High-Precision Large-Area Muon Tracking and Triggering with Drift- Tube Chambers at Future Colliders

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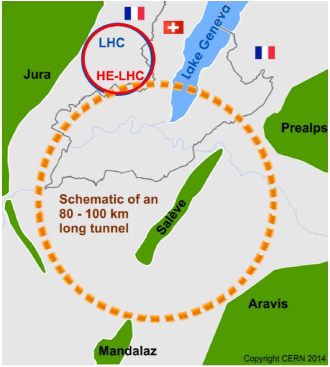
Vienna Conference of Instrumentation 2022

The FCC-hh project

Concept for a new pp collider

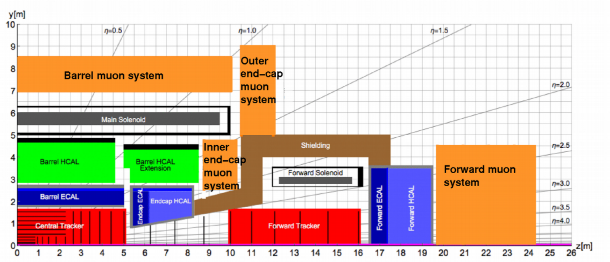


- 16 T dipole magnets in a tunnel of 100 km circumference.

$\Rightarrow$ $\sqrt{s}$=100 TeV.

- Peak luminosity: $3 \cdot 10^{25}$ cm^{-2}s^{-1}.
- Integrated luminosity: 20 ab^{-1}.

Conceptual detector design



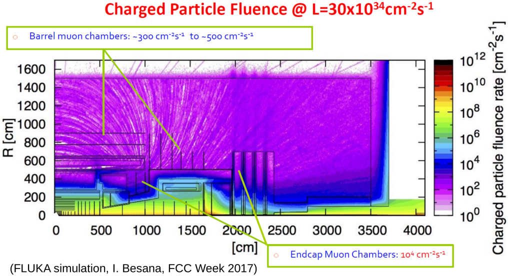
- 4 T magnetic field in the inner detector.

$\Rightarrow$ $\int B\,ds$ up to the barrel muon system: 18 Tm.

- Deflection angle α measurement of muon p_T.
- $\delta\alpha$=70 μrad required to achieve $\frac{\delta p_T}{p_T} < 10\%$.

Proposed instrumentation of the muon system

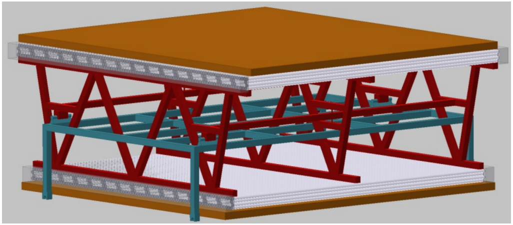
Background rates



(FLUKA simulation, I. Besana, FCC Week 2017)

- Max. nominal count rate $<$10 kHz/cm^2.
- Rate with safety factors $<$25 kHz/cm^2.
- Small diameter muon drift-tube (sMDT) chambers developed for the upgrade of the ATLAS detector can cope with these harsh conditions.

Precision sMDT chambers

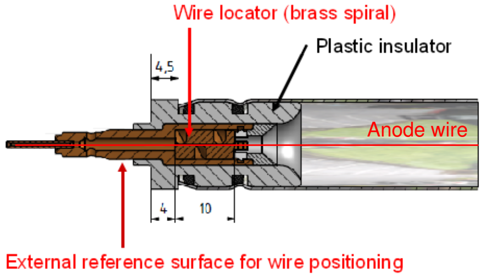


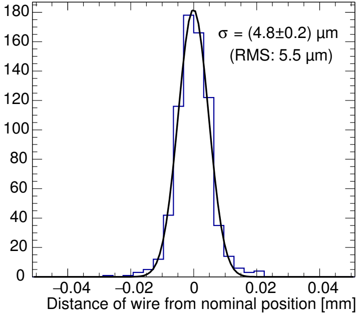
- 2$\times$4 layers of 15 mm diameter drift tubes at 1.5 m multilayer distance provide the requires 70 μrad angular resolution.
- sMDT chambers are the only cost-effective technology with the required high-rate capability and the required angular resolution.

Mechanical precision of sMDT chambers

- Tube reference surfaces accessible in chambers thanks to endplug design.

⇒ Possibility of measuring the wire positions with a coordinate measurement machine.





Unprecedented wire positioning accuracy of 5 μm!

Operation of sMDT under high γ background

Operating parameters of an sMDT

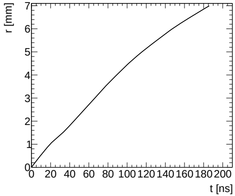
- Tube diameter: $2{\cdot}R$=15 mm. Tube wall thickness: 400 μm.
- Anode wire diameter: $2{\cdot}r_0$=50 μm.
- Gas mixture: Ar:CO_2(93:7) at 3 bar.
- Operating voltage: U_0=2730 V $\Rightarrow$ Gas gain: 20000.

Consequences of high γ background radiation

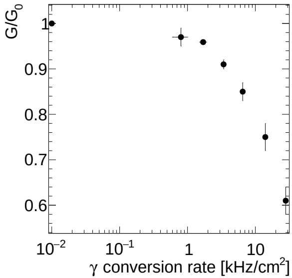
- γ rays creates hits by knocking out electrons from the tube walls by Compton scattering.
- γ hits can mask muon hits reducing the muon detection efficiency.
- Nonnegligible positive space inside a tube from ions drifting from the anode wire to the wall shielding the electric field on the anode wire and reducing the gas gain.

- Altered electric field inside the tube due to a constant positive space charge ρ_γ:

$$E(r) = \frac{U_0 - \frac{1}{4}\frac{\rho_\gamma}{\epsilon_0}R^2}{\ln\frac{R}{r_0}} \cdot \frac{1}{r} + \frac{1}{2}\frac{\rho_\gamma}{\epsilon_0} \cdot r.$$



- Due to the linearity of the space drift-time relationship the electron drift velocity is unaffected by the modification of the electric.

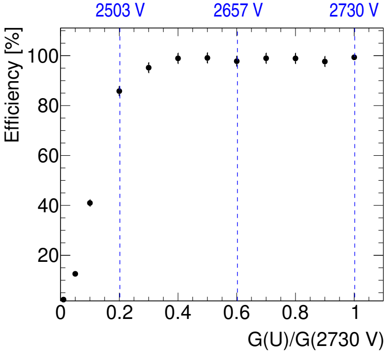


- Only consequence of the altered $E(r)$: gas gain drop due reduced field at the anode wire.
- Gain drop can be compensated by adjusting the operating voltage U_0.

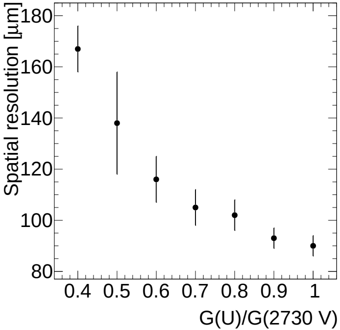
Consequences of the gain drop

The influence of the gain drop on the muon detection efficiency and the spatial resolution can be measured by reducing the operating voltage of the tubes in one layer.

Muon detection efficiency



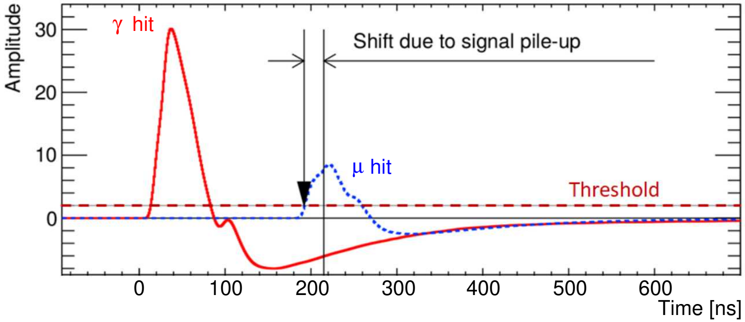
Spatial resolution



- No efficiency degradation down to a gain drop of 60%.
- Only small resolution degradation down to a gain drop of 40%.

$\Rightarrow$ Good performance without high-voltage adjustment down to a gain drop of 40% corresponding to a γ count rate of 30 kHz/cm^2.

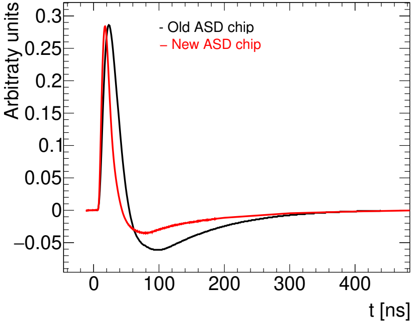
Resolution degradation due to signal pile-up

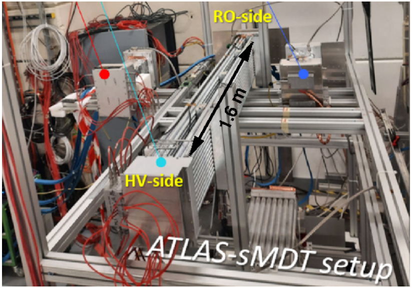


- Bipolar shaping is employed for the sMDT read-out in order to avoid baseline drifts.
- Muon hits falling into the negative tail of a preceding γ hit get deteriorated leading to a degradation of the spatial resolution.

New Amplifier Discriminator Chip

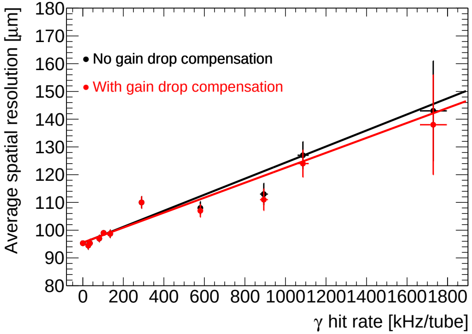
δ response functions





- So far sMDT chambers have been operated with the ATLAS ASD chip for 30 mm diameter drift-tube chambers.
- A new ASD chip with reduced negative amplitude and shorter pulses has been developed and operated on an sMDT chamber to minimize the pile-up effect.
- The new ASD chips were tested on a sMDT chamber with 1.6 m long in CERN's Gamma Irradiation Facility GIF++.

Spatial resolution as a function of the γ background rate



- Maximum γ hit flux: 7 kHz/cm^2.

⇒ Small resolution degradation due to gain drop.

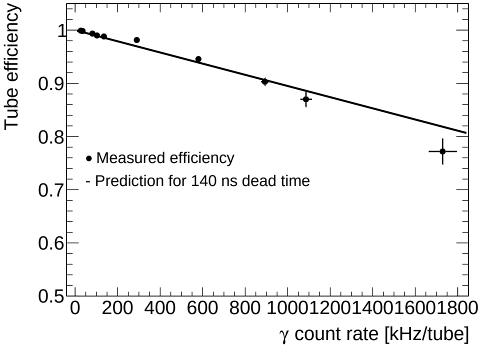
⇒ Resolution degradation caused by signal pile-up.

- High spatial resolution, 140 μm, even at the highest rate of 1.7 MHz/tube.

- Further improvements by minimizing pile-up effects through active baseline restoration are under investigation.

Influence of γ background on the efficiency

- High γ background leads to a large hit occupancy.
- Efficient track reconstruction with an 8-layer chamber possible up to an occupancy of 30% corresponding to a γ hit rate of 1.7 MHz/tube.
- Size of the efficiency degradation due to masking of muon hits given by the electronics' dead time.

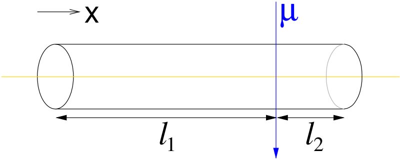


- Tube efficiency >80% up to 1.7 MHz/tube count rate (30%) occupancy.

$\Rightarrow$ Muon track reconstruction efficiency with >99% with an 8-layer sMDT chamber over the full range of background rates.

Second coordinate measurement and self-triggering

3D position measurement

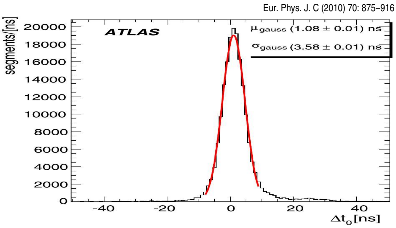


- Measurement of the x position from the differences of the propagation delays on either ends of the tubes:

$$\Delta l = l_2 - l_1 \approx c(t_2 - t_1).$$

⇒ To achieve precision on Δl of $\sim$cm one needs to measure $t_{1/2}$ with ps precision.

Self-triggering



- Do not use a trigger chamber for reference time measurement.
- Look for coincidences of hit tubes in the sMDT chamber.
- Straight-line track reconstruction in the coincidence region with the event time a fit parameter.
- Expected event time resolution: ~ 3 ns$\ll$25 ns (proton bunch spacing).

Conclusions

- Small diameter drift-tube chambers are the ideal choice for the cost-effective instrumentation of large-area muon systems when high spatial resolution is required.
- Studies of the last decades show that these chambers can be operated with high spatial resolution and muon detection efficiencies up to the highest background rates expected at future hadron collider experiments.
- Double-sided read-out with picosecond TDC allows for a 3D position measurement.
- The availability of modern high-performance FPGAs for data processing in real time make is possible to operate sMDT chambers in self-triggering mode.