

# muCool: Towards a high-brightness ultra-cold positive muon beam line at PSI

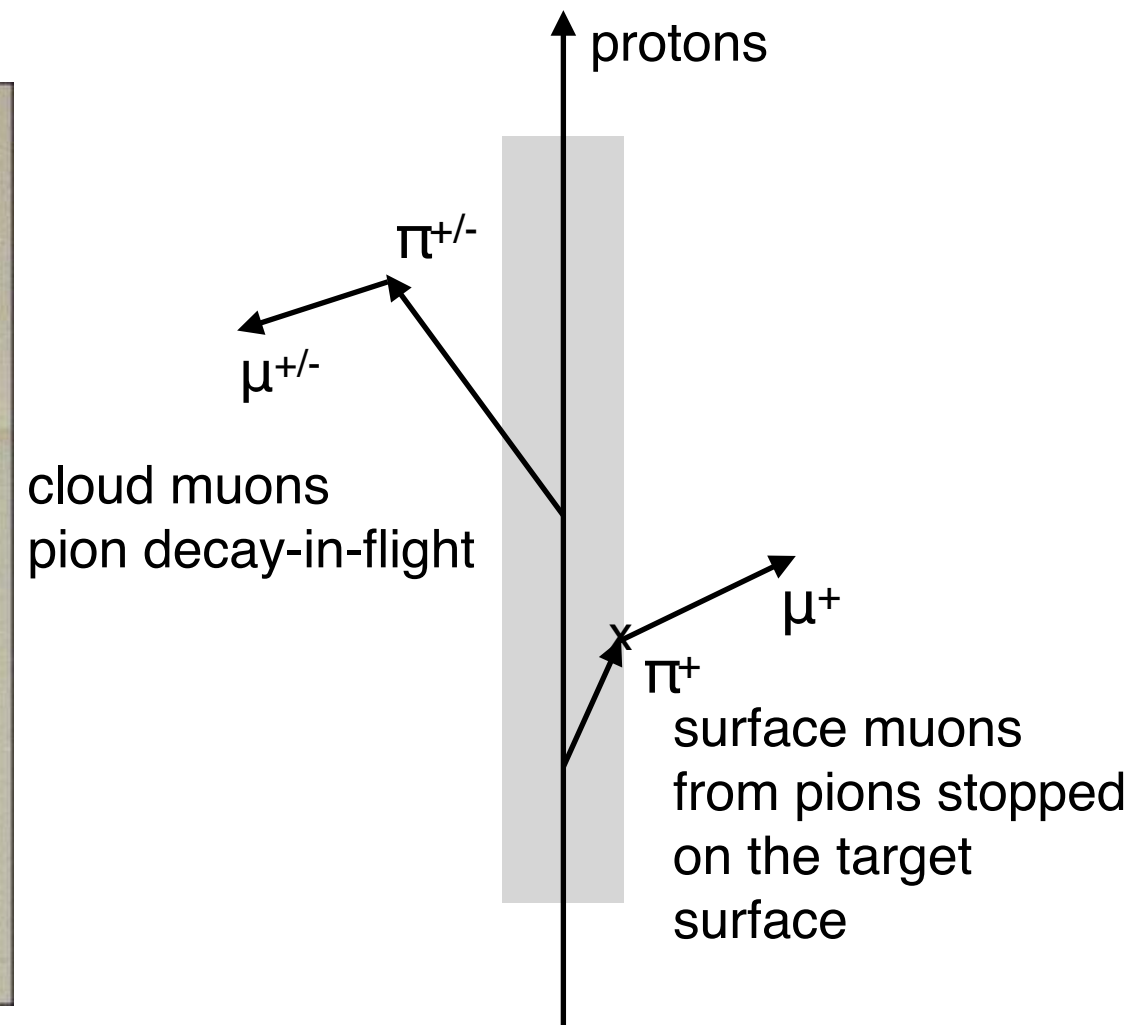
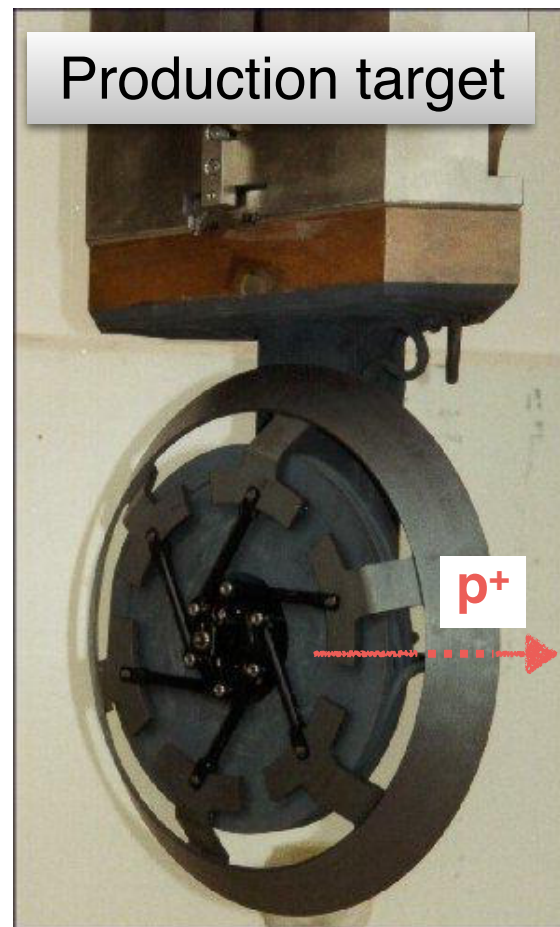
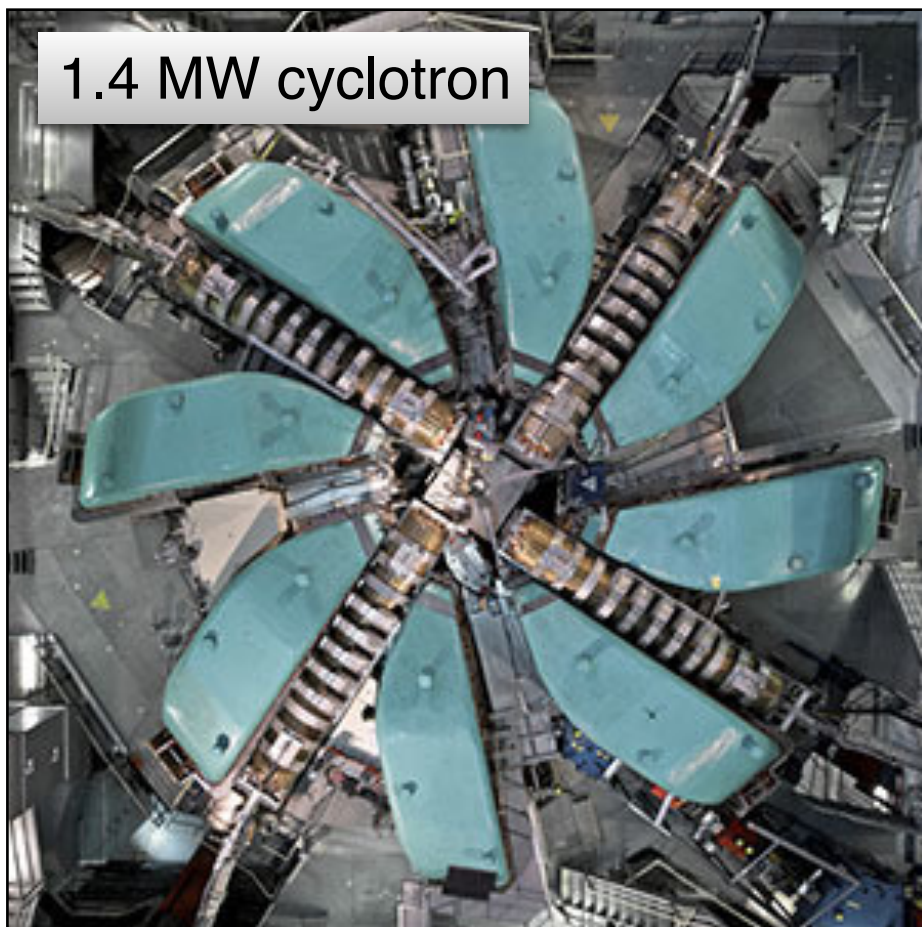


R. Iwai (ETHZ)  
on behalf of muCool collaboration



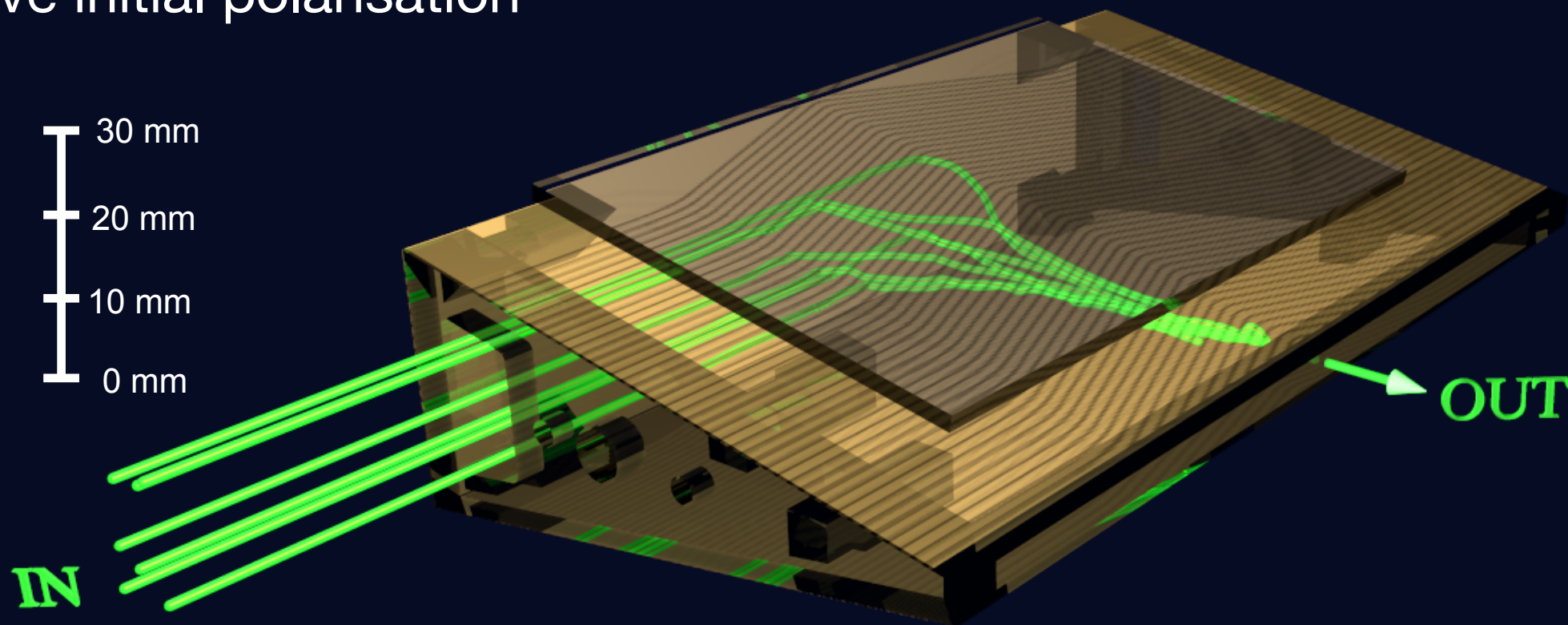
# Muon beams at PSI

- High power proton beam colliding graphite target
- Surface  $\mu^+$  at 4.1 MeV most widely used ( $\Delta x \sim \text{cm}$ )
  - Large room for improvement in phase space quality
- Standard beam cooling techniques not applicable due to limited  $\tau_\mu$  ( $2.2 \mu\text{s}$ )
  - muCool scheme



# muCool project

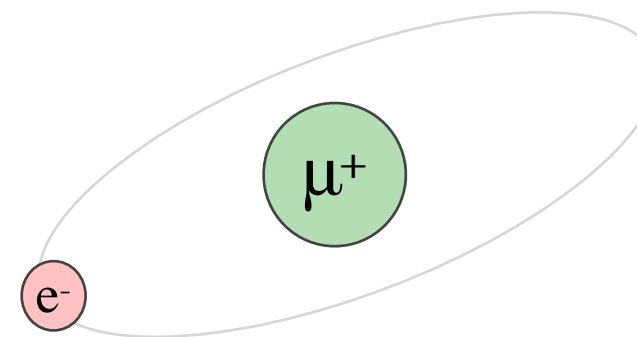
- Device to compress the phase space of a standard muon beam by 10 orders of magnitude
- Cryogenic He gas stopping target with complex fields
- Reduce energy ( $4.1 \text{ MeV} \rightarrow <1 \text{ eV}$ ) and beam size ( $10 \text{ mm} \rightarrow <1 \text{ mm}$ )
- Efficiency  $\sim 10^{-3}$
- Conserve initial polarisation



# Motivation

## Particle physics

- Muon  $g-2$ /EDM
- High quality Mu beam from SFHe
  - 1S-2S spectroscopy
  - Test anti-matter gravity

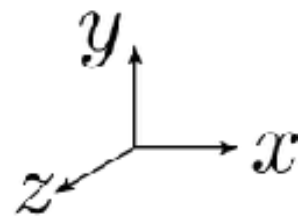
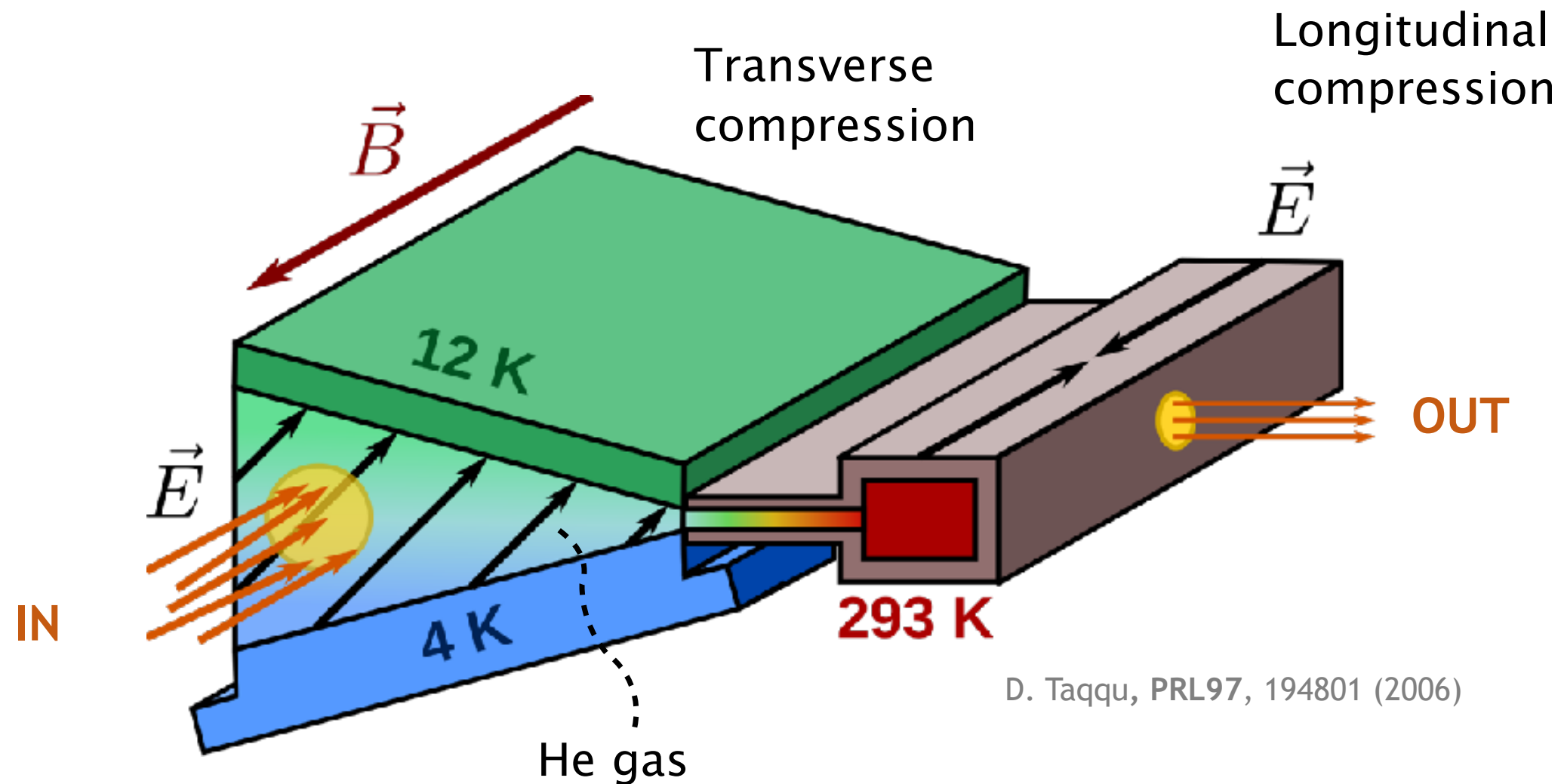


## Solid state physics ( $\mu$ SR)

- Study thin materials, small samples



# Working principle (old)



$$\vec{v}_D = \frac{\mu E}{1 + \omega^2 \tau_c^2} [\hat{E} + \omega \tau_c \hat{E} \times \hat{B} + \omega^2 \tau_c^2 (\hat{E} \cdot \hat{B}) \hat{B}]$$

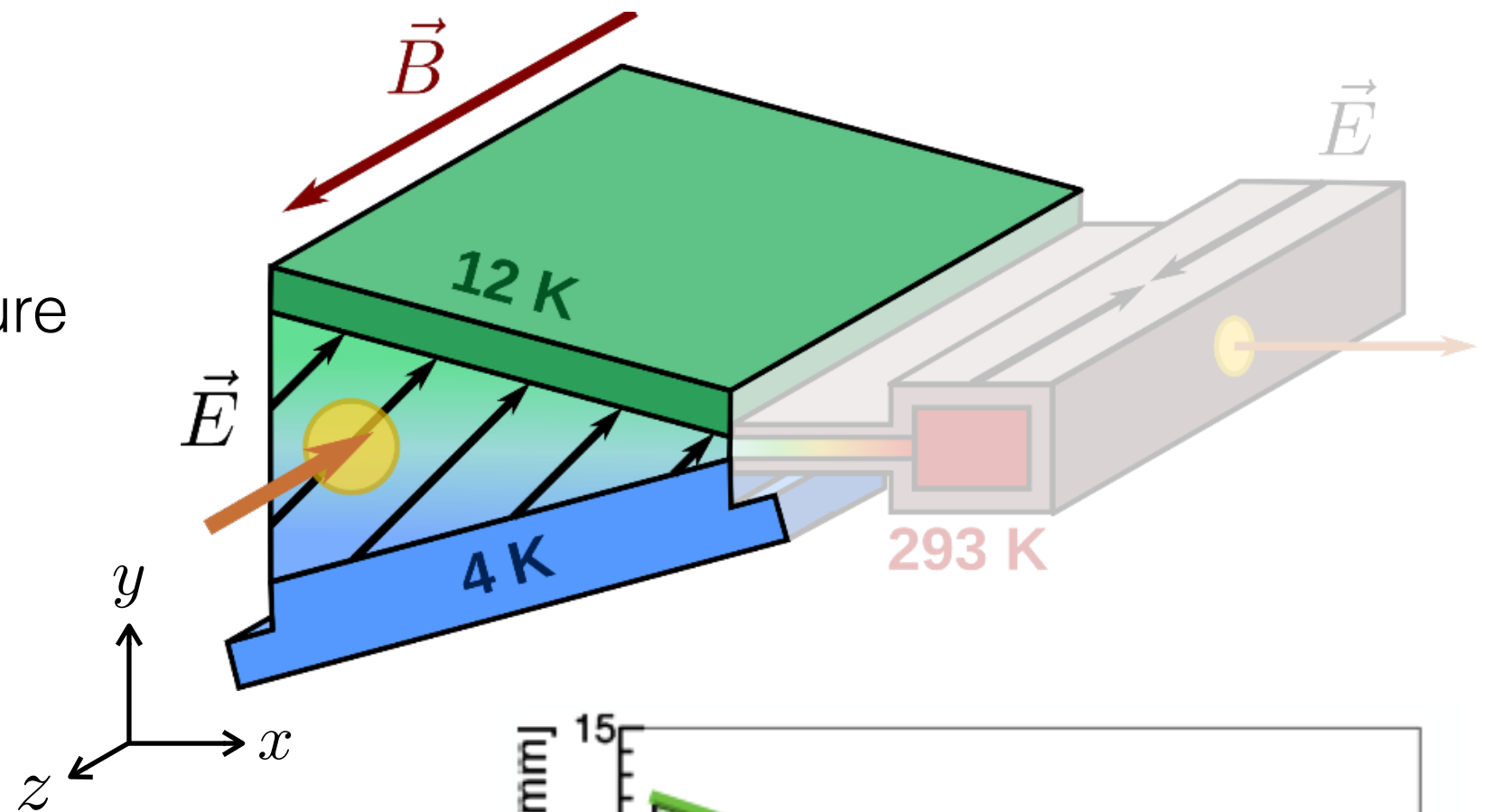
$\mu$  : muon mobility

$\omega$  : cyclotron frequency

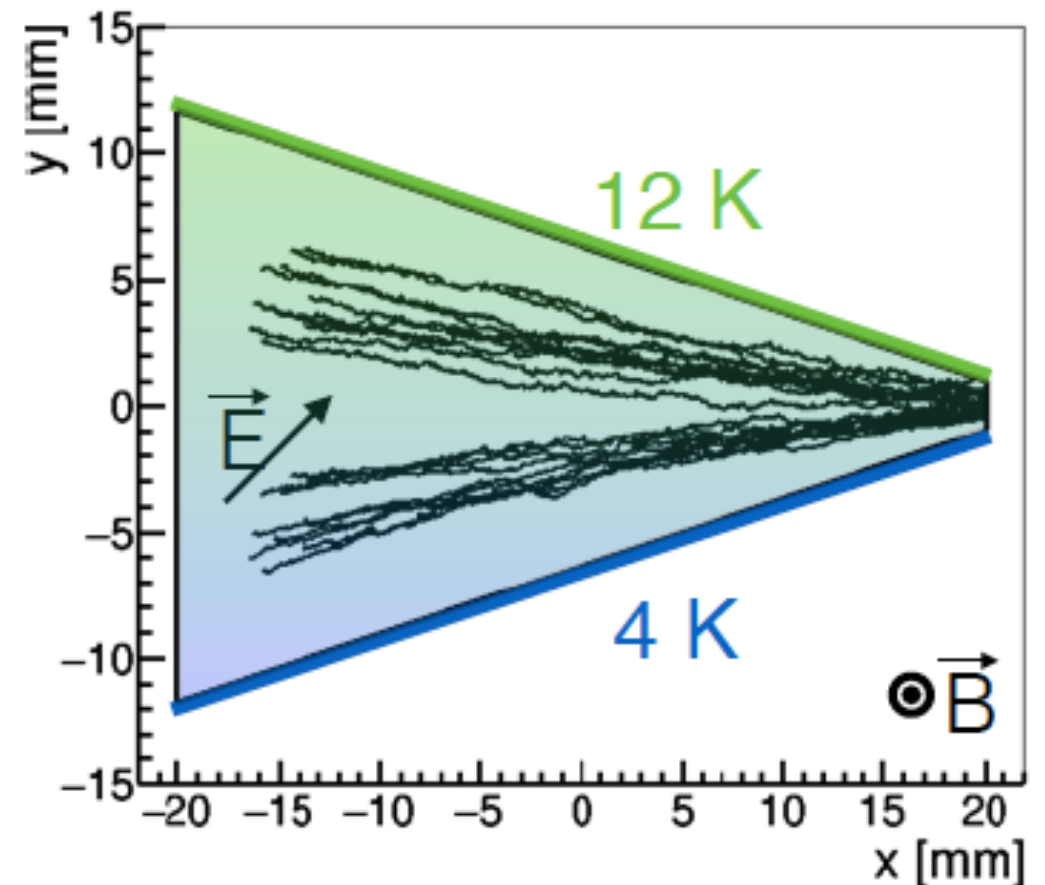
$\tau_c$  : mean time between collisions

# Transverse compression

- ▶ 5 mbar He gas
- ▶ Temperature gradient at cryogenic temperature
- ▶ Crossed E- and B-field



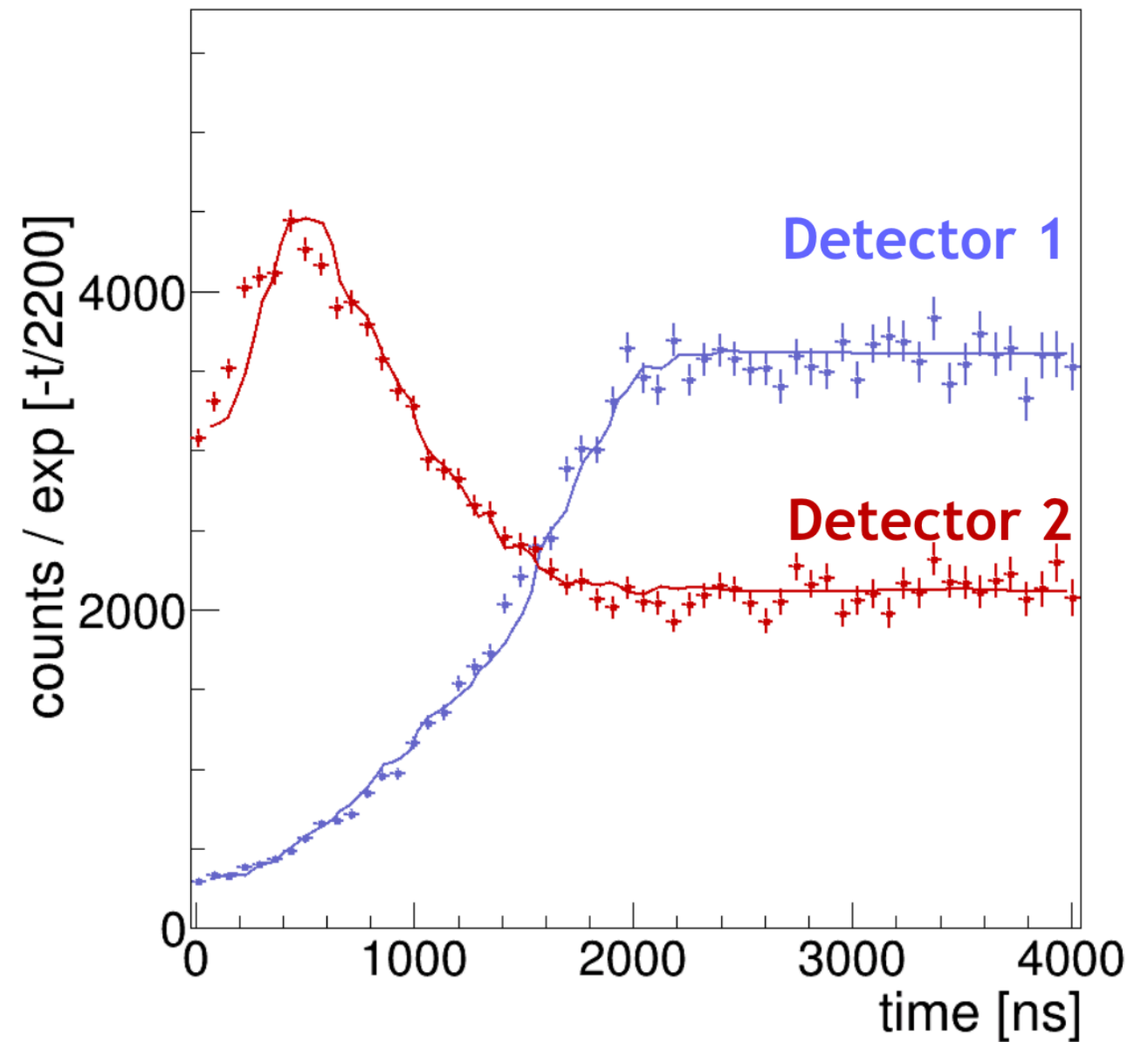
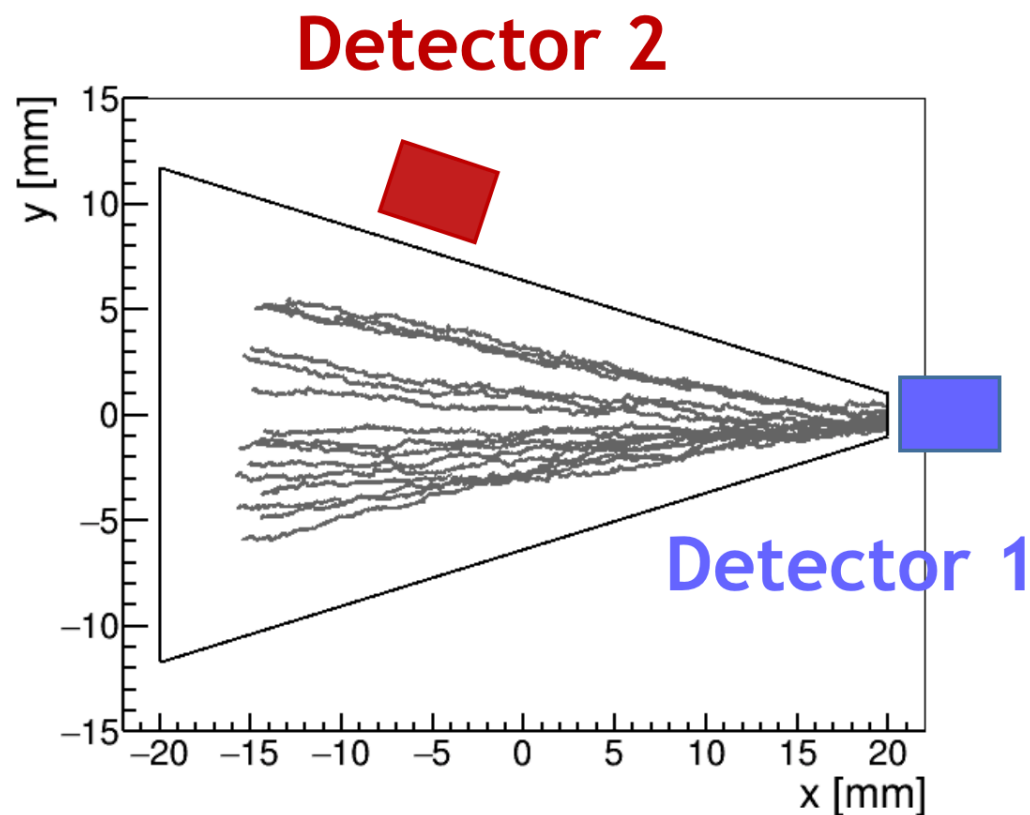
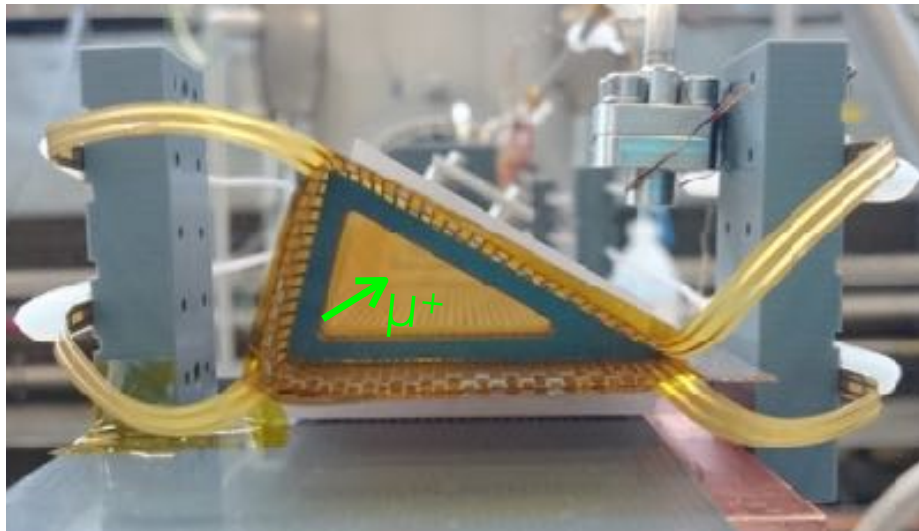
$$\vec{v}_D = \frac{\mu E}{1 + \omega^2 \tau_c^2} [\hat{E} + \omega \tau_c \hat{E} \times \hat{B} + \omega^2 \tau_c^2 (\hat{E} \cdot \hat{B}) \hat{B}]$$





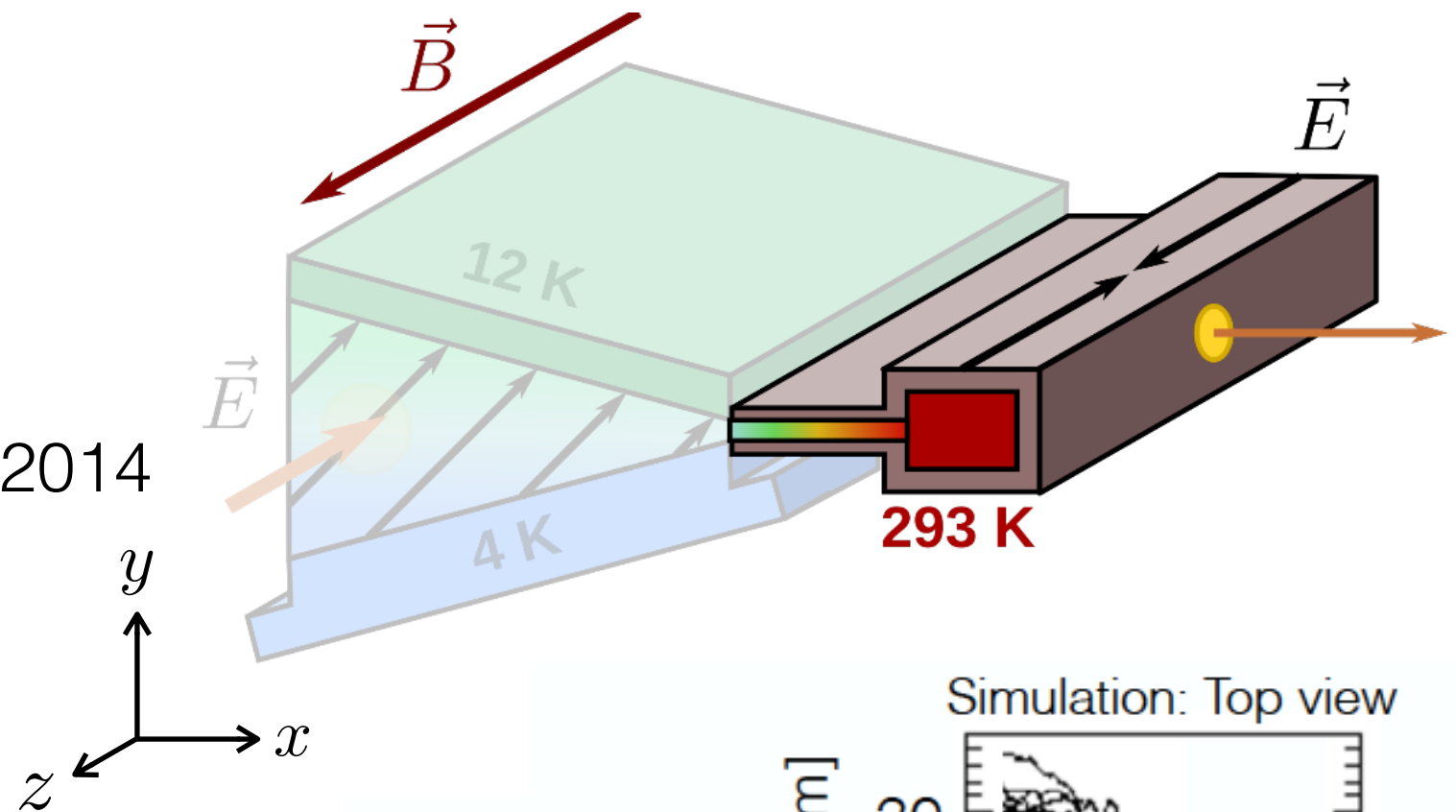
# Demonstration of transverse comp.

- ▶ Demonstrated in 2015 I. Belosevic et al., *Hyperfine Interact* (2019) 240: 41.
- ▶ Excellent agreement between measurement and simulation



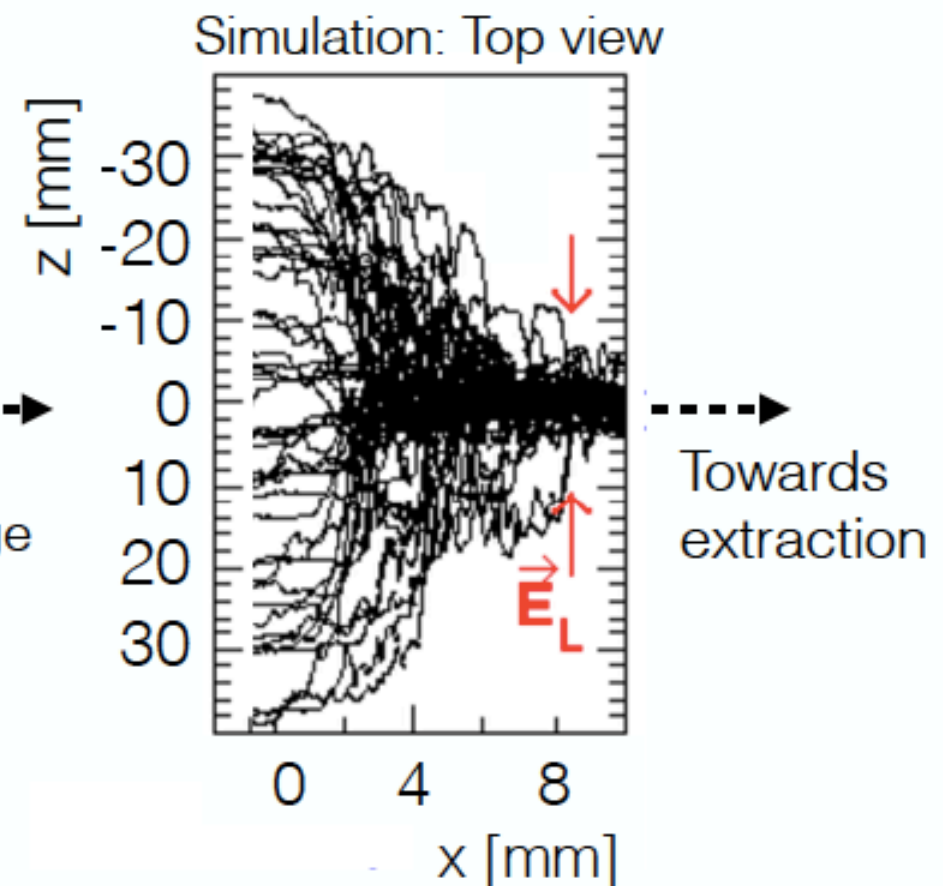
# Longitudinal compression

- ▶ 5 mbar He gas
- ▶ Room temperature
- ▶ Parallel E- and B-field
- ▶ Demonstrated in 2011/2014



$$\vec{v}_D = \frac{\mu E}{1 + \omega^2 \tau_c^2} [\hat{E} + \omega \tau_c \hat{E} \times \hat{B} + \omega^2 \tau_c^2 (\hat{E} \cdot \hat{B}) \hat{B}]$$

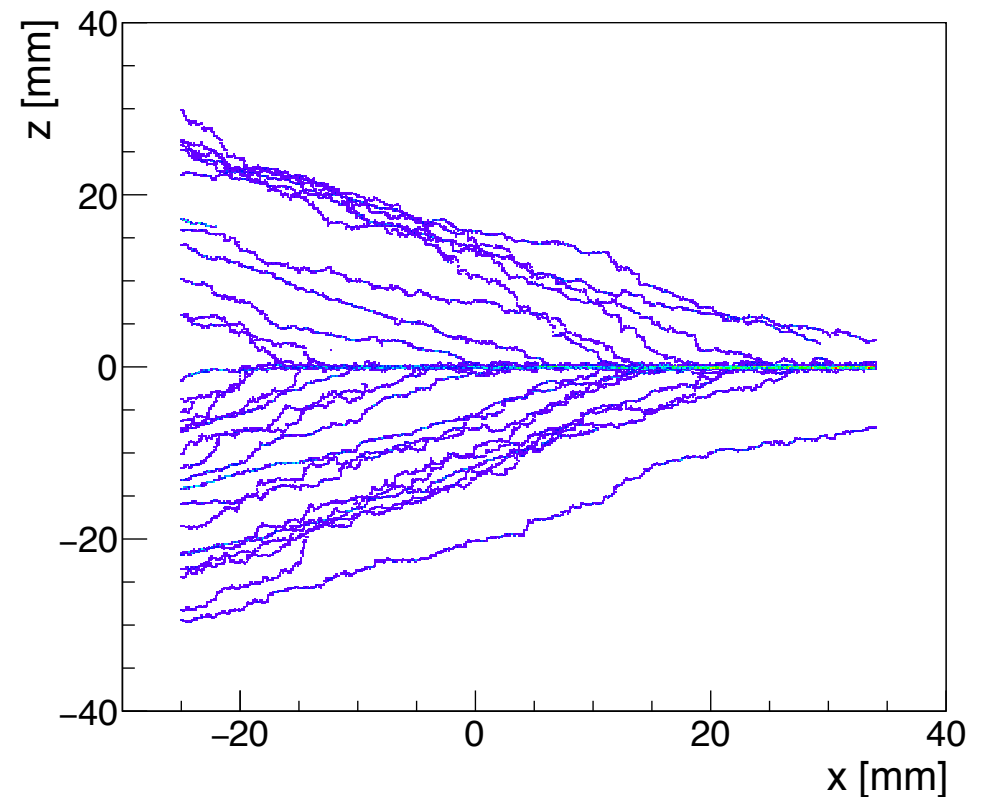
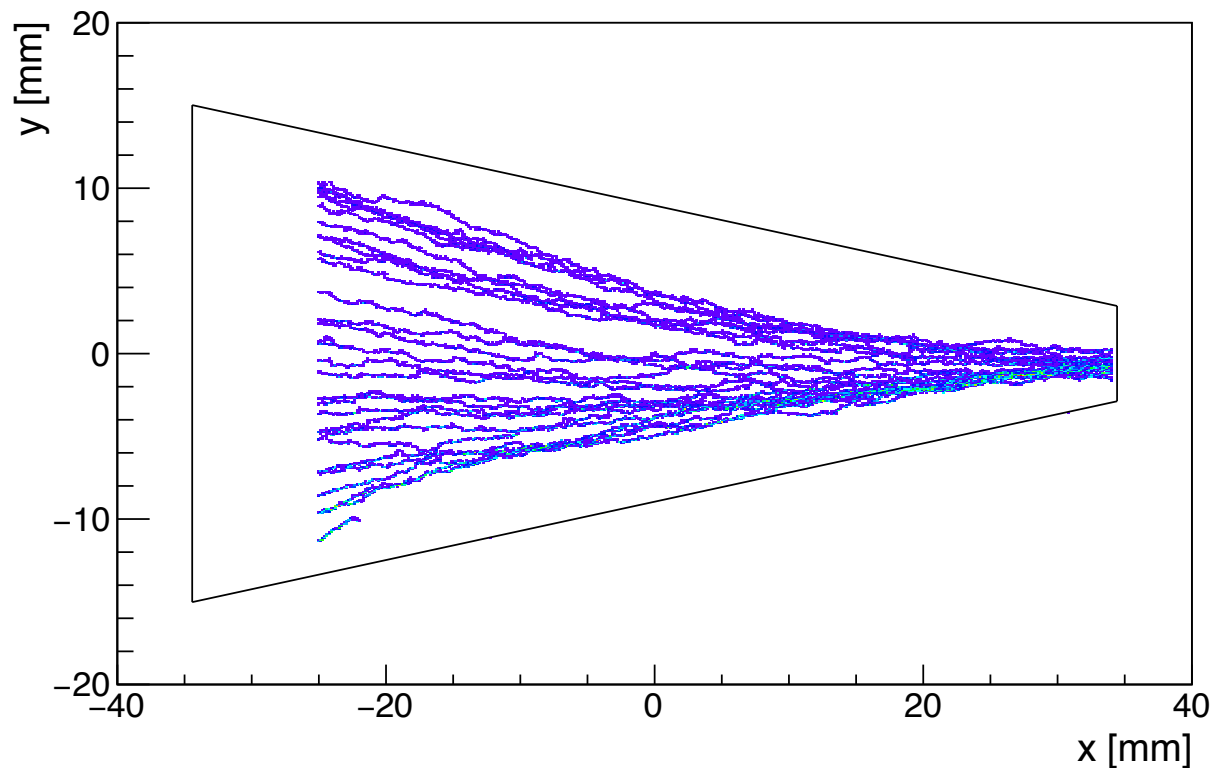
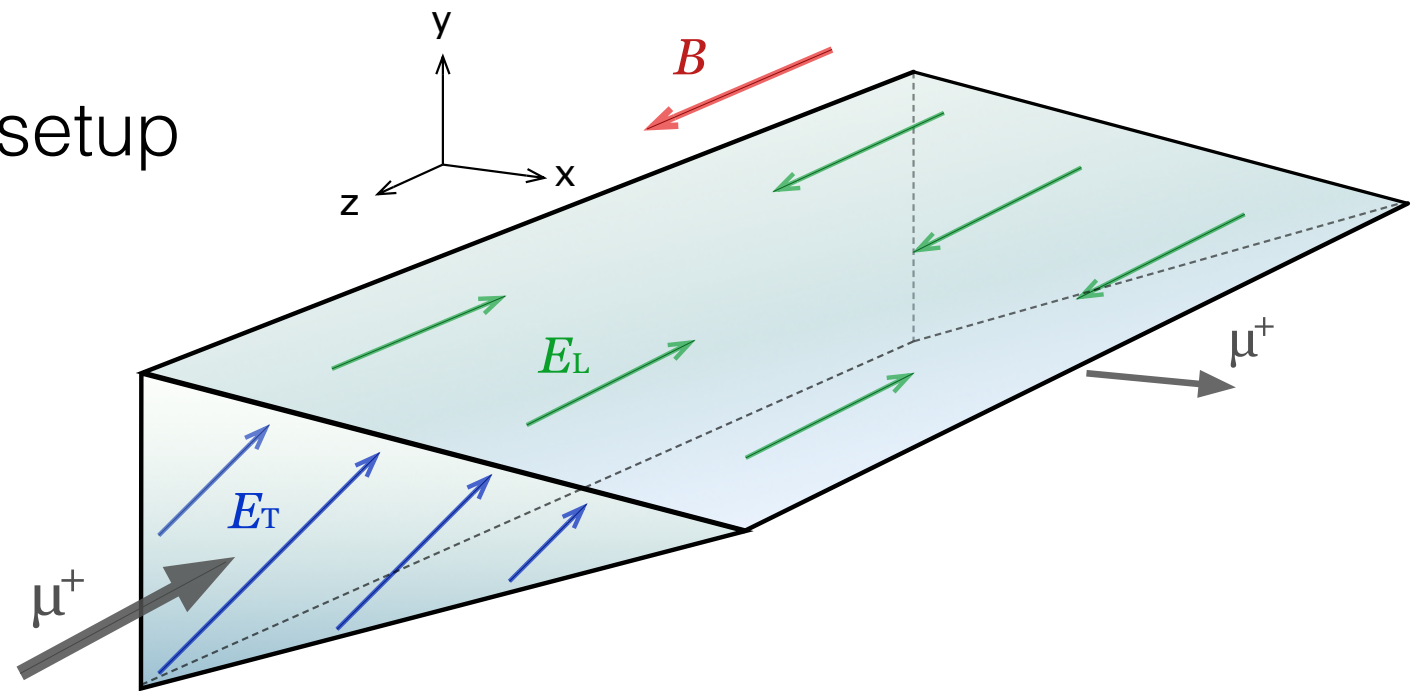
μ<sup>+</sup> from  
transverse stage





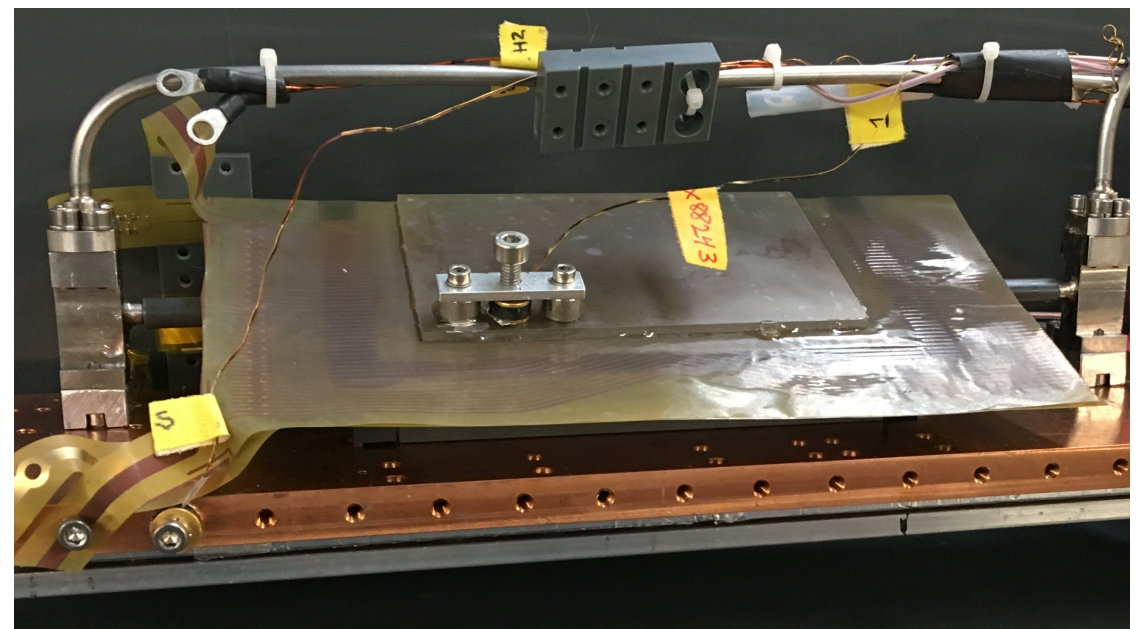
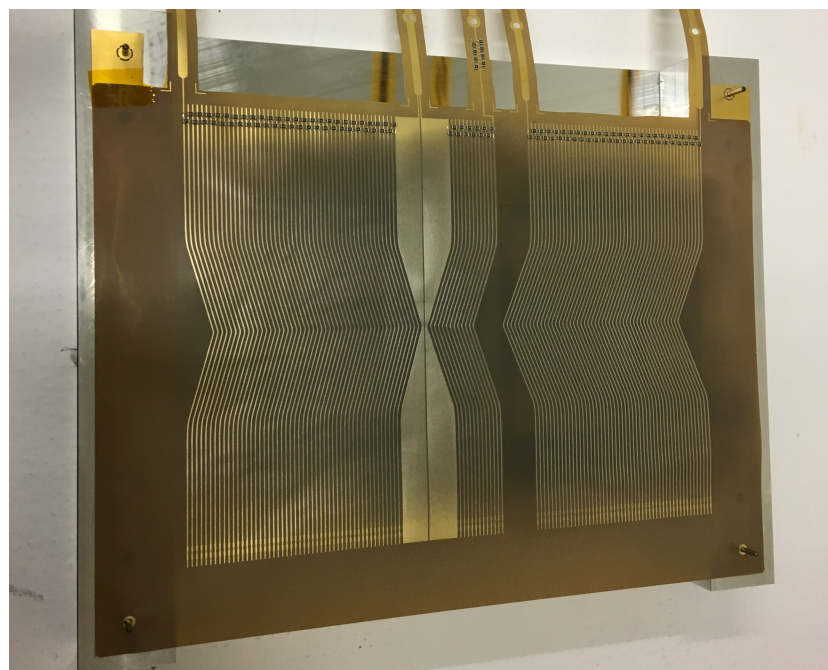
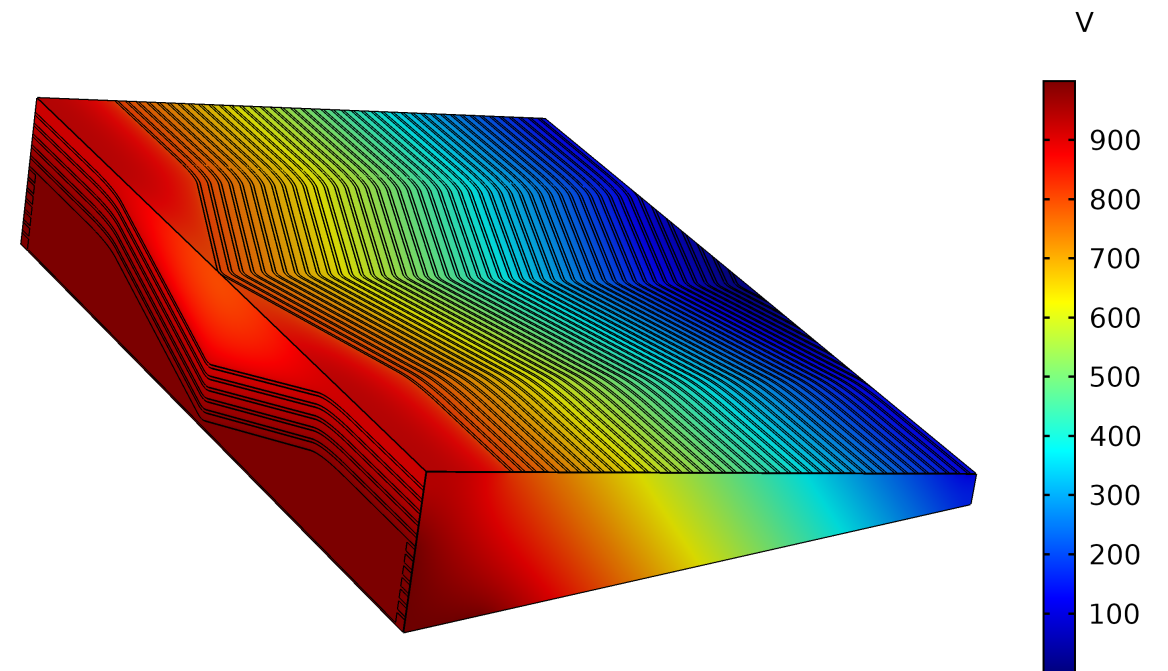
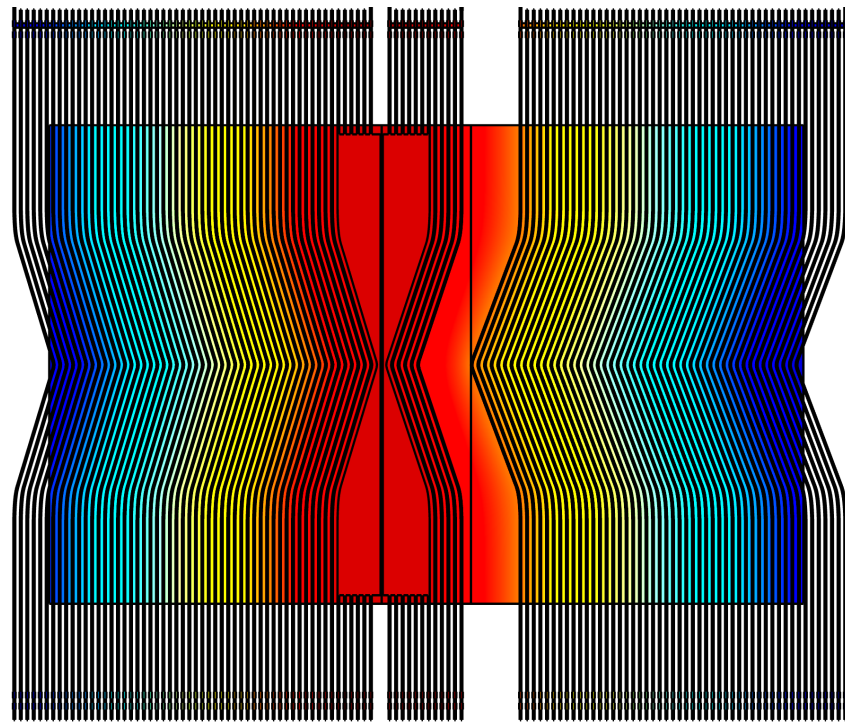
# Mixed transverse & longitudinal compression

- ▶ New scheme with simpler setup
- ▶ Single stage at cryogenic temperature



# Realised target

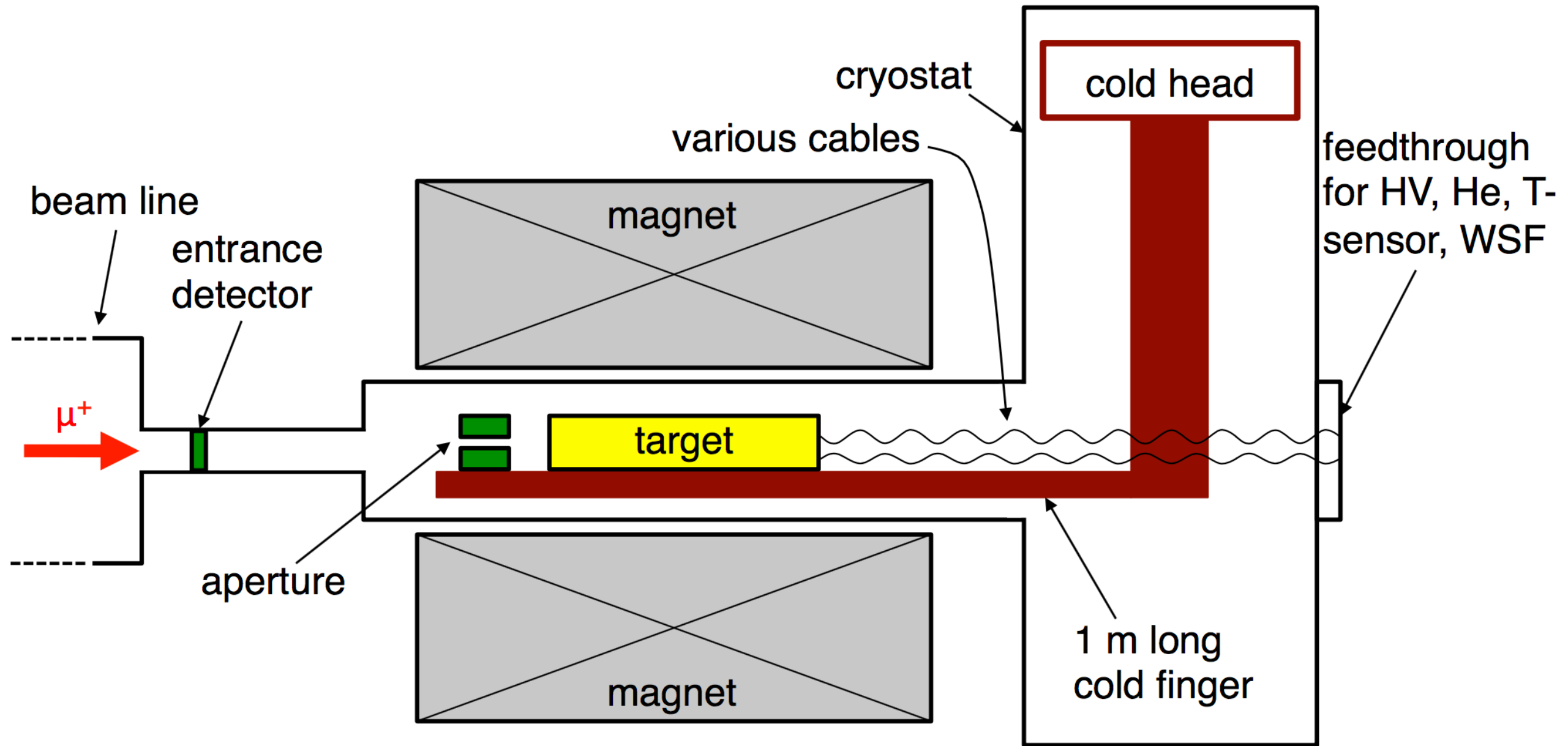
- Kapton foil with equipotential lines



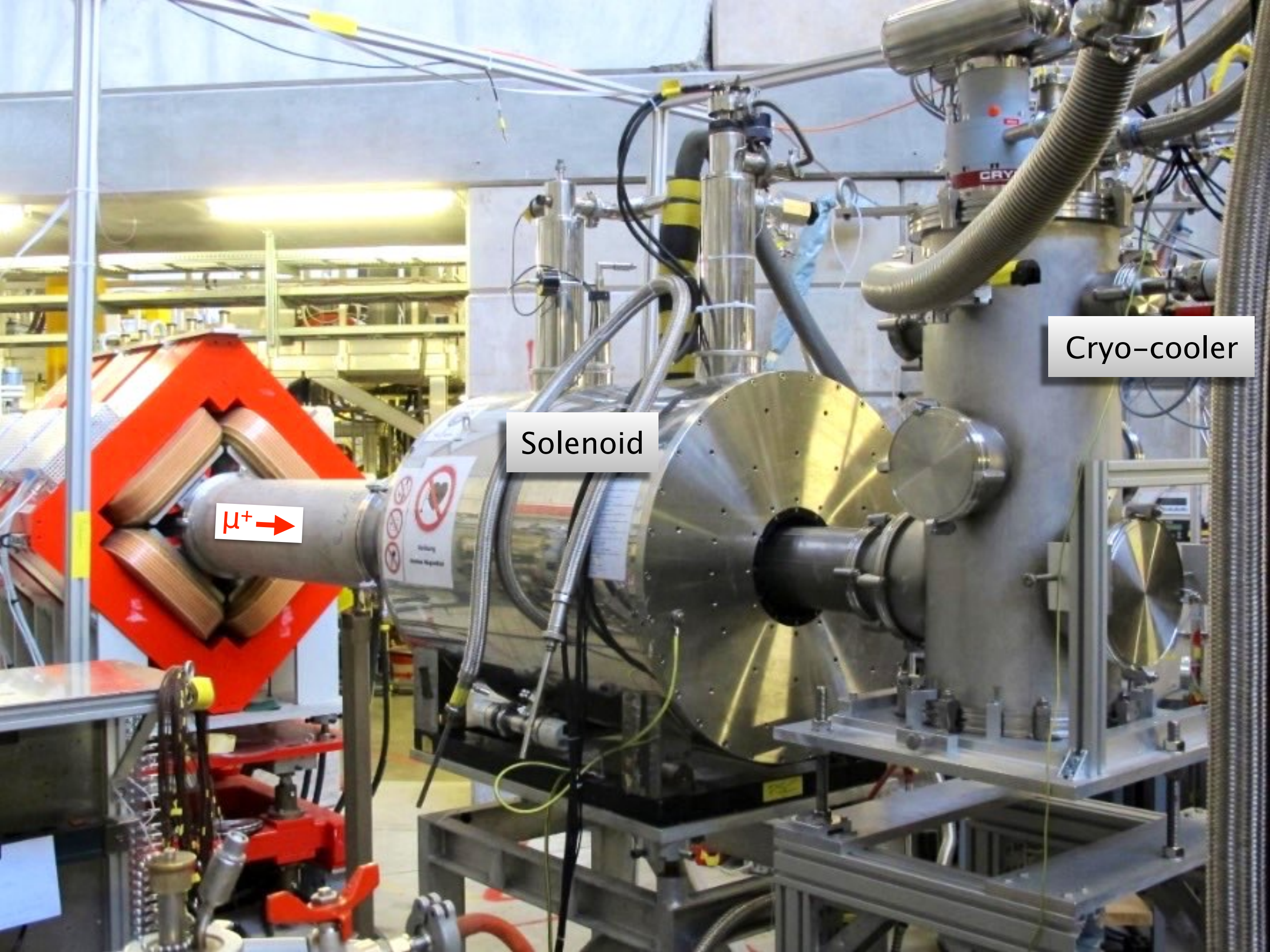


# Beam test setup

- First demonstration of mixed compression at the end of 2017







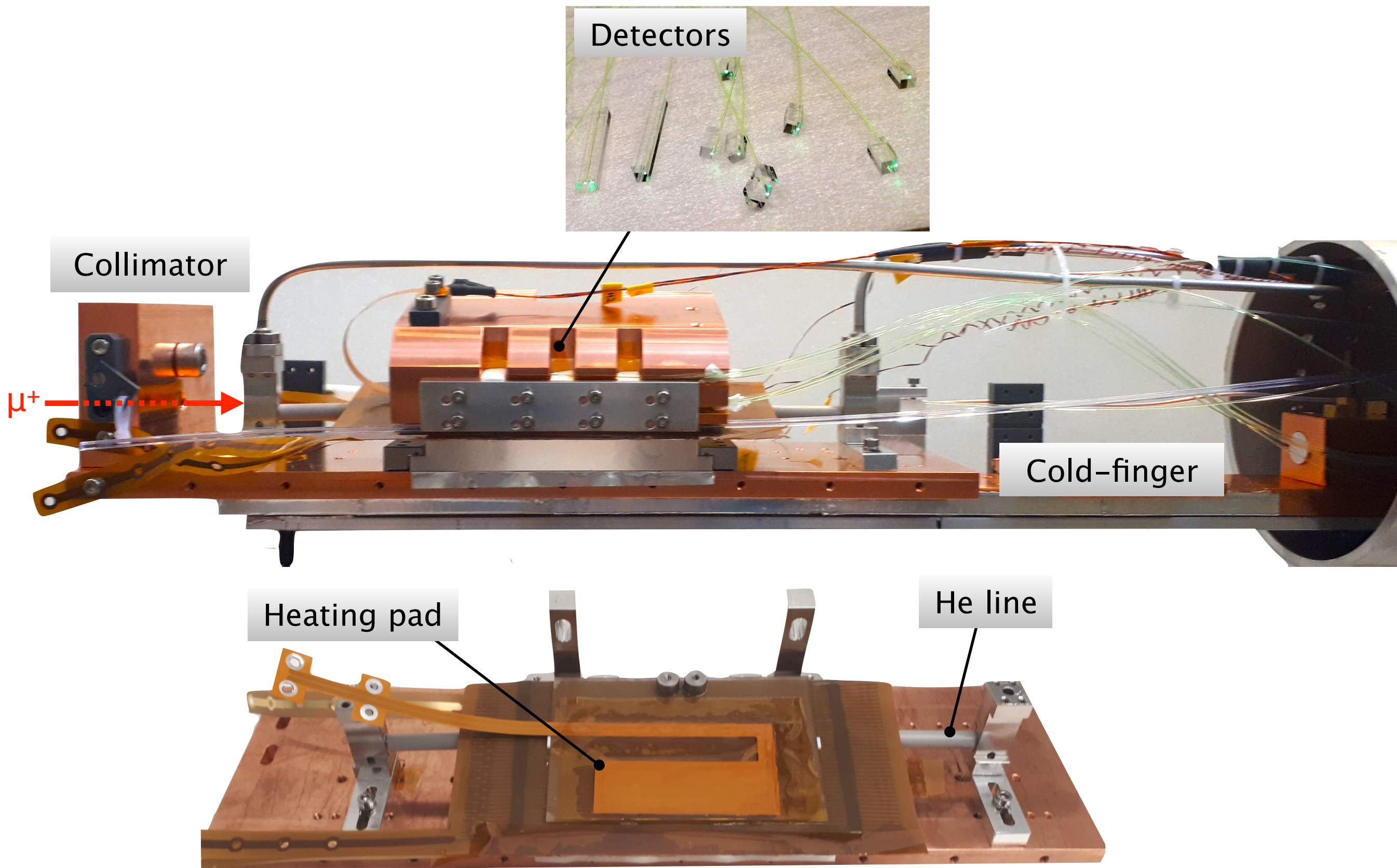
Cryo-cooler

Solenoid

$\mu^+$  →

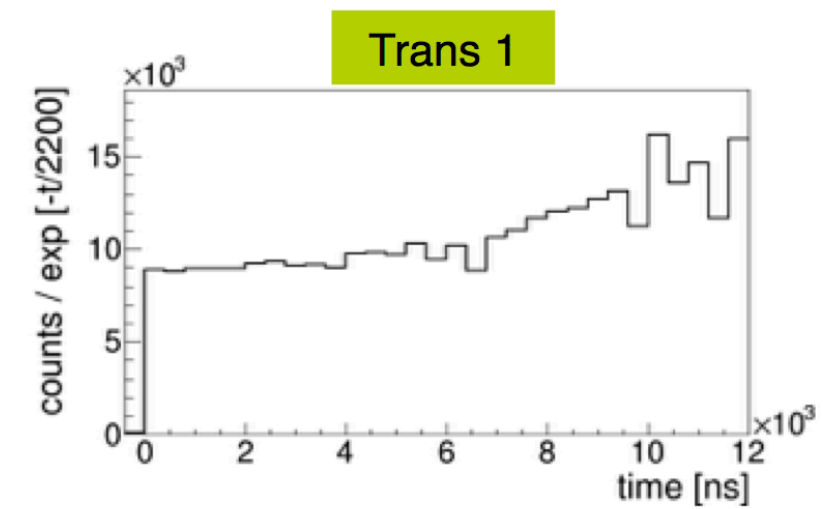
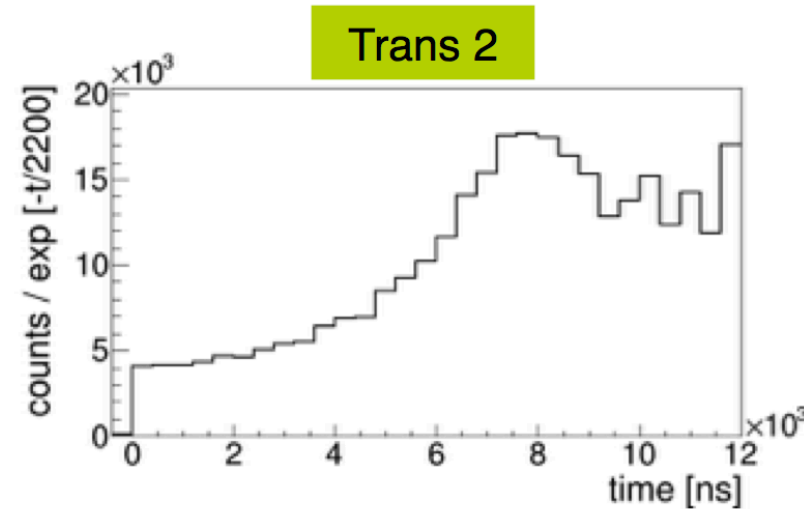
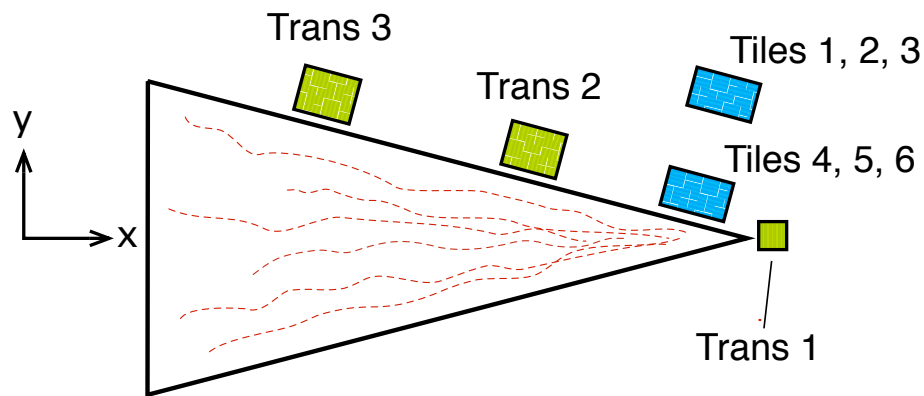


# Target installation

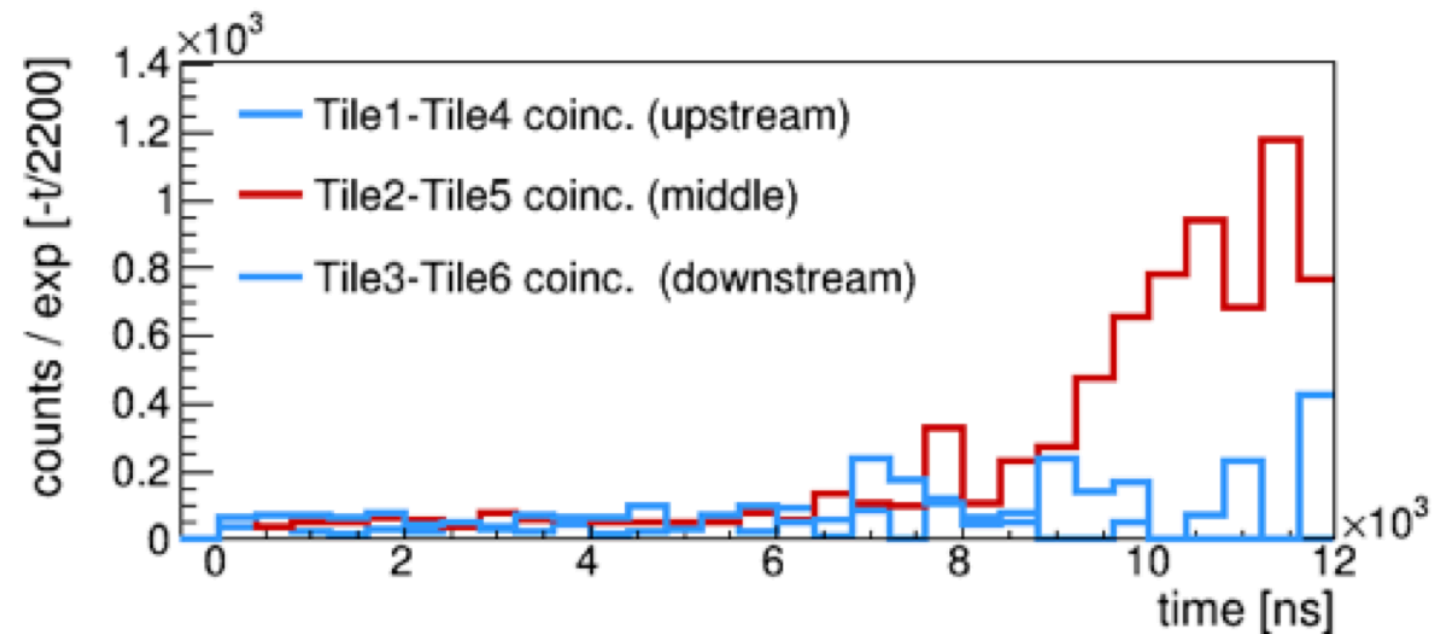
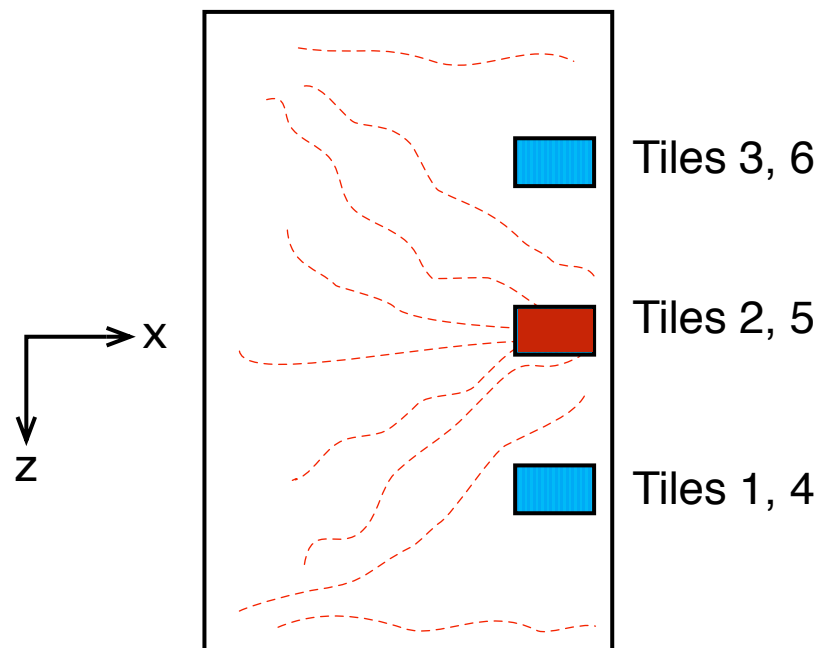


# Measurement of mixed compression

## Transverse direction



## Longitudinal direction



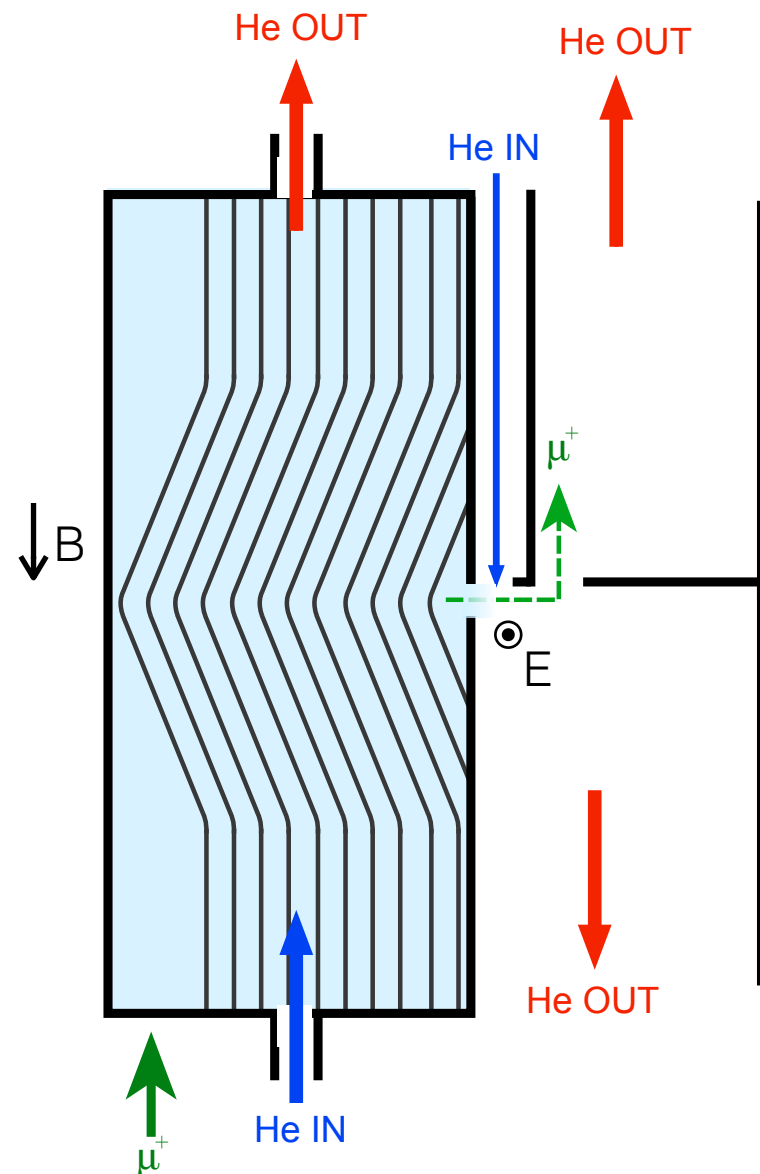
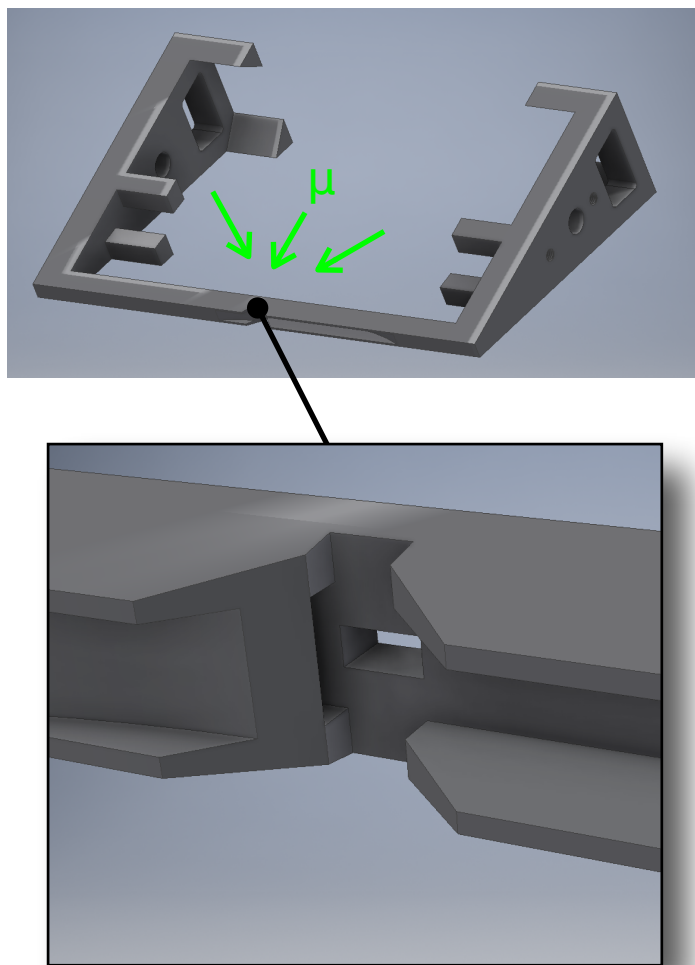


# muCool: Next steps

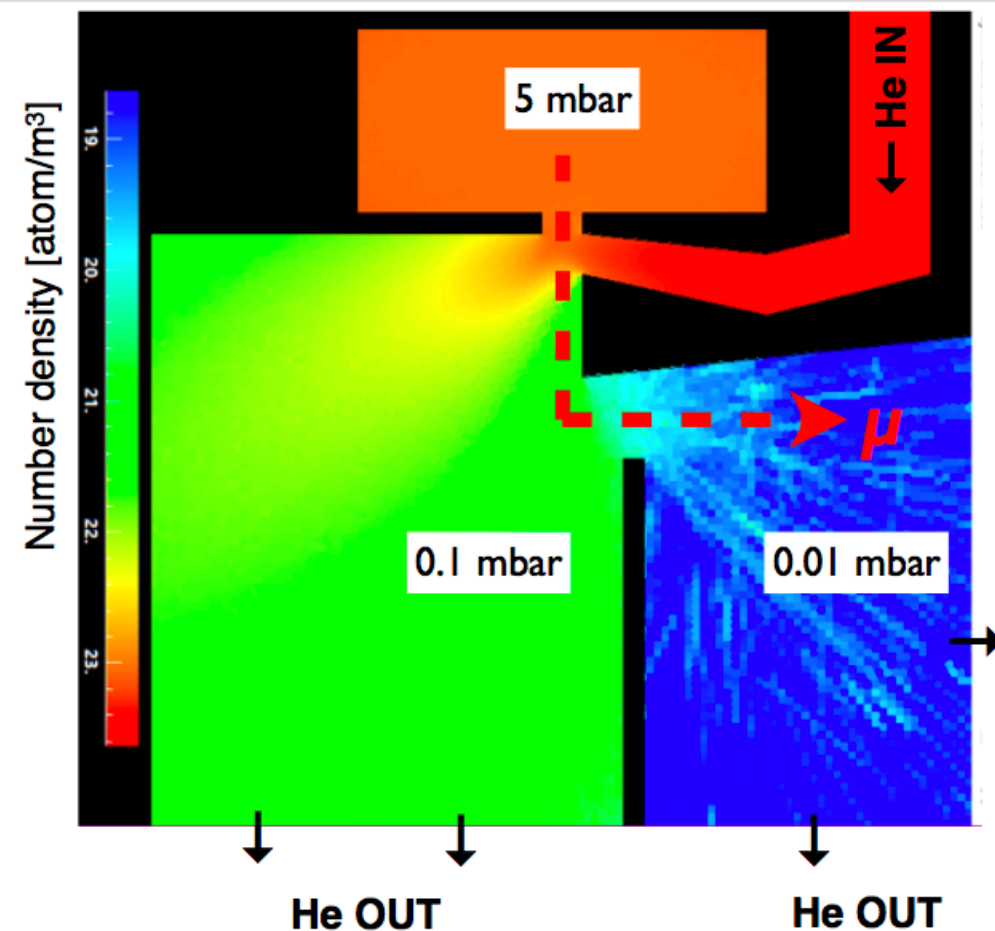
Increase E-field strength

Extract muons into vacuum

- ▶ Through 1×1 mm<sup>2</sup> orifice
- ▶ He gas injection and efficient pumping to maintain target pressure



Pressure distribution in extraction region



# Conclusions

muCool project developing a high-brightness ultra-cold positive muon beam

- ▶ Transverse and longitudinal compressions separately demonstrated. Excellent agreement between data and simulation.
- ▶ Mixed compression scheme partially demonstrated
- ▶ Next: Improve mixed compression & develop muon extraction



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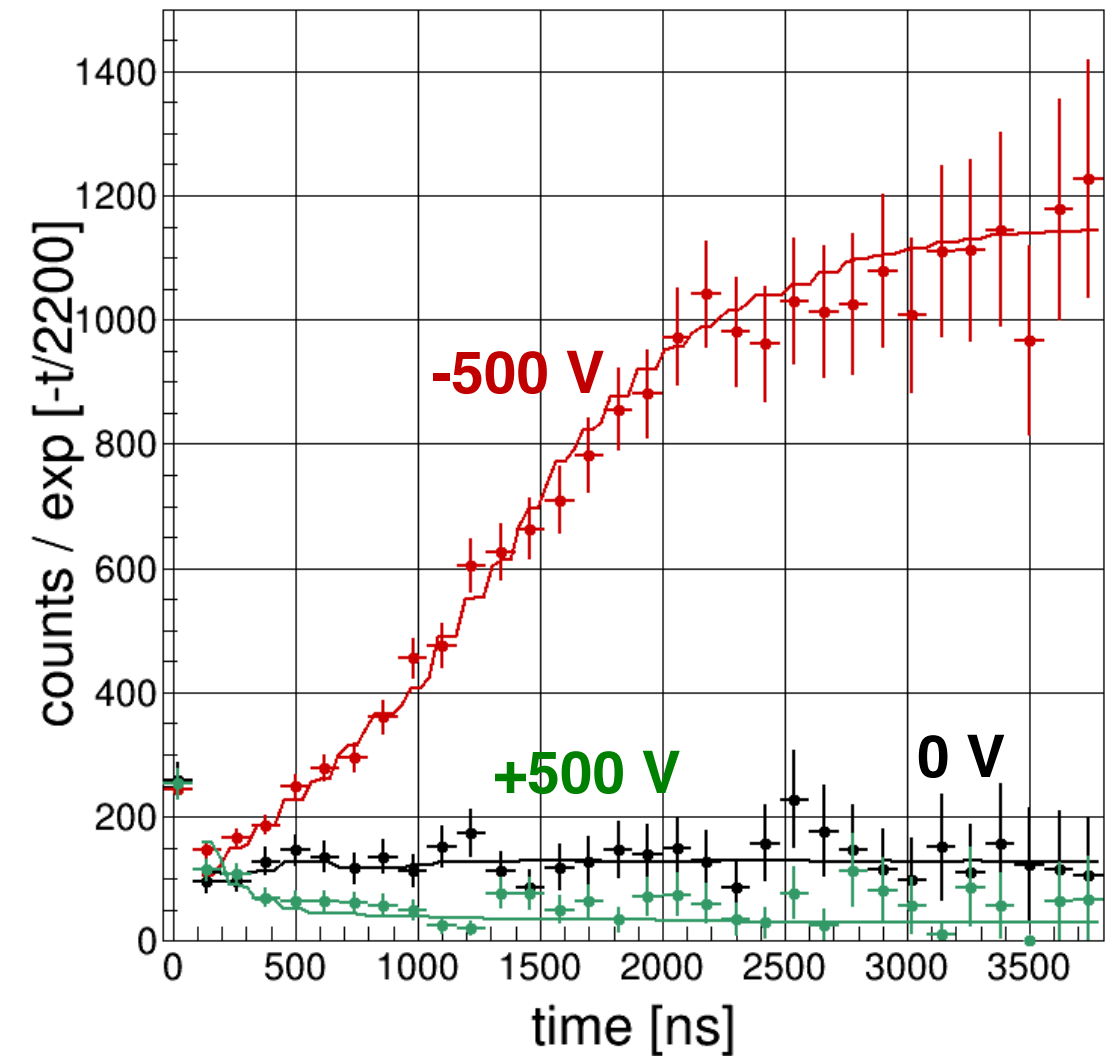
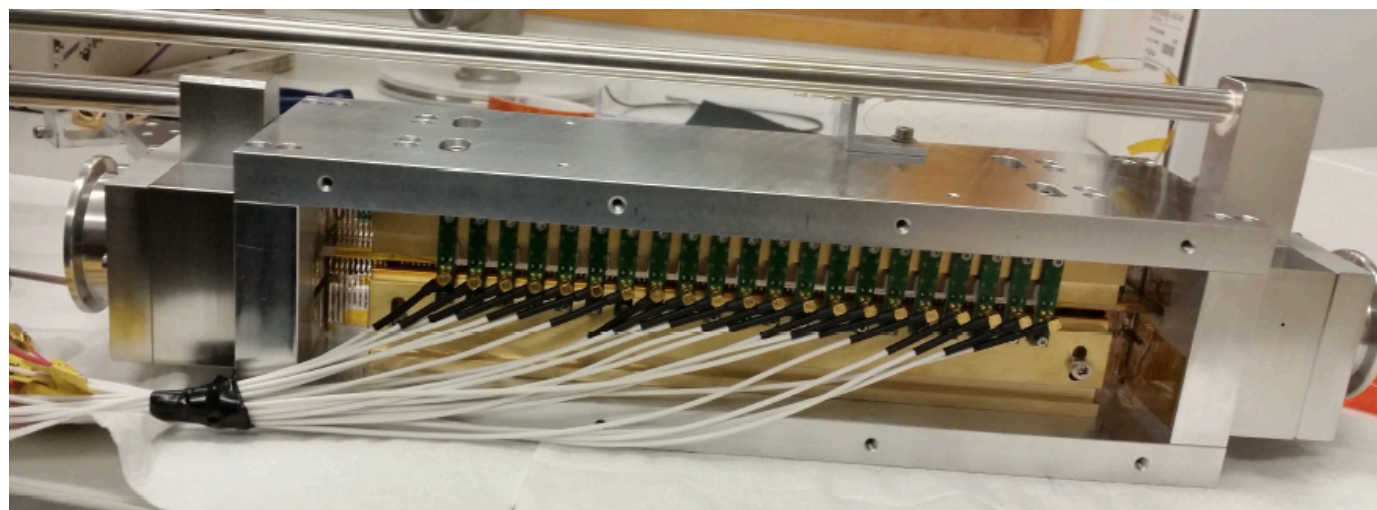
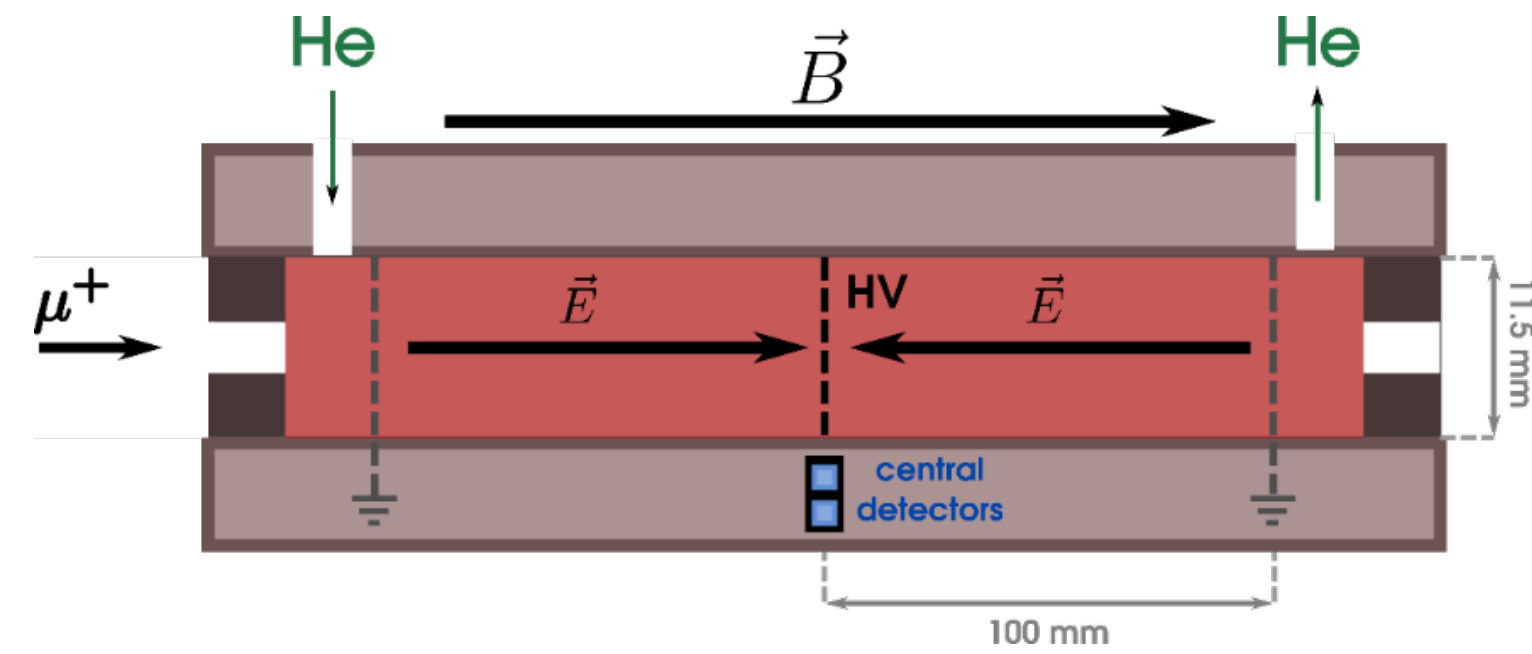
An aerial photograph of a river valley. A wide river flows from the top center towards the bottom right. A bridge crosses the river in the lower right quadrant. On the left bank, there is a cluster of buildings, including a large industrial-style building with a corrugated metal roof. The surrounding landscape is a mix of green fields, forests, and rolling hills in the background. The text "Back up" is overlaid in the center of the image.

**Back up**



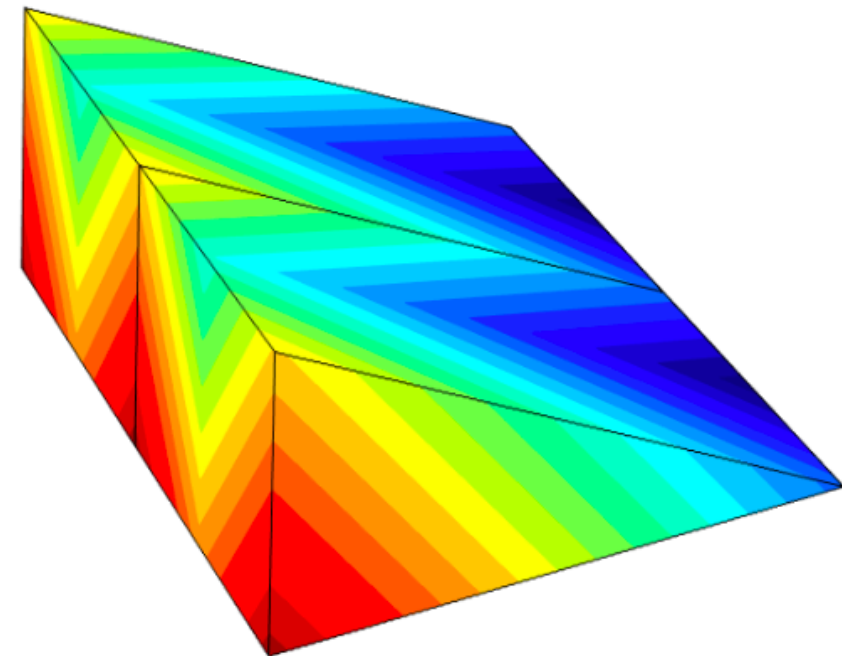
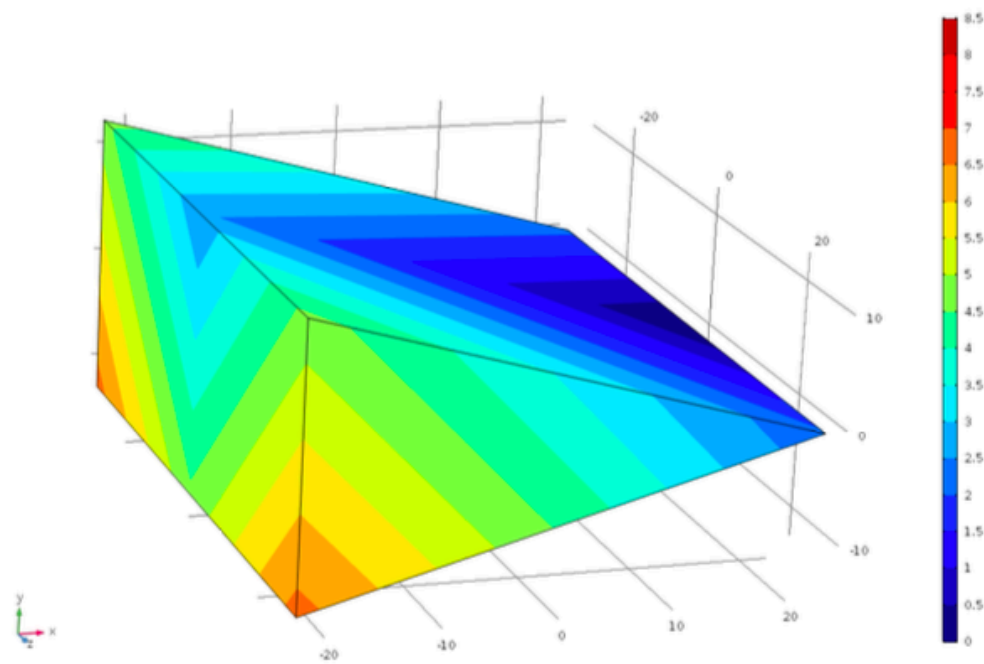
# Demonstration of longitudinal comp.

- ▶ Demonstrated in 2011/2014 I. Belosevic et al., Eur. Phys. J. C (2019) **79**: 430
- ▶ Excellent agreement between measurement and simulation



# Target for surface muons

- ▶ ~100 cm long needed





# Improve maximum E-field

- ▶ Limited by discharging He gas
- ▶ Overlay on electrodes, reducing “hot spot”, materials with lower  $\epsilon_r$

