muCool

Andreas Eggenberger

on behalf of the muCool collaboration:

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muCool: Goals

We are building a small device to compress the phase space of a surface μ^+ beam

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

Phase Space Compression

- To reduce phase space a dissipative mechanism is needed
  - ➡ Slow down (stop) μ^+ in He gas
- After slowing down in gas:
  - ➡ low energy
  - ➡ large volume BUT: can steer μ^+ with electric and magnetic fields

In our case:

Apply $\vec{E}$x$\vec{B}$-fields in 3 successive compression stages:

1. Transverse (perpendicular to beam axis)
2. Longitudinal (along beam axis)
3. Final compression and extraction into vacuum

Key Ingredient

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

Position-dependent drift velocity vector in He gas in the presence of crossed electric and magnetic fields

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

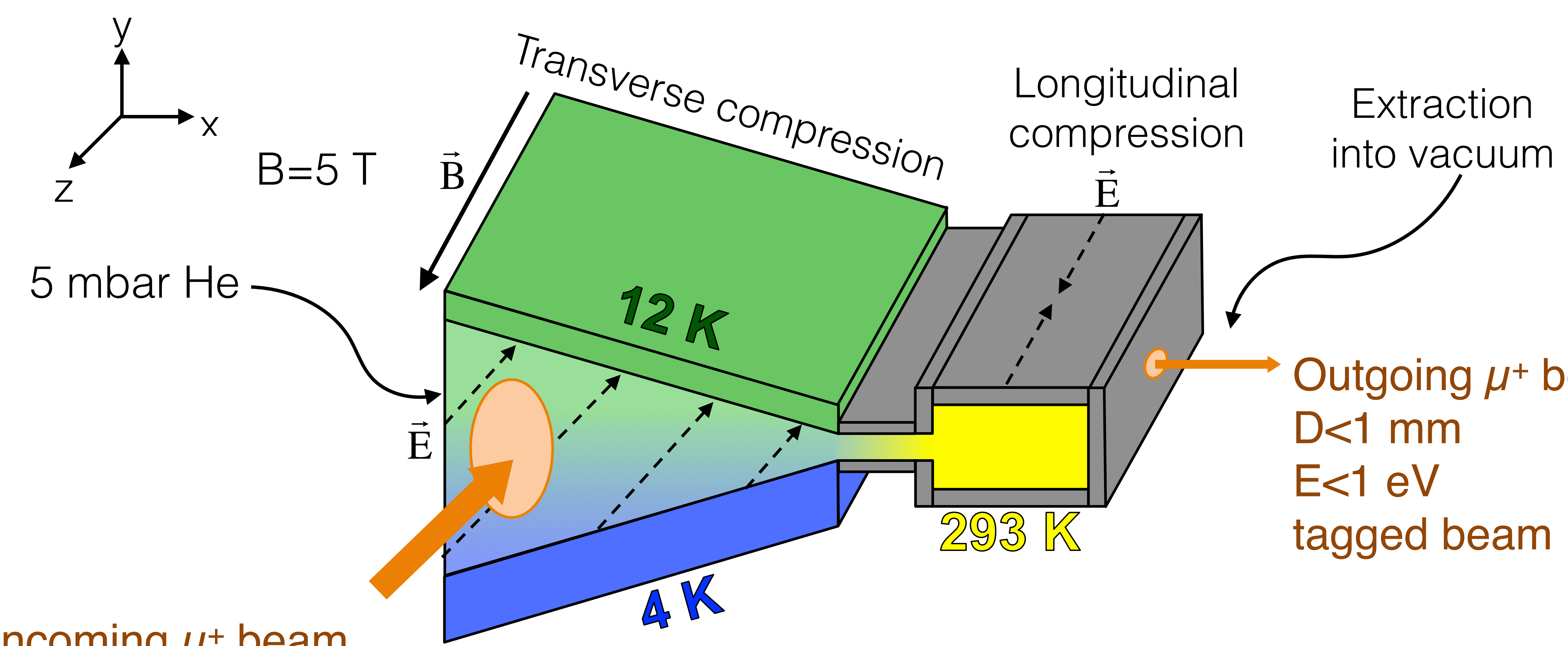
3 components with different weights:
change in density (i.e. collision frequency) ➡ change in direction

high density $\rightarrow v_{col}$ large $\rightarrow \hat{E}$ dominates

low density $\rightarrow v_{col}$ small $\rightarrow \hat{B}$ dominates

3 Compression Stages

Dimensions ~ 15 x 5 x 50 cm^3



Outgoing μ^+ beam
D<1 mm
E<1 eV
tagged beam

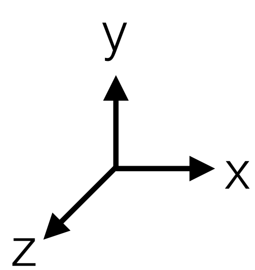
Incoming μ^+ beam
D~10 mm
E=4.1 MeV
continuous beam

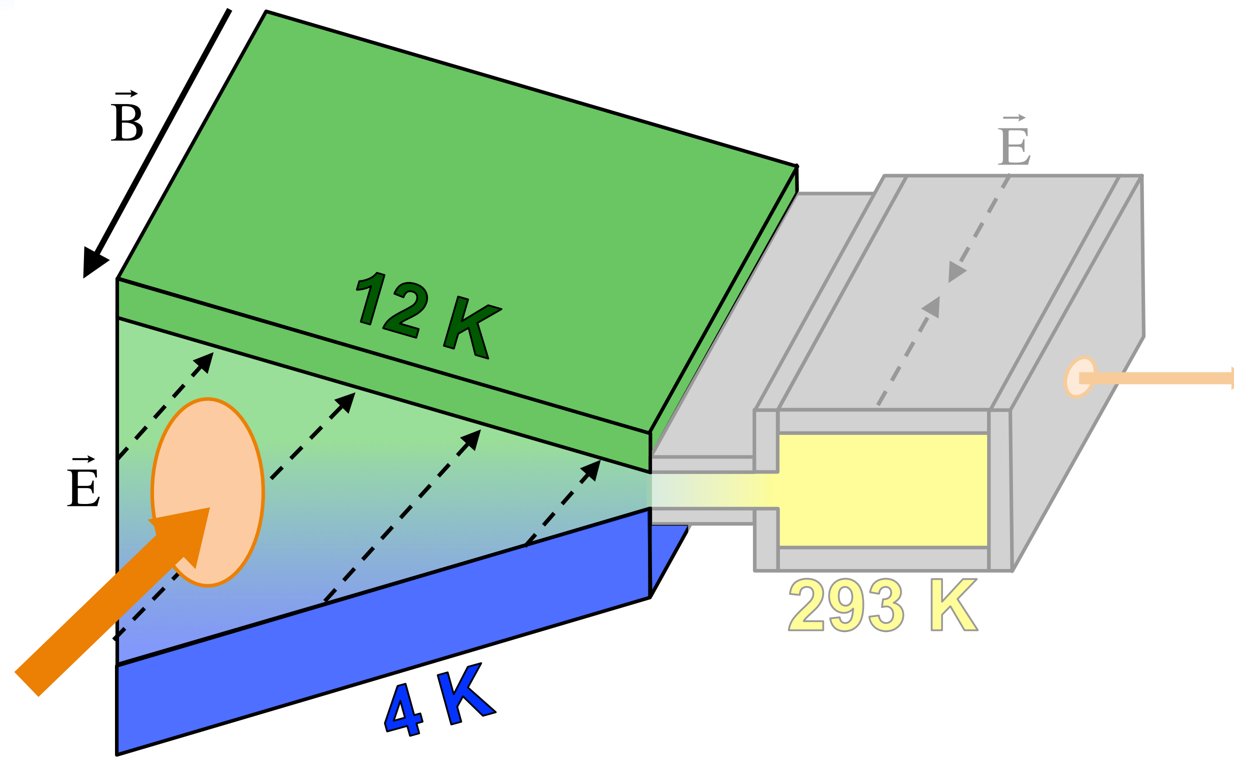
D. Taqqu, *PRL* **97**, 194801 *(2006)*
Y. Bao et al., *PRL* **112**, 224801 *(2014)*

Transverse Compression Stage

- 5 mbar He gas
- Cryogenic temperature
- Temperature gradient
- Crossed E- and B-fields

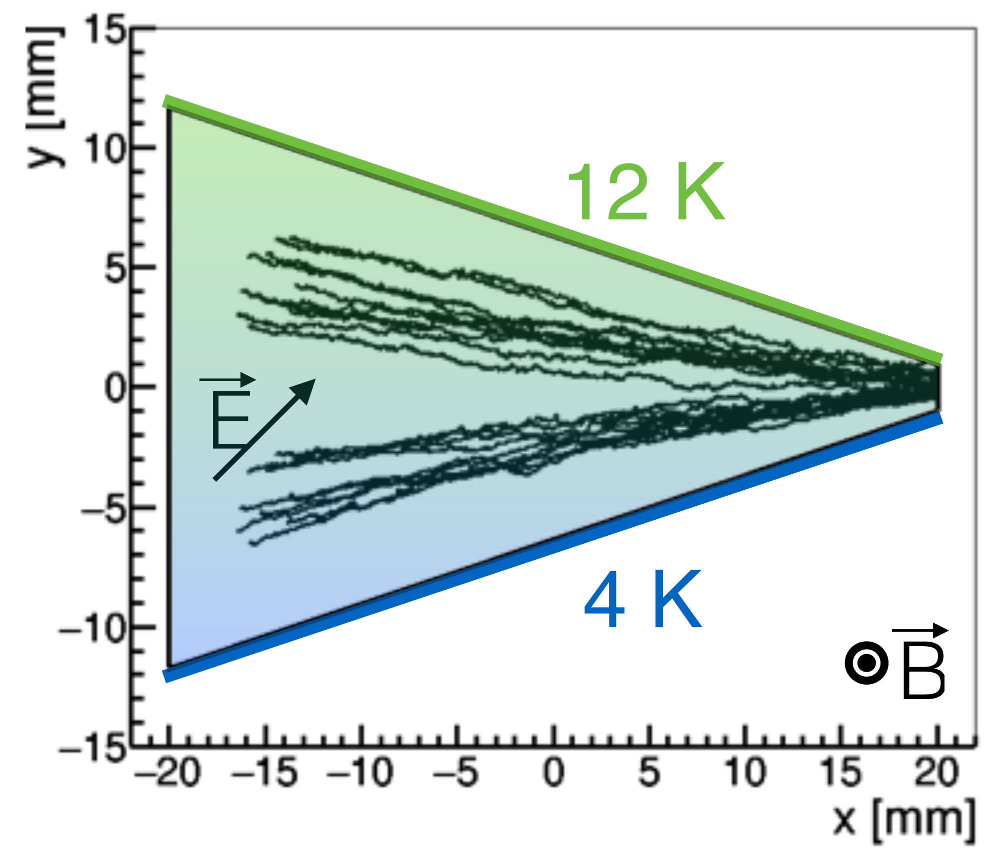
$$\hat{E} = \frac{1}{\sqrt{2}}(1,1,0)$$
$$\hat{B} = (0,0,1)$$
$$|\vec{E}| \approx 1.5\ \mathrm{kV/cm}$$



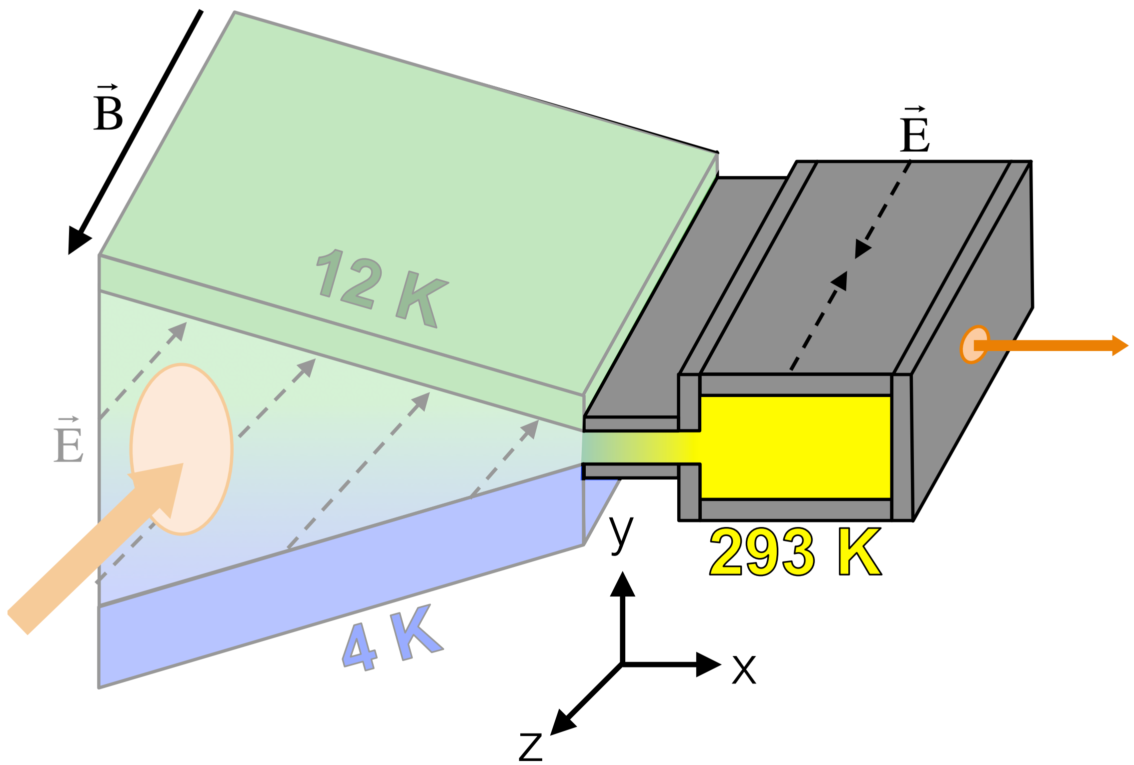


$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}} \times \hat{\mathbf{B}}\right]$$

high density $\rightarrow v_{col}$ large $\rightarrow \hat{E}$ dominates
medium density $\rightarrow v_{col}$ intermediate $\rightarrow \hat{E} \times \hat{B}$ dominates



Longitudinal Compression Stage



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

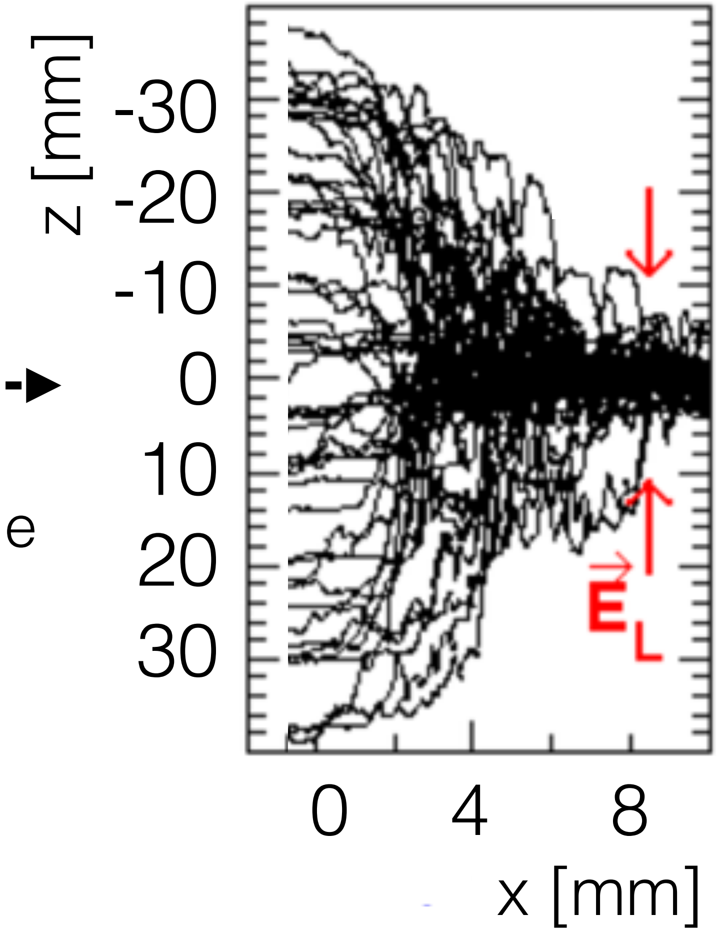
low density → v_{col} small → $\hat{B}$ dominates

- 5 mbar He gas
- Room temperature
- Parallel $\vec{E}$- and $\vec{B}$-fields

$$\hat{E} = \pm(0,0,1)$$
$$\hat{B} = (0,0,1)$$
$$|\vec{E}| \approx 60\ \mathrm{V/cm}$$

Simulation: Top view

μ+ from transverse stage



Towards extraction

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 $\vec{E}$x$\vec{B}$-drift

Demonstration of transverse compression

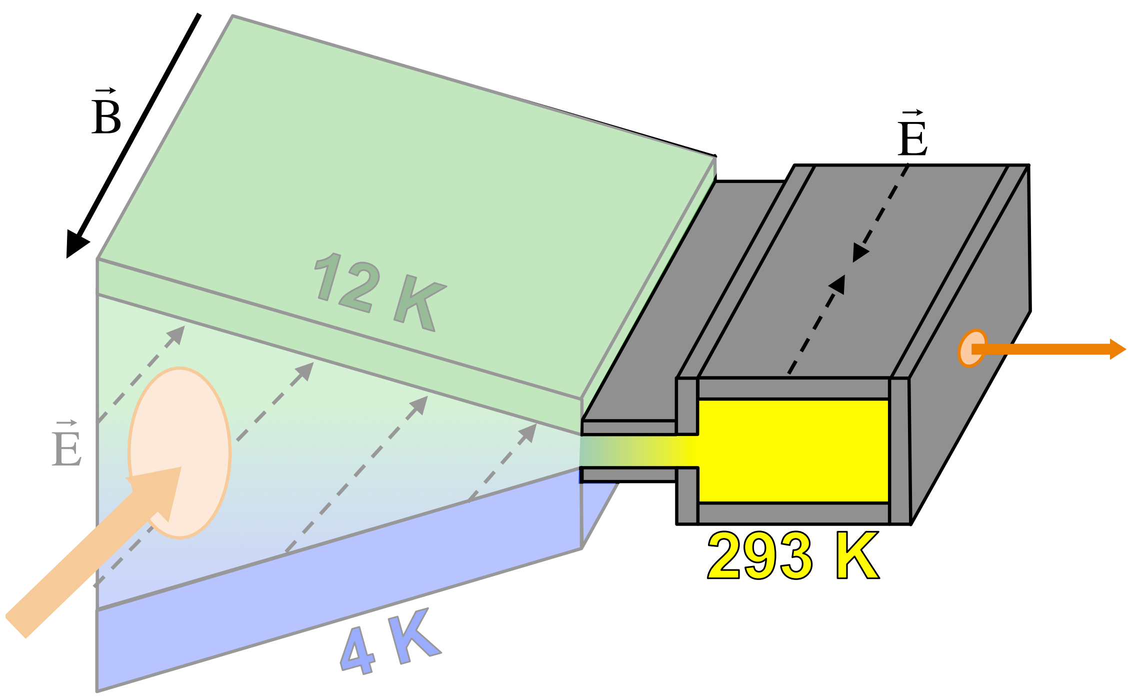
Still to do:

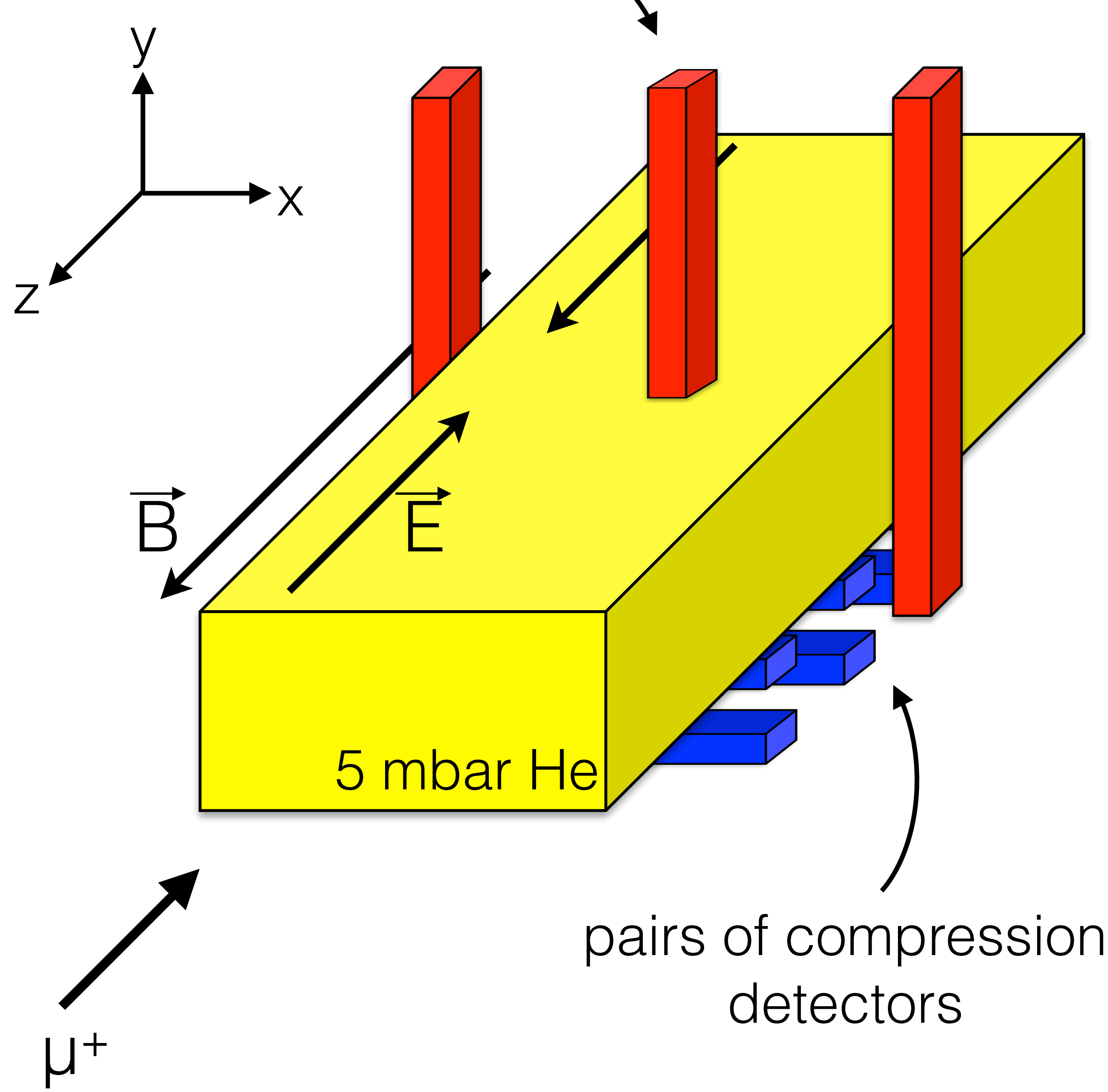
Combination of transverse and longitudinal compression

Extraction into vacuum

Extraction from B-field & re-acceleration

Longitudinal Setup

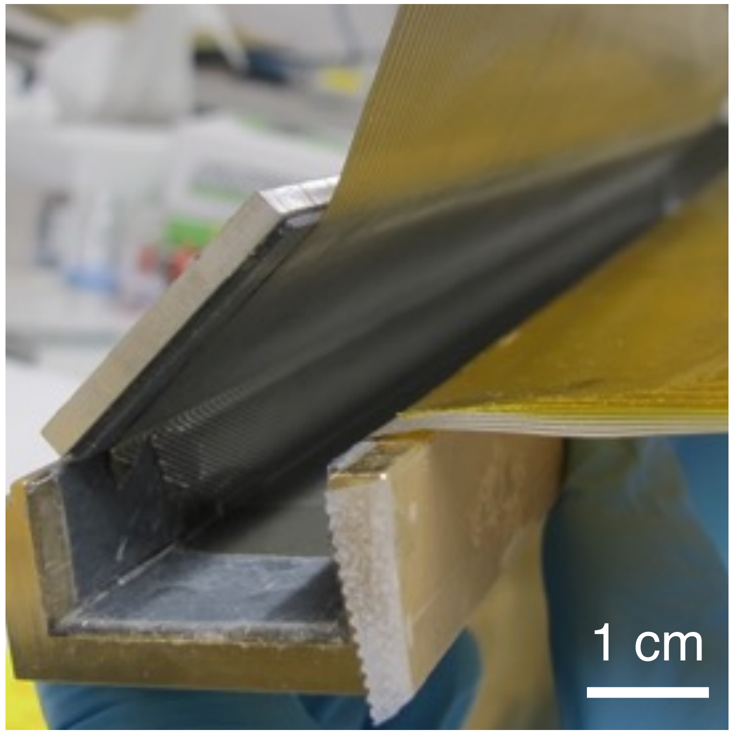




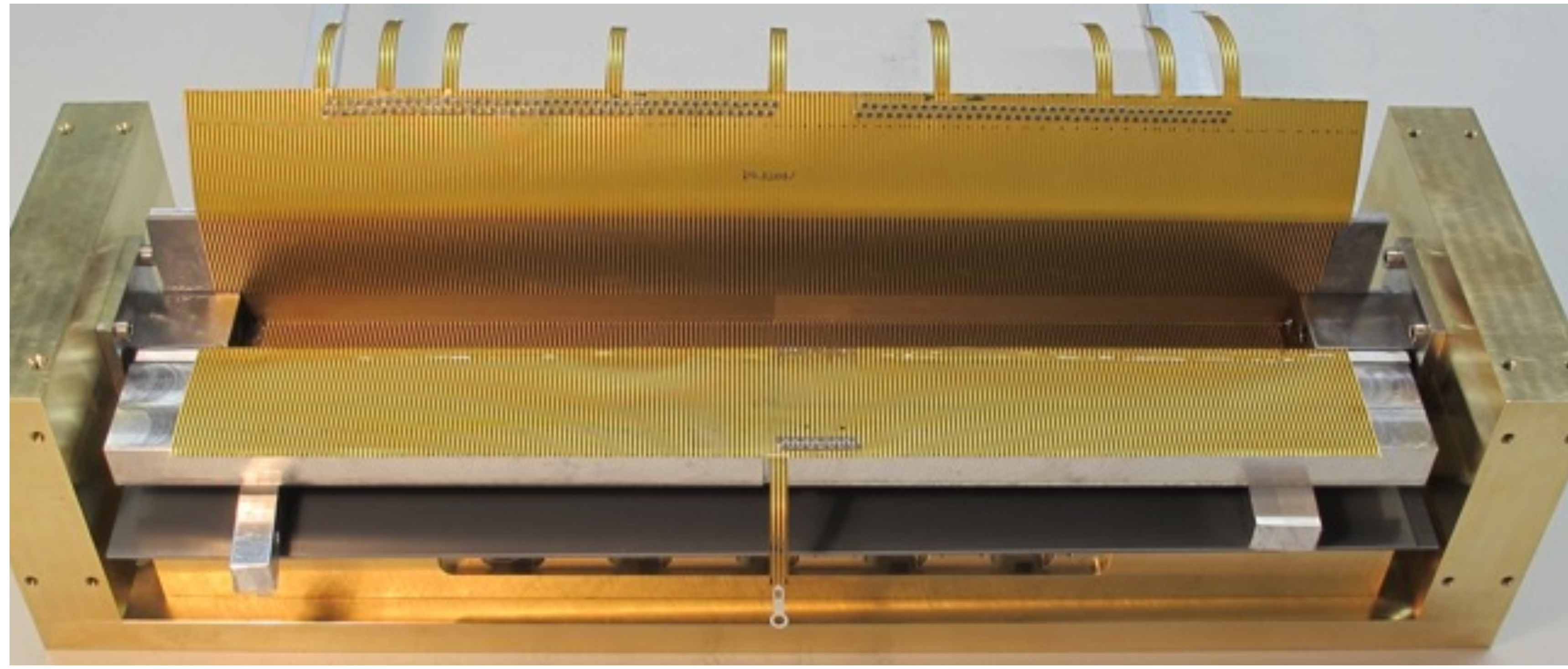
- He volume: 25 x 12 x 300 mm^3
- Kapton foil with electrodes
- Longitudinal injection (!)
- Pairs of compression detectors
- $\vec{E}$x$\vec{B}$-drift detectors

Longitudinal Target

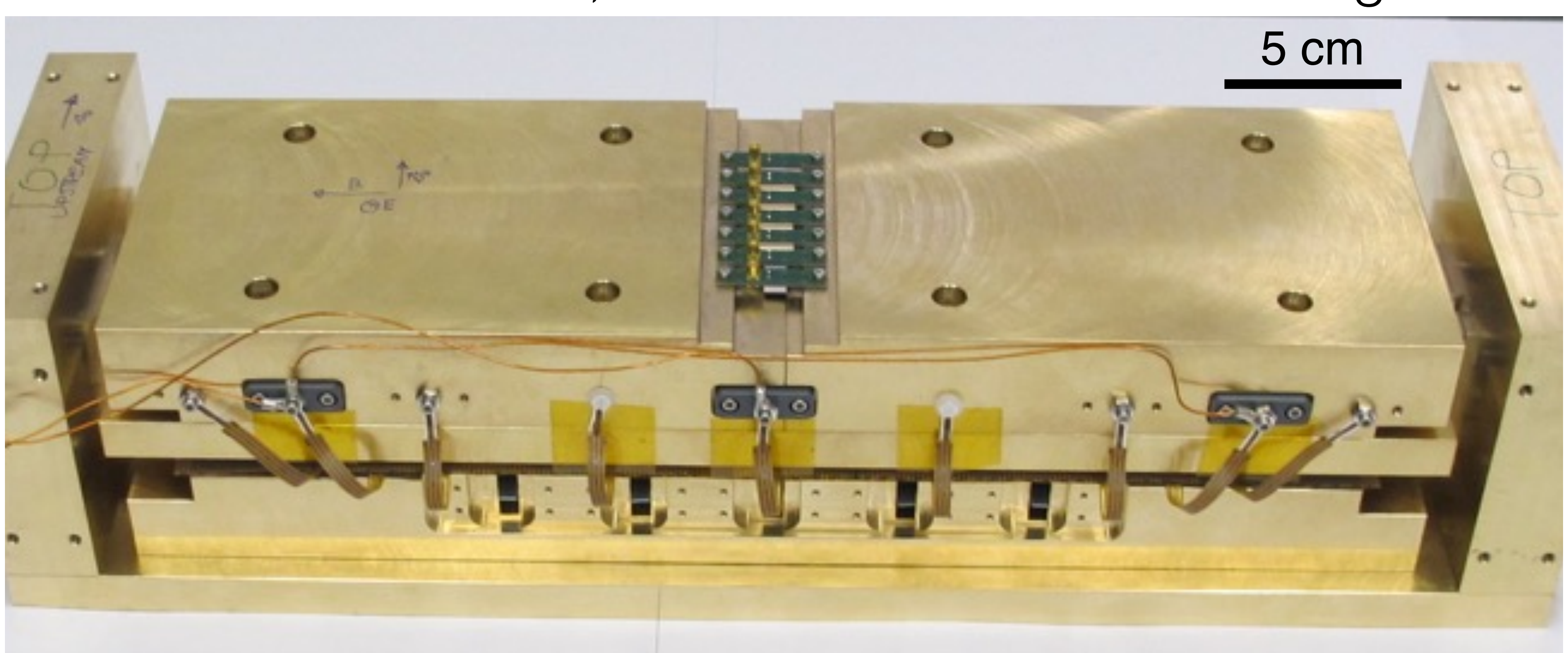
He volume



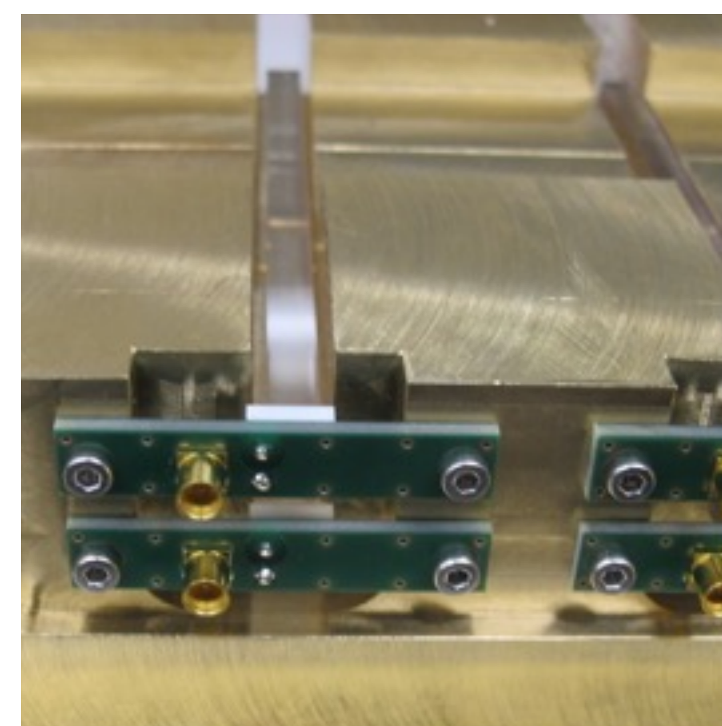
Almost finished target



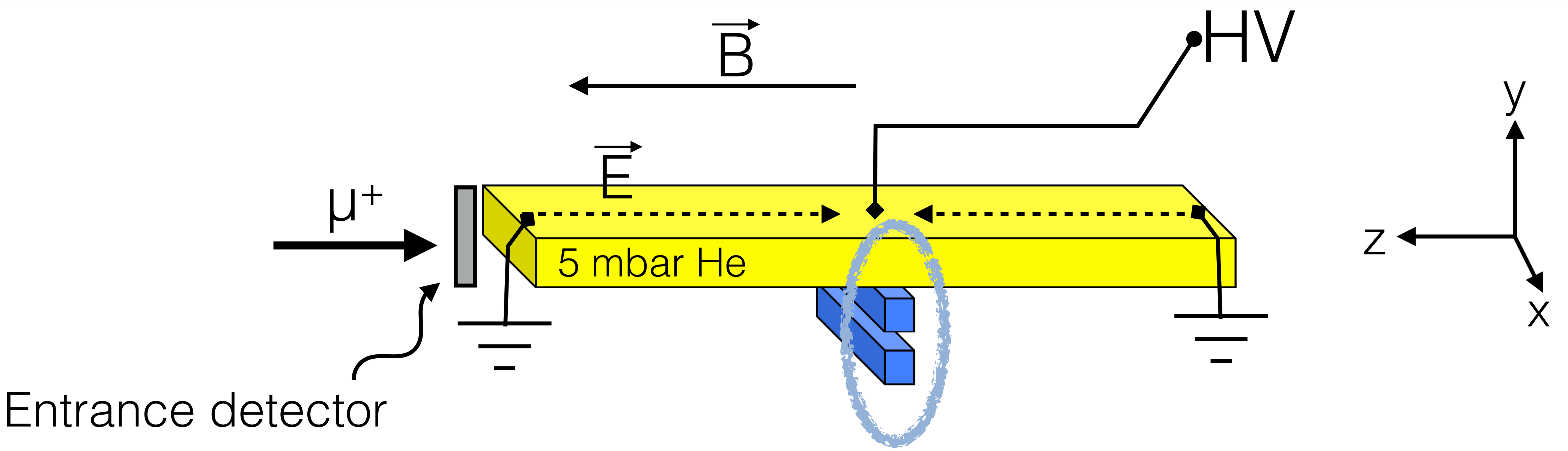
HV connections, detectors and brass shielding



Scintillators

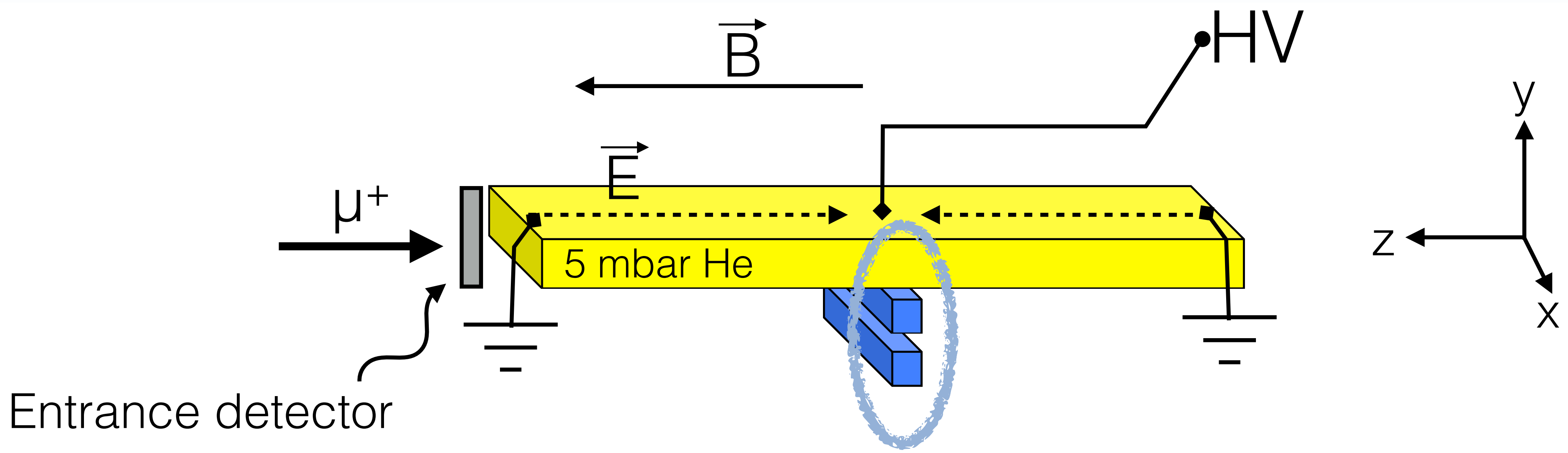


Longitudinal Compression



- πE1 beam line @ 9.1 MeV/c
- ~11 kHz on entrance detector
- μ^+ cross entrance detector -> t=0
- few % μ^+ stop in He gas target
- Apply electric potential
- Detect decay e^+ at time t

Longitudinal Compression



- πE1 beam line @ 9.1 MeV/c
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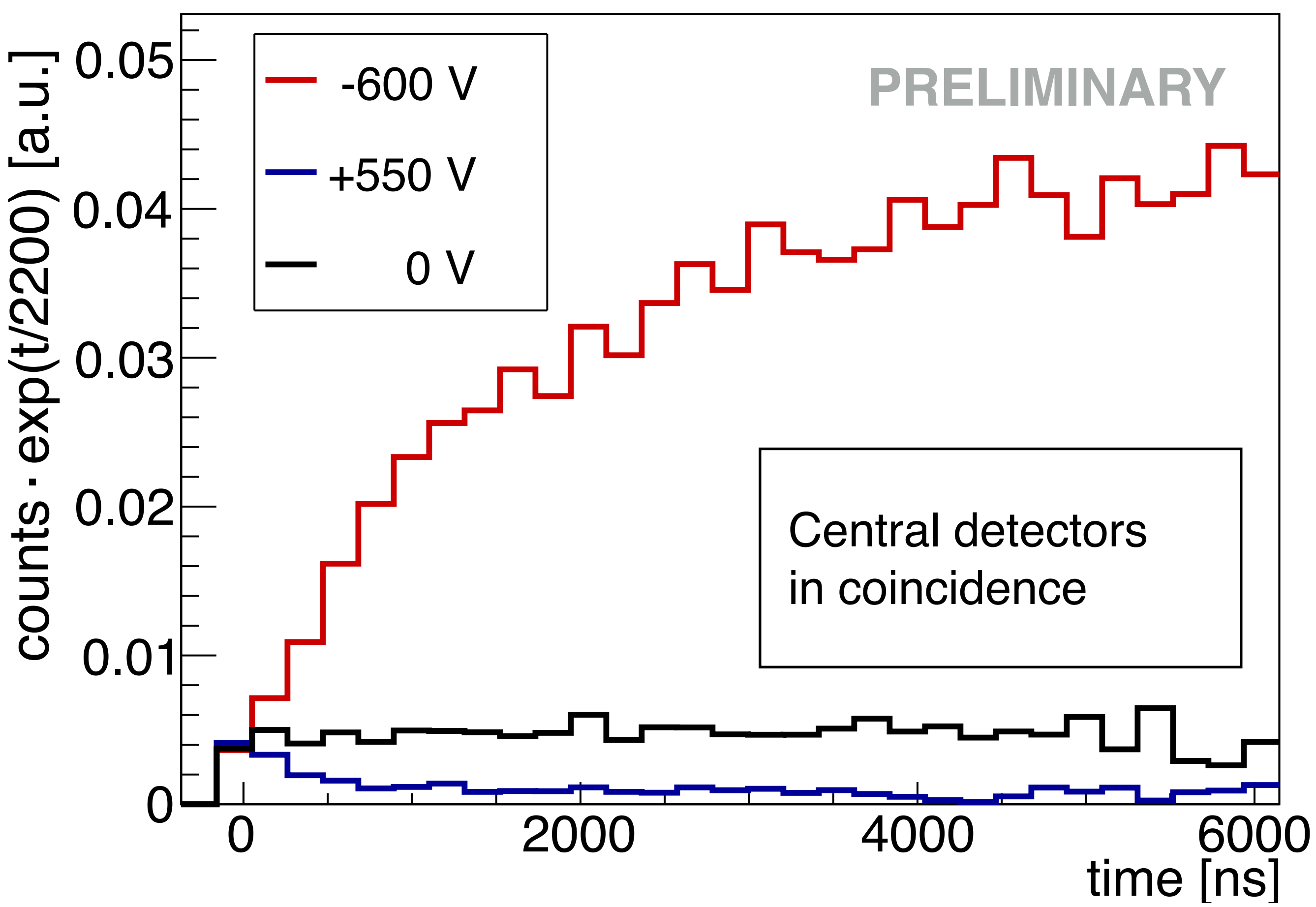
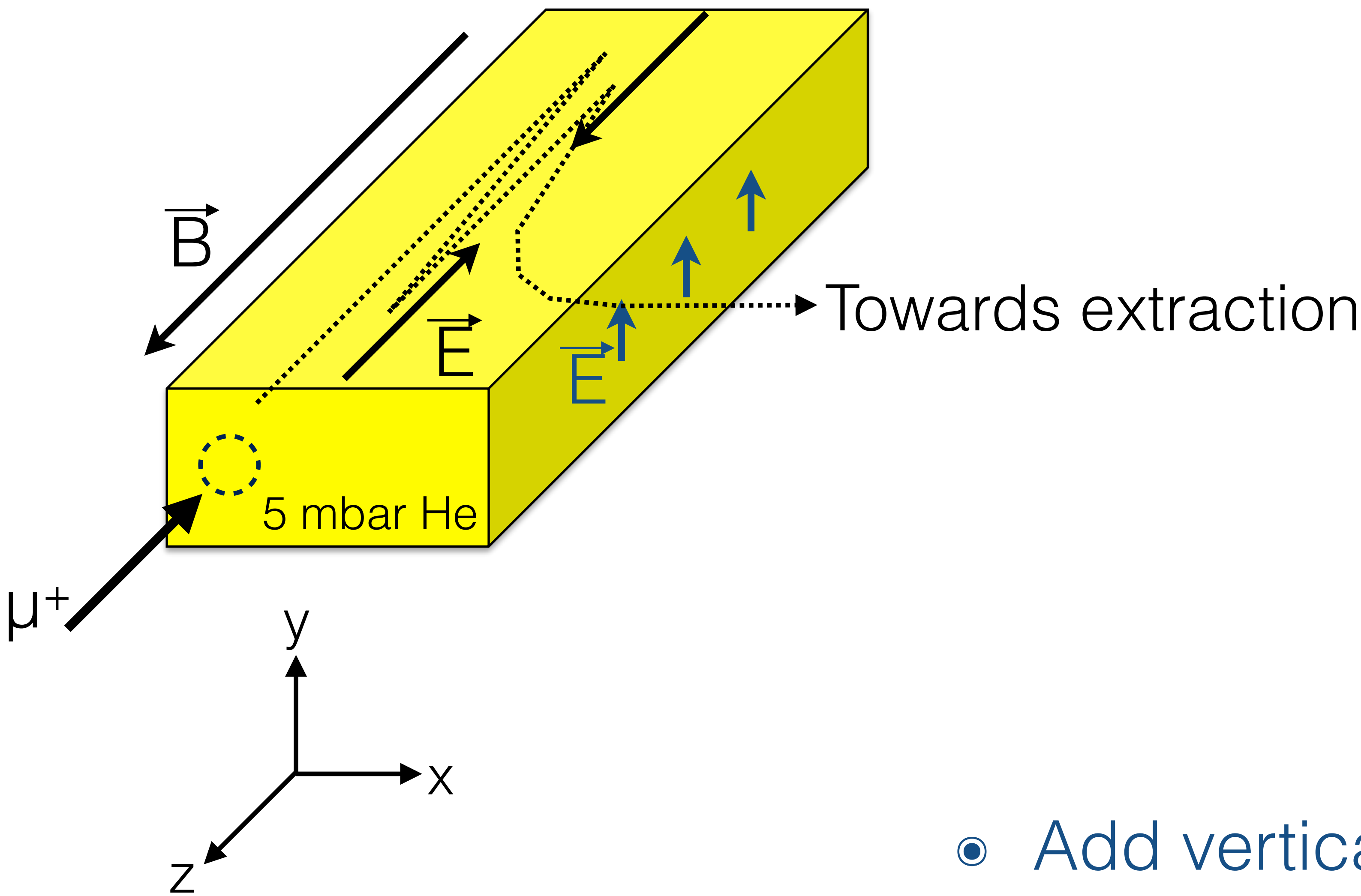
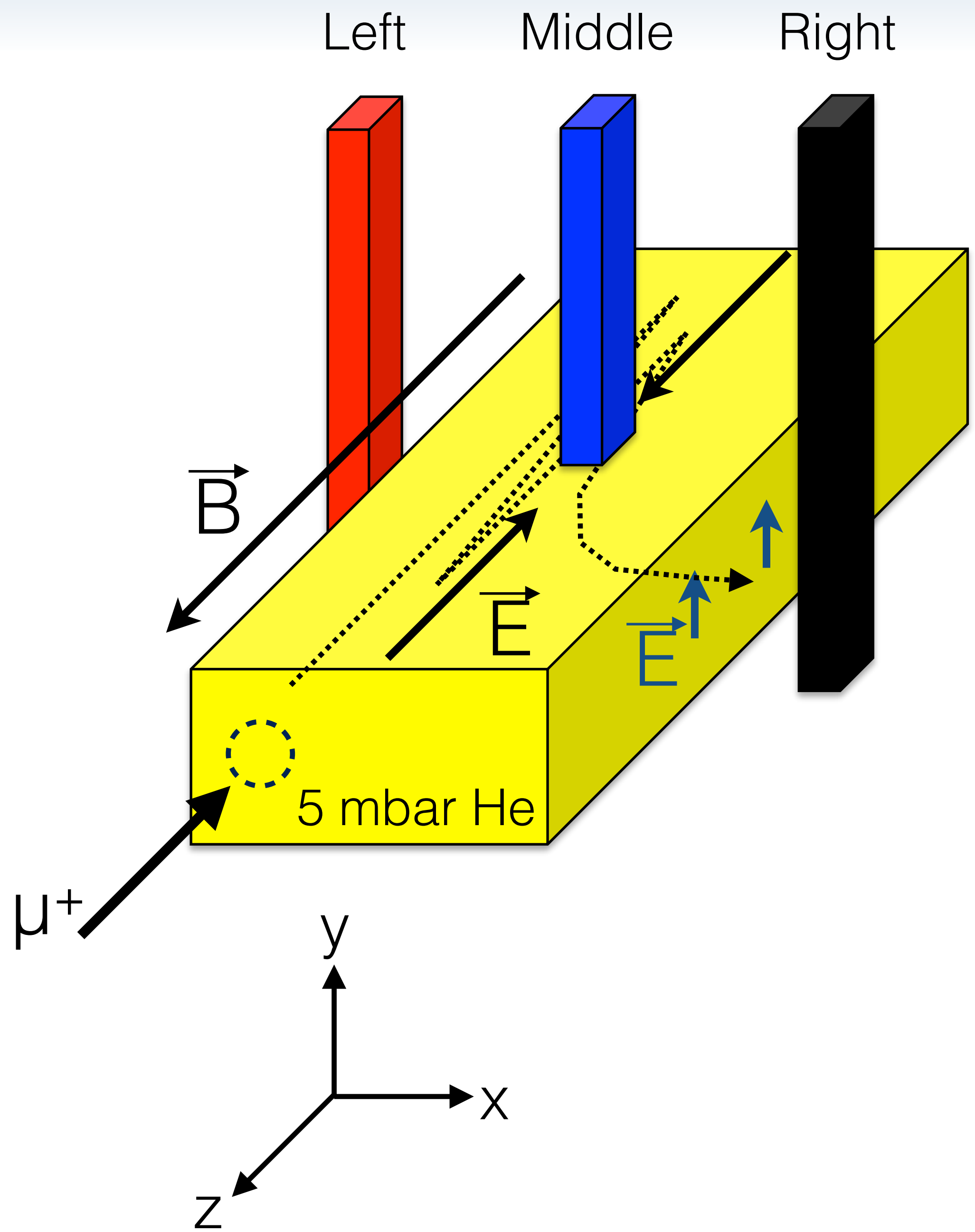


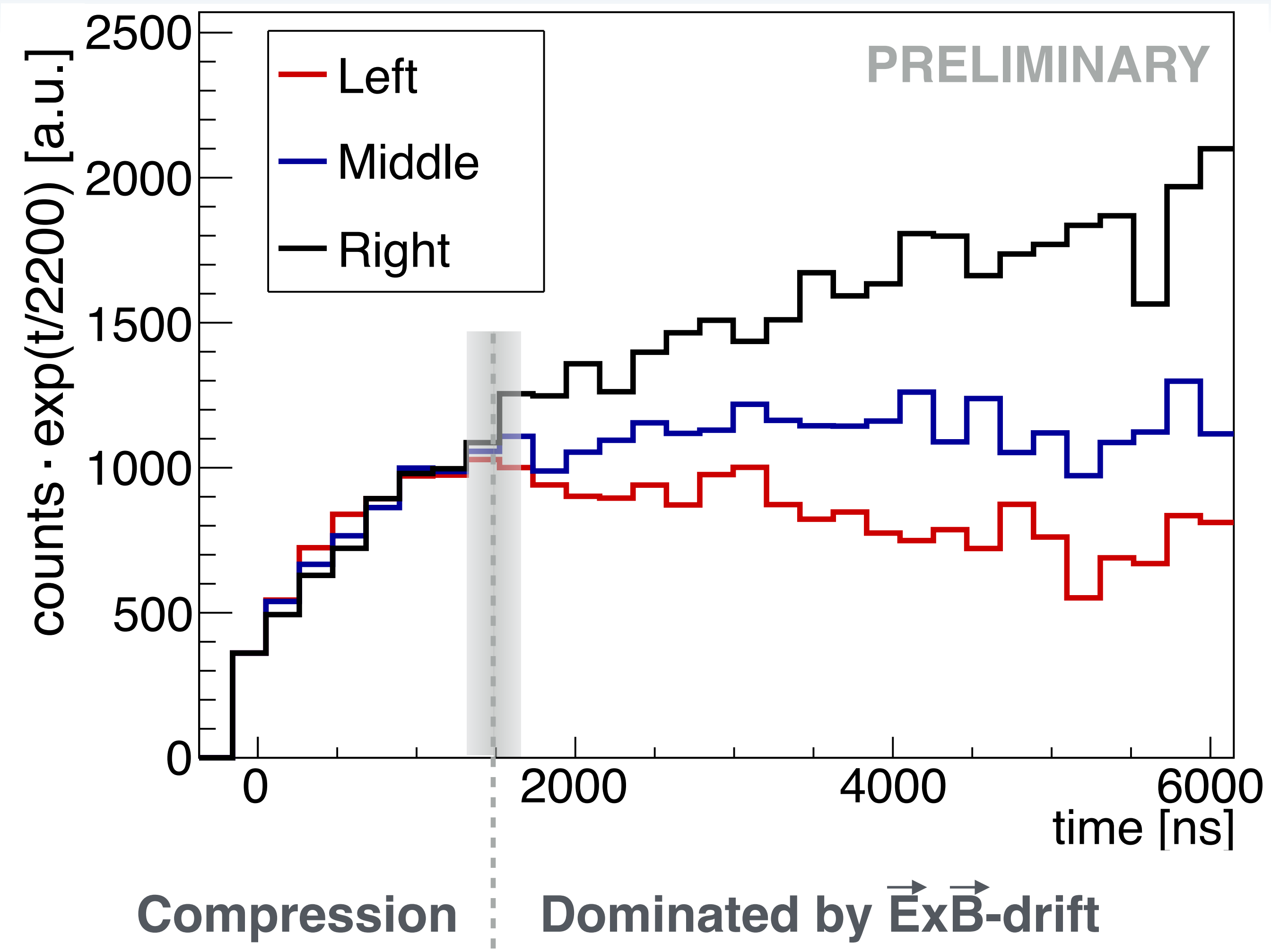
$\vec{E}\mathrm{x}\vec{B}$-Drift



- Add vertical (y) component to $\vec{E}$-field
- off-center injection of μ^+
- μ^+ drift in $\vec{E}\mathrm{x}\vec{B}$-direction

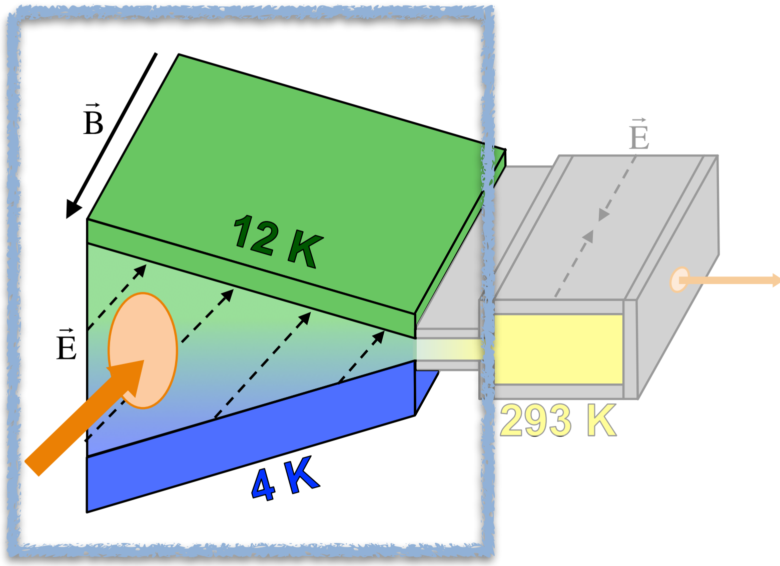
$\vec{E}\mathrm{x}\vec{B}$-Drift

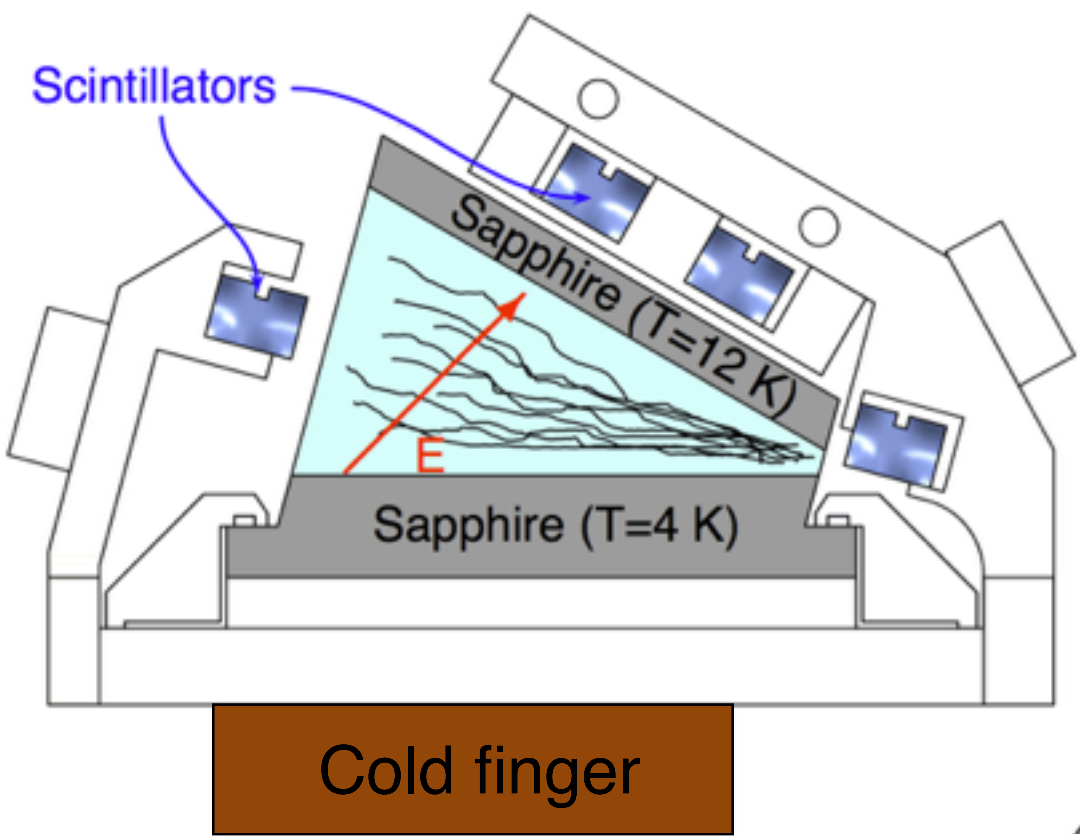




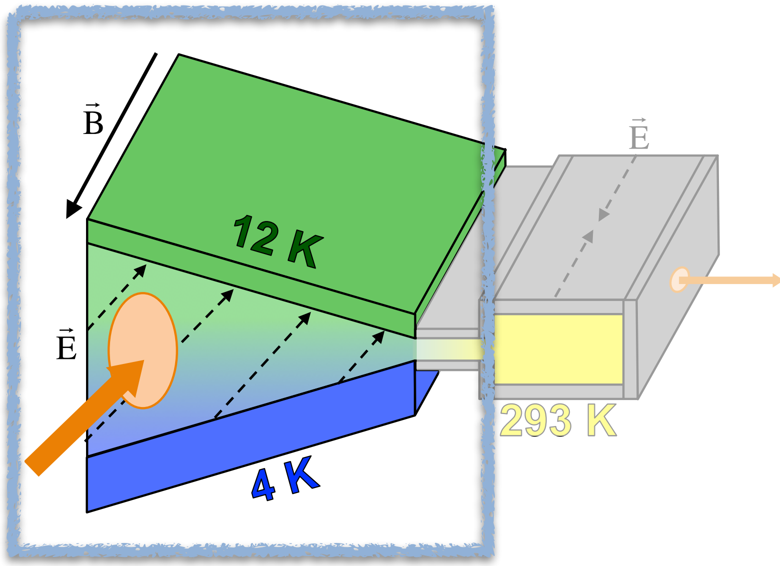
- Add vertical (y) component to E-field
- off-center injection of μ^+
- μ^+ drift in $\vec{E}\mathrm{x}\vec{B}$-direction

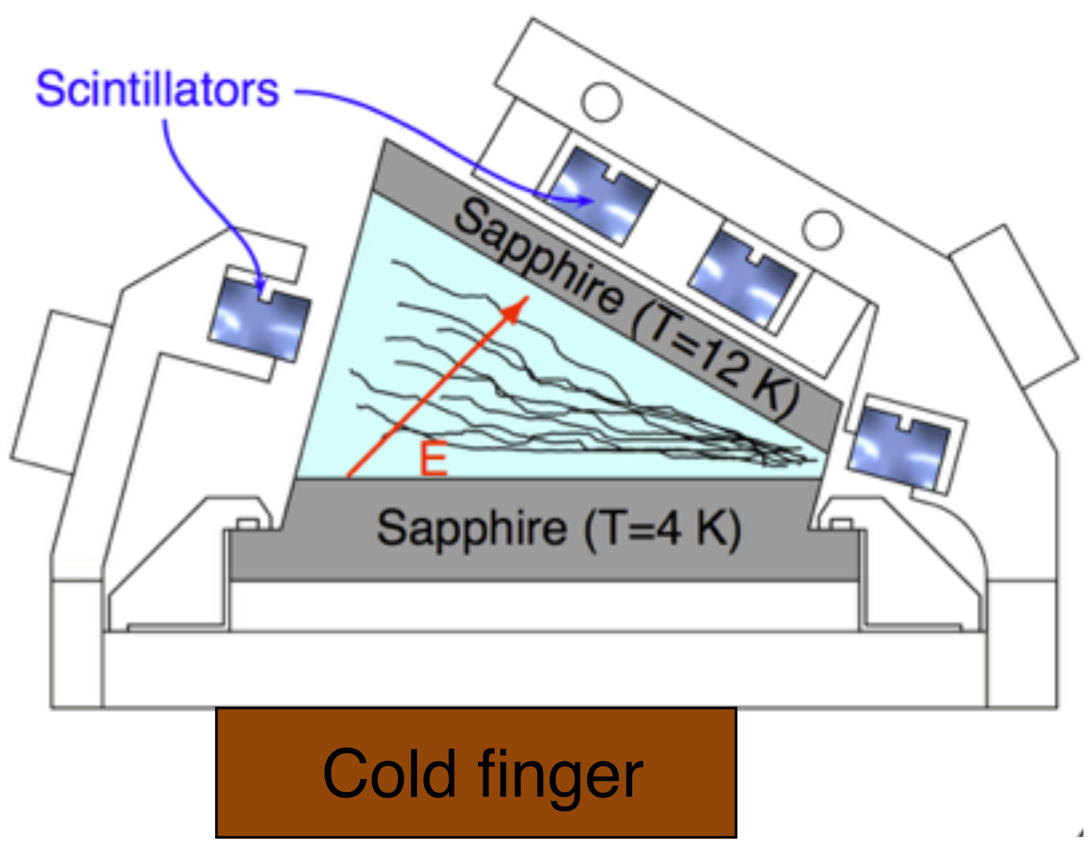
2014 - Transverse Compression





2014 - Transverse Compression

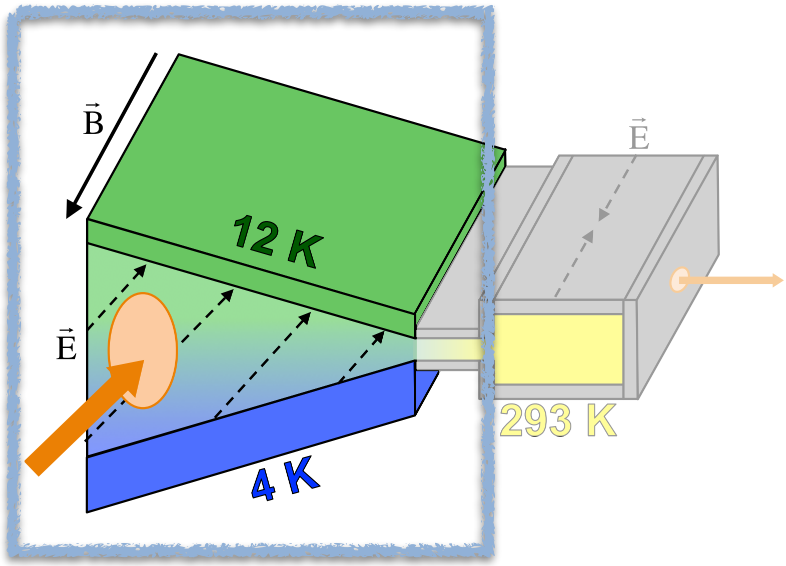




- ✓ First complete assembly
- ✓ Cold temperatures reached
- ✓ Positron detectors worked
- ✓ Beam alignment understood

- ✦ Gas leak at cold temperatures
- ✦ HV problems: HV dividers and connectors on sapphire
- ✦ Electric discharges

2015 - Transverse Compression



- ✓ First complete assembly
- ✓ Cold temperatures reached
- ✓ Positron detectors worked
- ✓ Beam alignment understood

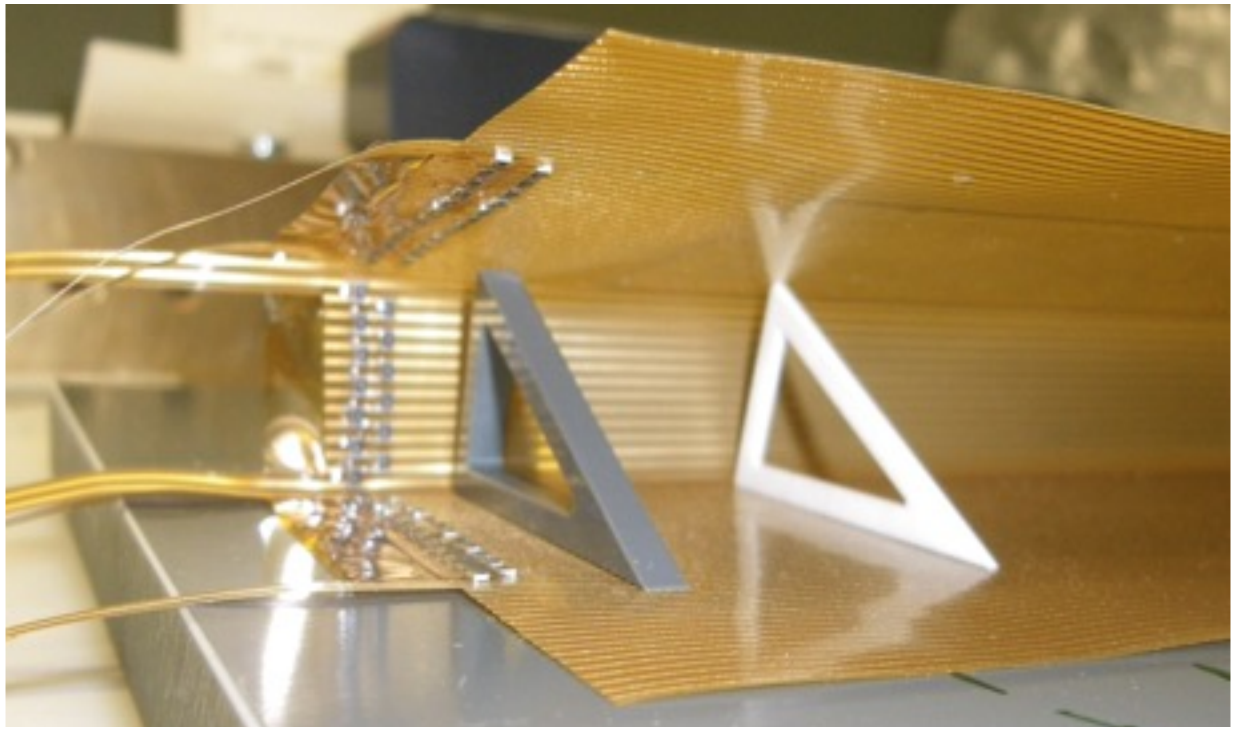
- ✦ Gas leak at cold temperatures
- ✦ HV problems: HV dividers and connectors on sapphire
- ✦ Electric discharges

1 year of improvements

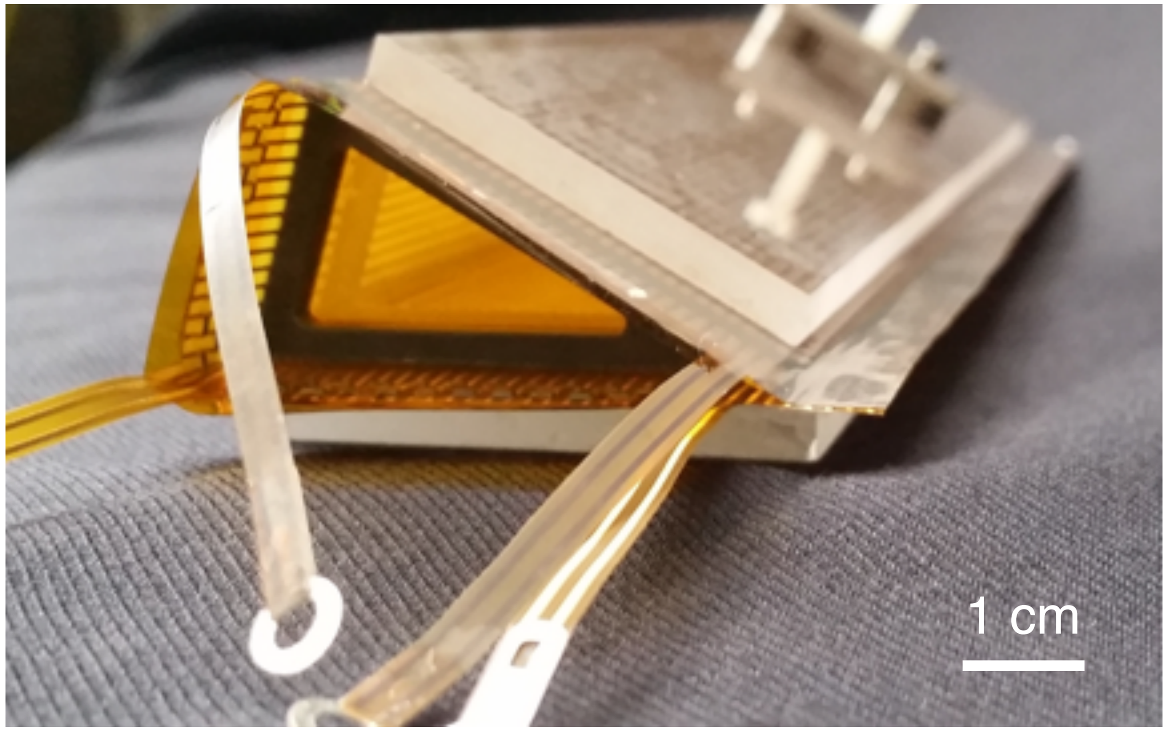
- ➡ Leak tight at cold, even after several thermal cycles
- ➡ Temperature gradient: 6.1 - 18.6 K (inside 5 T solenoid)
- ➡ HV stability: Up to 1.5 kV/cm @ 7.5 mbar, 6-18 K

Transverse Target

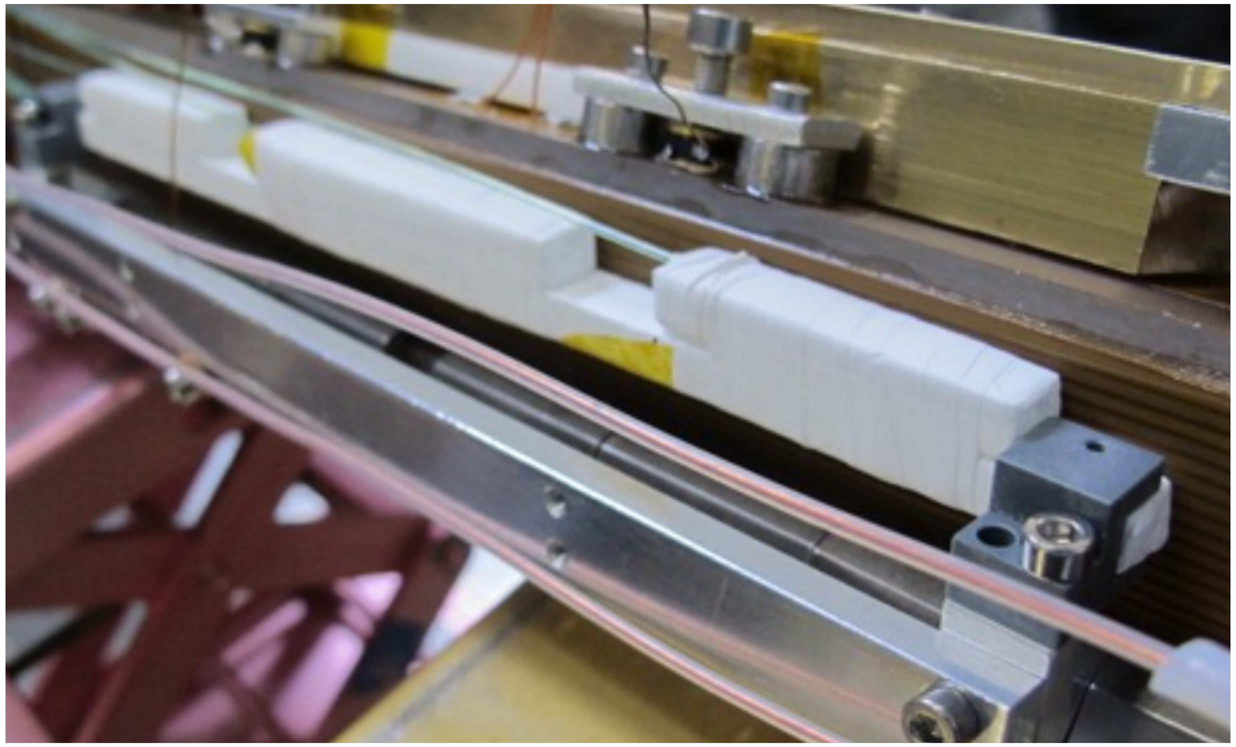
During construction



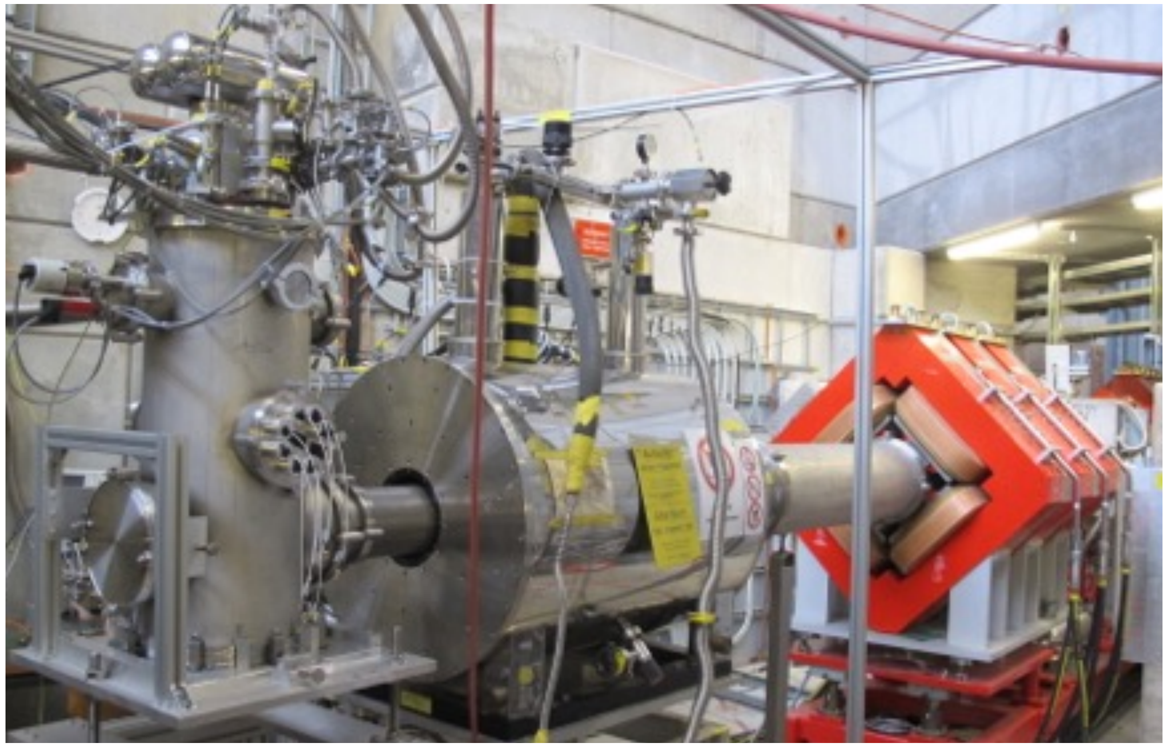
Finished target



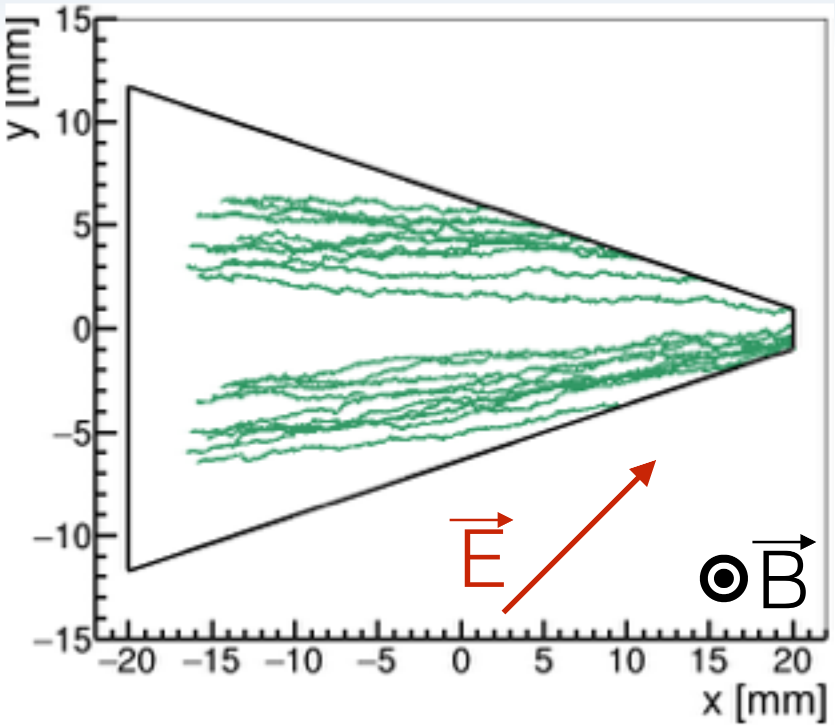
Scintillators wrapped in Teflon



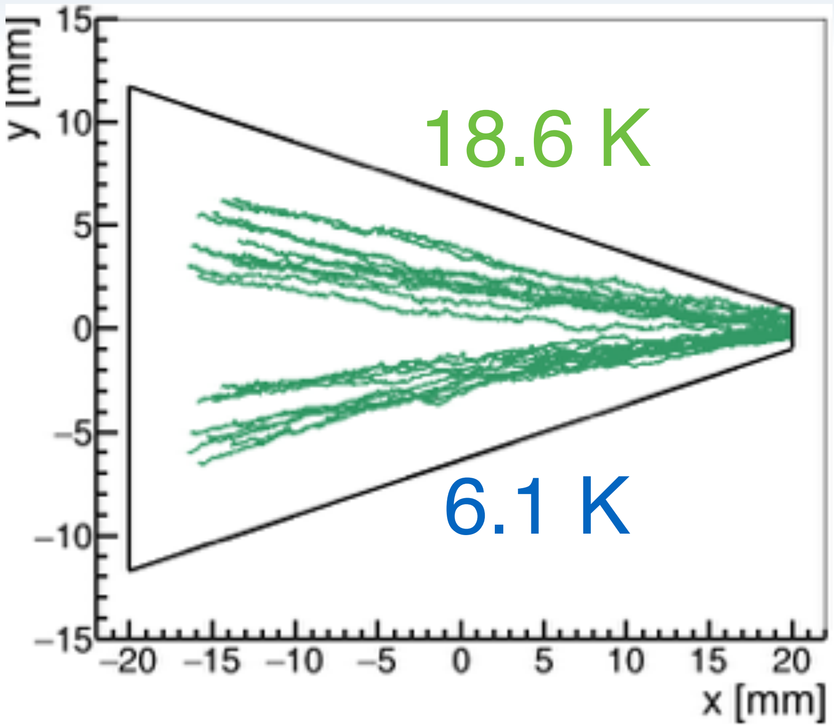
Setup at πE1



Simulations of Transverse Compression



No temperature gradient

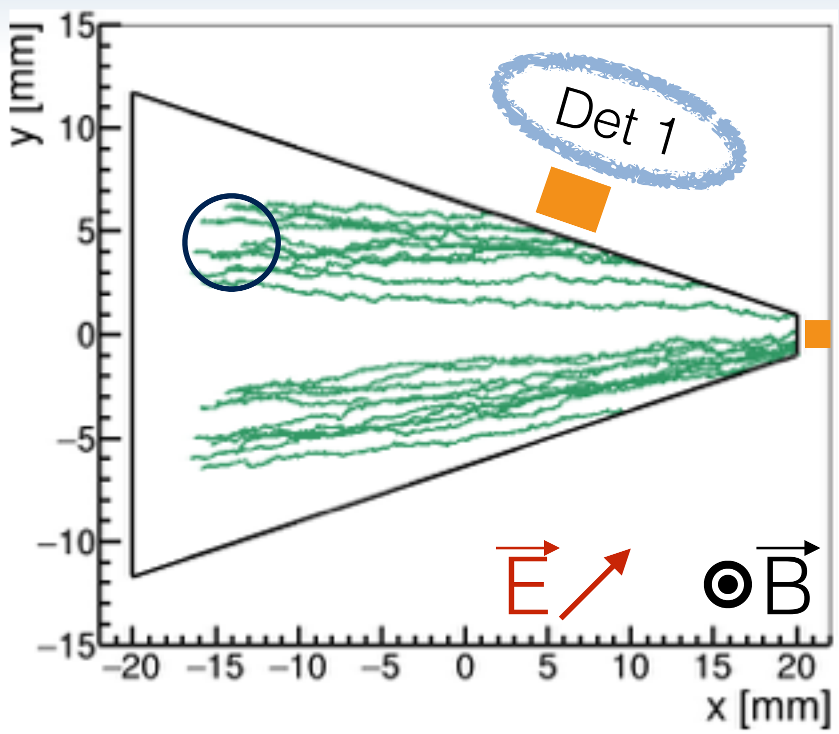


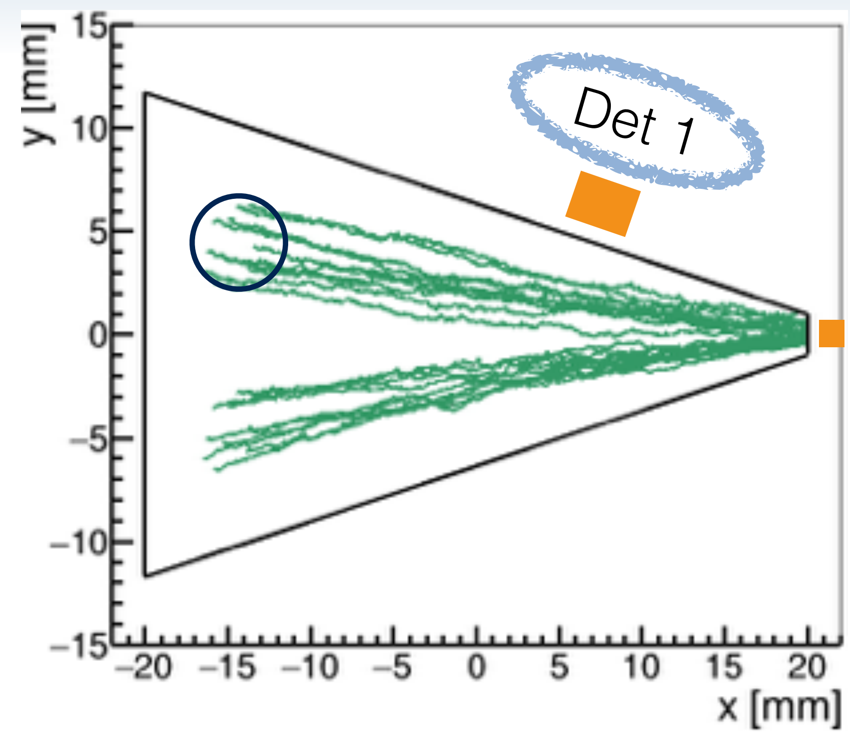
Temperature gradient

~~no position-dependent $\vec{v}_{drift}$~~

position-dependent $\vec{v}_{drift}$ ✓

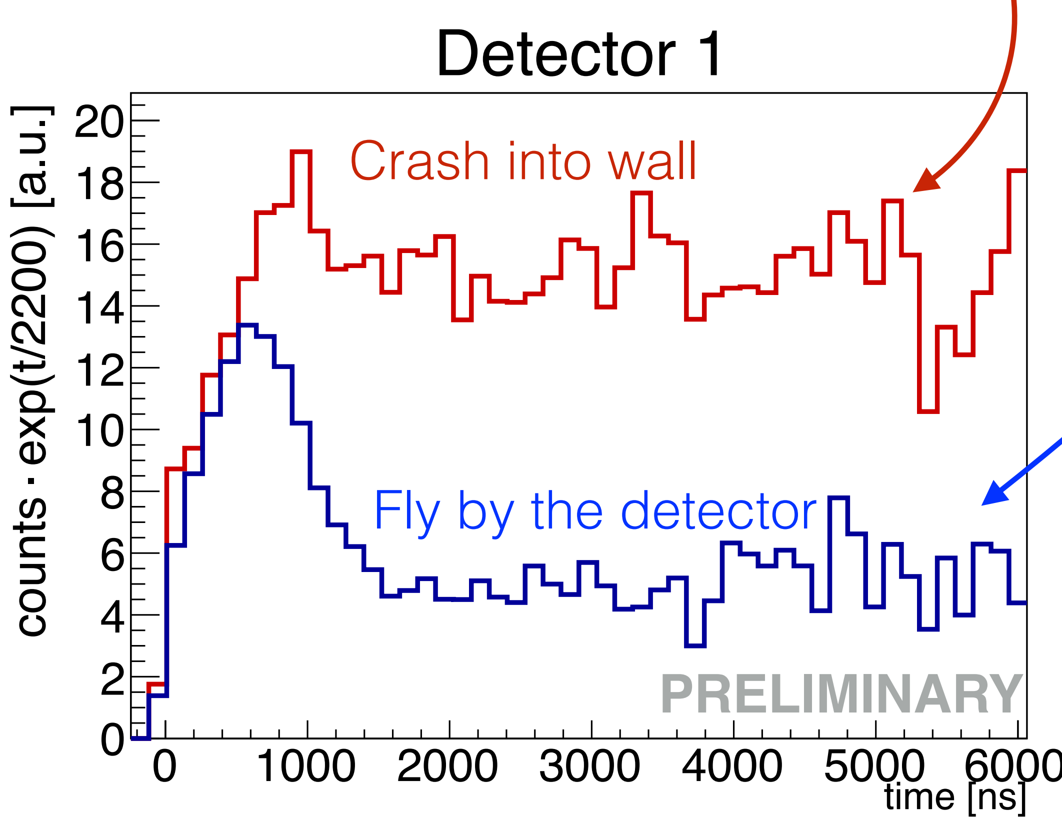
Demonstration of Transverse Compression



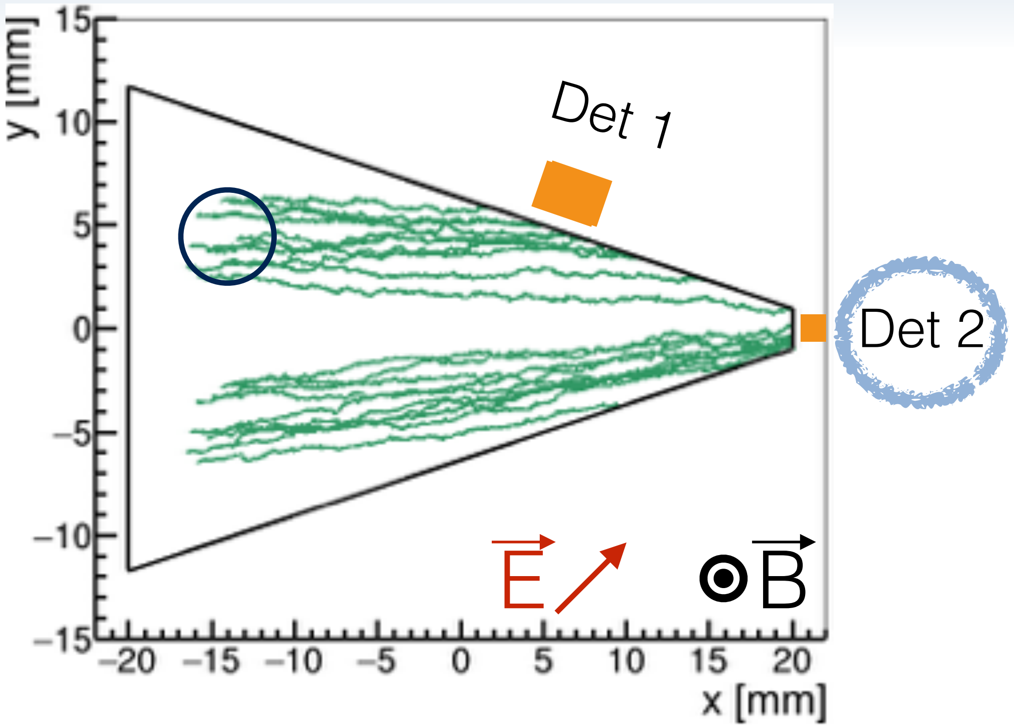


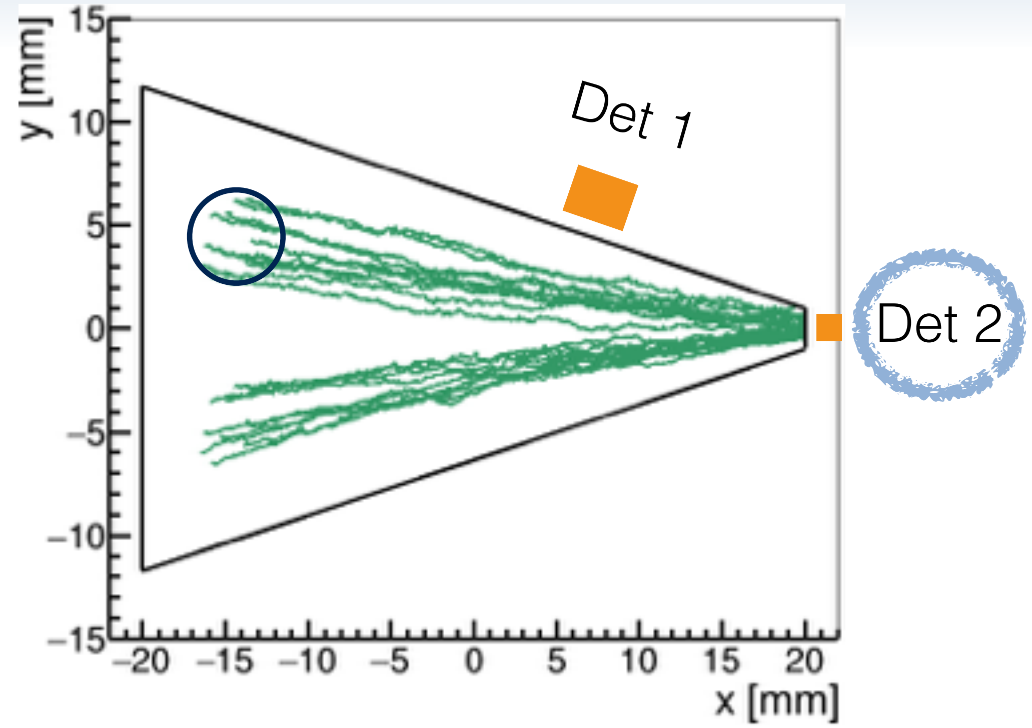
No temperature gradient

Temperature gradient



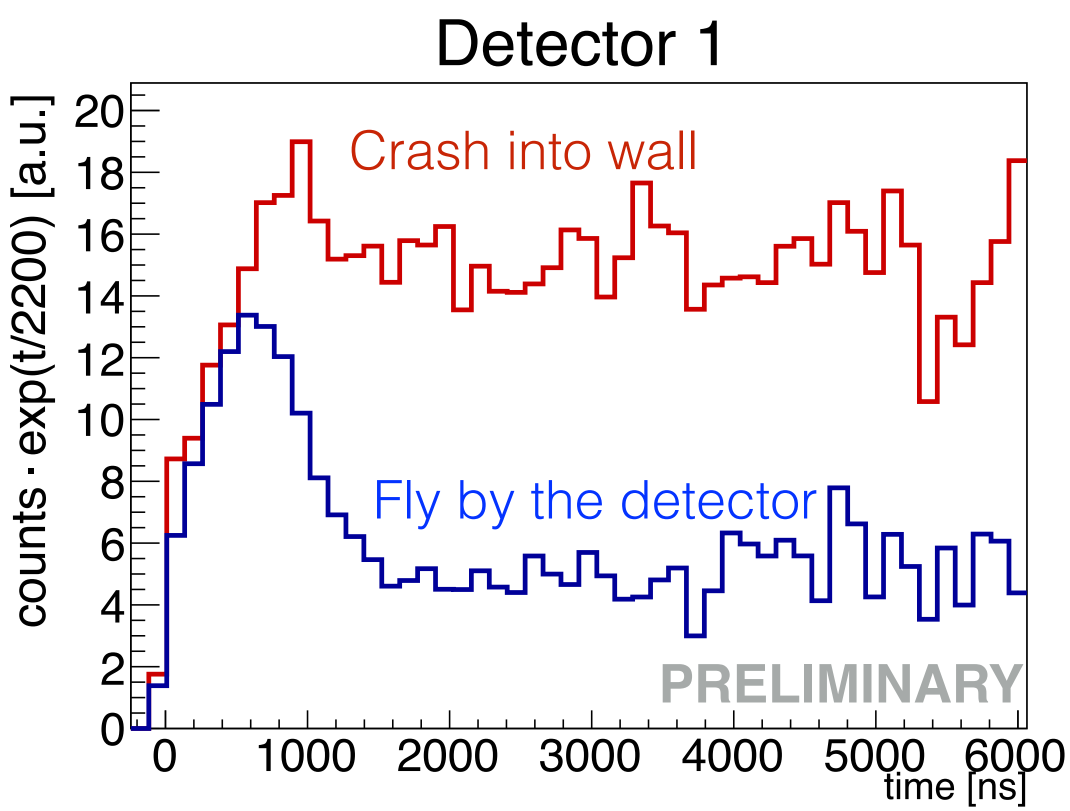
Demonstration of Transverse Compression

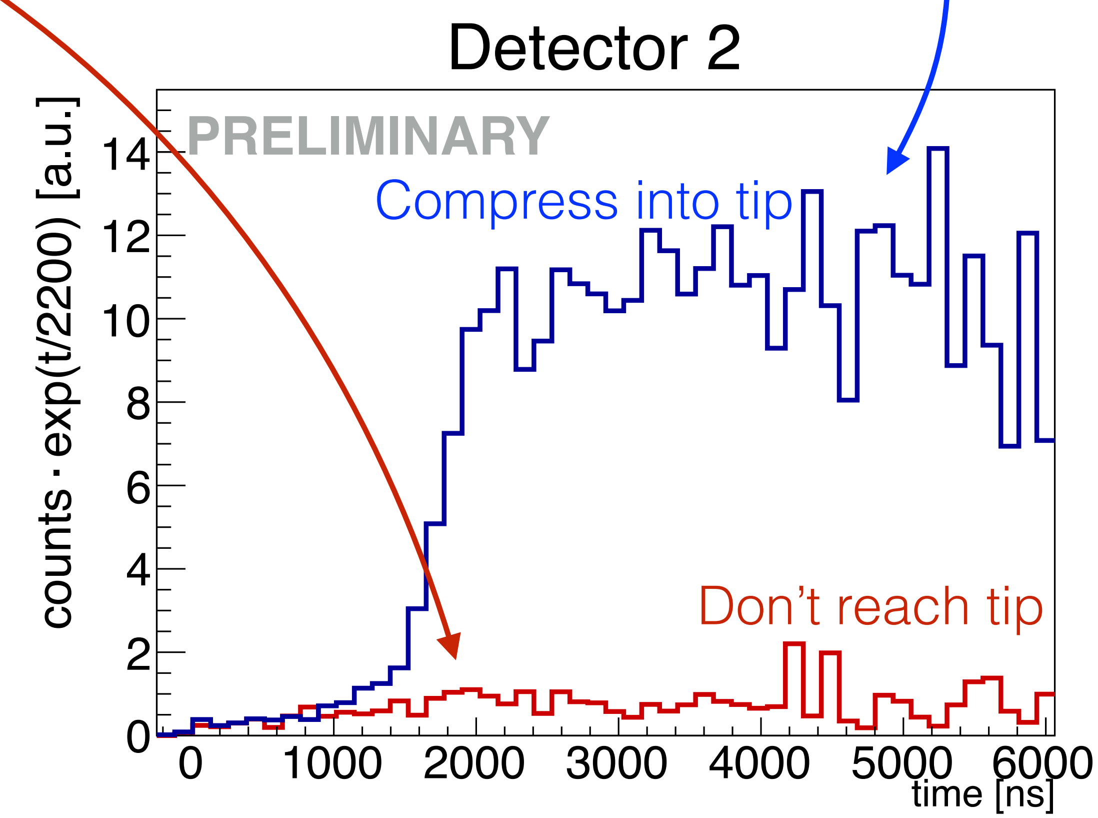




No temperature gradient

Temperature gradient





Conclusion

4 weeks of beam time in 2015

- ✓ Longitudinal compression with low background
- ✓ $\vec{E}\mathrm{x}\vec{B}$-drift after longitudinal compression
- ✓ Transverse setup works well
- ✓ Transverse compression demonstrated

2016: Further setup development

- Data analysis, comparison with simulations
- Combine cold transverse and warm longitudinal stage
- Test extraction into vacuum
- ➡ Requires about 1 year of lab work & offline tests

Thanks to:

Konrad Deiters

Florian Barchetti

Franz Kottmann

Thomas Prokscha

Urs Greuter

Michael Horisberger

Robert Scheuermann

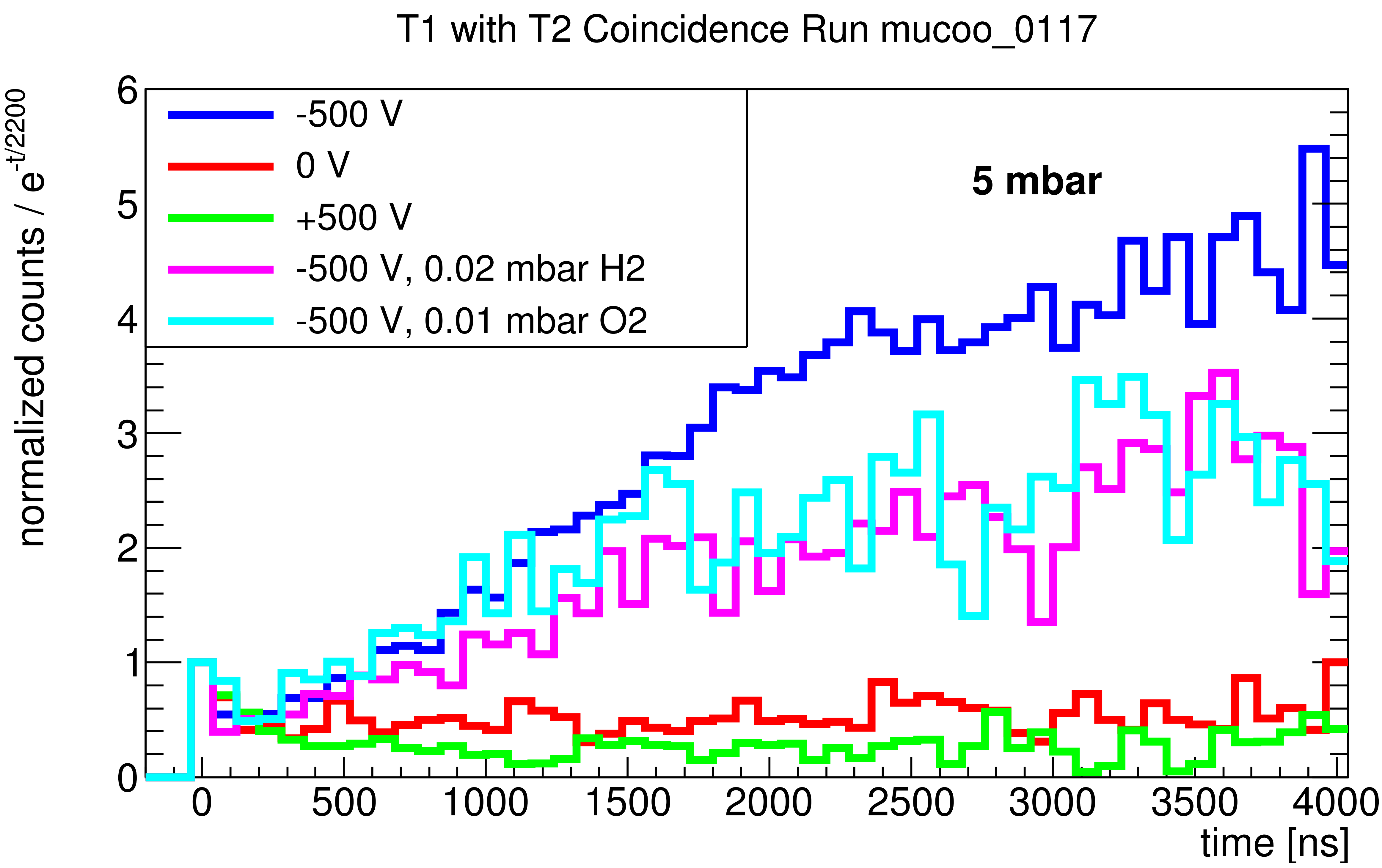
PSI and ETH workshops

PSI support groups

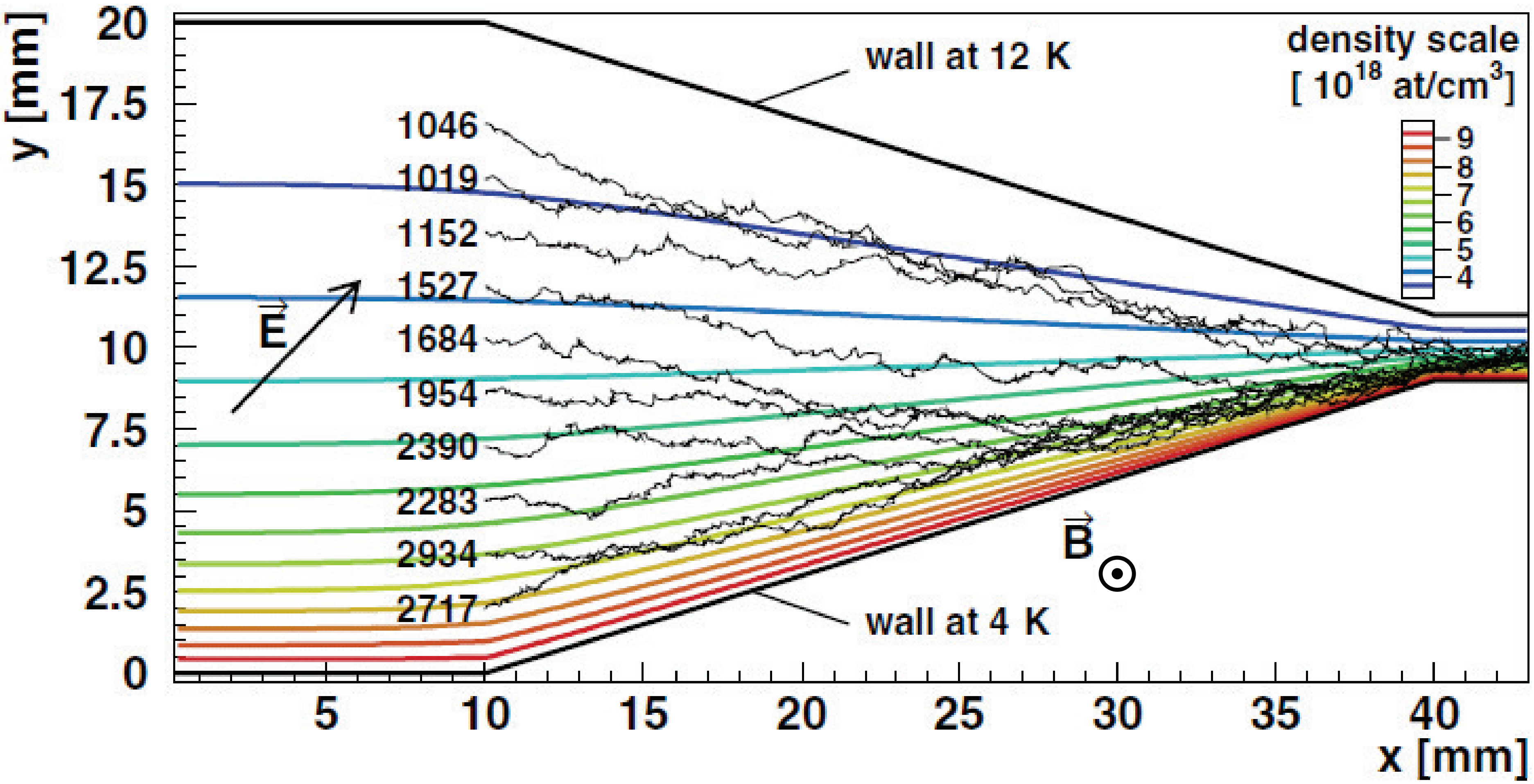
… and thank you for your attention!

Back ups…

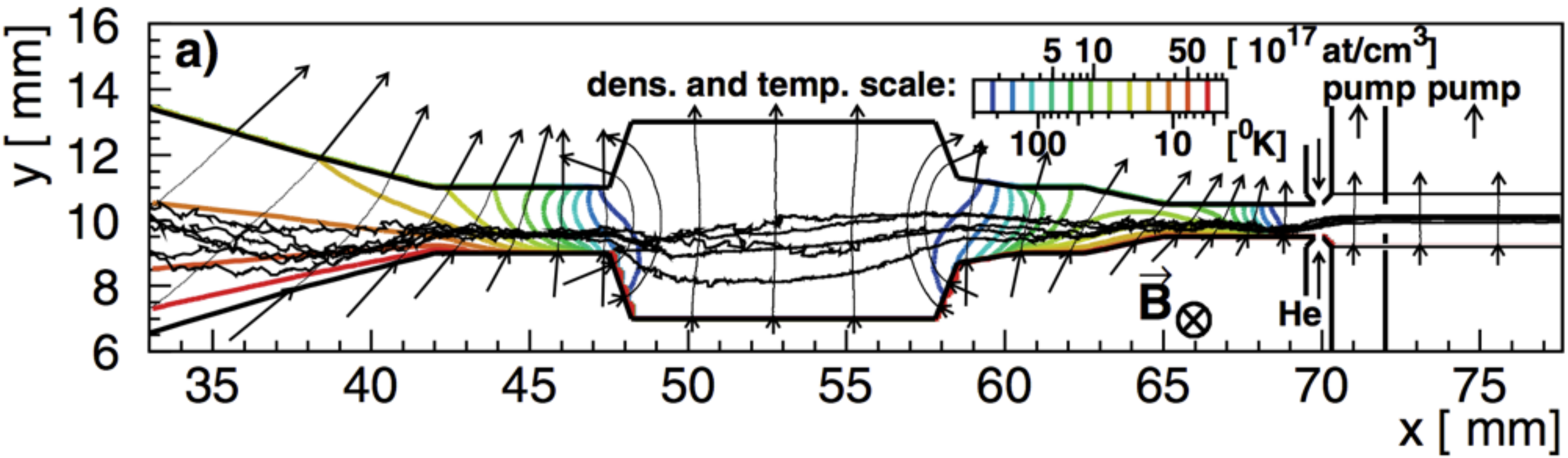
Impurities - 2014



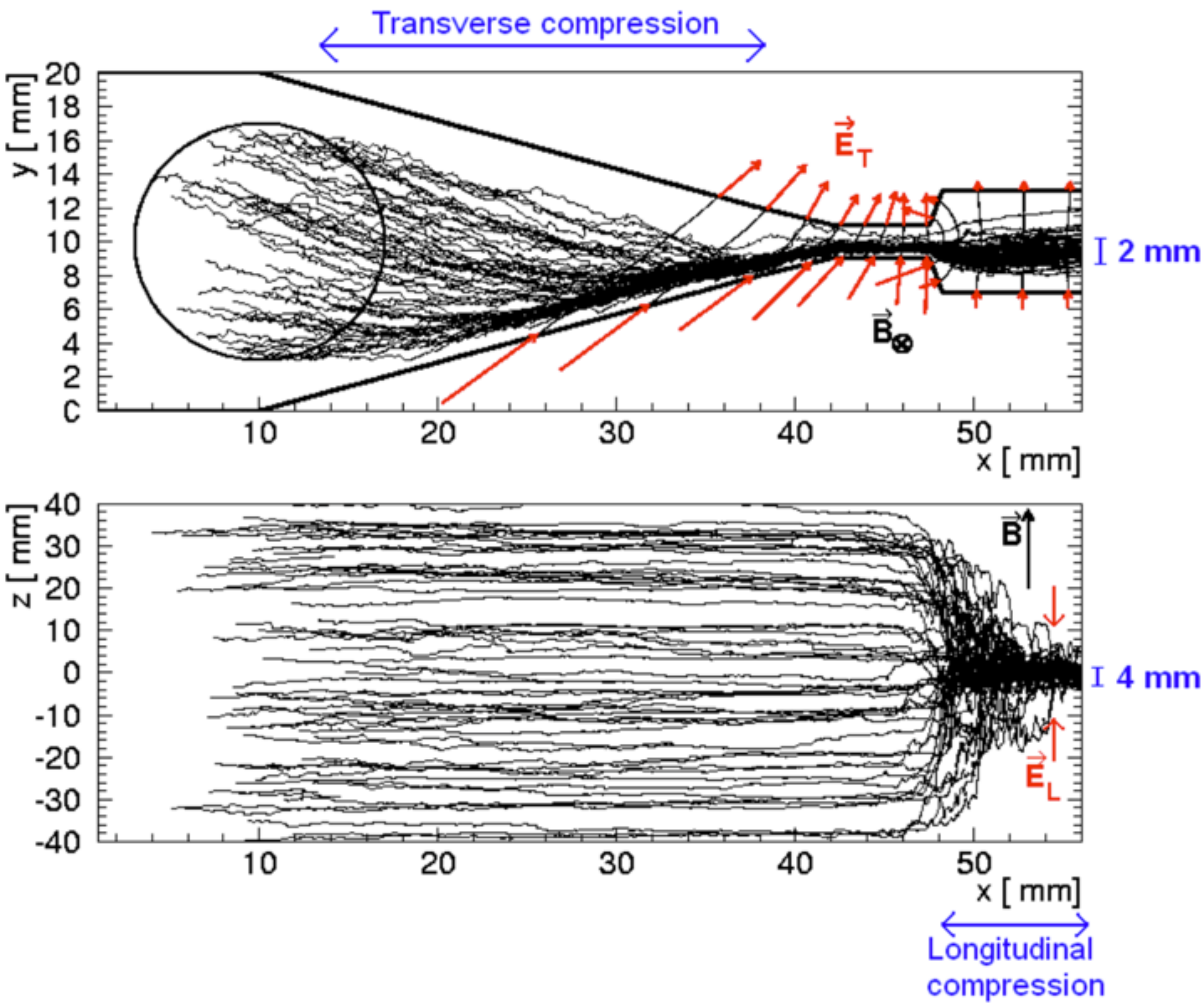
Simulation: Transverse Compression (D. Taqqu, 2006)



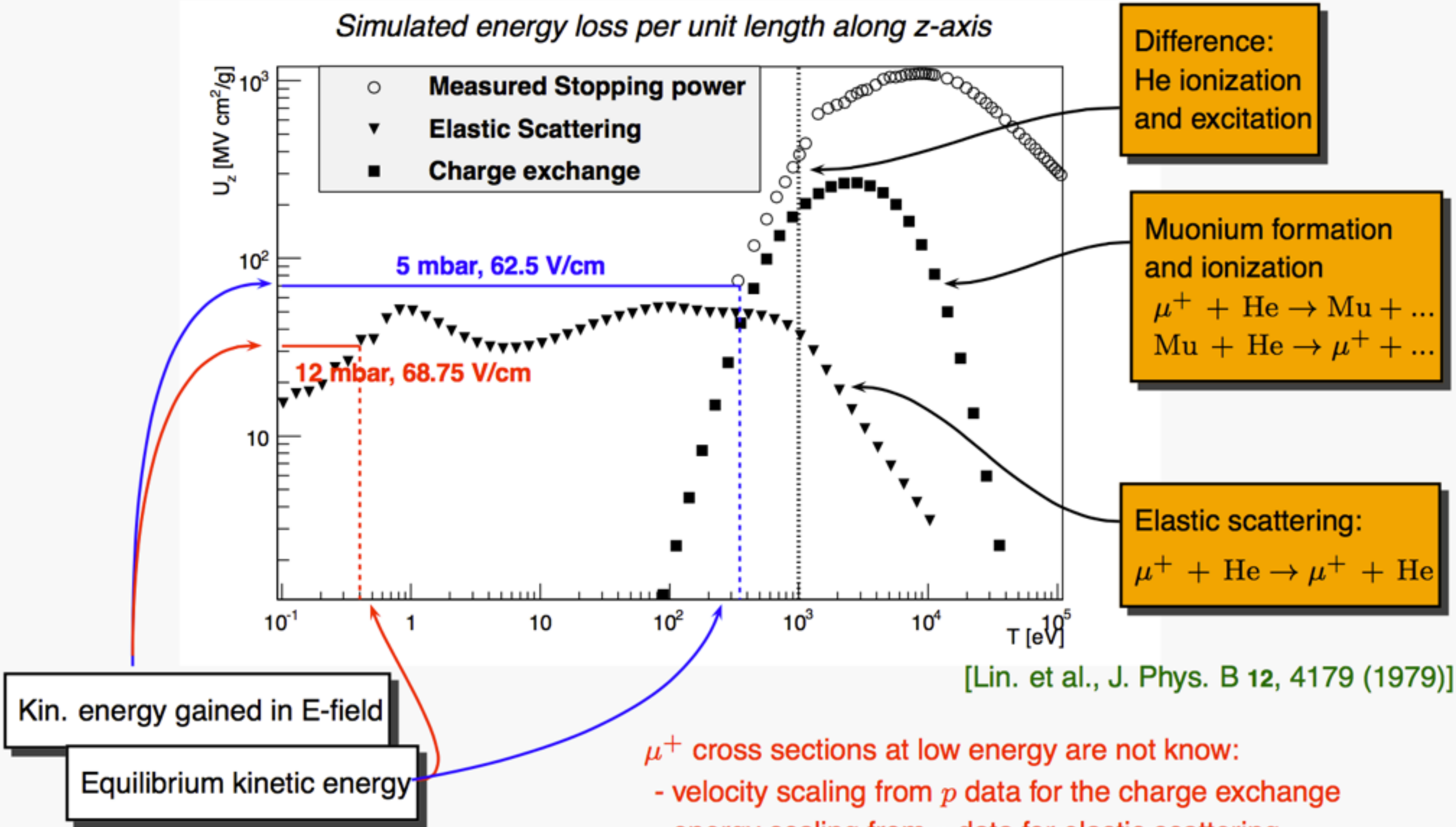
Simulation: Full Compression (D. Taqqu, 2006)



Simulation: Projections of Compression (D. Taqqu, 2006)



Energy loss

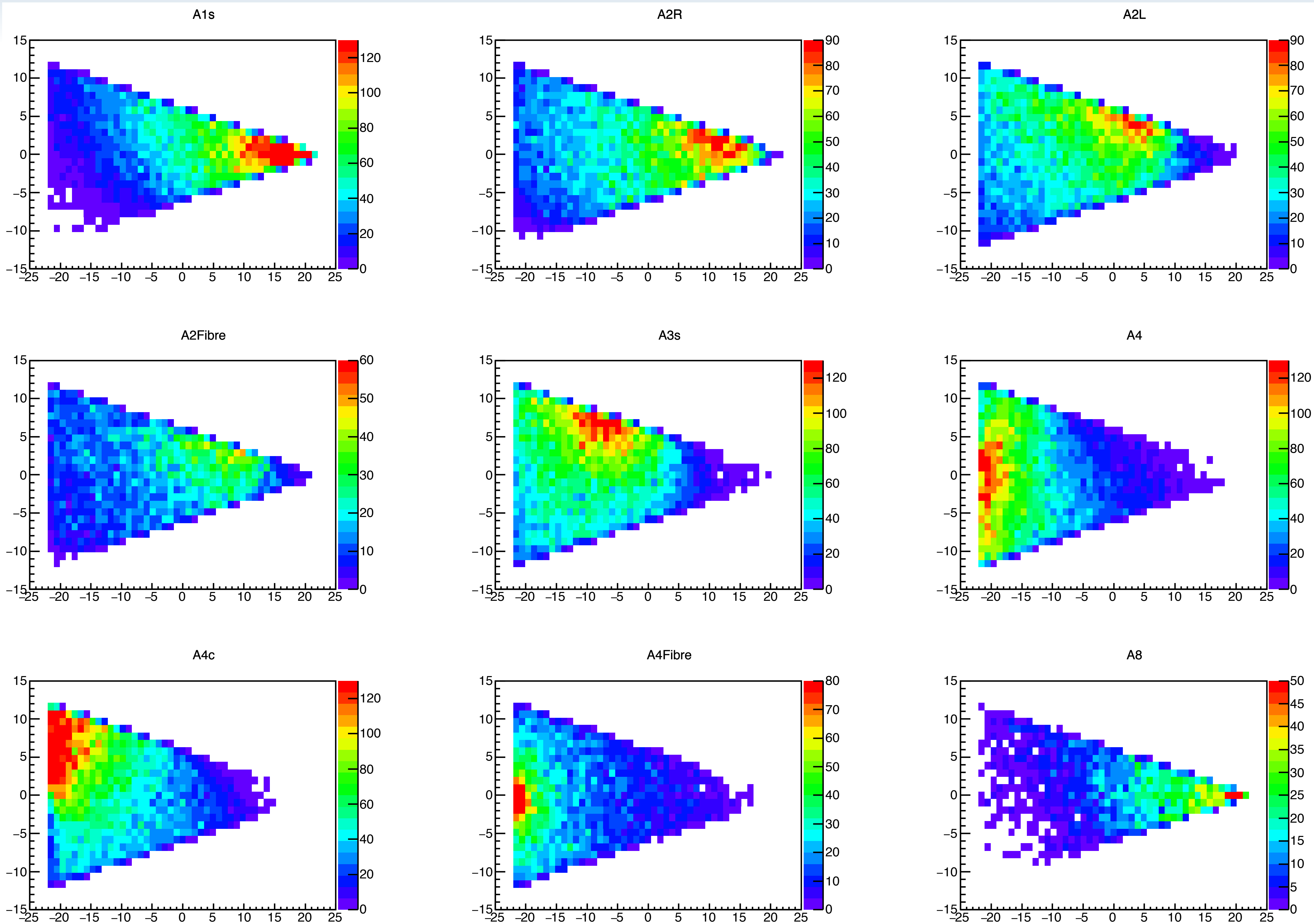


[Lin. et al., J. Phys. B **12**, 4179 (1979)]

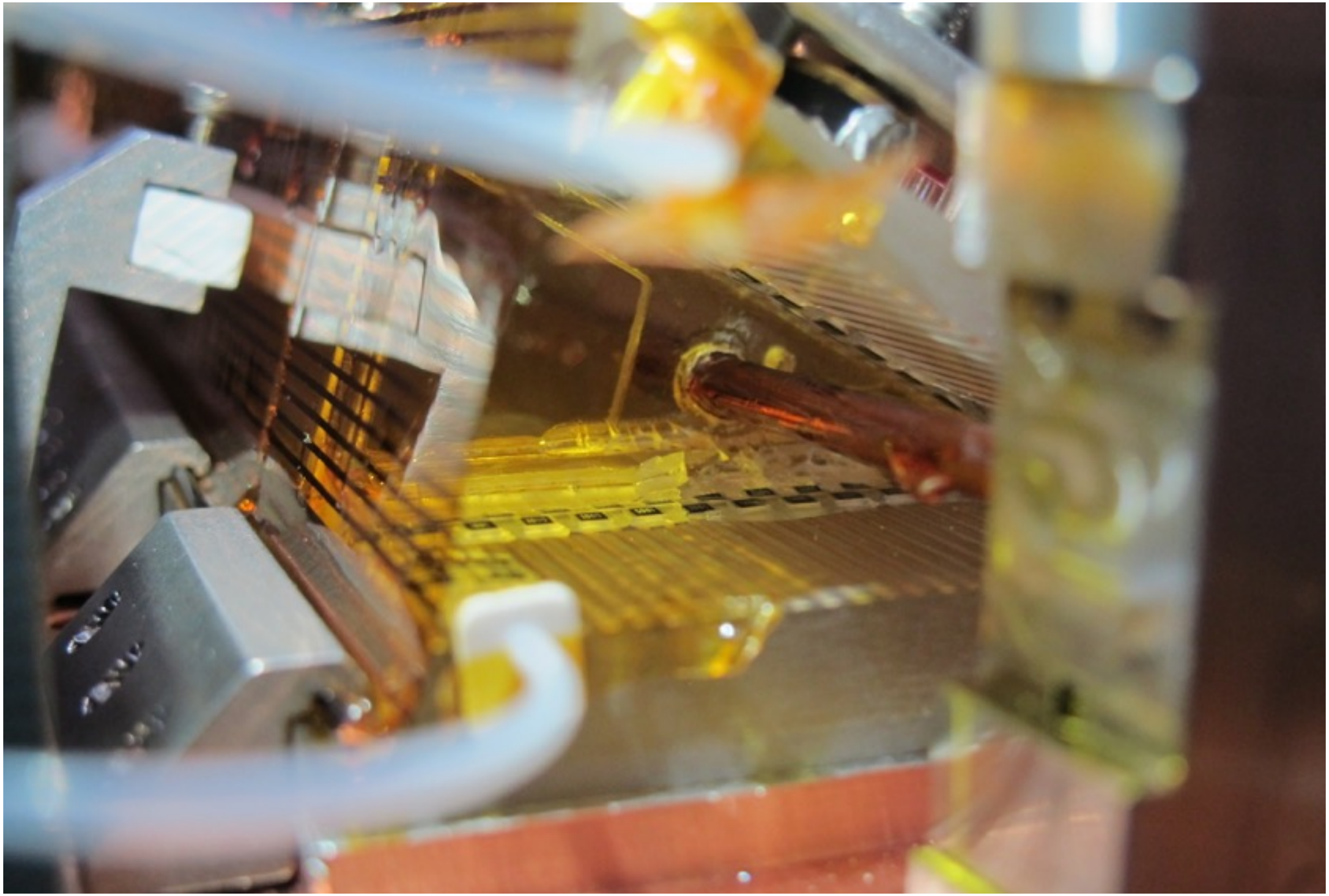
μ^+ cross sections at low energy are not know:

- velocity scaling from p data for the charge exchange
- energy scaling from p data for elastic scattering

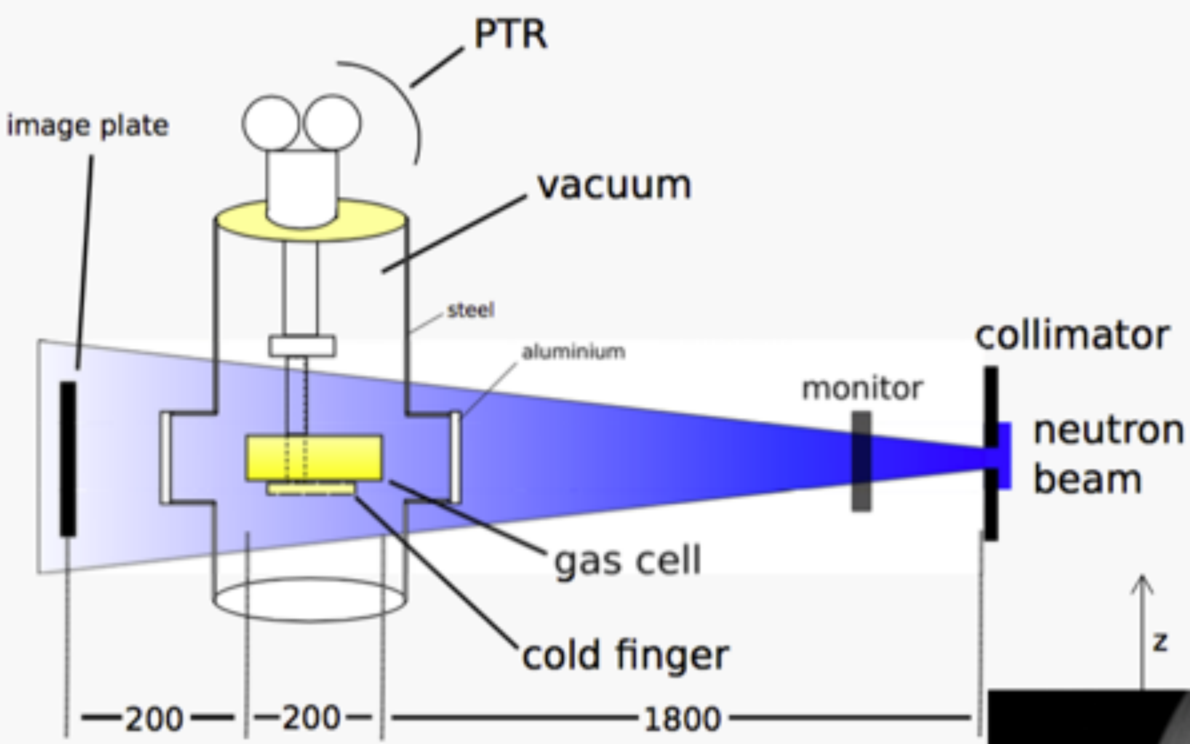
Acceptance Map 2015

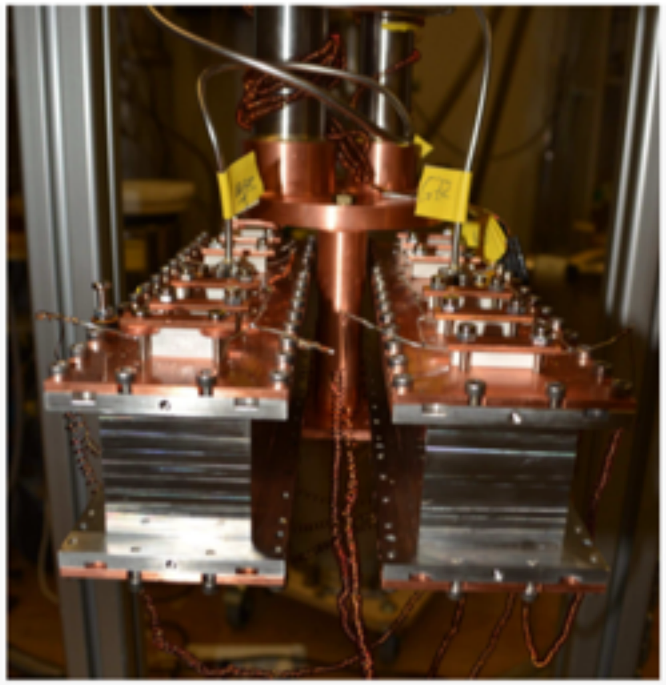


Engineering Run of Transverse 2014



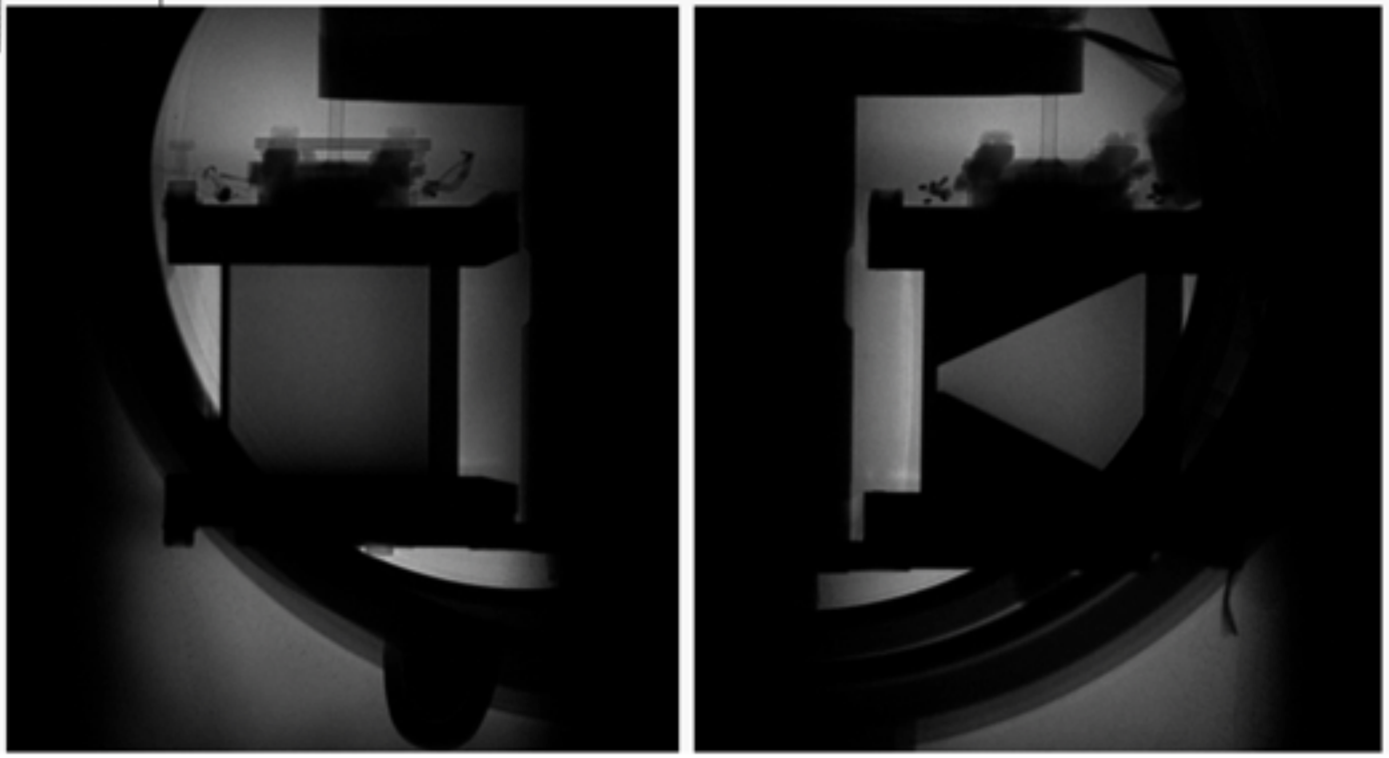
Density Gradient (I)



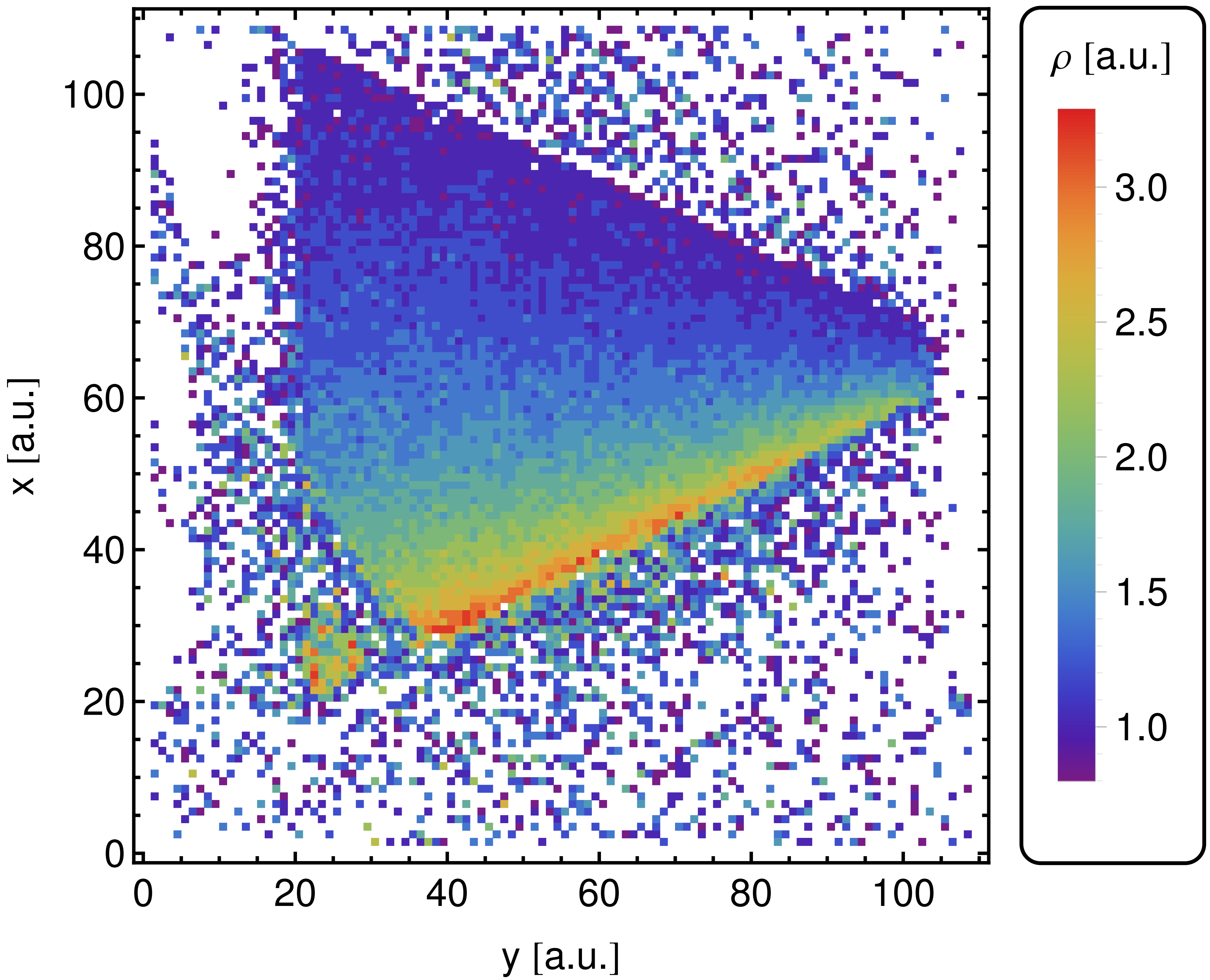


(Morpheus beam line, PSI)

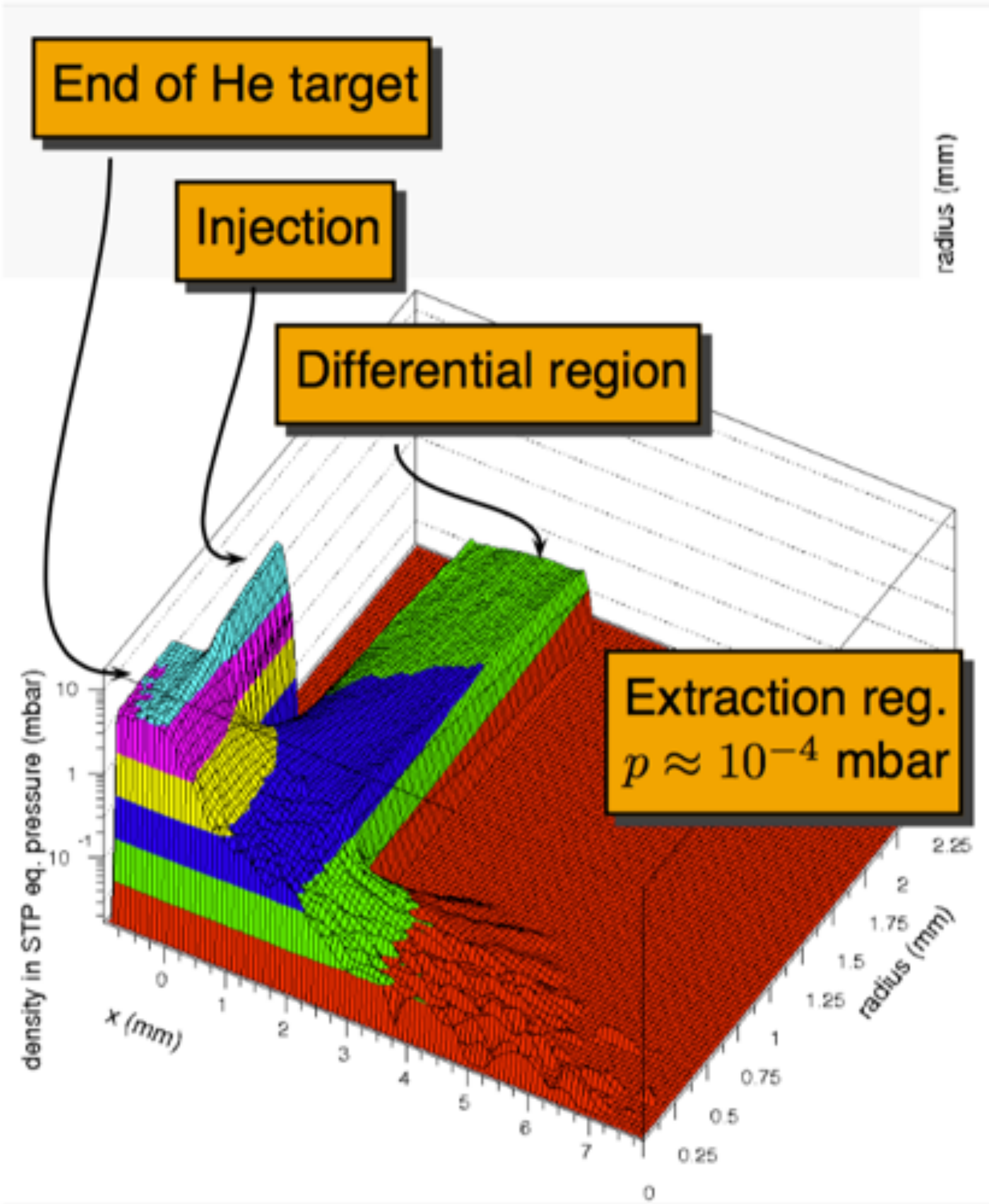
(Raw data/images) →

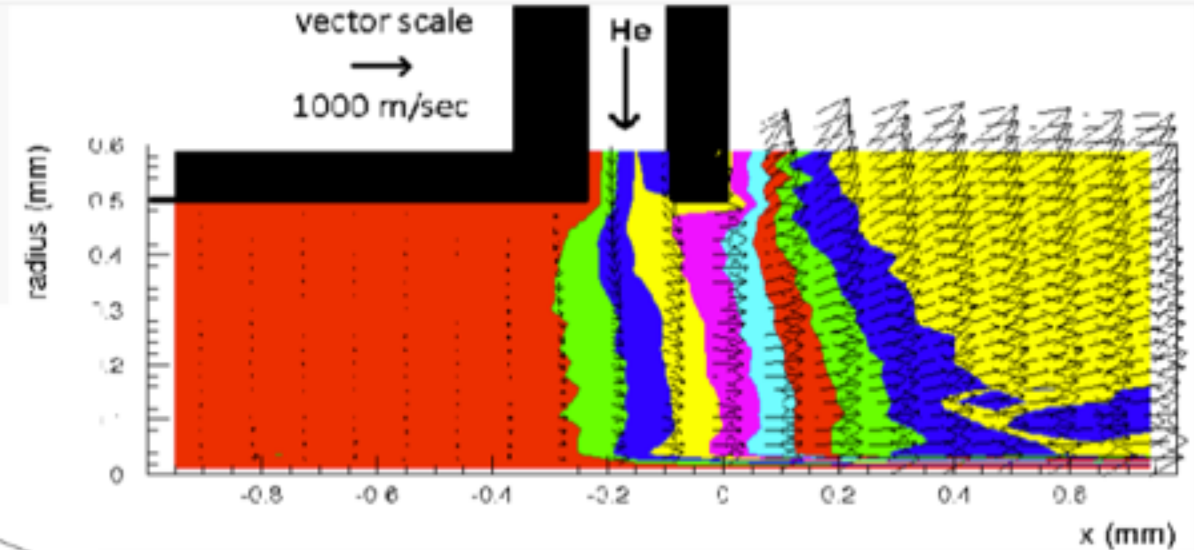


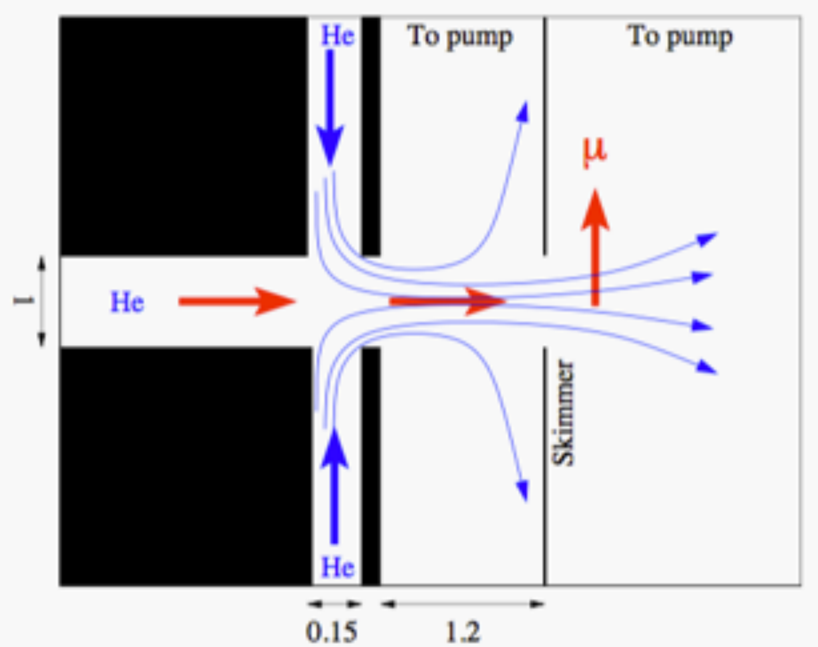
Density Gradient (II)



Extraction from Vacuum

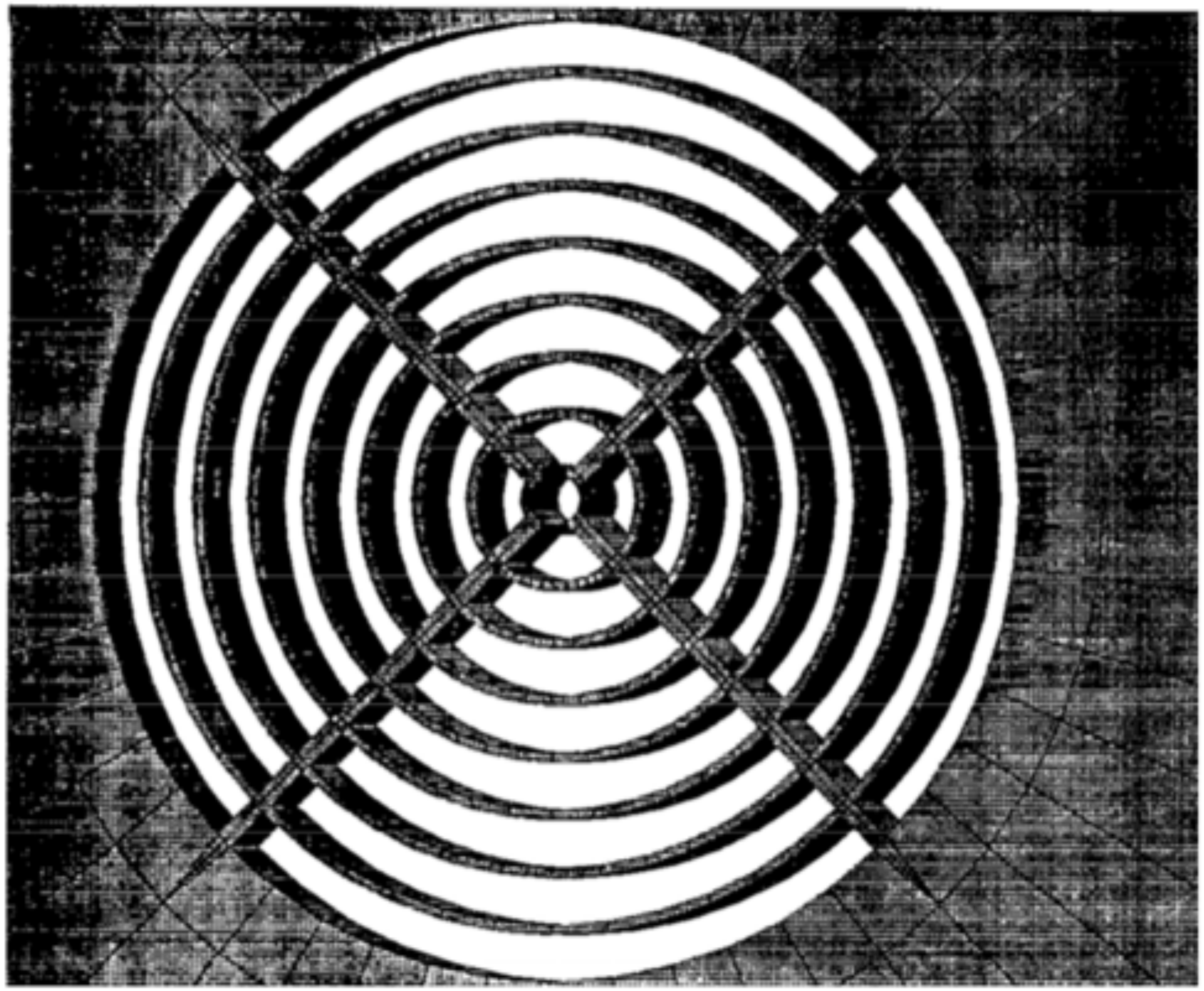




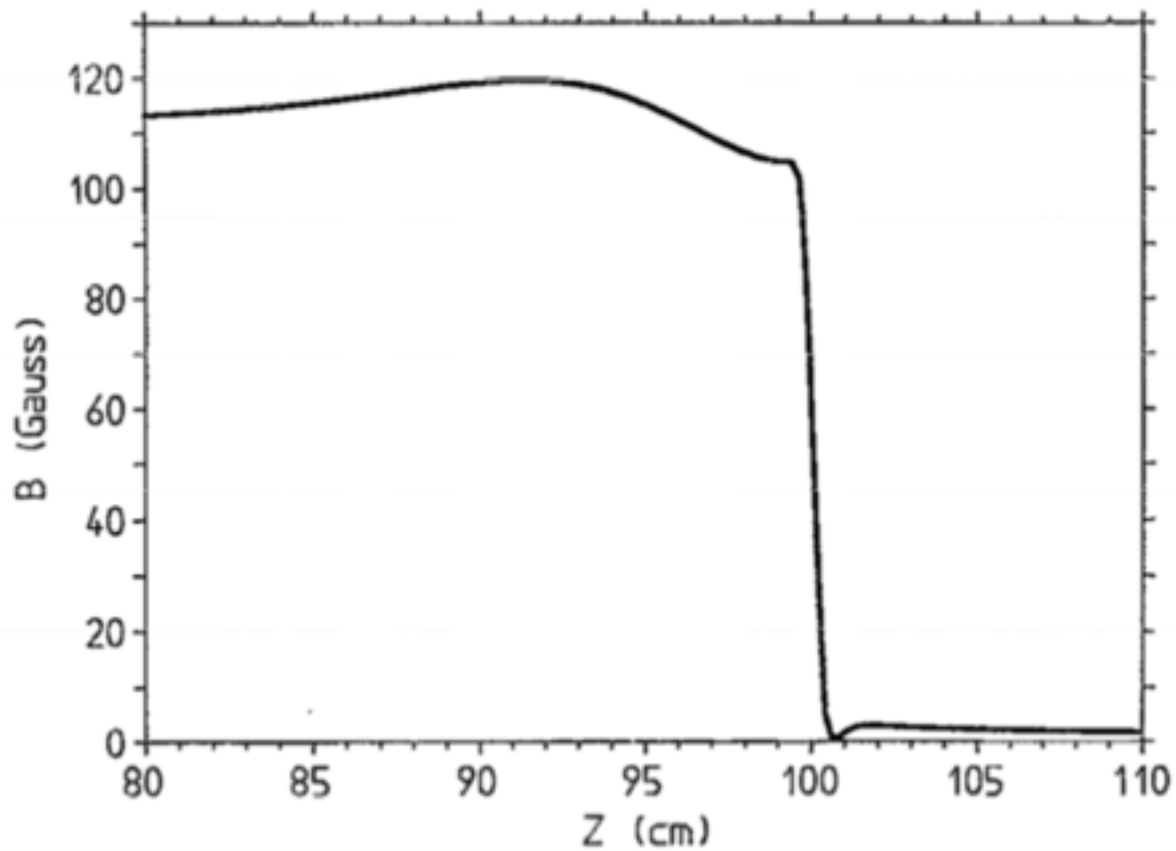


- No flow inside target!
- Reinjection of helium “blocks” outflow of helium from target cell and compensates losses

Extraction from B-Field



Gerola et al., Rev. Sci. Inst. **66**, 3819 (1995)



- Field termination with a magnetic grid
- Tested with slow positrons/electrons
- ~50% transmission and increased transverse energy by O(10 eV)