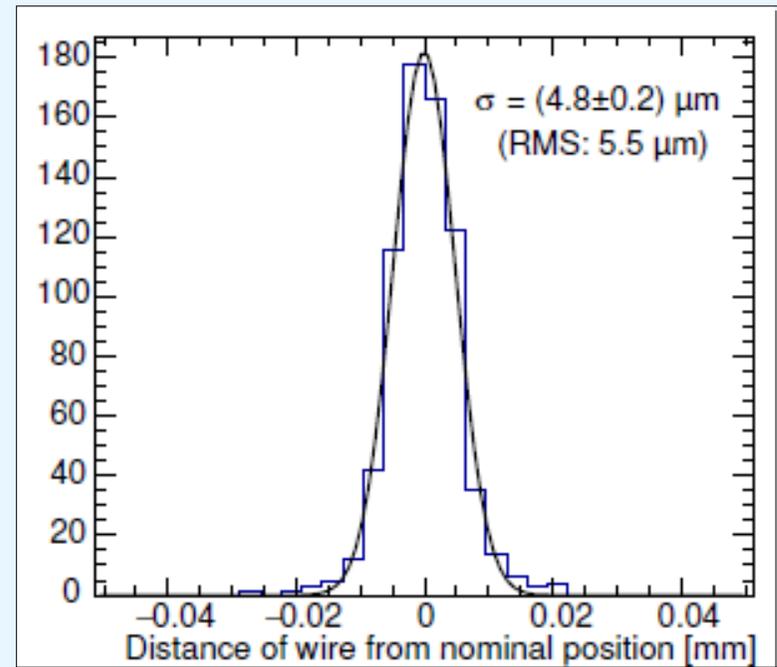
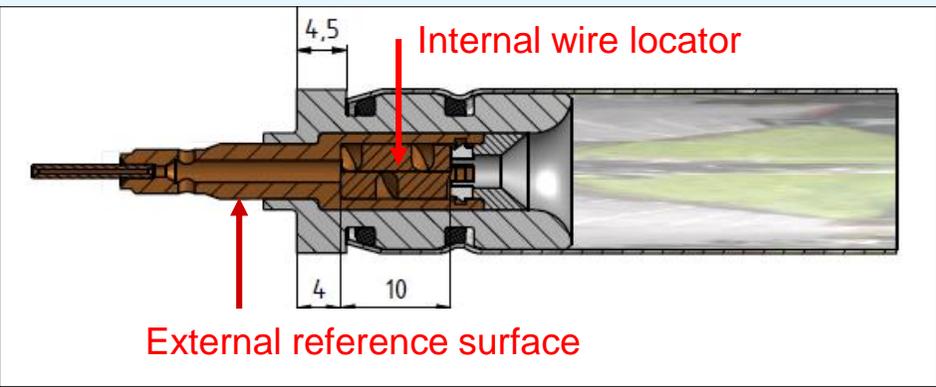


Quality Control: Mechanical Wire Position Measurement



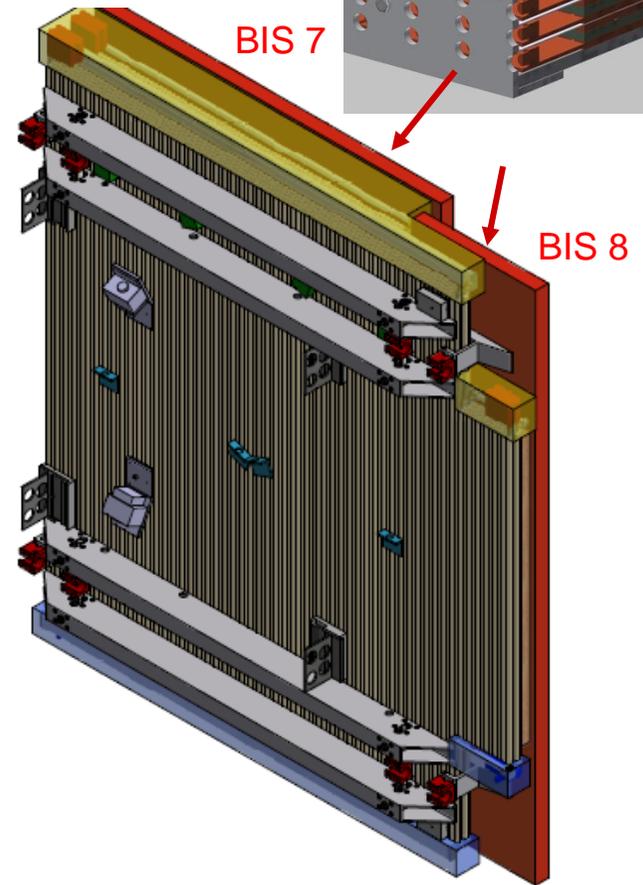
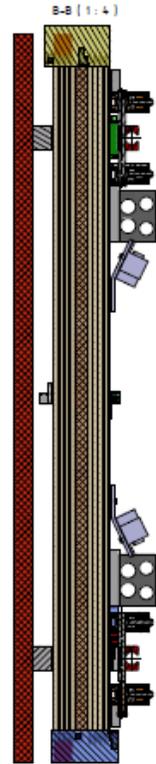
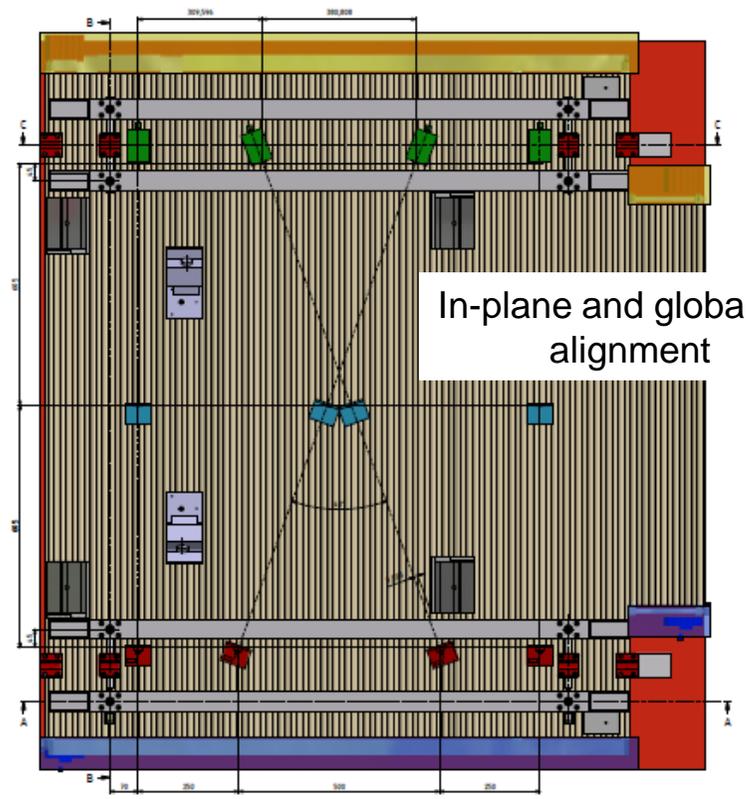
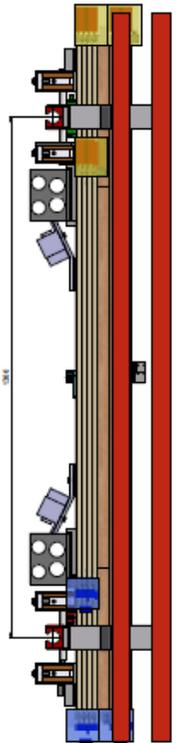
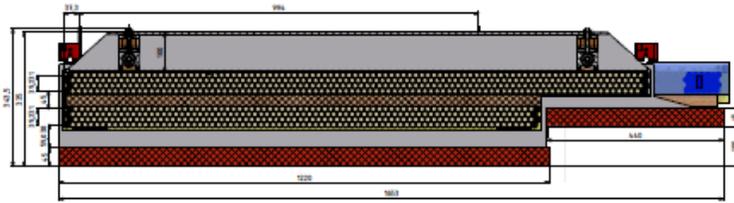
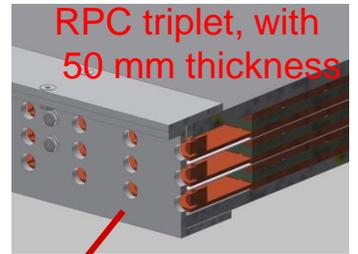
- Measurement of individual sense wire and alignment sensor positions with with 3D coordinate measuring machine.
⇒ Wire positions known with 2 μm precision.

- ⇒ Wire positioning accuracy of better than 5 μm , at the limit of the jigging precision, most precise chambers of such size (MDTs: 20 μm).



Integrated BIS Chamber Design

Highly integrated design of sMDT + RPC chambers for Phase 1 upgrade, well advanced
Model for Phase 2 BIS layer design. Very challenging space constraints.



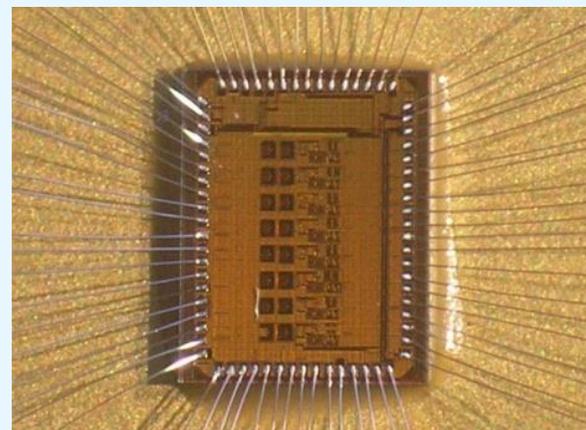
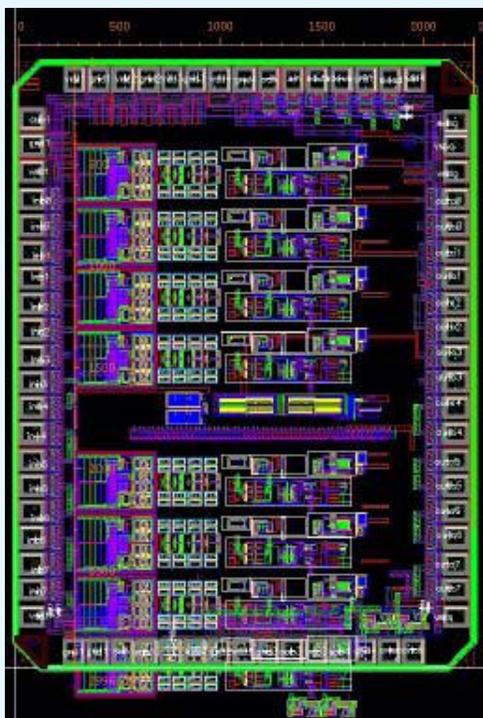
(s)MDT Readout Electronics Development for Phase 2

New ASD and TDC chips in 130 nm IBM CMOS technology supported by CERN (now Global Foundries) with sufficient radiation hardness are already under development,

both for replacement of MDT front-end boards and for the new sMDT chambers at HL-LHC.

Latest submissions in August 2016. Expected to be final ASD iteration.

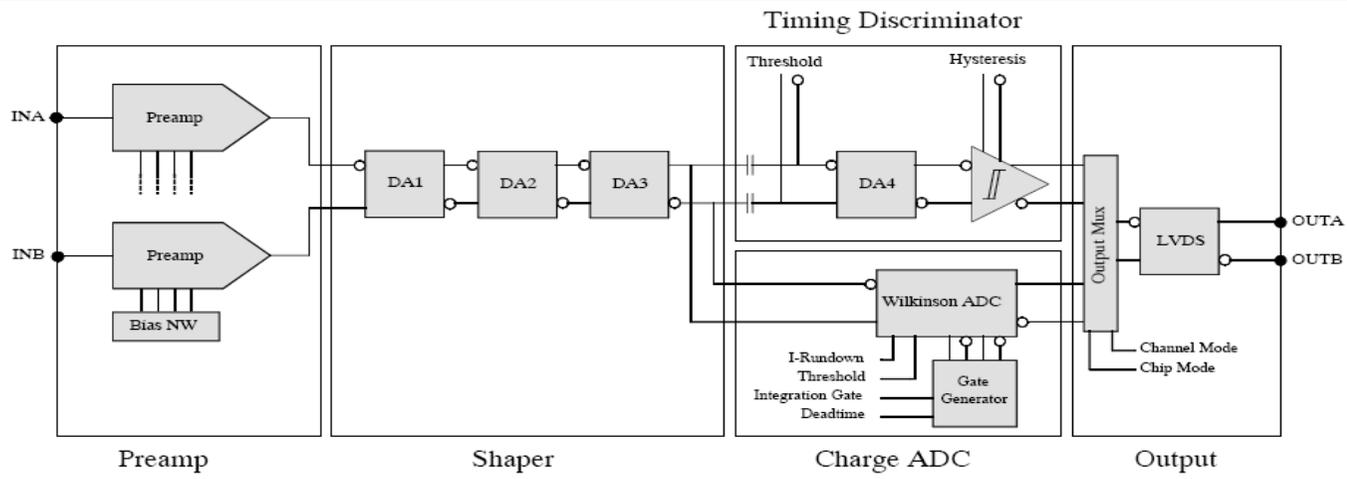
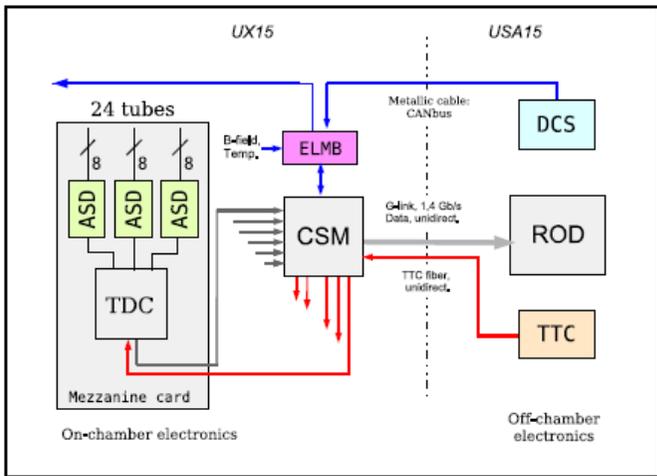
Prototype ASD II chips,
6.6 mm² size



Alternatively, also FPGA implementation of the new fast-readout TDC under investigation.

(s)MDT Readout Electronics Development for Phase 2

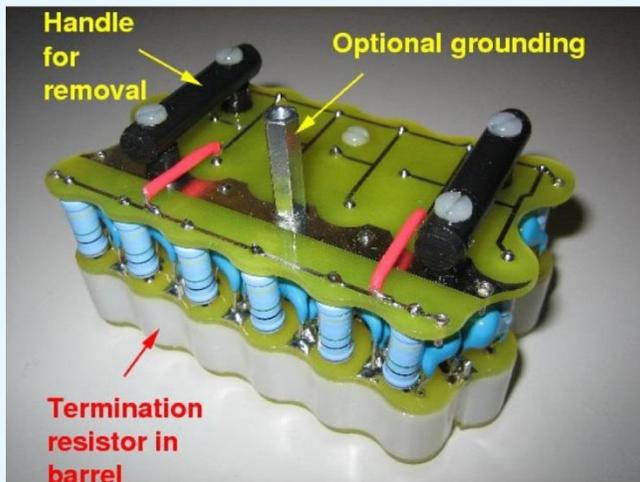
- Performance requirements for the ASDs are unchanged compared to Phase 1, but present chips in 500 nm Agilent CMOS technology cannot be fabricated anymore.
 ⇒ Same architecture as the present ASD chip:
 bipolar shaping, peaking time 15 ns, Wilkinson ADC for time-slewing corrections: 100 μm → 80 μm
 MDT drift tube resolution.



- New TDCs will enable fast readout of drift time information for the (s)MDT-based 1st level muon trigger with order 1 ns resolution at up to 5 Gbps data rate at HL-LHC.
- Design of a new data concentrator (Chamber Service Module, CSM) also started.

sMDT Readout Electronics

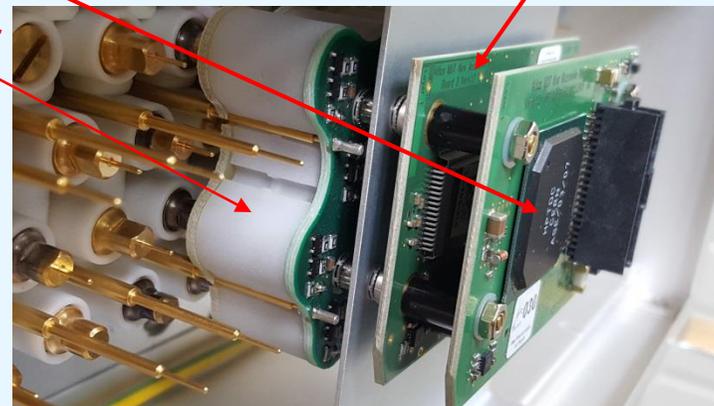
High-voltage
distribution boards (24 channels)



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

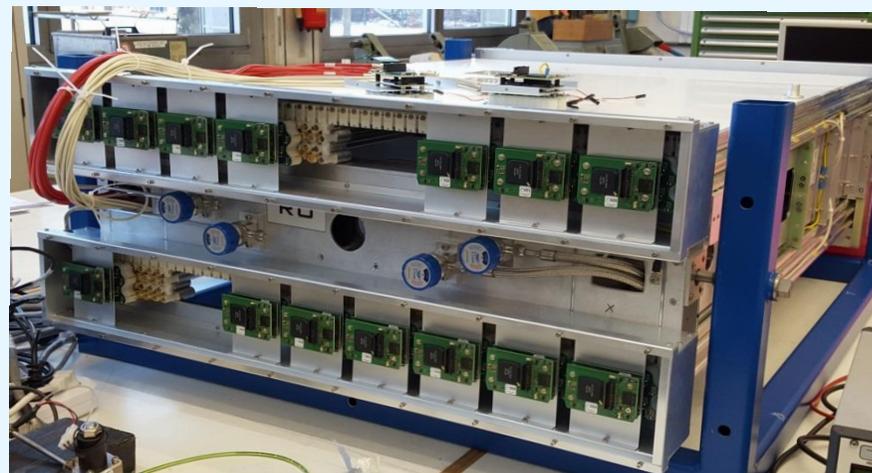


Challenge of 4 x denser tube grid:

Direct connection to endplug signal pins.

HV protection of termination resistors and
coupling capacitors.

⇒ Stacked passive and active boards.



Conclusions

ATLAS muon spectrometer Phase 2 upgrades are defined (IDR October 2016, followed by TDR mid 2017).

R&D for new muon chambers (barrel: thin-gap RPCs, sMDTs; endcap: sTGCs) and for (s)MDT front-end electronics replacement with fast readout for new MDT-based 1st level muon trigger is quite advanced.

The new RPC development is also pursued as an AIDA 2020 project.

Well understood detector technologies have been further improved to cope with higher rates and space constraints.

They also fit well into the existing framework of services, alignment, DAQ and software.

Pilot projects and detailed designs are already on the way for Phase 1 upgrades.

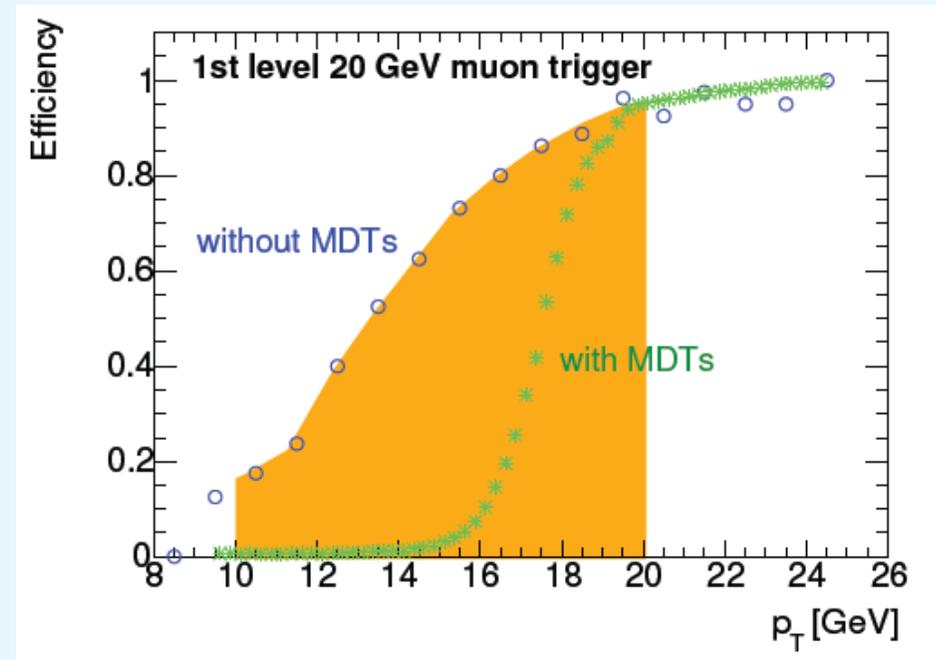
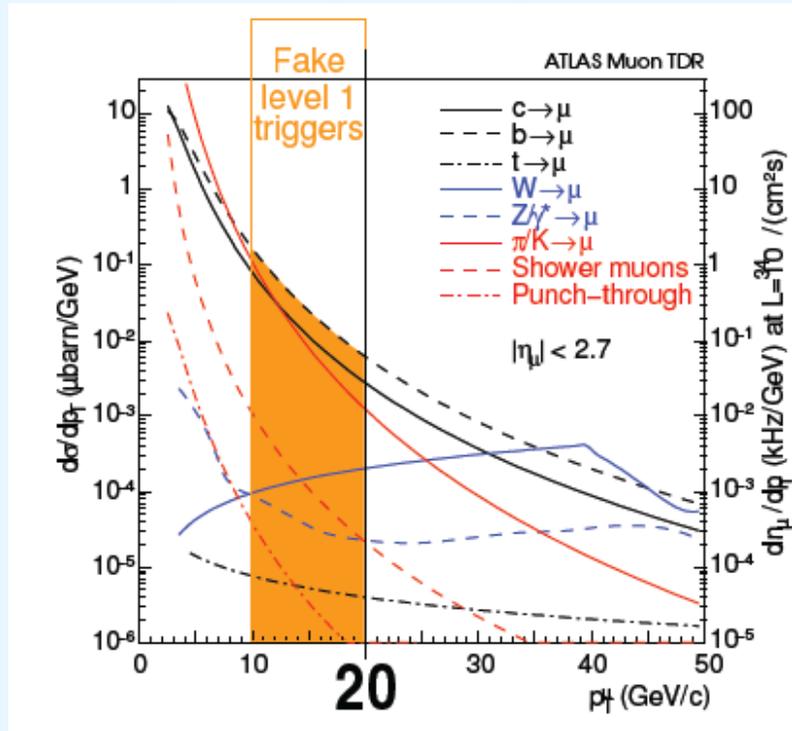
Muon System Upgrade Strategy for HL-LHC

Improvement of the 1st level muon trigger selectivity

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

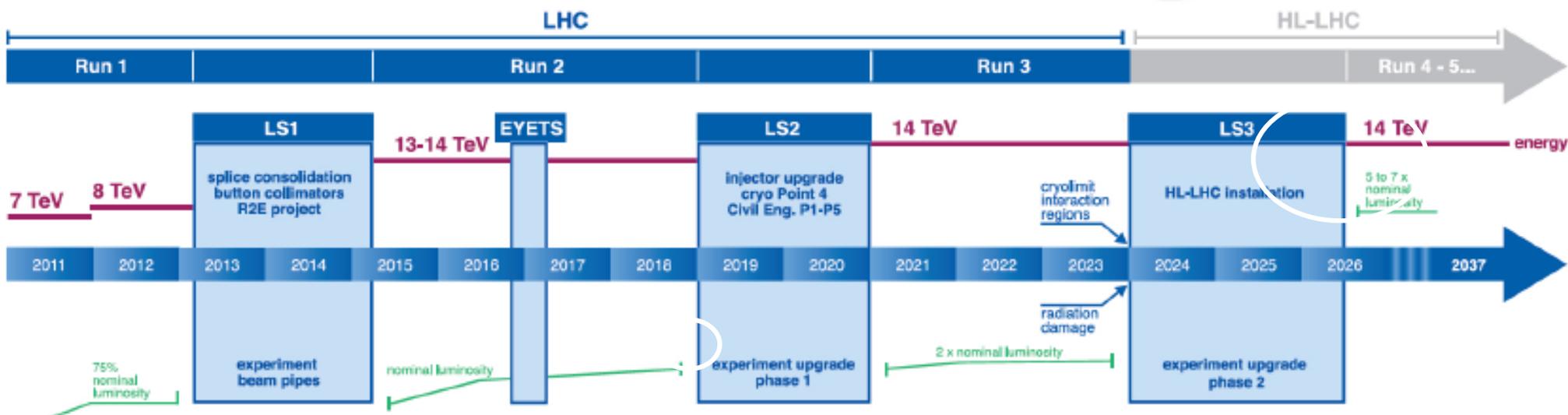
Requires implementation of fast readout of the MDT chambers, i.e. replacement of the MDT on-chamber electronics, in particular new TDC and data concentrator (CSM).

New MDT front-end and RPC trigger electronics is also required to cope with the increased rate (≥ 1 MHz) and longer latency of the 1st level trigger at HL-LHC.



ATLAS Barrel Muon Chamber Upgrades

LHC / HL-LHC Plan



2014 (LS1): BME
2 sMDT + RPC chambers
 to improve acceptance and momentum resolution in the bottom barrel sector. In operation since Run 2.

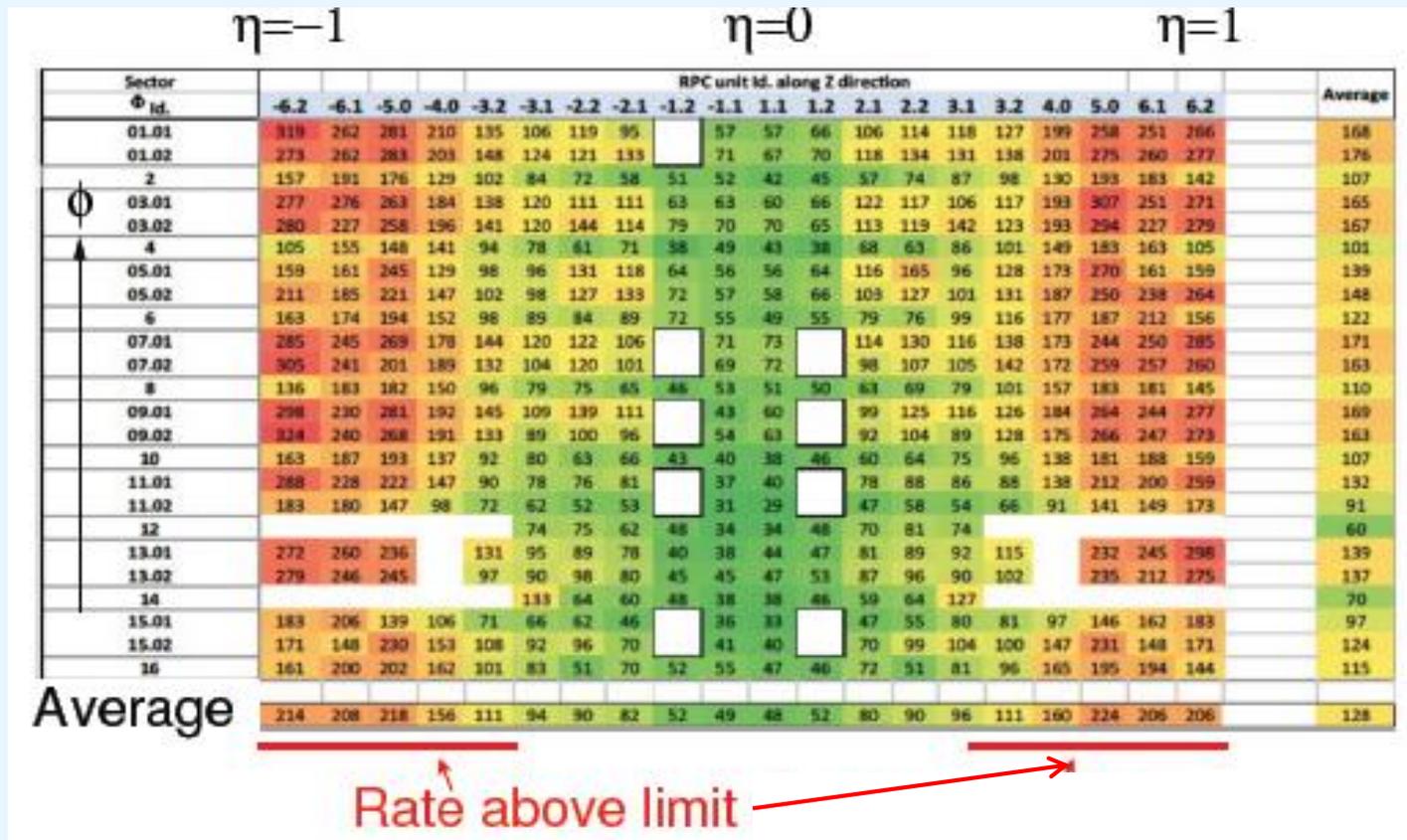
Q1 2017: BMG
12 sMDT chambers
 to improve the momentum resolution (by factor of 2 at 1 TeV) in the detector feet.

2019-20 (LS2): BIS 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 (LS3): BIS, BIL 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.

Background Rates in RPCs at HL-LHC

Present RPCs are certified up to rates of 100 Hz/cm² over 10 years of LHC operation w/o efficiency loss. Both rates and total operation time will be exceeded at HL-LHC.

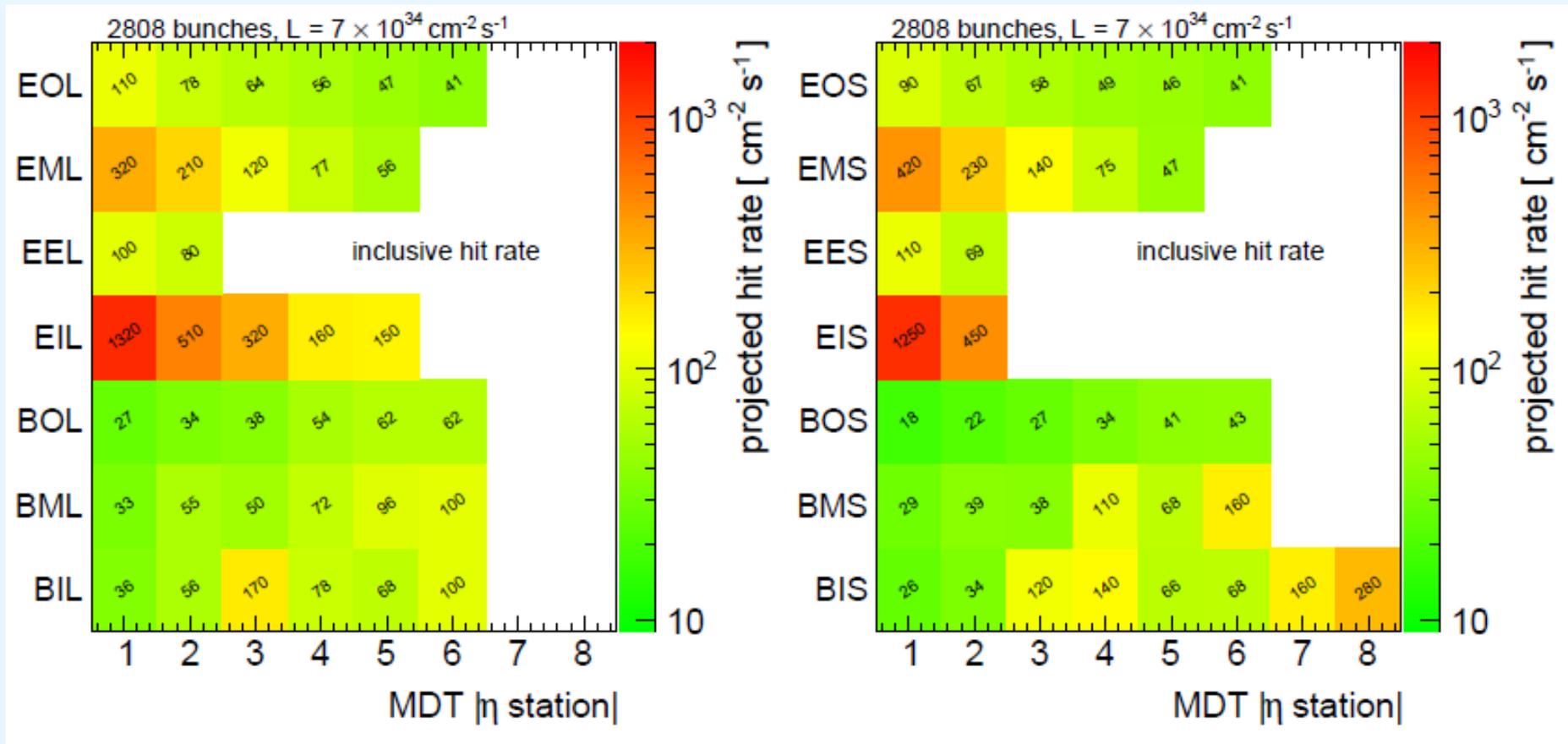


maximum in present
BM layer RPCs
[Hz/cm²]

⇒ Reduce HV and accumulated charge (but also efficiency). Backup with new BI RPCs.

Background rates up to 600 Hz/cm² are expected in the new RPCs in BI layer at HL-LHC!

Expected Background Rates in MDTs at HL-LHC



RPC FEE for BIS7/8 Pilot Project

