Development and Construction of Muon Drift Tube (sMDT) Chambers for High-Luminosity LHC Upgrades

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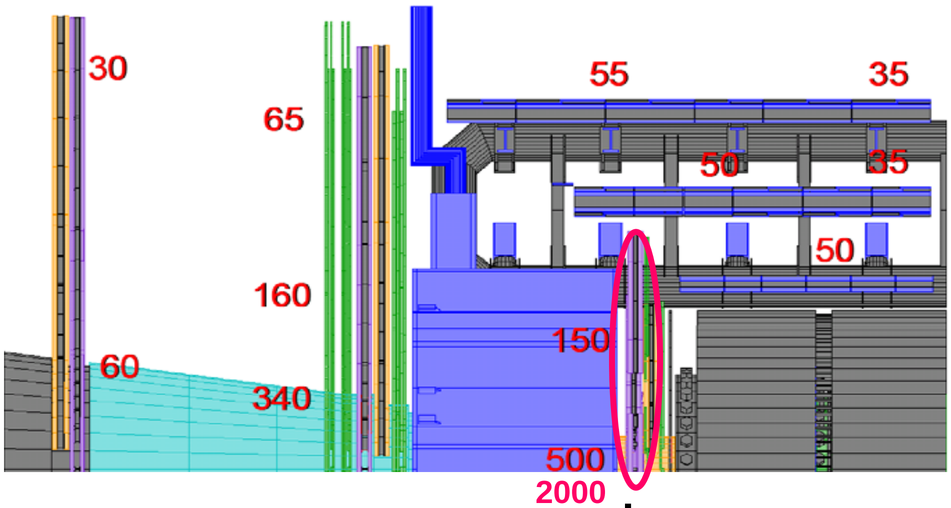
ATLAS Muon Spectrometer and HL-LHC Upgrade

Max. background hit rates of neutrons and γ's in ATLAS from particle interactions in the detector and shielding expected at LHC design luminosity and energy (in Hz/cm^2), confirmed by actual backgr. measurements during ATLAS operation:



At HL-LHC (5-7 x LHC design luminosity):
max. background hit rates of 14 kHz/cm^2 expected.

Design rate capability of ATLAS MDT chambers:
500 Hz/cm^2, 300 kHz/tube (2 m) , 21% occupancy.

Parameters of ATLAS Muon Drift Tube (MDT) chambers:

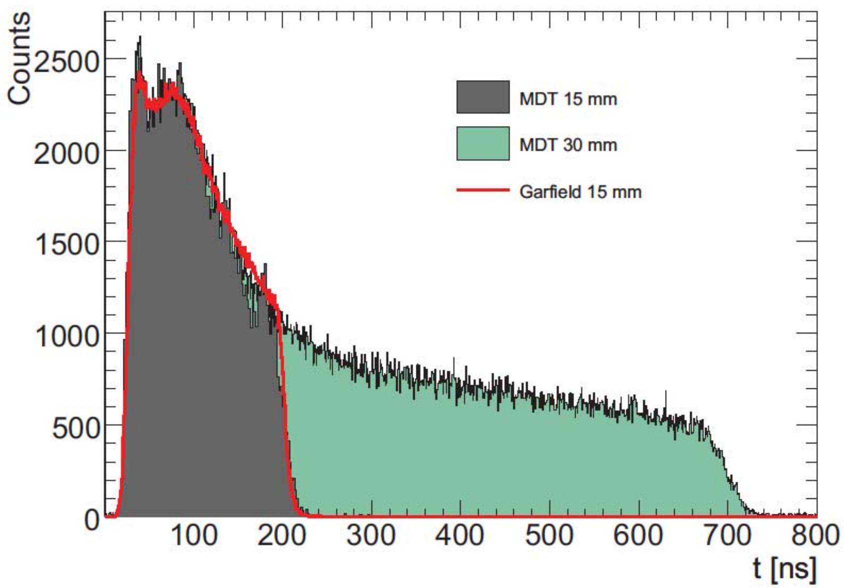
Tube material	Aluminum
Tube diameter	30 mm
Wall thickness	0.4 mm
Sense wire	50 μm ∅ W/Re
Gas mixture	Ar:CO_2 (93:7)
Gas pressure	3 bar
Gas gain	2 x 10^4
Wire potential	3080 V
Max. drift time	700 ns
Wire pos. accuracy	20 μm
Single-tube resolution (at low background rate)	80 μm
Nr. of drift tube layers	2 x 3 (4)
Chamber resolution (at low background rate)	35 μm

Smaller Diameter Drift Tubes (sMDT) for High Rates: Occupancy

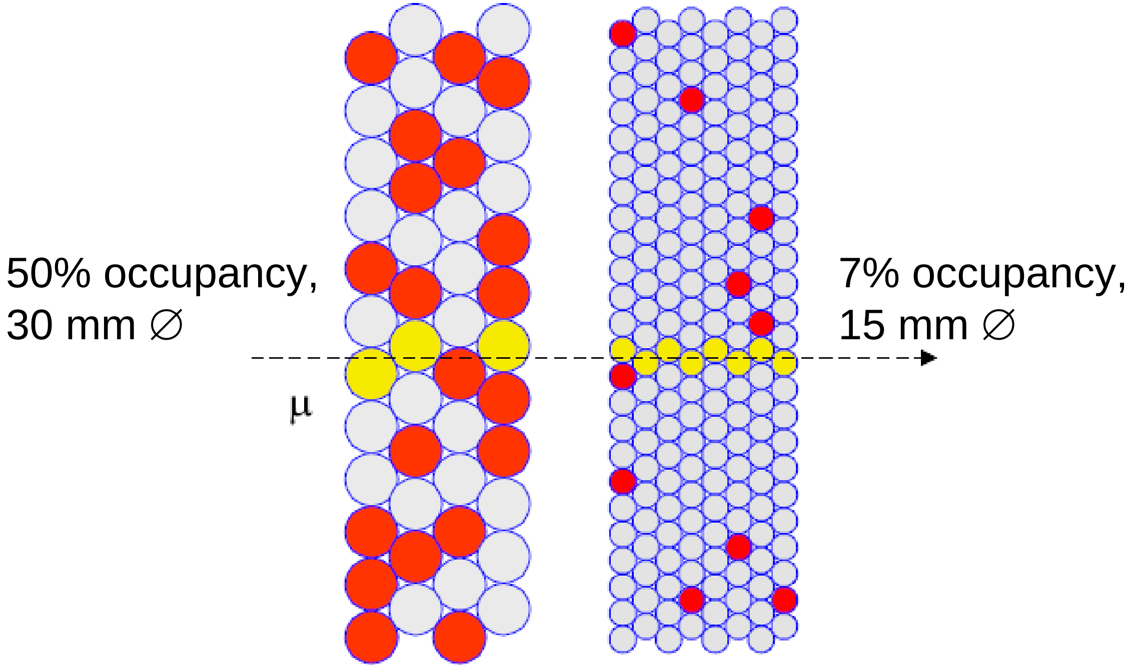
15 mm ∅ instead of 30 mm ∅ tubes, same gas mixture and gas gain:

Huge improvement of tracking efficiency at high bg. rates due to:

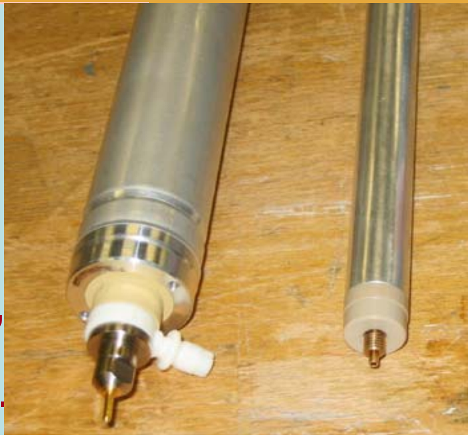
- ❑ Occupancy ~ max. drift time (700 ns → 185 ns): 3.8 x smaller.
- ❑ Background hit rate ~ tube cross section: 2 x smaller.
  ⇒ Occupancy 7.6 x smaller for given tube length.
- ❑ Twice the number of tube layers in the same detector volume.



Drift time spectra



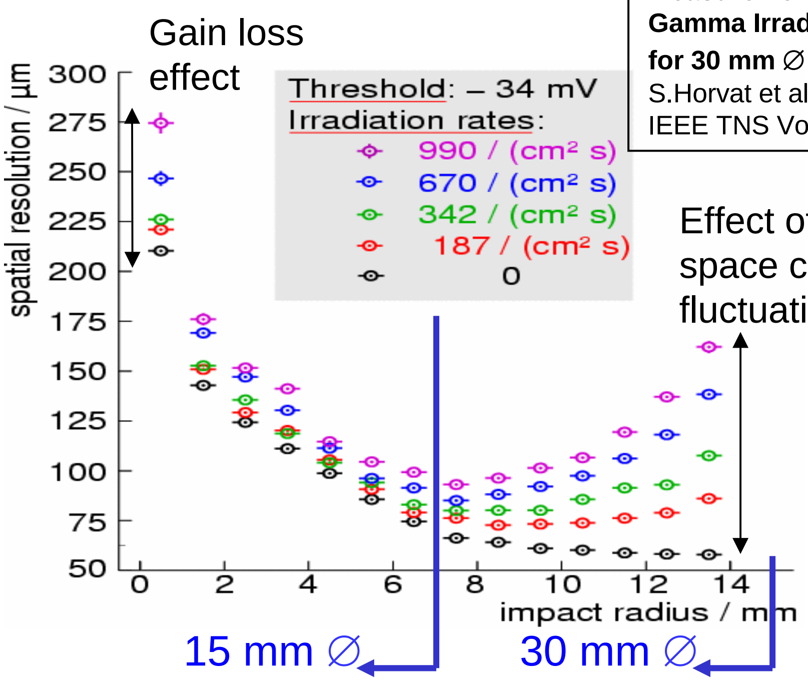
15 mm ∅ instead of 30 mm ∅ tubes, same gas mixture and gas gain G_0

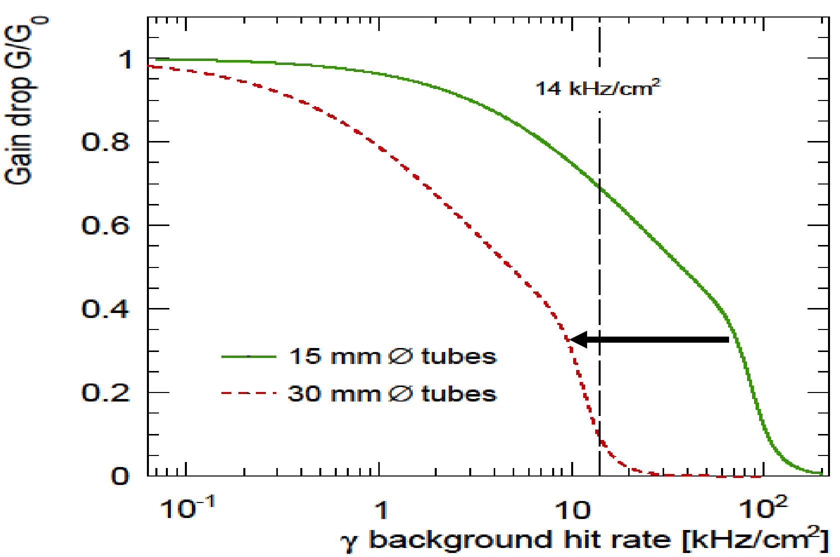


Degradation of the spatial resolution at high bg. rates because of

- gain loss due to } ~ tube inner radius r^3 (for γ, neutrons): 8.7 x smaller,
- space charge } ~ tube inner radius r^4 (for charged part.): 18 x smaller,
- radiation induced space charge fluctuations: additional factor 2 x smaller.
- Furthermore: saturation of space charge generation.

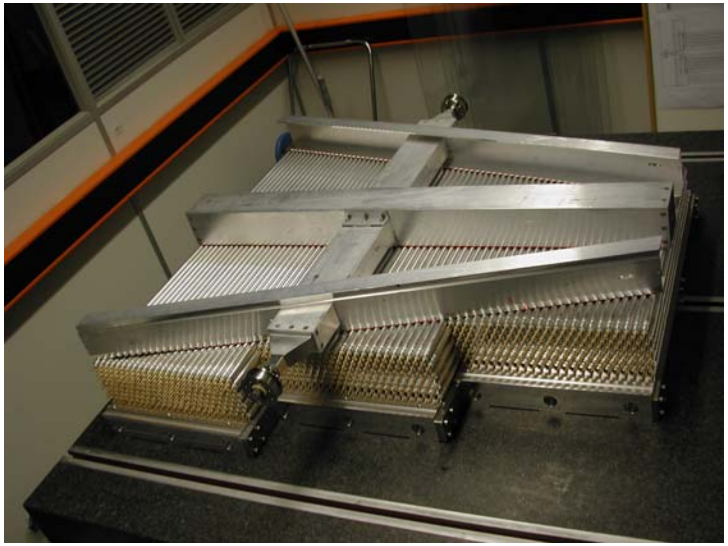
Measurements at the CERN Gamma Irradiation Facility GIF for 30 mm ∅ tubes:
S.Horvat et al.,
IEEE TNS Vol.53, No.2 (2006) 562

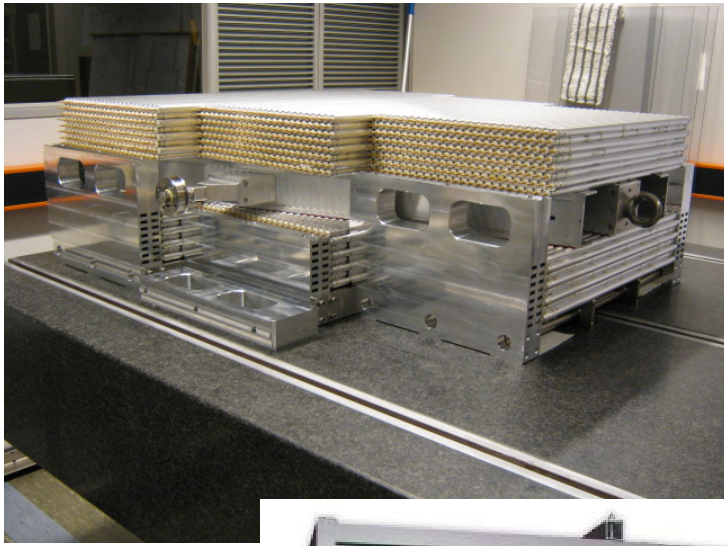


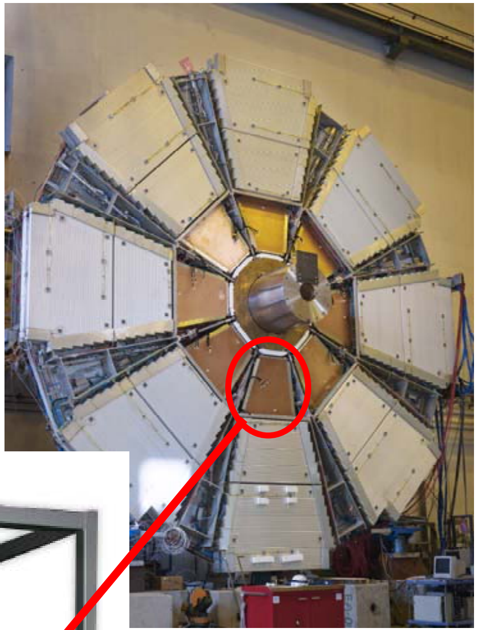


Gain loss G/G_0 strongly suppressed by factor of 8.7 for 15 mm diameter tubes.
Saturation of space charge:
iterative calculation using Diethorn's formula.

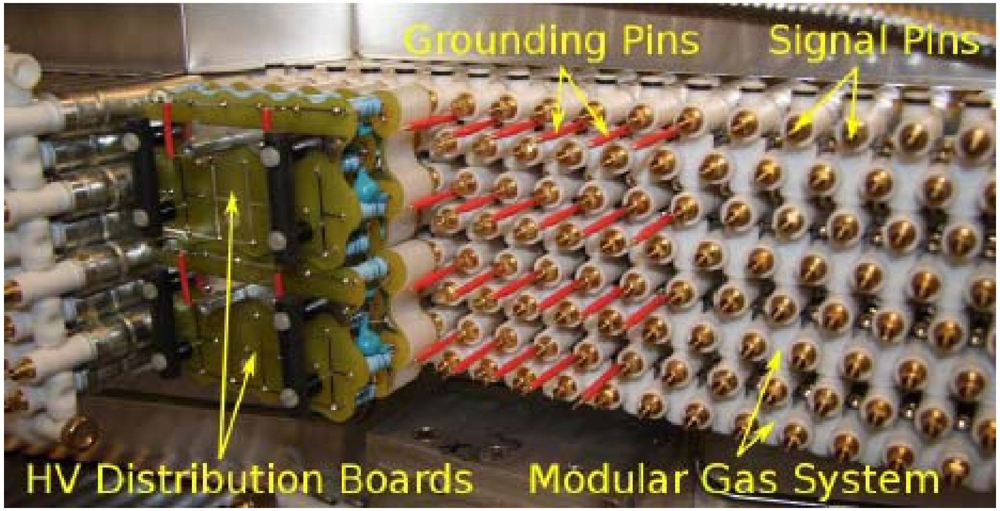
sMDT Prototype Chamber Construction





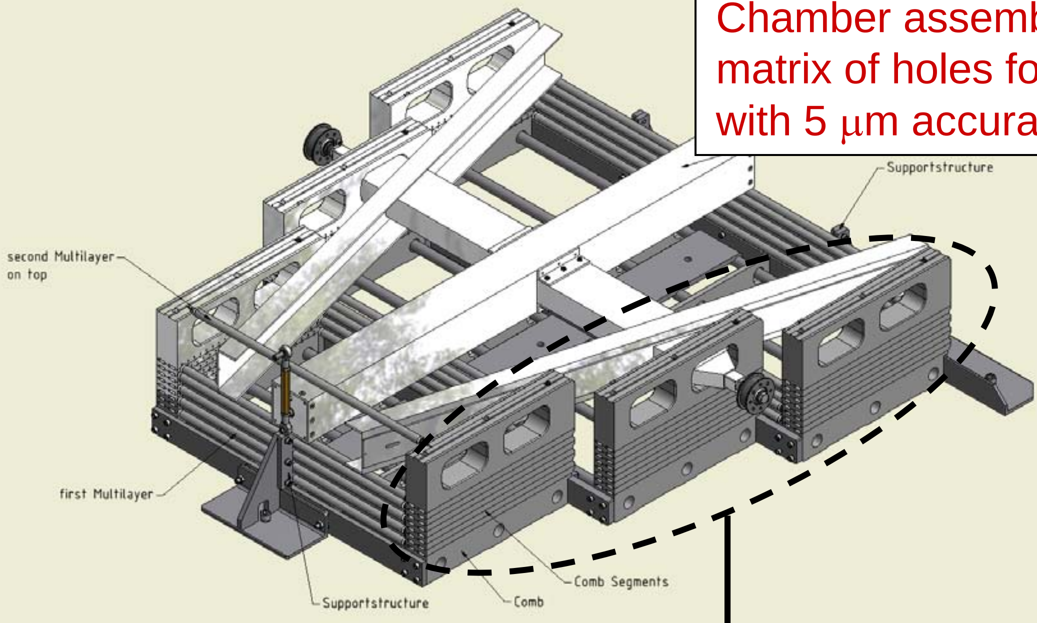


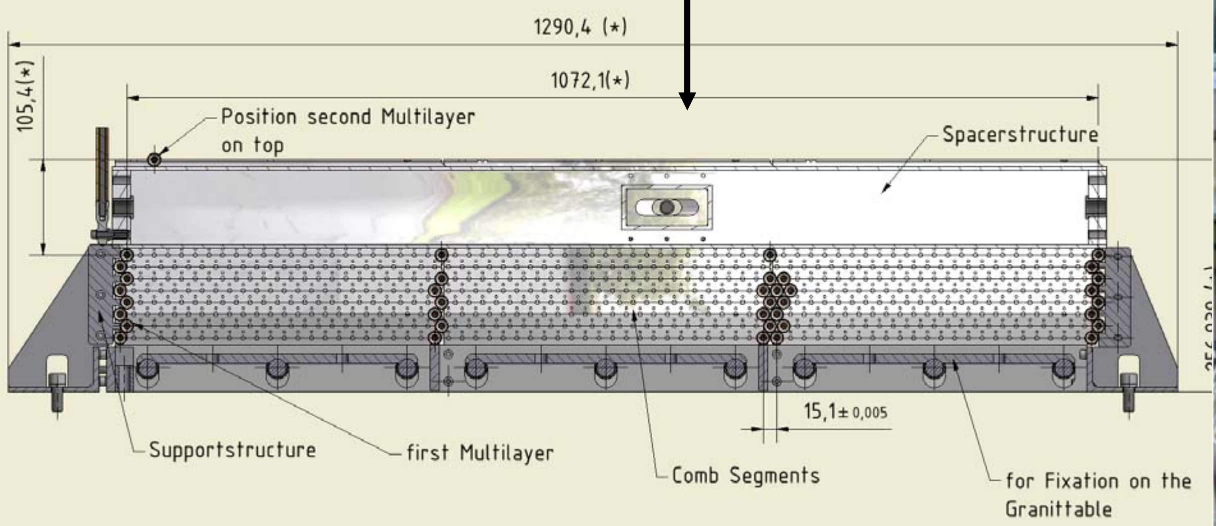
2 x 8 layers of 15 mm ∅ drift tubes
assembled in 2 working days

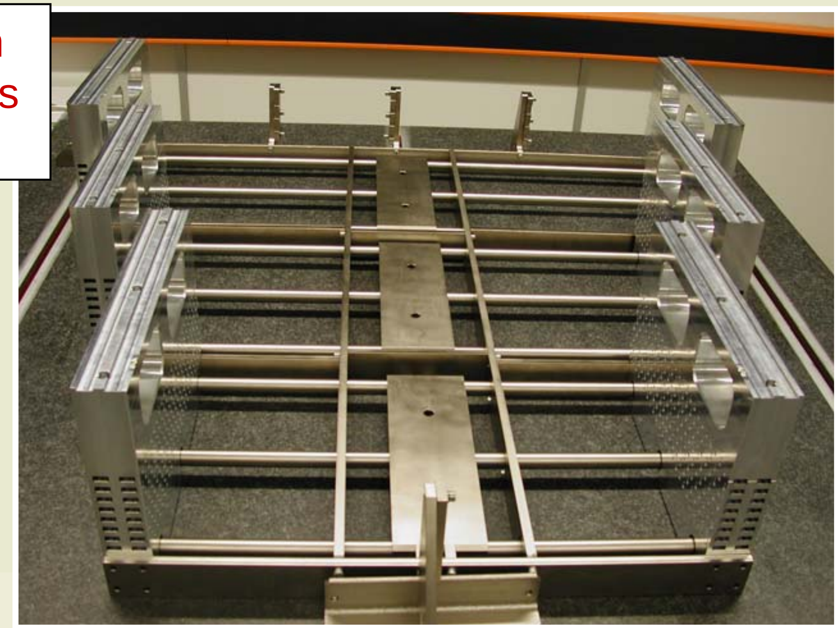


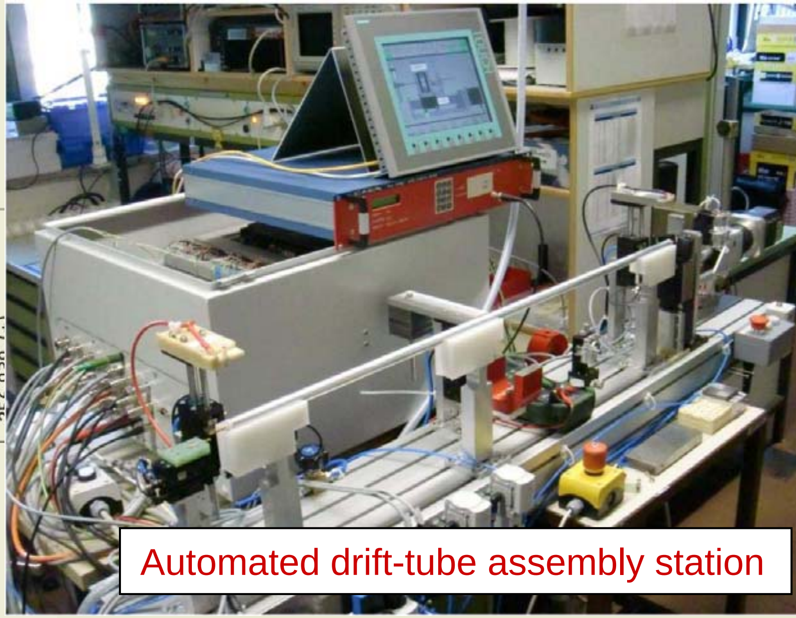
Chamber Assembly

Chamber assembly jig with matrix of holes for endplugs with 5 μm accuracy





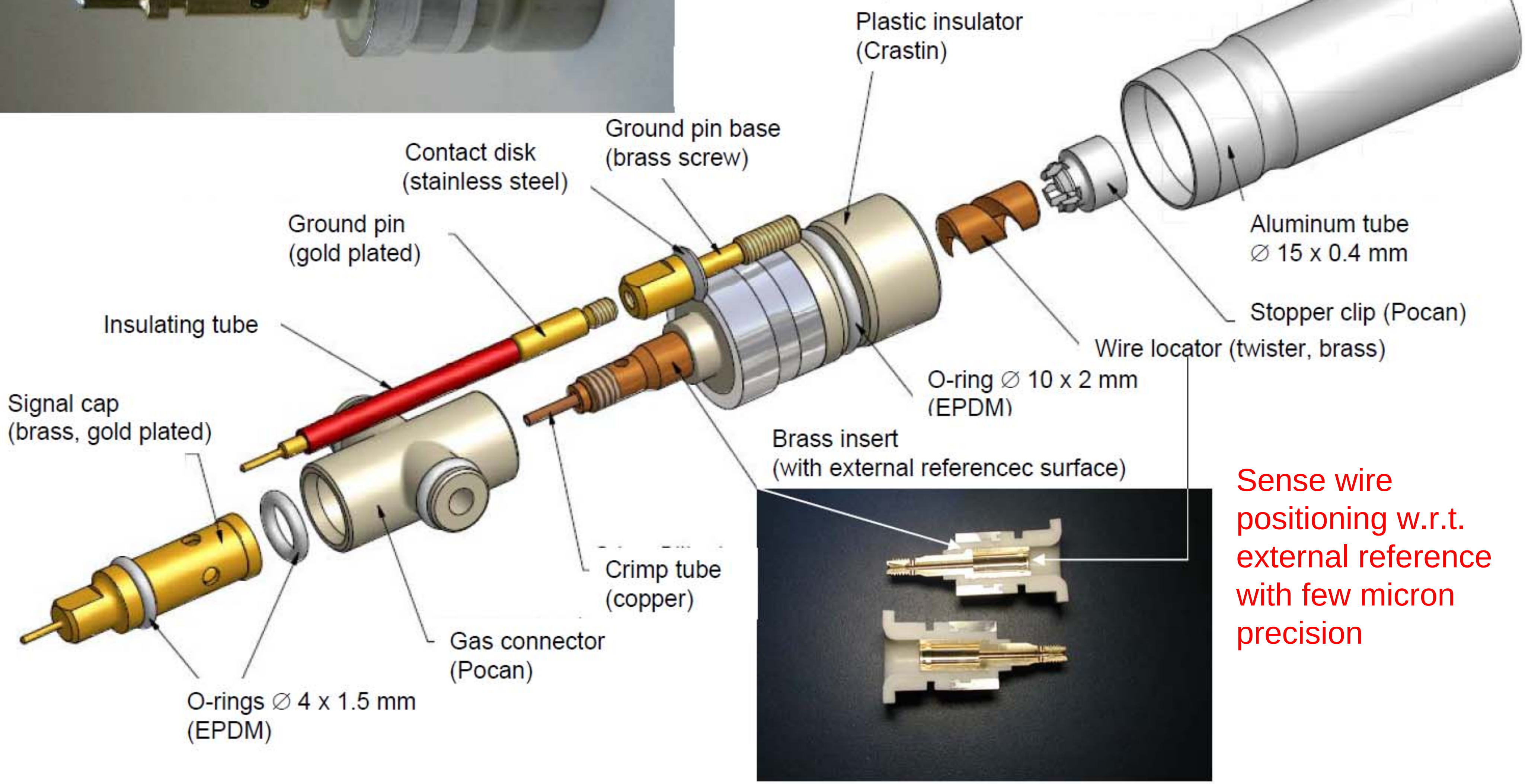




Automated drift-tube assembly station

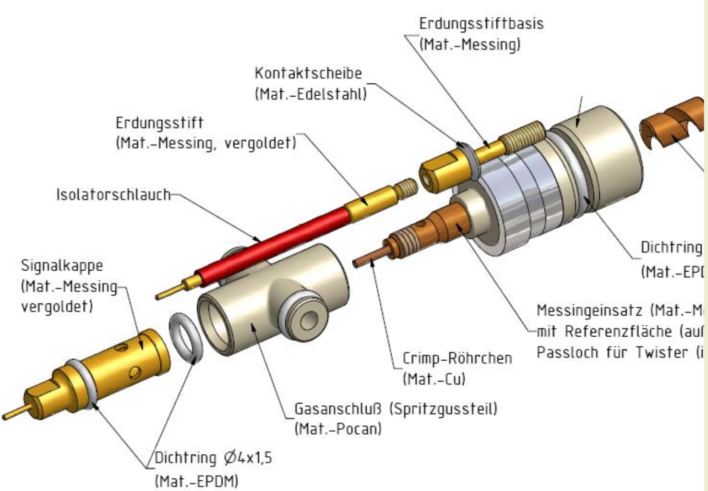
Drift Tube Design

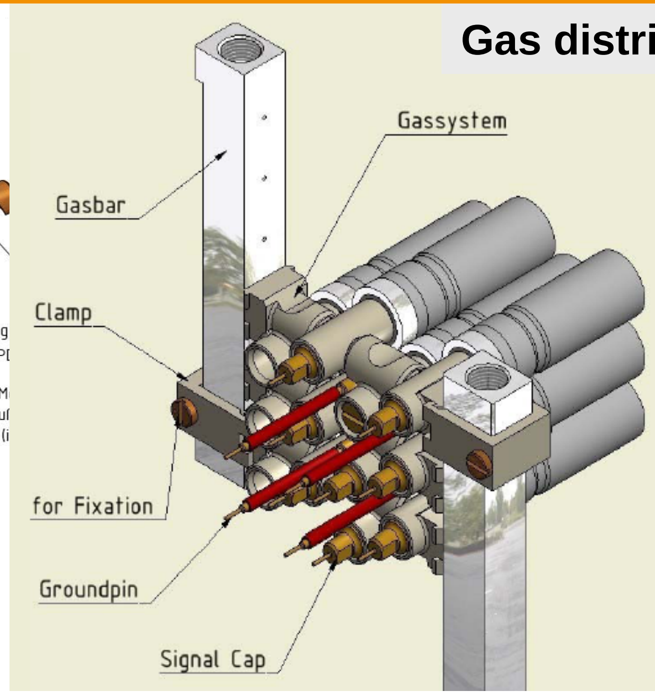
Injection molded plastic components certified w.r.t. aging



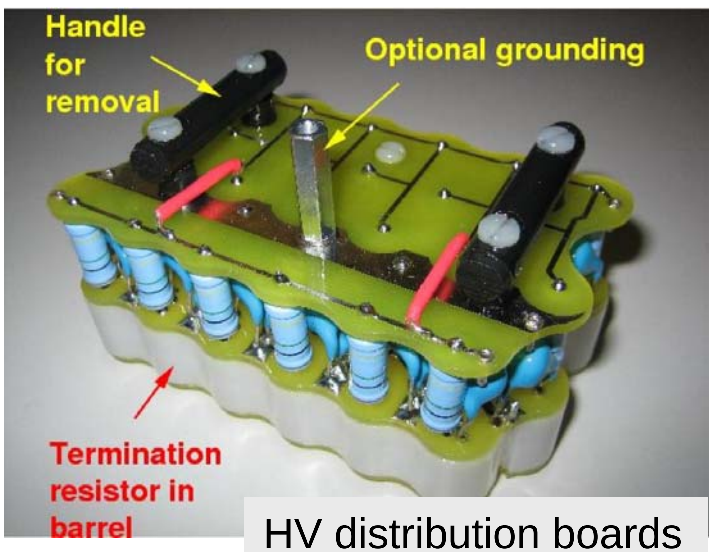
Sense wire positioning w.r.t. external reference with few micron precision

Gas System and Electronics Interfaces: 4 x Density

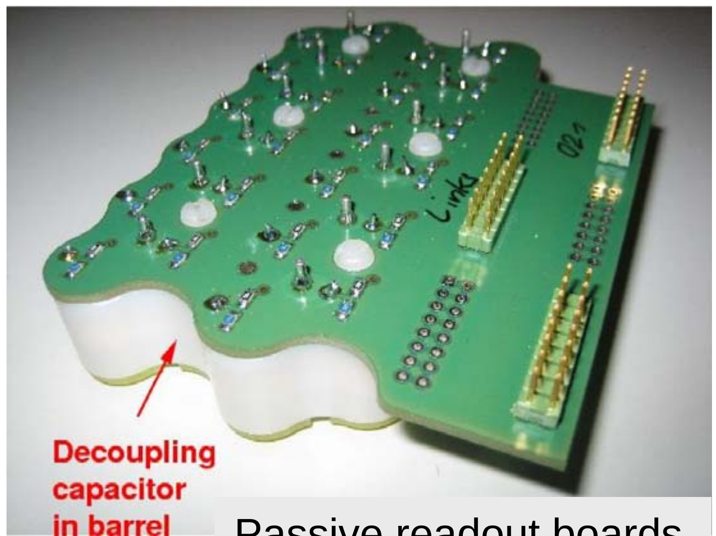




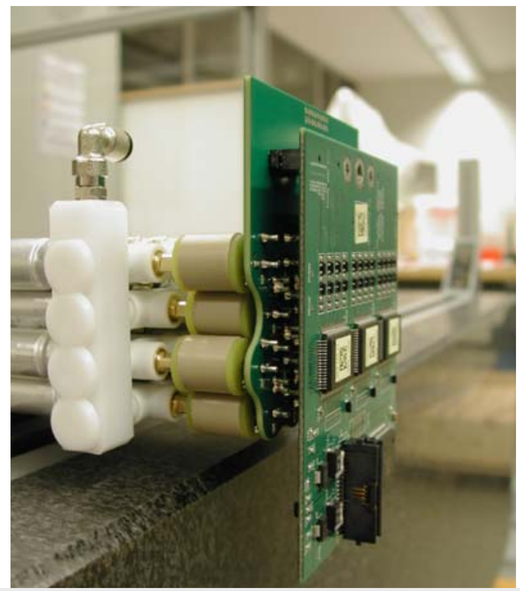
Gas distribution system



HV distribution boards



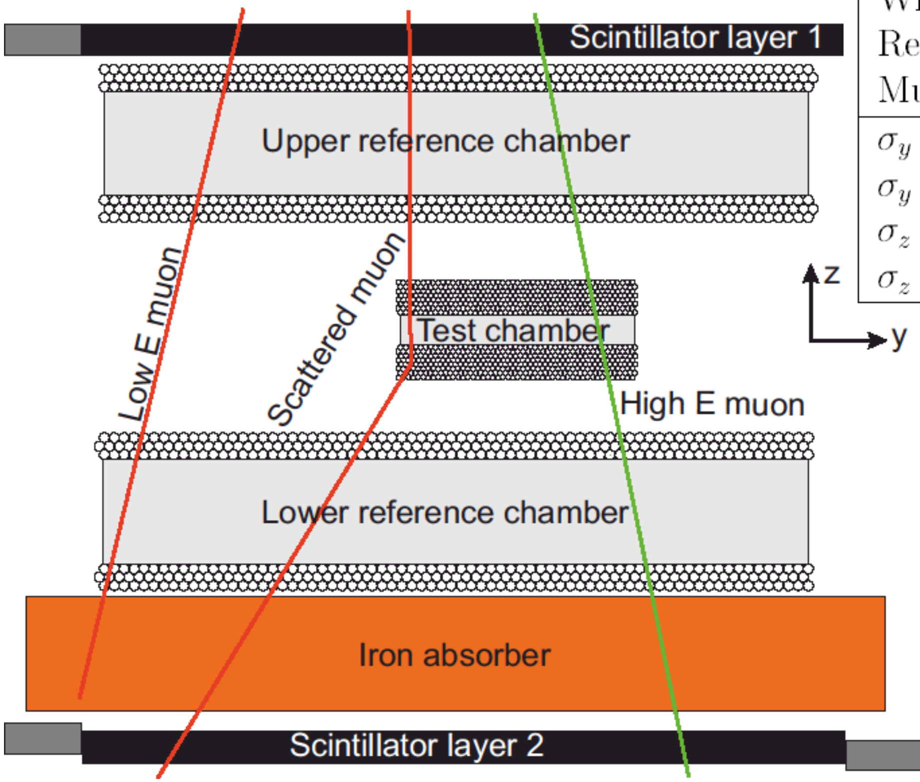
Passive readout boards



Active readout electronics:
from ATLAS MDT

Measurement of Sense Wire Positions

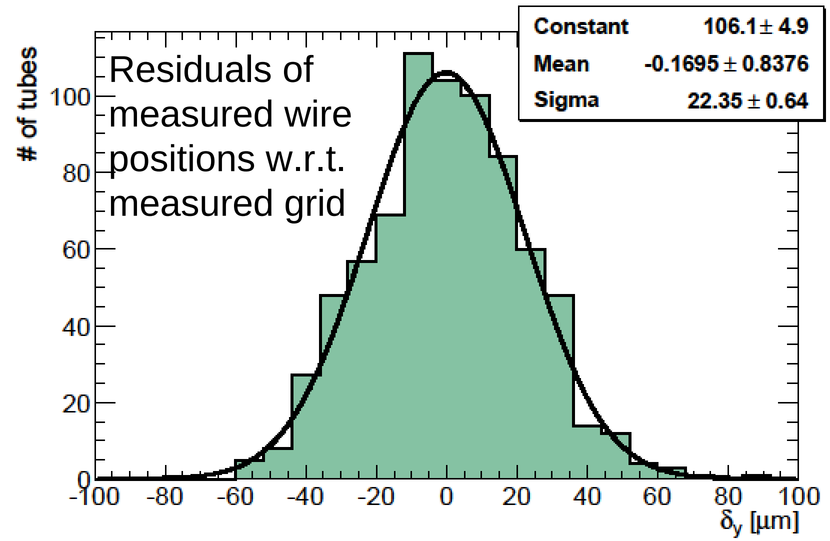
Wire position measurement with < 5 μm/wire accuracy using cosmic ray tracks and two MDT reference chambers with precisely known wire positions



Wire positioning accuracy of better than 20 μm achieved for the whole prototype chamber as required.

Measured parameters of the wire grid:

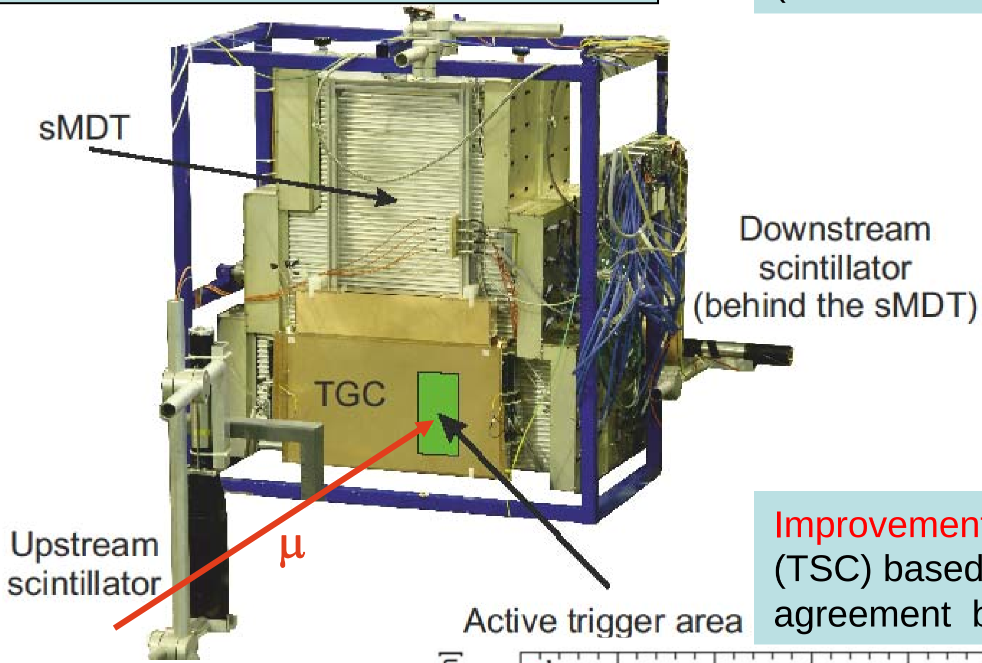
Parameter	Nominal value [mm]	Measured value [mm]
Wire pitch y	15.100	15.1018 ± 0.0003
Wire pitch z	13.077	13.091 ± 0.007
Relative layer shift y	7.550	7,550 ± 0.0005
Multilayer z distance	90.400	90.382 ± 0.010
σ_y w.r.t. nominal grid	0.020	0.018
σ_y w.r.t. fitted grid	0.020	0.016
σ_z w.r.t. nominal grid	0.020	0.016
σ_z w.r.t. fitted grid	0.020	0.013



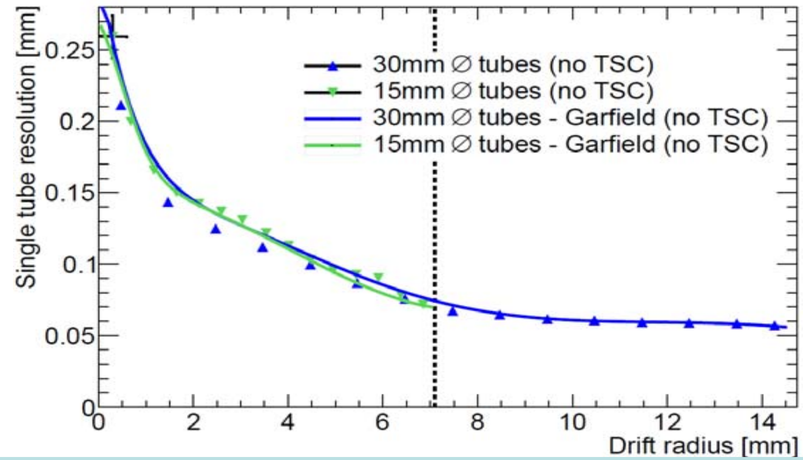
Muon Beam Test: Spatial Resolution

CERN SPS-H8 180 GeV muon beam.

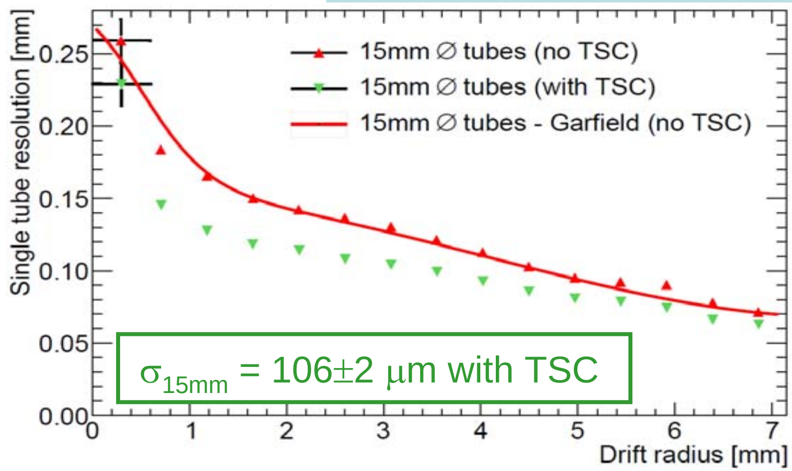
No background radiation.

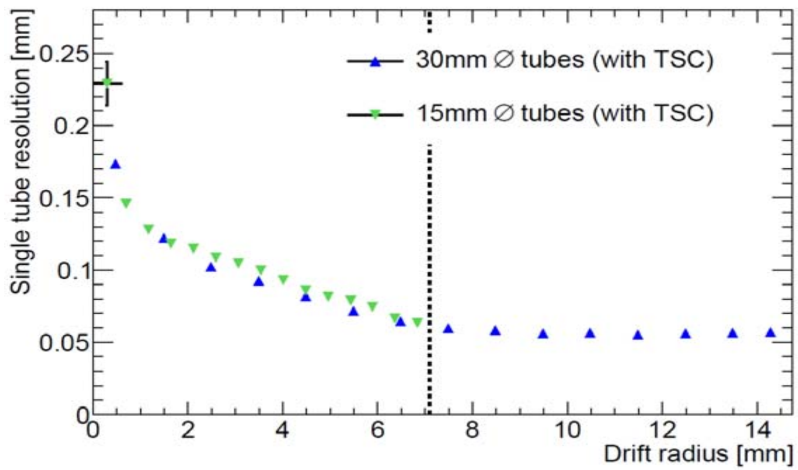


Agreement between 15 and 30 mm ∅ tubes in the common radial range, as expected, and with the Garfield simulation (identical readout electronics with bipolar shaping):



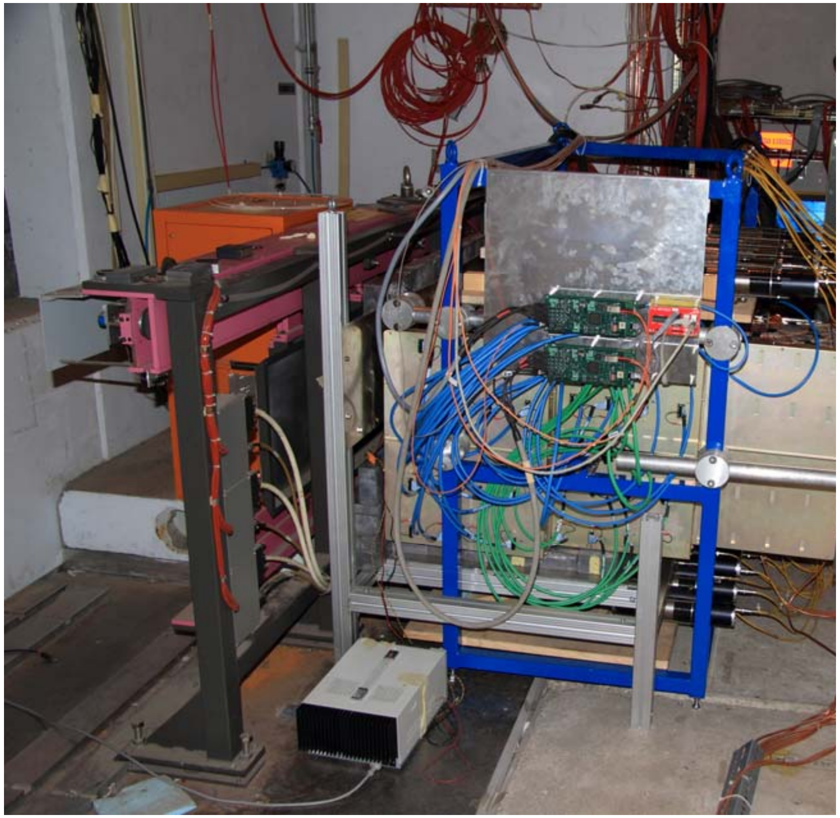
Improvement of drift tube resolution by 20 μm using time slewing corrections (TSC) based on the measurement of the leading-edge signal charge, agreement between 15 and 30 mm ∅ tubes also after TSC:



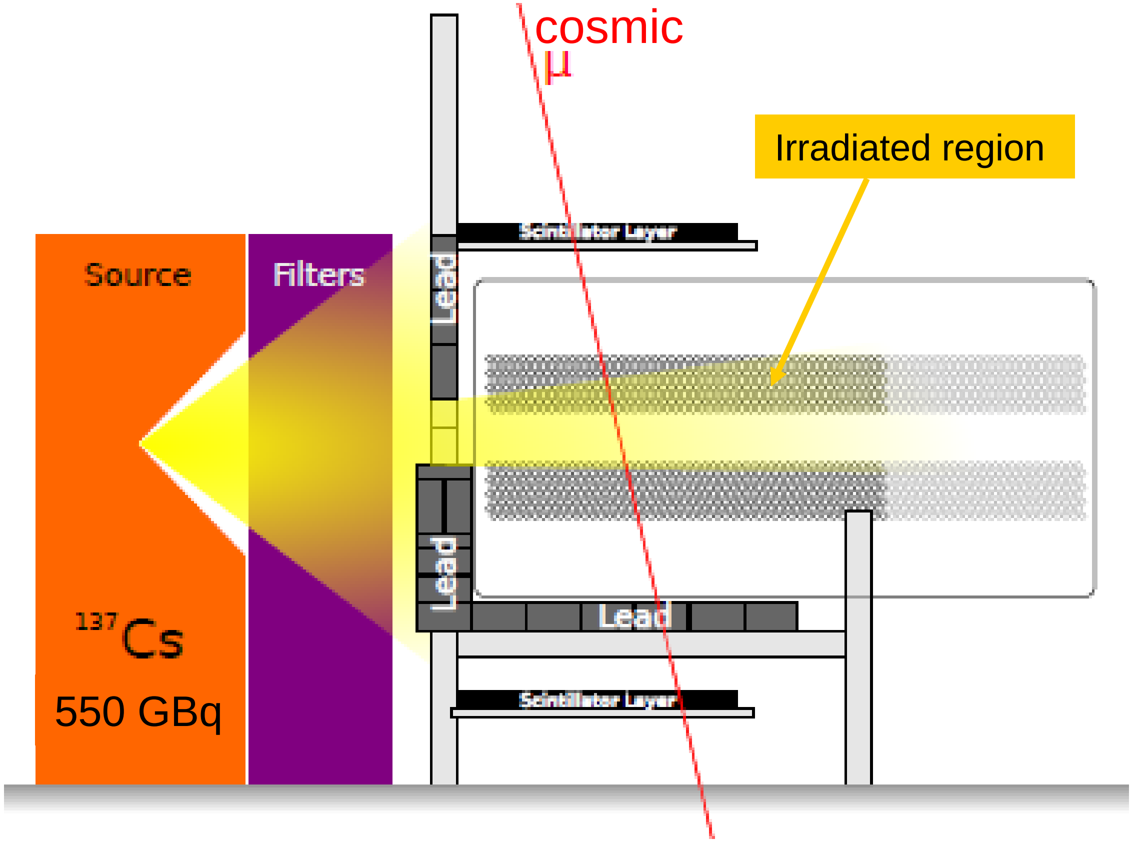


Irradiation Tests

Tracking efficiency and spatial resolution measured at the CERN Gamma Irradiation Facility (GIF) up to background hit rates of 1400 kHz/ tube, corresponding to background flux of 19 kHz/cm^2 (in 0.5 m long tubes in the highest-rate region in ATLAS).



No muon beam at GIF:
Shielded regions of the sMDT chamber serve as precise reference for cosmic muon tracks extrapolated to irradiated tubes.

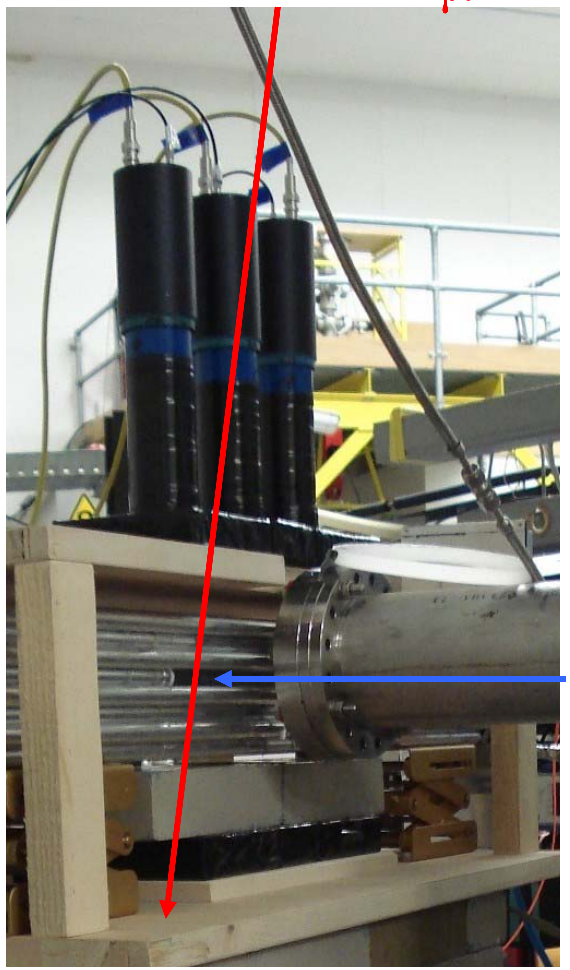


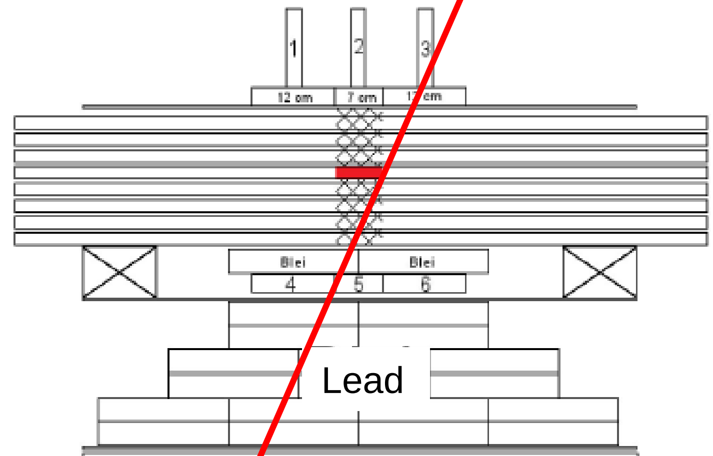
Spatial resolution degradation due to space charge also measured under irradiation with a 20 MeV high-intensity (100-200 kHz/10 cm^2) proton beam (4.5 x higher prim. ionization than γ rad.) at the Munich Van der Graaf Tandem accelerator up to equivalent γ hit rates of almost 100 kHz/cm^2.

Dedicated sMDT chamber.
Unirradiated tubes serve as reference for cosmic muon tracks.

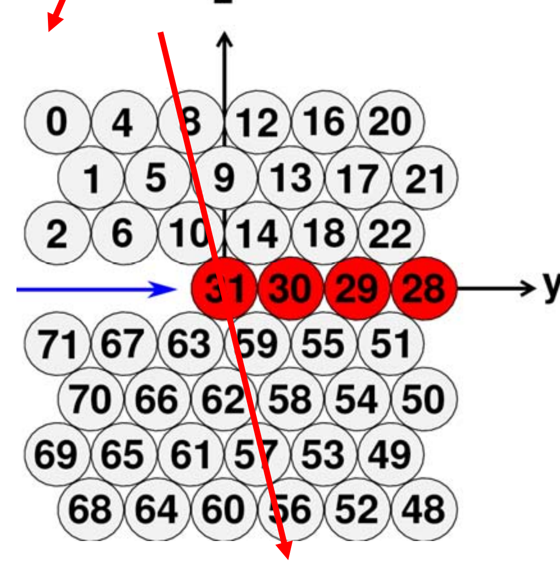
Tracks from cosmic muons passing the irradiated region of the tube hit by the beam are used,
track selection along the tubes using the trigger counter segmentation.

Cosmic μ





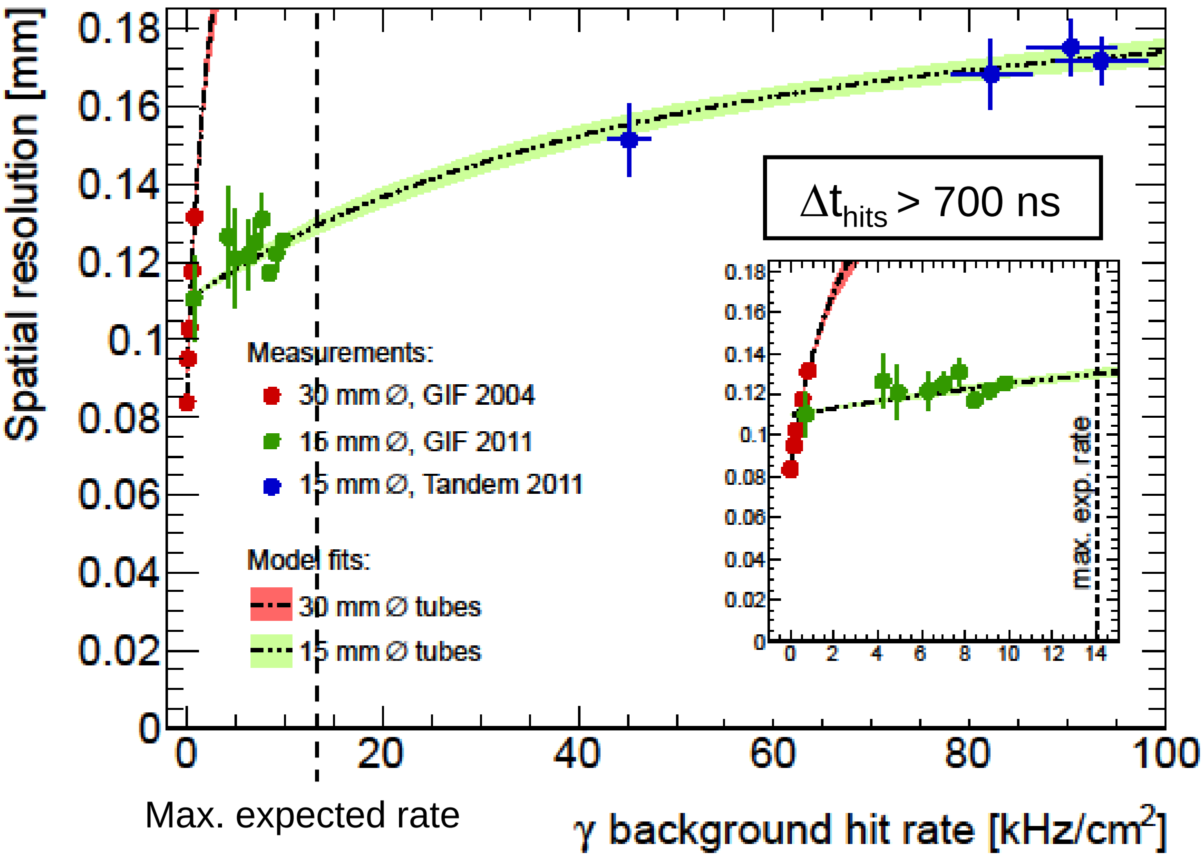
Proton beam



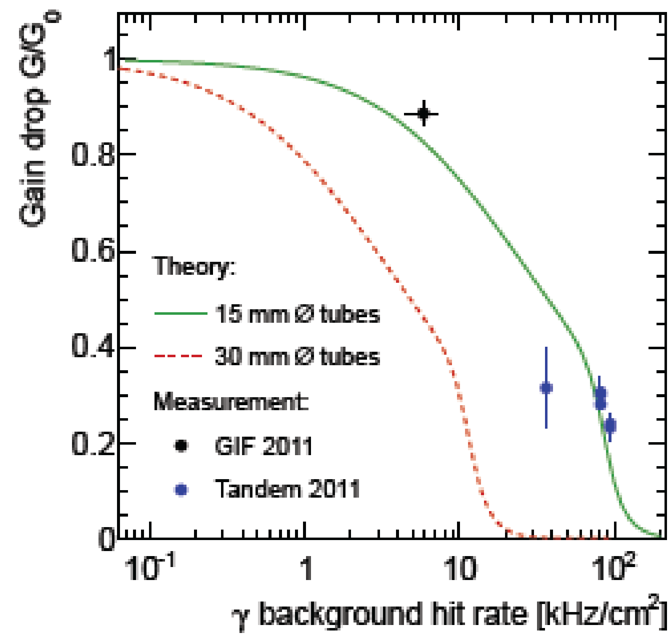
Spatial Resolution at High Rates

Average drift-tube resolution over huge range of the equivalent γ background flux, consistent results from GIF and Tandem measurements:

- Strongly suppressed gain loss effects for 15 mm diameter tubes.
- Saturation of space charge and gain loss effect clearly visible for 15 mm tube diameter (model fit).
- Resolution degradation limited up to very high space charge and background rates.



Max. expected rate

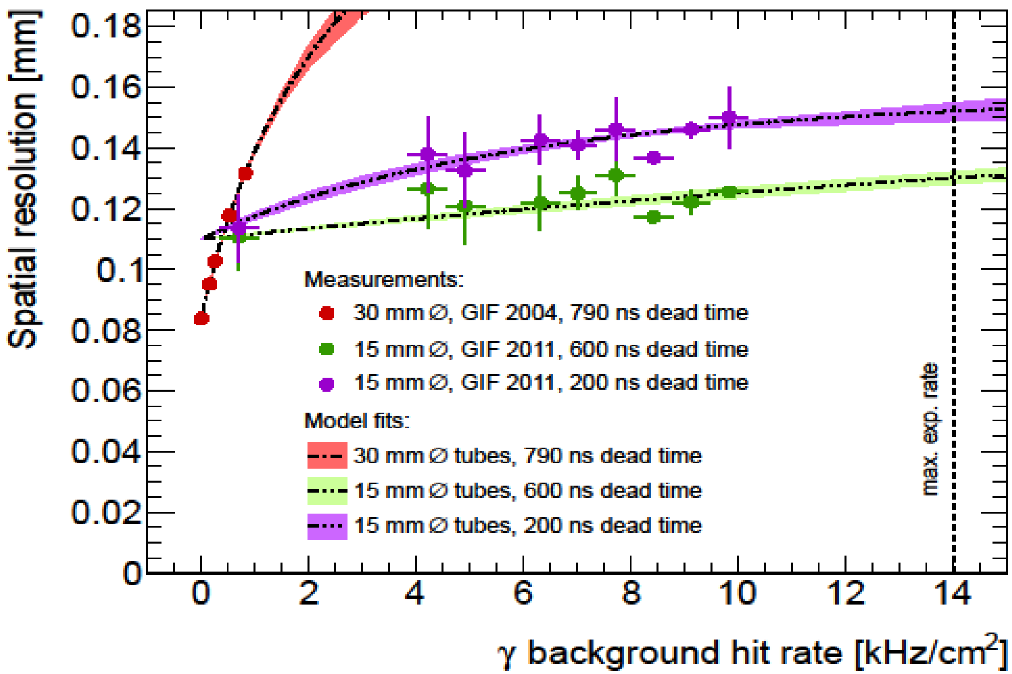


Corresponding gain drop measurement from signal current of individual drift tubes.

Gain loss suppression by factor of 8.7 for 15 mm diameter tubes confirmed.

Spatial Resolution at High Rates

Average drift-tube resolution as a function of the γ background flux at GIF:



all Δt_{hits}

Δt_{hits} > 700 ns no signal pile-up effects

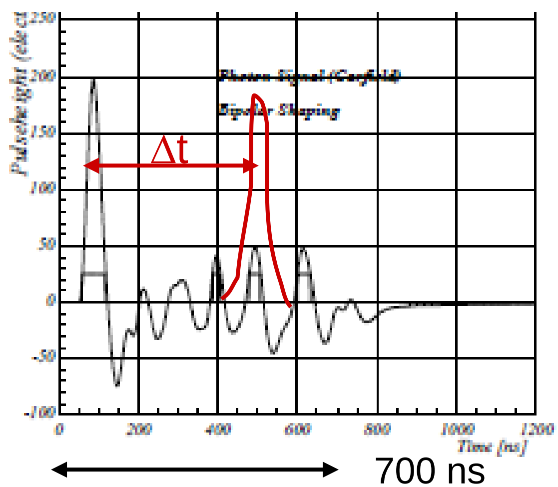
Degradation of the resolution for "pile-up" hits,

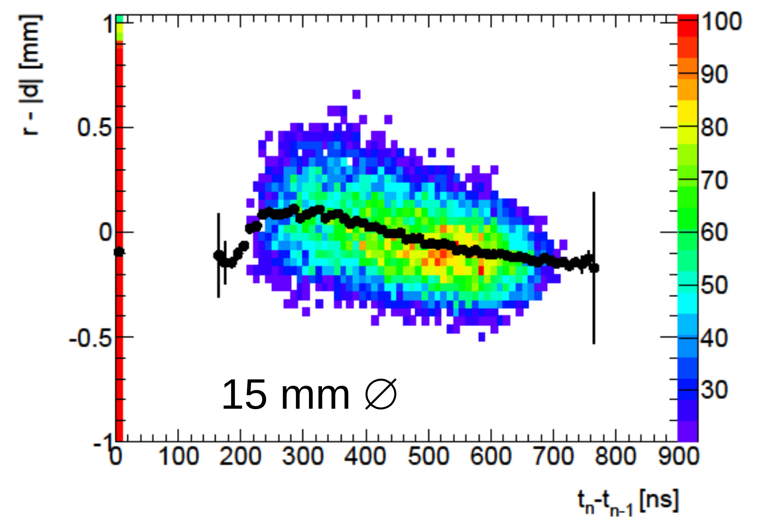
distorted by afterpulsing from preceding hits with the bipolar shaping scheme of the existing MDT electronics.

⇒Track residual distribution shifted and broadened for decreasing Δt between successive hits.

Typical MDT photon signal with afterpulses for bipolar shaping and pile-up pulse.

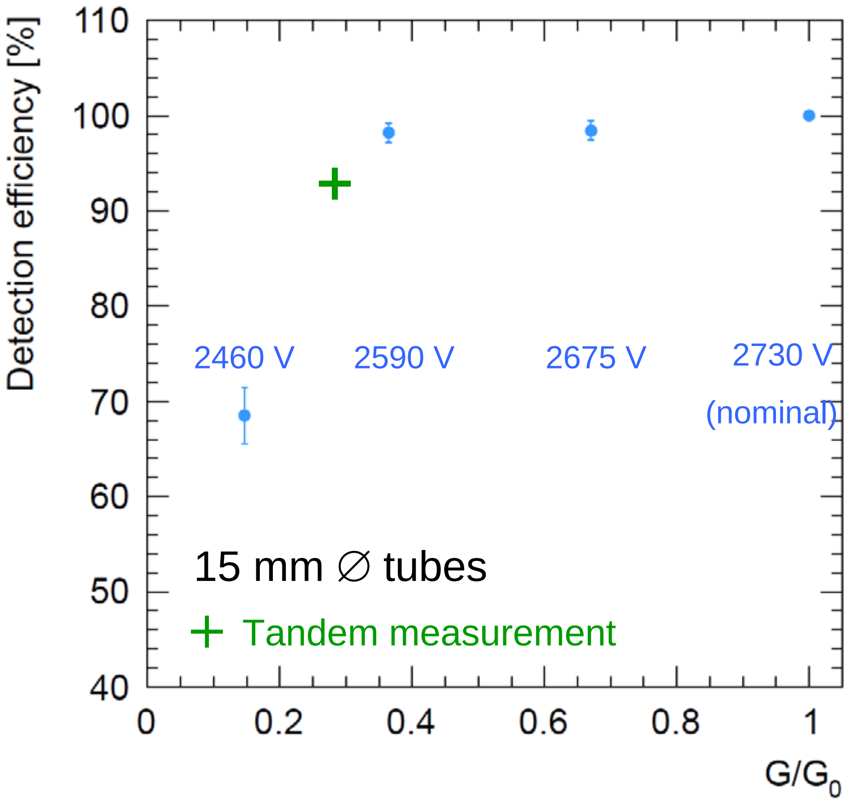
Electronics optimized for 30 mm diameter tubes.

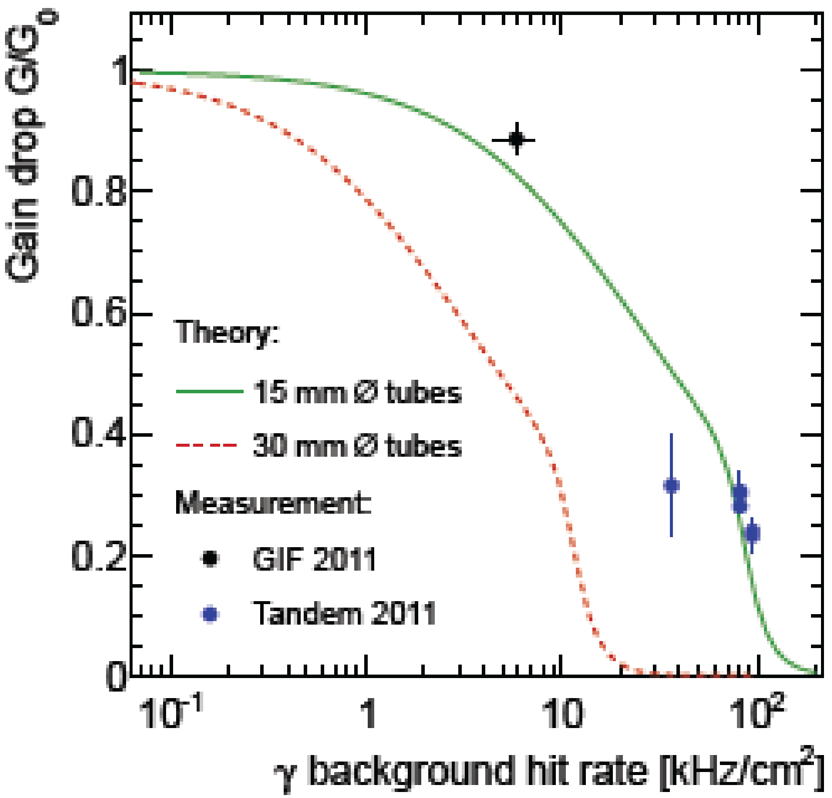




Muon detection efficiency of 15 mm diameter drift tubes as a function of the gas gain
measured in the CERN muon beam by reducing the applied voltage
and under proton irradiation.

Tubes fully efficient down to 40% of the nominal gain, corresponding to 50 kHz/cm² γ flux!

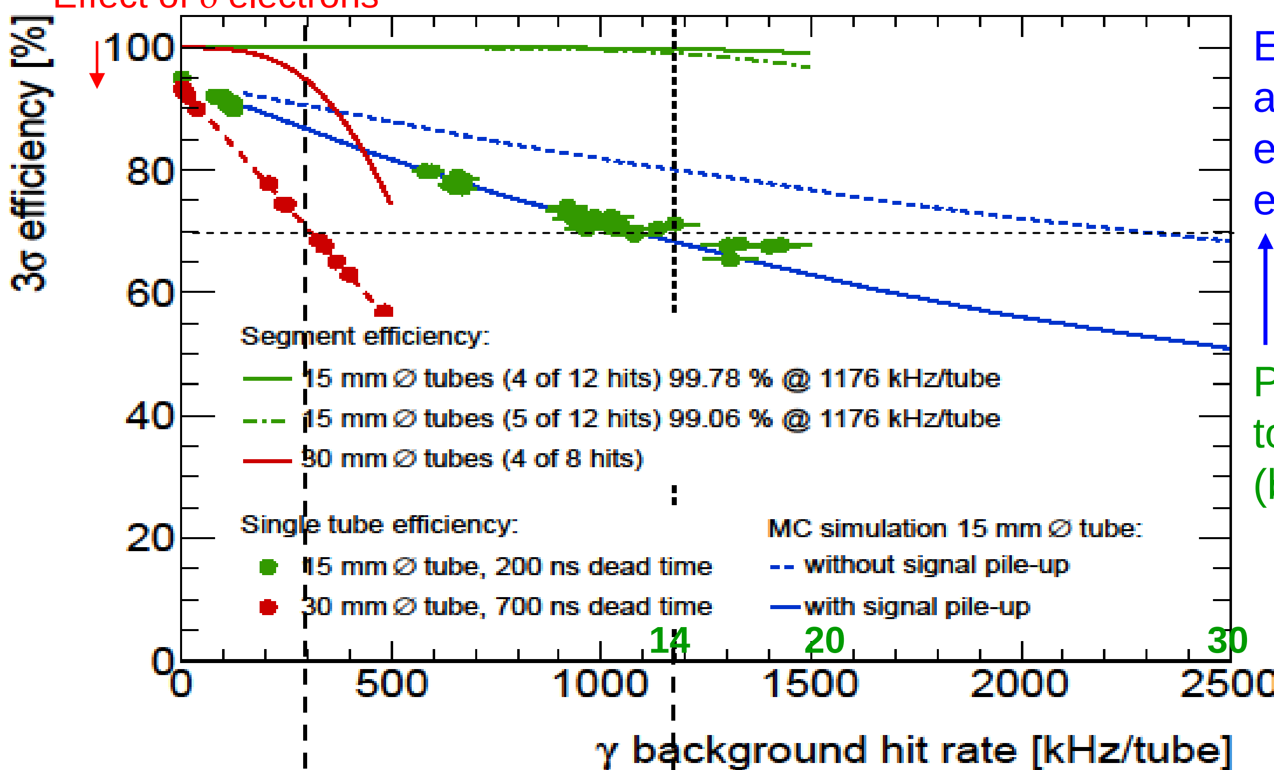




Tracking Efficiency at High Rates

"3σ efficiency" of 15 mm diameter drift tubes, relevant for tracking efficiency, measured at GIF
(probability of reconstructing a hit on the extrapolated muon track within 3 x drift tube resolution)
follows the MC expectations, which are determined by the adjustable electronics dead time
(maximum of 700 ns for 30 mm ∅, minimum of 200 ns for 15 mm ∅).
Track efficiency above 99% at max.expected rate due to larger number of 15 mm ∅ tube layers.

Effect of δ electrons



kHz/cm² γ flux in 15 mm ∅ tubes in ATLAS

Expected gain in efficiency after corrections for signal pile-up effects (software and/or readout electronics).

Partial rejection of pile-up hits due to their degraded resolution (before corrections).

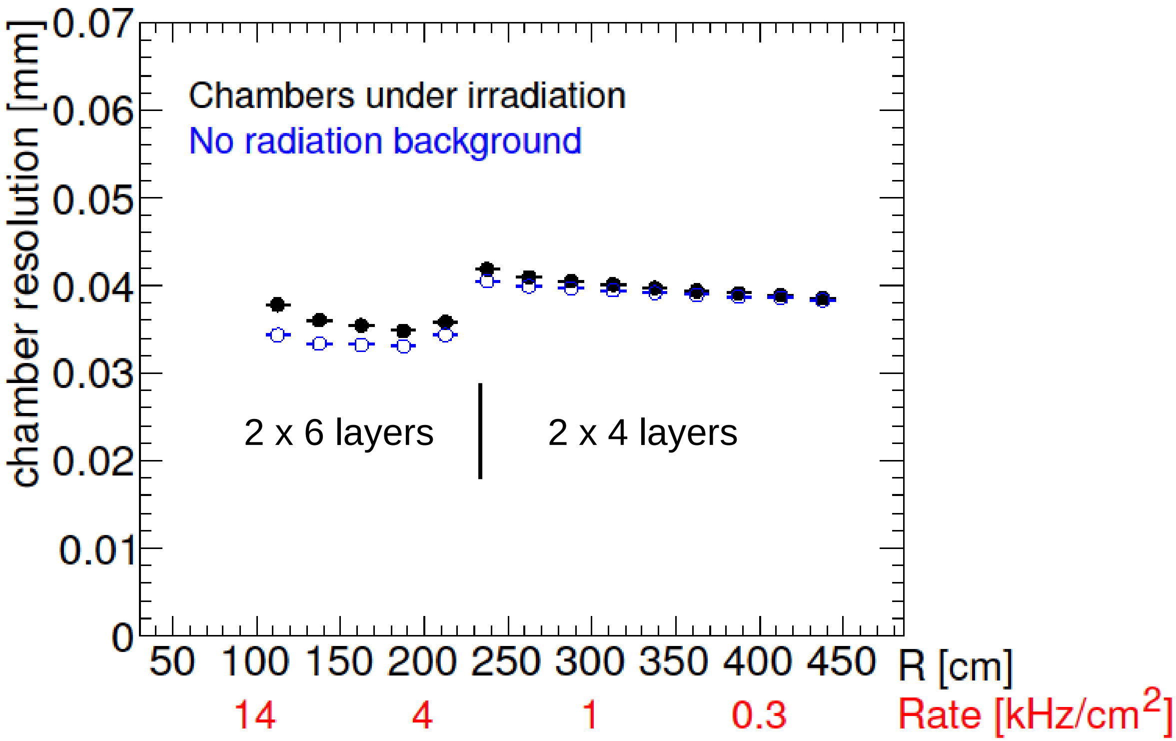
Max. rate at design luminosity

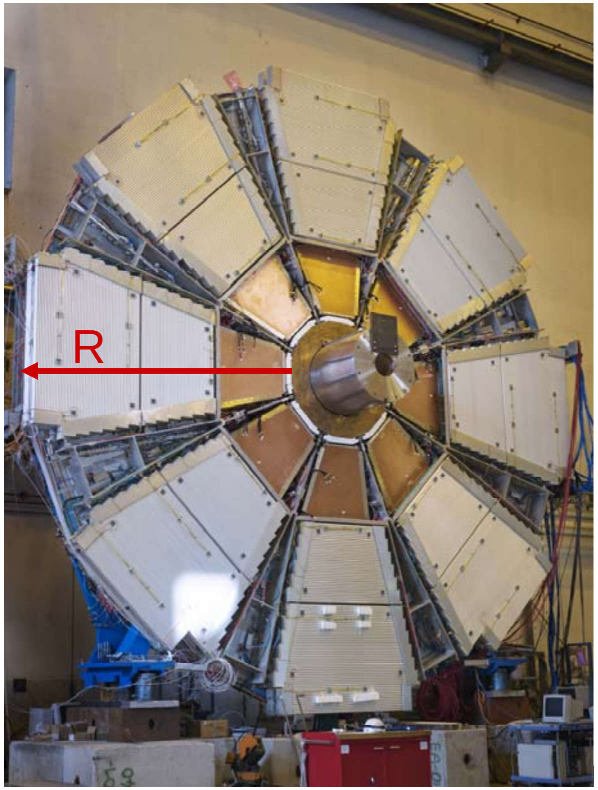
Max. rate at 7 x design luminosity

Track Resolution at High Rates

Expected sMDT track segment resolution in the inner endcap layer of the ATLAS muon spectrometer which experiences the highest background hit rate, increasing exponentially with decreasing distance R to the beam pipe (R_{min} = 100 cm corresponds to $|\eta|$ = 2.7).

Excellent resolution up to the maximum expected rate (35 μm), only minor degradation due to background radiation.





Other Developments

- Drift tube aging tests:
  Irradiation of 15 mm ∅ tubes with 200 MBq ^{90}Sr source over 6 months showed
  no sign of aging for > 6 C/cm accumulated charge on the wire
  (max. requirement for HL-LHC: 4 C/cm, ATLAS MDT tubes certified up to 0.6 C/cm).

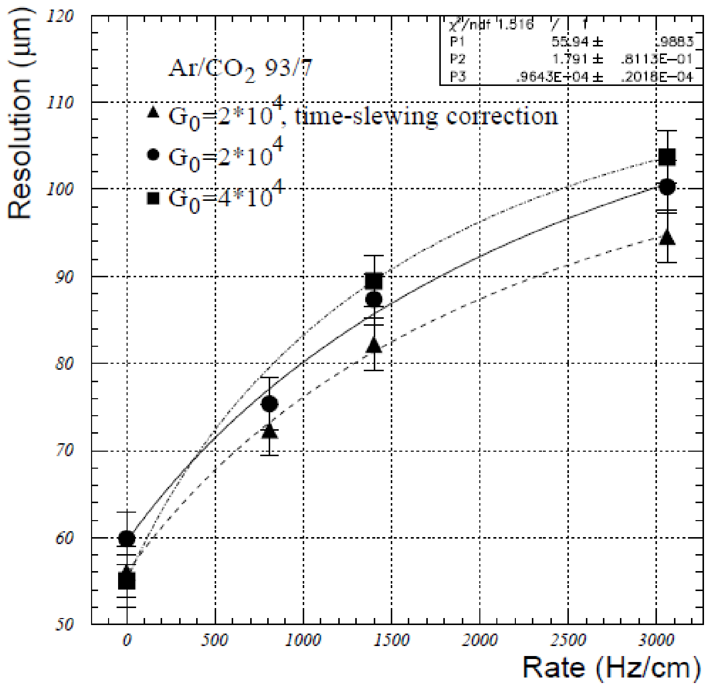
  $Ar:CO_2$ gas was chosen for MDT chambers to prevent aging.
  In addition: low gas gain, chromatized aluminum tubes,
  only certified endplug materials with no outgassing, clean gas distribution system.

- Development of a new version of the MDT chamber readout electronics in progress,
  with higher radiation hardness (130 nm CMOS technology) and bandwidth.

- Concept for using MDT and sMDT chambers in the ATLAS L1 muon trigger:
  improving decisively the momentum resolution and selectivity of the trigger at
  high-luminosity upgrades of the LHC (see ATLAS trigger upgrade talk in this session).

Conclusions

- New muon drift tube (sMDT) chamber technology ready for LHC upgrades.
- Excellent high-rate performance of 15 mm diameter drift tubes far beyond the requirements.
- Straight-forward integration into the existing ATLAS detector.
- First sMDT chamber installation in the 2013/14 LHC shutdown.



Saturation of resol. degradation for 30 mm ∅ tubes at GIF:
M.Aleksa thesis, TU Vienna, 1999.