Performance of Muon Drift-Tube Detectors for LHC Upgrades at Very High Irradiation Rates

B. Bittner, J. Dubbert, O. Kortner, H. Kroha, A. Manfredini, S. Nowak, S. Ott, R. Richter, Ph. Schwegler, D. Zanzi

Max-Planck-Institut für Physik, Munich

O. Biebel, A. Engl, R. Hertenberger, A. Zibell

Ludwig-Maximilians University, Munich

The Wonder of Science

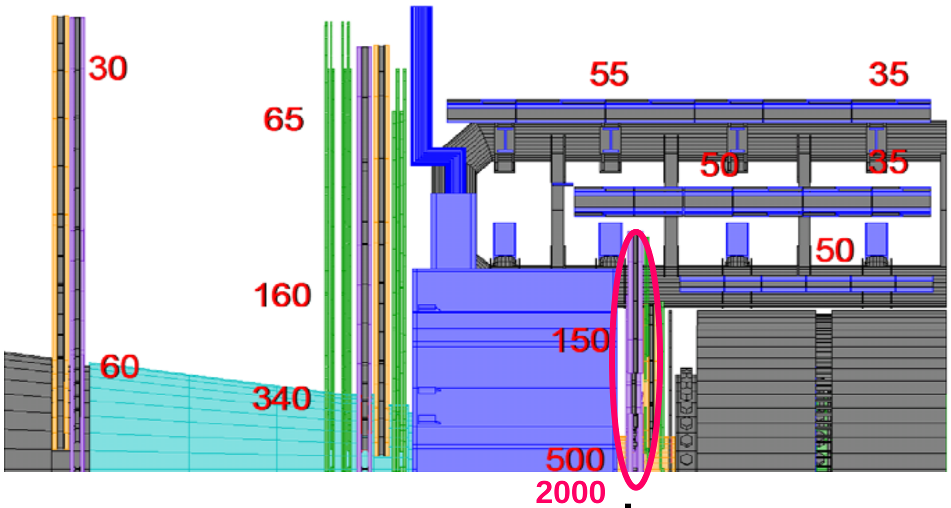
2012 IEEE NSS/MIC/RTSD

2012 IEEE Nuclear Science Symposium

October 29 – November 3, 2012, Anaheim, California

ATLAS Muon Drift Tube (MDT) Chambers and HI-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 background measurements during ATLAS operation:

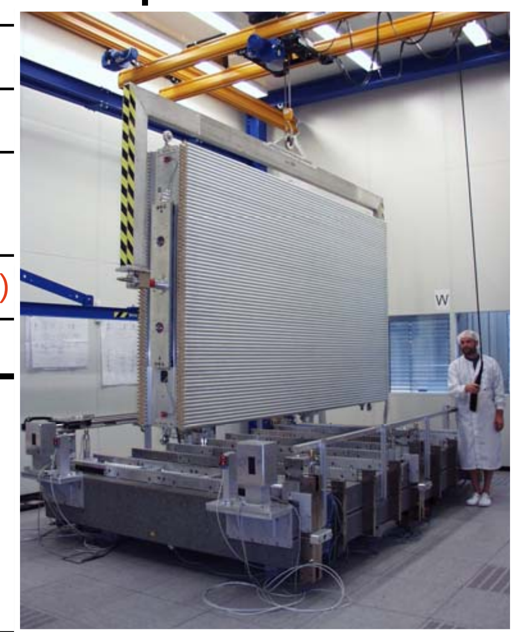


At HL-LHC (up to 7 x LHC design luminosity): max. background hit rates of 14 kHz/cm^2 expected.

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

Parameters of the ATLAS 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 (without bg. radiation)	80 µm
Nr. of drift tube layers	2 x 3 (4)
Chamber resolution	35 µm

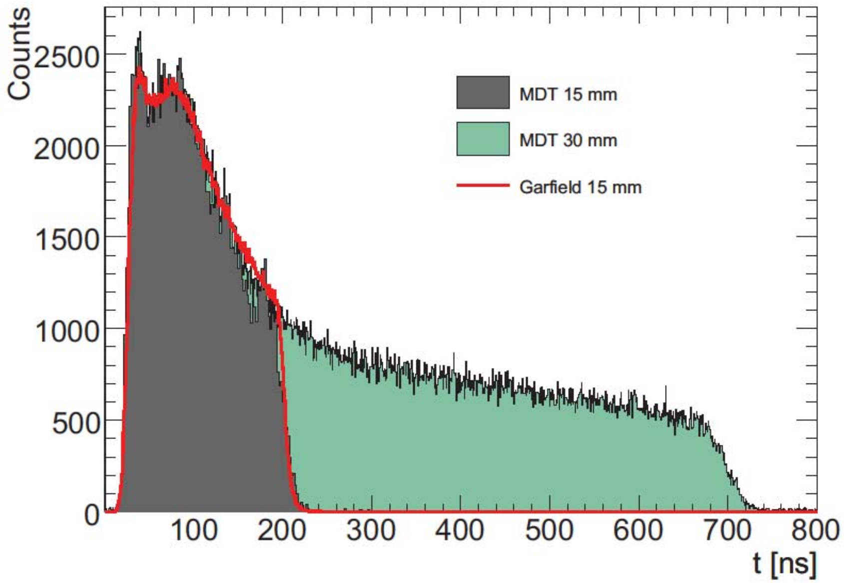


Small Diameter Drift Tubes (sMDT) for High Rates: Tracking Efficiency

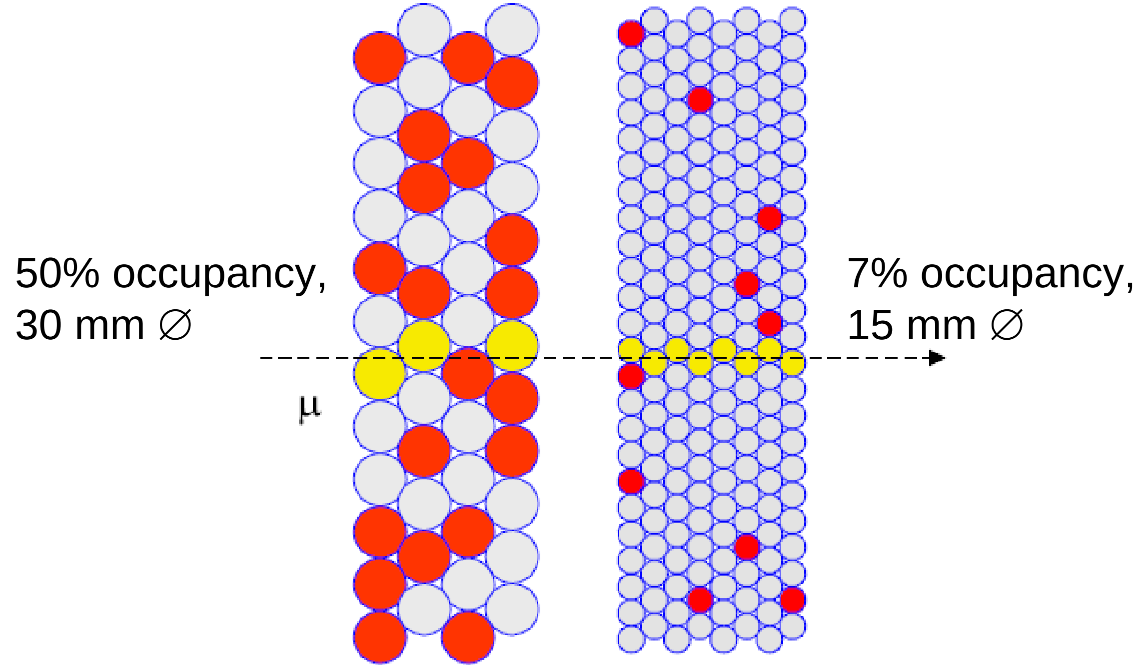
15 mm ∅ instead of 30 mm ∅ tubes, same gas mixture and gas gain:

Vast improvement of tracking efficiency at high background 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.
- ❑ Up to twice the number of tube layers fit into the same detector volume.



Drift time spectra

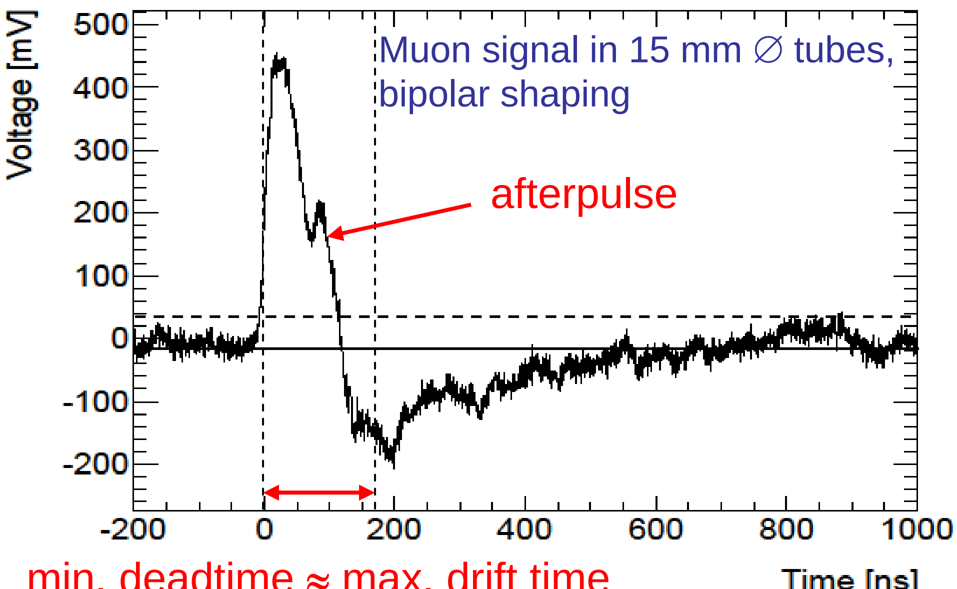


Small Diameter Drift Tubes (sMDT) for High Rates: Tracking Efficiency

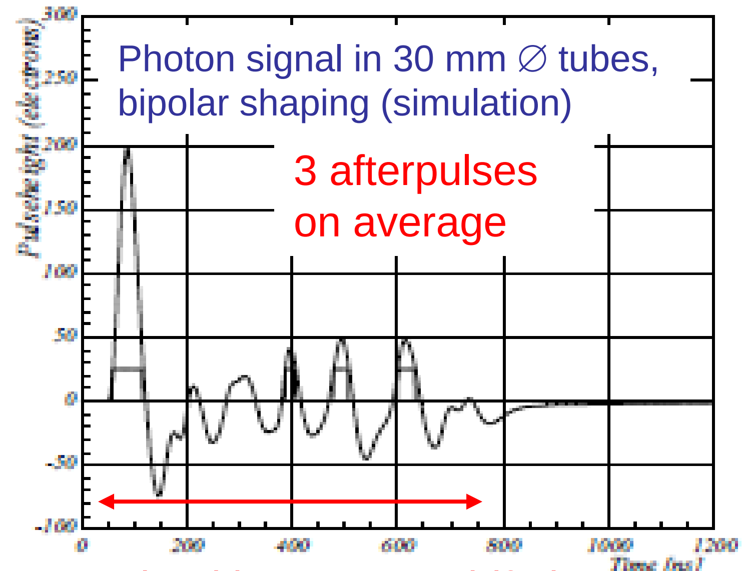
15 mm ∅ instead of 30 mm ∅ tubes, same gas mixture and gas gain:

- ❑ 3σ single-tube efficiency
  = probability to detect a hit on the muon trajectory within 3 x drift tube resolution,
  basis for evaluating the chamber tracking efficiency,
  deteriorates at high rates due to masking of muon hits by background hits,
  mainly determined by the electronics deadtime.

- ❑ Shorter maximum drift time allows for reduction of electronics deadtime from 790 ns to 175 ns
  (adjustable within these limits in the MDT readout electronics)
  since afterpulses (from delayed arrival of ionisation clusters) occur within the max. drift time.



min. deadtime ≈ max. drift time



max. deadtime ≈ max. drift time

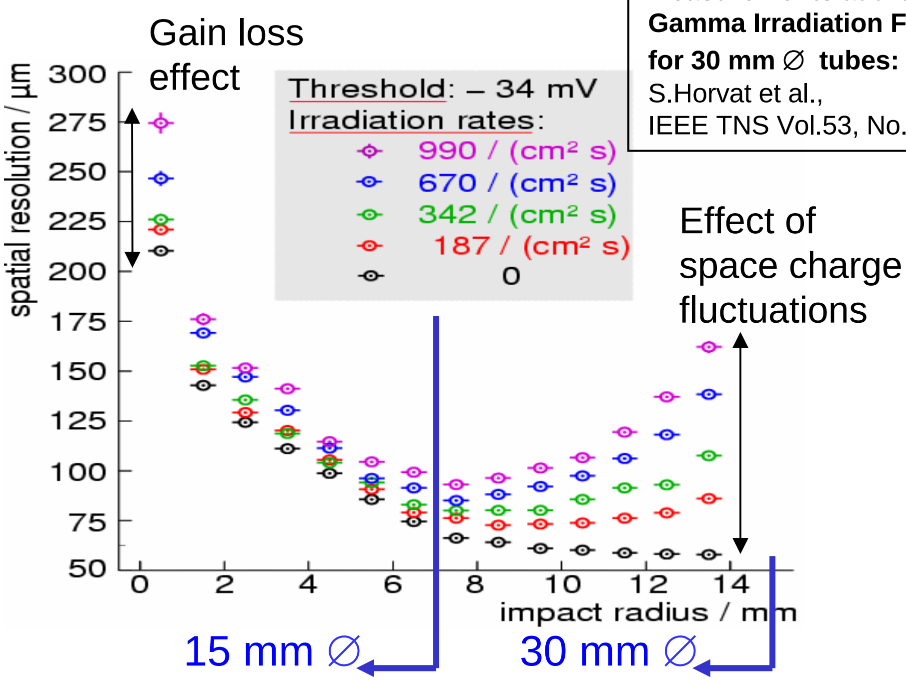
Small Diameter Drift Tubes (sMDT) for High Rates: Spatial Resolution

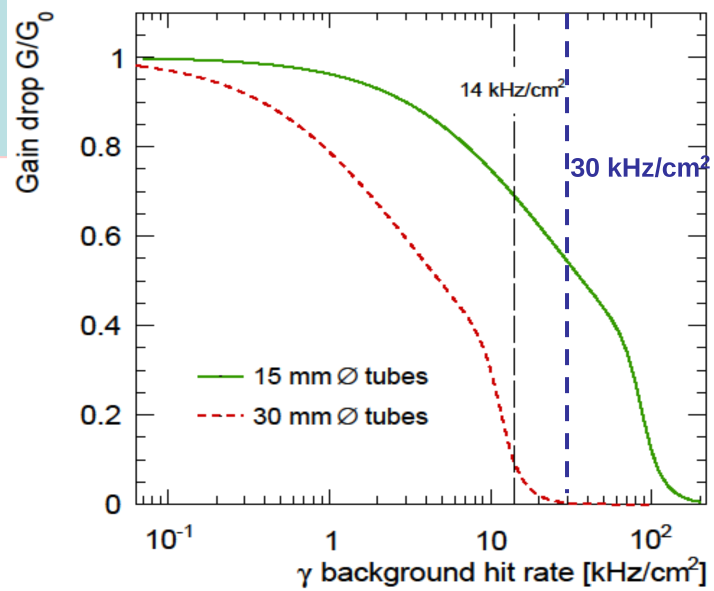
15 mm ∅ instead of 30 mm ∅ tubes, same gas mixture and nominal gas gain:

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

- ❑ Gain loss due to } ~ inner tube radius r^3 (for γ, neutrons): 8.7 x smaller
- space charge } ~ inner tube radius r^4 (for charged part.): 18 x smaller
- ❑ Radiation induced space charge fluctuations: eliminated.
- ❑ 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

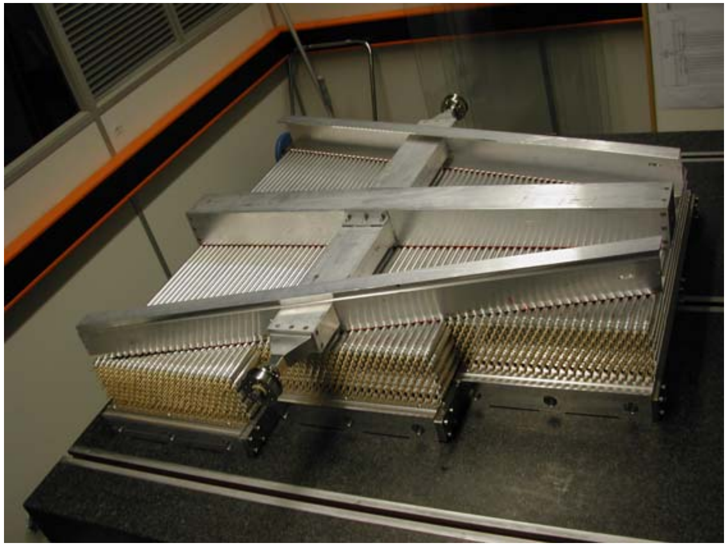


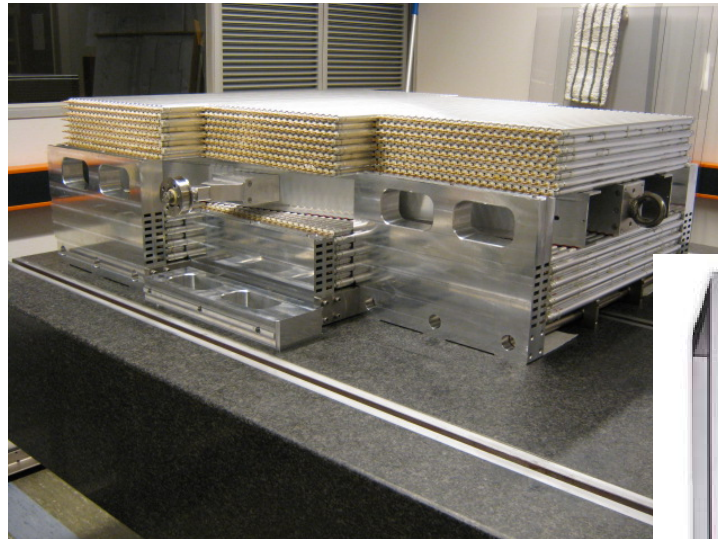


Gain loss G/G_0 strongly suppressed for 15 mm diameter tubes.
Saturation: iterative calculation according to Diethorn's formula:

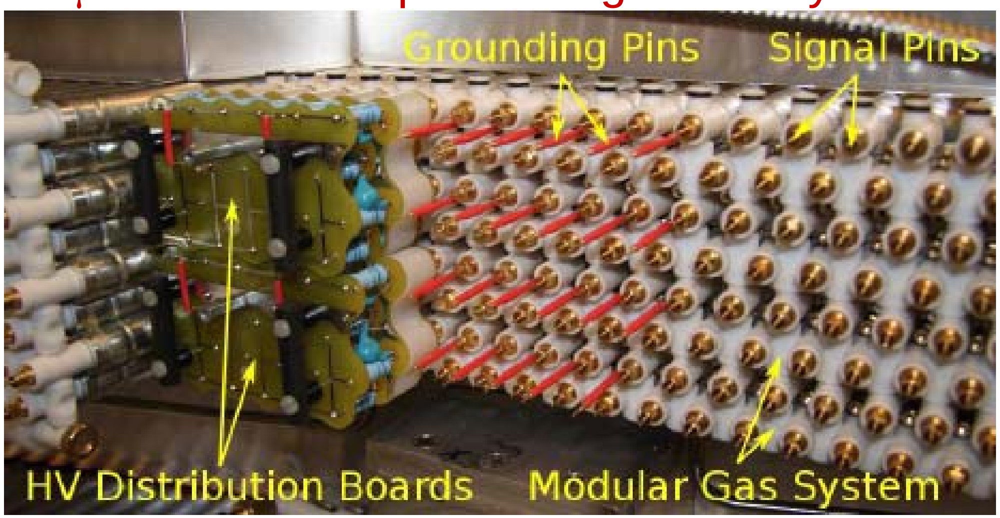
$$G = \left[\frac{E_{wire}}{3E_{min}}\right]^{\frac{r_{wire}E_{wire}\ln 2}{\Delta V}}$$

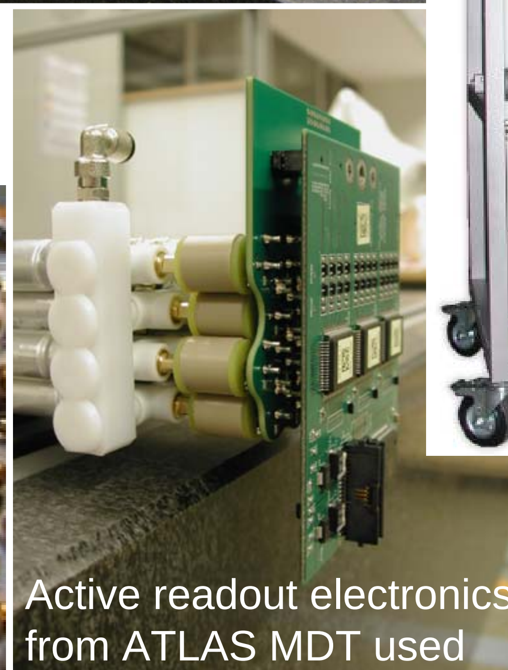
E_{wire} = electric field at the sense wire, depends on the space charge density, thus on the hit rate, and on the inner tube radius.





2 x 8 layers of 15 mm ∅ drift tubes,
assembled within 2 working days,
15 μm sense wire positioning accuracy





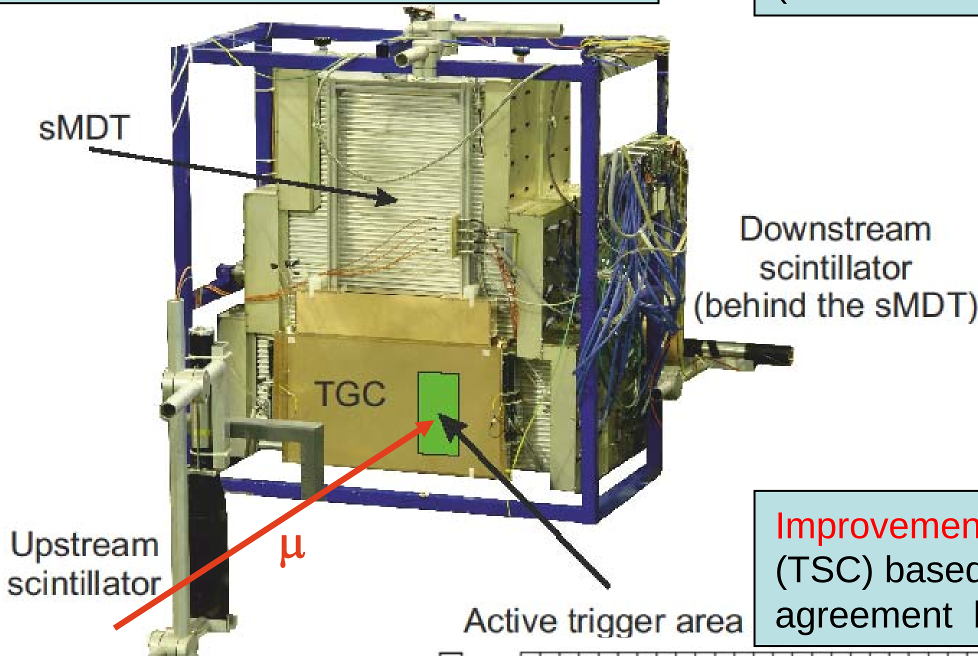
Active readout electronics from ATLAS MDT used

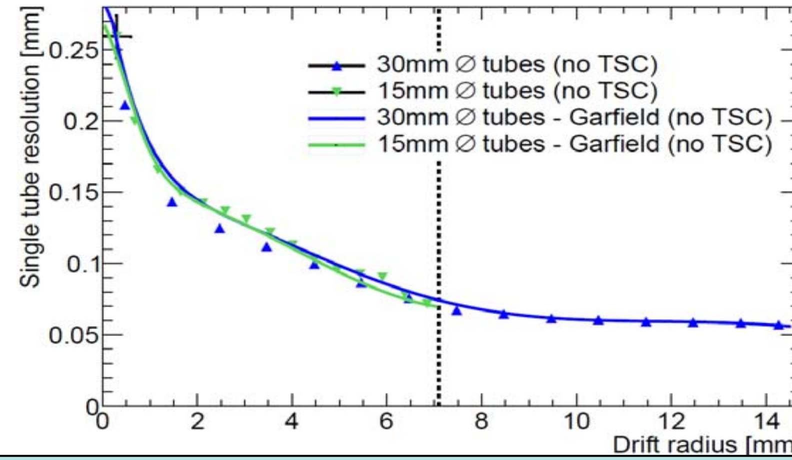
Muon Beam Test: Spatial Resolution

CERN SPS-H8 180 GeV muon beam.

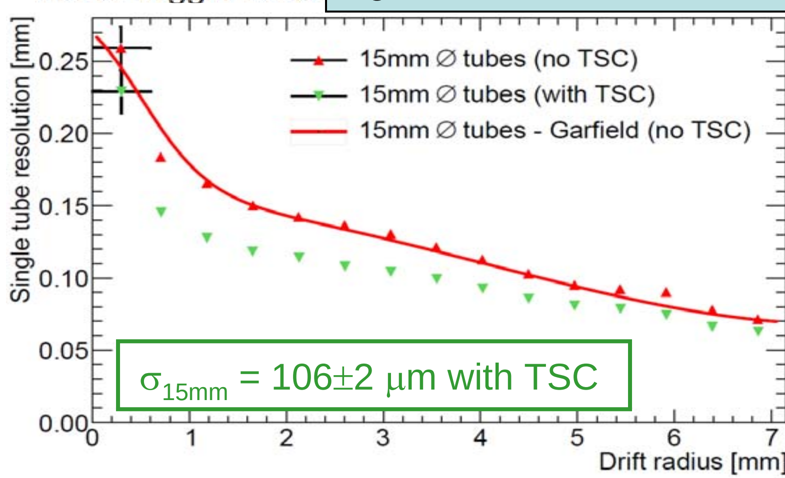
No background radiation.

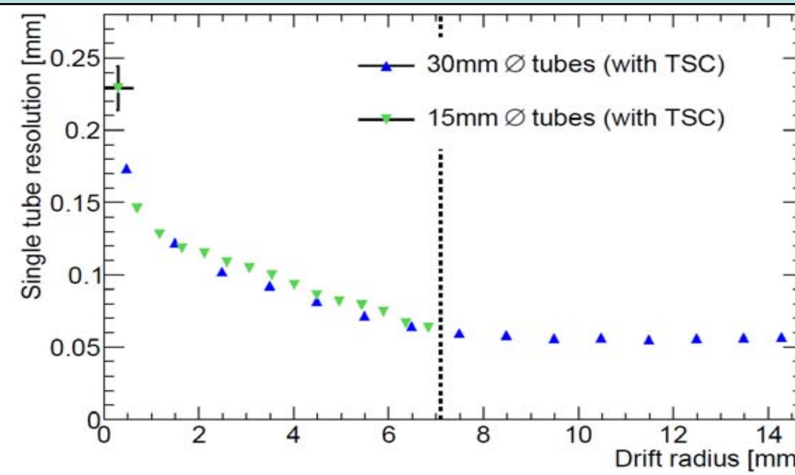
Agreement between 15 and 30 mm ∅ tubes in the common radial range, as expected, and with the Garfield simulation (identical readout electronics with bipolar shaping):





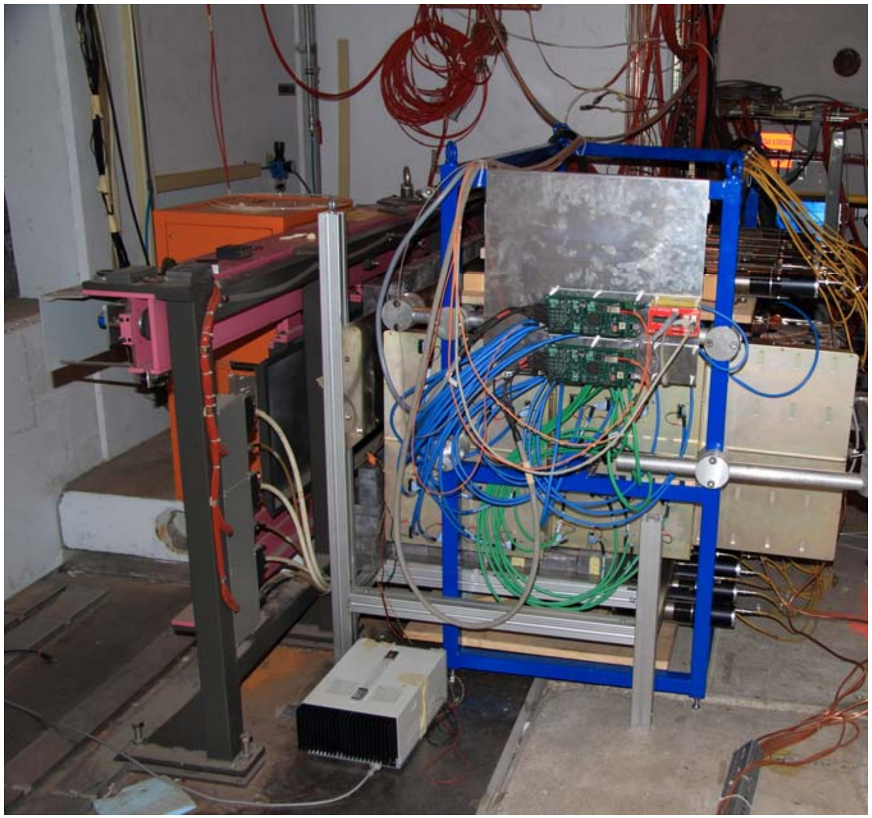
Improvement of drift tube resolution by 20 μm using time slewing corrections (TSC) based on the measurement of the leading-edge signal charge, agreement between 15 and 30 mm ∅ tubes also after TSC:



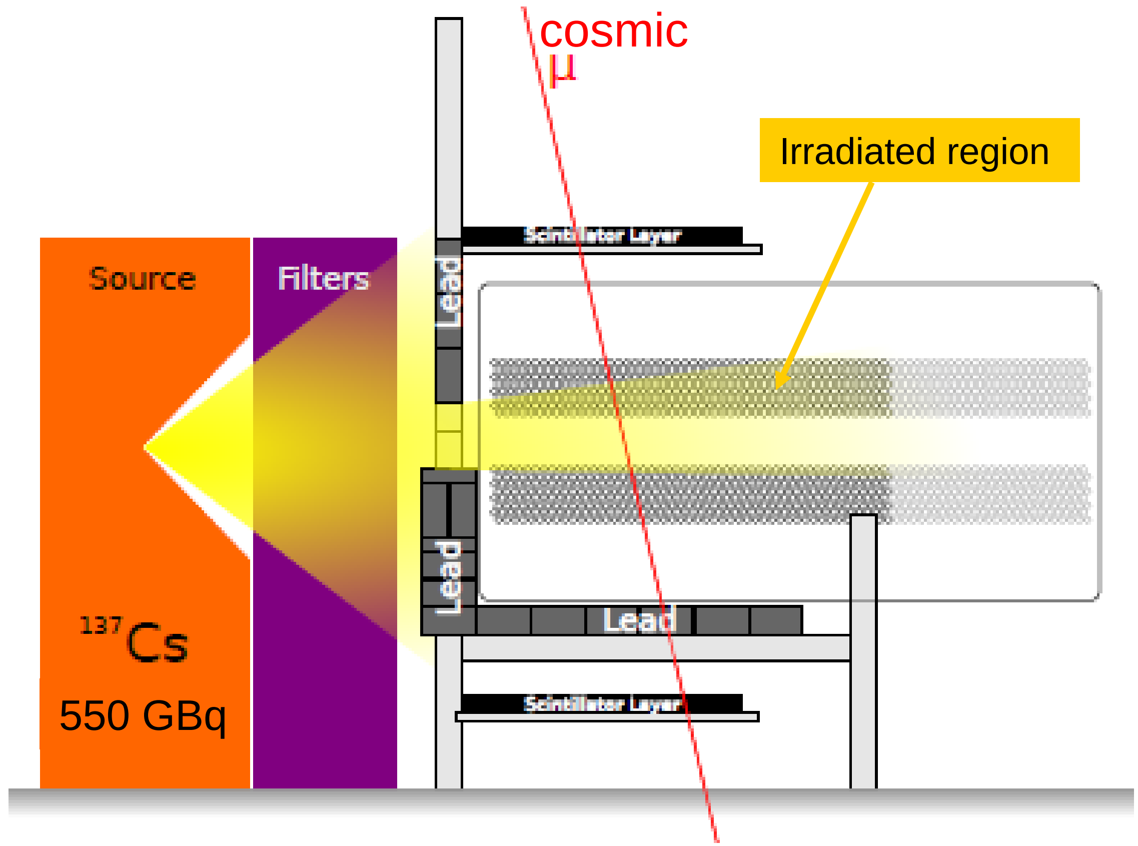


Irradiation Tests I, 2010/11

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 tracking reference for cosmic muon trajectories extrapol. to the irradiated tubes.



Irradiation Tests II, 2011/12

Spatial resolution degradation due to space charge also measured under irradiation with a 20 MeV high-intensity (5 – 280 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 flux of 70 kHz/cm^2.

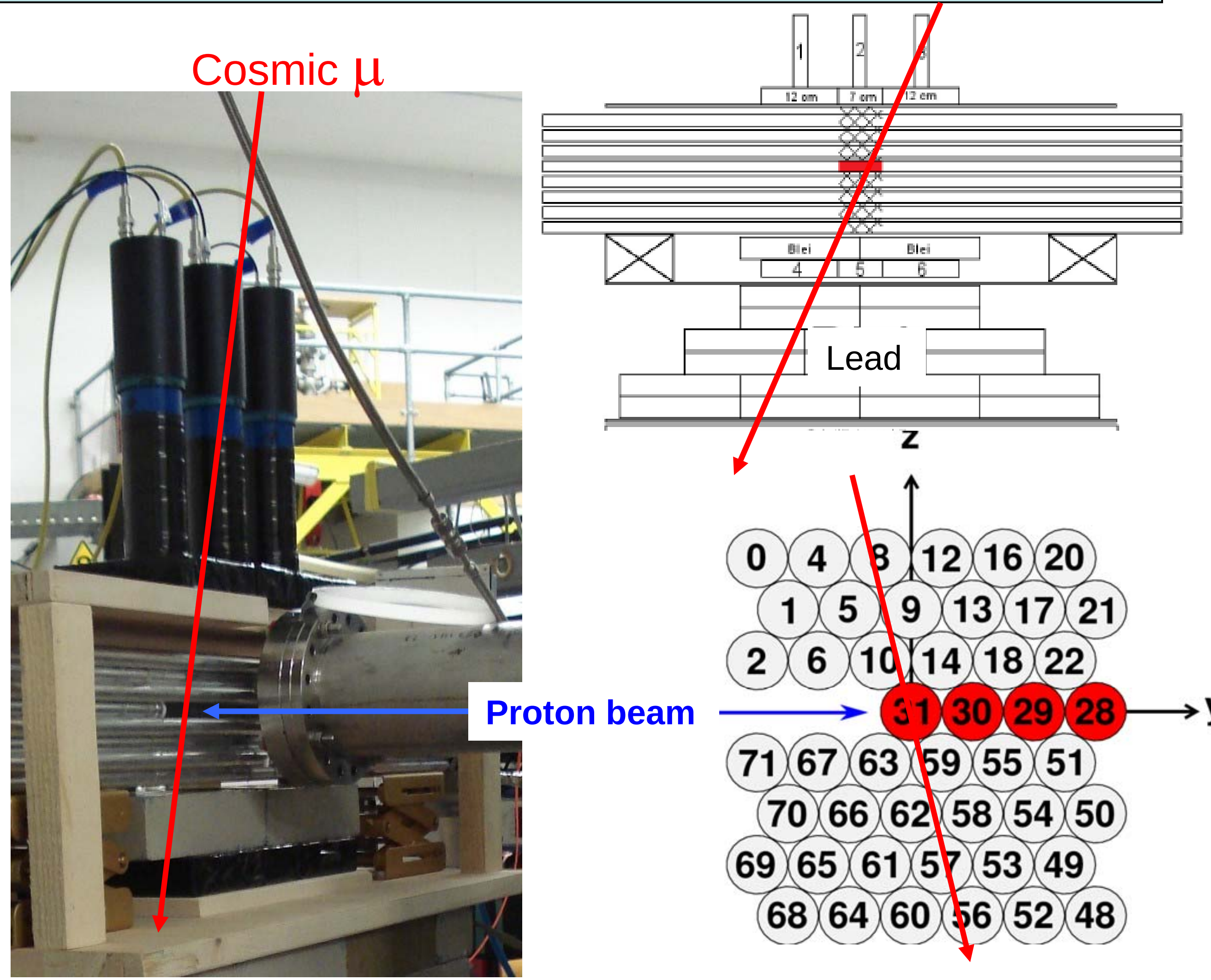
Dedicated sMDT chamber.

Not illuminated tubes serve as precise tracking reference for cosmic muons.

Irradiated region of illuminated tubes used for resolution measurement (space charge).

Unirradiated regions of illuminated tubes used for 3σ efficiency measurement (hit masking).

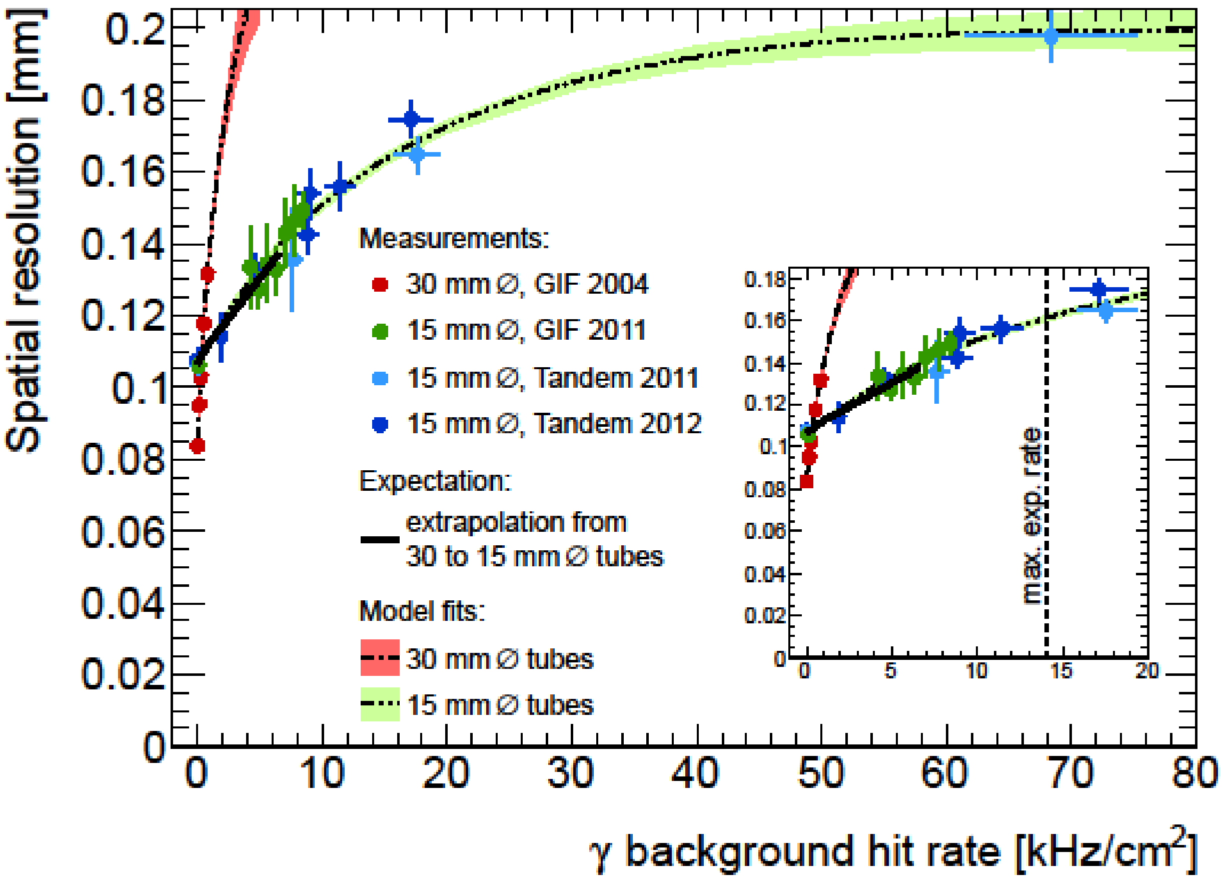
Selection of regions via trigger counter segmentation.

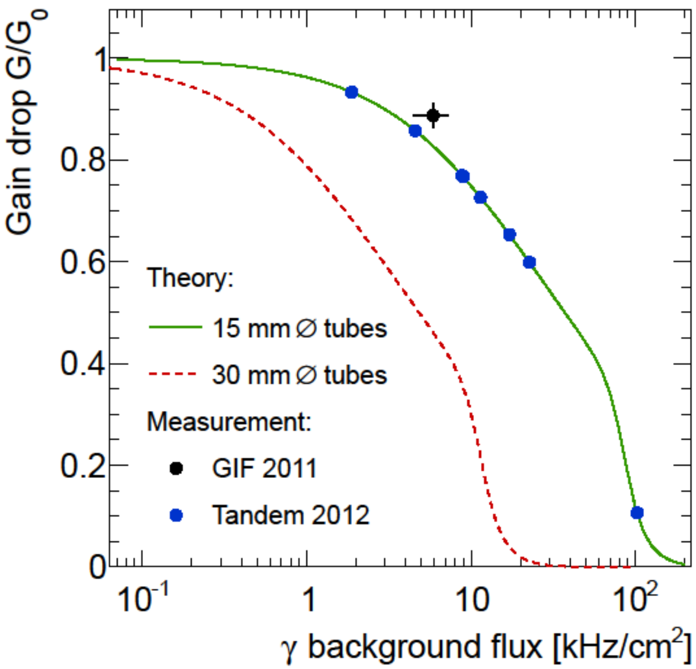


Spatial Resolution at High Rates

Average drift-tube resolution over huge range of the equivalent γ background flux:

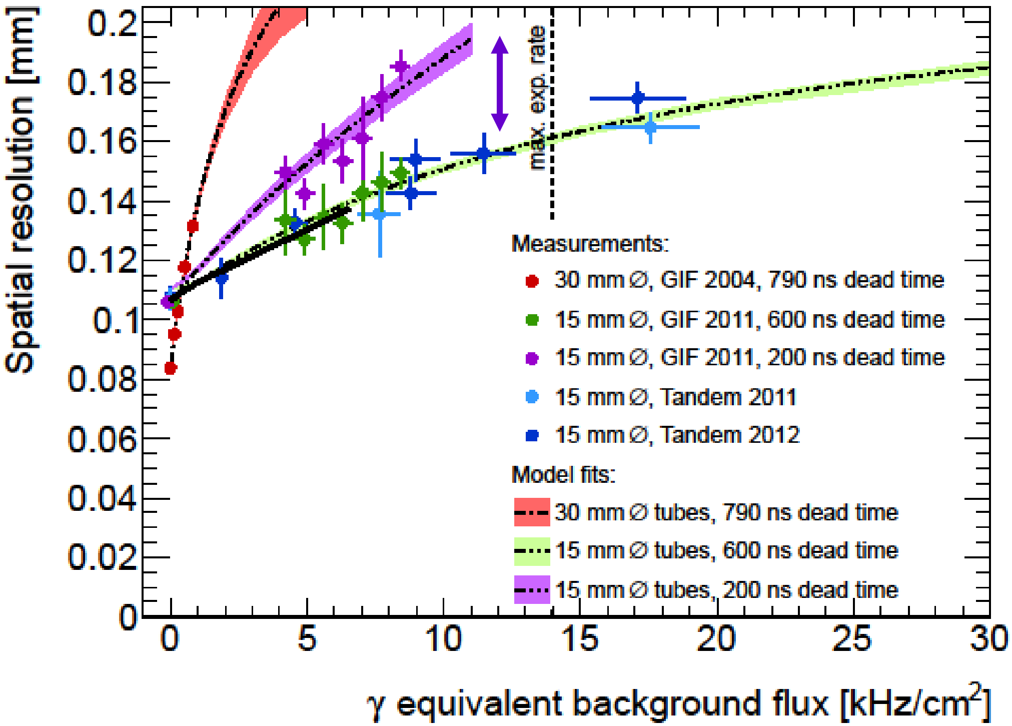
- Gain loss strongly suppressed gain for 15 mm diameter tubes.
- Saturation of space charge and gain loss effect clearly seen for 15 mm ∅.
- Resolution degradation limited up to very high background rates.





Gas gain corresponding to space charge and equivalent γ flux for the GIF and Tandem measurements

Spatial Resolution at High Rates

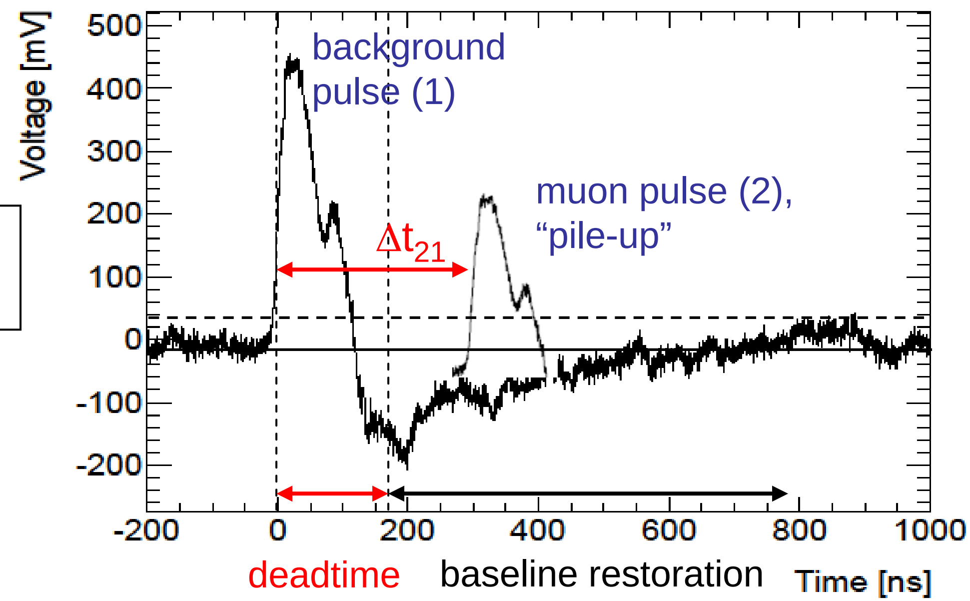


Degradation of the resolution of "pile-up" hits with small Δt_{21} < 700 ns to predecessor hit due to long baseline restoration time of existing MDT electronics optimised for 30 mm ∅ tubes and 790 ns deadtime.

Relevant at high tube counting rates, i.e. for GIF not for Tandem measurements.

Also:
Degradation of detection efficiency of "pile-up" hits.

⇒ Optimisation of pulse shaping for 15 mm ∅ tubes and short deadtime: fast baseline restoration



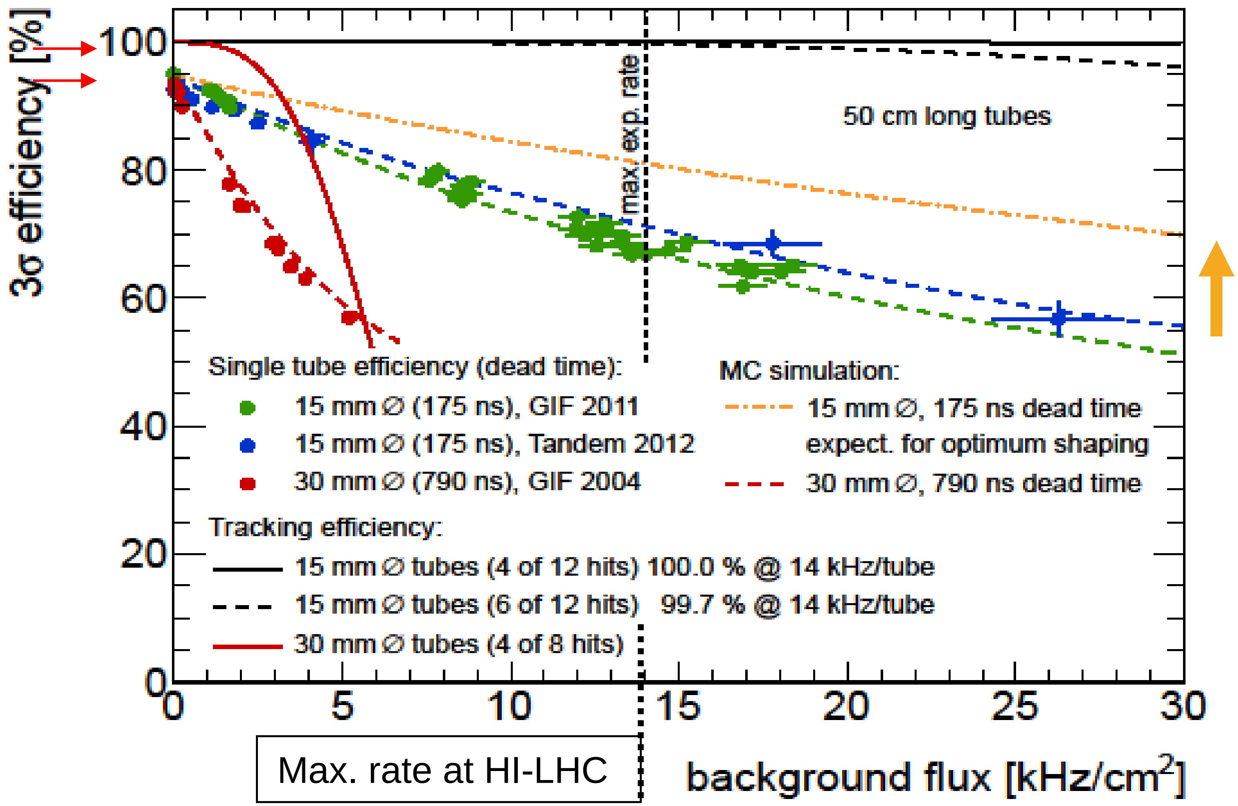
Tracking Efficiency at High Rates

Vast improvement of 3σ single-tube efficiency compared to 30 mm ∅ observed both at GIF and Tandem (using existing MDT readout electronics).

Track reconstruction efficiency in 2 x 6 layer sMDT chambers virtually 100 % at the highest expect rate at HI-LHC and still far beyond.

Further improvement of 3σ efficiency with optimised pulse shaping for 15 mm ∅ tubes and short deadtime at very high background rates: increased efficiency for pile-up hits at time intervals < 700 ns.

Effect of δ electrons

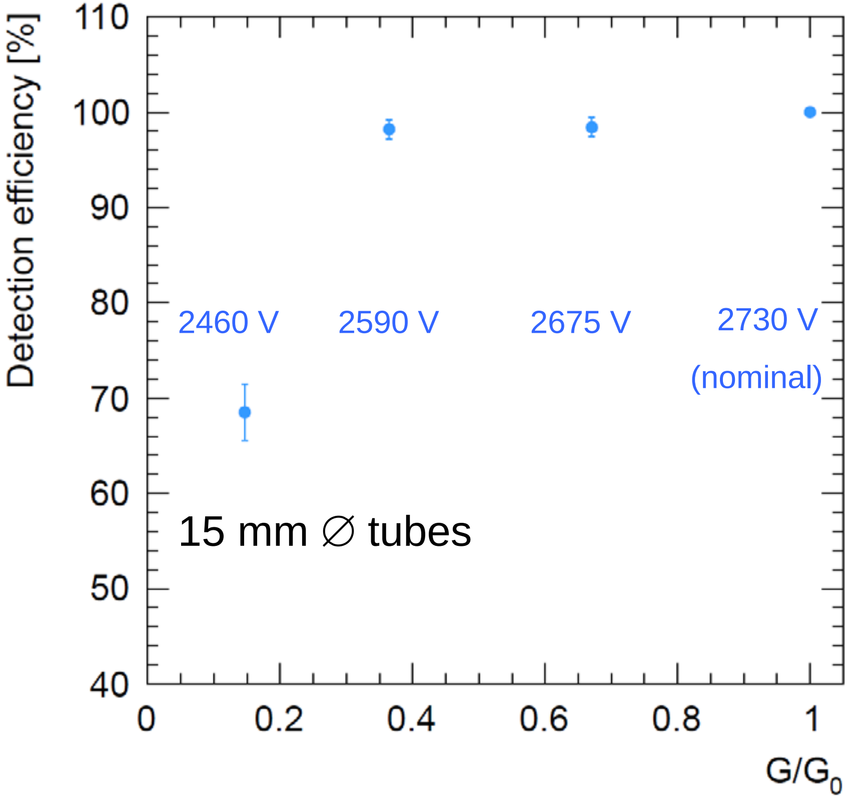


Expected further improvement of efficiency for pile-up signals using optimised shaping for 15 mm ∅ tubes

Muon Detection Efficiency

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.

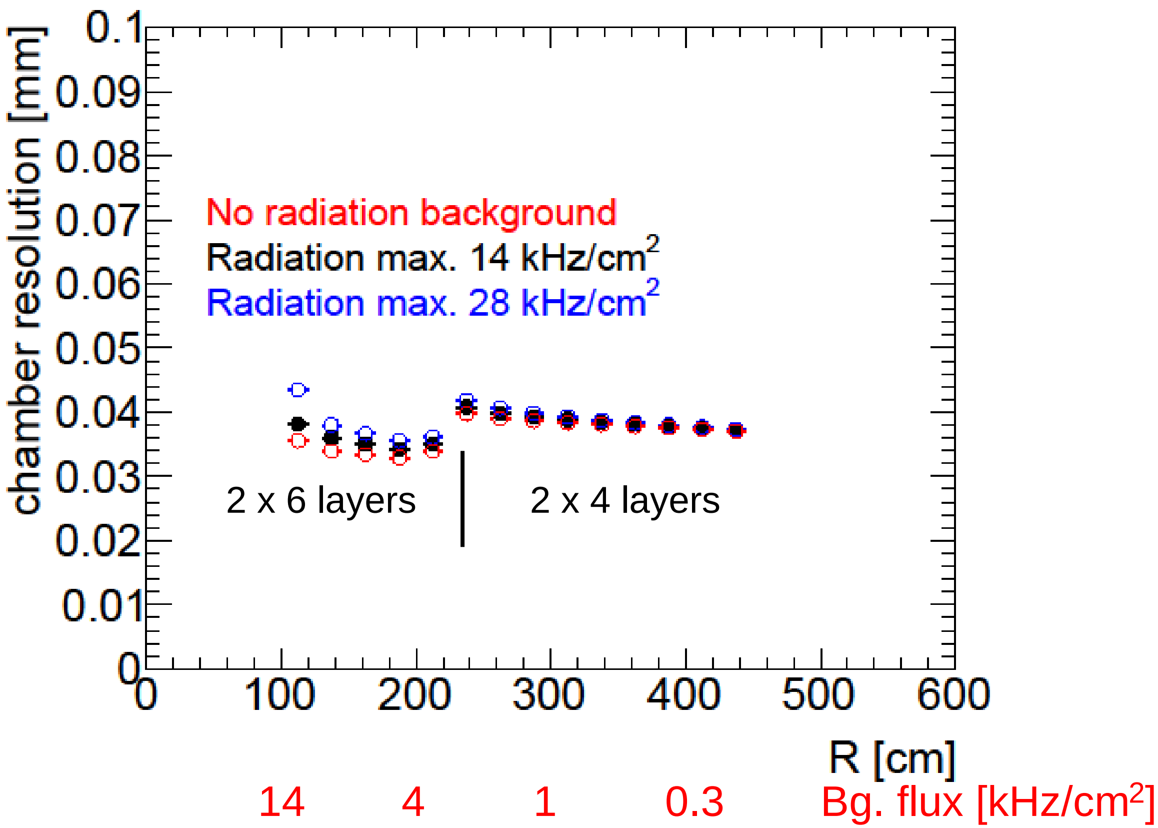
Tubes fully efficient down to 40% of the nominal gain G_0 corresponding to a γ backgr. flux of 50 kHz/cm^2 .

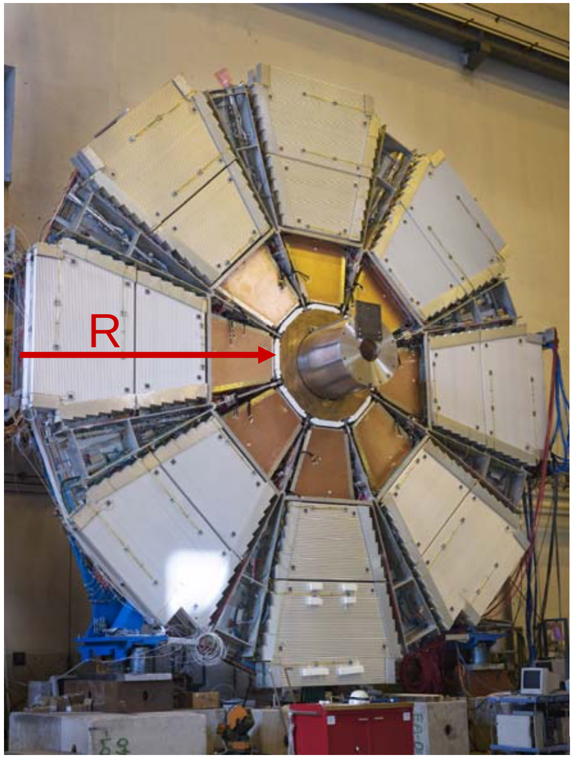


Track Resolution at High Rates

Expected sMDT track segment resolution in the inner endcap layer of the ATLAS muon spectrometer which experiences the highest background flux, 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 (37 μm),
only minor degradation due to background radiation, even at twice the expected max. rate.





Aging Properties

ATLAS MDT tubes certified up to 0.6 C/cm accumulated charge on the wire.

Maximum requirement for HI-LHC: 4 C/cm.

Irradiation of 15 mm ∅ sMDT tubes with 200 MBq ^{90}Sr source over 6 months showed no sign of aging up to 6 C/cm.

$Ar:CO_2$ gas chosen for MDT chambers to prevent aging.

In addition:
- low gas gain 2×10^4,
- clean aluminum tubes with chromatized surfaces,
- only certified endplug materials with no outgassing,
- clean gas distribution system,
- extensive experience from MDT chamber construction.

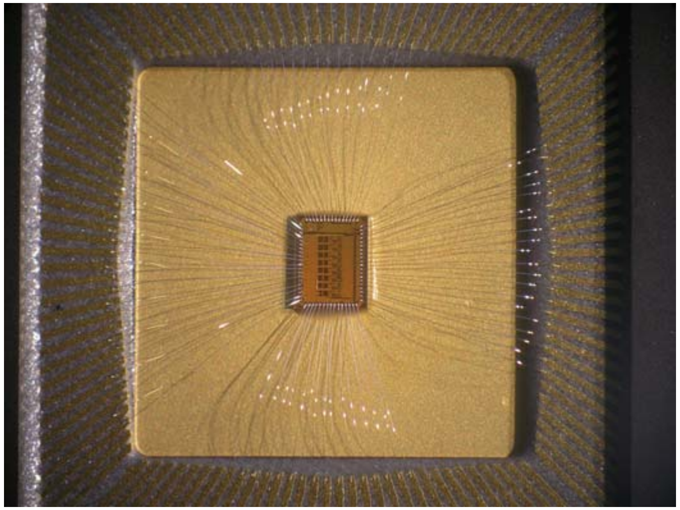
Readout Electronics Upgrade

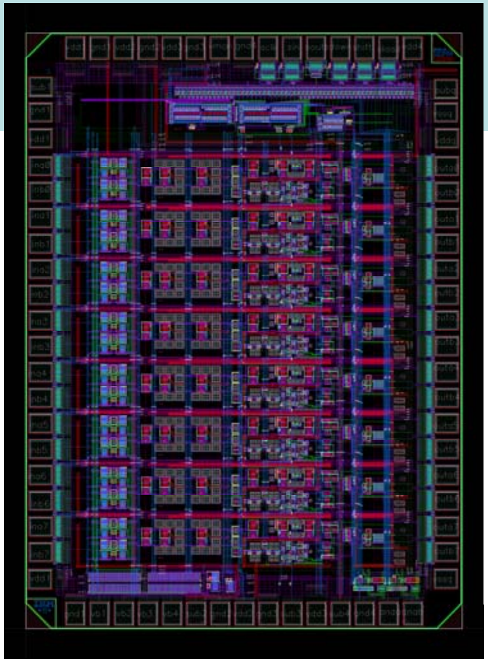
Development of a new version of the MDT front end chip (ASD) in progress with

- higher radiation hardness (120 nm IBM CMOS technology),
- higher bandwidth,
- optimised shaping for very high rates,
- preparation for implementation of (s)MDT based, high-resolution Level 1 muon trigger.

For replacement on existing MDT chambers and for new sMDT chambers.

First 8-channel prototype produced and working.



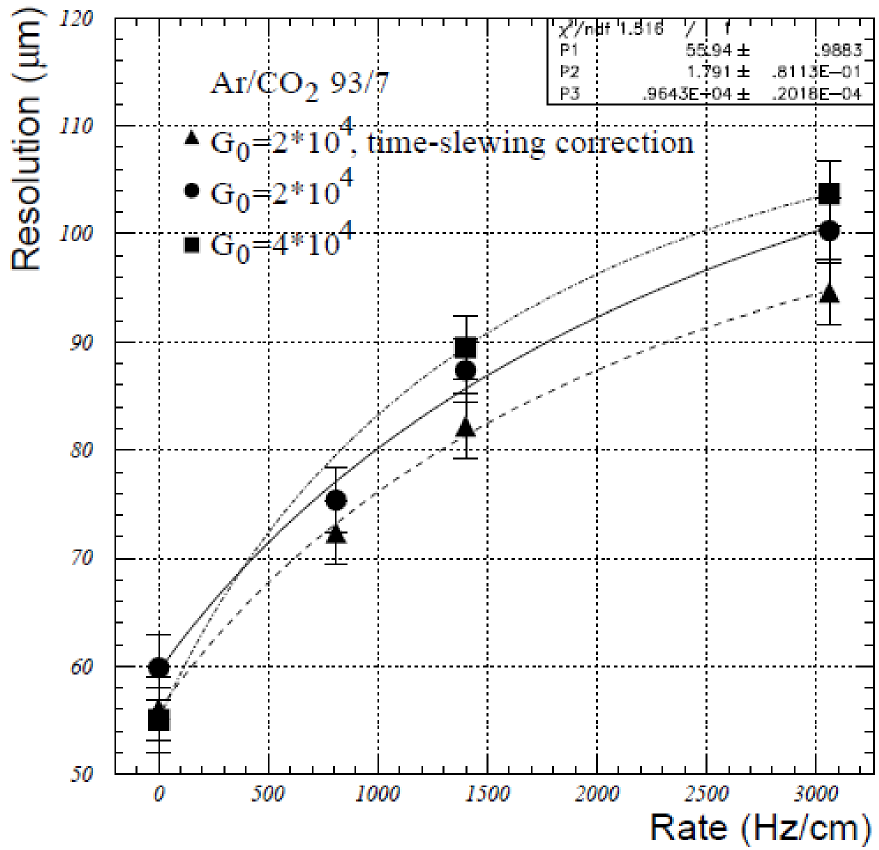


Conclusions

- 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 for HI-LHC.
- First installation of new sMDT chambers in ATLAS in the 2013/14 LHC shutdown. A test chamber already in operation during 2012 run.

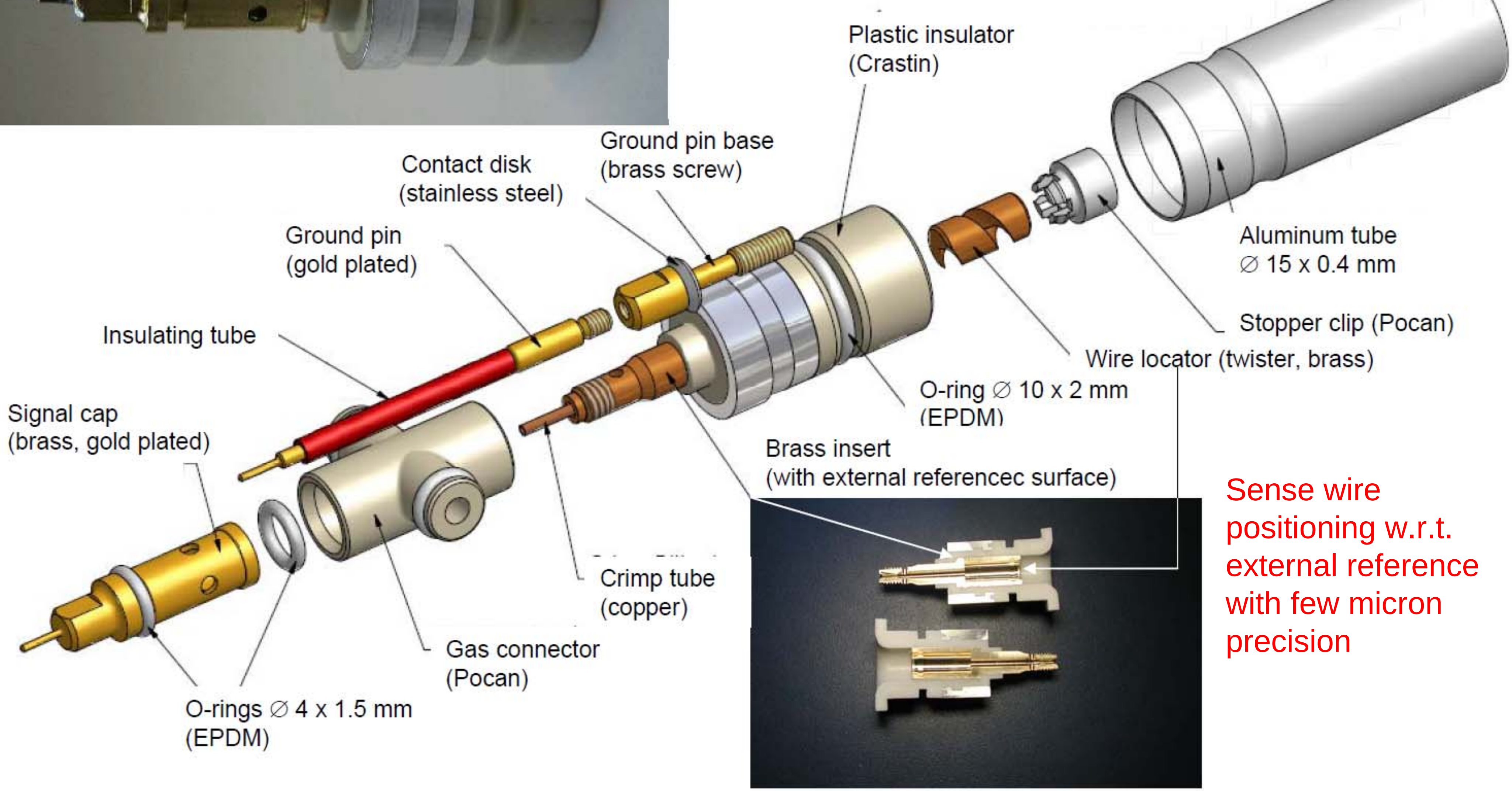
See poster N14-157 for more about the chamber technology and design.

Rate dependence of the resolution of 30 mm ∅ tubes measured at GIF:
M.Aleksa PhD thesis, TU Vienna, 1999.



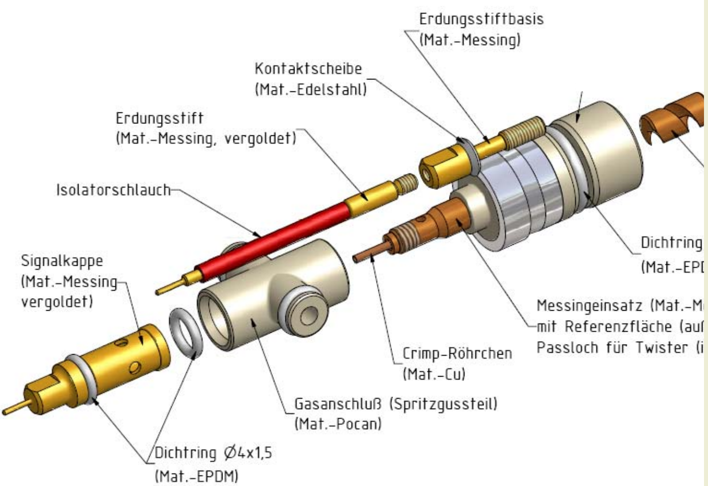
Drift Tube Design

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

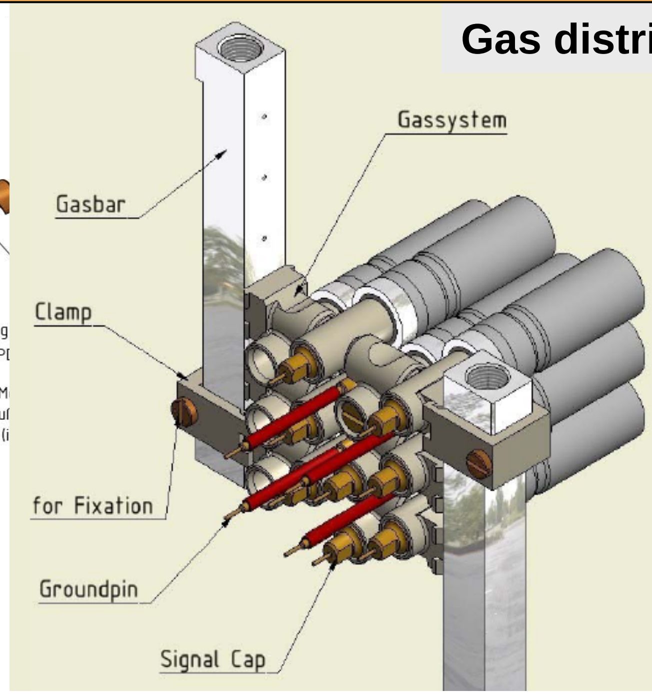


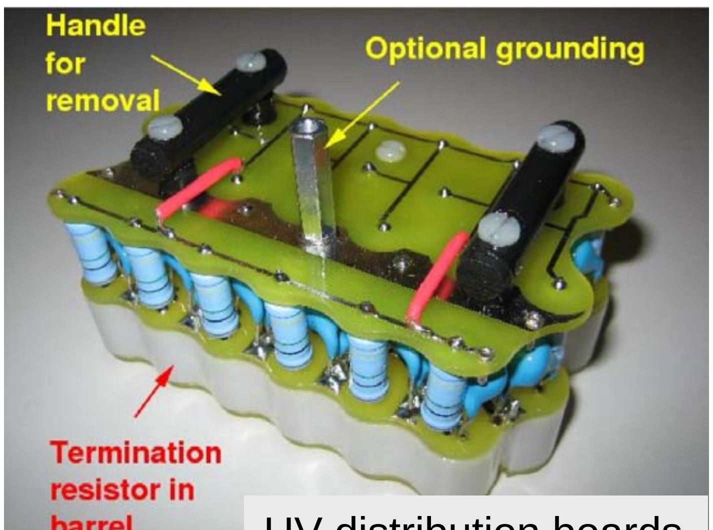
Sense wire positioning w.r.t. external reference with few micron precision

Gas System and Electronics Interfaces

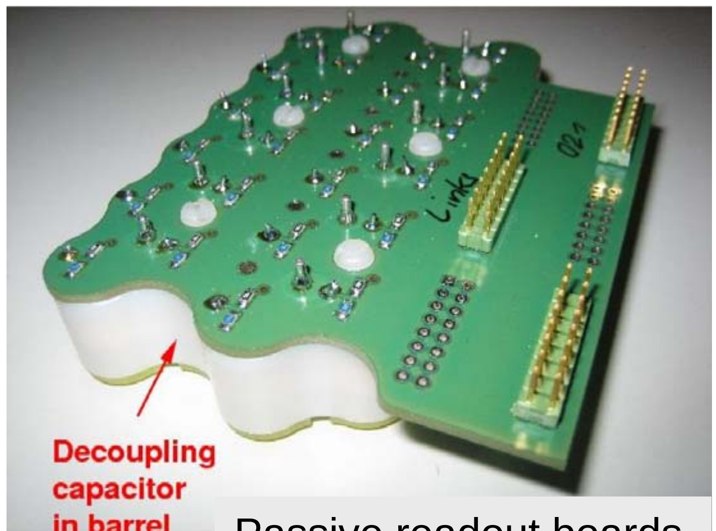


Gas distribution system

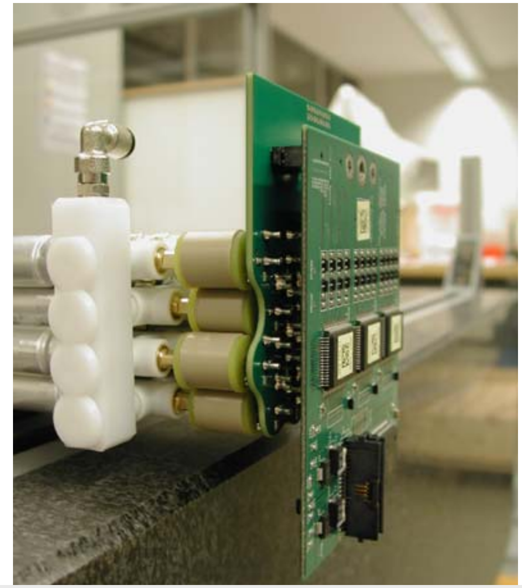




HV distribution boards



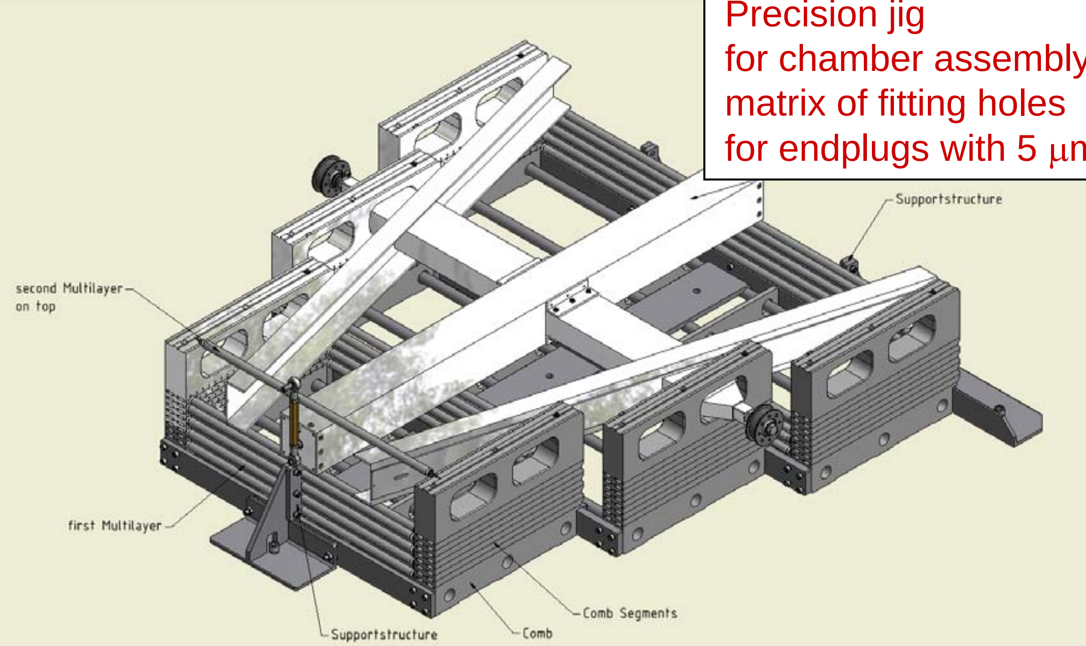
Passive readout boards

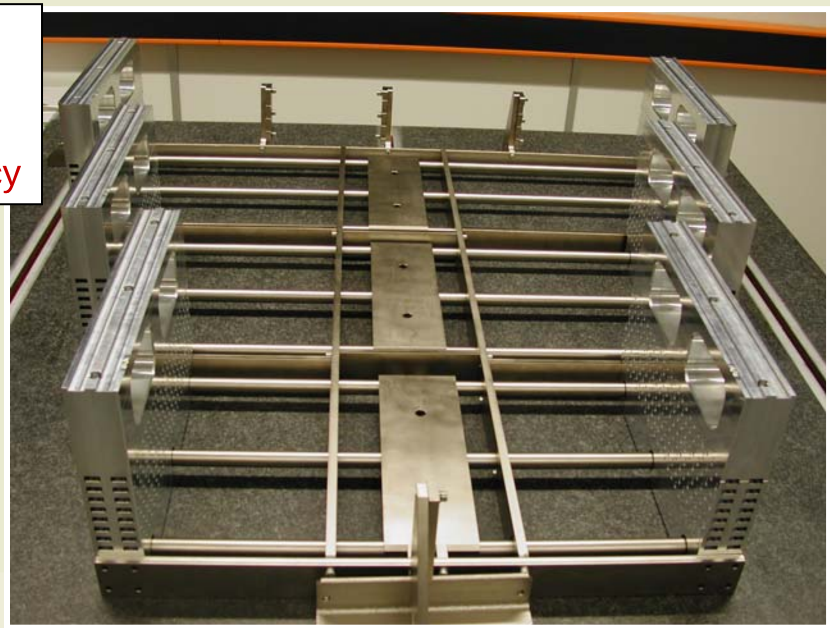


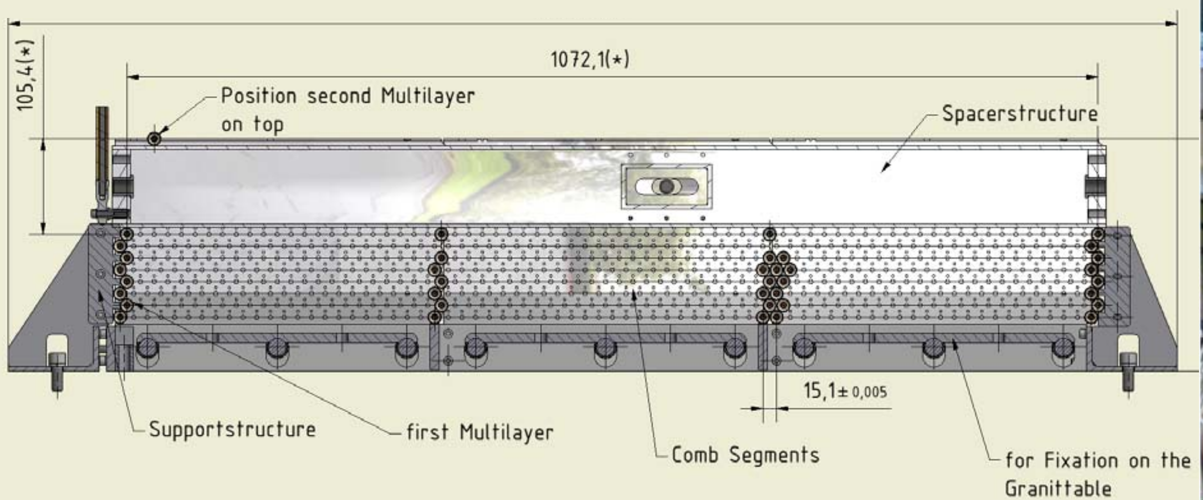
Active readout electronics: from ATLAS MDT

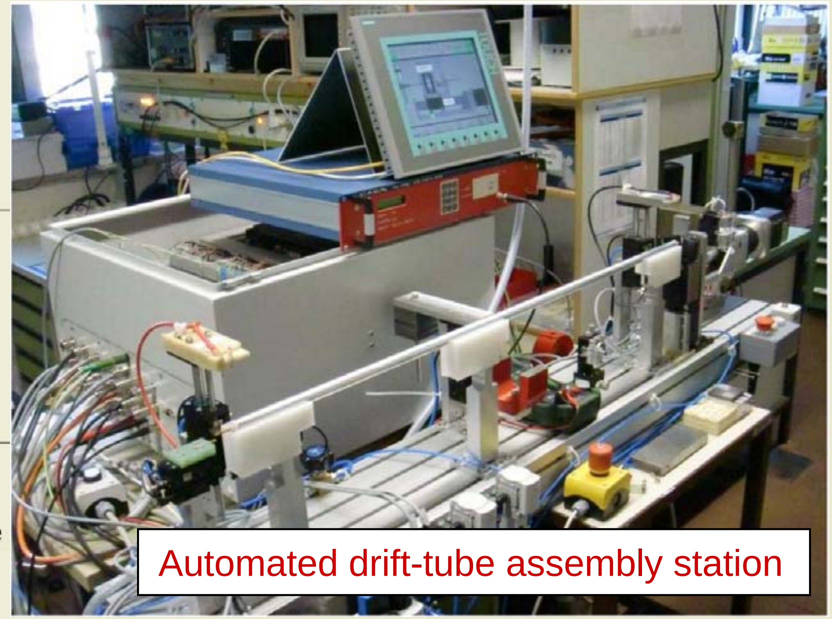
Chamber Assembly

Precision jig
for chamber assembly:
matrix of fitting holes
for endplugs with 5 μm accuracy





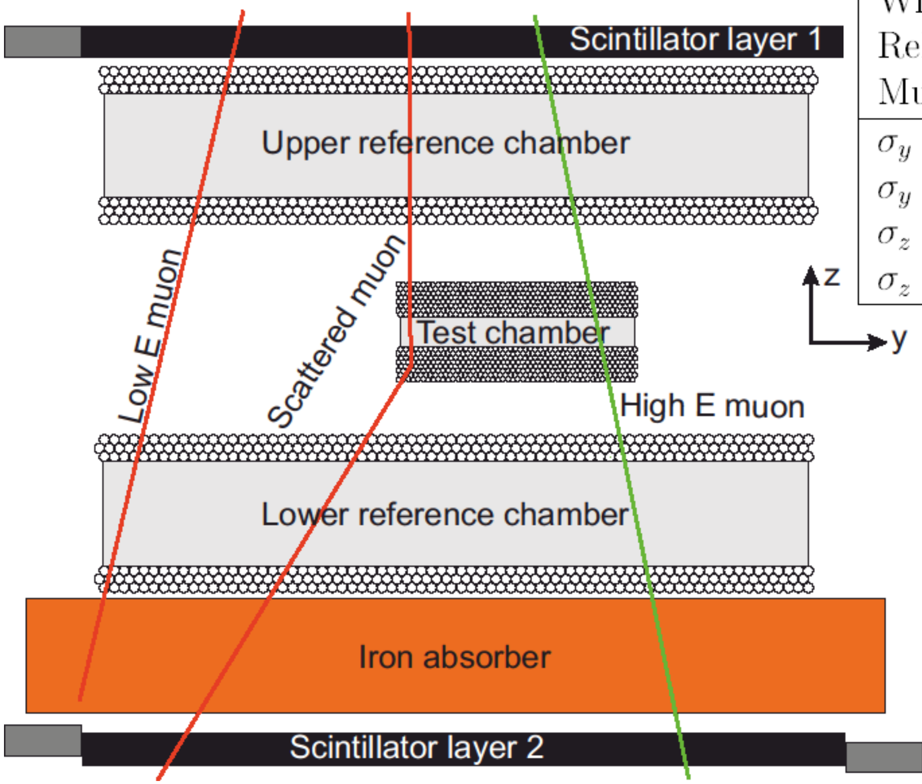




Automated drift-tube assembly station

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	$7,550 \pm 0.0005$
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