muCool:
Towards a novel low-energy, high-brightness μ^+ beam lines

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on behalf of the muCool collaboration

PAUL SCHERRER INSTITUT

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ICISE Quy Nhon, Vietnam

Overview

- muCool principle
- Experimental tests of the longitudinal and transverse compression
- Outlook

Impact

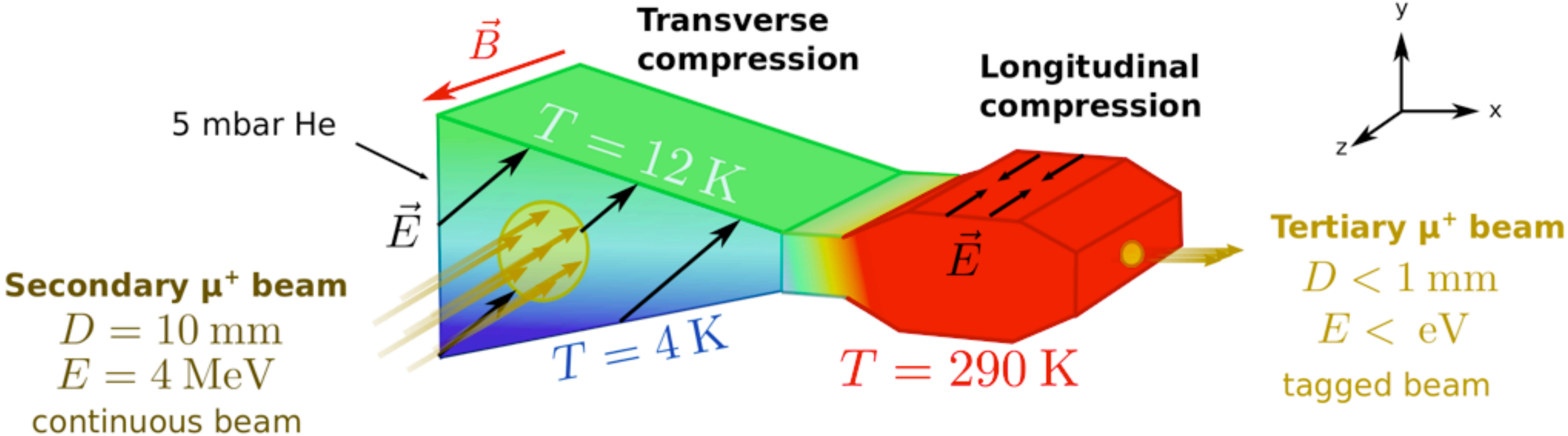
- Particle physics experiments
  - Improved injection into magnetic systems and much improved beam quality for muon g-2, muon EDM
  - Efficient formation of muonium for muonium spectroscopy, muonium gravity tests
- μSR applications

muCool goals

- Compress phase space by 10 orders of magnitude
- Energy of $\mu^+ < 1$ eV
- Beam size < 1 mm^2
- Efficiency ~ 10^{-3}
- Tagged beam
- Conserves initial polarisation
- Add-on to existing conventional surface μ^+ beam lines

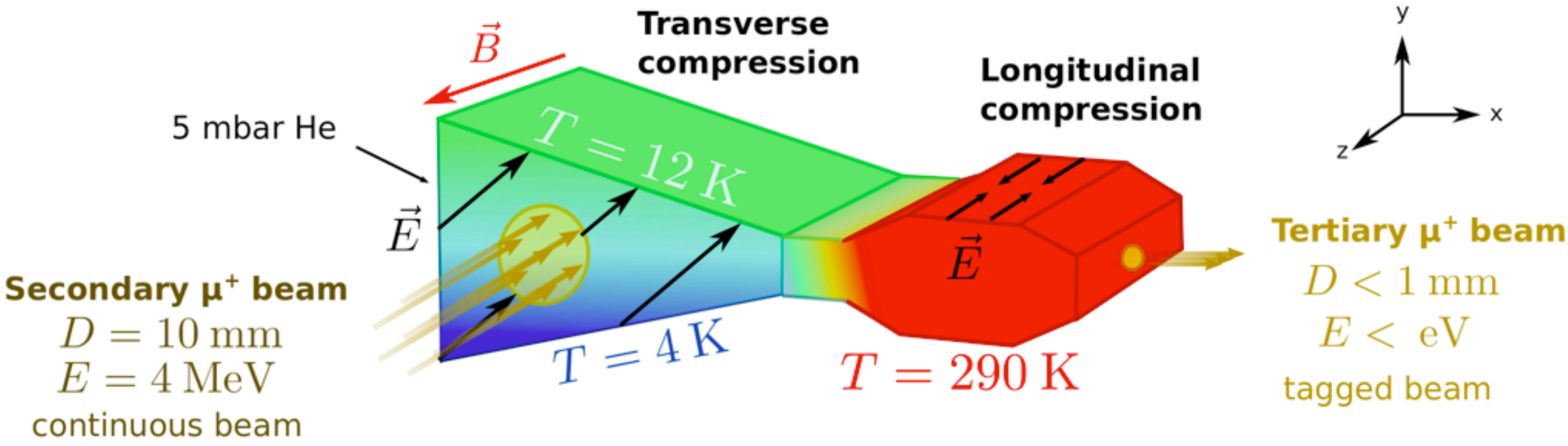
D. Taqqu, PRL **97**, 194801 (2006)

muCool principle



- Stages approach
  - transverse compression
  - longitudinal compression
  - extraction in vacuum
- Phase space reduction based on
  - dissipative energy loss in matter (He gas)
  - position dependent drift of muon swarm
- Increase in brillance (after reaccelerating to ~ 10 keV) by factor **10^7** : $B = [\varepsilon/(\varepsilon_L\ \varepsilon_T)]$
  - longitudinal emittance ε_L ($\Delta E\ \Delta t$) reduced by factor **10^4**
  - transverse emittance ε_T ($\Delta r\ \Delta\phi$) reduced by factor **10^6**
  - efficiency ε ~ **10^{-3}**

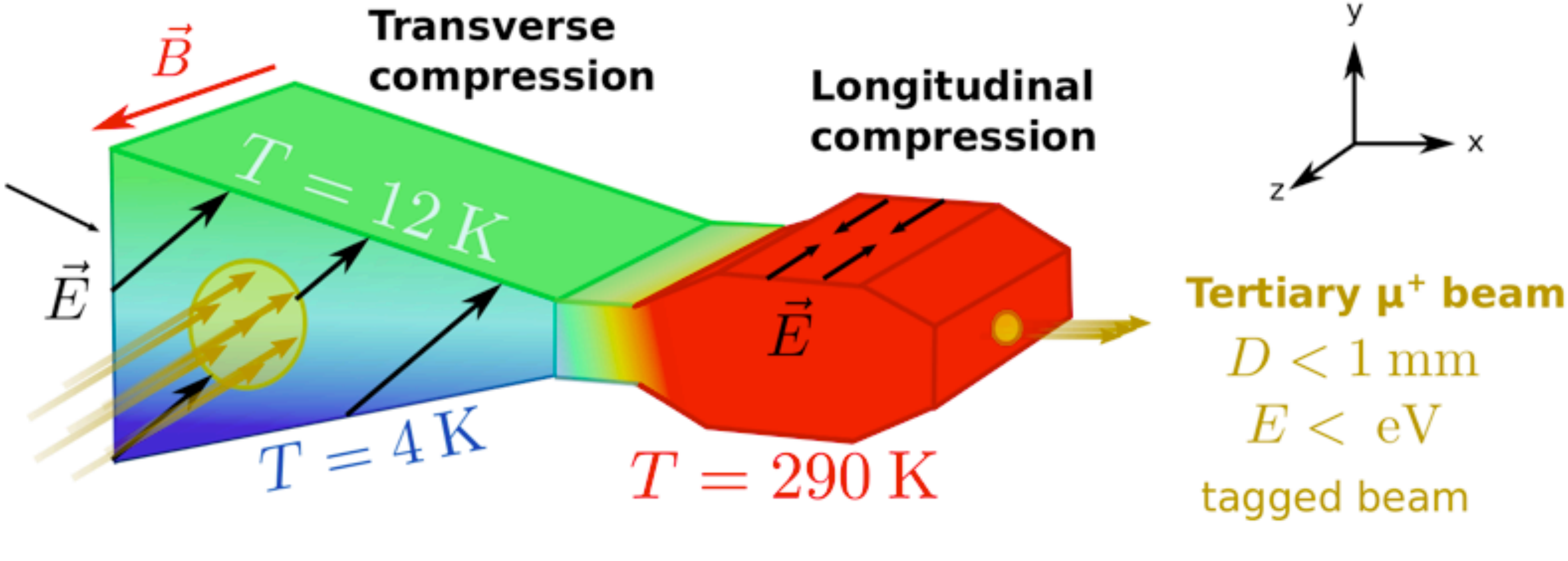
muCool principle



ω = eB/m: cyclotron frequency
μ = muon mobility
ν_{col} = collision frequency

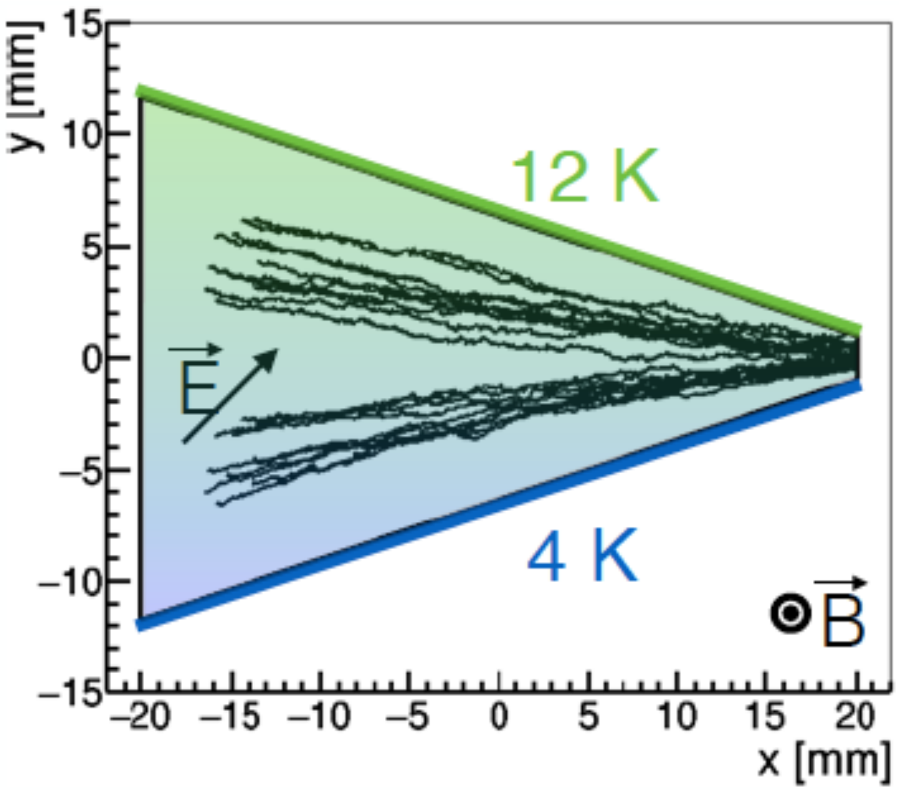
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

muCool: Transverse compression

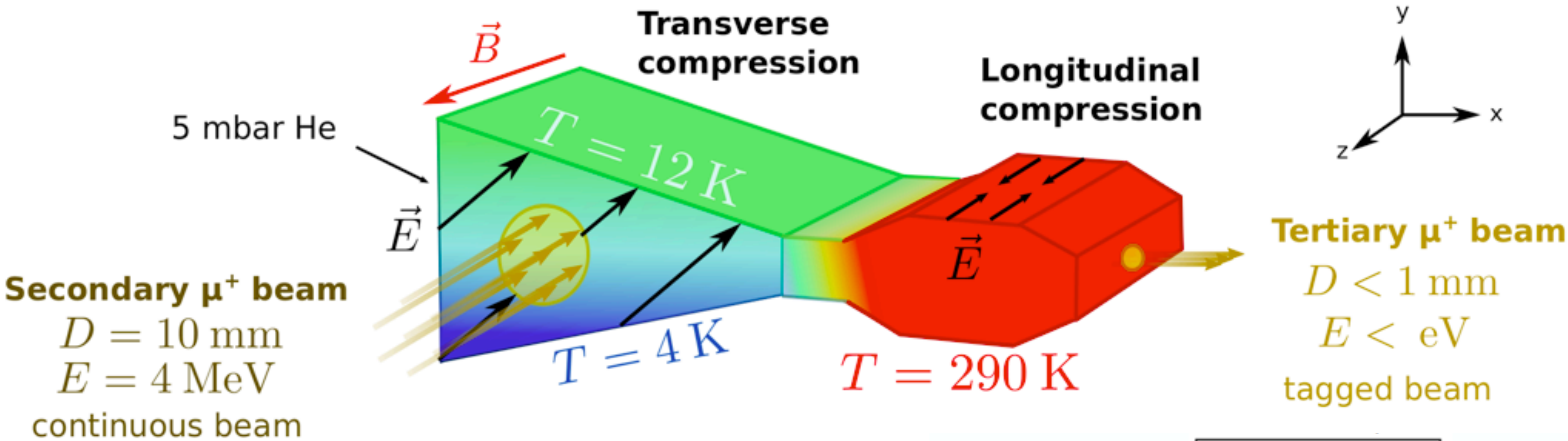


- 5 mbar He gas
- Cryogenic temperature
- Crossed E- and B-fields (E~ 1.5 kV/cm, B ~ 5 T)
- high density -> ν_{col} large -> Ê dominates
- medium density -> ν_{col} intermediate -> Ê x B dominates

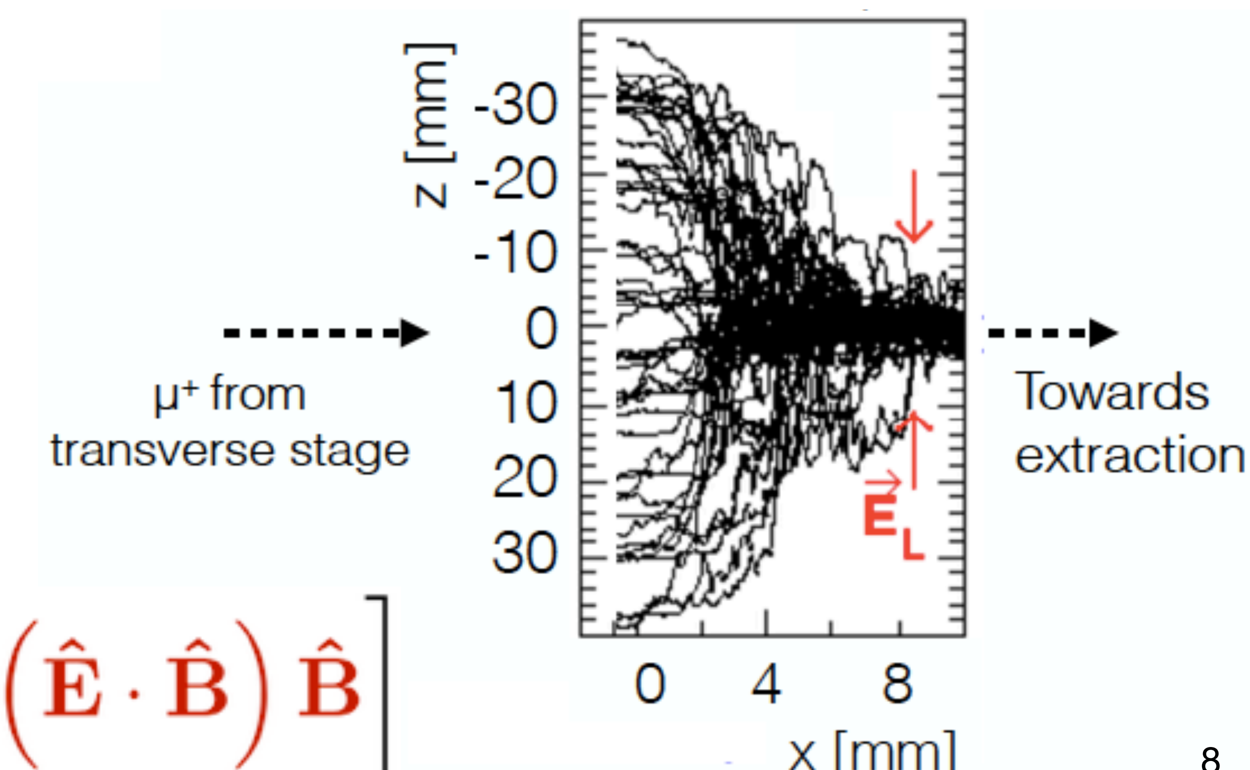
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}}\right]$$



muCool: Longitudinal compression



- 5 mbar He gas
- Room temperature
- Parallel E- and B-fields (E~ 60 V/cm, B ~ 5 T)
- low density -> v_{col} small -> B dominates



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Status: The Path to Muon Beam Compression

2011:

First test of longitudinal compression

Y. Bao et al., *PRL* **112**, 224801 *(2014)*

2013:

Demonstration of stationary He gas density gradient

G. Wichmann et al, NIM A **814**, 33-38 *(2016)*

2014:

Improved longitudinal setup

Engineering run for transverse compression

2015:

Longitudinal compression with subsequent $\vec{E}\mathrm{x}\vec{B}$-drift

Demonstration of transverse compression

Still to do:

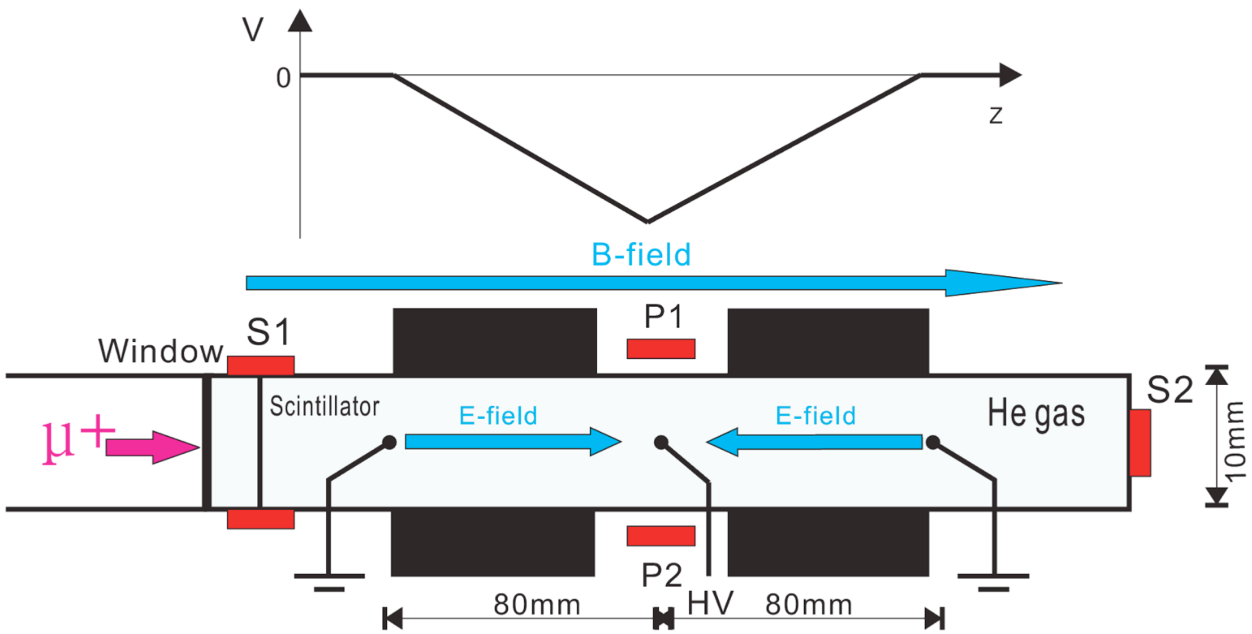
Combination of transverse and longitudinal compression

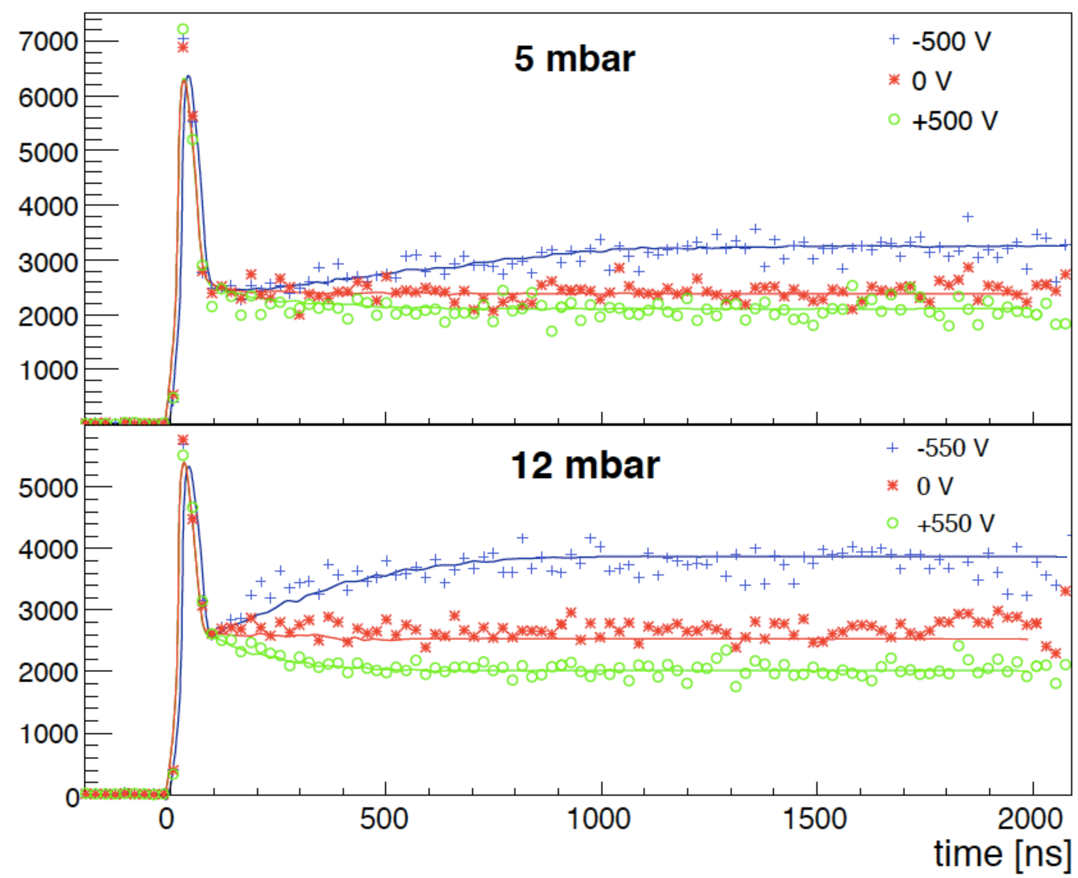
Extraction into vacuum

Extraction from B-field & re-acceleration

Result

Longitudinal compression: First test





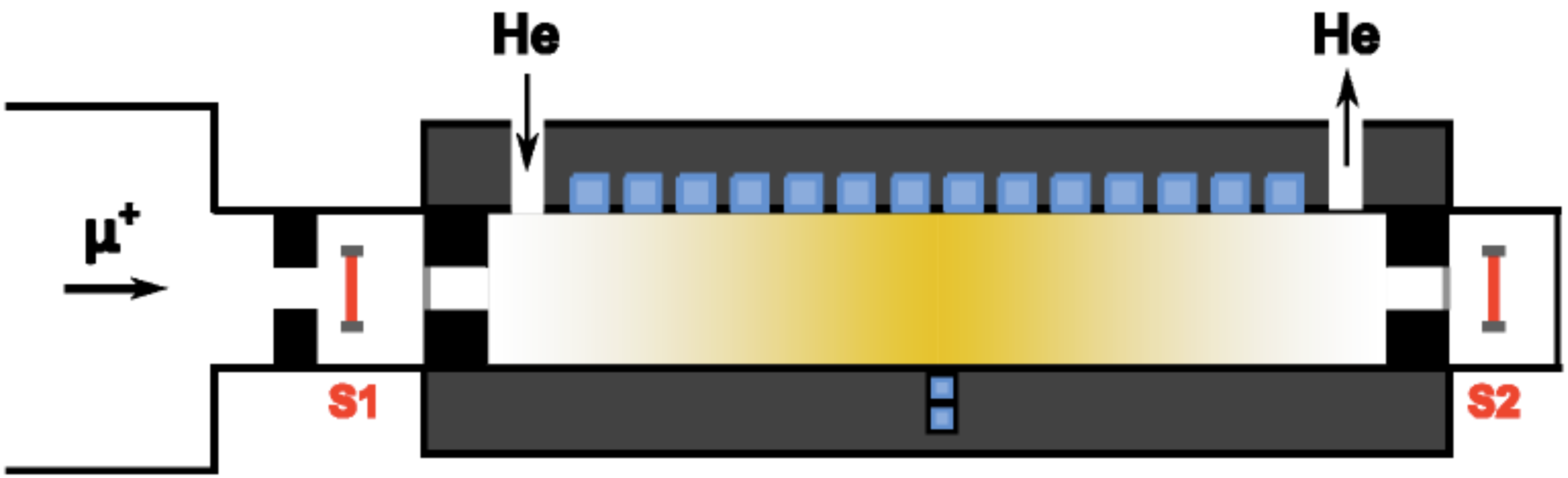
- First test of longitudinal compression in 2011
- PSI πE1 beamline; μ^+ at 10 MeV/c

- **First proof of longitudinal compression**
  - **observe compression behavior by temporal evolution of counts in the central detectors**
  - only a small fraction of muons stopped in the gas

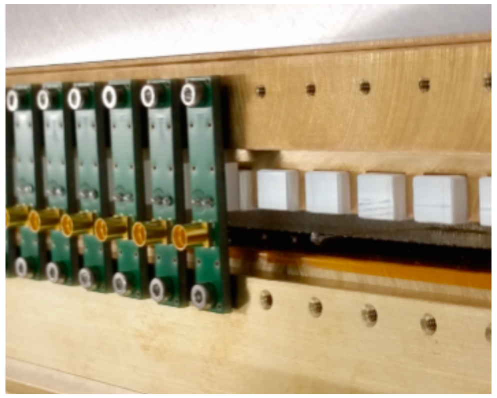
- Monte Carlo simulation includes:
  - chemical absorption
  - small misalignment

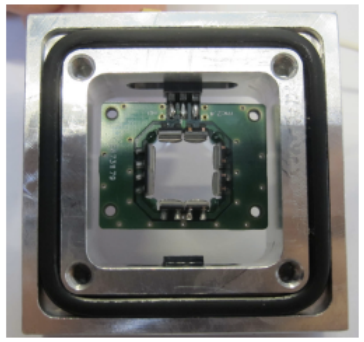
Longitudinal compression: Improved setup

- Upgraded setup of longitudinal compression in 2014
- Improved cleanliness of target: no chemical absorption
- Better shielding of detectors, larger volume: less background
- More scintillators (26): observe temporal evolution of compression
- Scintillators in telescope configuration: high spatial sensitivity at center



Longitudinal compression: Improved setup





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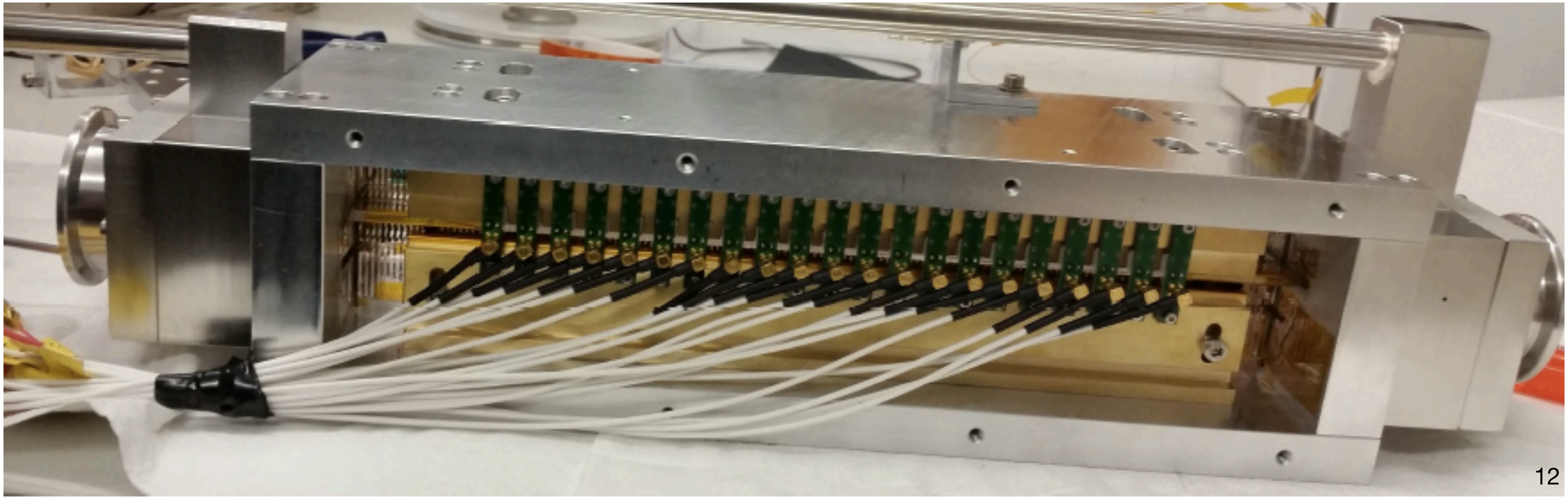
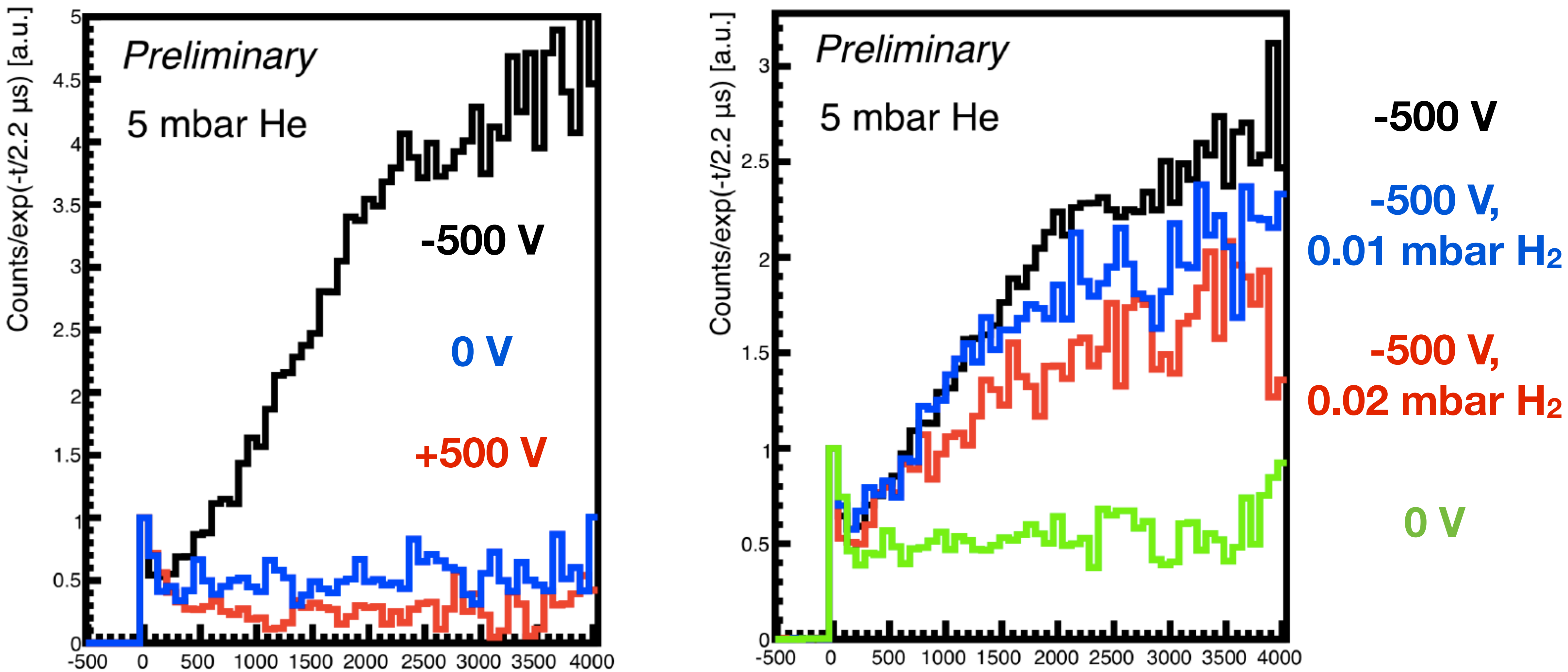


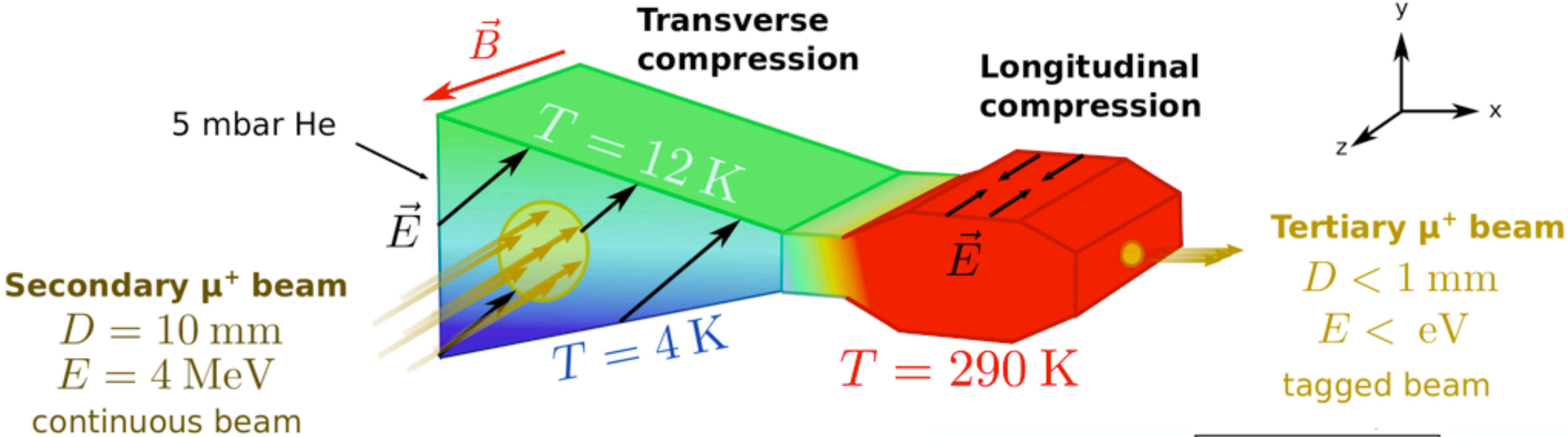
Result

Longitudinal compression: Improved setup

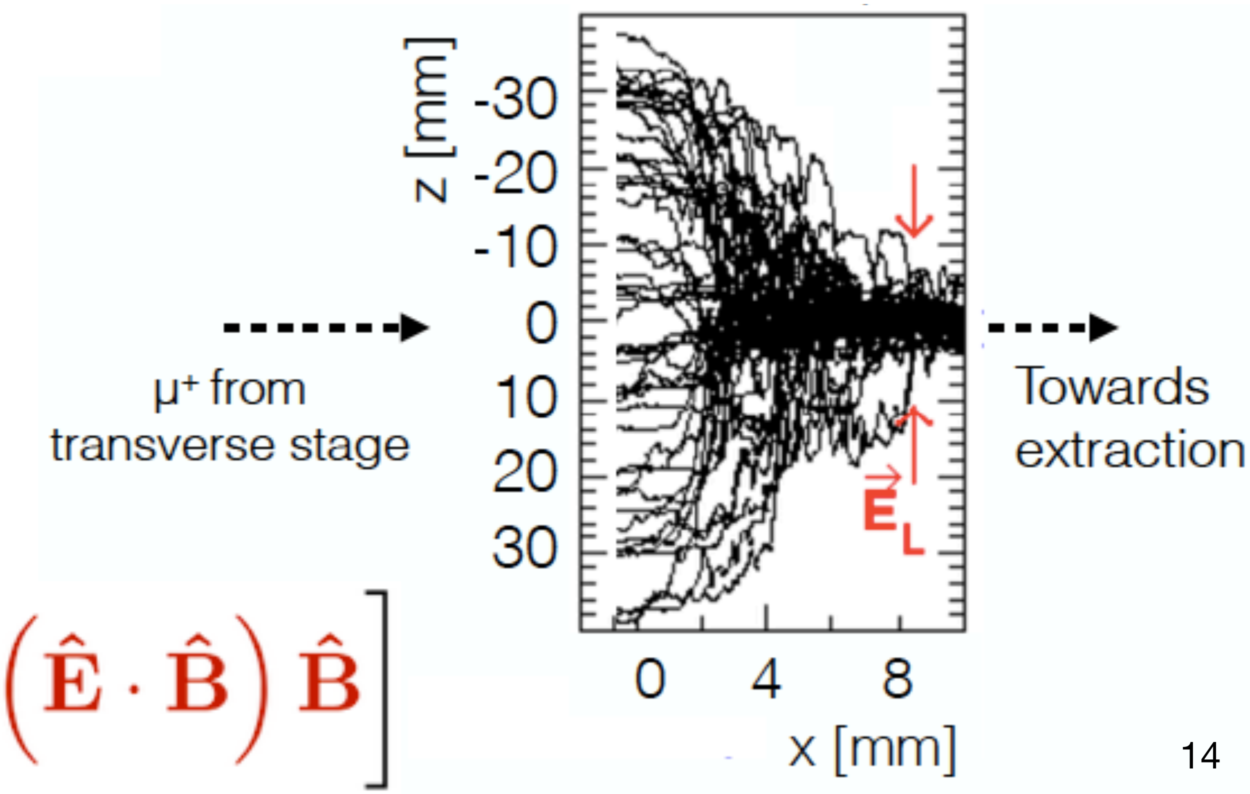


- 2014 results
  - better muon stopping efficiency and much improved compression
  - confirmed effect of chemical absorption due to impurities

muCool: Longitudinal compression

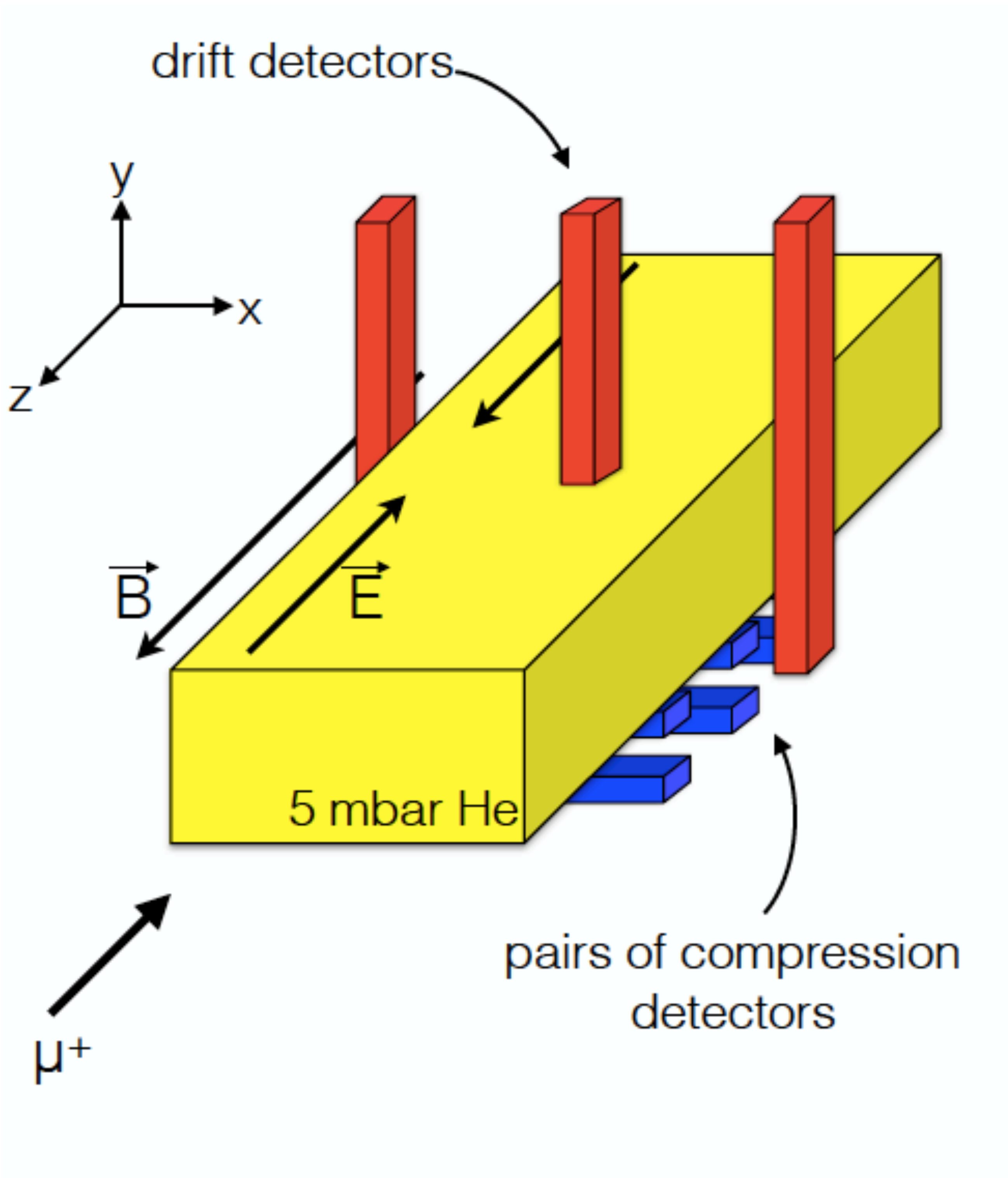


- 5 mbar He gas
- Room temperature
- Parallel E- and B-fields (E~ 60 V/cm, B ~ 5 T)
- low density -> v_{col} small -> B dominates



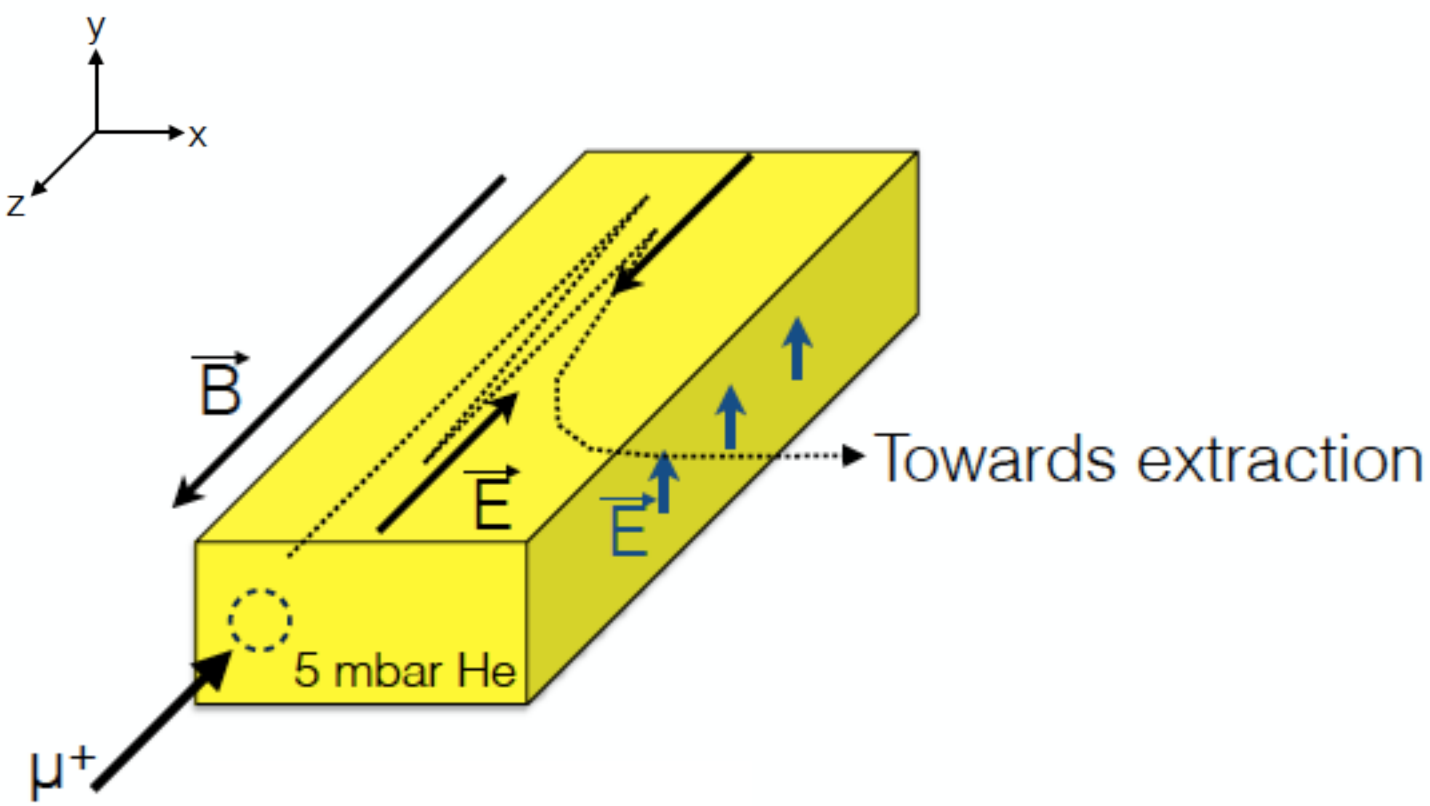
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \left(\frac{\omega}{\nu_{col}}\right)^2 \left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

Longitudinal compression: With ExB drift



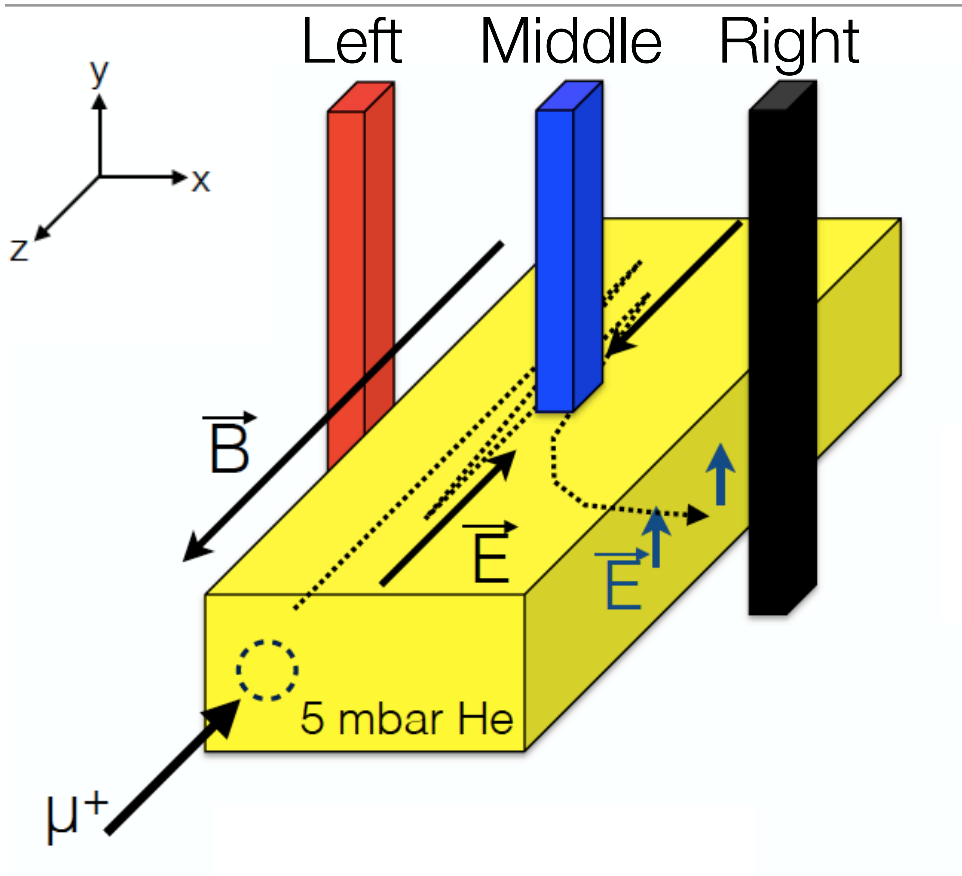
- Longitudinal compression with ExB drift in 2015
- He volume: 25 x 12 x 300 mm^3
- Kapton foil with electrodes
- Scintillators in telescope configuration
- ExB-drift detectors

Longitudinal compression: With ExB drift



- Add vertical (y) component to E-field
- Off-center injection of μ^+
- μ^+ drift in ExB-direction

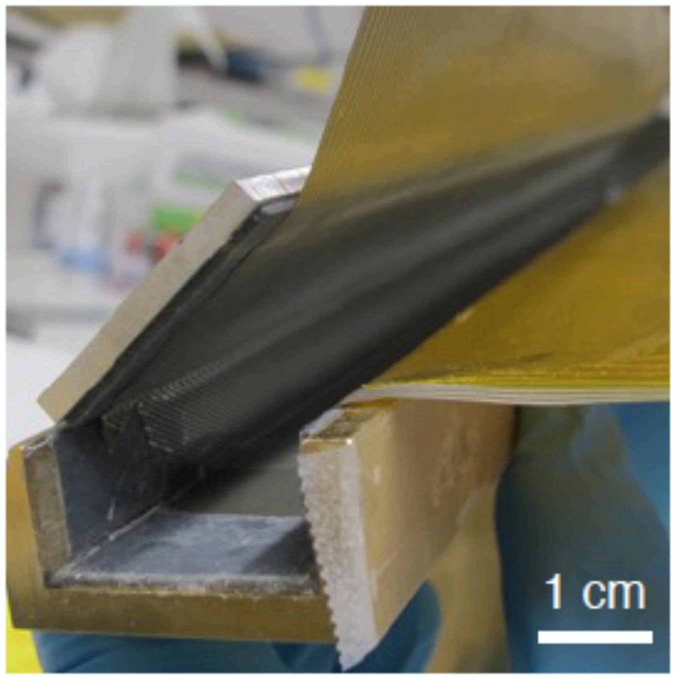
Longitudinal compression: With ExB drift



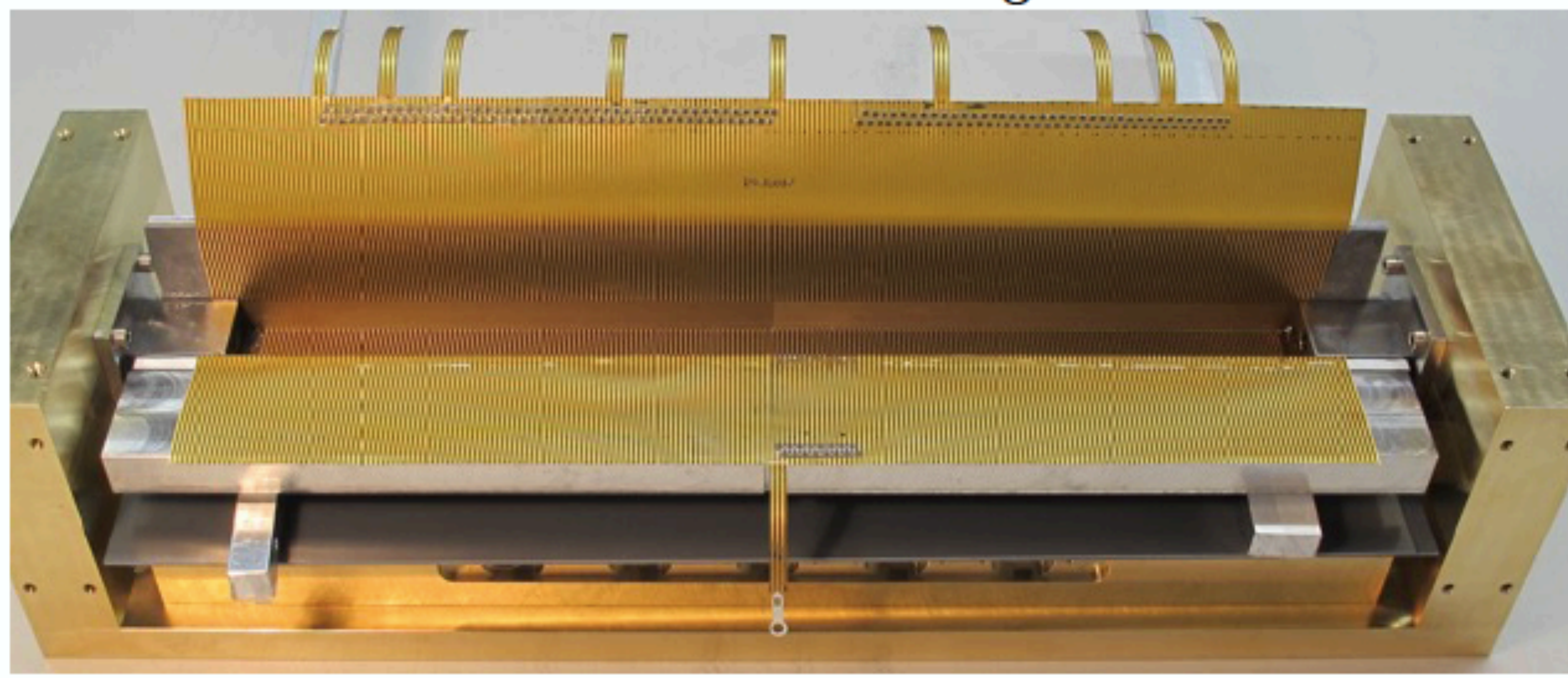
- Add vertical (y) component to E-field
- Off-center injection of μ^+
- μ^+ drift in ExB-direction
- **μ^+ drift signal**

Longitudinal compression: With ExB drift

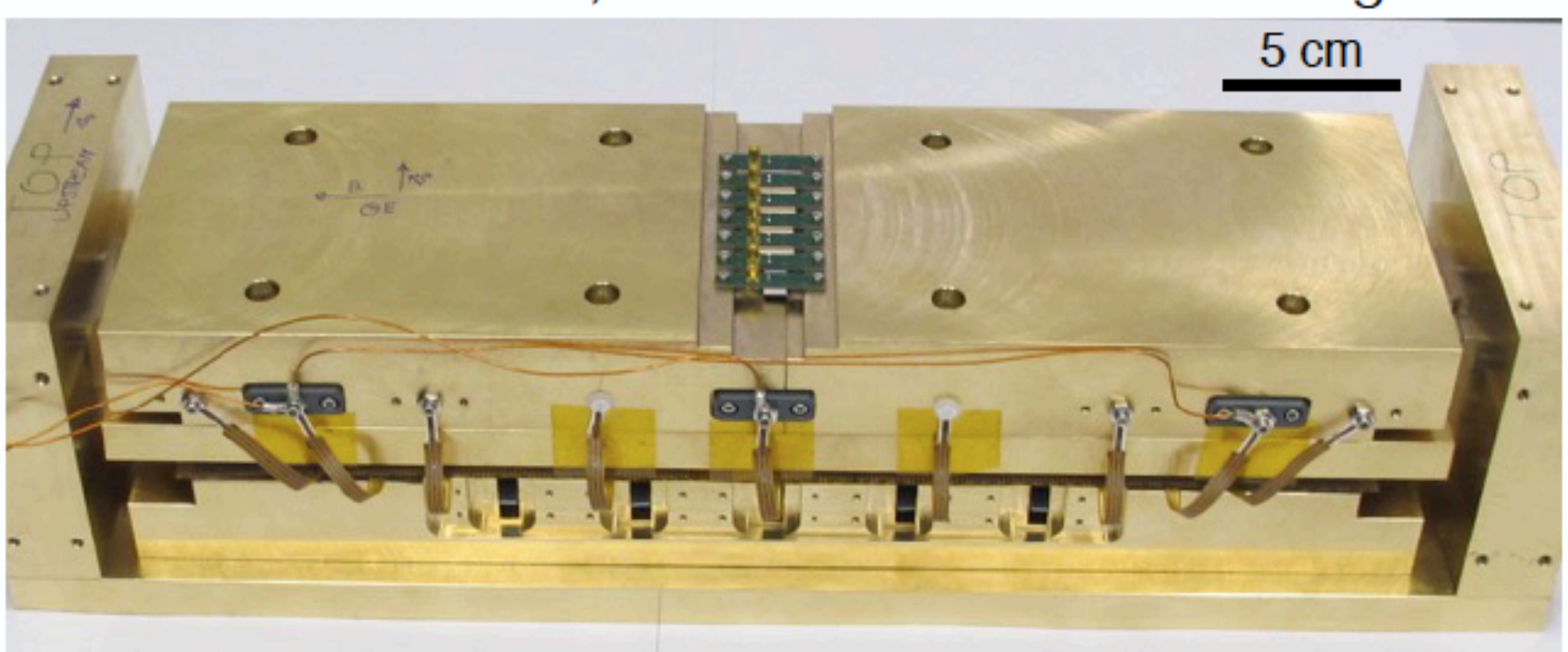
He volume



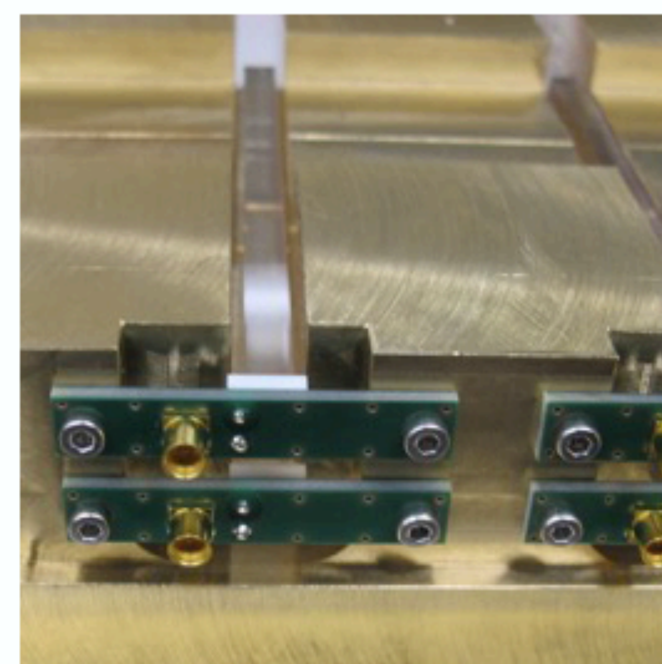
Almost finished target



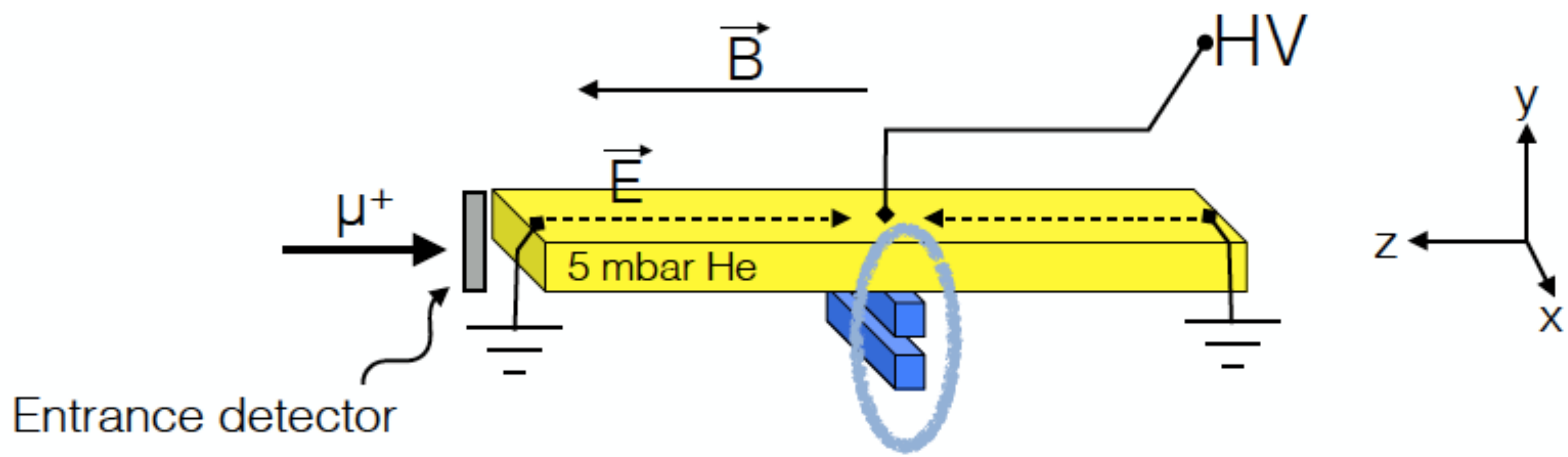
HV connections, detectors and brass shielding

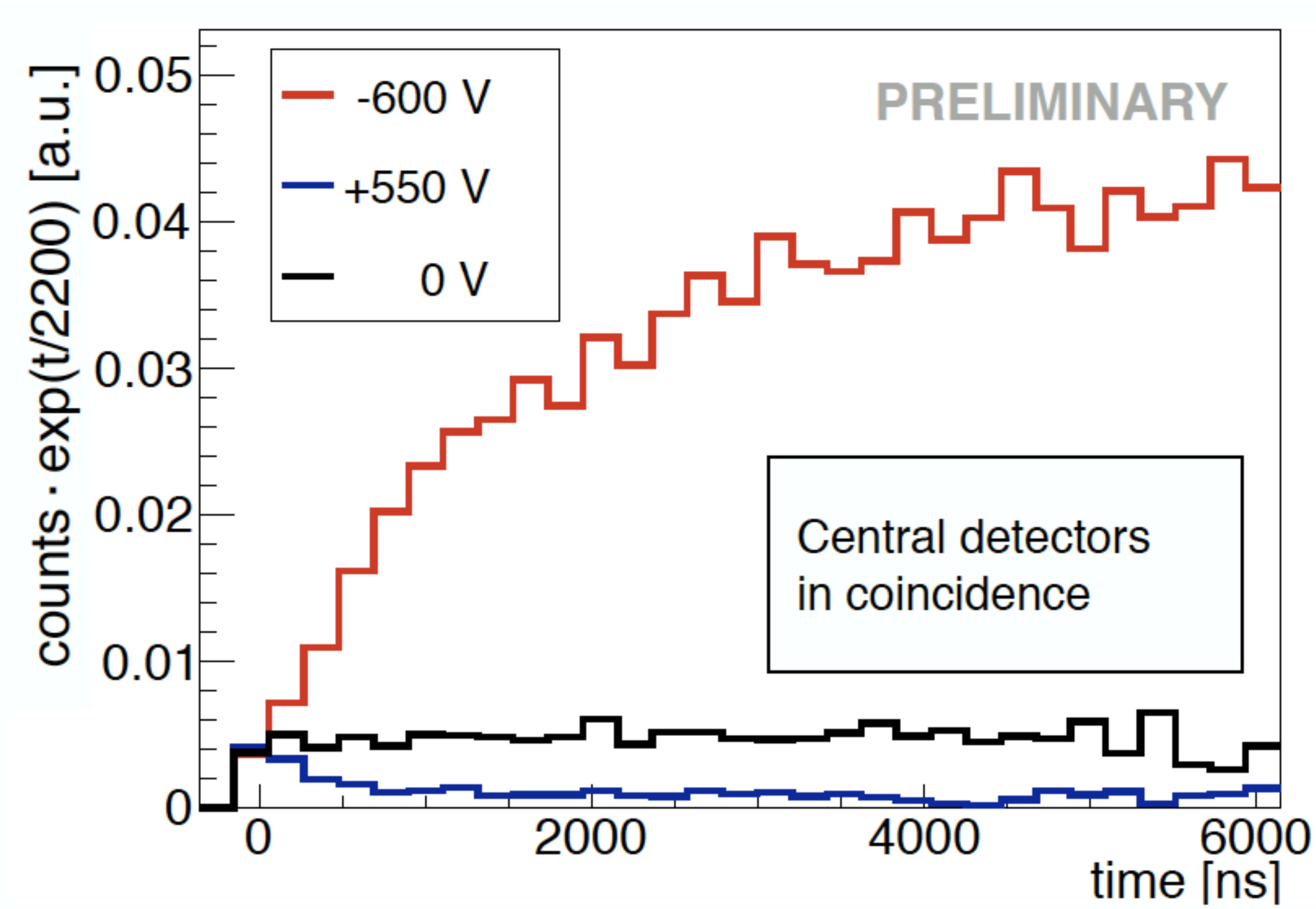


Scintillators



Longitudinal compression: With ExB drift

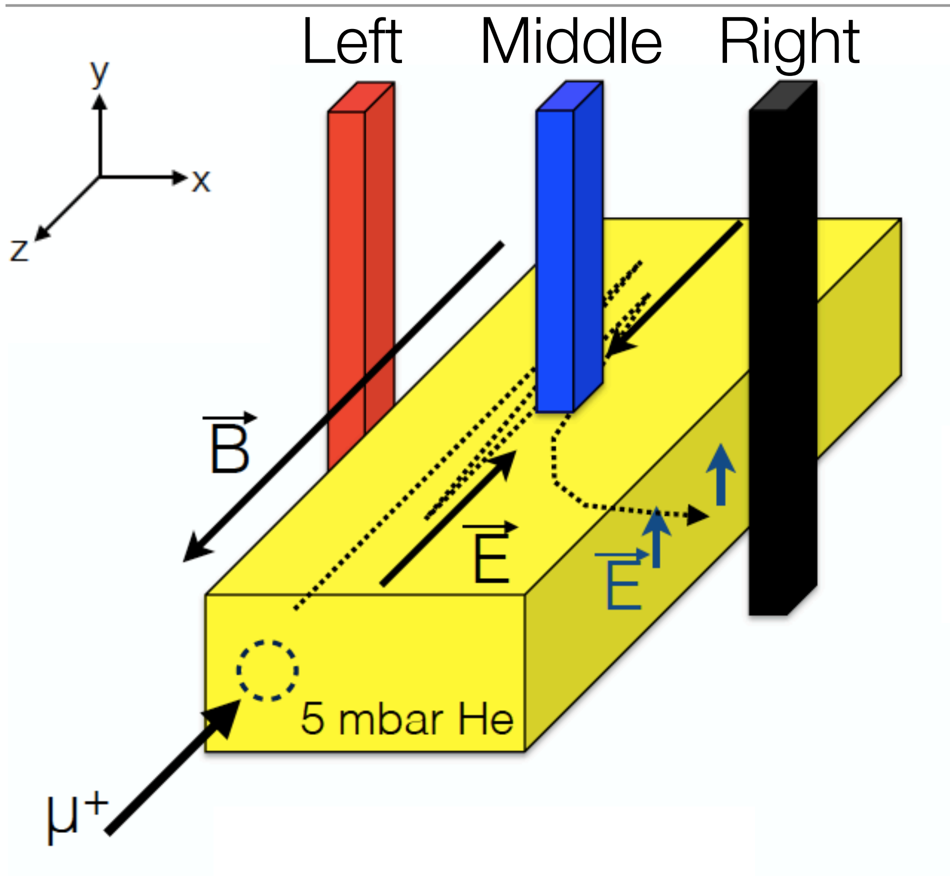


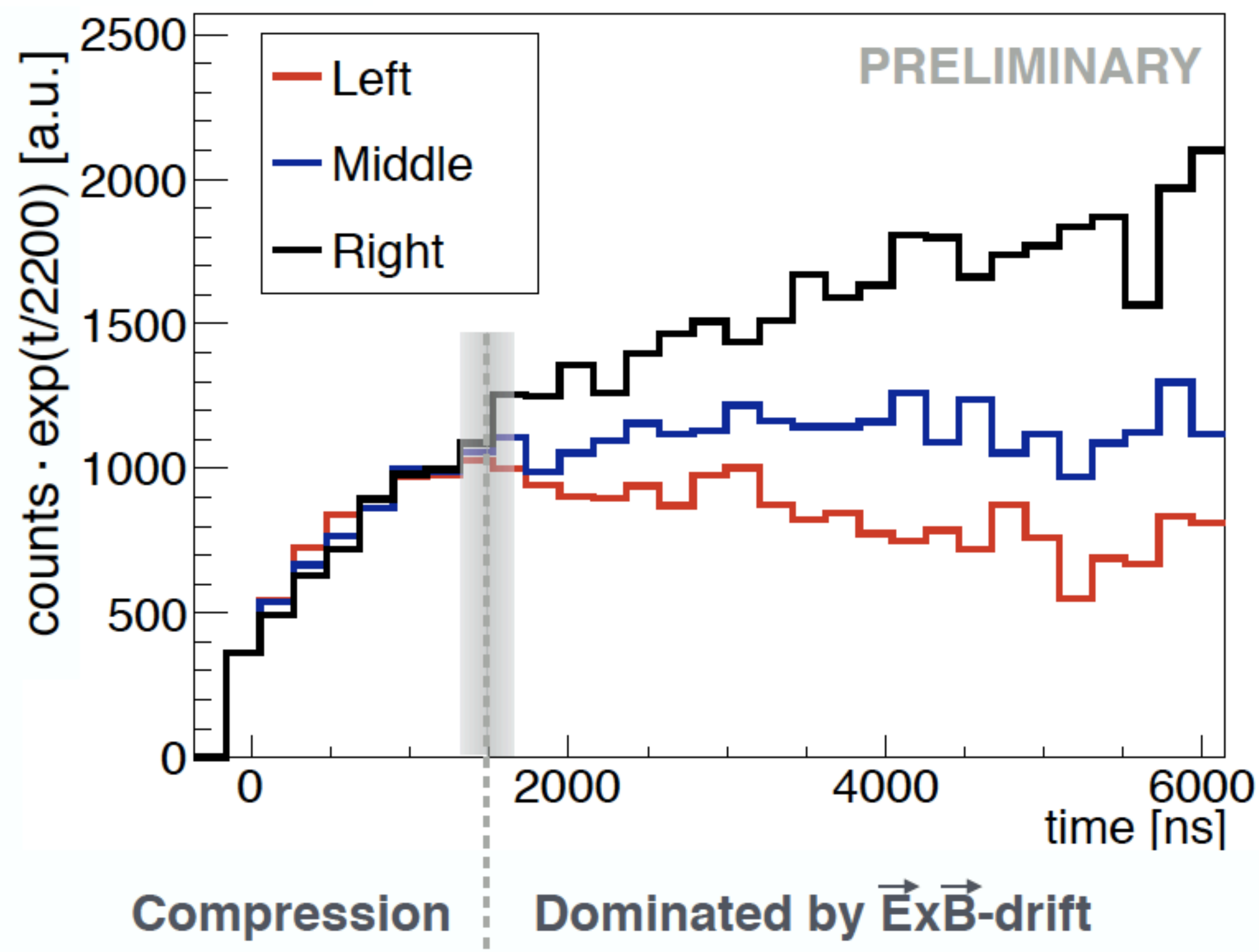


- Longitudinal compression with ExB drift in 2015
- PSI πE1 beamline; μ^+ at 9.1 MeV/c
- ~11 KHz on entrance detector
- Few % μ^+ stopped in the target
- **Confirmed compression results**

Result

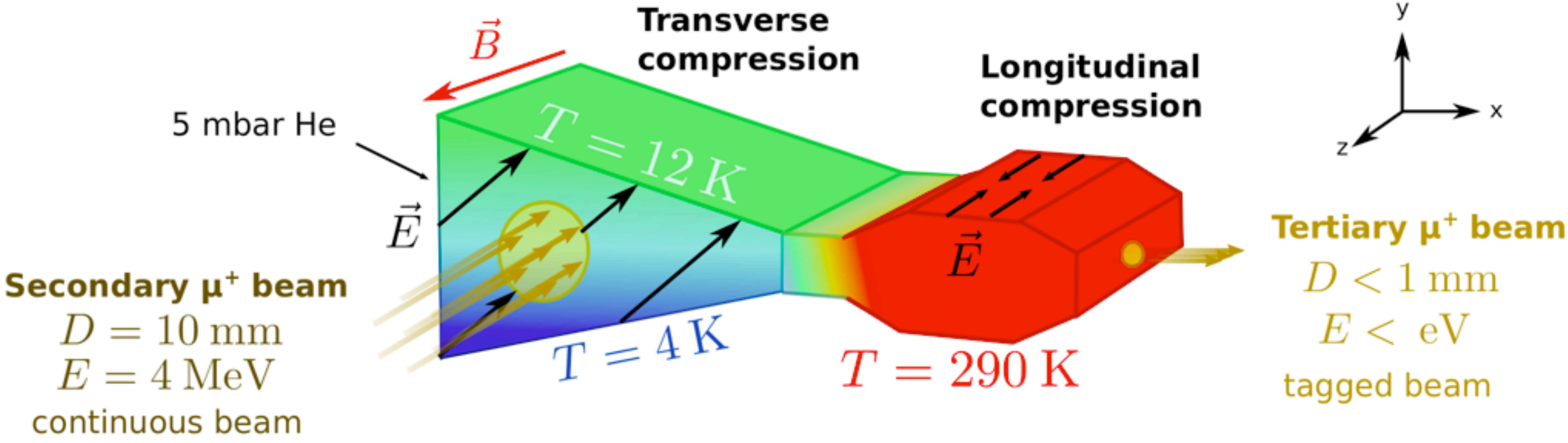
Longitudinal compression: With ExB drift





- Add vertical (y) component to E-field
- Off-center injection of μ⁺
- μ⁺ drift in ExB-direction
- **μ⁺ drift signal**

muCool: Transverse compression



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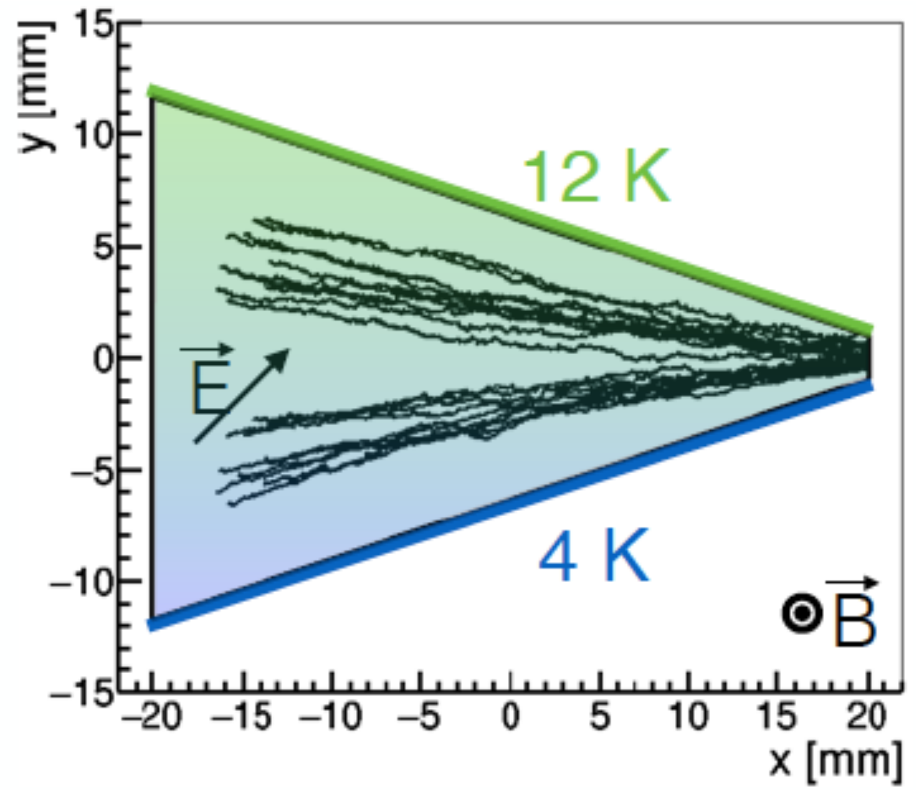
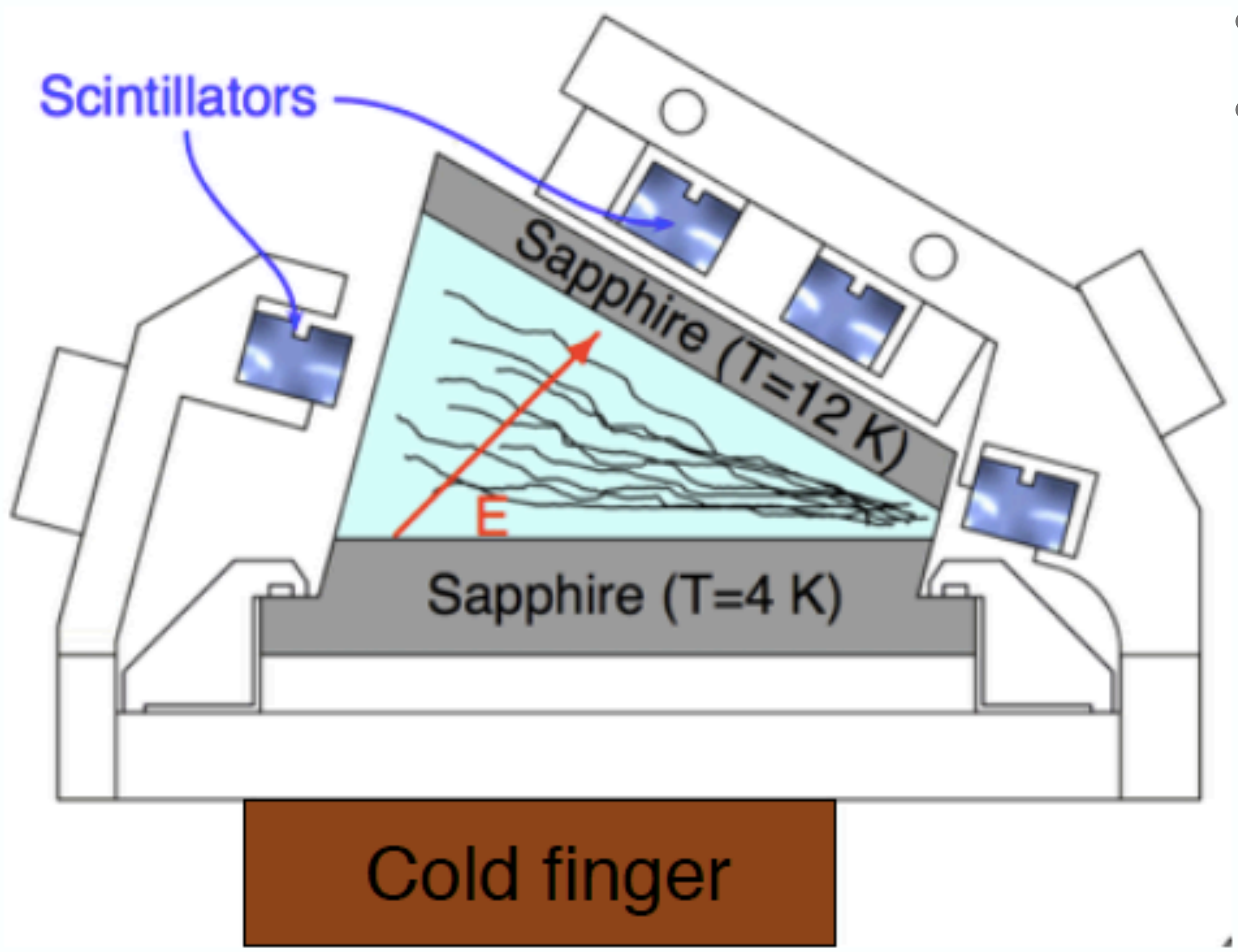


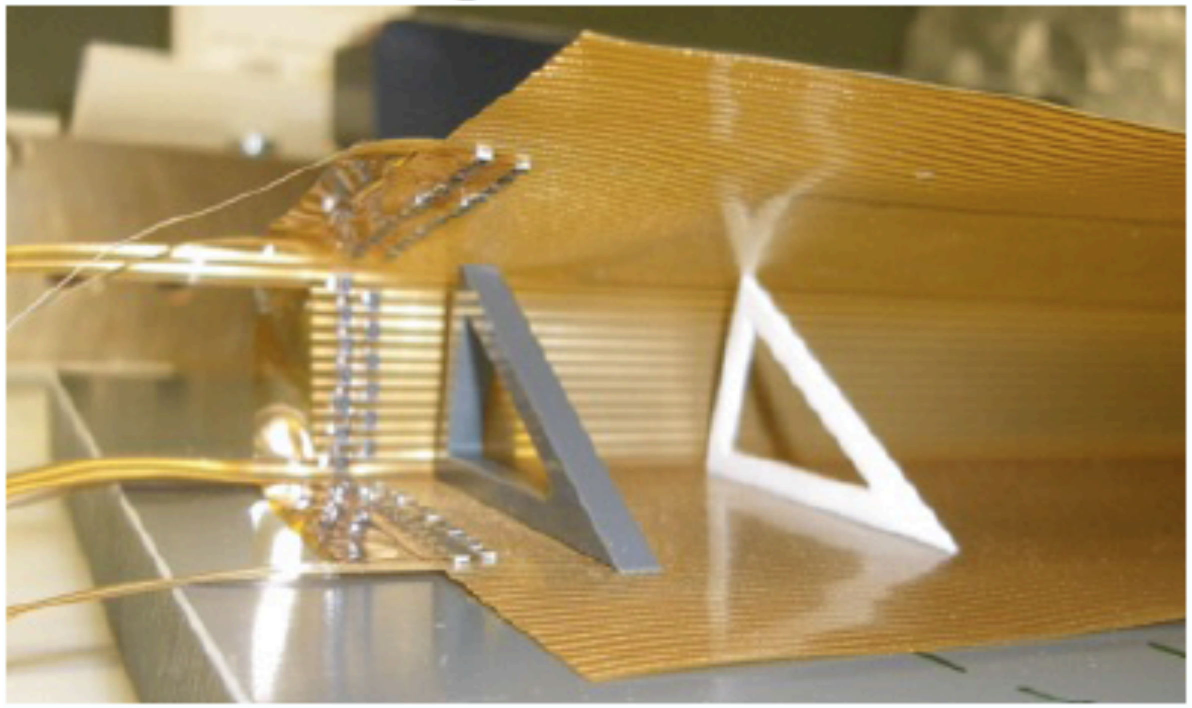
Transverse compression: First demostrator



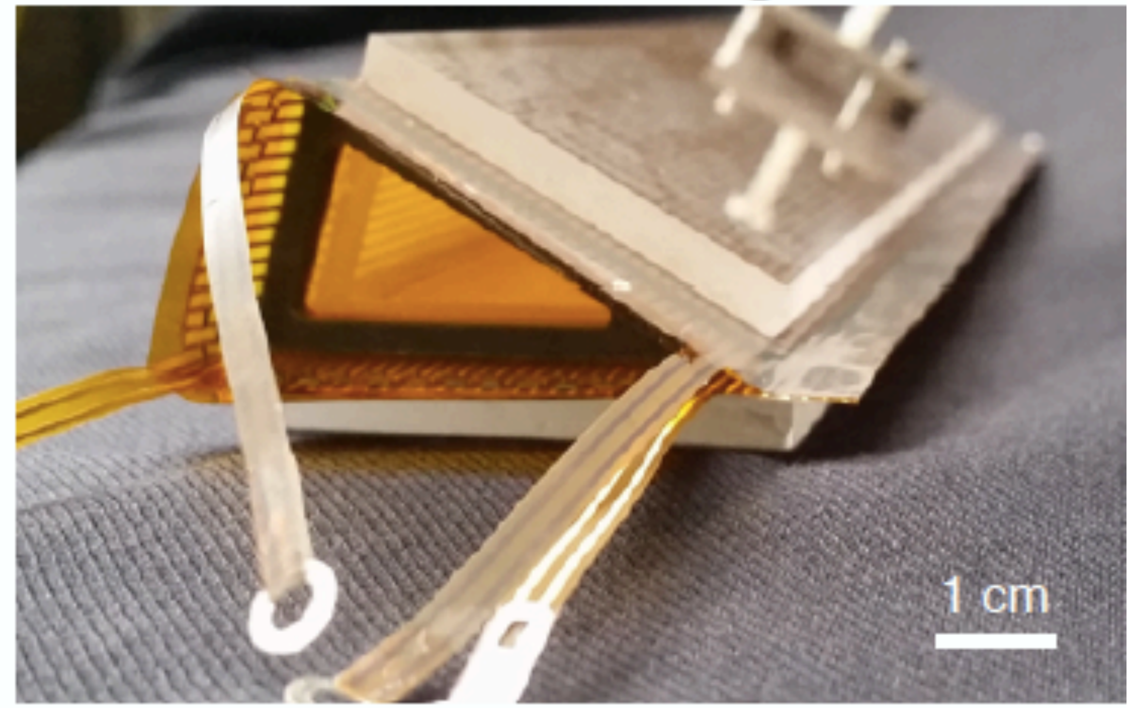
- Transverse compression in 2015
- Complete assembly
- Temperature gradient: 6.1-18.6 K (5T)
- HV stability: Up to 1.5 kV/cm @ 7.5 mbar, 6-18 K

Transverse compression: First demostrator

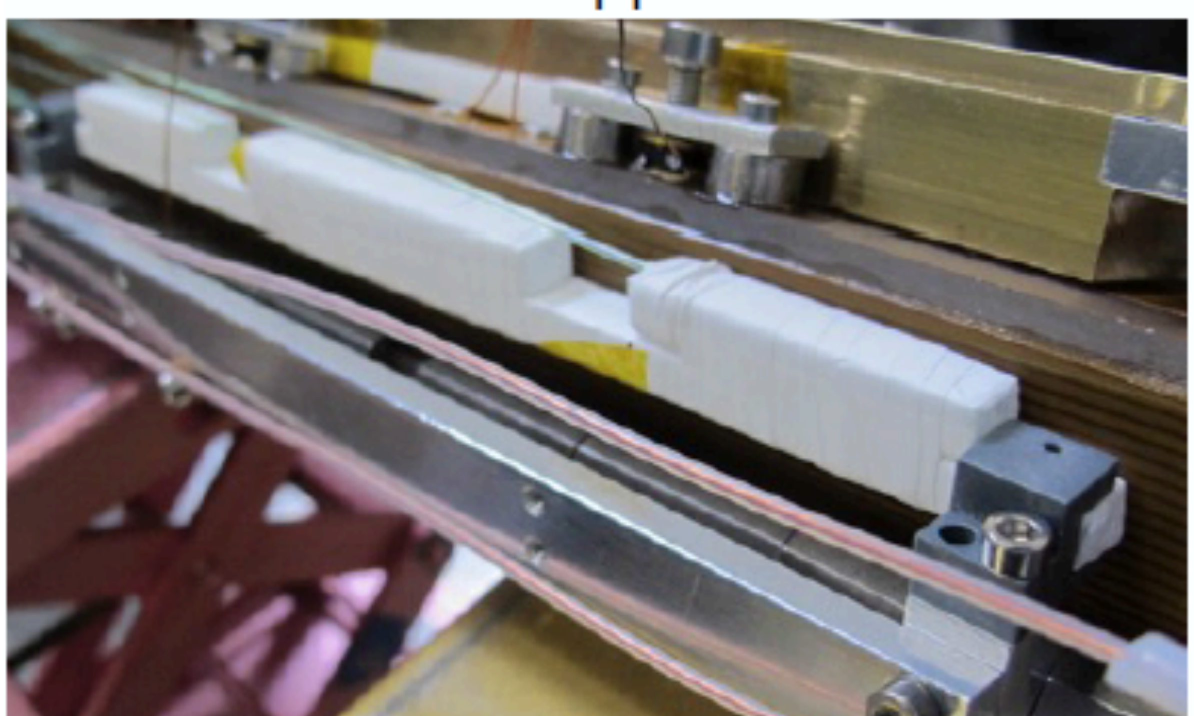
During construction



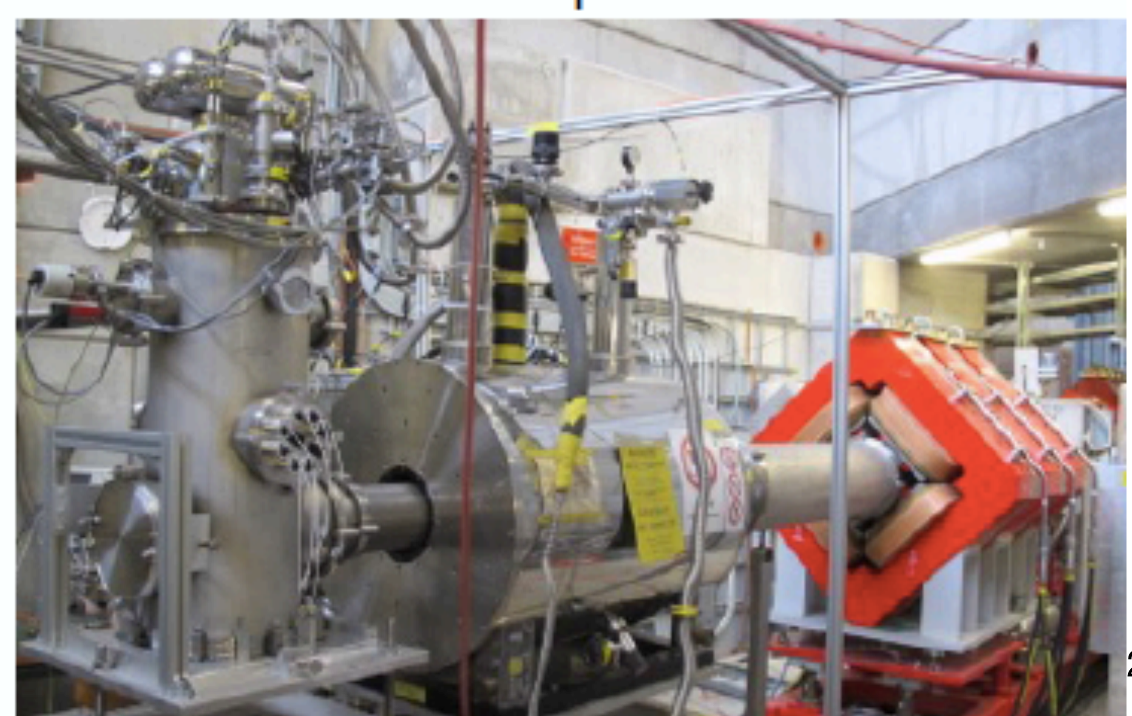
Finished target



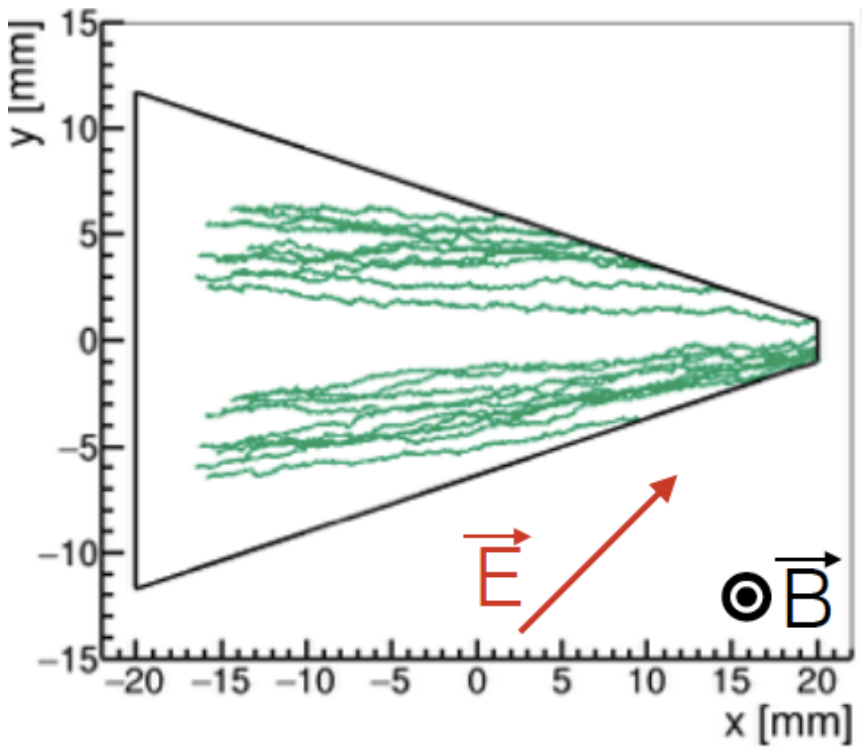
Scintillators wrapped in Teflon



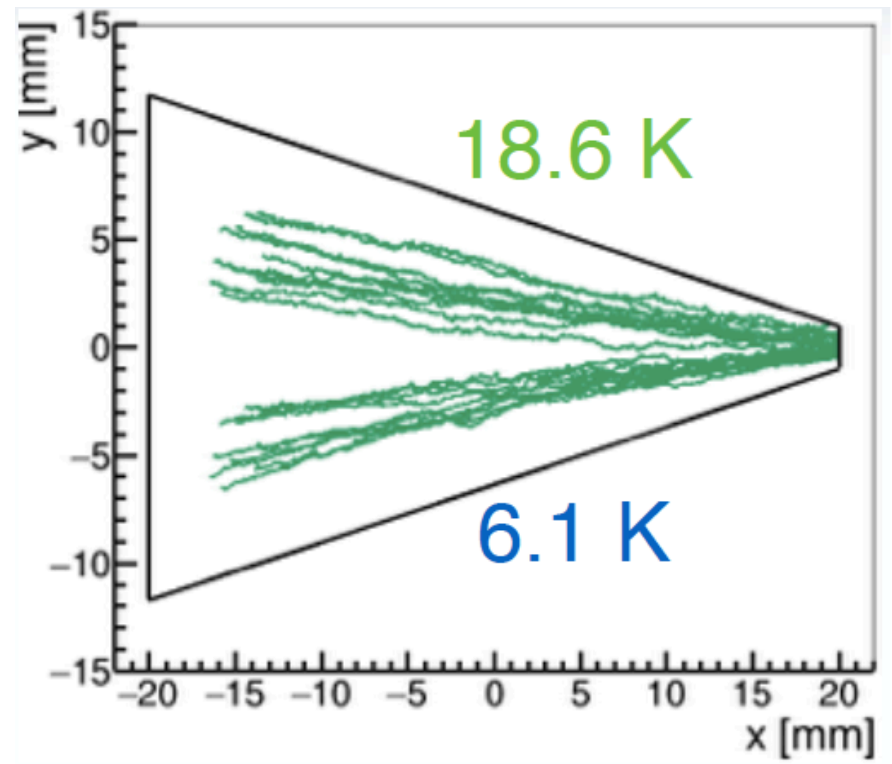
Setup at πE1



Transverse compression: Simulations



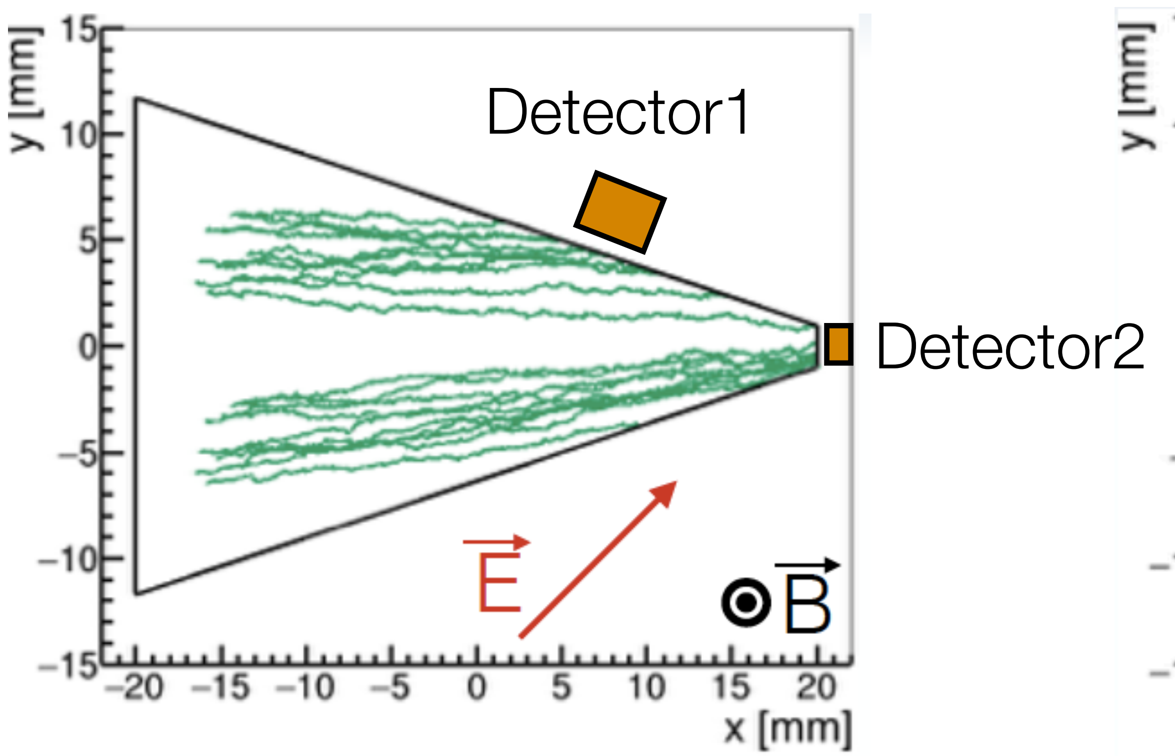
without temperature gradient

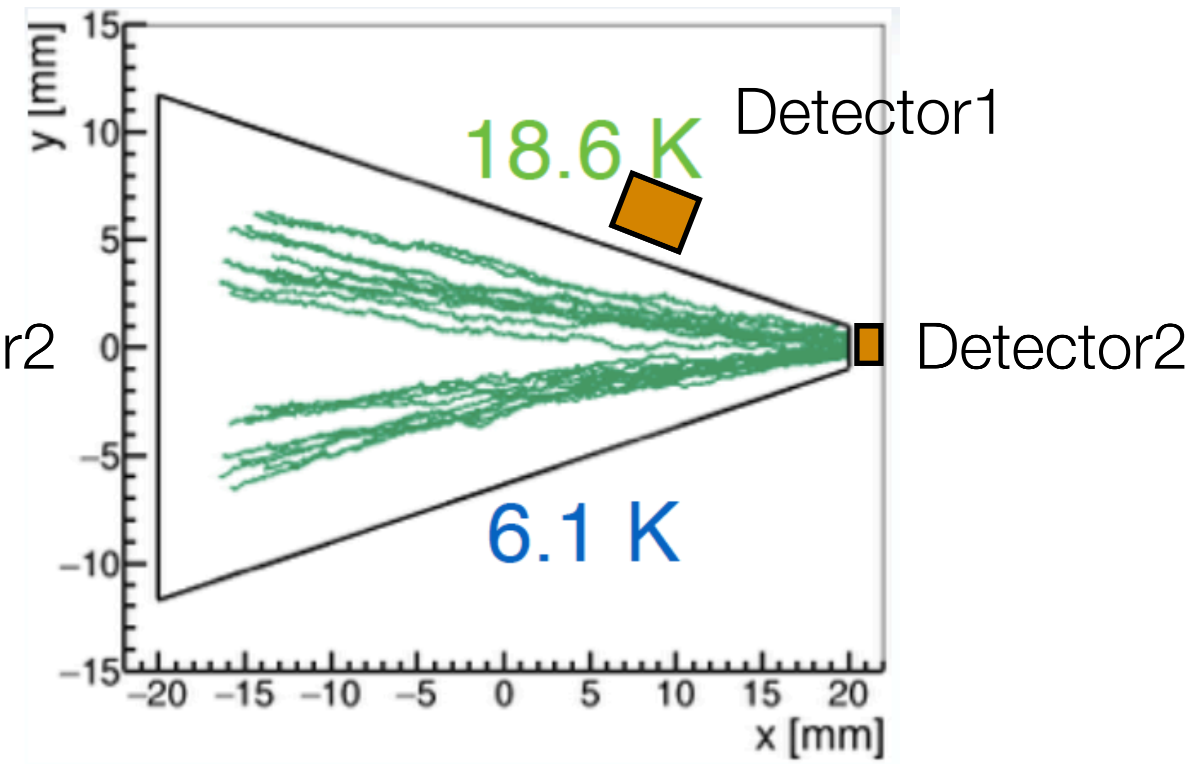


with temperature gradient

- Position dependent **v**-drift with temperature gradient

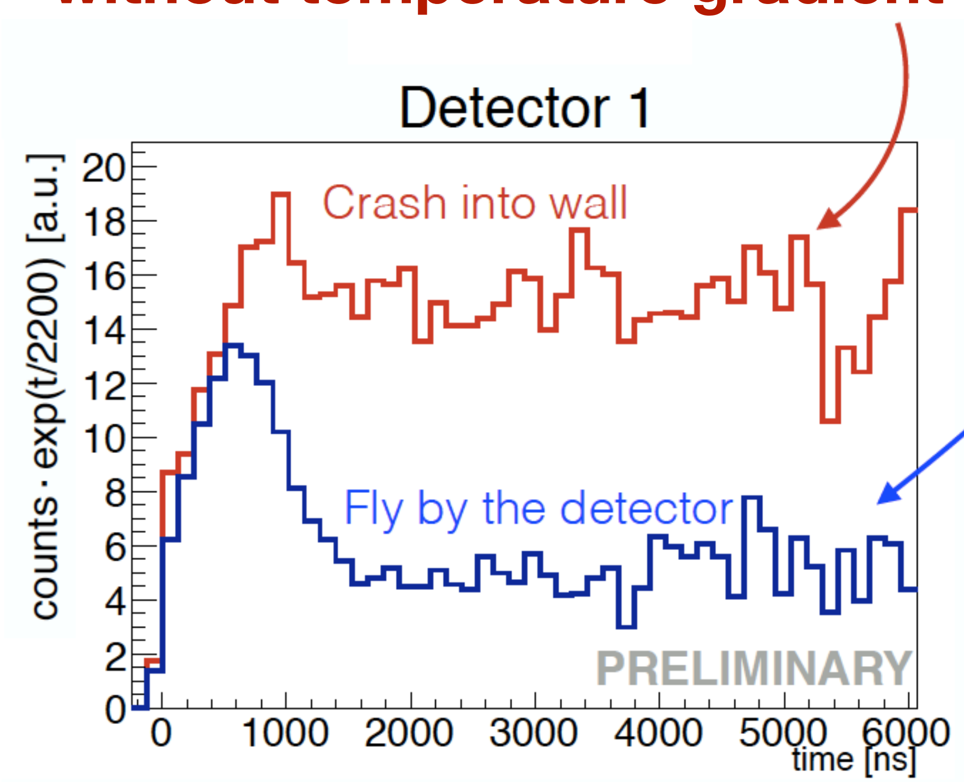
Transverse compression: Data





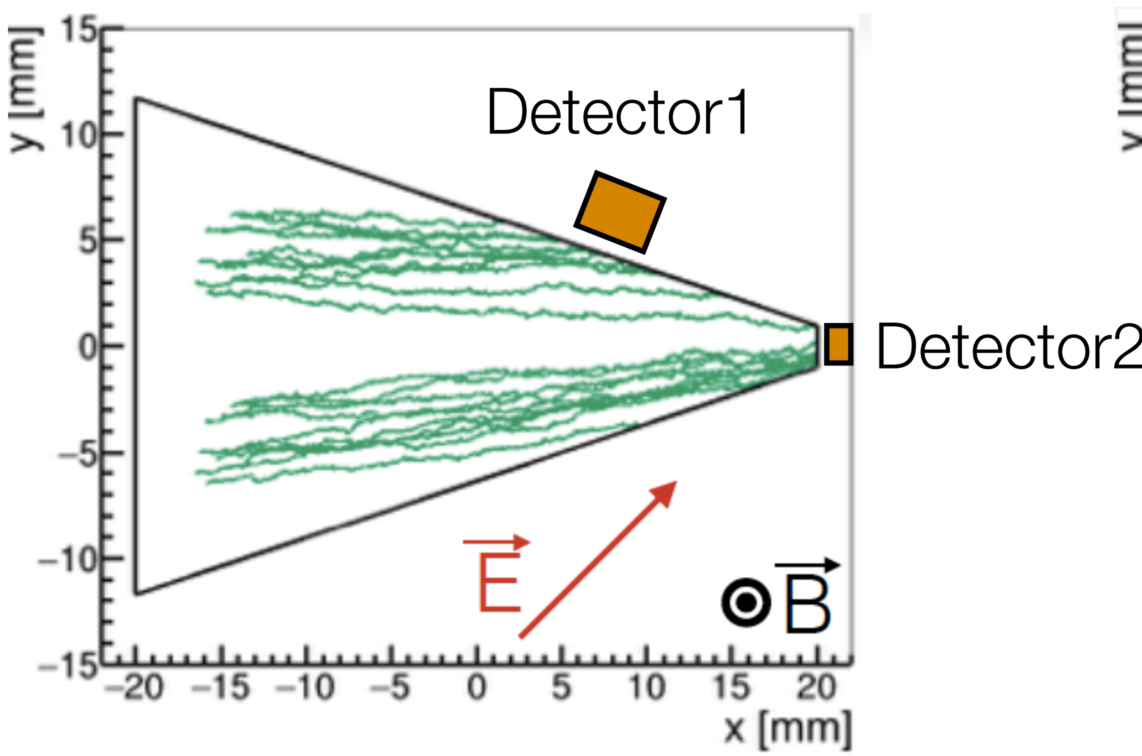
without temperature gradient

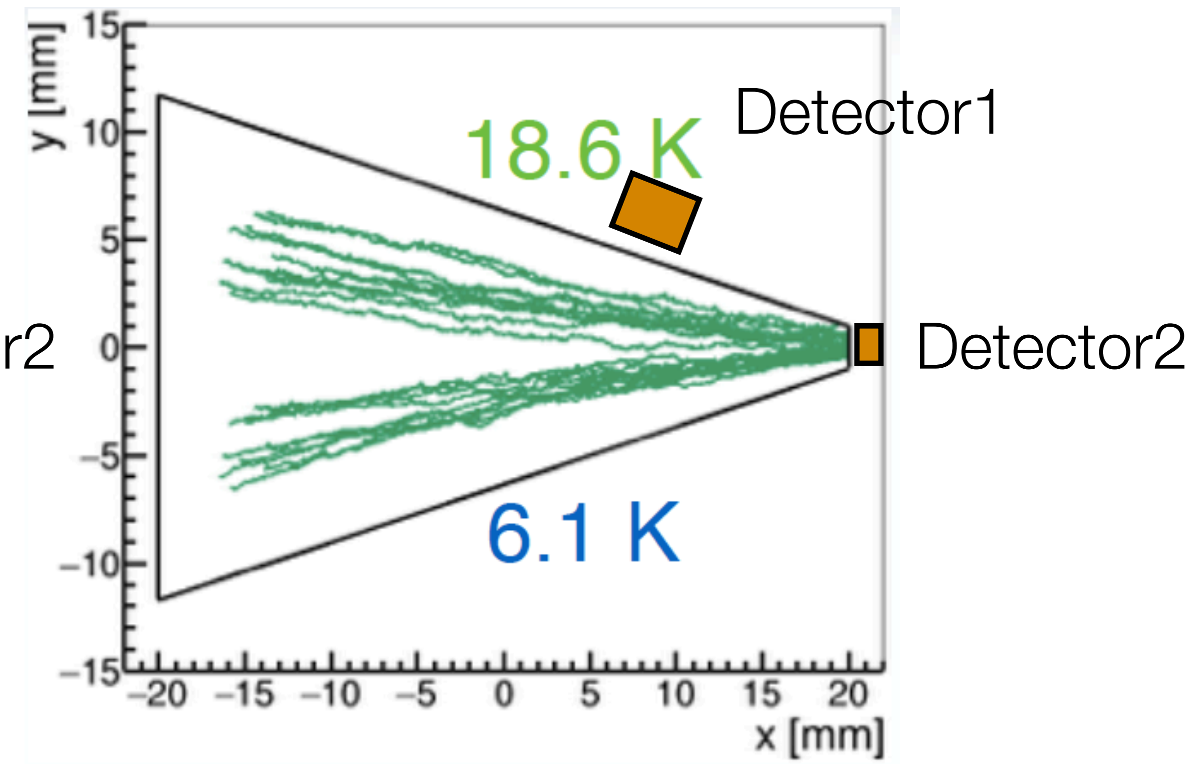
with temperature gradient



Result

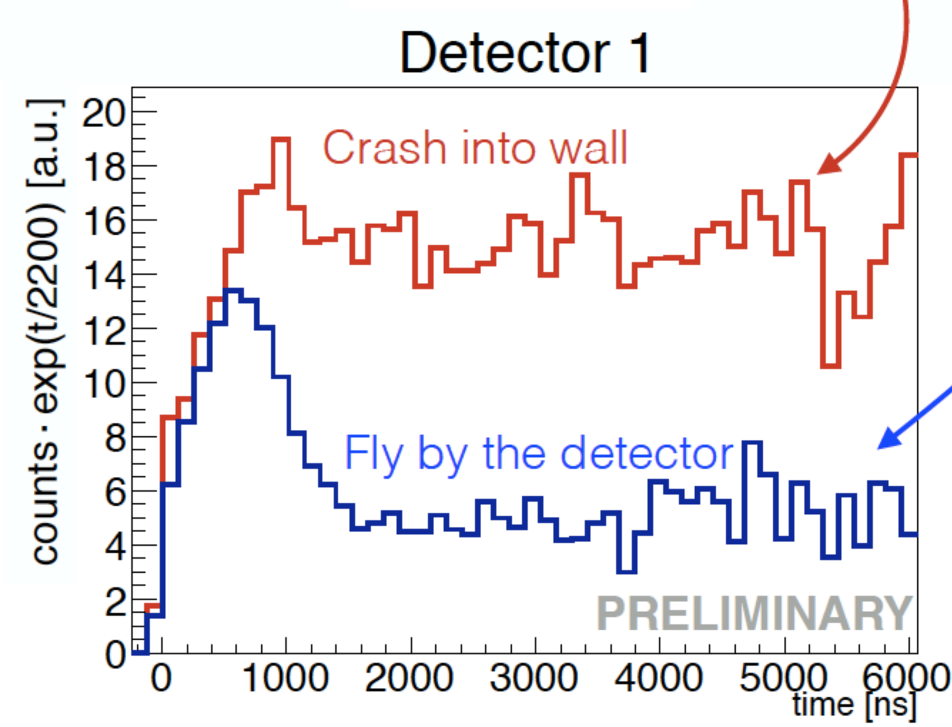
Transverse compression: Data

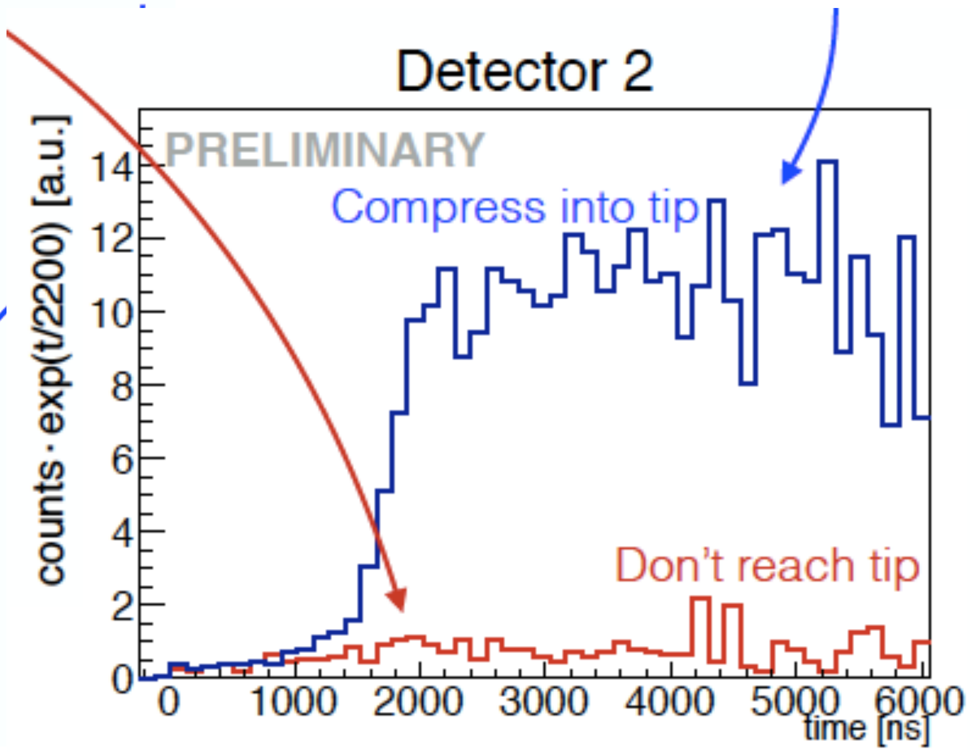




without temperature gradient

with temperature gradient





Conclusions

- Interesting physics opportunities in particle physics and material science using slow, high-brightness muon beams
- The muCool collaboration aims at delivering a such a beam using a novel technique employing a density gradient in helium gas and electric and magnetic fields. This thertiary beam lines will have a increased brightness of 10^7 w.r.t. secondary beam lines at the cost of 10^{-3} efficiency
- Longitudinal and Transverse compressions have been demostrated experimentally
- Further steps: combine cold transverse and warm longitudinal stage; extraction into vacuum

muCool Collaboration

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