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Commissioning of the new small-diameter Monitored Drift Tube detectors for the Phase-1 upgrade of the ATLAS muon spectrometer

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Moscow (Russia)
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Current status of the ATLAS Muon Spectrometer

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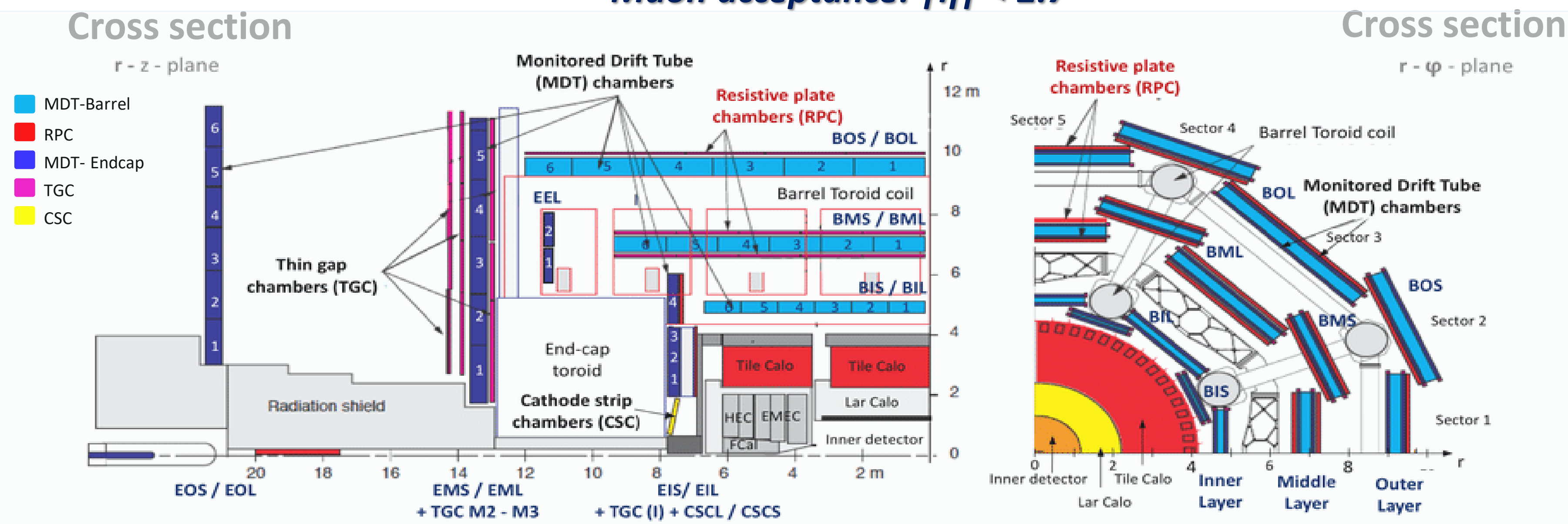
The ATLAS Muon Spectrometer was designed to provide muon identification, excellent triggering, timing and momentum measurements at LHC nominal luminosity of $10 \times 34\ cm^{-2}s^{-1}$

Muon acceptance: |η| < 2.7



Four Technologies used for the Muon System:

✓ ***Precision Tracking Chambers***

- *MDT (Monitored Drift Tubes), |η| < 2.7:*
- *CSC (Cathode Strip Chambers), 2.0 < |η|< 2.7:*

✓ ***Primary Trigger Chambers***

- *RPC (Resistive Plate Chamber), |η| < 1.05*
- *TGC (Thin Gap Chamber), 1.05 < |η| < 2.4*

Current status of the ATLAS Muon Spectrometer

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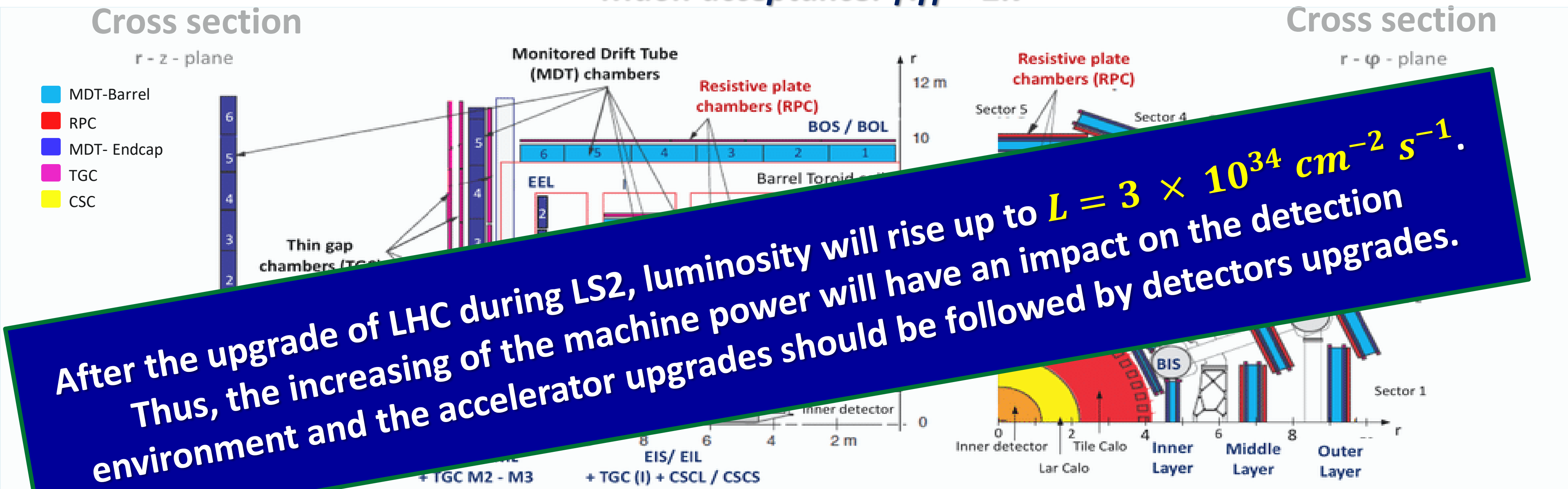

After the upgrade of LHC during LS2, luminosity will rise up to $L = 3 \times 10^{34}\ cm^{-2}\ s^{-1}$. Thus, the increasing of the machine power will have an impact on the detection environment and the accelerator upgrades should be followed by detectors upgrades.

Four Technologies used for the Muon System:

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ATLAS Muon Spectrometer Phase-I Upgrade

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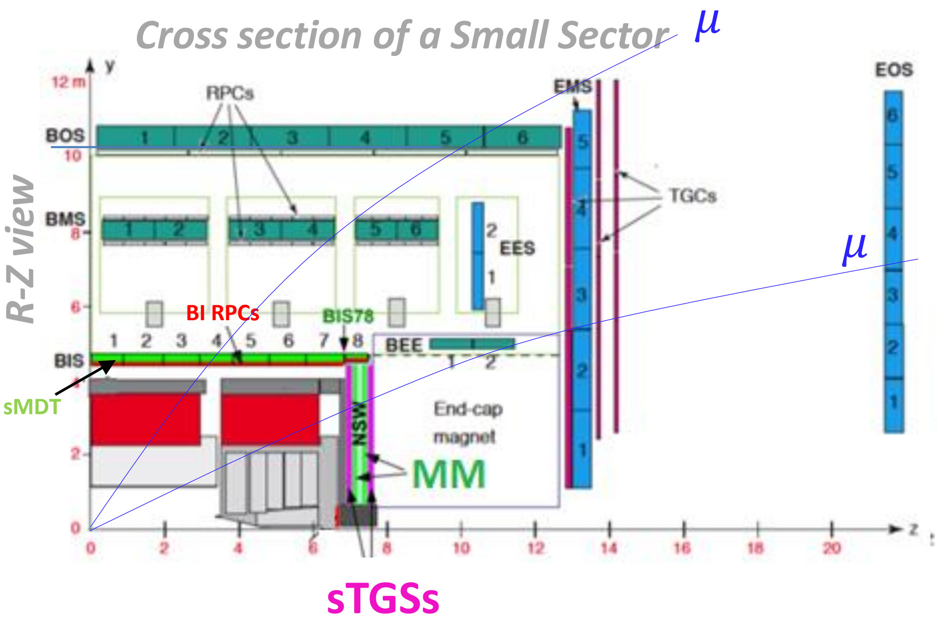
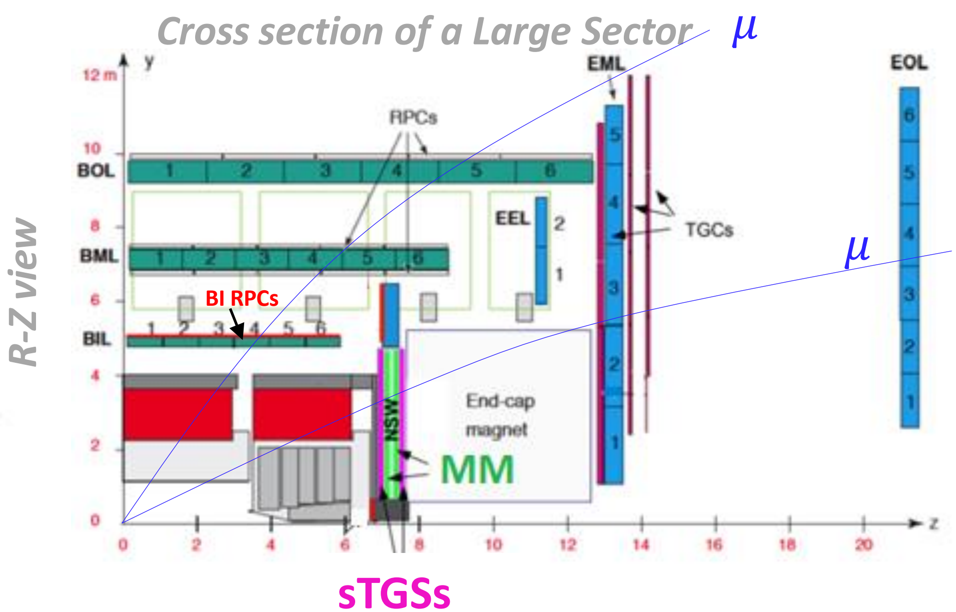
ATLAS Muon Spectrometer upgrade is motivated by the improving of the high p_T muon trigger system

1. Endcap muon tracking and trigger upgrade at $1.3 < |\eta| < 2.7$:

The *New Small Wheels* project combine the two different gaseous detector technologies:

- high-resolution **small-strip Thin Gap Chamber (sTGC) - > 96** detectors for the triggering
- Micro-pattern gaseous detector - **Micromegas (MM) -> 64** detectors for the tracking





The NSW will replace part of the muon Endcap station (Cathode Strip Chamber) that could lead to improve the online muon identification capability by using its precise reconstruction of candidate muon track segments

ATLAS Muon Spectrometer Phase-I Upgrade

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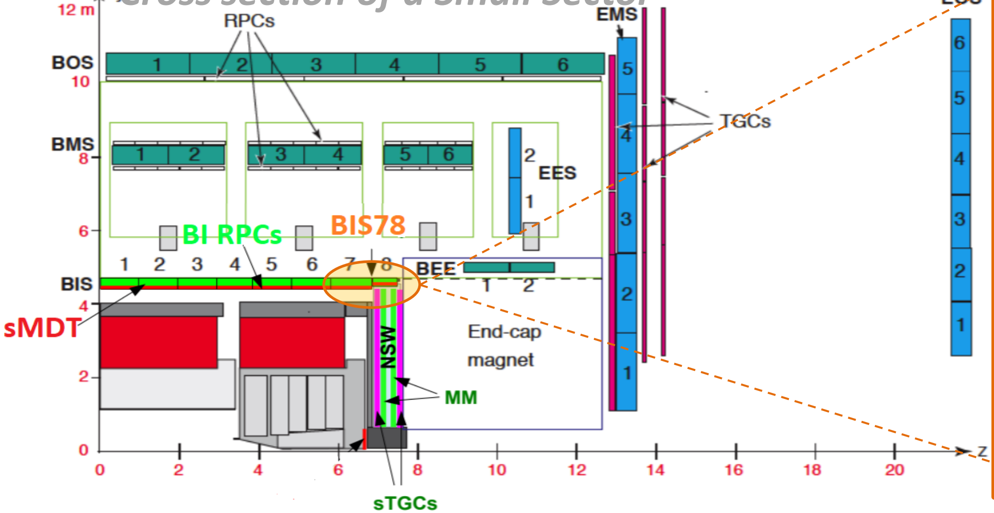
ATLAS Muon Spectrometer upgrade is motivated by the improving of the high p_T muon trigger system

2. Barrel muon trigger upgrade at $|\eta|< 1.3$:

The *Barrel Inner (BI) Upgrade* project consists of:

- **new triple-Resistive Plate Chamber (t-RPC) -> 276** detectors for the triggering:
  - to close acceptance gaps by compensating the potential efficiency loss of the present RPC
  - to improve the trigger selectivity
  - to increase the redundancy of the muon system
- **new small Monitored Drift Tubes chambers (sMDT) -> 96** detectors for the tracking:
  - to replace current MDT chambers and allow for a 3-station RPC trigger
  - to increase the tracking rate capability

Cross section of a Small Sector



In 2019/20 (Long shutdown-2) the BIS78 Phase-1 Upgrade project will realize as a pilot for Phase-2:

16 sMDT and 32 t-RPC chambers will install in the barrel-endcap transition region at $1.0 < |\eta| < 1.3$

In total: ~ 11000 drift tubes!

BIS78 sMDT Detectors for ATLAS Muon Spectrometer Upgrade

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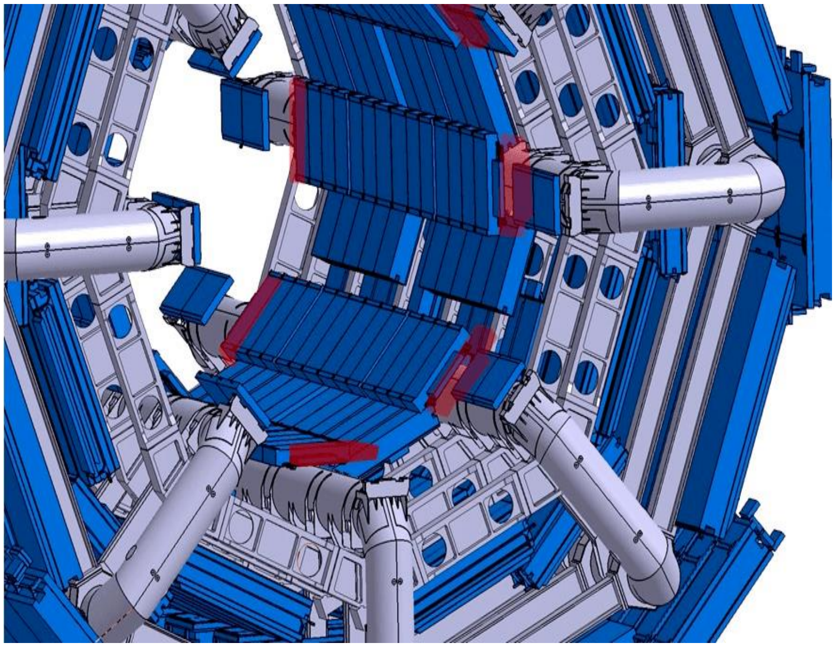
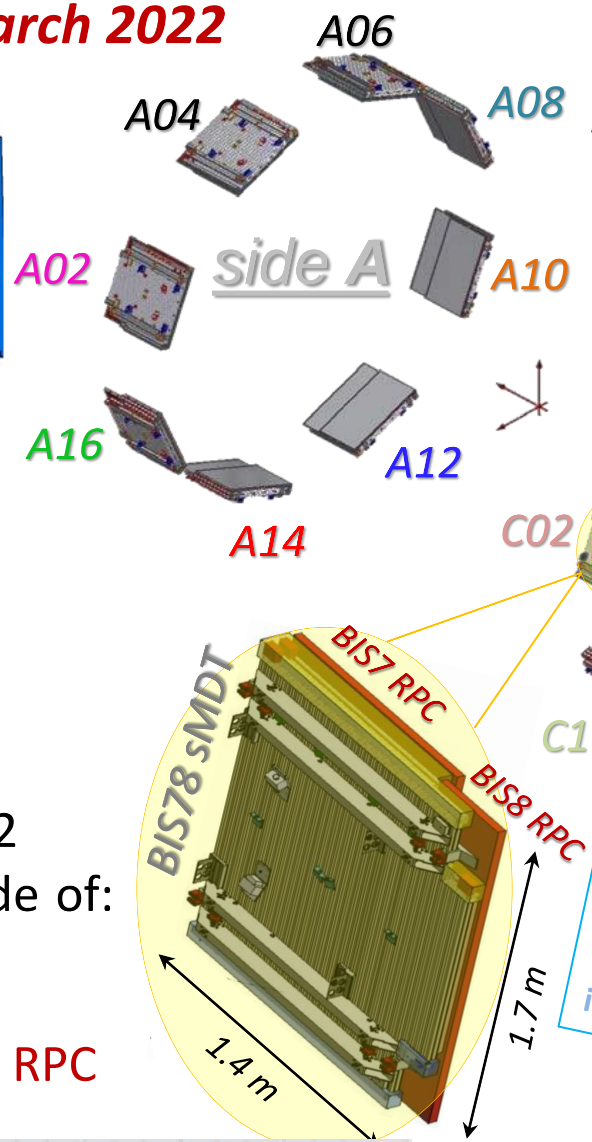
BIS78 project in Phase-1/Run-3 March 2022





12 different sMDT detector types

Chamber envelopes re-defined and maximized with the Technical Coordination for installation in ATLAS for Phase-1

Layout:

16 new muon stations replacing the 32 existing BIS7-8 MDTs. Each station made of:

- one BIS78 sMDT detector
- two t-RPC triplets: BIS7 RPC + BIS8 RPC

New small Drift Tube Chamber Technology

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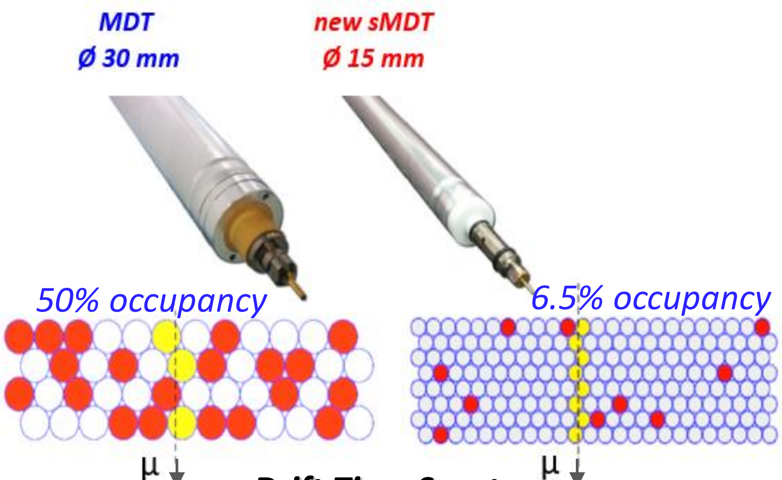
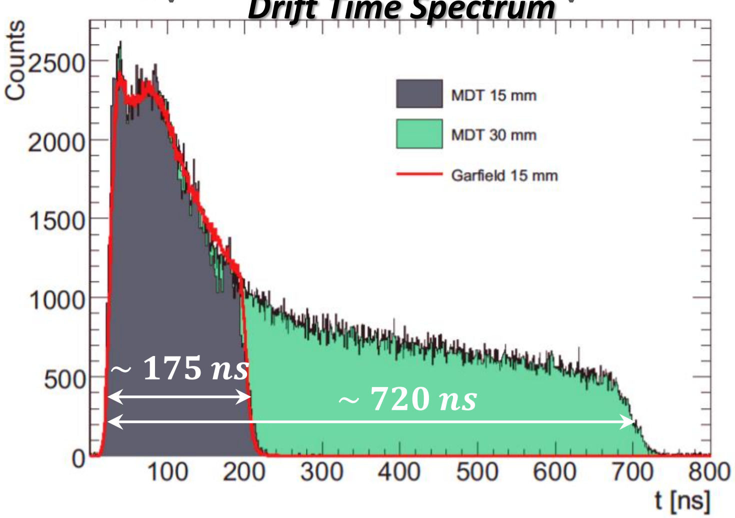
The sMDT Technology has been developed since 2008 in order to cope with the expected high background rates at the HL-LHC





sMDT baseline parameters

Properties	*Current MDT*	*sMDT*
Tube Diameter	$30\ mm$	*15 mm*
Number of tube layers	4	*8*
Operating Gas Mixture	$Ar{:}\ CO_2$ (93:7)	$Ar{:}\ CO_2$ (93:7)
Operating Pressure	$3\ bar$	$3\ bar$
Operating HV working point	*3070 V*	*2730 V*
Gas gain	2×10^4	2×10^4
Max. Drift time	$\sim 720\ ns$	$\sim 175\ ns$
Single tube space resolution	*83 ± 2 μm*	$106 \pm 2\ \mu m$

Main Advantages of the 15 mm Ø sMDT detector:

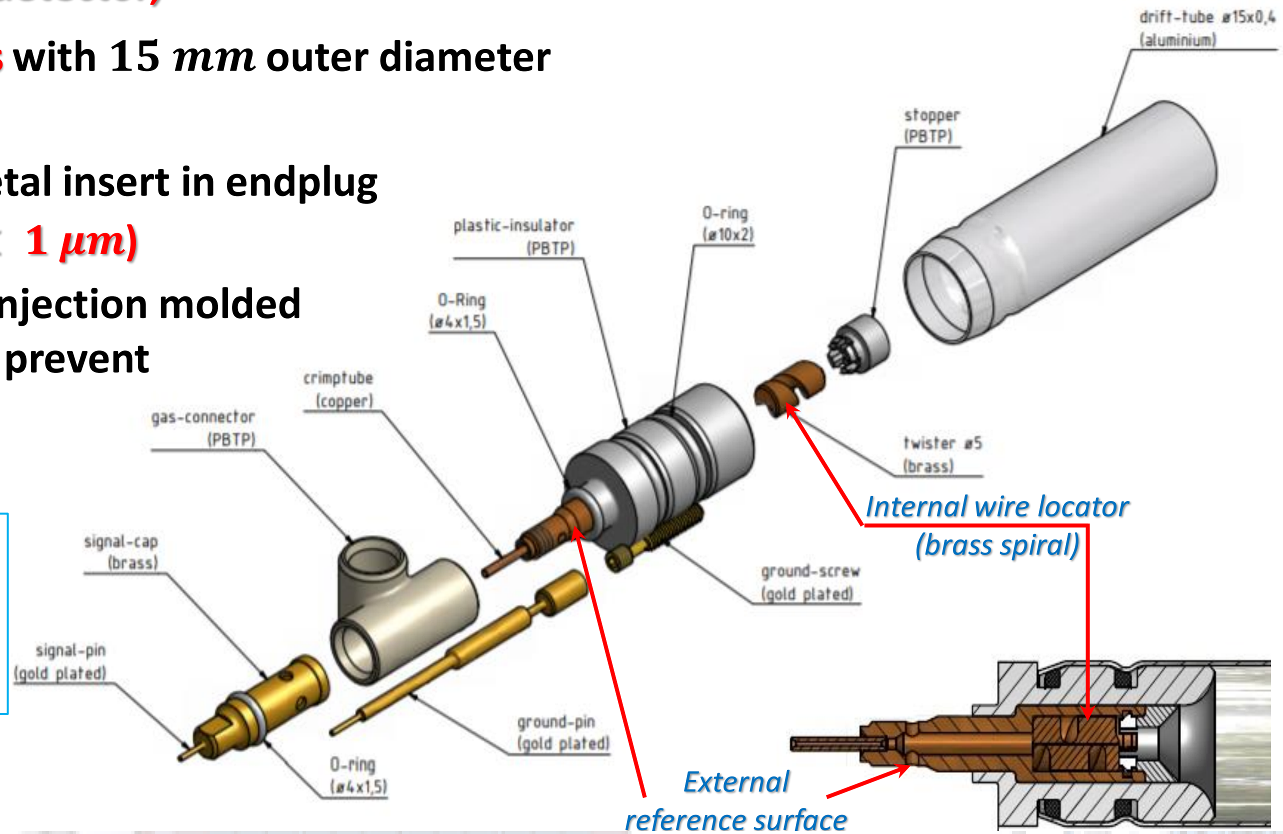
- ✓ 10 times high rate capability with respect to the current MDT detectors, i.e. 8 times lower background detector occupancy
- ✓ 4 times lower electronics dead time (= max. drift time)
- ✓ 2 times more tube layers within the same detector volume allowing for additional increase in the muon tracking efficiency
- ✓ No aging effects after foreseen integrated luminosity of HL-LHC (even up to 9 C/cm)

sMDT Detector Design

Design of the new sMDT chambers will be quite similar to the one of existing MDT detector

- The sMDT chamber design and construction procedures **optimized for mass production** at the Max Planck Institute for Physics (Munich);
- Simple drift tube design and use the inexpensive materials to ensure **high reliability of the new sMDT detector;**
- **Standard industrial Al tubes** with $15\ mm$ outer diameter ($0.4\ mm$ wall thickness)
- Wire position defined by metal insert in endplug alone with high accuracy **($< 1\ \mu m$)**
- Endplug and gas connector injection molded plastic materials selected to prevent outgassing and cracking

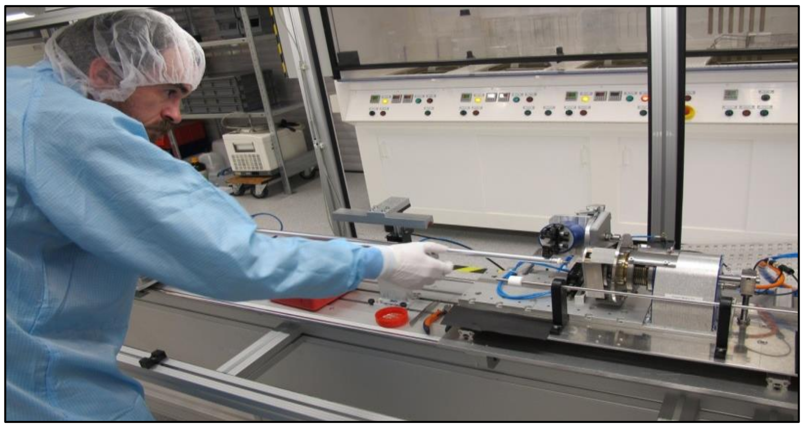
The drift tube design and fabrication procedures are the same as used for the construction of the BMG sMDT chambers in 2016



sMDT Assembly Procedures (I)

All drift tubes for sMDT detector are assembled by using a semi-automated wiring station in a temperature controlled clean room (class 1000) at the Max-Planck-Institute in Munich

1. Endplug sealing and wire insertion with air-flow without any manual intervention



2. Wire tensioning up to 350 ± 15 g and crimping, the tension measurement

3. HV and Helium leak test at 3 bar

Tubes mass productions

sMDT Assembly Procedures (II)

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After passing the QC tests, the drift tubes are assembled into chambers in climatized clean room

4. Drift tube positioning in precision jigs

5. Gluing tubes during sMDT assembly by using an automated glue dispenser

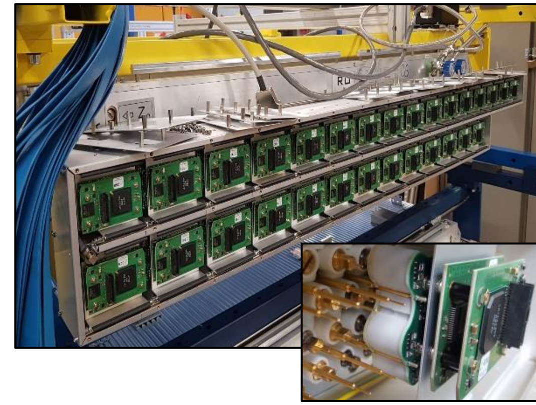
6. Brackets for the precise mounting of the alignment sensor platforms as a part of jigging

- Assembly procedures has been designed for the mass production of chambers with large numbers of tube layers
- One complete sMDT chamber for BIS78 project can be assembled within 2 working days, including the precise mounting of the alignment sensor platforms

sMDT Assembly Procedures (III)

7. Alignment system is mounted

8. Gas supply, high voltage and readout electronics are installed



9. Readout and ground cables are connected

sMDT is ready for the validation campaign!

- The in-plan alignment monitoring systems as well as the 12 temperature sensors are mounted with 20 μm positioning accuracy on the surface of the sMDT detector
- Assembled BIS78 sMDT chamber are fixed on rails in the transport frame
- Gas supply systems, high-voltage and readout electronics are installed on the chambers

sMDT Assembly Procedures (III)

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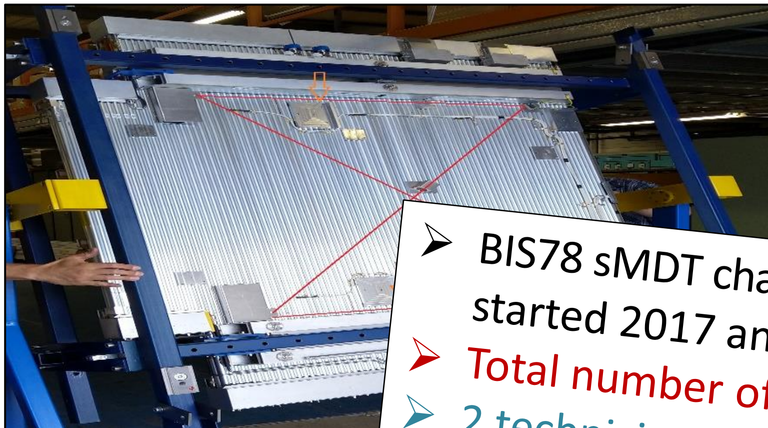
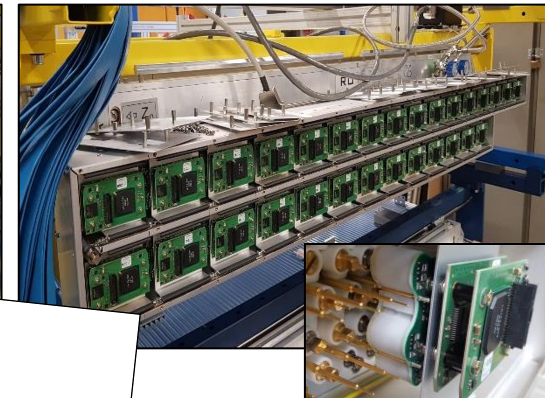
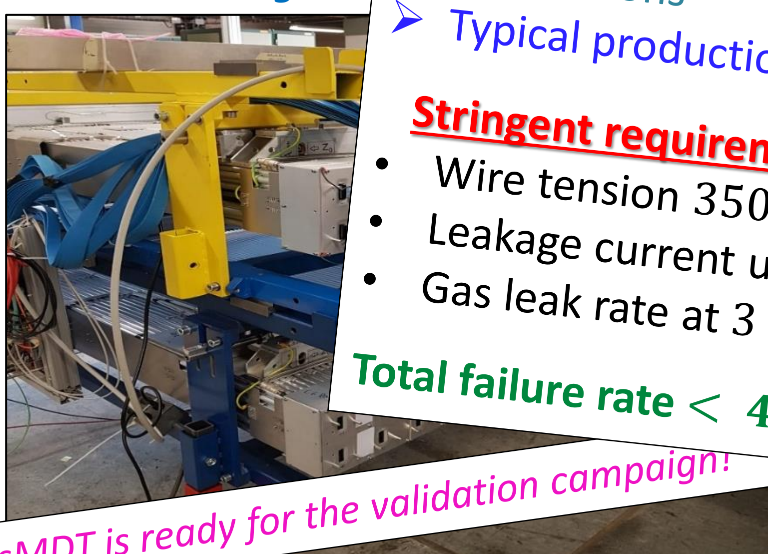
7. Alignment system is mounted



8. Gas supply, high voltage and readout electronics are installed



9. Readout and groun



- BIS78 sMDT chamber construction has been started 2017 and finished 2019
- Total number of BIS78 tubes: ~ 11000
- 2 technicians only require for the tubes mass productions
- Typical production rates of ~ 100 tubes per day

Stringent requirements:

- Wire tension $350 \pm 15\ g \rightarrow$ wire sag $\pm 10\ \mu m$
- Leakage current under $HV < 2\ nA/m$
- Gas leak rate at $3\ bar < 10^{-8}\ bar \times L/s$

Total failure rate $< 4\%$.

itoring systems as
ensors are mounted
racy on the surface

amber are fixed on

voltage and readout
the chambers

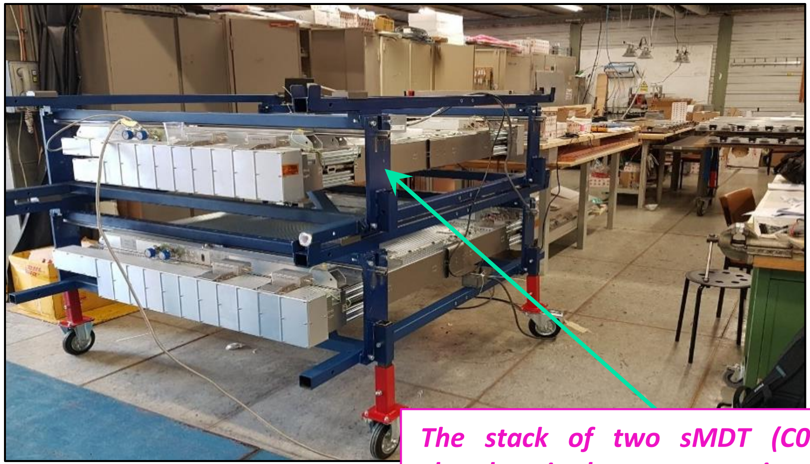
sMDT is ready for the validation campaign!

BIS78 sMDT detectors @CERN BB5 facility

Assembled sMDT detectors arrived from MPI (Munich) to CERN BB5 facility

Short-term sMDT storage @CERN BB5

sMDT detectors under validation tests



The stack of two sMDT (C08/C16) chambers in the transportation frame

Gas Leak Rate Test

Identify the Gas Leak Rate of the detector by monitoring the drop of the internal pressure as a function of time and check the gas tightness

- The detector is pressurized at $3\ bar$ in the operating gas mixture $Ar:CO_2\ (93:7)$
- The pressure drop is measured for each individual multi layers (ML 1 and ML 2) after $24\ hours$ During the test, the gas valves remain closed.
- Instrumentations: pre-mixed gas bottle, MKS Baratron and 12 temperatures sensor glued on the surface of the sMDT detector

- MKS Baratron heated reference differential manometer Accuracy: 0.3 mbar at 3000 mbar
- The detector gas leak are estimated by the following equation:

Reference temperatures (293.15 K) *Final & Initial pressures*

$$\Delta p = \frac{T_{ref}}{(t_f - t_i)} \times \left(\frac{p_f}{T_f} - \frac{p_i}{T_i}\right) \times \frac{V_{DUT}}{N_{Endplug}}$$

Final & Initial Temperatures

- Accuracy of the pressure drop measurement:

$$\delta(\Delta p) \approx \sqrt{2(\delta p)^2 + 2\left(3000\ mbar\,\frac{\delta T}{T_{ref}}\right)^2} = 1.6 - 2\ mbar$$

→ ***Acceptance criteria***

- The detector under test is validated if the pressure drop in the detector + gas system does not exceed:

$$\Delta p \leq 2 n_{tubes} \times 10^{-8}\ bar \times Liters \times s^{-1}$$

Gas Leak Test Summary:

→ ***"A-side" sMDT chamber***

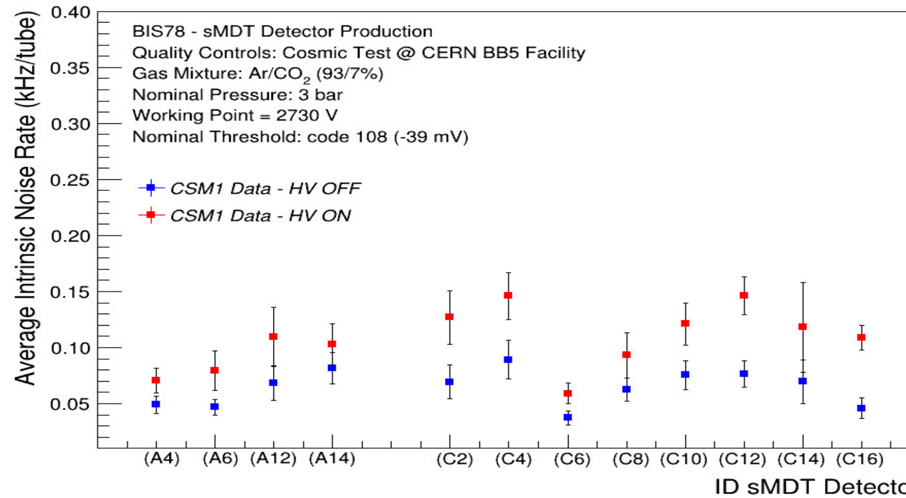
6/8 chambers fully tested
2 fully validated
4 require in-depth investigation
2 detectors not tested

→ ***"C-side" sMDT chamber***

8/8 chambers fully tested
4 fully validated
4 require in-depth investigation

Connectivity & Electronics Noise Test

The Noise Rate Measurement at the different detector configuration allows comparing the intrinsic noise rate for each individual electronics channel/tube in the sMDT detector, enabling to precisely identify the noisy channel/tube



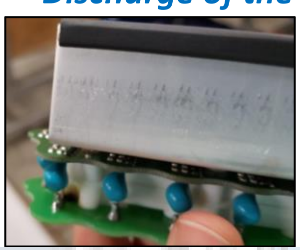
- **The detector is pressurized at 3 *bar* in the operating gas mixture $Ar{:}\,CO_2$ $(93{:}7)$**
- **The Noise Rate Test are performed for the individual Chamber Service Module (CSM 1 and CSM 2) in the detector configurations: HV turned OFF and ON**
  Operating $HV_{WP} = 2730\,V$
- **The measurements at nominal $THR = 108$ *ASD (-39 mV)***

→ ***Criteria for excluding noisy tube:***

$$Noise_i^{ON} > 5\,kHz \text{ and } Noise_i^{ON} > 2 \times Noise_i^{OFF}$$

The potential high noise rate sources in the sMDT detectors:

Discharge of the electr. components ***Broken wire***



Noise Rate Test Summary:

→ ***"A-side" sMDT chamber***

Noise Rate (HV OFF) = (61.3 ± 8.3) *Hz/tube*
Noise Rate (HV ON) = (90.6 ± 9.3) *Hz/tube*
Rejected tube = 0.1 %

→ ***"C-side" sMDT chamber***

Noise Rate (HV OFF) = (65.7 ± 6.0) *Hz/tube*
Noise Rate (HV ON) = (114.9 ± 10.1) *Hz/tube*
Rejected tube = 0.7 %

Cosmic Ray Test (I)

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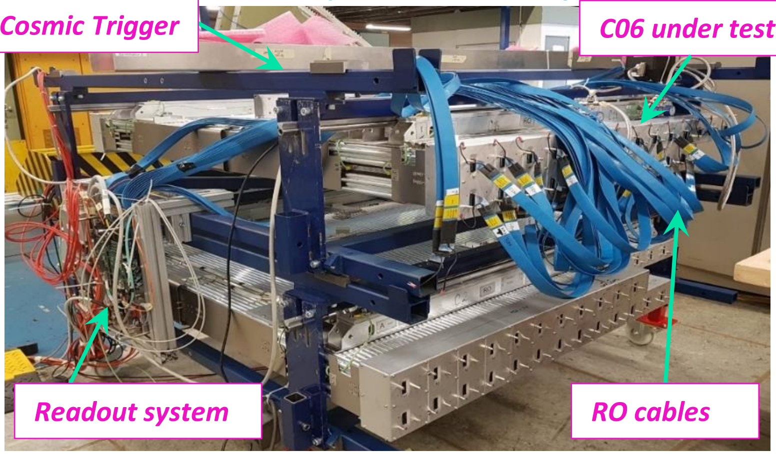
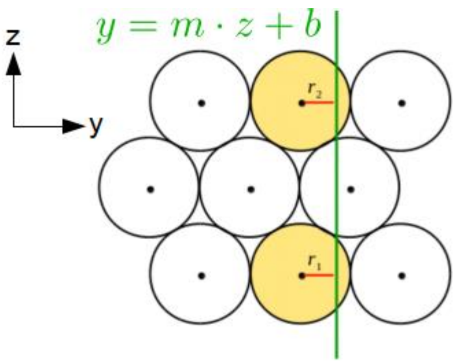
The last commissioning test is the Spatial Resolution & Muon Efficiency Measurements which allows to check that the drift tube is recorded hit, if a reconstructed track is passing through the tube

- The detector is operated at the ***WP = 2730 V*** and the $3\ bar$ in gas mixture $Ar{:}\,CO_2\ (93{:}7)$
- The duration of the data taking is *15 hrs* per CSM.
- The cosmic trigger active area is $114\ cm\ x\ 9\ cm$.
- Expected trigger rate is $17.1\ Hz$.

sMDT setup @CERN BB5 facility



Spatial Resolution



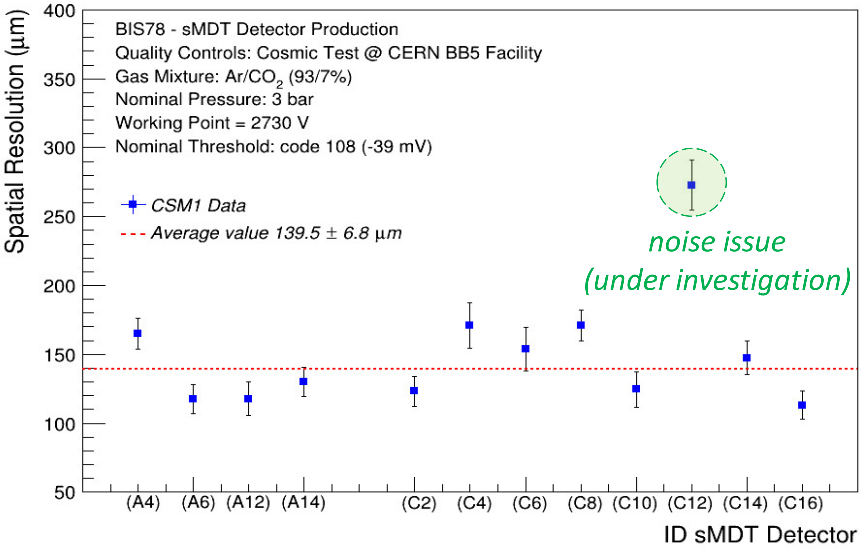
- Select nearly *vertical muon tracks*

→ For perfectly vertical tracks:

$$\sigma(r_1) = 2^{-0.5} \cdot \sigma(r_2 - r_1)$$

- For tracks with inclination $|m| < 0.01$:

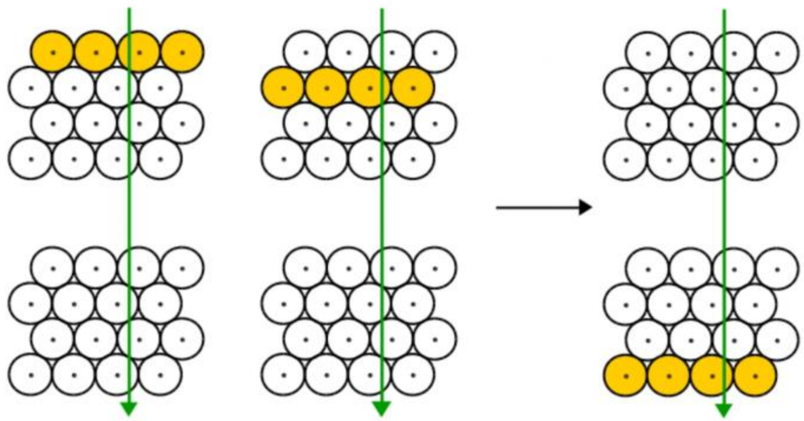
$$\sigma(r_{1/2}) = \sigma\left(\frac{r_2 - r_1}{\sqrt{2}} \mp \frac{m \cdot (z_2 - z_1)}{\sqrt{2 \cdot (1 + m^2)}}\right)$$



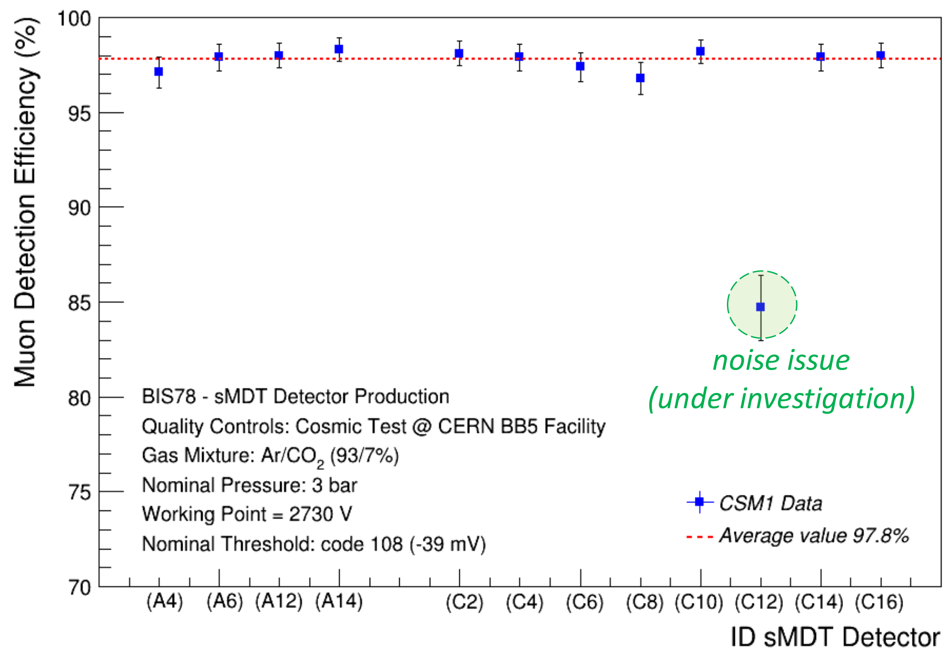
Cosmic Ray Test (II)

The last commissioning test is the Spatial Resolution & Muon Efficiency Measurements which allows to check that the drift tube is recorded hit, if a reconstructed track is passing through the tube

Muon Detection Efficiency



- **Muon track is reconstructed by excluding one layer of tubes**
- **Muon detection efficiency of a tube is determined as to how often does an excluded tube have a hit when its gas volume is traversed by a reconstructed muon track**



- **Measurement reproduces know dependence of the efficiency on the distance of the muon track from anode wire**

→ ***Average Efficiency of BIS78 sMDT detector (97.8 ± 0.2) % within the ATLAS requirements***

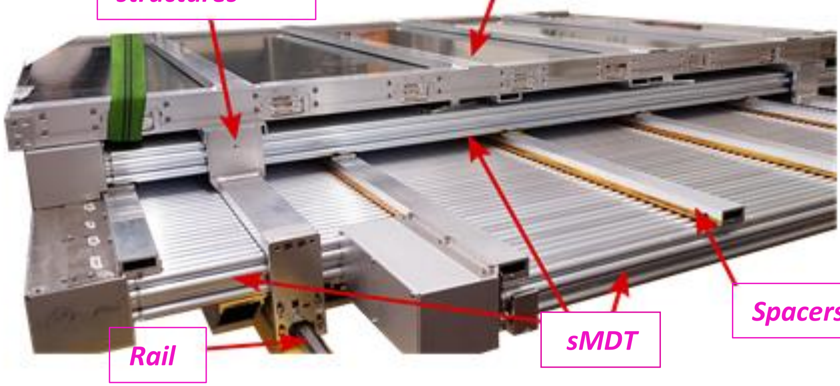
→ ***The muon efficiency is < 100% because of the efficiency drop close to the tube walls***

sMDT/t-RPC Integration & BIS78 Interference Test

sMDT/t-RPC Integration

Given the smallness of the space available for the BIS78 sMDT and RPC chambers, an integrated mechanical design of the two chamber types with low tolerances are required.

t-RPC BIS7/8 and sMDT integration for the A04 Muon station

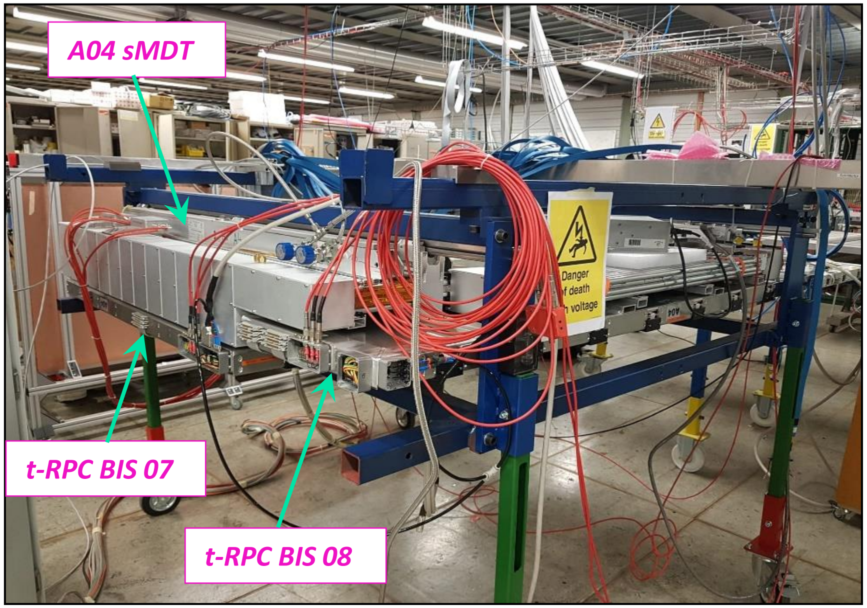


Detailed study shown that the effect of the RPC detector + its electronics is negligible to sMDT system (chamber + its electronics @ operating THR. = -39 V) in the term of noise

BIS78 Interference Test

The noise study of the sMDT A04 chamber after integration with the triple-RPC BIS 7 + BIS 8 detectors has been performed.

BIS78 A04 - Noise Study @BB5



Summary of the BIS78 A04 Interference Test

sMDT mode	sMDT A04 - OFF				sMDT A04 - ON			
CSM ID	CSM 1		CSM 2		CSM 1		CSM 2	
t-RPC mode	RPC - OFF	RPC - ON	RPC - OFF	RPC - ON	RPC - OFF	RPC - ON	RPC - OFF	RPC - ON
Aver. intr. noise, [kHz/tube]	0.18 ±0.03	0.23 ±0.04	0.25 ±0.05	0.28 ±0.06	0.43 ±0.03	0.17 ±0.03	0.18 ±0.03	0.18 ±0.05

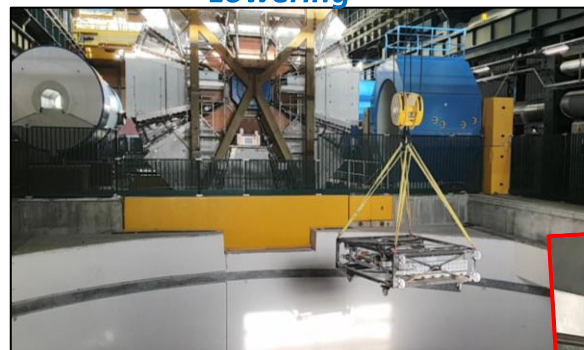
BIS78 Detector Module Installation @ATLAS P1

17th of September 2020 the first BIS78 Detector Module has been successfully installed to the A04 sector of the ATLAS Muon spectrometer.

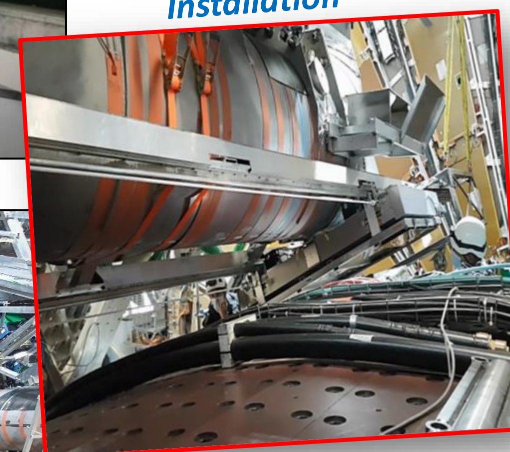
BIS 78 Module Installation Sequence:

- Insertion into the installation frame
- Lowering into the ATLAS Cavern
- Docking of the installation frame to the ATLAS Muon Spectrometer rail system
- Installation of the muon station with two winches
- Final positioning and fixation of support frame on rails

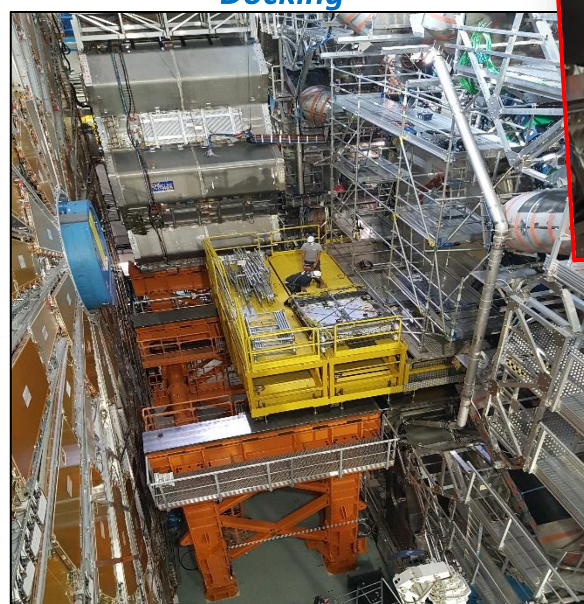
Lowering

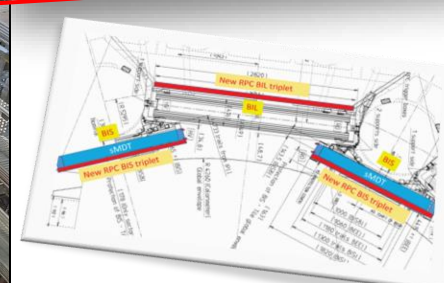


Installation

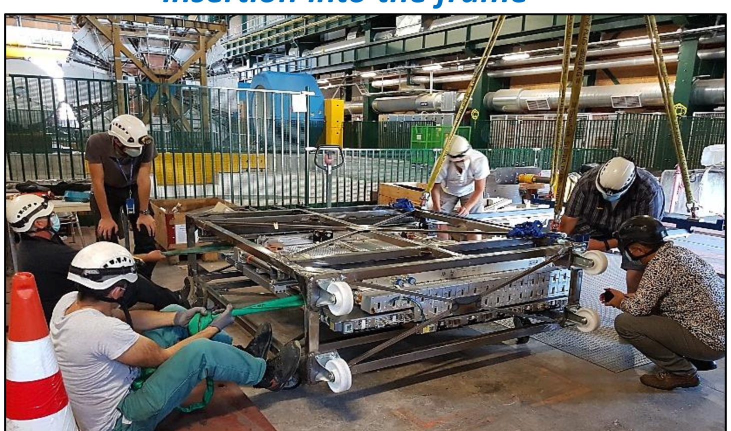


Docking





Insertion into the frame



Conclusions

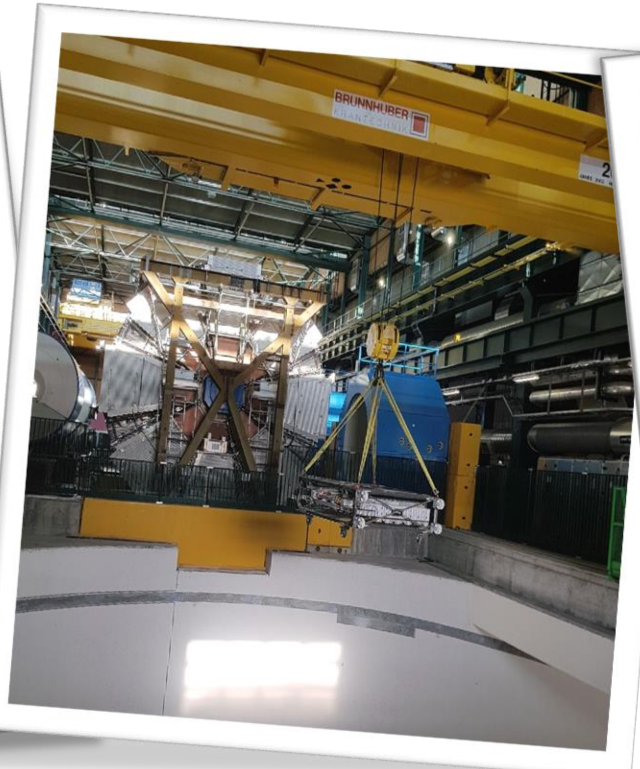
During next year, the ATLAS Muon Spectrometer will go through a series of upgrade in order to cope with the foreseen increasing of LHC performance

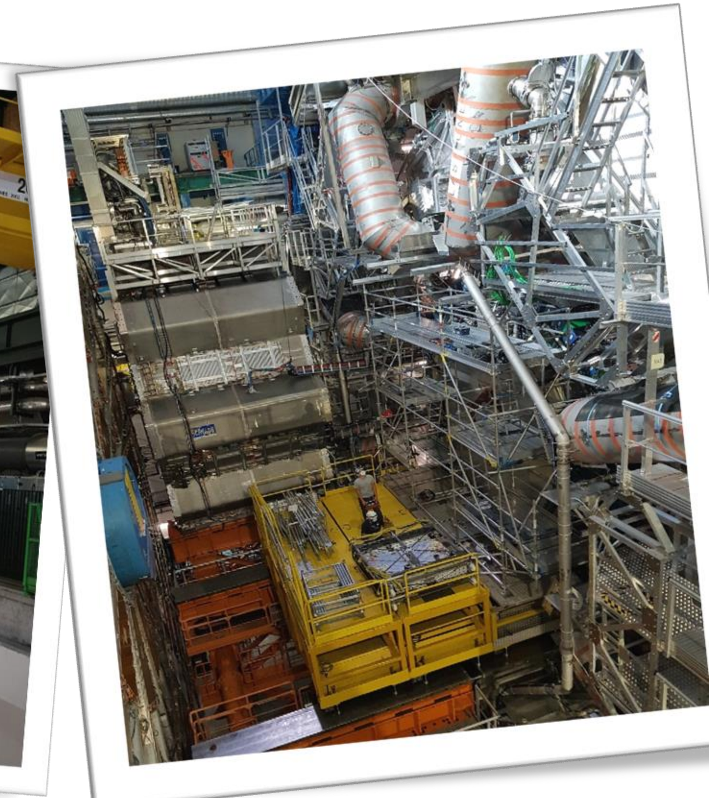
New BIS78 Detector Module (sMDT + t-RPC chambers) have been constructed for the Phase-1 Upgrade as a pilot project for the ATLAS barrel Muon Spectrometer, in order to increase the trigger acceptance and to prepare for the high background rate requirements of the HL-LHC

BIS78 sMDT A/C-side status and progress:

- Successful and on-time production of A/C-side (11000 tubes in total for the 16 sMDT detectors) from 2017 to 2019
- 16/16 sMDT chambers have been fully assembled and validated at MPI Munich
- 1st of June 2020, BIS78 sMDT chambers have been shipped from MPI to CERN BB5 facility
- @ CERN BB5 facility, the validation campaign after BIS78 sMDT transport is still underway:
  - 14/16 detectors have been fully tested
  - 8 required in-depth investigation
  - 2 have been not tested
- The C-side BIS78 sMDT chambers have been stored @CERN and will be re-validated before the final installation
- The first BIS78 Detector Module has been successfully installed to the A04 sector of the ATLAS Muon spectrometer and its commissioning is underway
- Commissioning and installation activities fully resumed after the COVID-19 stop

Thank for Your Attention!





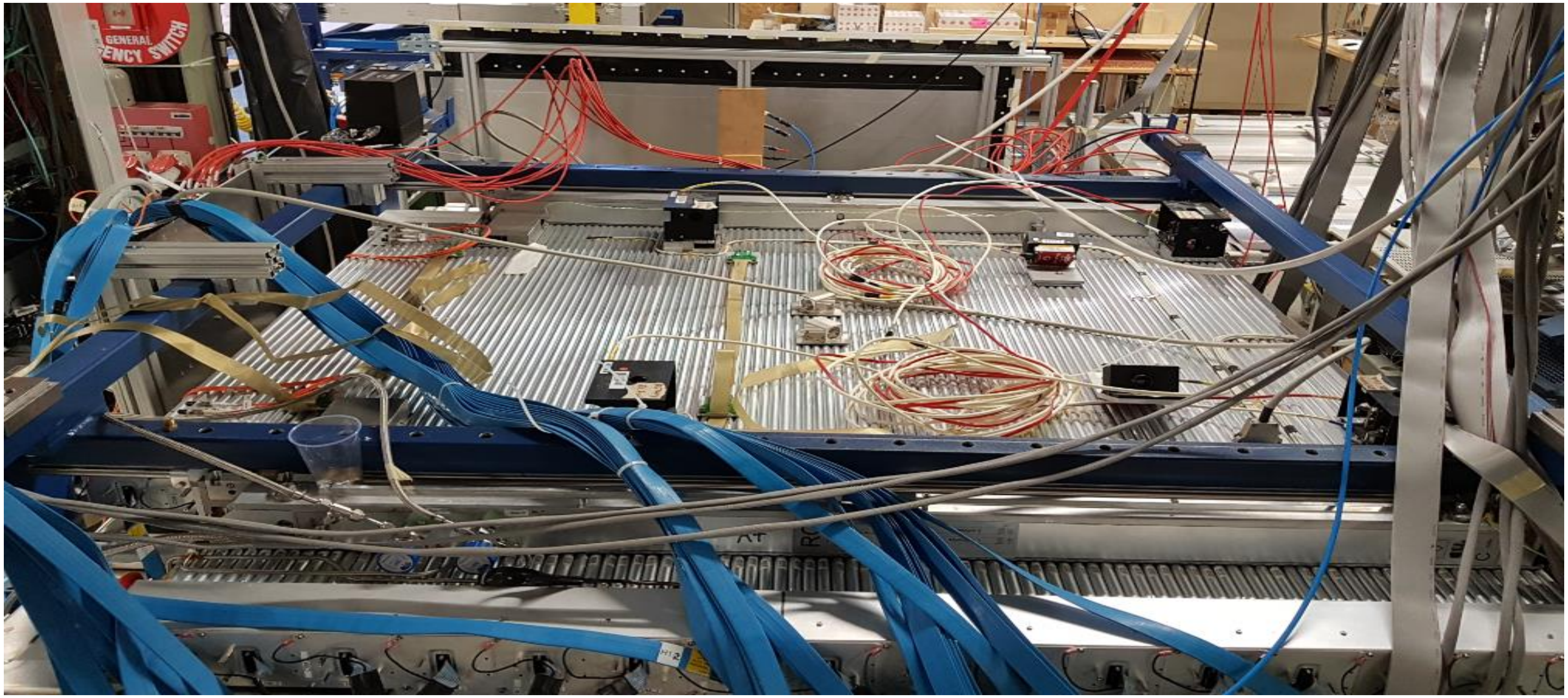
Backup slides

Preparation of the chamber for the functional test with cosmic muons

1. Evacuate the chamber to $< 10\ mbar$ in order to extract the contamination of the chamber gas with ethanol from the leak testing.
2. Fill the chamber with $Ar{:}CO_2$ $(93{:}7)$ to *3 bar* absolute pressure.
3. Wait for 30 minutes to get a temperature equilibrium between the chamber and the gas.
4. Measure the chamber temperature and the gas pressure and close all valves on the chamber.
   → Needed for a measurement of the leak rate of a fully equipped chamber.
5. Apply the nominal operating voltage of $2730\ V$ and measure the dark current of the chamber.
   Requirement: Current $< 2\ nA/tube$ at $< 60\%\ humidity$.
6. Measurement of the accidental hit rate in each tube with and without high voltage.
7. Cosmic-ray run to acquire a dataset corresponding to ~1 million cosmic muons through the chamber (15 h with the set-up at MPI/BB5, can be shortened by increasing the trigger surface).
8. Measurement of the maximum drift time of each tube to obtain a measure for the uniformity of the space drift-time relationship across the chamber.
9. Measurement of the muon detection efficiency of each tube.
10. Measurement of the single tube resolution.
11. After >24 h measurement of the chamber temperature and the gas pressure for each multilayer separately to obtain the leak rate of each multilayer.

A04 sMDT detector preparation @CERN BB5 facility

- **Before the module installation the B-field sensors as well as the axial, praxial, and CCC sensors of the barrel alignment system are mounted on the surface of the A04 sMDT detector @CERN BB5 facility.**



from Production to Installation …