

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

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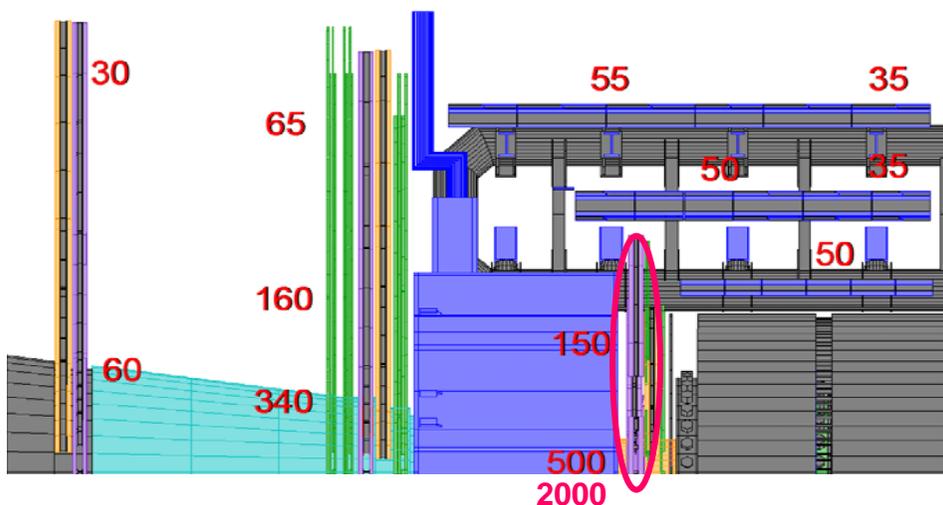
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# ATLAS Muon Spectrometer and HL-LHC Upgrade

Max. background hit rates of neutrons and  $\gamma$ 's in ATLAS from particle interactions in the detector and shielding expected at LHC design luminosity and energy (in Hz/cm<sup>2</sup>), 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<sup>2</sup> expected.

Design rate capability of ATLAS MDT chambers:  
500 Hz/cm<sup>2</sup>, 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 $\mu$ m $\varnothing$ W/Re
Gas mixture	Ar:CO <sub>2</sub> (93:7)
Gas pressure	3 bar
Gas gain	$2 \times 10^4$
Wire potential	3080 V
Max. drift time	700 ns
Wire pos. accuracy	20 $\mu$ m
Single-tube resolution (at low background rate)	80 $\mu$ m
Nr. of drift tube layers	2 x 3 (4)
Chamber resolution (at low background rate)	35 $\mu$ m

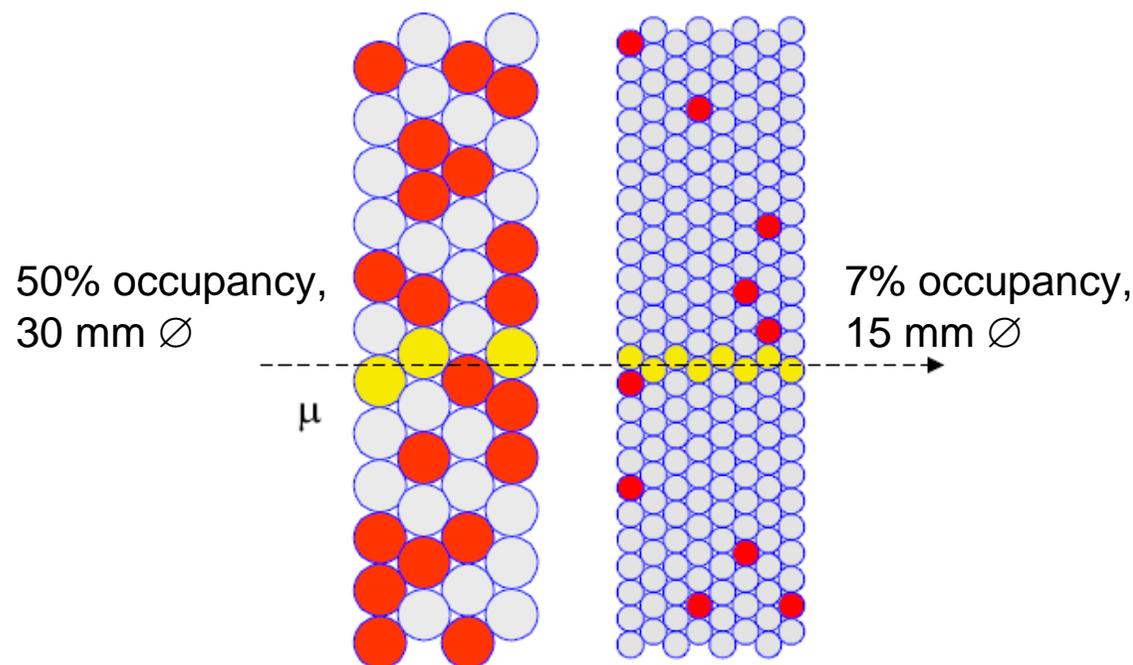
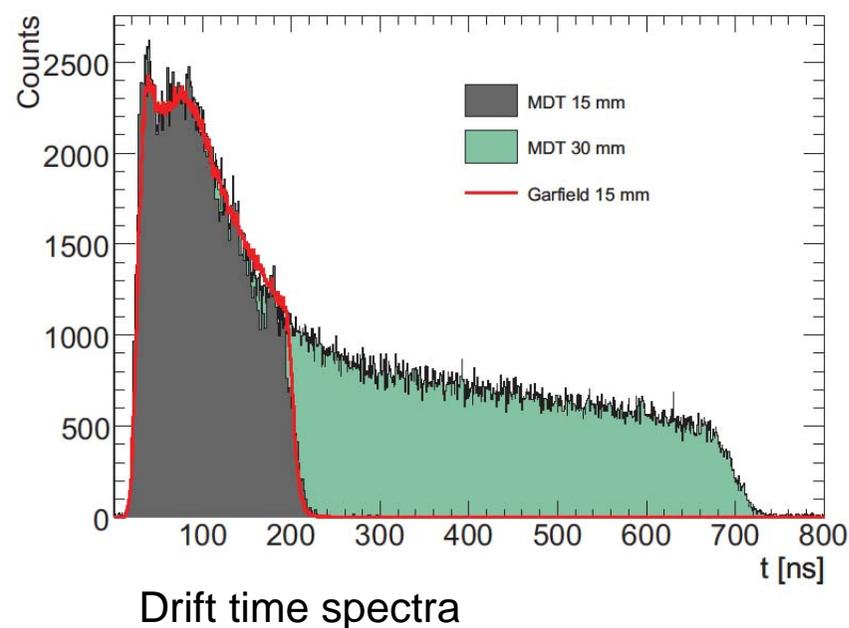


# Smaller Diameter Drift Tubes (sMDT) for High Rates: Occupancy

15 mm  $\varnothing$  instead of 30 mm  $\varnothing$  tubes, same gas mixture and gas gain:

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

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



# Smaller Diameter Drift Tubes for High Rates: Spatial Resolution

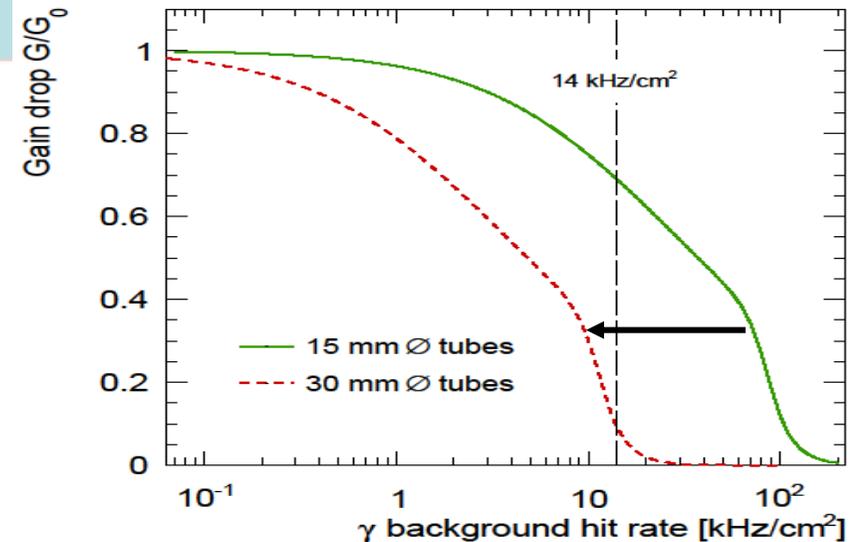
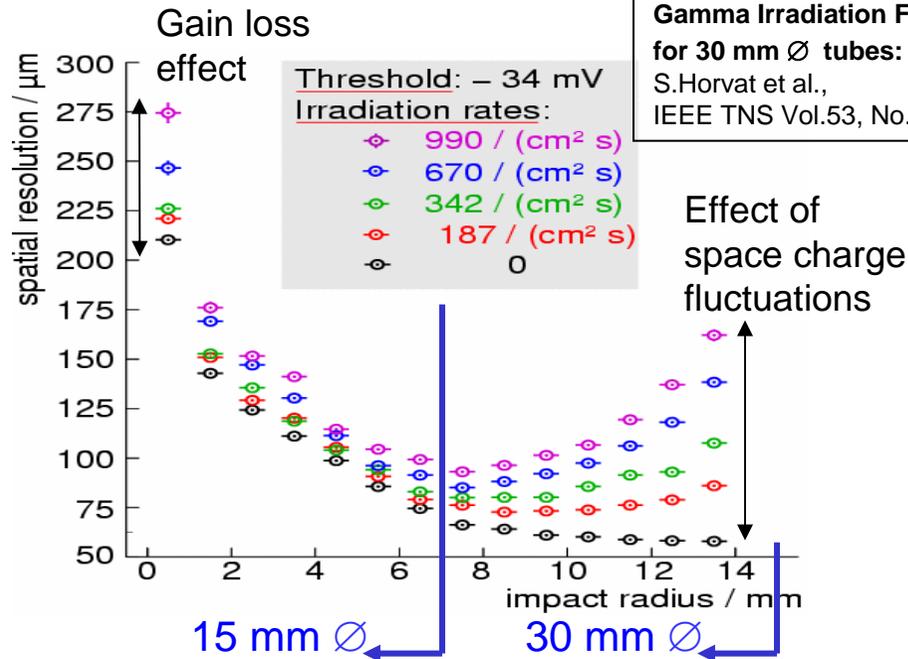
15 mm  $\varnothing$  instead of 30 mm  $\varnothing$  tubes, same gas mixture and gas gain  $G_0$

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

- gain loss due to } ~ tube inner radius  $r^3$  (for  $\gamma$ , 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.

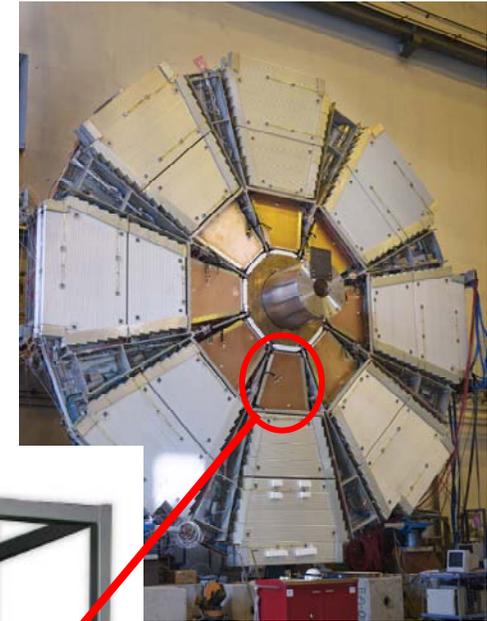
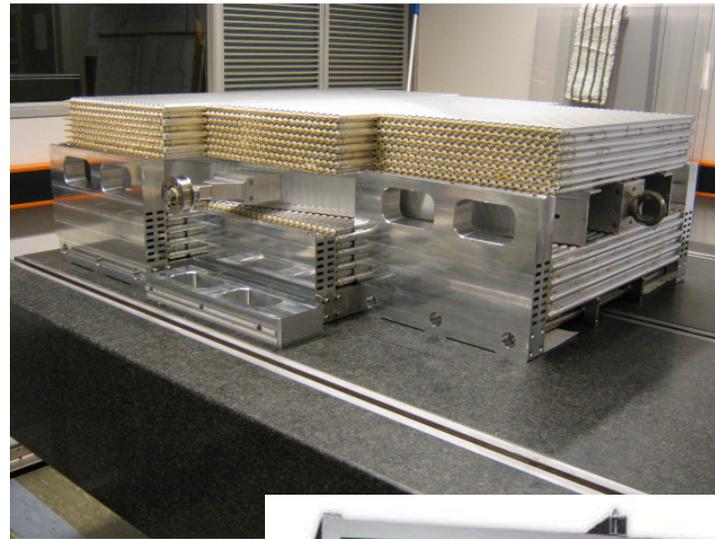
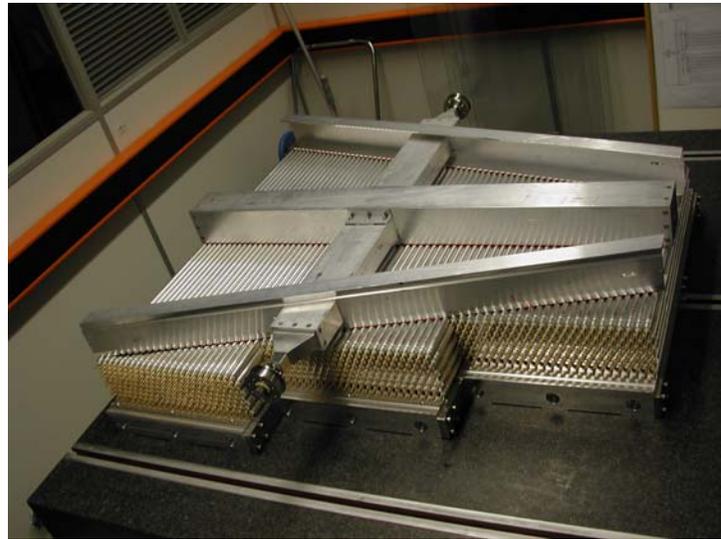


Measurements at the CERN  
Gamma Irradiation Facility GIF  
for 30 mm  $\varnothing$  tubes:  
S.Horvat et al.,  
IEEE TNS Vol.53, No.2 (2006) 562

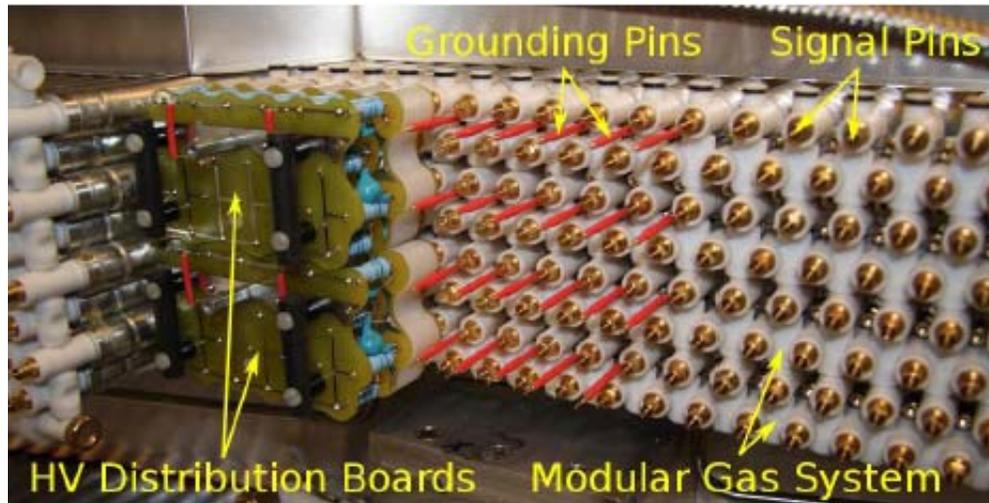


Gain loss  $G/G_0$  strongly suppressed by factor of 8.7 for 15 mm diameter tubes.  
Saturation of space charge:  
iterative calculation using Diethorn's formula.

# sMDT Prototype Chamber Construction

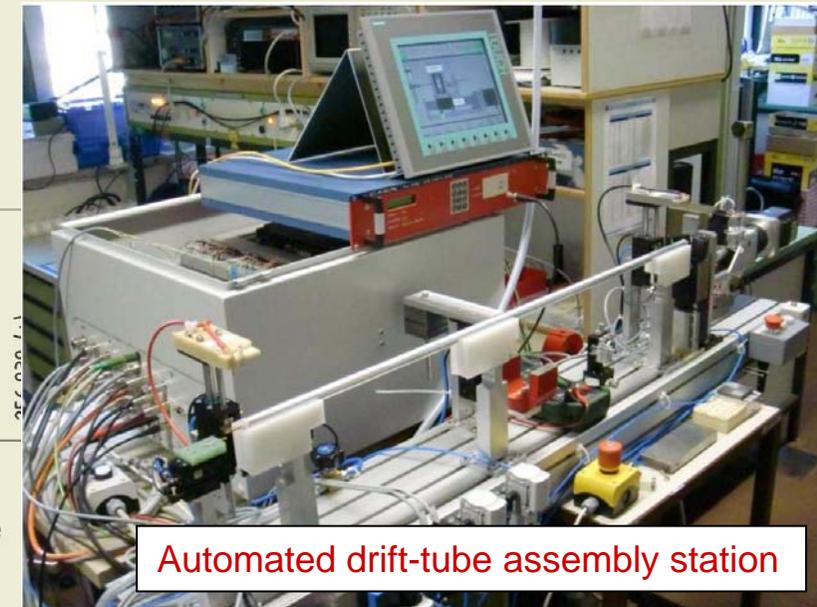
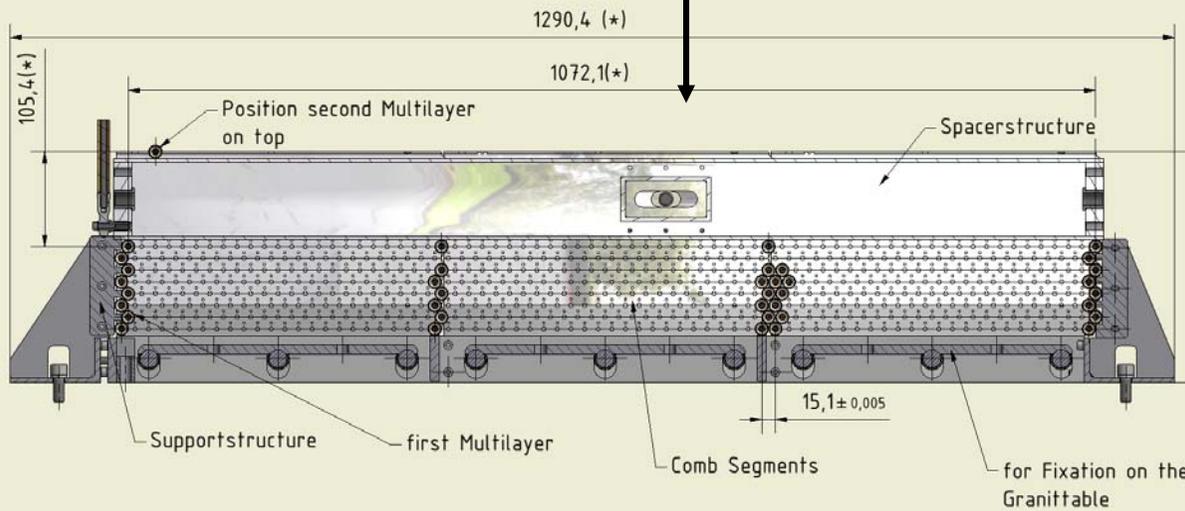
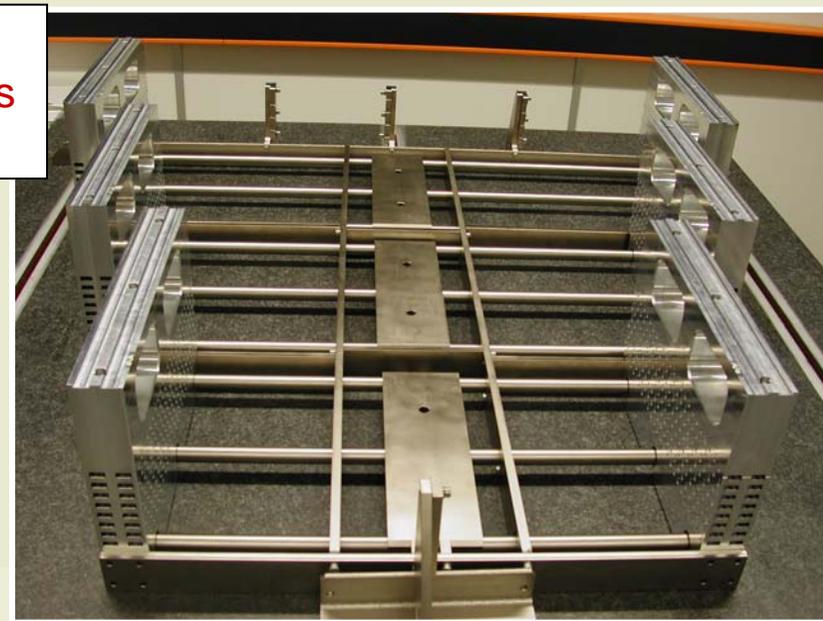
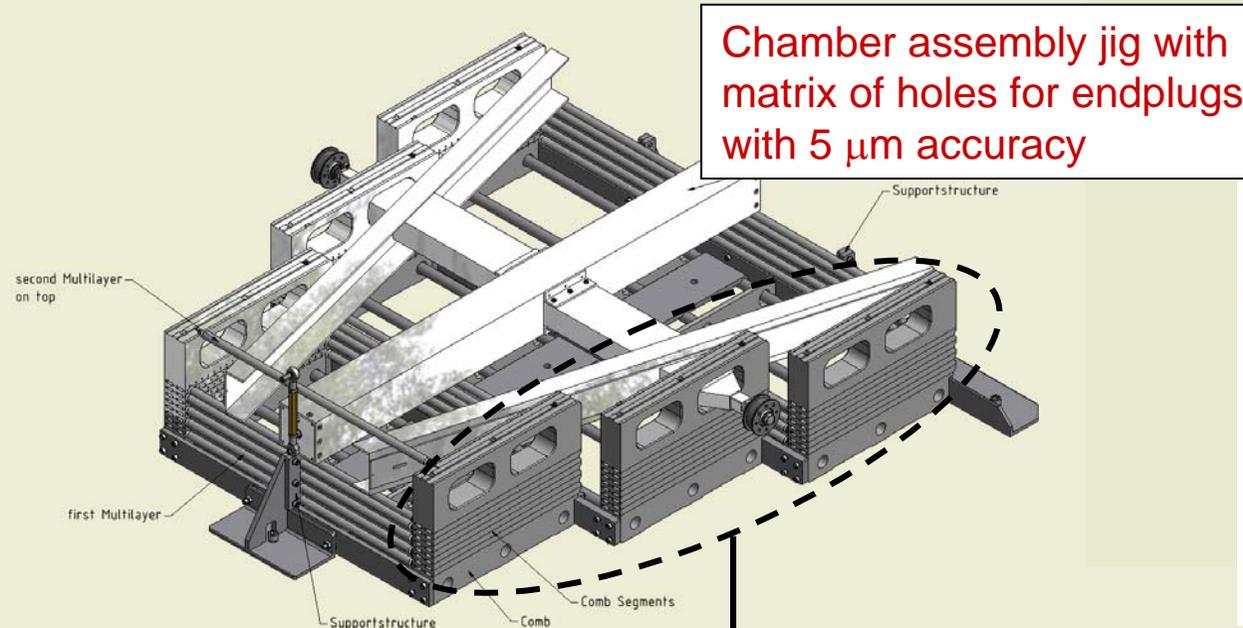


2 x 8 layers of 15 mm  $\varnothing$  drift tubes  
assembled in 2 working days



# Chamber Assembly

Chamber assembly jig with matrix of holes for endplugs with 5  $\mu\text{m}$  accuracy

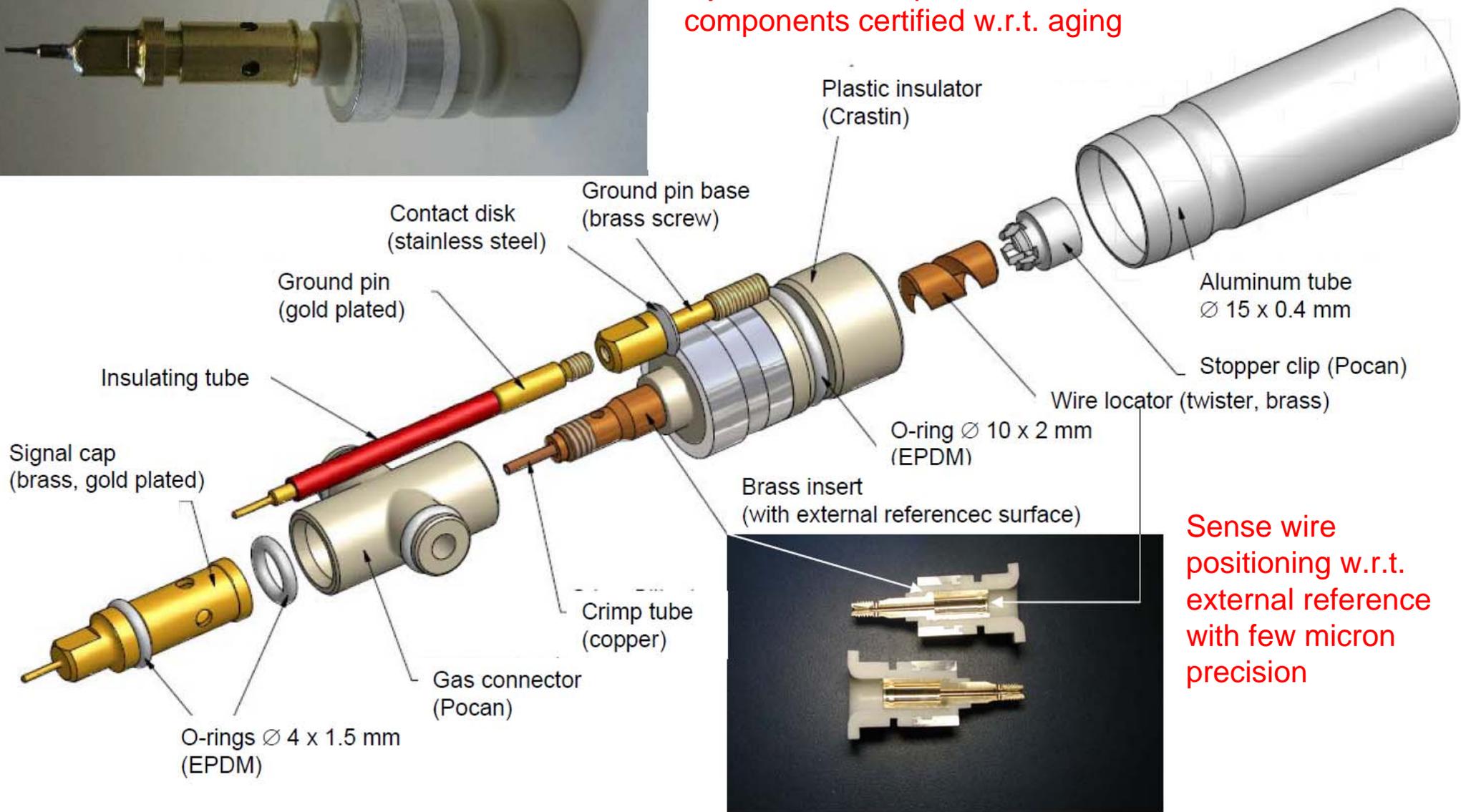


Automated drift-tube assembly station

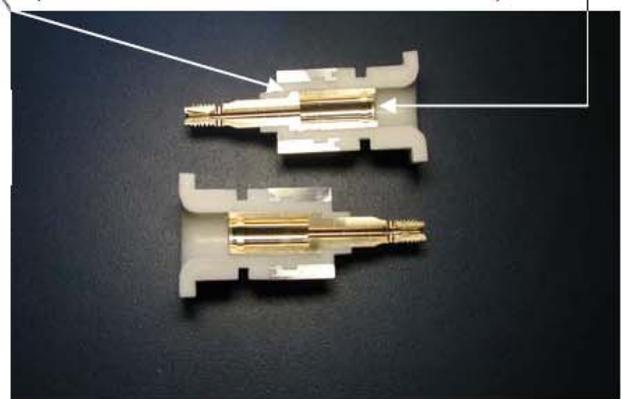
# Drift Tube Design



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

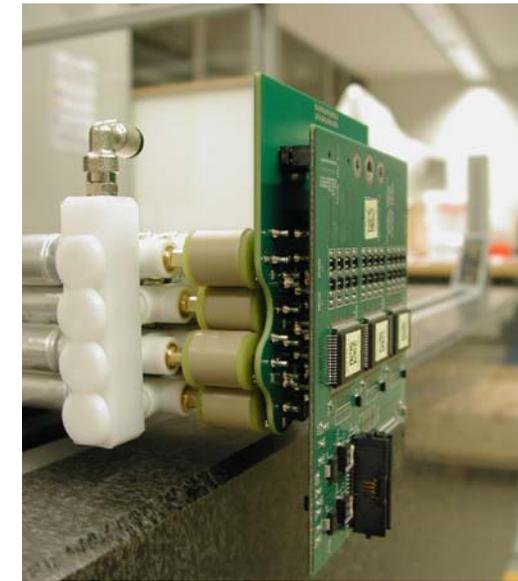
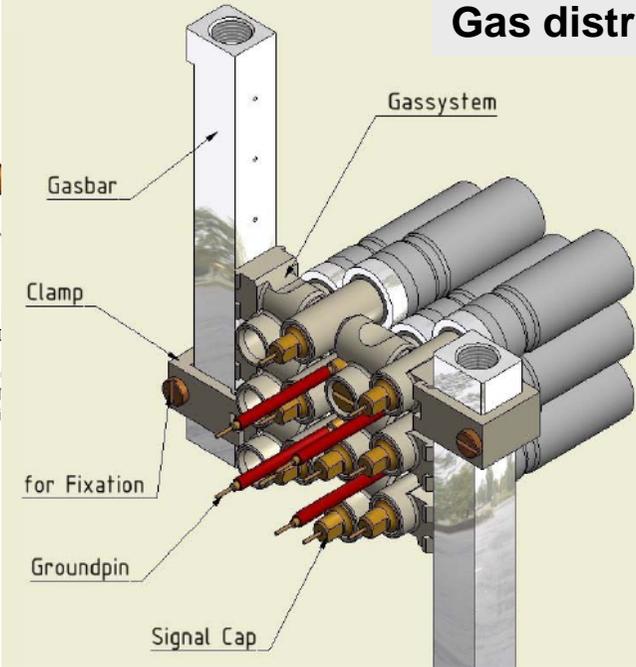
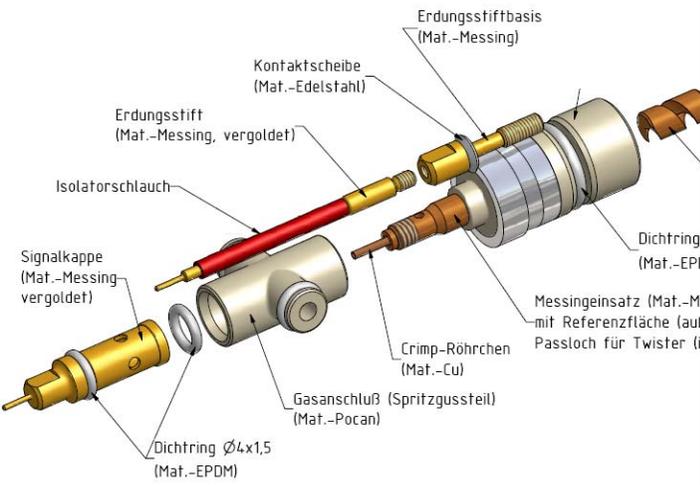


Sense wire positioning w.r.t. external reference with few micron precision

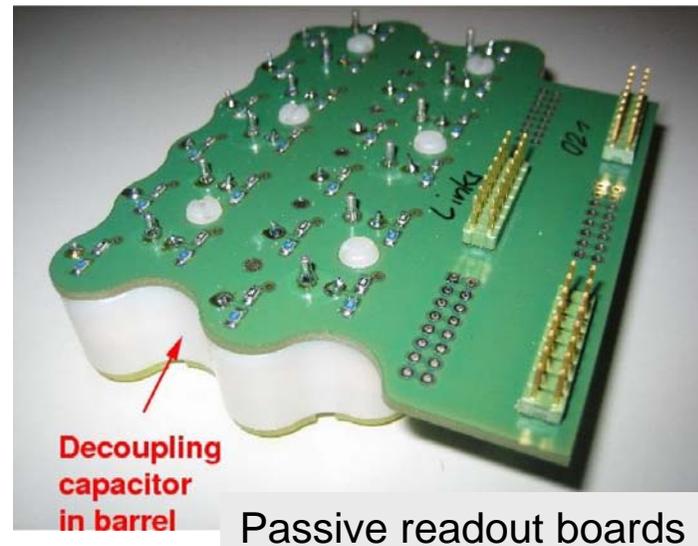
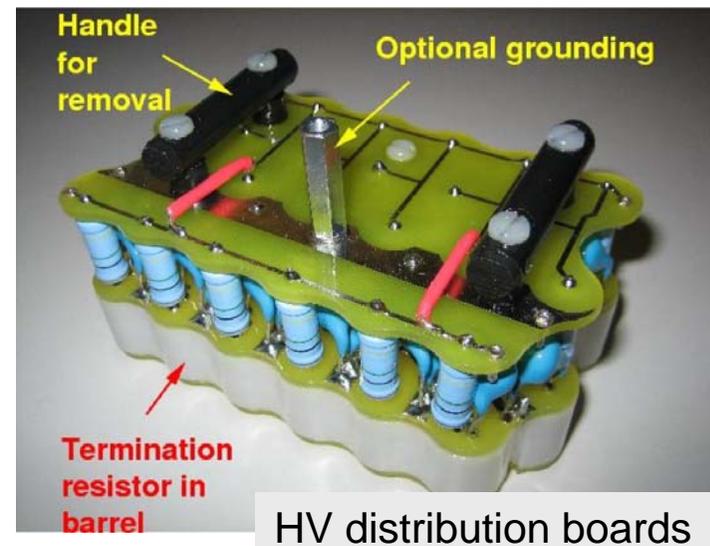


# Gas System and Electronics Interfaces: 4 x Density

Gas distribution system



Active readout electronics: from ATLAS MDT



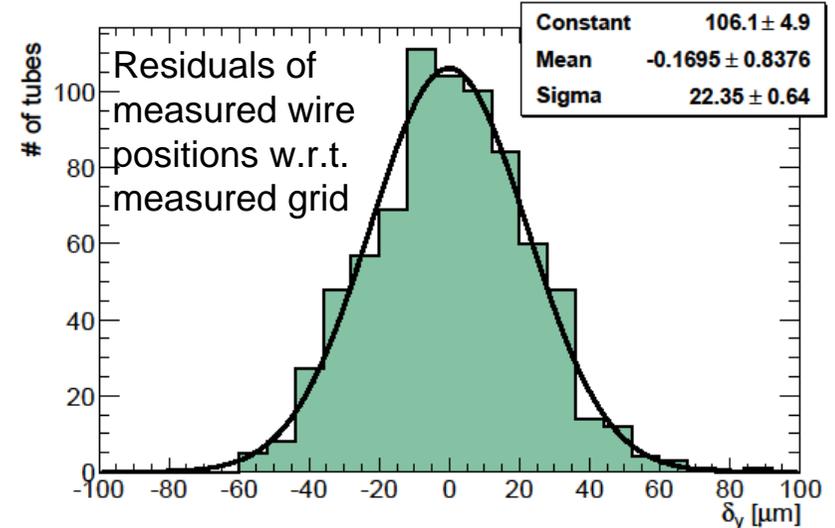
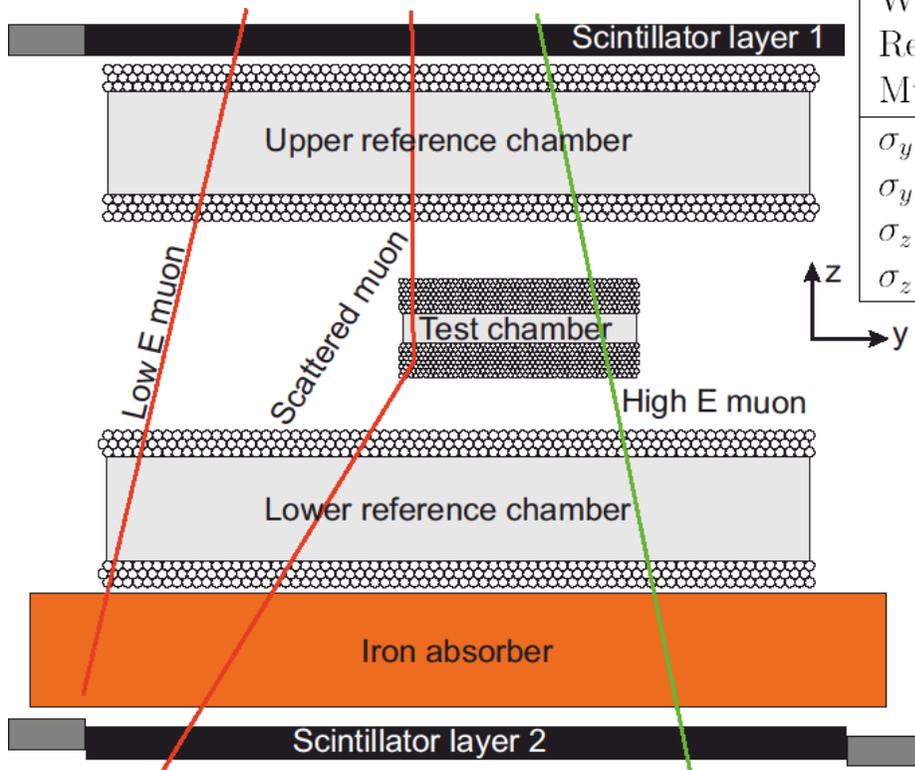
# Measurement of Sense Wire Positions

Wire position measurement with  $< 5 \mu\text{m}/\text{wire}$  accuracy using cosmic ray tracks and two MDT reference chambers with precisely known wire positions

Wire positioning accuracy of better than  $20 \mu\text{m}$  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	$15.1018 \pm 0.0003$
Wire pitch z	13.077	$13.091 \pm 0.007$
Relative layer shift y	7.550	$7,550 \pm 0.0005$
Multilayer z distance	90.400	$90.382 \pm 0.010$
$\sigma_y$ w.r.t. nominal grid	0.020	0.018
$\sigma_y$ w.r.t. fitted grid	0.020	0.016
$\sigma_z$ w.r.t. nominal grid	0.020	0.016
$\sigma_z$ w.r.t. fitted grid	0.020	0.013

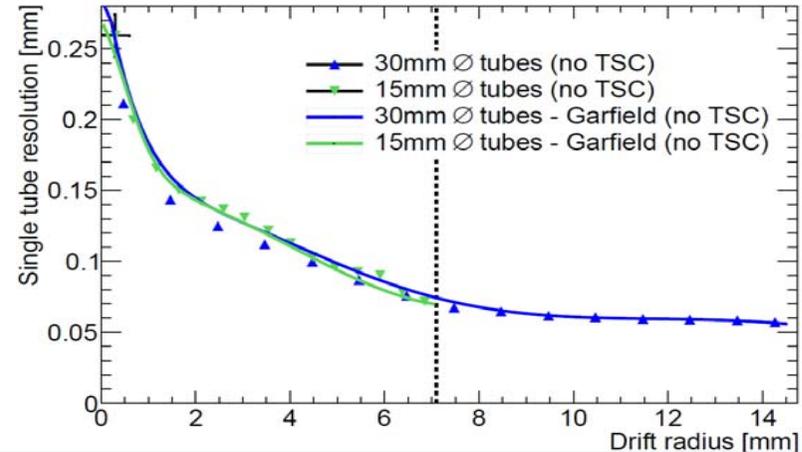
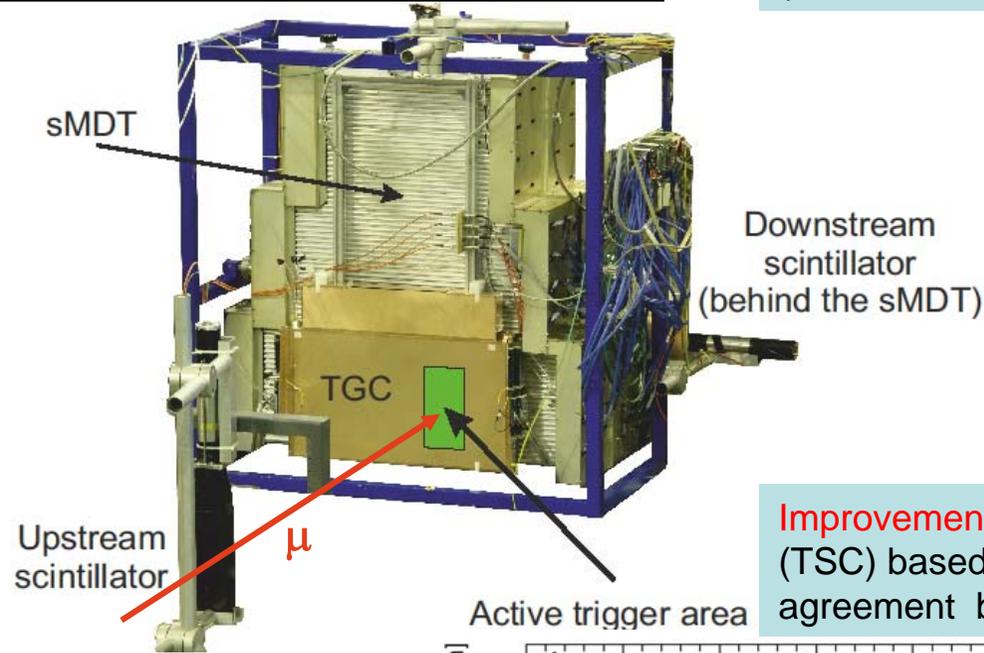


# Muon Beam Test: Spatial Resolution

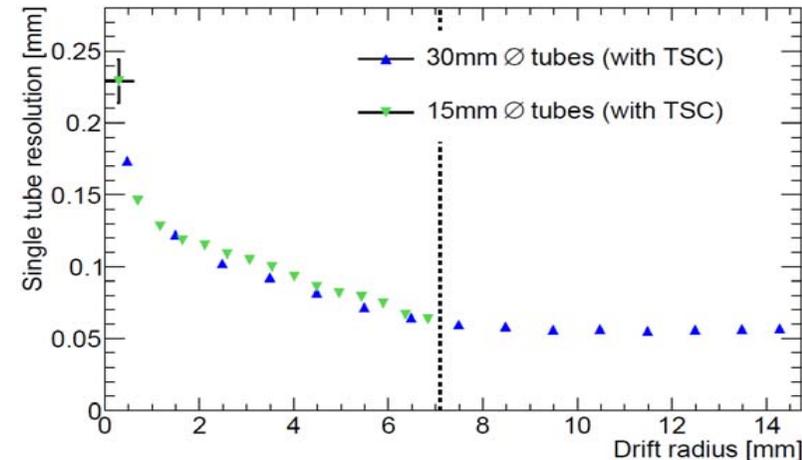
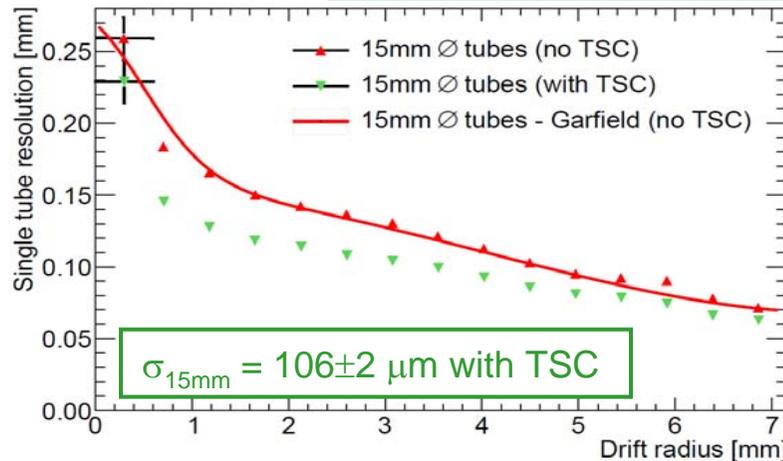
CERN SPS-H8 180 GeV muon beam.

No background radiation.

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



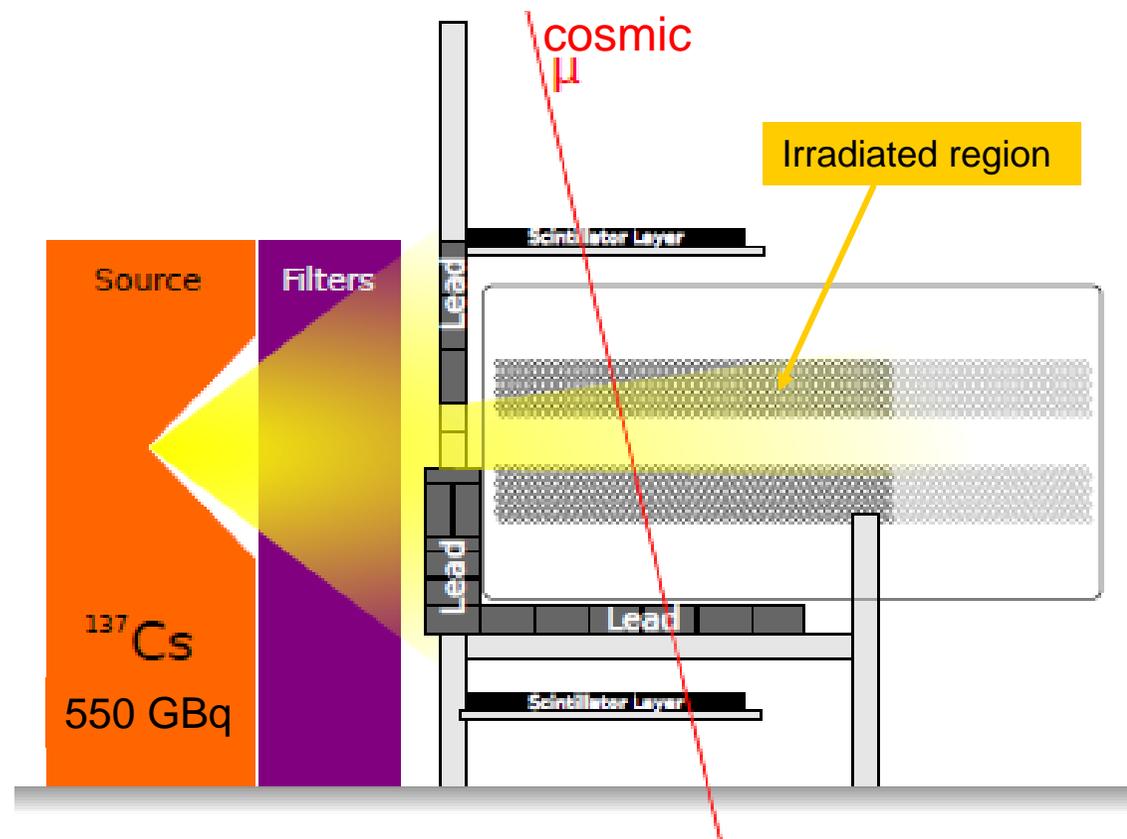
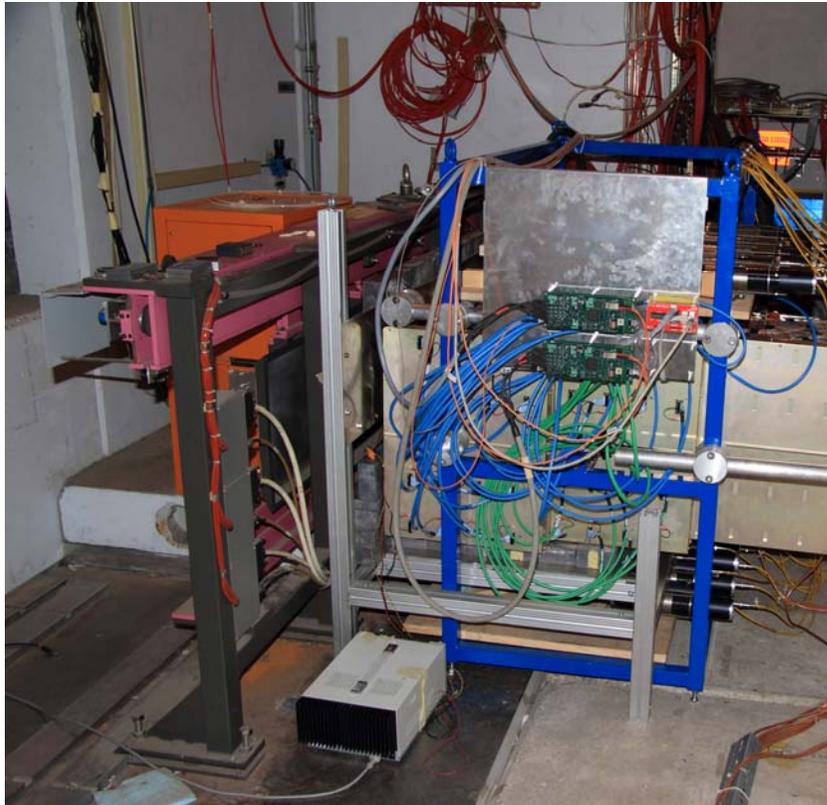
Improvement of drift tube resolution by 20  $\mu\text{m}$  using time slewing corrections (TSC) based on the measurement of the leading-edge signal charge, agreement between 15 and 30 mm  $\varnothing$  tubes also after TSC:



# 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<sup>2</sup> (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.



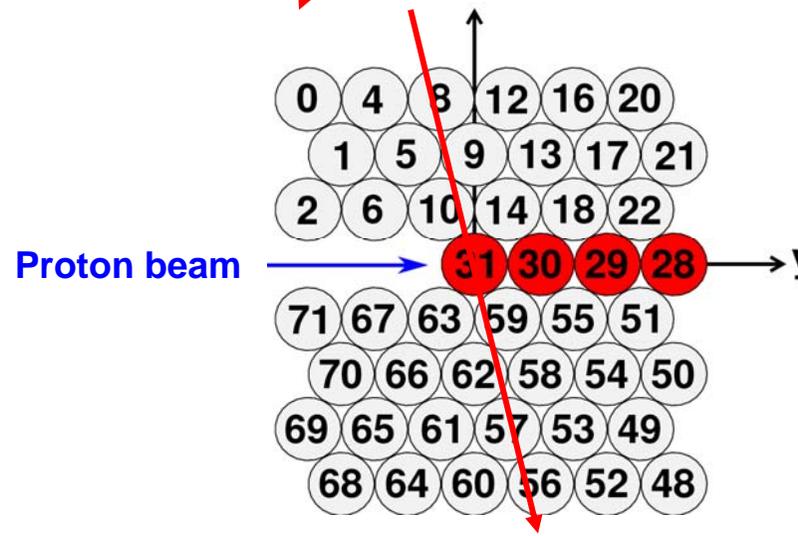
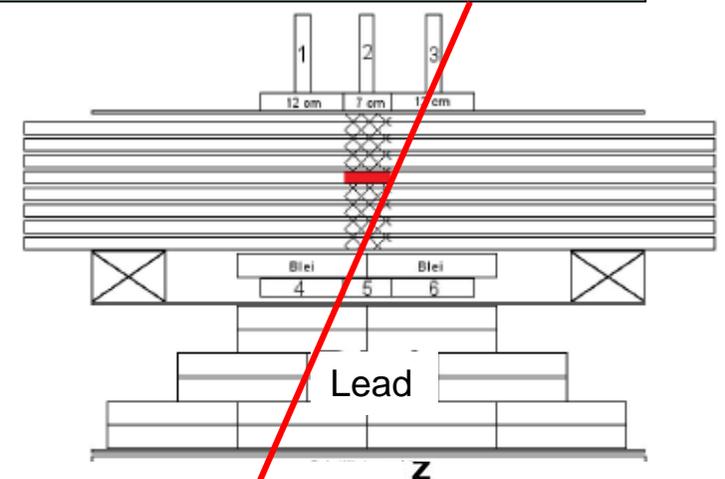
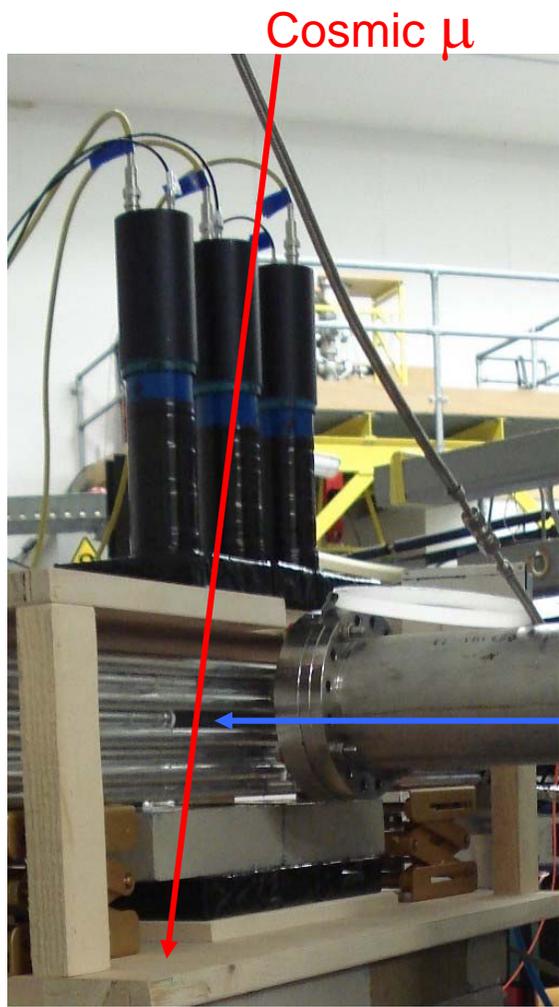
# Irradiation Tests

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

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.

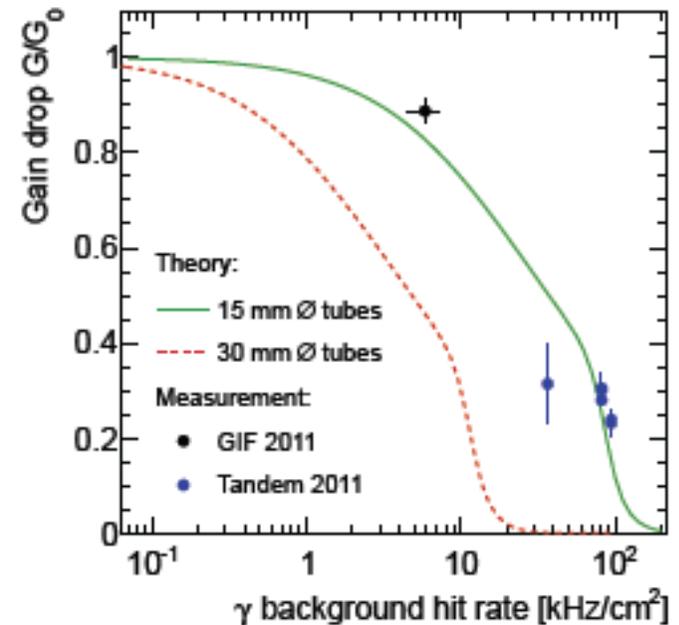
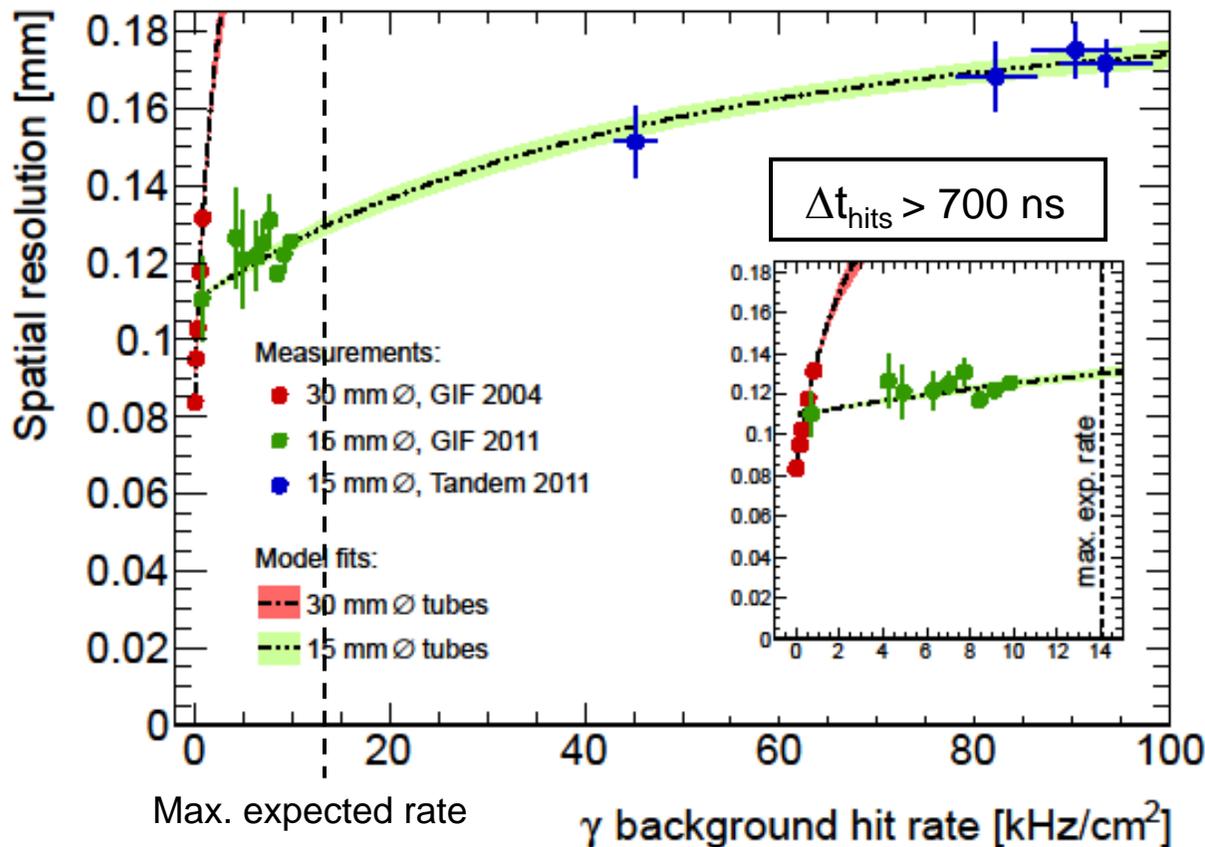
Unirradiated regions of the dedicated sMDT chamber serve as precise tracking reference.



# Spatial Resolution at High Rates

Average drift-tube resolution over huge range of the equivalent  $\gamma$  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.

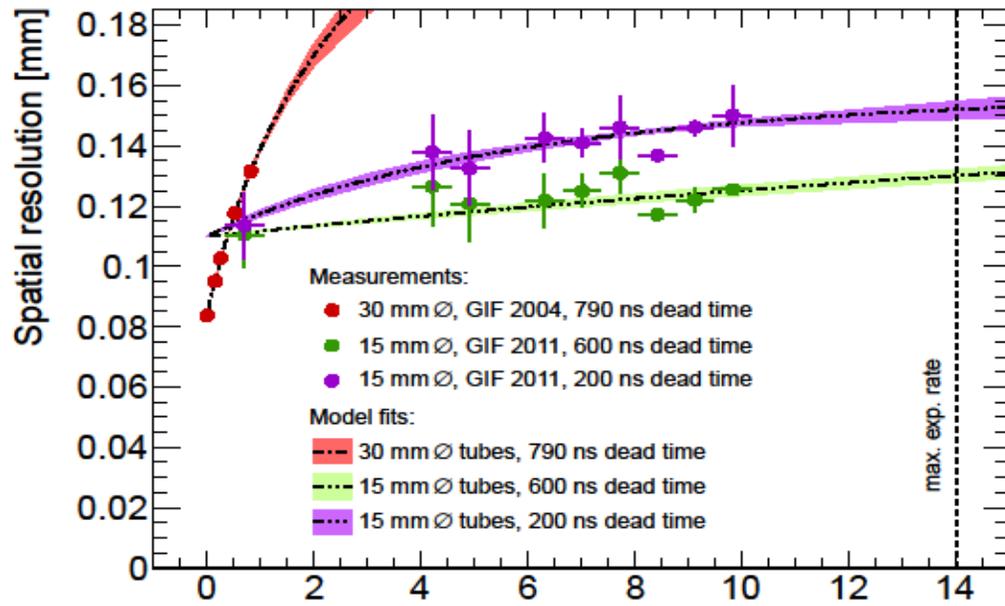


Corresponding gain drop measurement from signal current of individual drift tubes.

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  $\gamma$  background flux at GIF:



all  $\Delta t_{\text{hits}}$

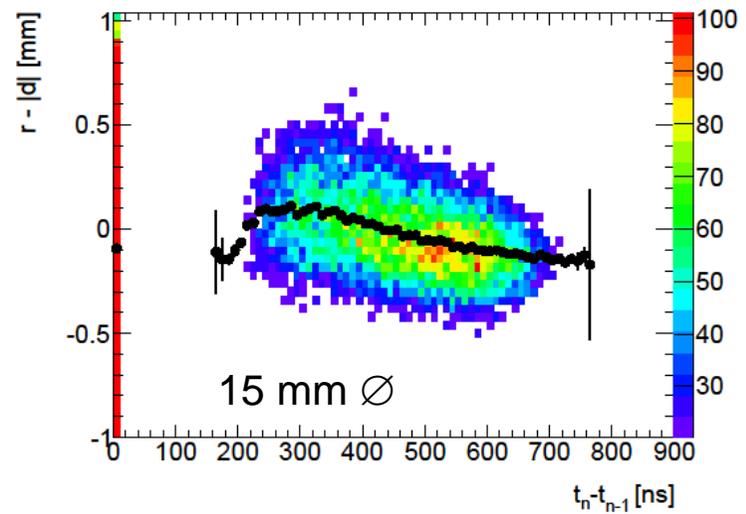
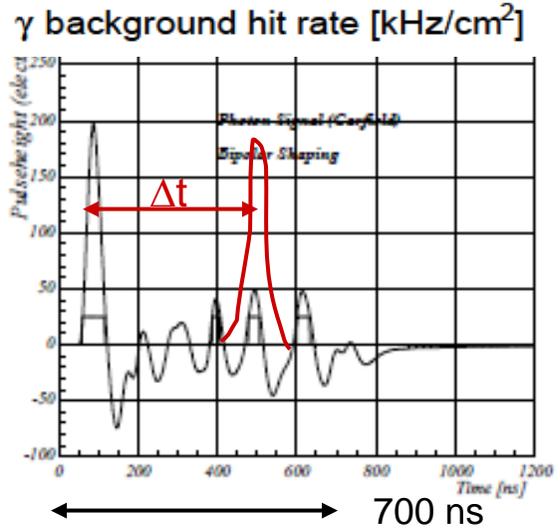
$\Delta t_{\text{hits}} > 700$  ns

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.  
 $\Rightarrow$  Track residual distribution shifted and broadened for decreasing  $\Delta t$  between successive hits.

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

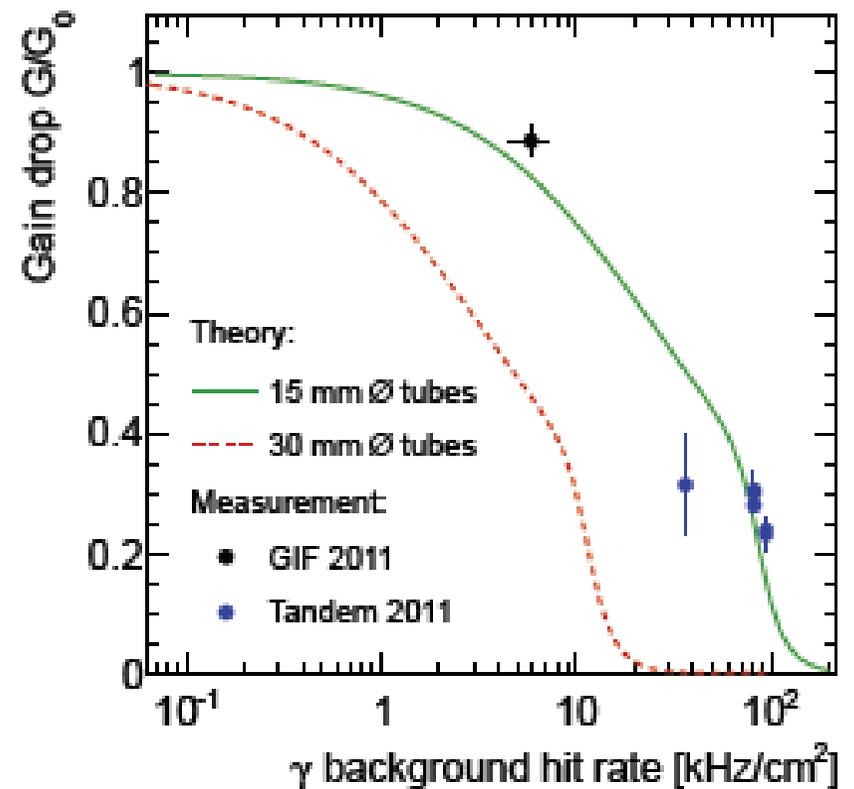
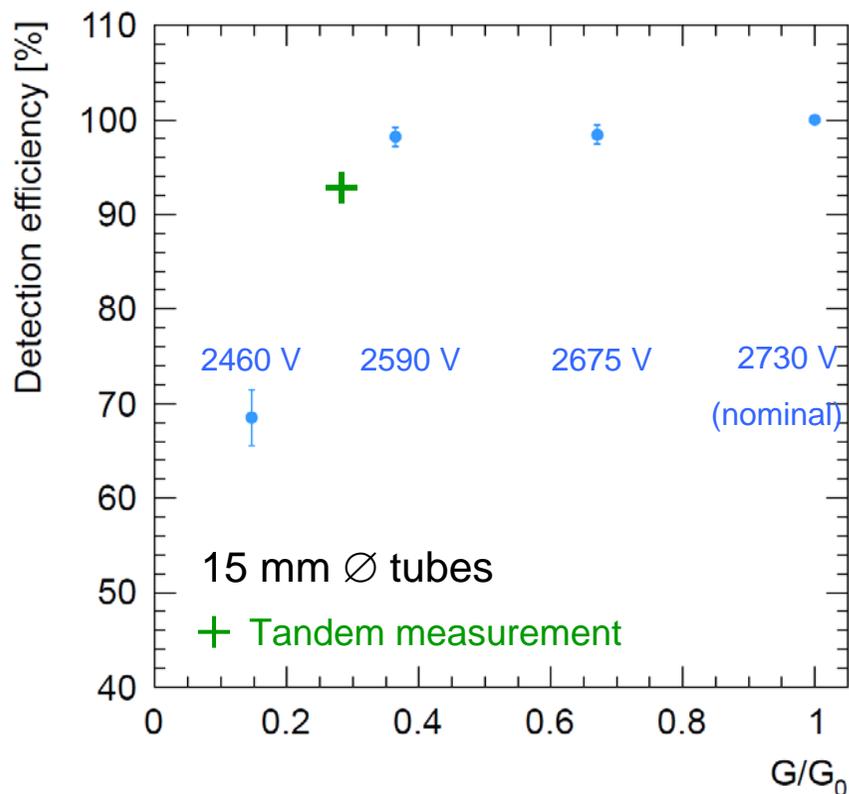
Electronics optimized for 30 mm diameter tubes.



# Muon Detection Efficiency

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.

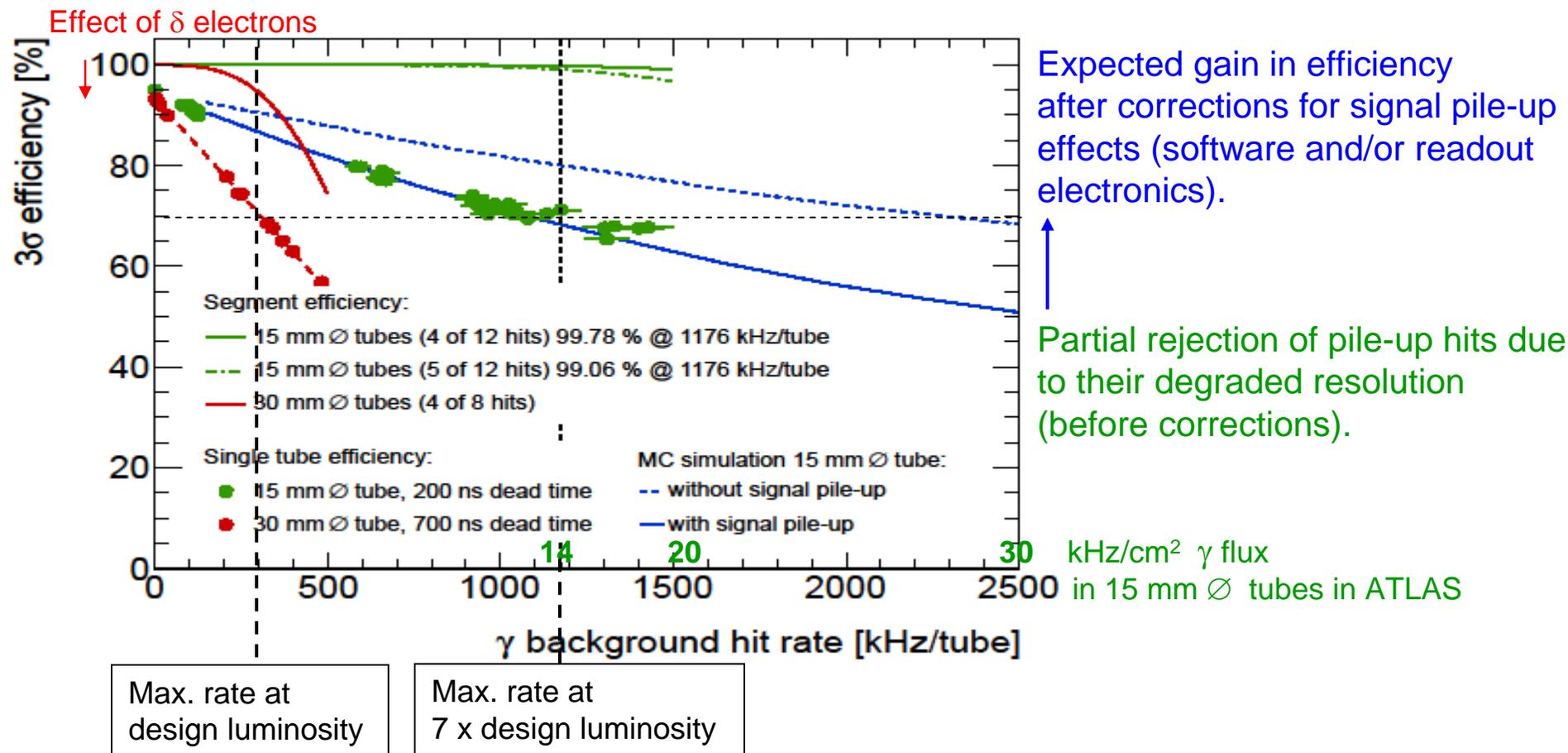
Tubes fully efficient down to 40% of the nominal gain, corresponding to 50 kHz/cm<sup>2</sup>  $\gamma$  flux!



# Tracking Efficiency at High Rates

“ $3\sigma$  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  $3 \times$  drift tube resolution) follows the MC expectations, which are determined by the adjustable electronics dead time (maximum of 700 ns for 30 mm  $\varnothing$ , minimum of 200 ns for 15 mm  $\varnothing$ ).

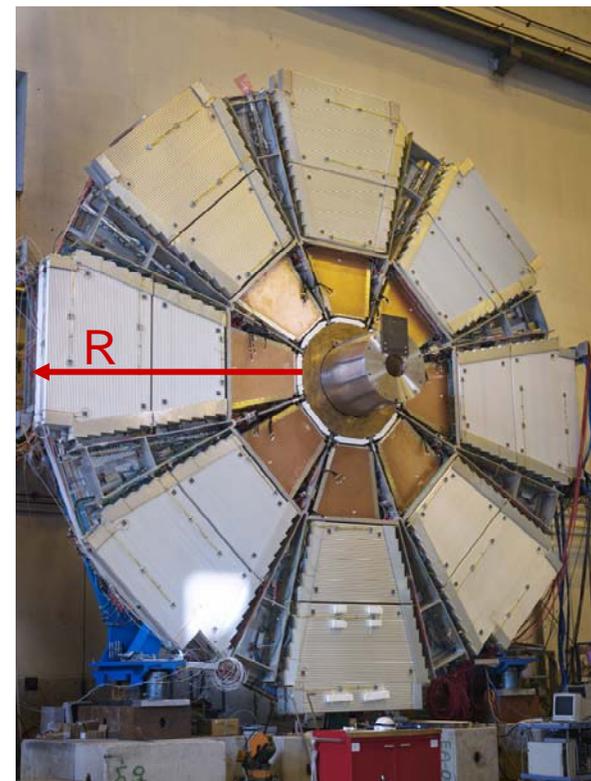
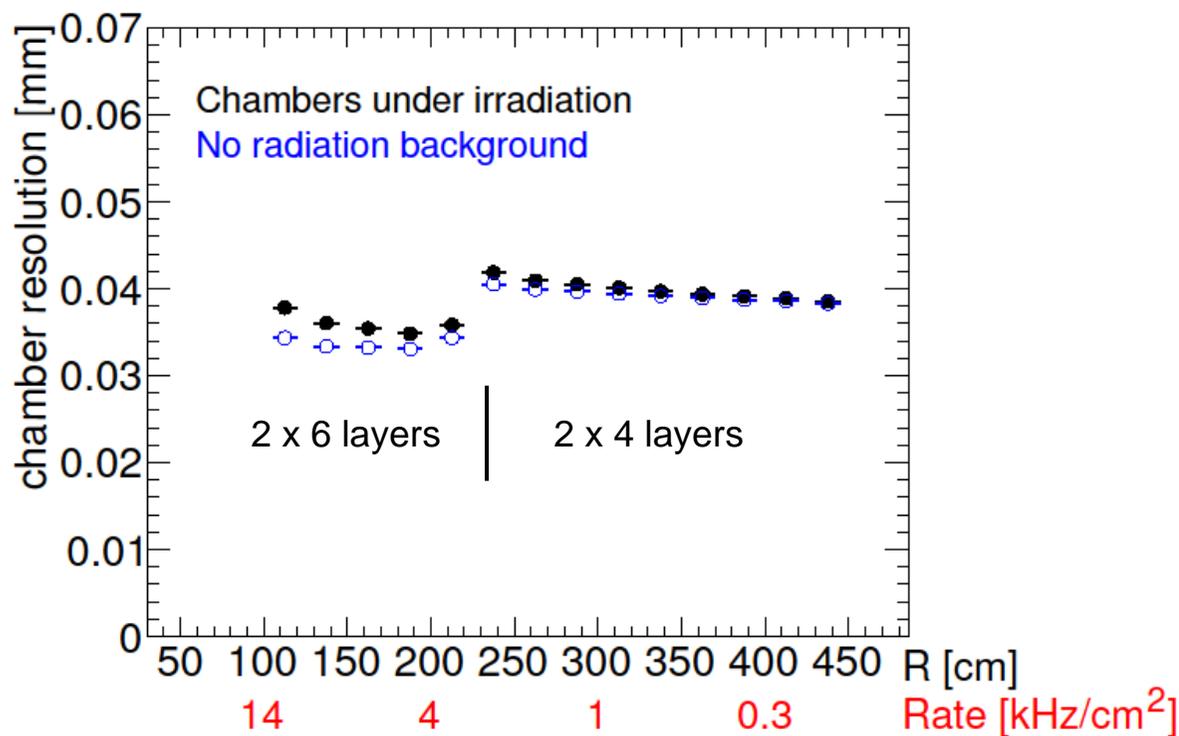
Track efficiency above 99% at max. expected rate due to larger number of 15 mm  $\varnothing$  tube layers.



# 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 ( $35 \mu\text{m}$ ), only minor degradation due to background radiation.



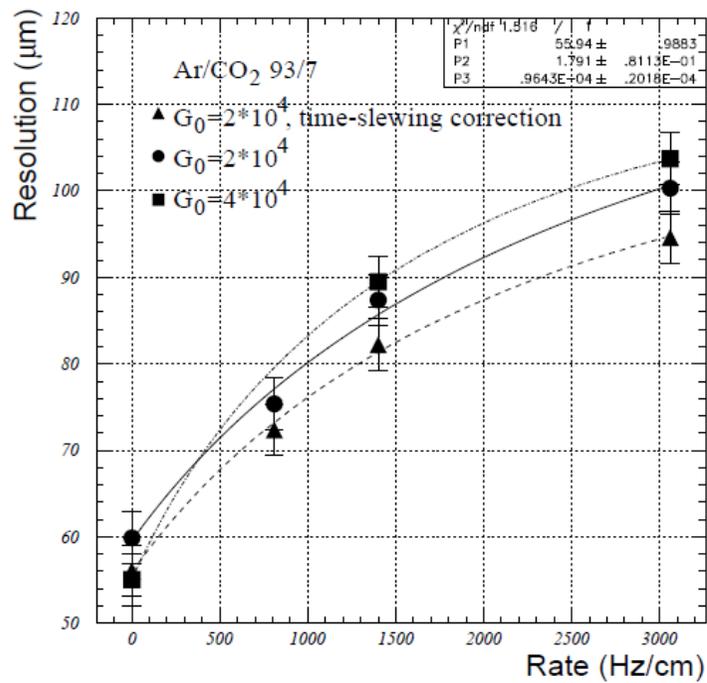
# Other Developments

- **Drift tube aging tests:**  
Irradiation of 15 mm  $\varnothing$  tubes with 200 MBq  $^{90}\text{Sr}$  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<sub>2</sub> 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.
- First sMDT chamber installation in the 2013/14 LHC shutdown.



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