Precision Muon Tracking Detectors for High-Energy Hadron Colliders

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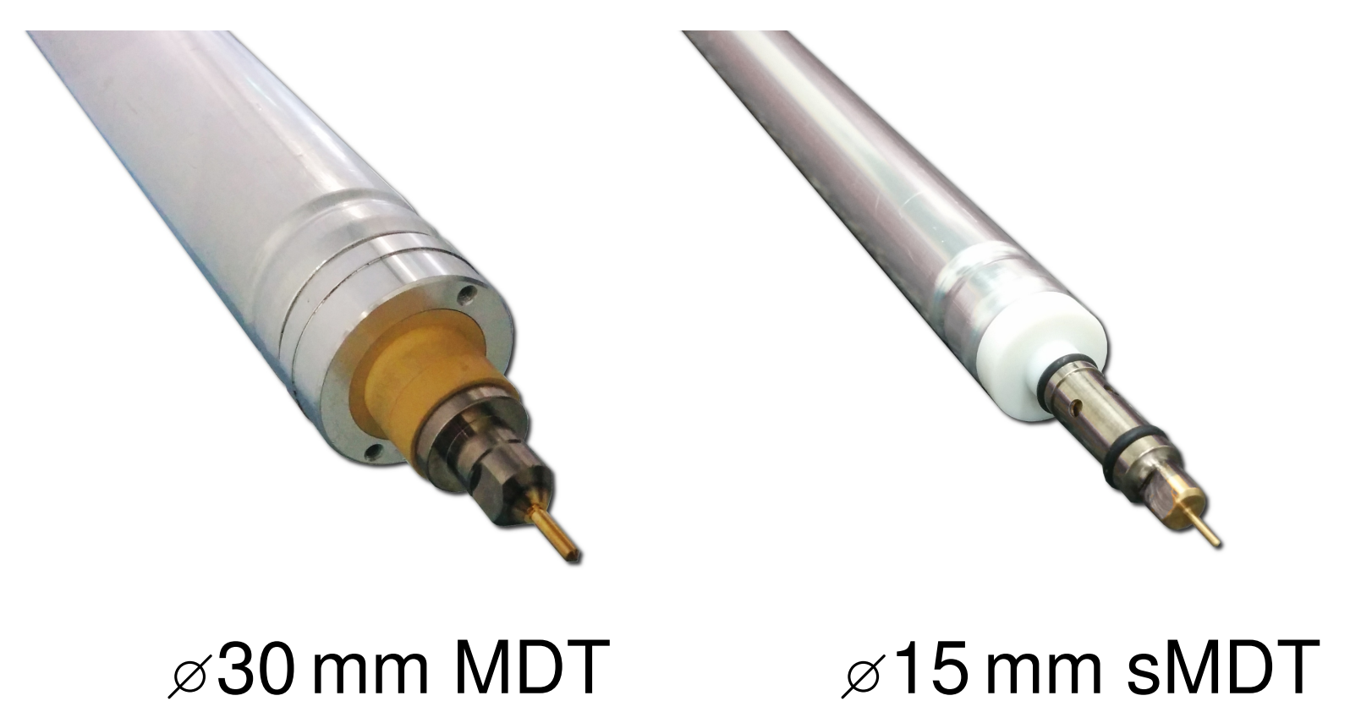
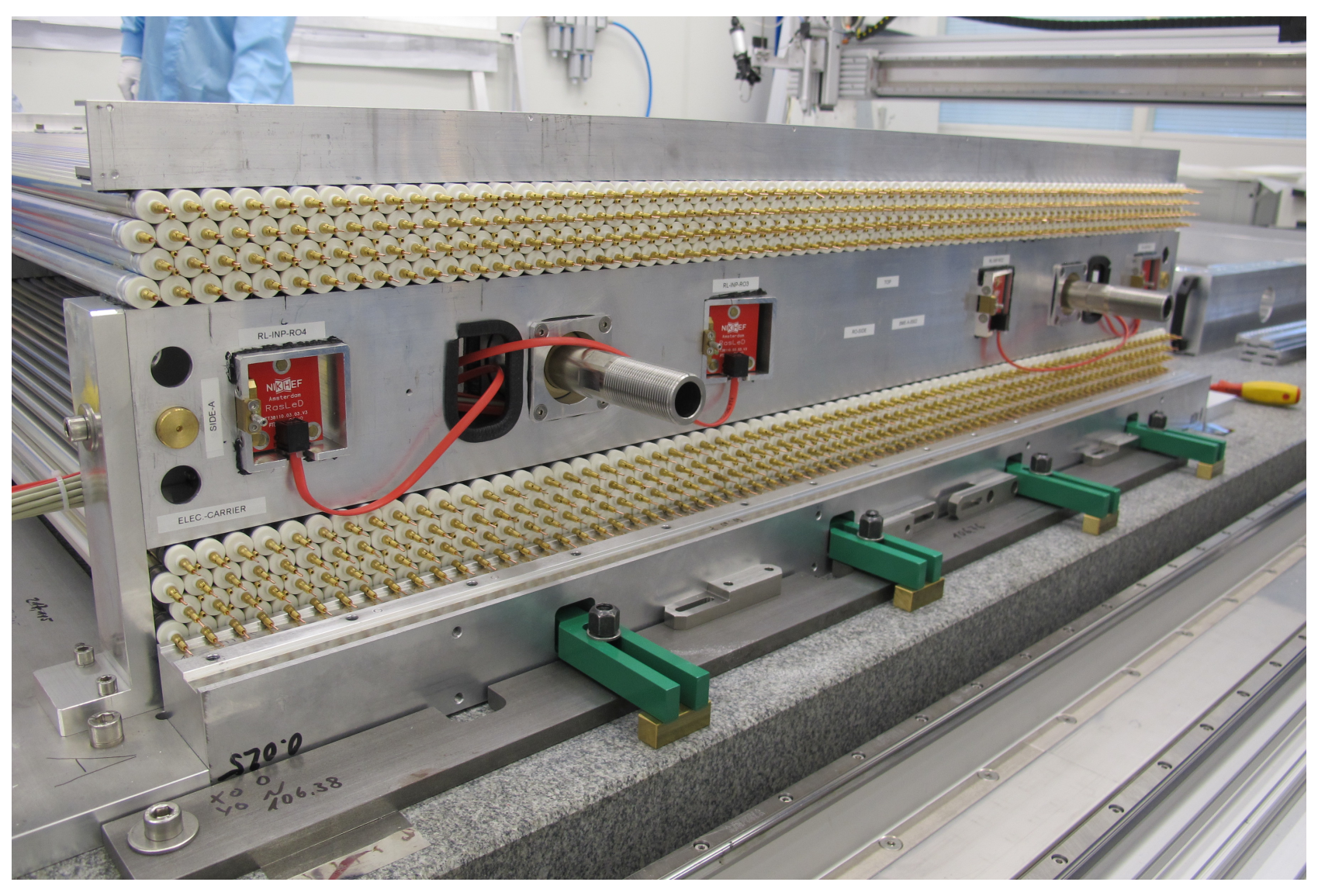
Abstract

The experience of the ATLAS muon spectrometer shows that drift-tube chambers provide highly reliable precision muon tracking over large areas. The ATLAS muon chambers are exposed to unprecedentedly high background of photons and neutrons induced by the proton collisions. Still higher background rates are expected at future high-energy and high-luminosity colliders beyond HL-LHC. Drift-tube detectors with 15 mm tube diameter (30 mm in ATLAS) and improved read-out electronics optimized for high rate operation have been developed for such conditions. Tests at the Gamma Irradiation Facility at CERN showed that the rate capability of sMDT chamber is improved by more than an order of magnitude compared to the ATLAS chambers as space charge effects are strongly suppressed and operation with minimal electronics dead time becomes possible. Studies of the new readout electronics are shown. Several full-scale chambers have been constructed with unprecedentedly high sense wire positioning accuracy of better than 5 micron. The chamber design and assembly methods have been optimized for large-scale production, reducing considerably cost and construction time while maintaining the high mechanical accuracy and reliability.

Muon Drift Tube Chambers

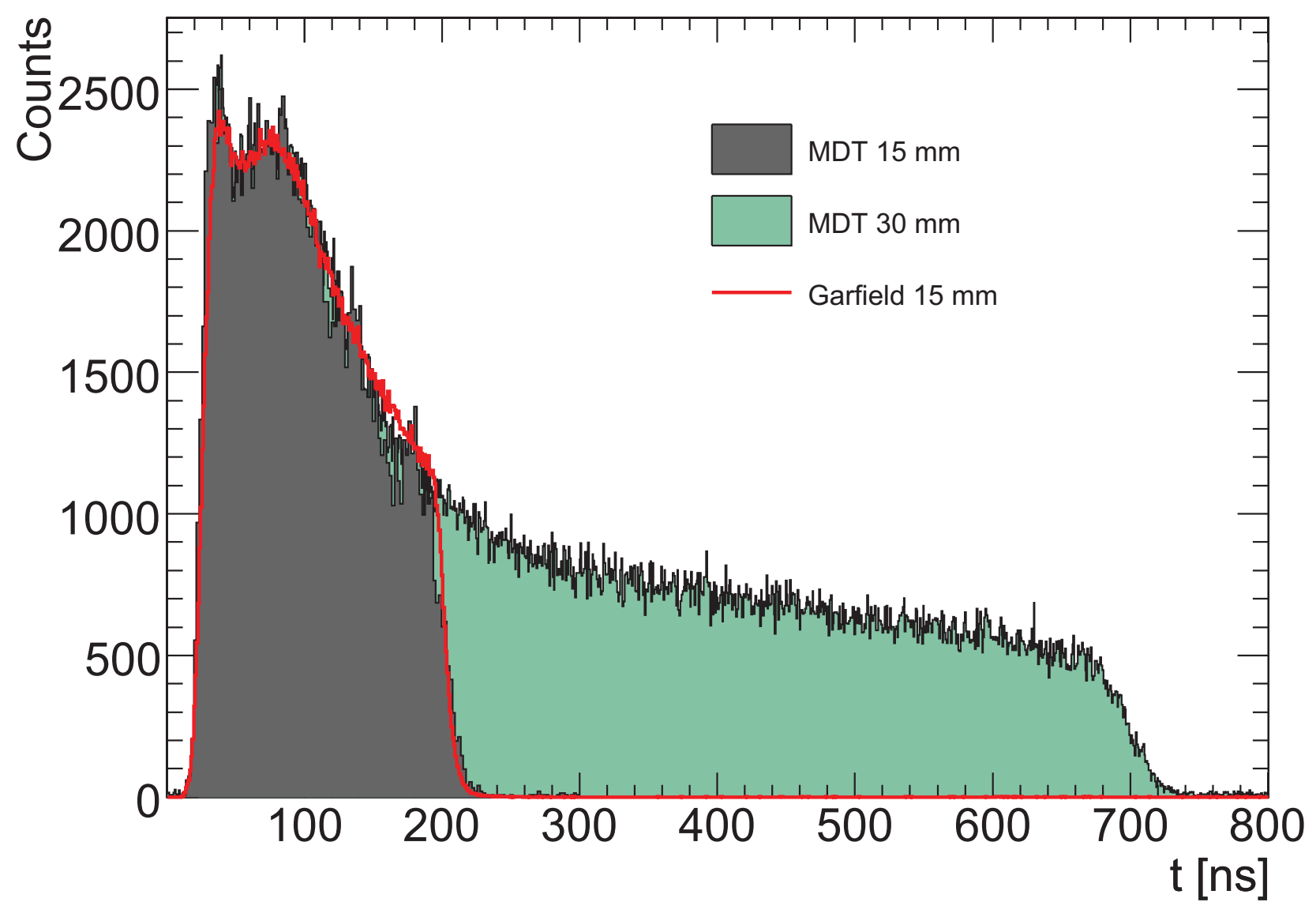


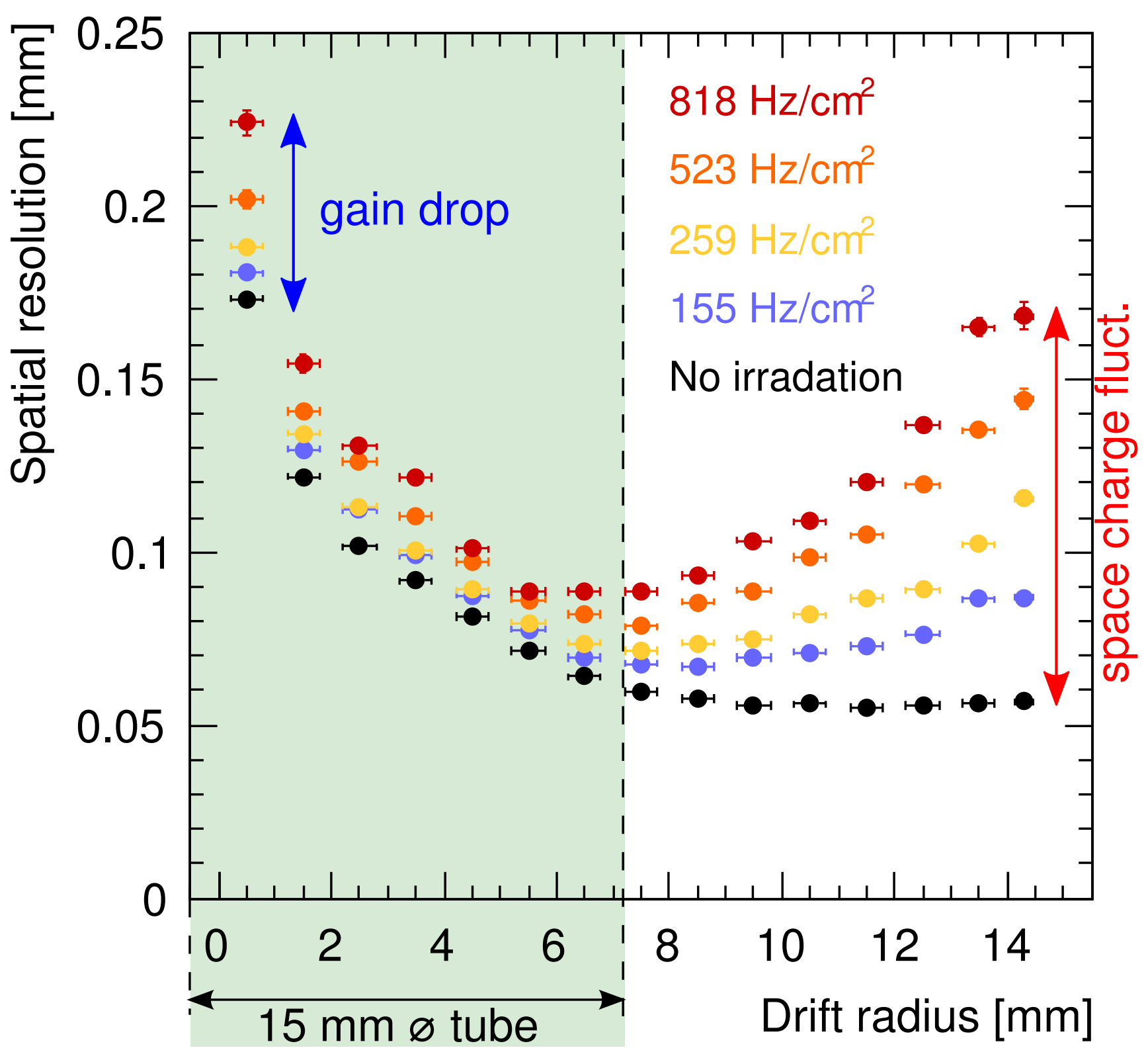
Assembled sMDT chamber for ATLAS

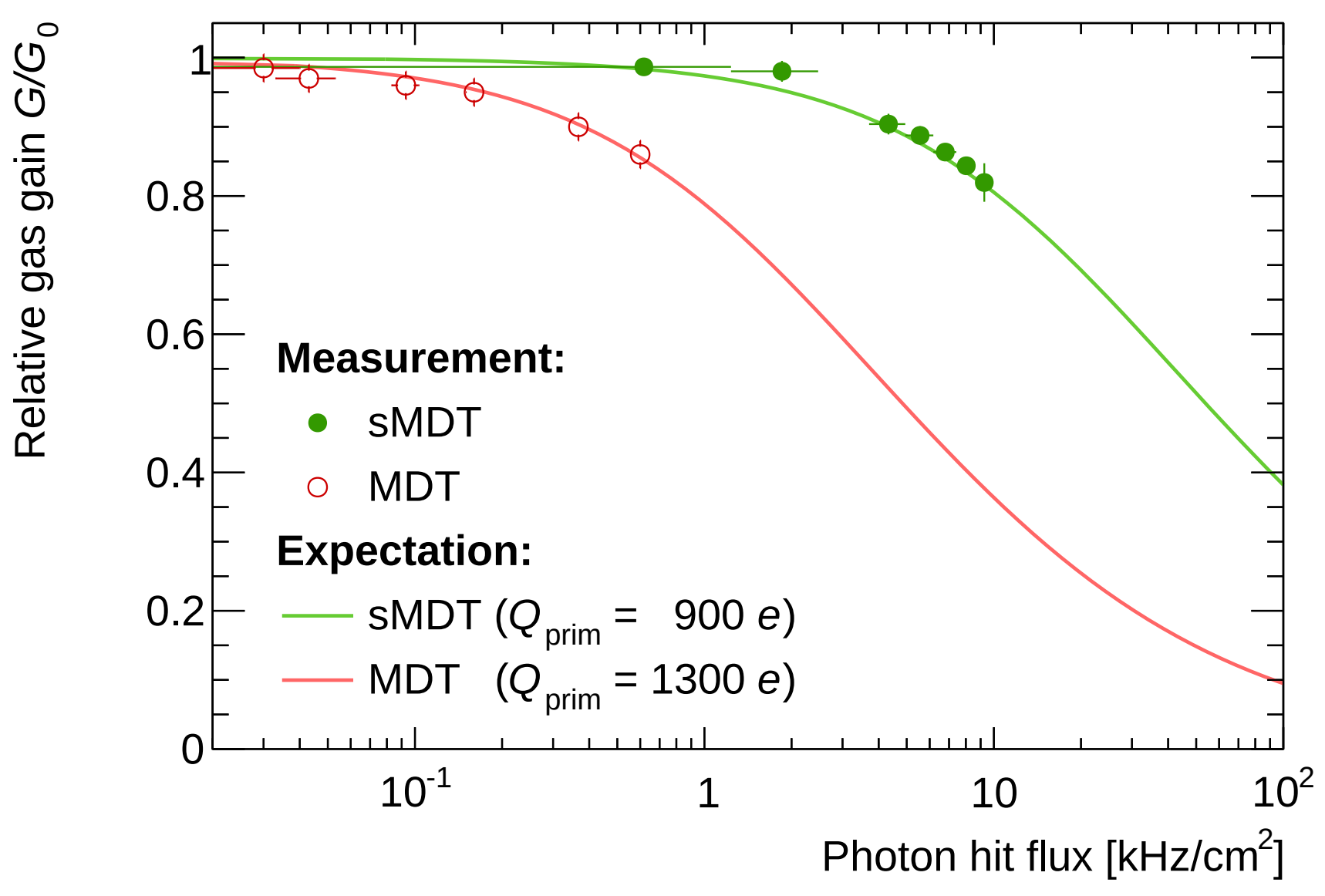


Monitored Drift Tube chambers, MDT: Precision tracking detectors in the ATLAS Muon Spectrometer with 30 mm drift tube diameter operated with Ar:CO$_2$ gas at 3 bar and a gas gain of 20000.

Small-Diameter MDT chambers, sMDT: Precision muon tracking detectors with 15 mm drift tube diameter and **an order of magnitude higher rate capability** than the MDTs for ATLAS upgrades and future hadron colliders.

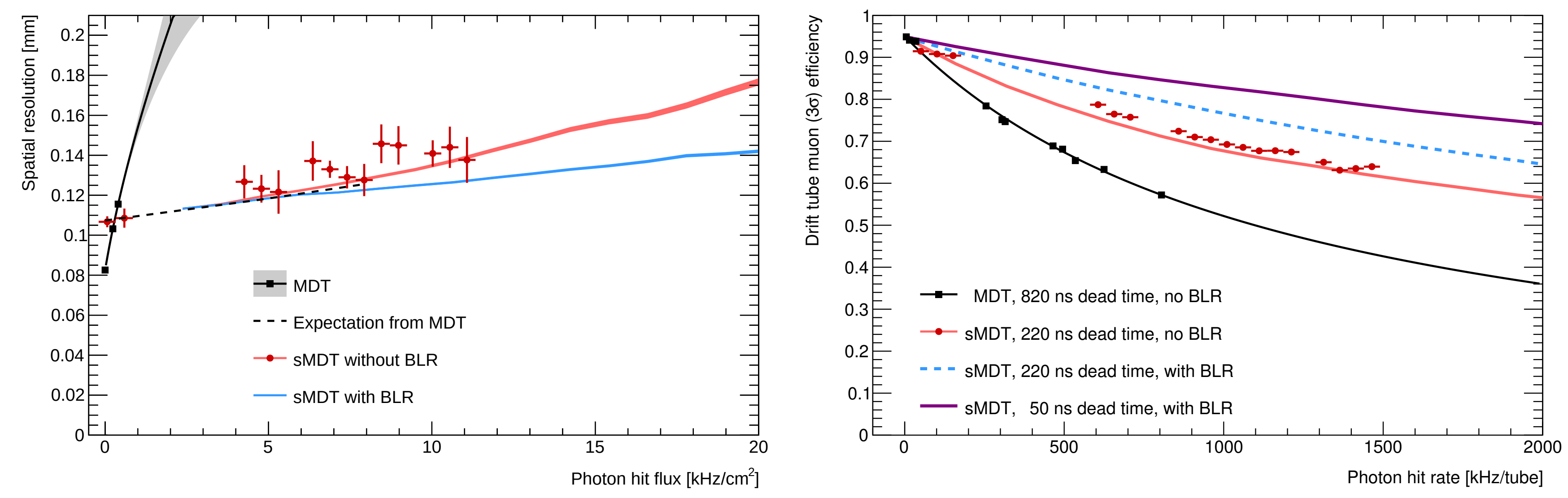






- The high background radiation of neutrons and photons at high energy hadron colliders creates space charge in the muon drift tube detectors due to the slowly drifting ions created in the avalanche near the sense wire and masks muon hits due to finite electronic signal length and dead time.
- Space charge fluctuations deteriorate the drift tube spatial resolution only for large drift radii occuring in MDTs.
- The decrease of gas amplification due shielding of the wire potential by the space charge is proportional to the tube radius R^3 for neutron and γ radiation, converting predominantly in the aluminum tube walls, and therefore is strongly suppressed in sMDT tubes.
- The 4 times shorter maximum drift time of sMDTs (185 ns)compared to MDTs (700 ns) under the same operating conditions leads, together with the smaller tube cross section, to 8 times lower background occupancy and allows for drastic reduction of the electronics dead time.
- Minimimum dead time leads to vast improvement of the muon detection efficiency at high counting rates which is fully exploited by using readout electronics with active baseline restoration.

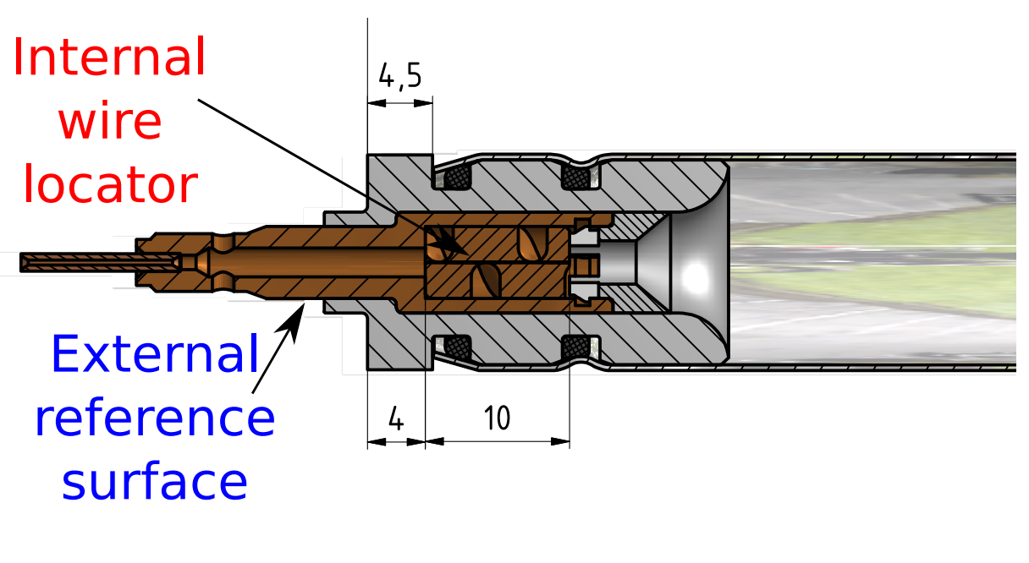
sMDT High-Rate Performance at CERN Gamma Irradiation Facility



Active baseline restoration (BLR) suppresses the obsreved signal pile-up effects promising further improvement of spatial resolution and muon efficiency (hit within $3\sigma_{resol}$ of the extapolated muon track) at high counting rates.

sMDT Chamber Design

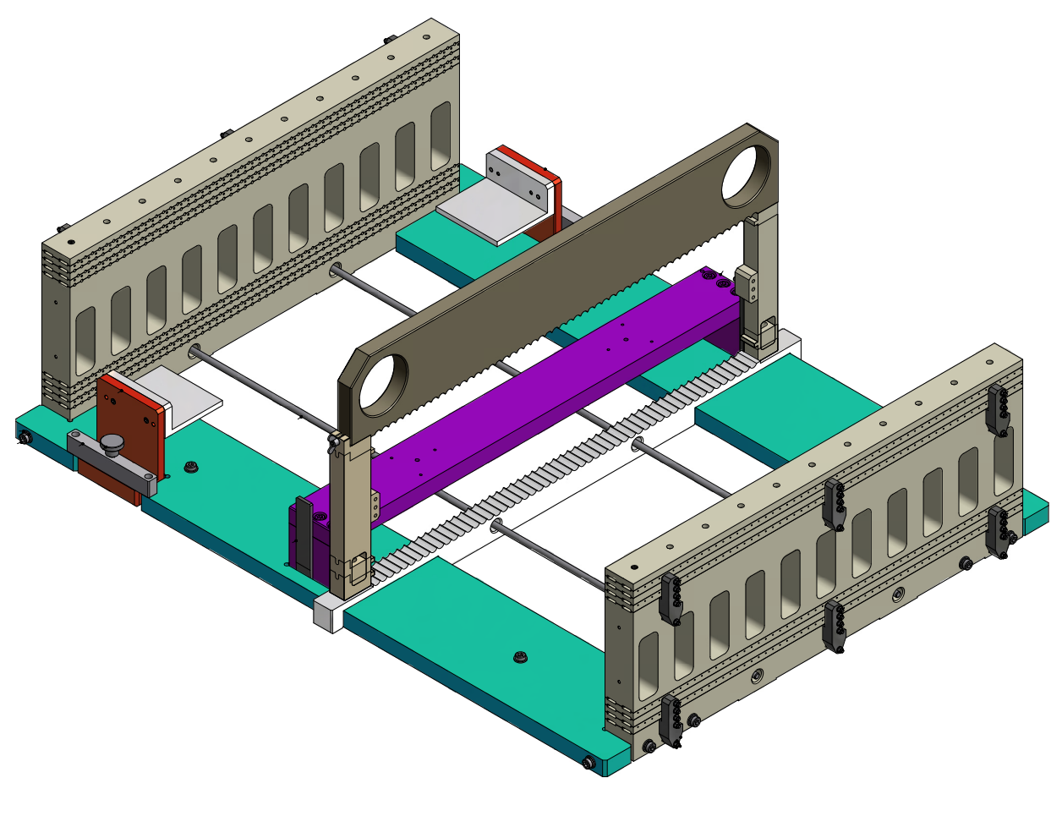
- sMDT chamber design and assembly optimized for mass production and speed independent of number of tube layers per chamber.
- Simple, low-cost drift tube design reliability and mechanical precision.
- Standard industrial aluminum tubes with 0.4 mm wall thickness.
- Plastic endplug materials selected to prevent outgassing and cracking.
- No wire aging observed up to 9 $\frac{C}{cm}$ charge on the wire (15 times current ATLAS requirement).



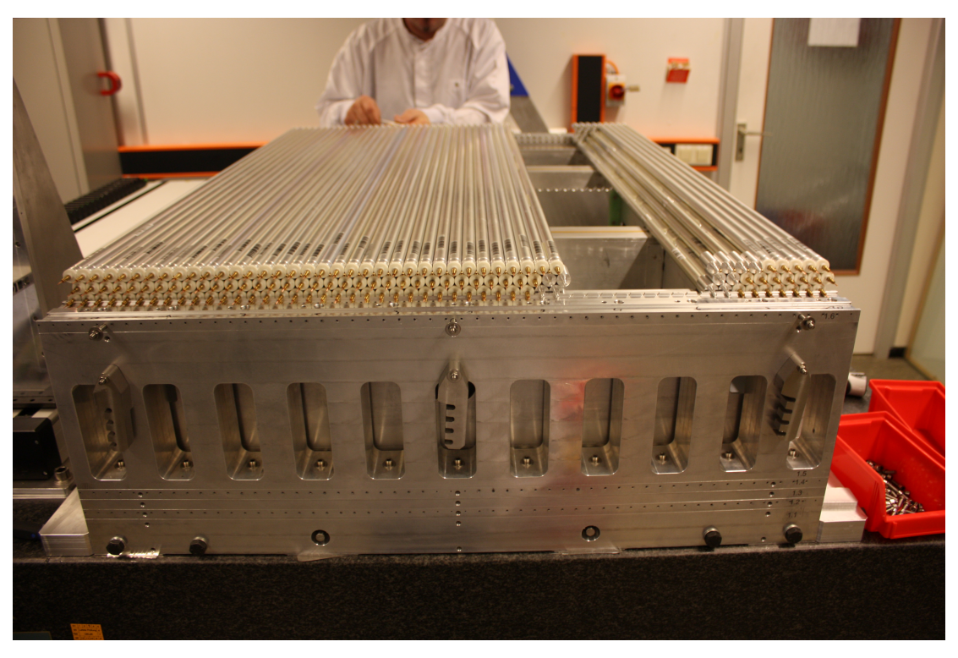
Cross section of an sMDT endplug

sMDT Chamber Assembly

- Semi-automated drift-tube production and chamber assembly in an air-conditioned clean room.
- Automated measurement of wire tension, gas leak rate and leakage current at nominal operating voltage (2730 V).



sMDT wire positioning by insertion of endplug reference surfaces into precisely machined jigs



sMDT chamber assembly

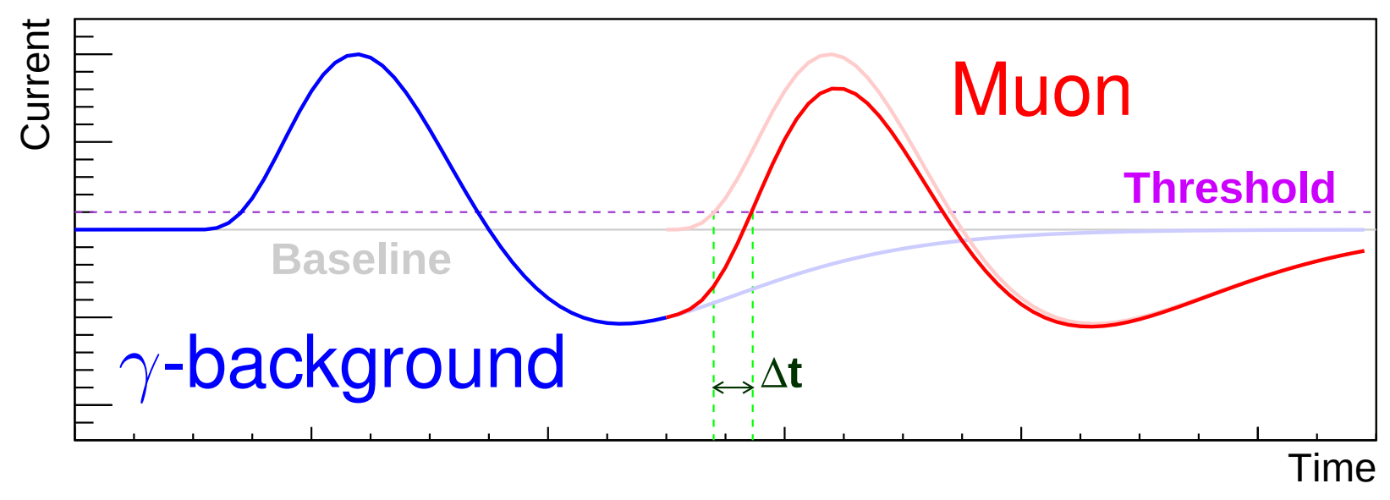
- Assembly of a chamber within one working day.
- Measurement of wire positions with coordinate measuring machine with few μm accuracy.
- **Sense wire positioning accuracy of better than 5 μm.**

Limitation of Standard MDT Read-Out Electronics at High Rates

- Bipolar shaping used to guarantee baseline stability at high rates.
- Disadvantage: long undershoot following the shaped signal pulse.

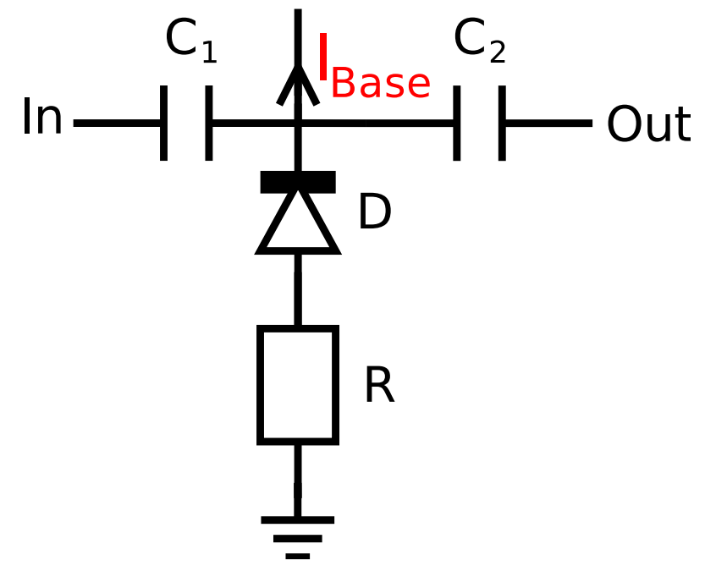
$\Rightarrow$ For desired operation at short dead time: amplitude of secondary muon pulses effectlively reduced and jitter of discriminator threshold crossing time increased.

Signal pile-up at high hit rates



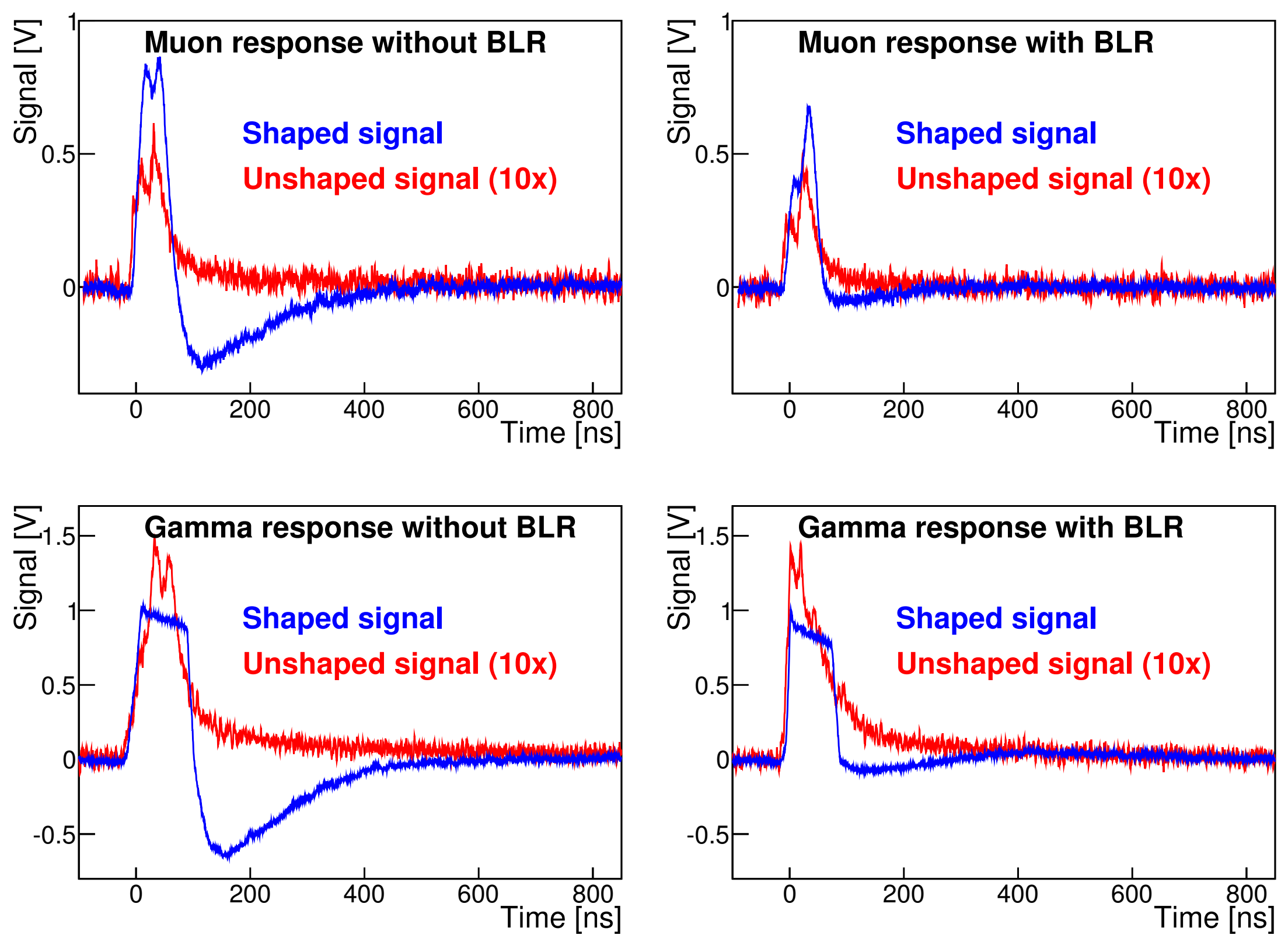
Signal Shaping Circuit With Optional Active Baseline Restoration

Principle of active baseline restoration (in the simplest version according to L.B.Robinson, Rev.Sci.Instr. 32 (1961) 1057):



- Diode conducting at $I_{Base} \neq 0$ working point.
- Diode non-conducting for positive signal polarity. $\Rightarrow$ signal stays unchanged.
- Diode conducting for negative polarity (undershoot) restoring baseline by draining current to ground.

Effect of Active Baseline Restoration



- Muon and γ background signals recorded before and after standard MDT bipolar shaping, the latter with and without turning on additional active baseline restoration (BLR) on a prototype circuit board.
- The BLR function clearly suppresses the bipolar undershoot. Promising option for operation of sMDT chambers at very high background counting rates.

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