muCool: Towards a much improved phase space slow positive muon beam

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for the muCool Collaboration

Overview

- Existing slow muon sources
- muCool principle
- Experimental tests of longitudinal and transverse compression
- Conclusions

Why Slow, High-Brightness Muon Beams?

- Particle physics experiments:
  - Efficient formation of muonium for muonium spectroscopy, muonium-antimuonium conversion searches, muonium gravity tests, …
  - Improved injection into magnetic systems and much improved beam quality for muon g-2, muon EDM, …
- Material science (µSR) applications:
  - Study of surface effects
  - Study of small samples

LEMS at PSI

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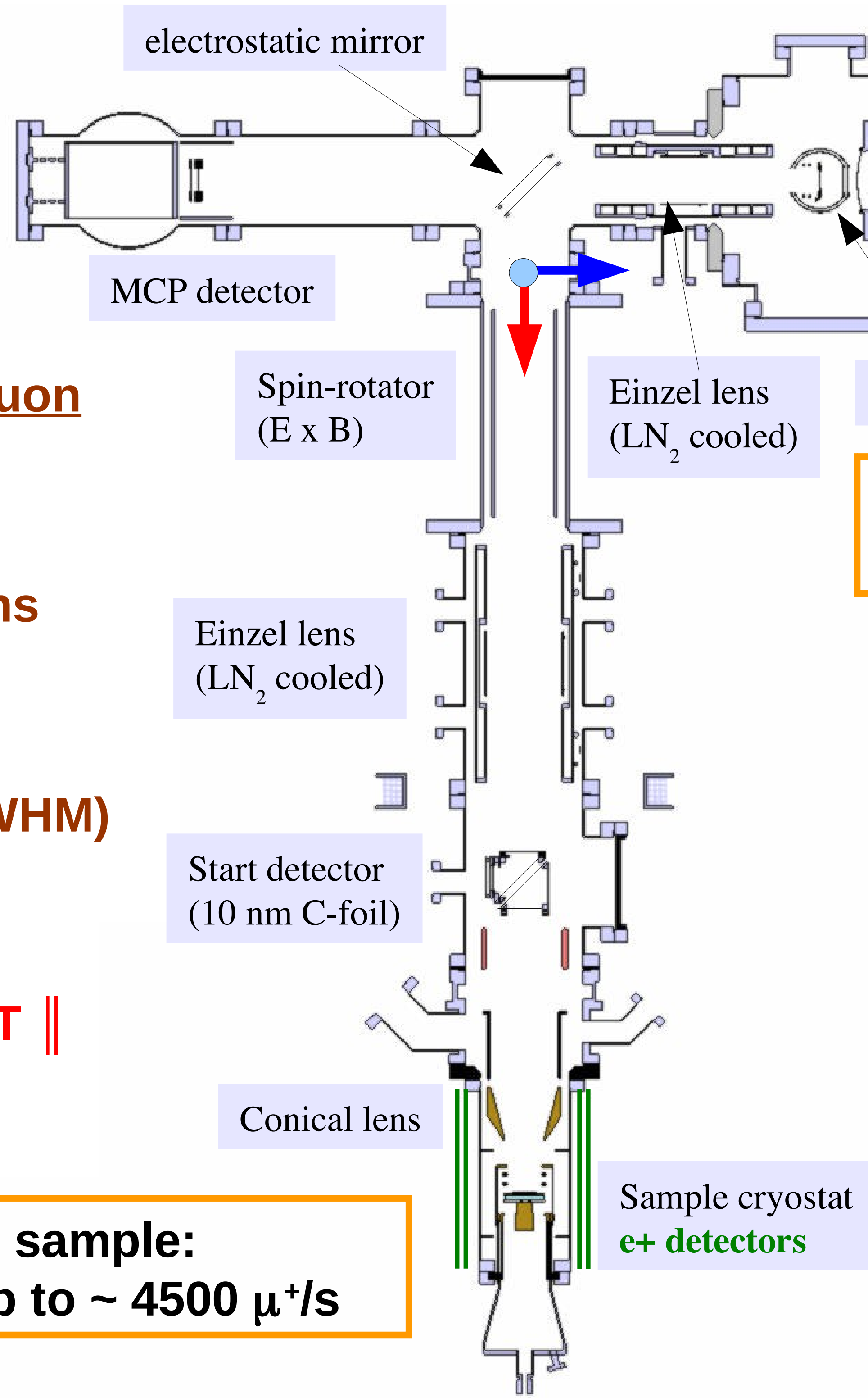
- UHV system, 10^{-10} mbar
- some parts LN_2 cooled



~1.9 • 10^8 μ^+/s

~ 11000 μ^+/s; accelerate up to 20 keV

at sample: up to ~ 4500 μ^+/s

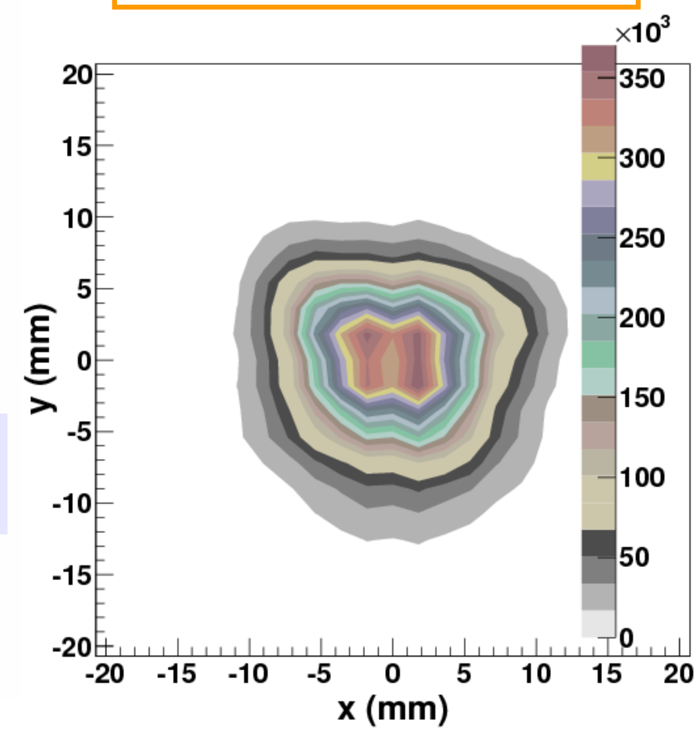
Polarized Low Energy Muon Beam

Energy:	**0.5-30 keV**
ΔE, Δt:	**400 eV, 5 ns**
Depth:	**1 – 300 nm**
Polarization	**~100 %**
Beam Spot:	**12 mm (FWHM)**

Sample environment:

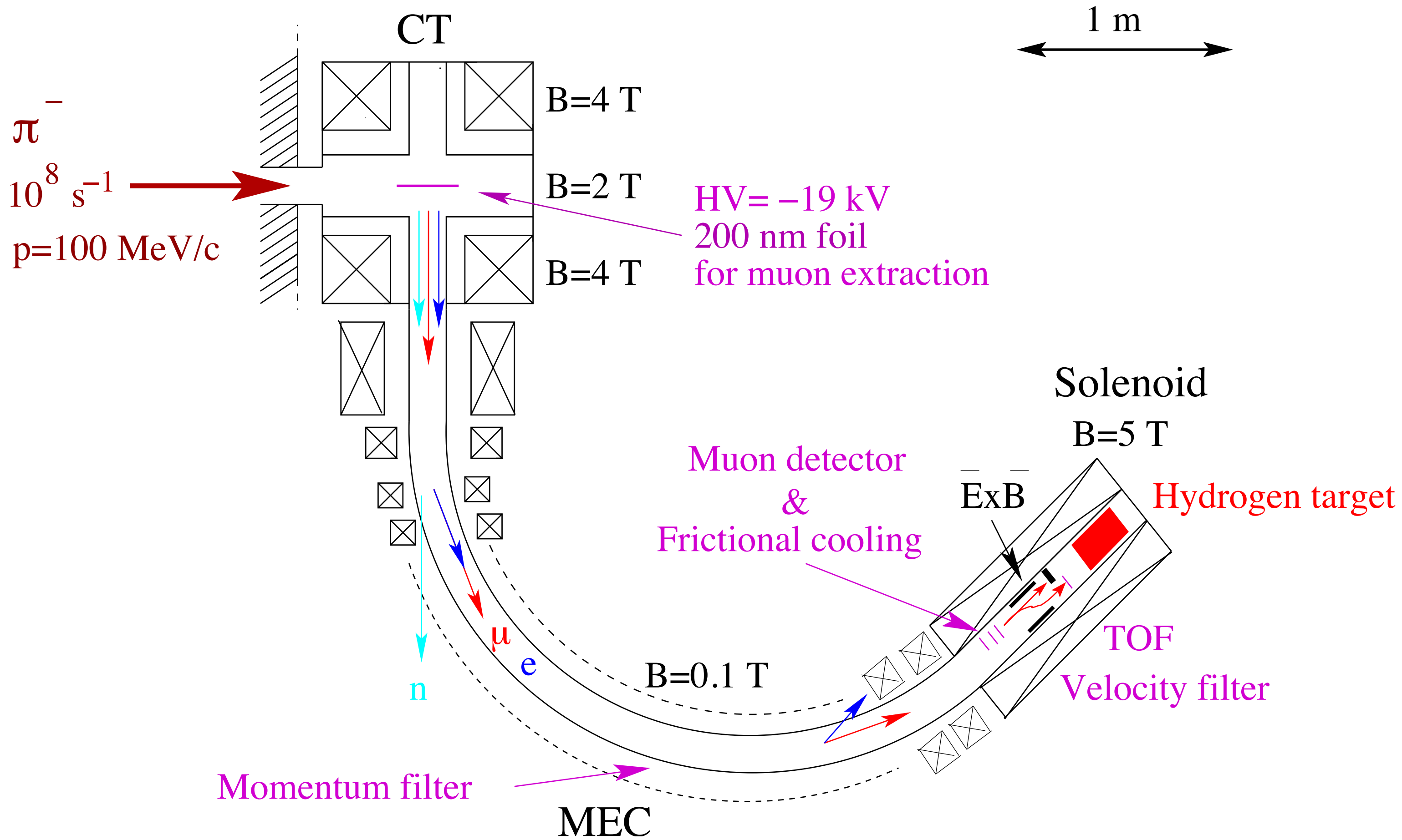
B = 0 – 0.3 T ⊥ , 0 – 0.03 T ∥ sample surface
T = 2.5 – 320 K

Beam spot at sample

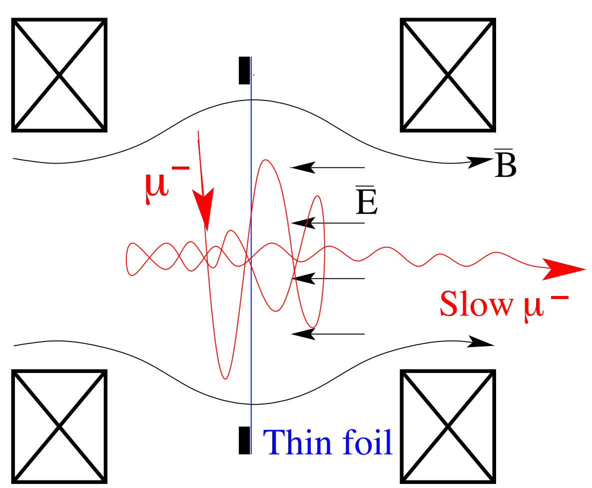


http://www.psi.ch/low-energy-muons/

Cyclotron Trap



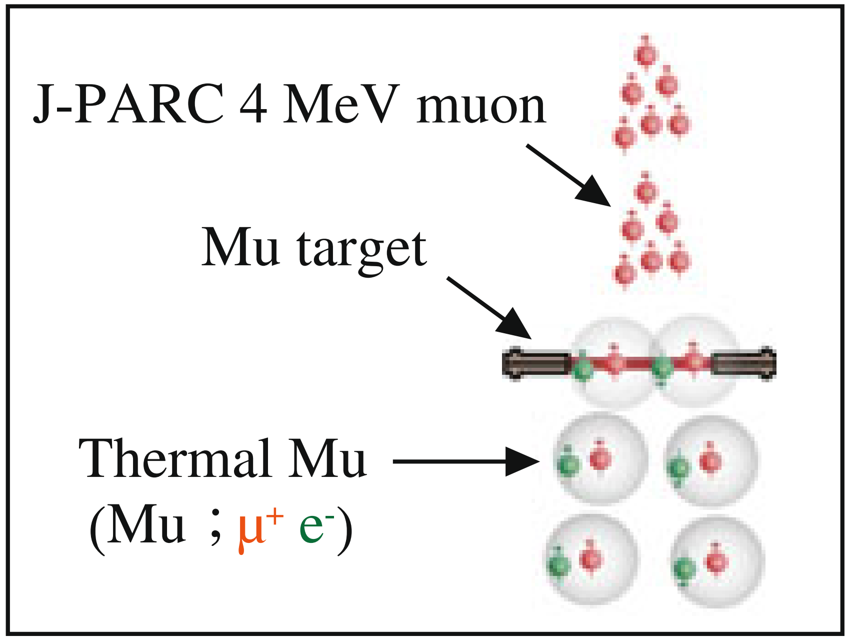
Principle of the cyclotron trap



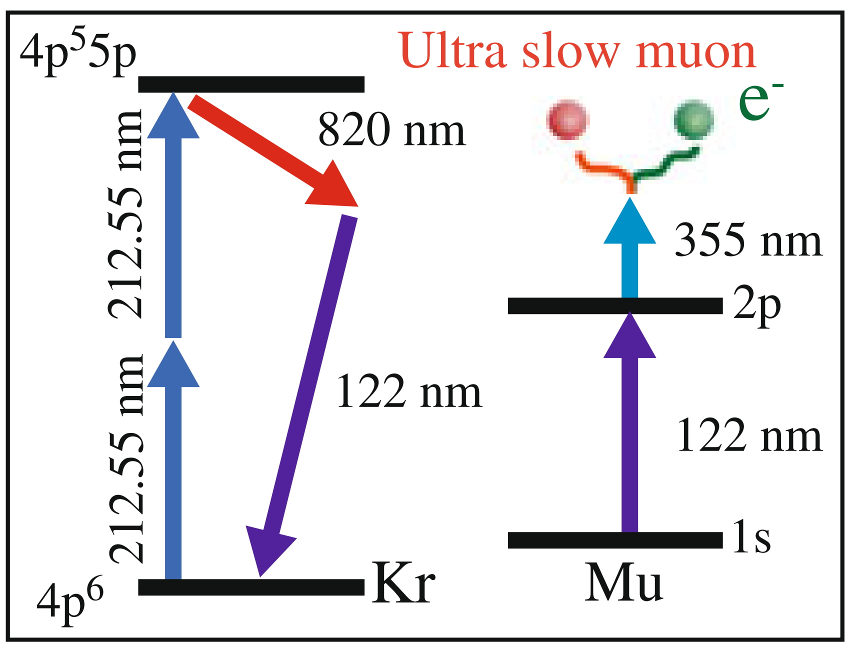
- Used for the Lamb shift measurements in muonic atoms
- Typically ~1000 μ^-/s on 2x1 cm^2 @ 5 keV
- Gain by factor 4-5 for μ^+ straightforward (cross-section)
- Higher gains for μ^+ in principal possible by injecting surface muons directly

R. Pohl et al., Nature **466**, 213 (2010)
L.M. Simons, Hyperfine Int. **81**, 253 (1993)

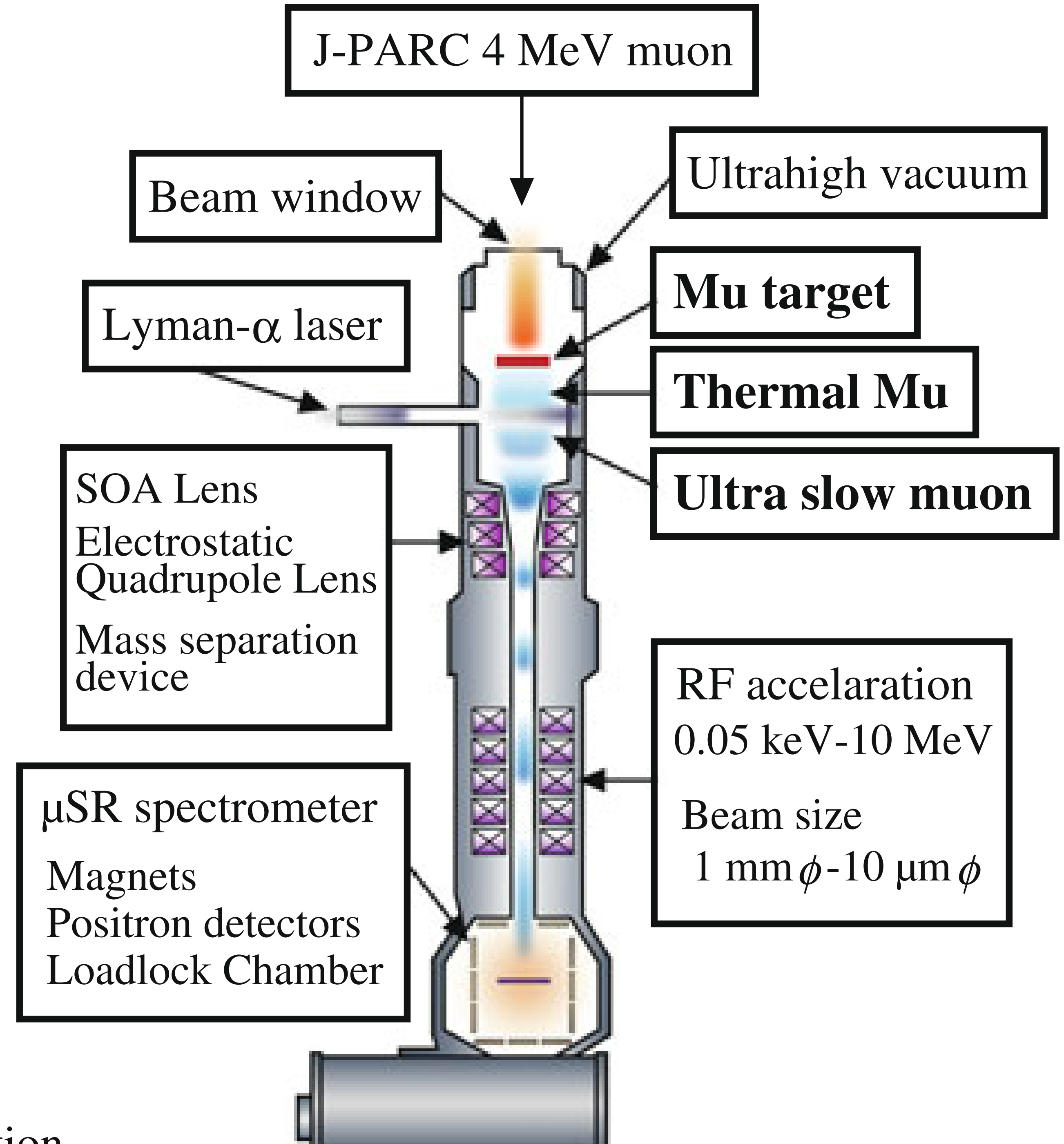
Laser Ionization Method



Mu generator



Lyman-α laser generation and Mu dissociation by laser resonant ionization method

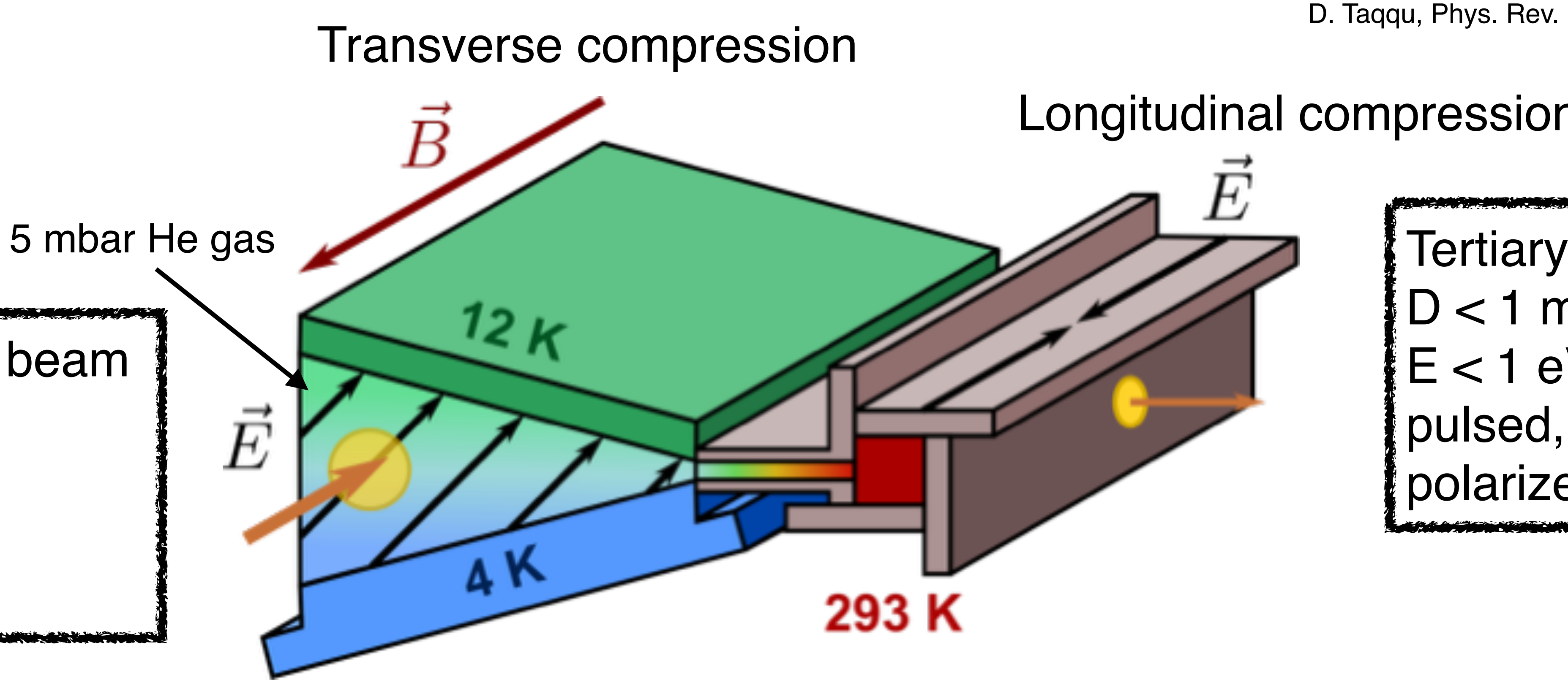


Y. Miyake et al., Hyperfine Int. **216**, 79 (2013)

muCool Principle

D. Taqqu, Phys. Rev. Lett. **97**, 194801 (2006)

Secondary μ⁺ beam
D ≈ 10 mm
E ≈ 4 MeV
continuous
polarized



Tertiary μ⁺ beam
D < 1 mm
E < 1 eV
pulsed, tagged
polarized

Muon swarm compression inside a helium gas target employing position-dependent muon drift velocity.

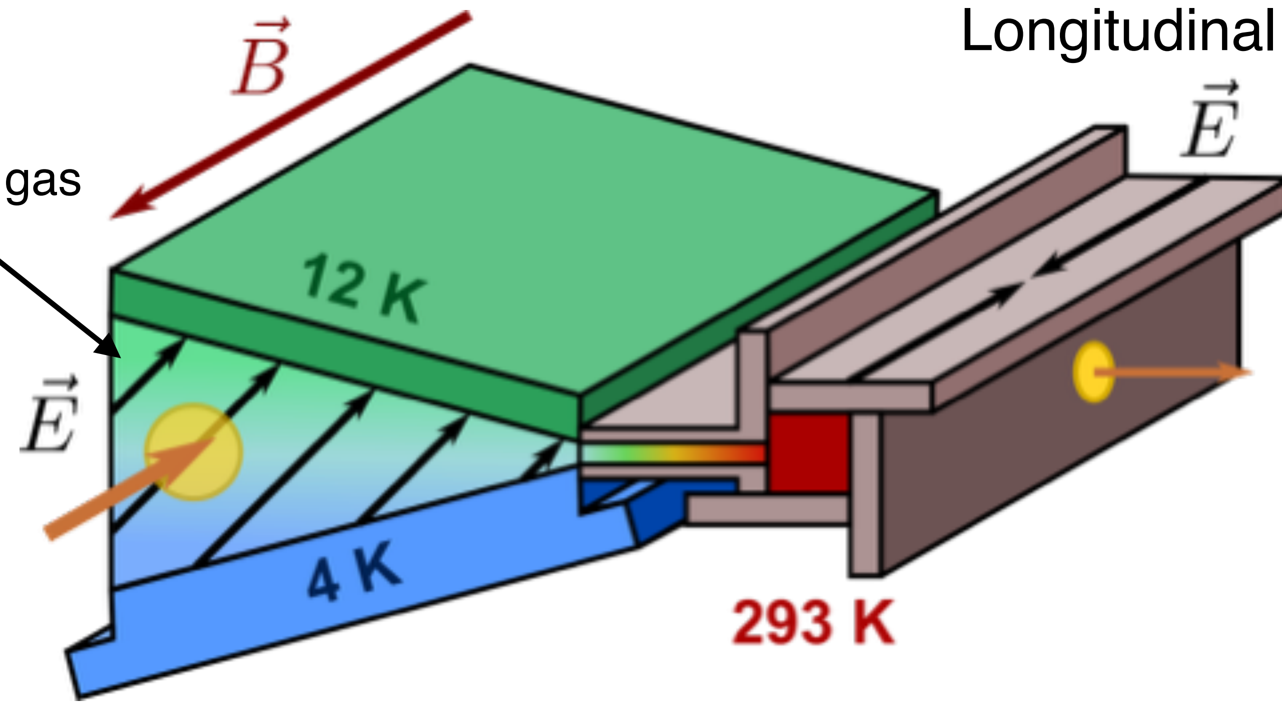
Increase in brilliance (after reaccelerating to ~10 keV) by factor **10^7**: $B \sim I/\varepsilon_L \varepsilon_T$

- Longitudinal emittance ε_L ($\Delta E \cdot \Delta t$) reduced by factor **10^4**
  Transverse emittance ε_T ($\Delta r \cdot \Delta \phi$) reduced by factor **$10^6$**
  → Phase space reduced by factor **10^{10}**
- Efficiency of factor **10^{-3}**: $I_{out} = 10^{-3}\ I_{in}$

muCool Principle

Transverse compression

Longitudinal compression



Secondary μ+ beam
D ≈ 10 mm
E ≈ 4 MeV
continuous
polarized

Tertiary μ+ beam
D < 1 mm
E < 1 eV
pulsed, tagged
polarized

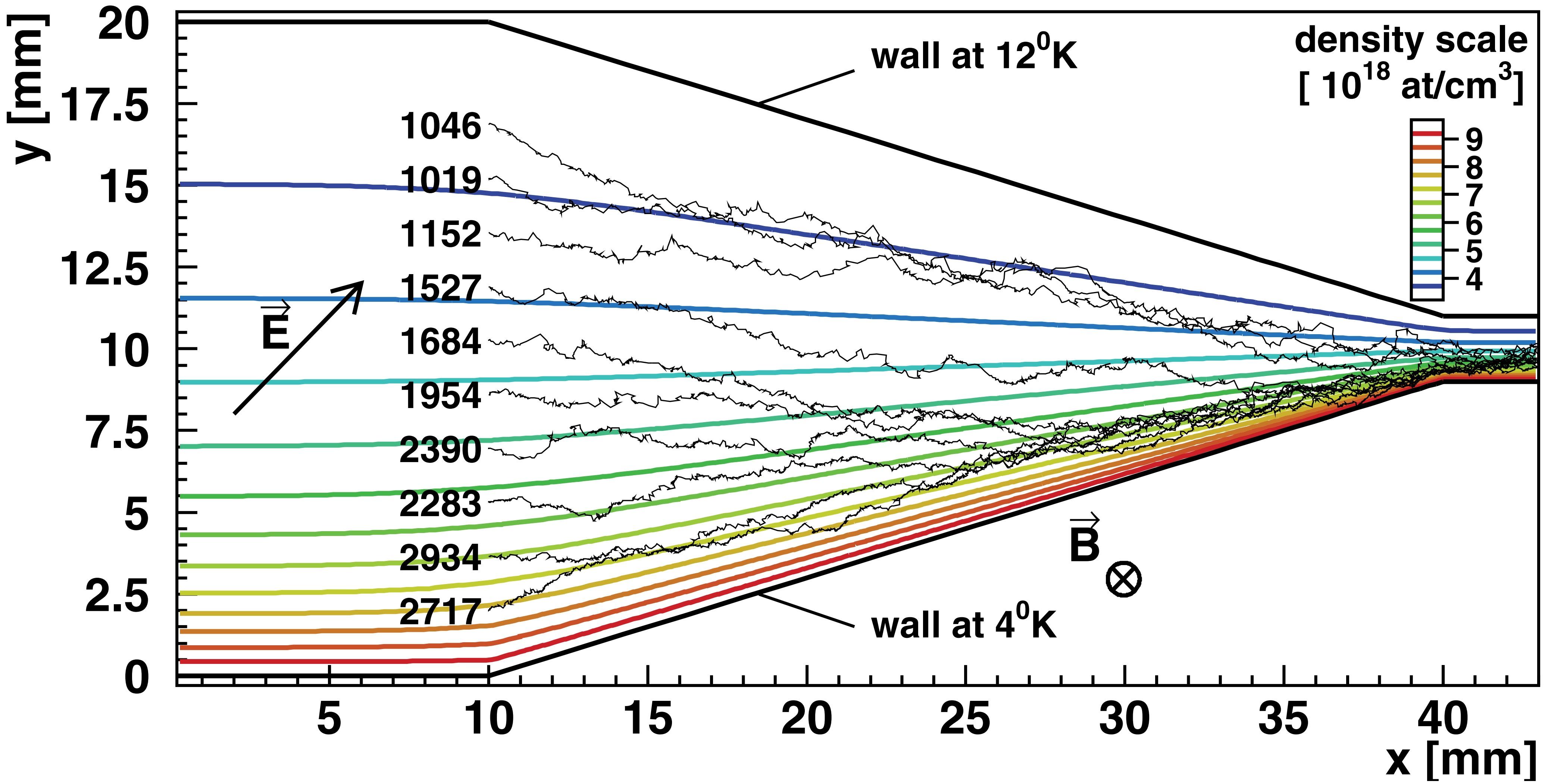
$$\vec{v}_D = \frac{\mu E}{1+\omega^2\tau^2}\left[\hat{E} + \omega\tau\hat{E}\times\hat{B} + \omega^2\tau^2(\hat{E}\cdot\hat{B})\hat{B}\right]$$

μ = eτ/m: mobility
τ = τ(p,T): time between collisions
ω = eB/m: cyclotron frequency

Transverse compression: $\vec{v}_D = \frac{\mu E}{1+\omega^2\tau^2}\left[\hat{E} + \omega\tau\hat{E}\times\hat{B}\right]$ E ~ 2 kV/cm, B = 5 T

Top: low density, large τ → drift along ExB
Bottom: high density, small τ → drift along E

muCool Principle



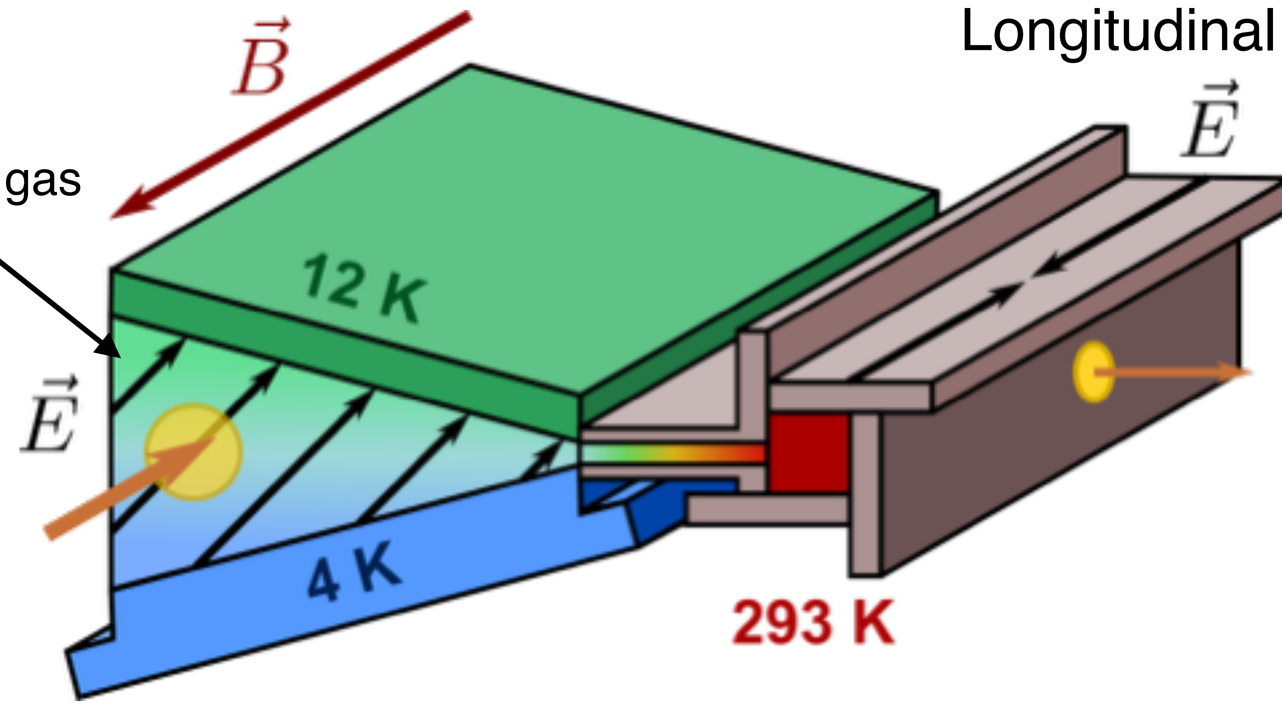
- Simulation of transverse compression stage
- Several muon trajectories (together with their drift times in ns) are shown starting at different y-positions and all compressing into the funnel on the right

muCool Principle

Transverse compression

Longitudinal compression

Secondary μ⁺ beam
D ≈ 10 mm
E ≈ 4 MeV
continuous
polarized



Tertiary μ⁺ beam
D < 1 mm
E < 1 eV
pulsed, tagged
polarized

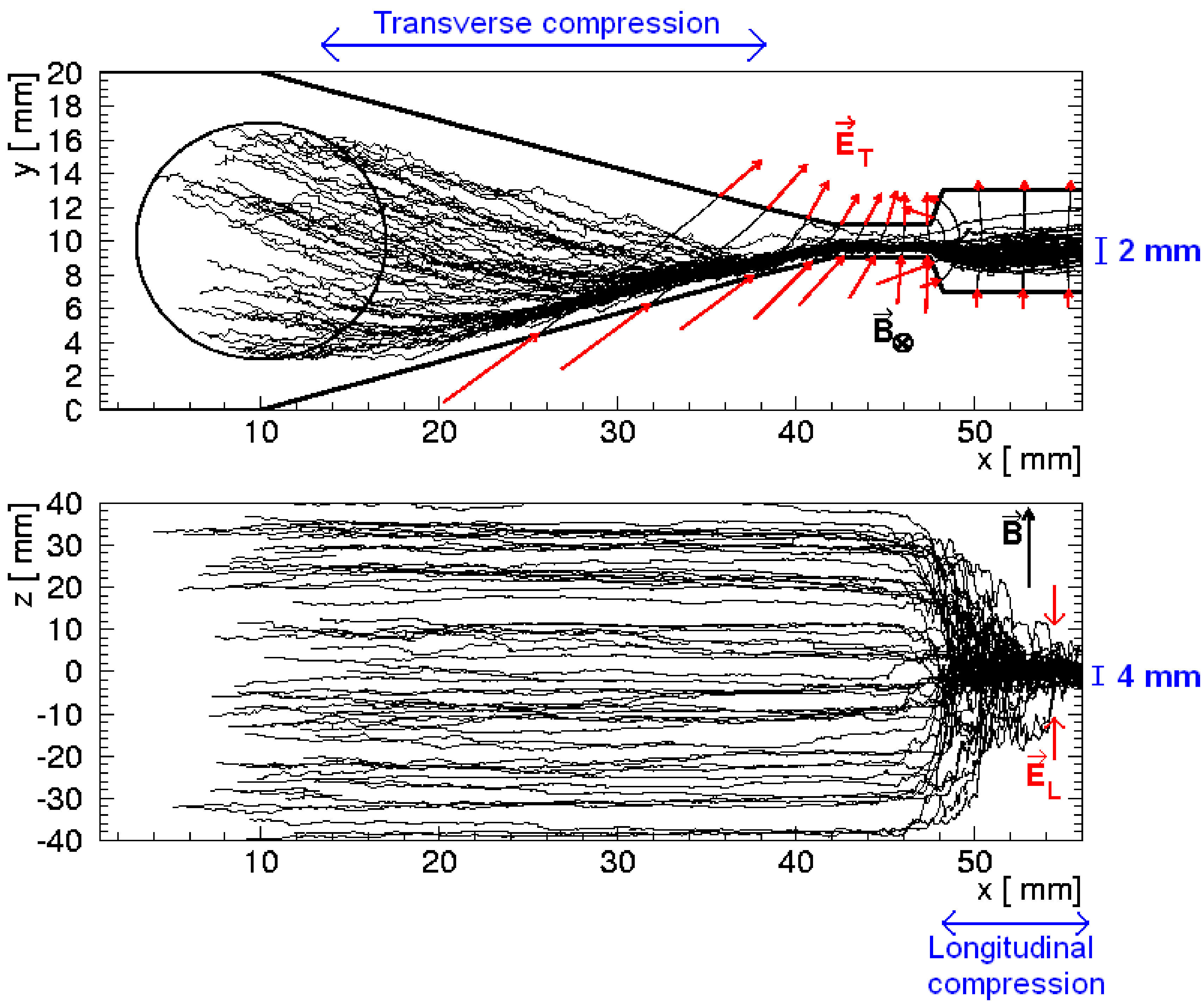
$$\vec{v}_D = \frac{\mu E}{1+\omega^2\tau^2}\left[\hat{E} + \omega\tau\hat{E}\times\hat{B} + \omega^2\tau^2(\hat{E}\cdot\hat{B})\hat{B}\right]$$

μ = eτ/m: mobility
τ = τ(p,T): time between collisions
ω = eB/m: cyclotron frequency

Longitudinal compression: $\vec{v}_D = \frac{\mu E}{1+\omega^2\tau^2}\left[\hat{E} + \omega^2\tau^2(\hat{E}\cdot\hat{B})\hat{B}\right]$ E ~ 60 V/cm, B = 5 T

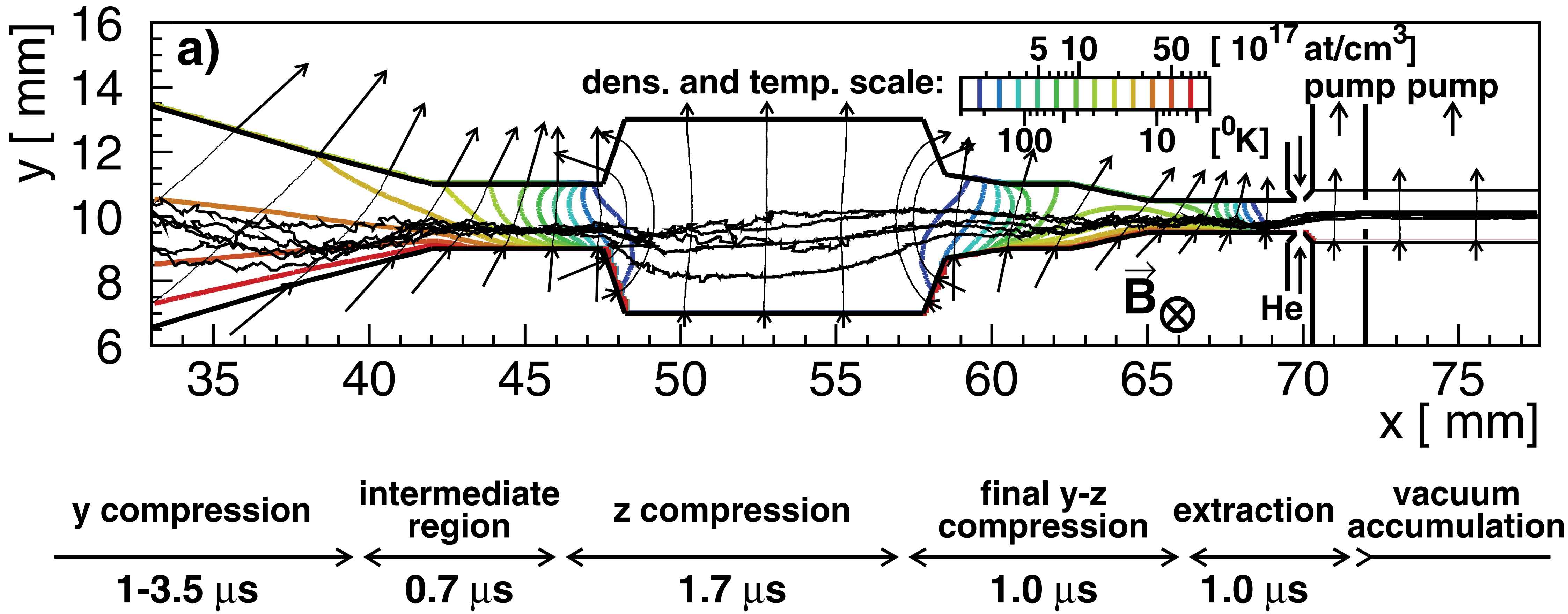
Compression along E- and B-field direction

muCool Principle



- Simulation of transverse and longitudinal compression

muCool Principle



- The full system will feature an additional compression stage
- The total time needed for the compression will be ~ 8 µs
- Wall and neutralization losses should be minimal
- Expect an efficiency of O(10^{-3})

Experimental Tests in Stages

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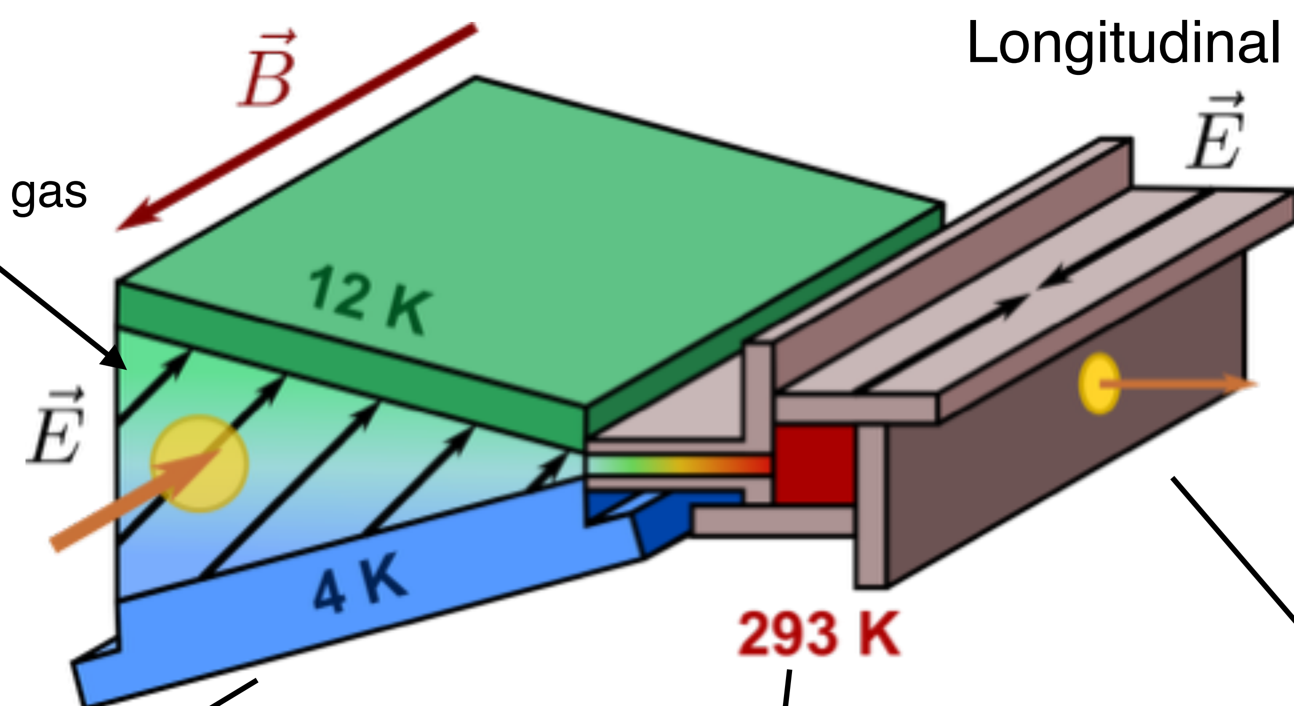
Secondary μ^+ beam
$D \approx 10$ mm
$E \approx 4$ MeV
continuous
polarized



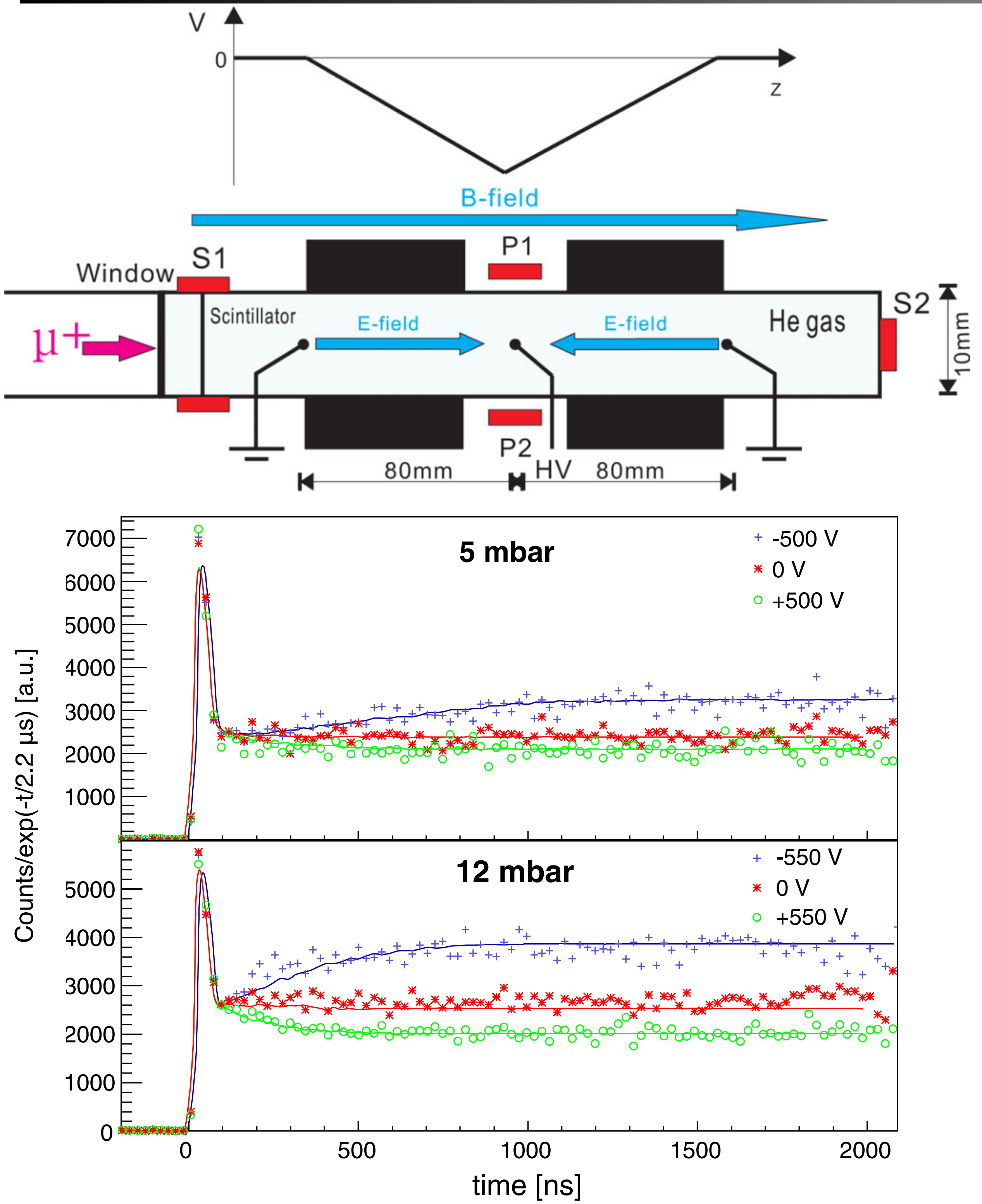
Tertiary μ^+ beam
$D < 1$ mm
$E < 1$ eV
pulsed, tagged
polarized

Transverse compression:
- First experimental test in Dec. 2014
- Improved tests in Dec. 2015

Longitudinal compression:
- First experimental test in 2011
- Improved tests in Dec. 2014

Extraction into vacuum:
- Under development

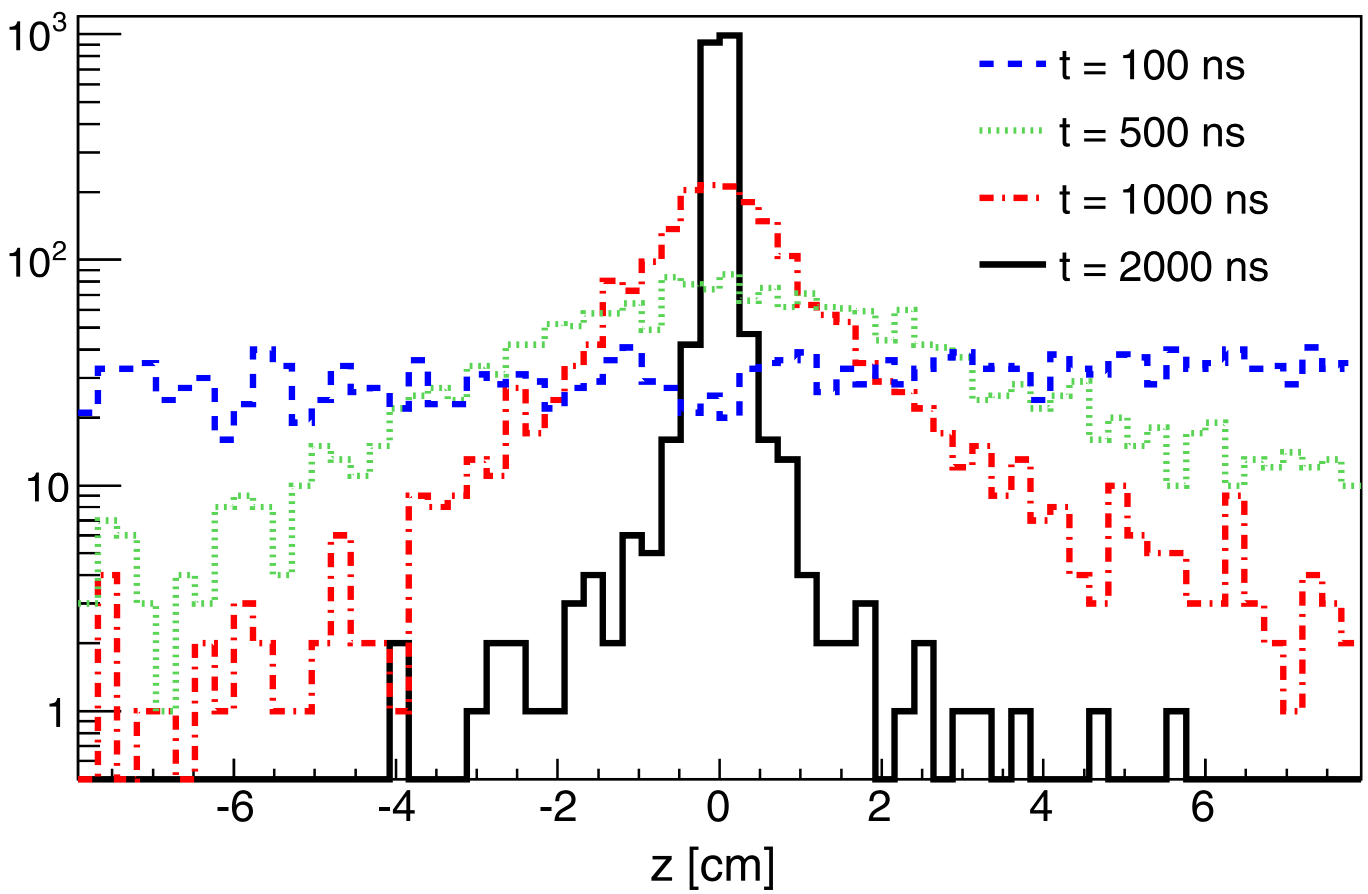
Test of Longitudinal Compression



Bao et al., Phys. Rev. Lett. **112**, 224801 (2014)

- First test of longitudinal compression in 2011
- πE1 beamline tuned to 10 MeV/c
- Only small fraction of muons stopped in gas
- Developed special simulation able to reproduce measured data after introduction of:
  - small misalignment
  - chemical absorption

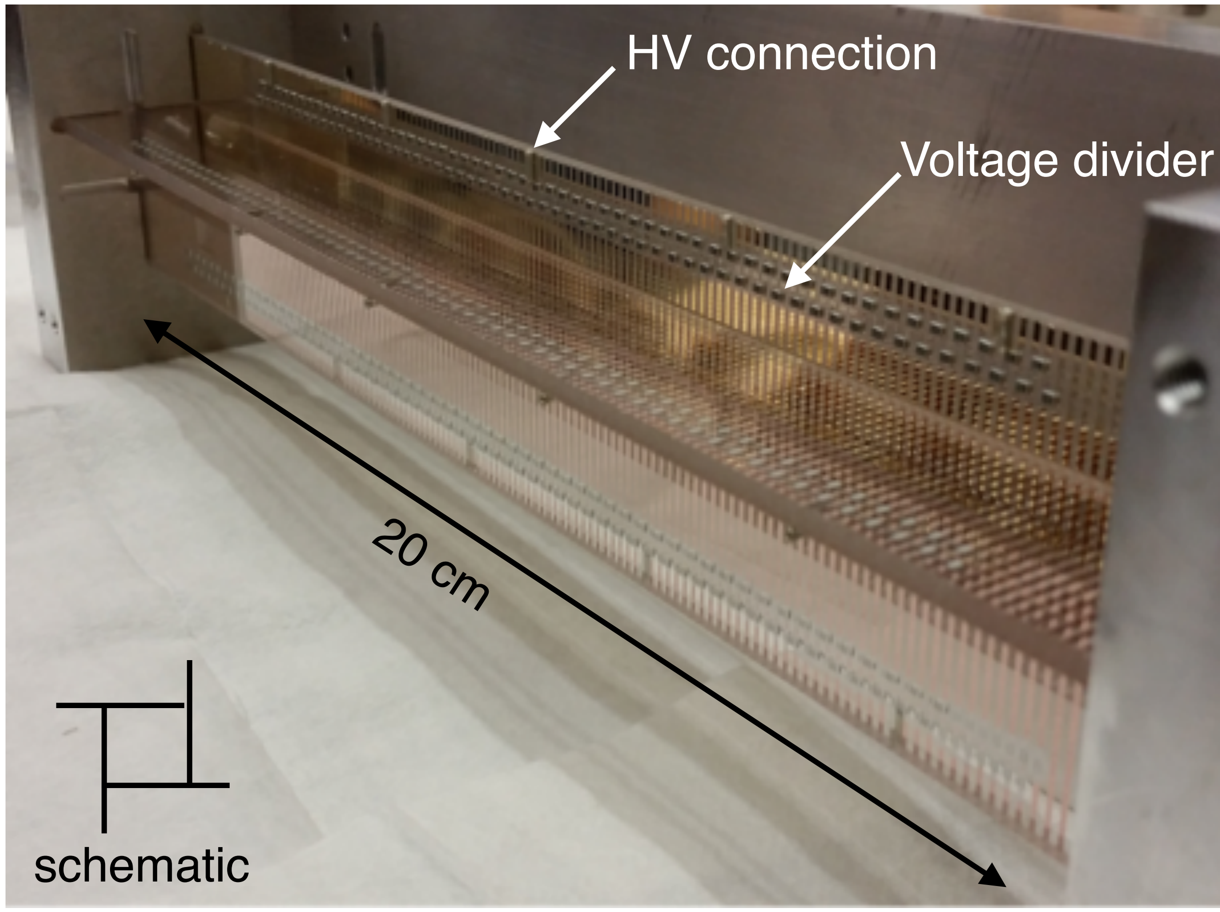
Test of Longitudinal Compression

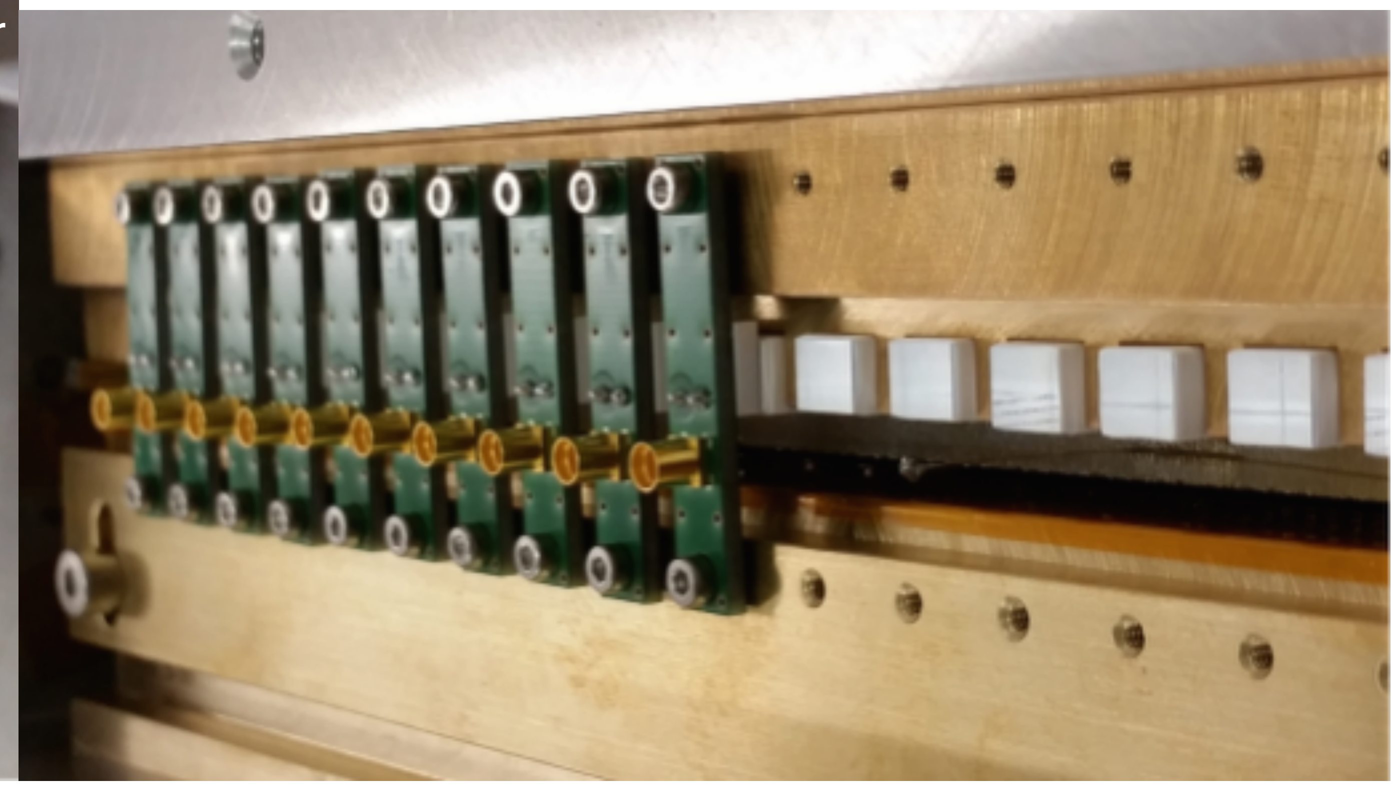


- From simulation:
  Compression is indeed fast and completed in < 2 µs

- Situation in real setup will be somewhat different:
  Here slowing down of ~10 keV muons mixed with compression

Improved Setup





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

Results of Improved Setup

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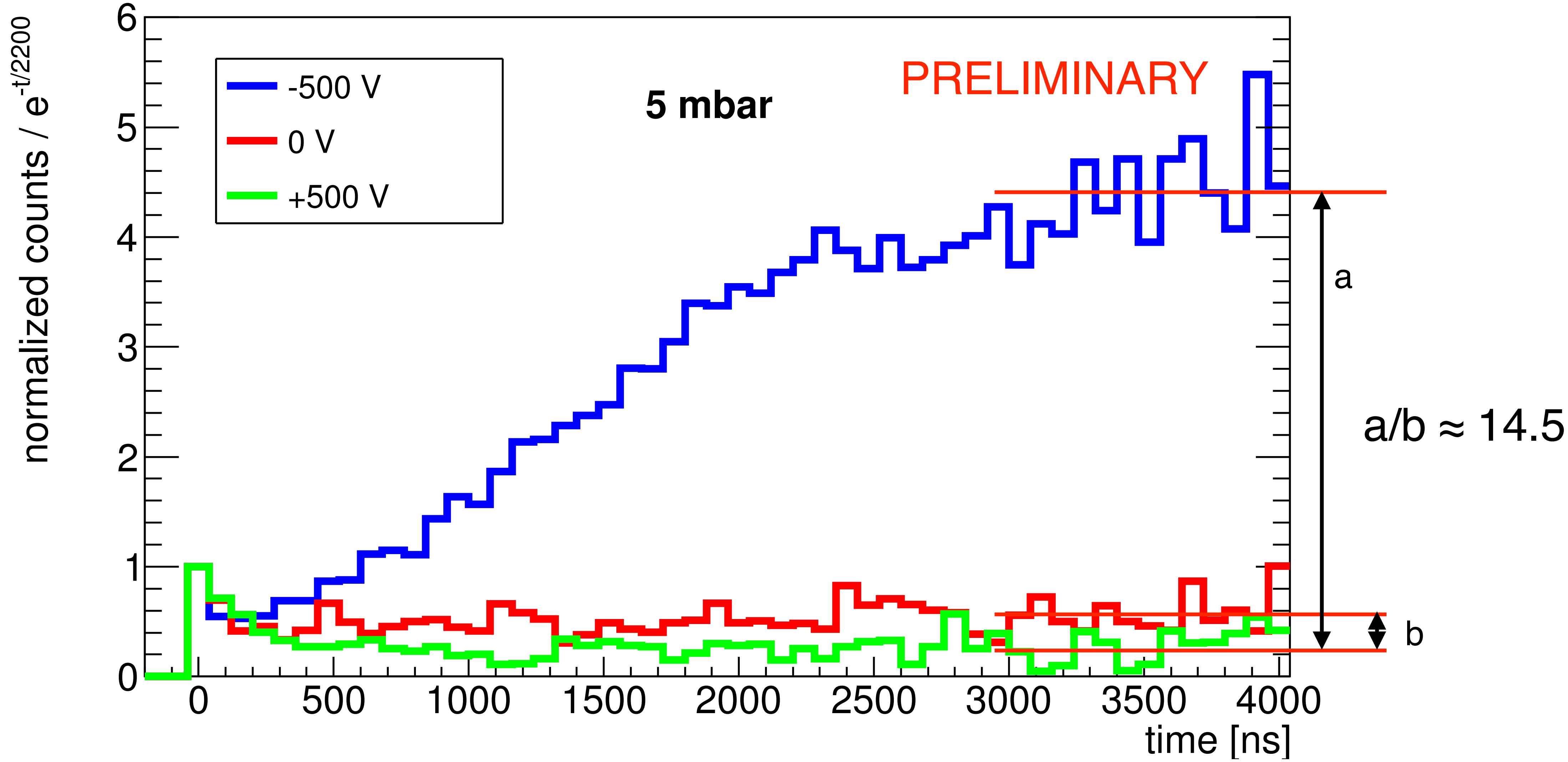
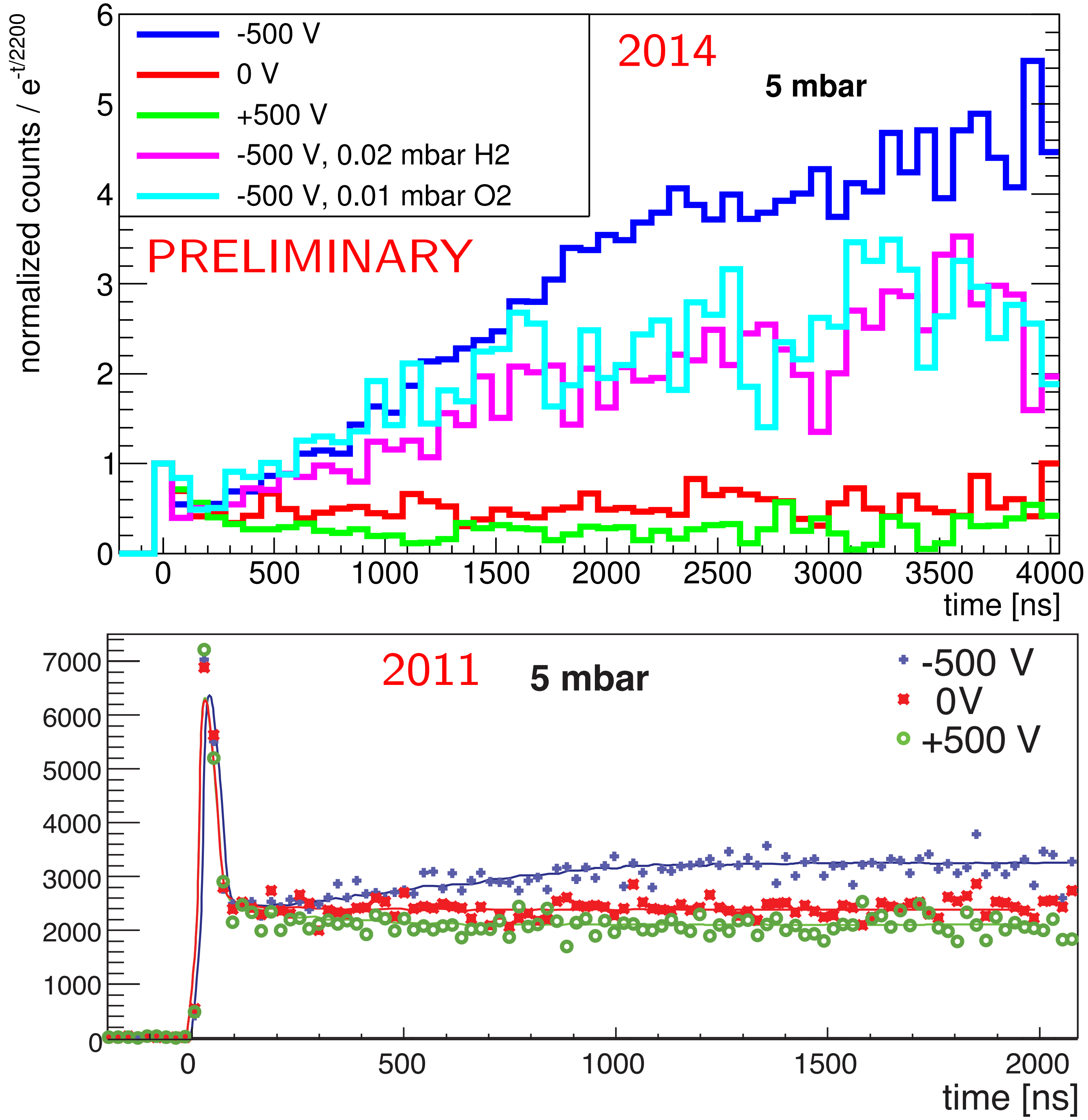


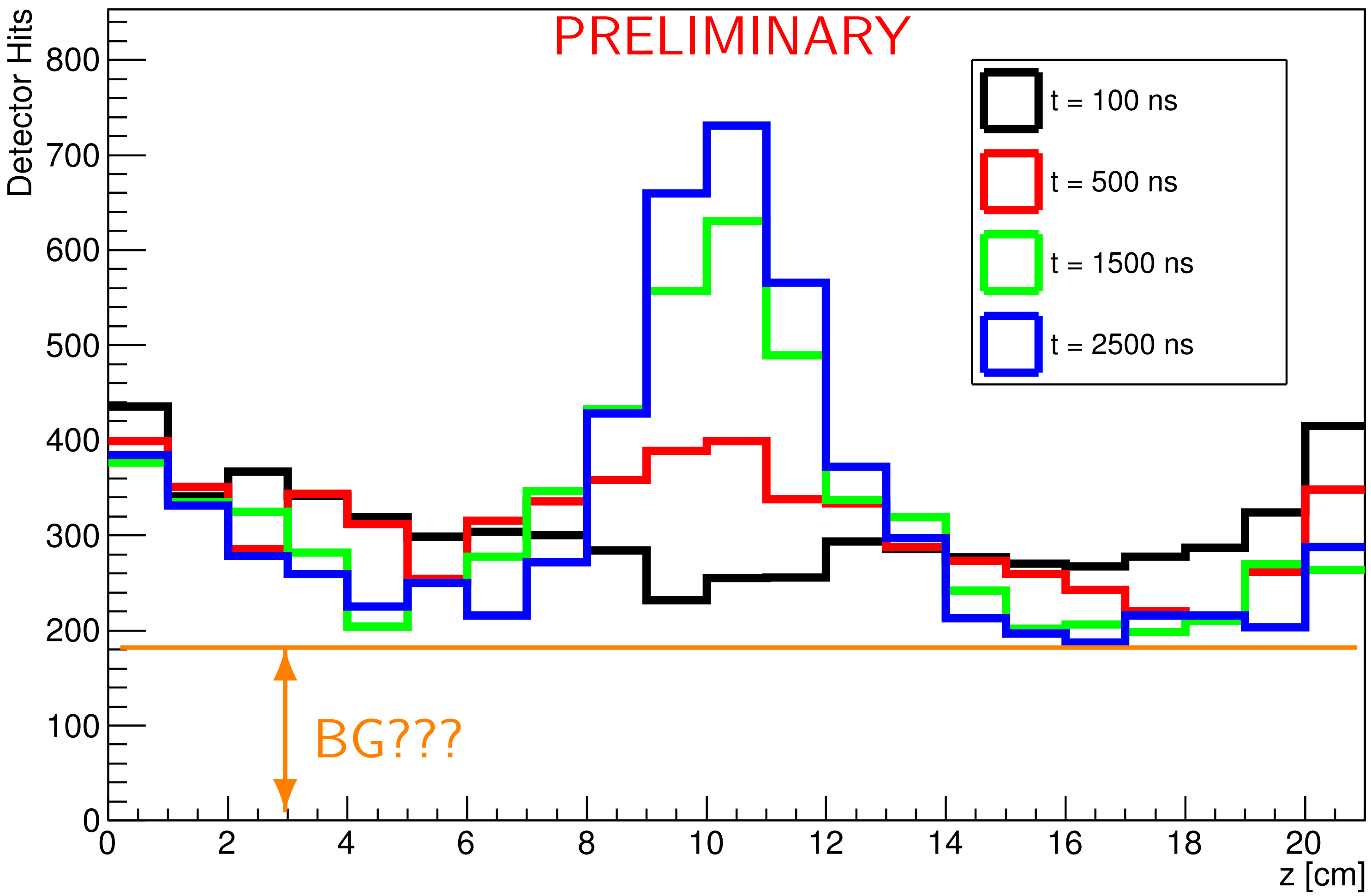
- Compression efficiency ~ a/b
- From simulation: (100 ± xx)% compression

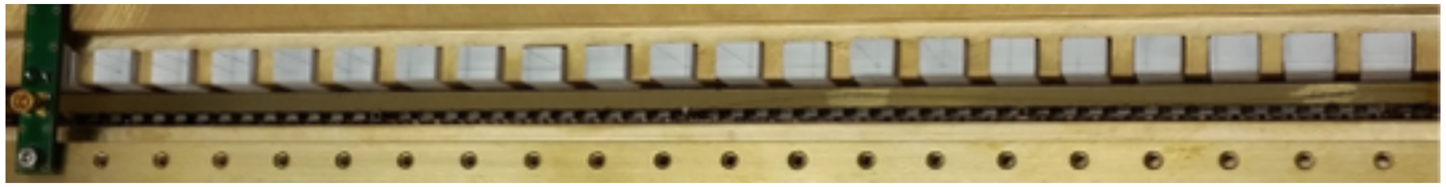
Results of Improved Setup



- Observed much improved compression signals:
  - Longer drift times
  - Larger compression effects due to less background and spatially more sensitive detectors
- Confirmed effect of chemical absorption due to impurities

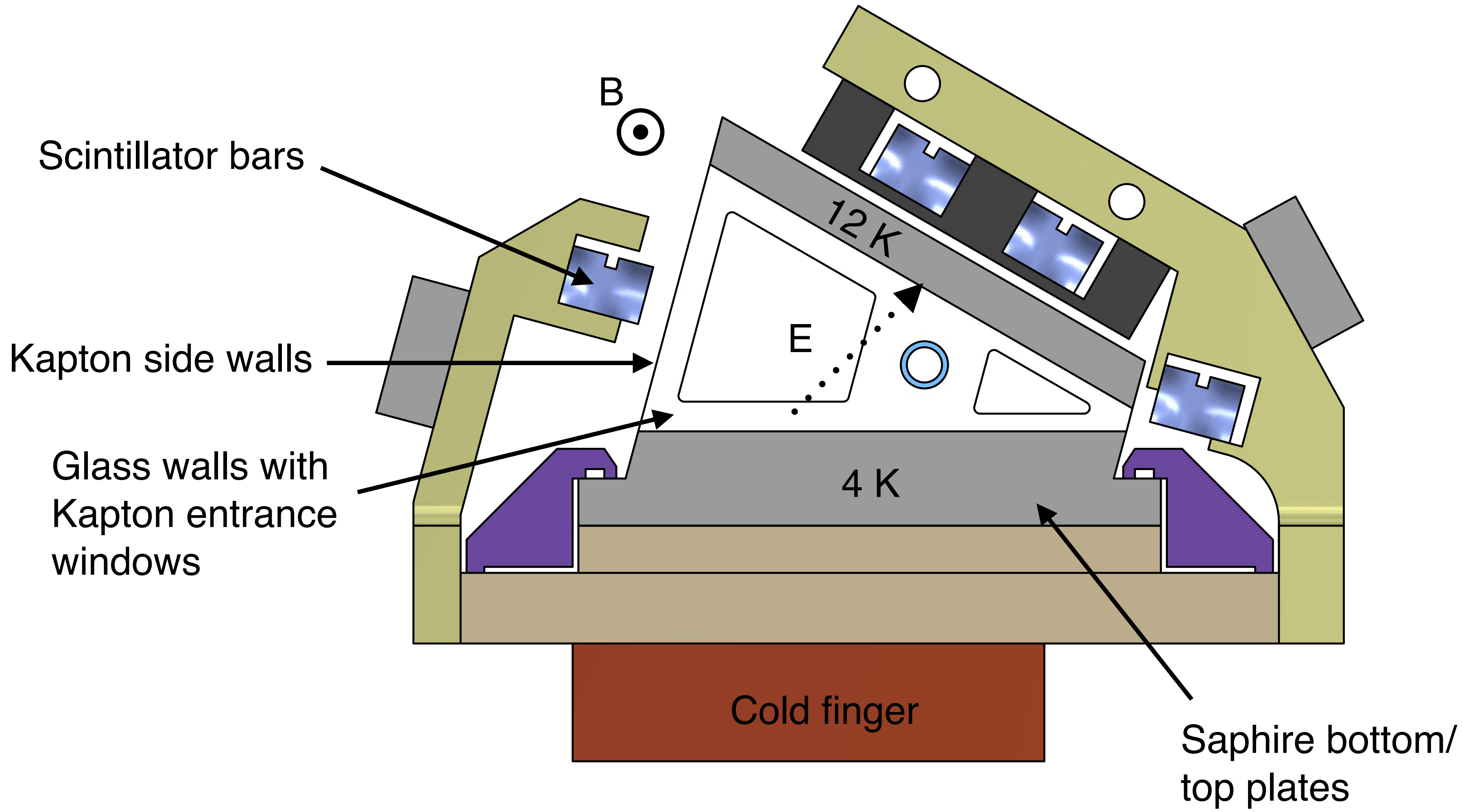
Results of Improved Setup





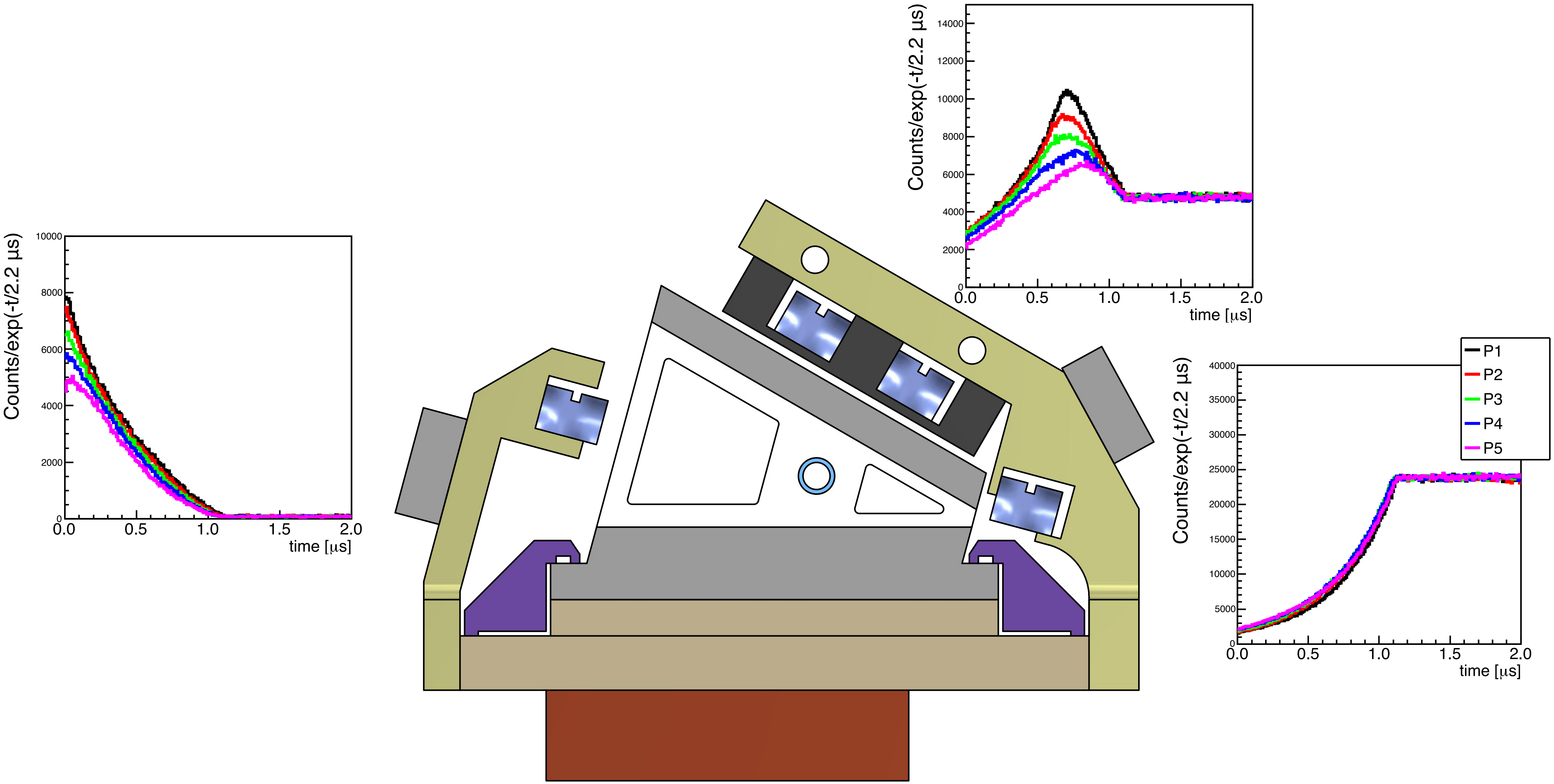
- Observe temporal evolution of compression with row of scintillators

Test of Transverse Compression



- Test of transverse compression follows the same principle as for longitudinal. Observe compression behavior by temporal evolution of counts in detectors around the target cell.

Test of Transverse Compression



- Simulated signals in the different scintillator bars for muons starting at different initial heights

Setup for Transverse Compression

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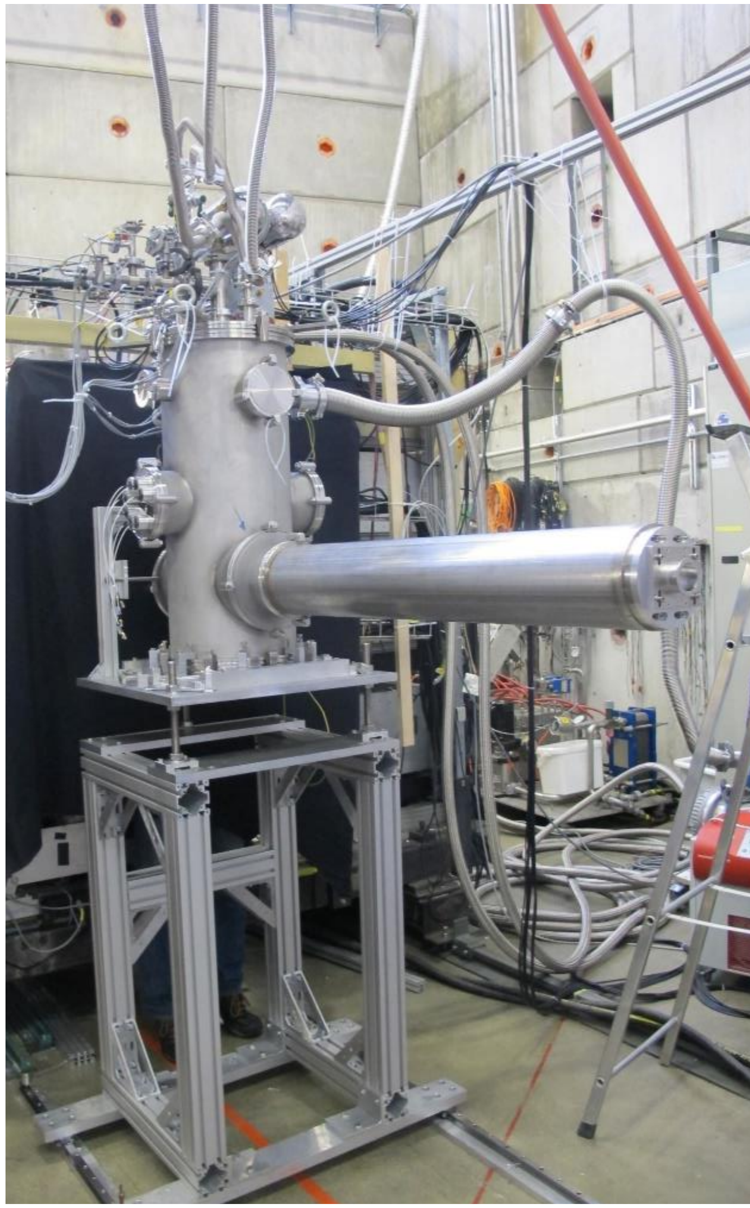
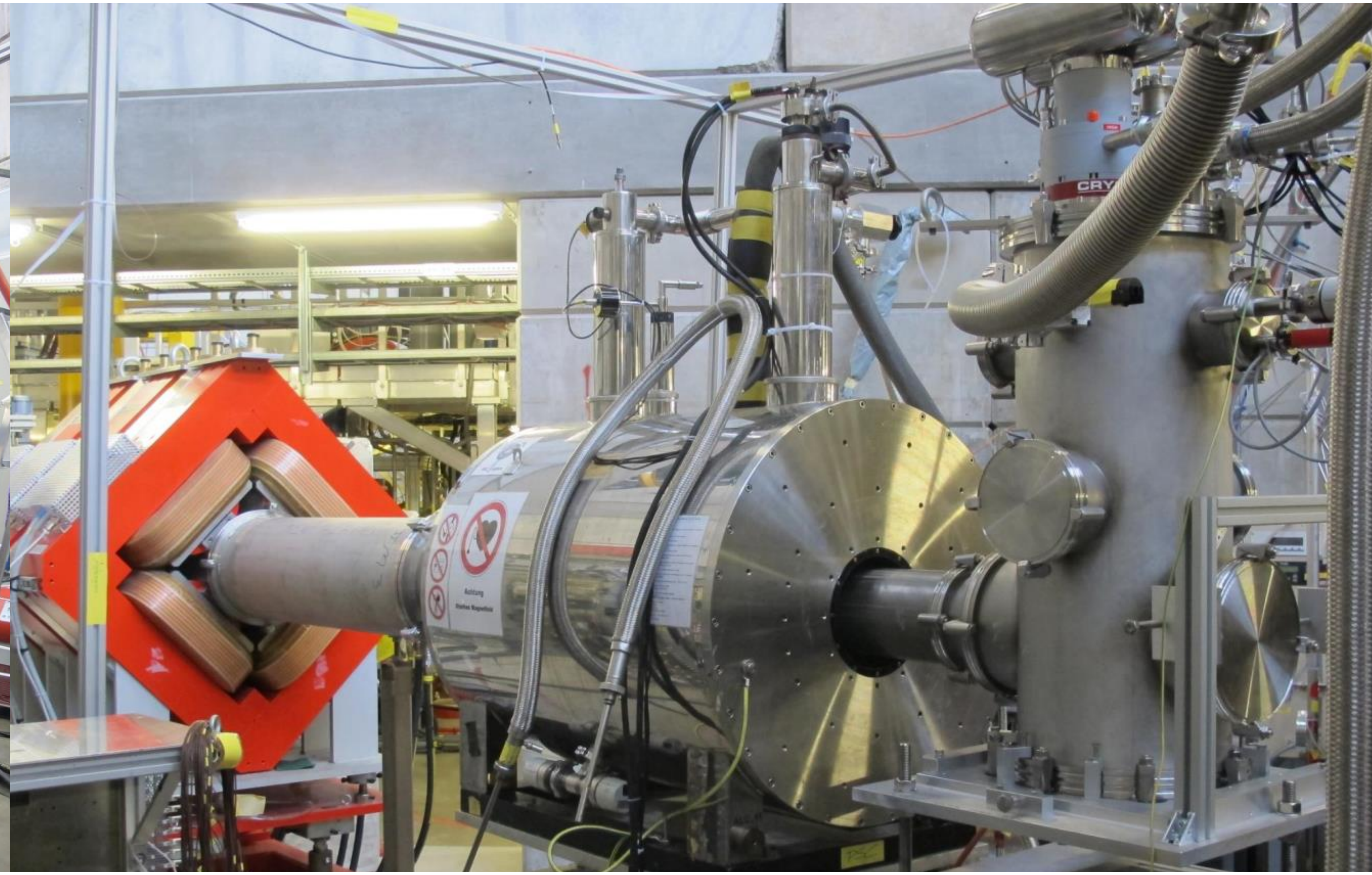
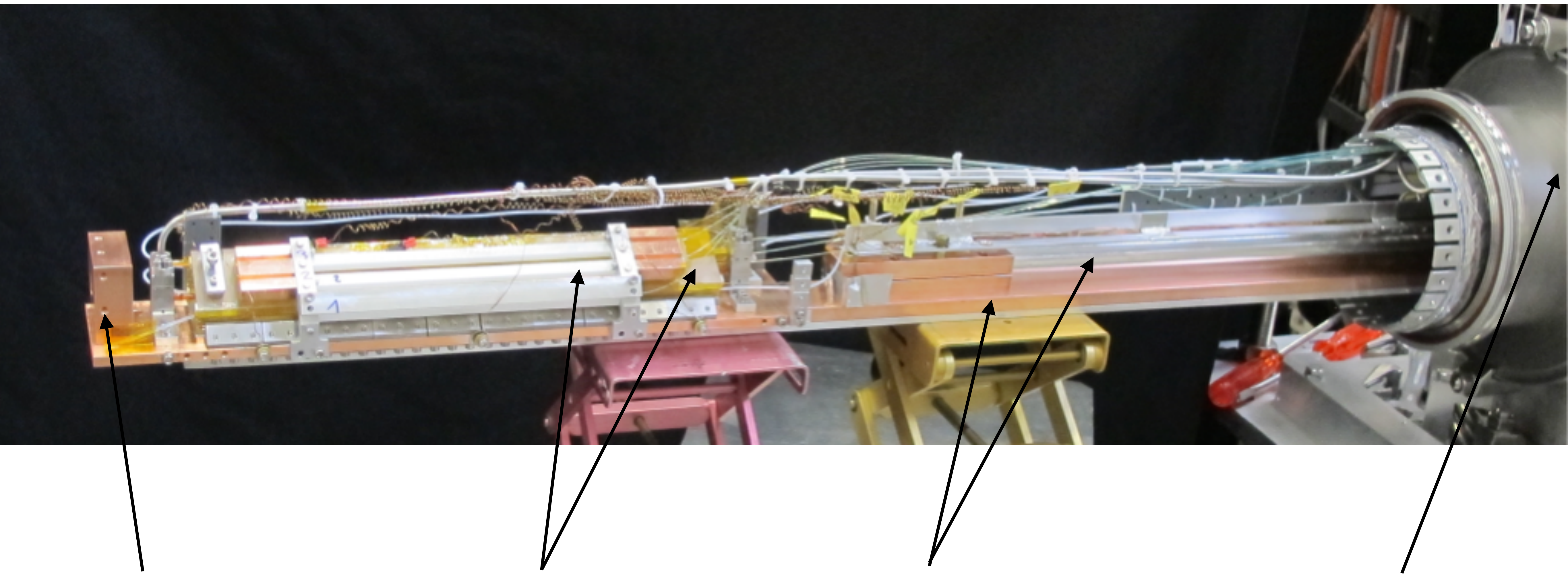


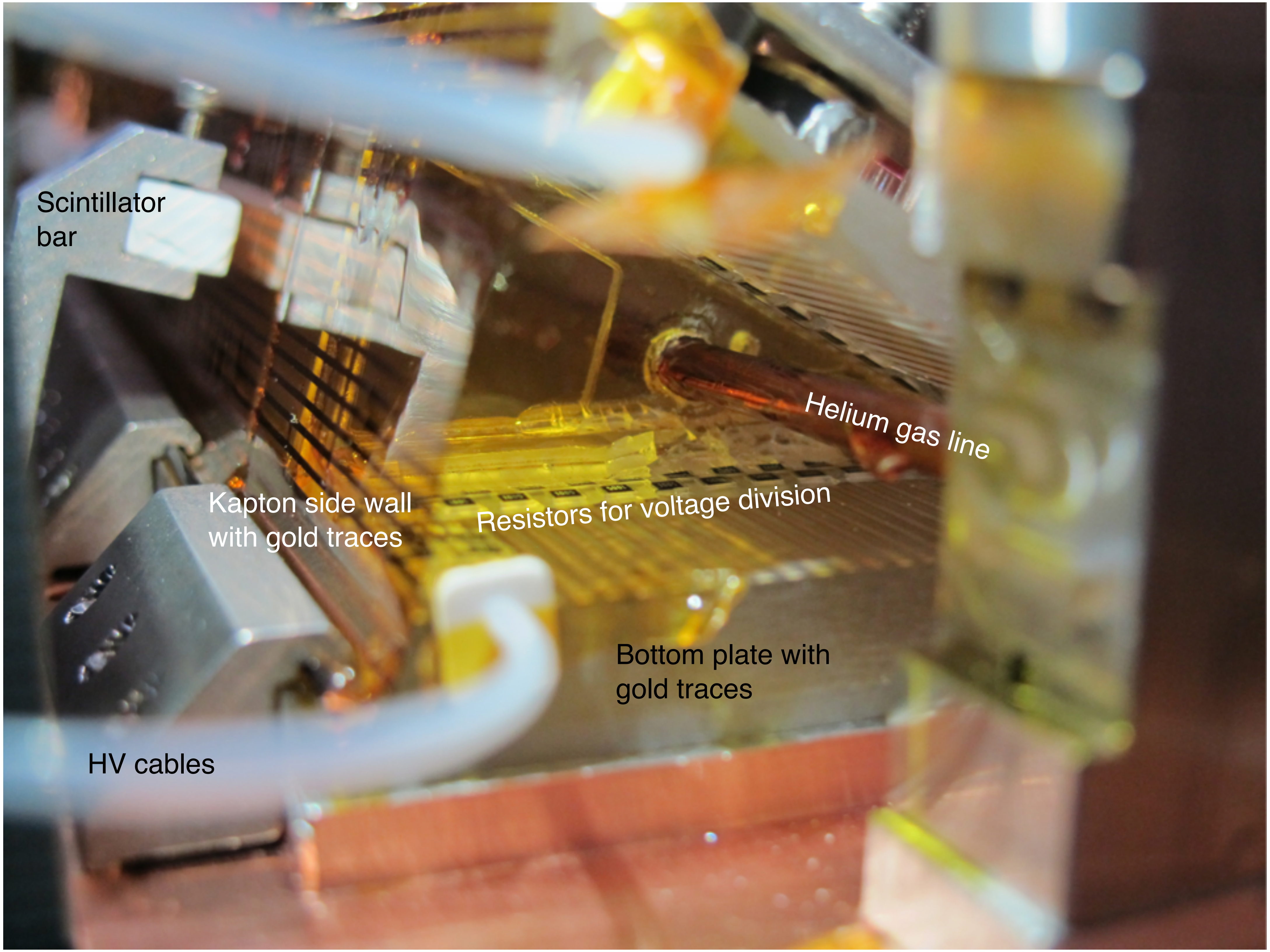


- Setup in the πE1 area of PSI. ~20 kHz μ^+ @ 10 MeV/c
- Cryostat with long cold-finger inside superconducting 5 T magnet

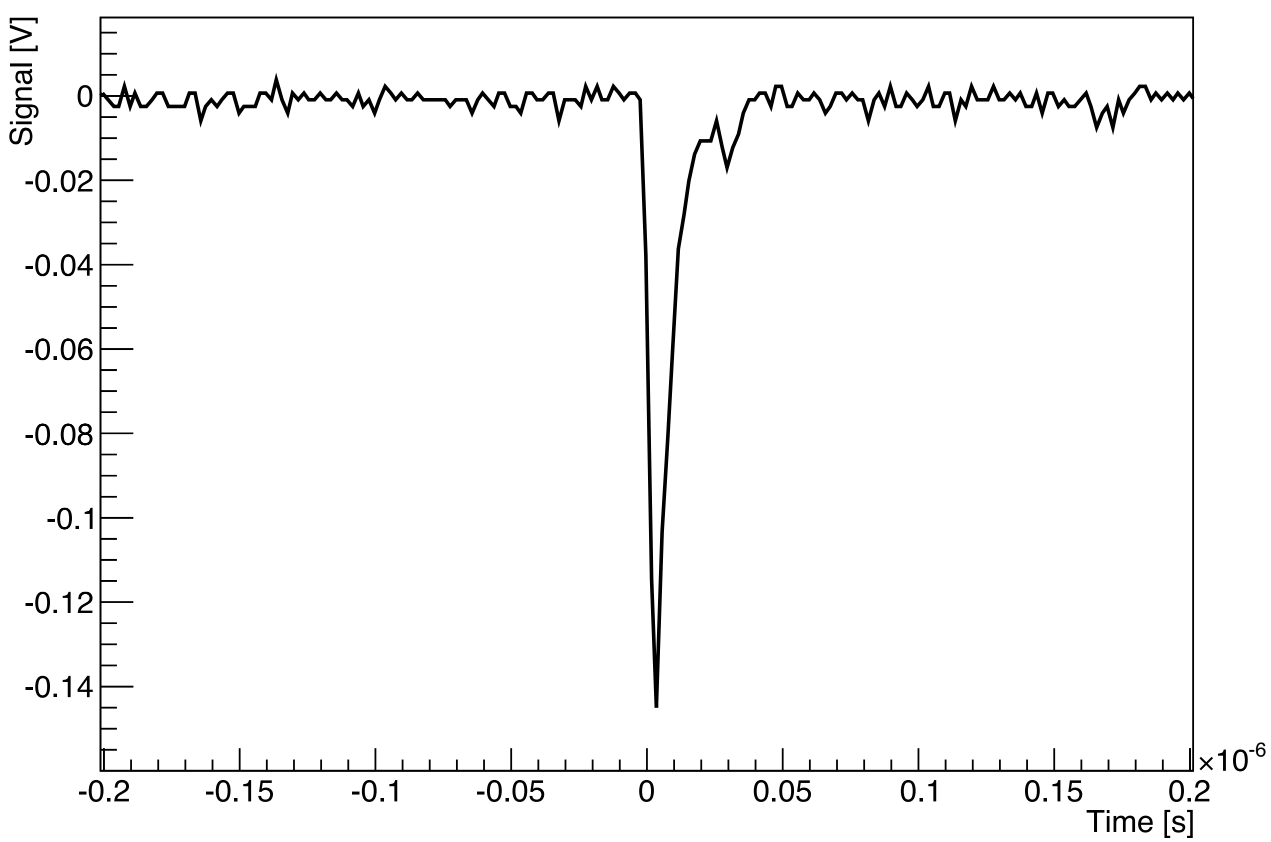
Setup for Transverse Compression



Setup for Transverse Compression



Results from First Test 2014



Scintillator signal after 2 m of fibre

- **Things that worked**:
  - Reached ~5 K on bottom plate of target cell
  - Nice and clear signals seen from scintillator bars read out by 2 m long fibers
  - Possibility to align target with positrons once cold
- **Things that didn't work**:
  - Finished cell just a few days before end of beam time
  - Gas cell developed a cold leak
  - Lost some HV contacts
- But: Concept in principal viable

Lots of work in last year!

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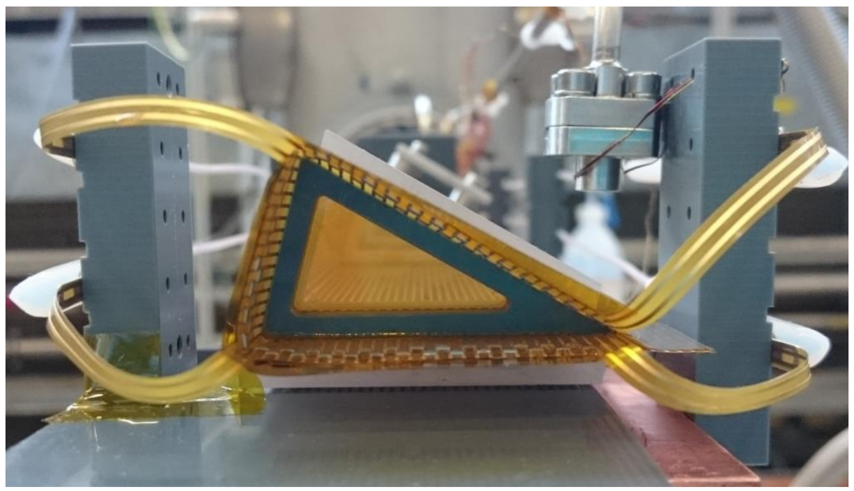

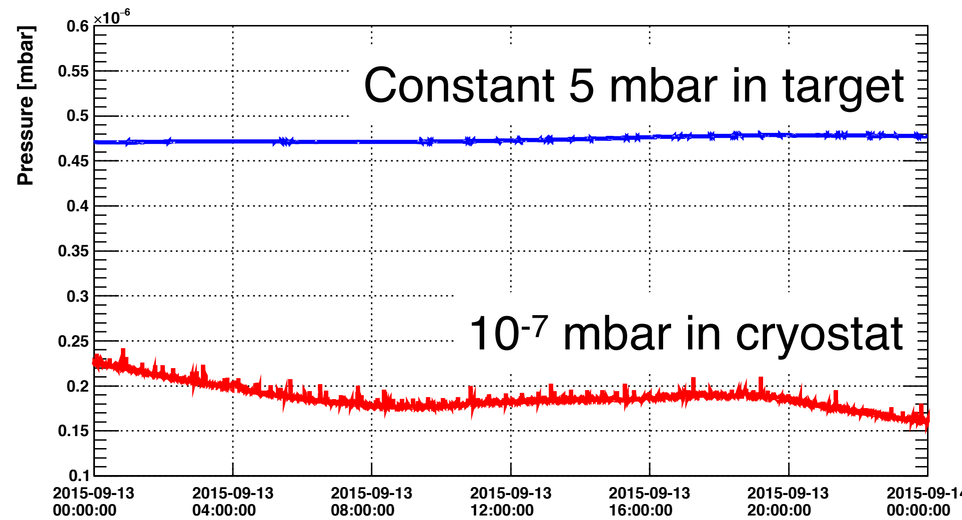

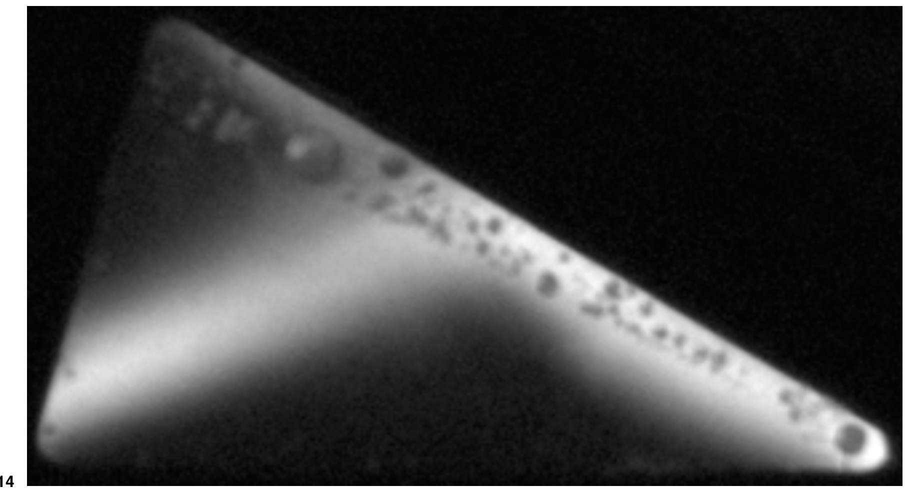

- Improved cell design and high-voltage connection
- Gas-tight cell at cryogenic temperatures and over several temperature cycles
- Reached electric field strength of ~ 2 kV/cm with magnetic field

→ ready for tests of transverse compression this December!

Conclusions

- Interesting physics opportunities in particle physics and material science using slow, high-brightness muon beams
- The muCool collaboration aims at generating such a beam using a novel technique employing a density gradient in helium gas and electric and magnetic fields. The efficiency will be of $O(10^{-3})$ with an increased brightness of the muon beam of 10^7.
- Longitudinal compression has been demonstrated experimentally with good progress towards transverse compression

muCool Collaboration

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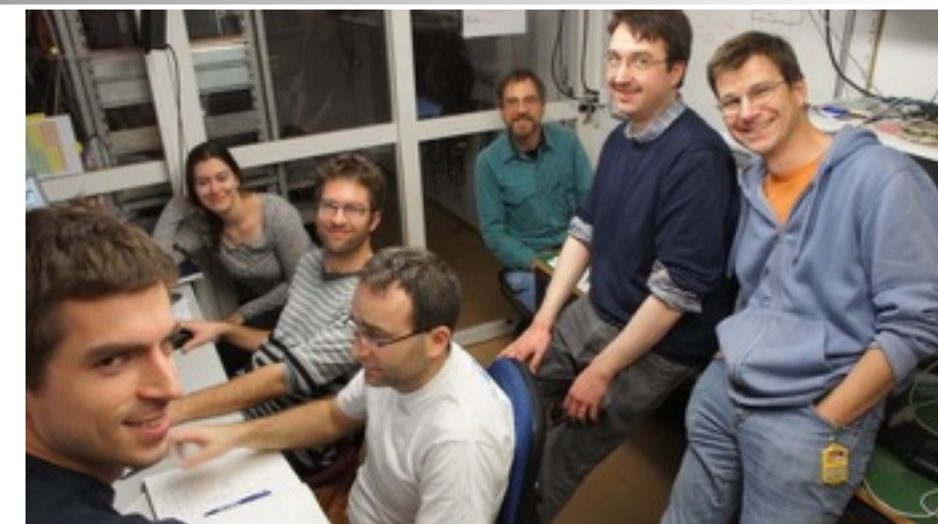
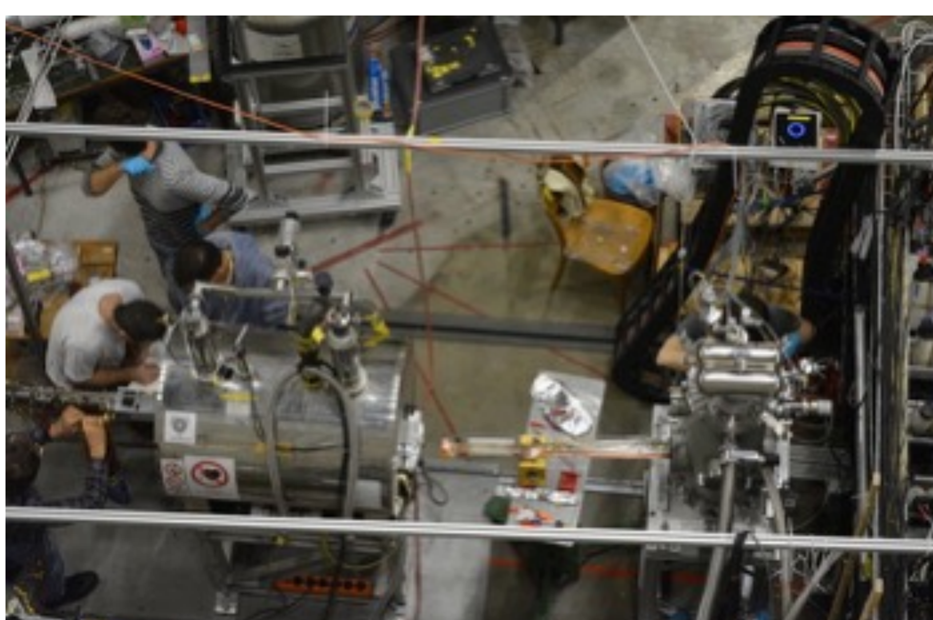
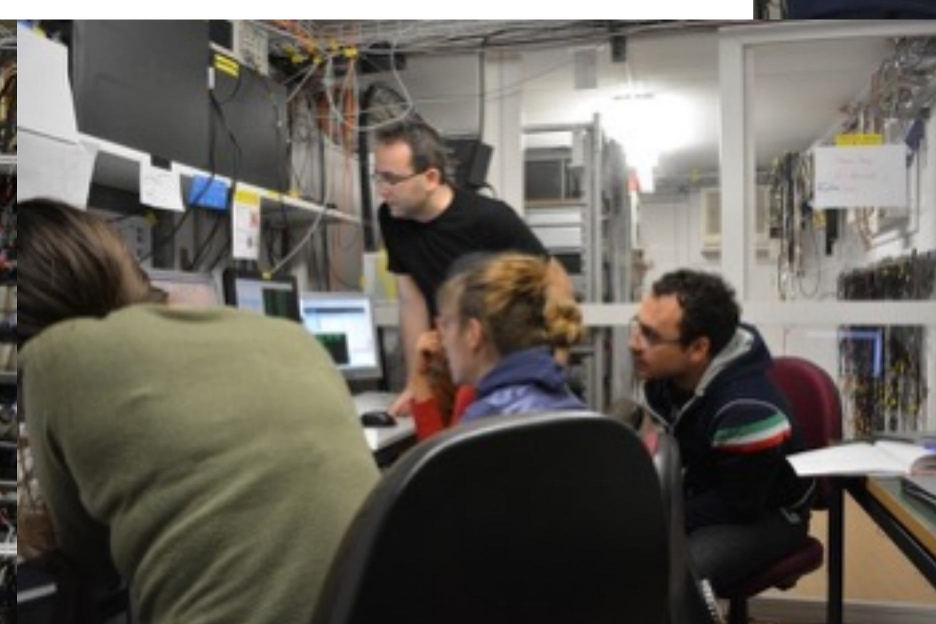
D. M. Kaplan and T. J. Phillips
Illinois Institute of Technology, USA

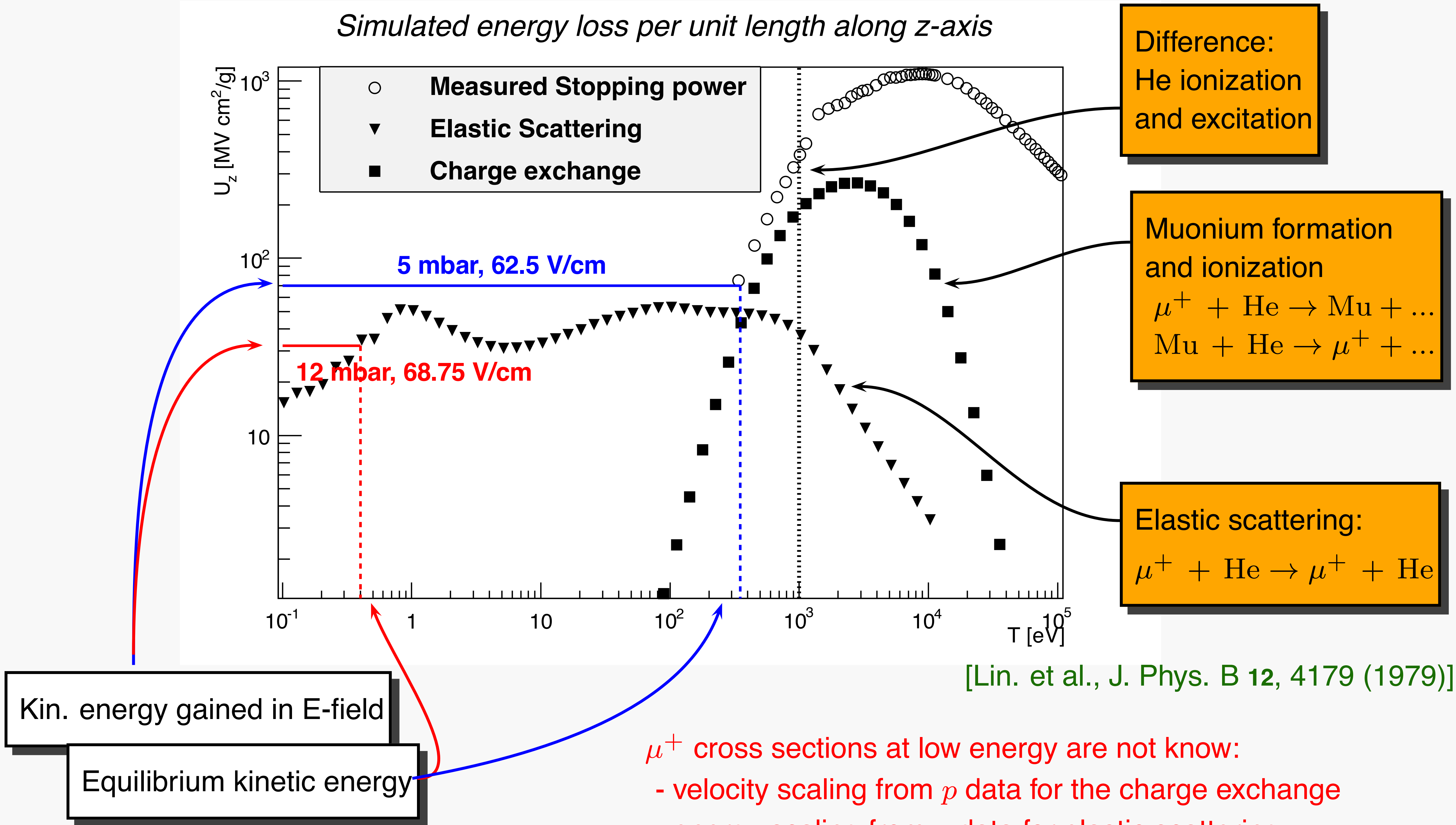






Backup

Physical Processes at Low Energy

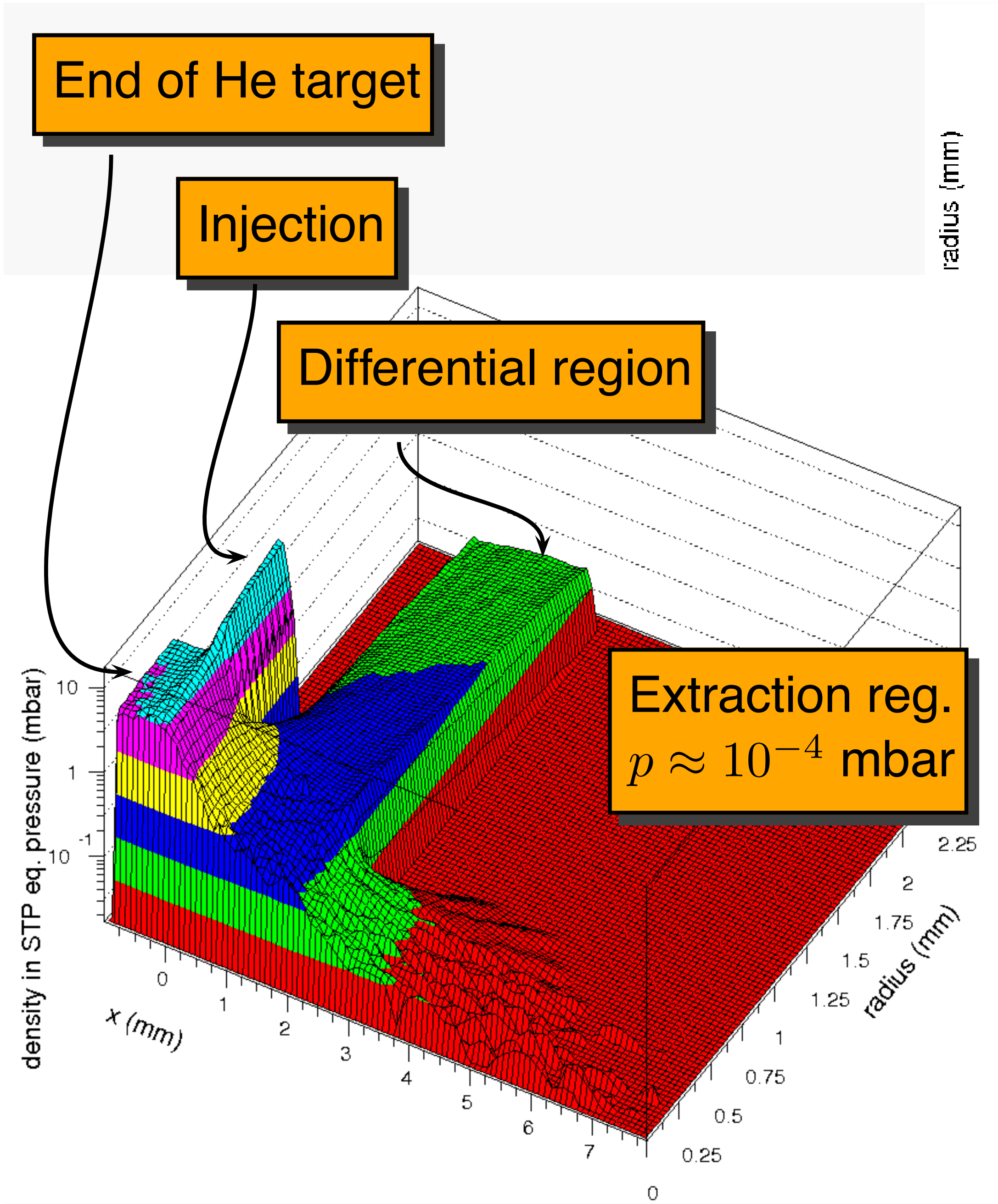


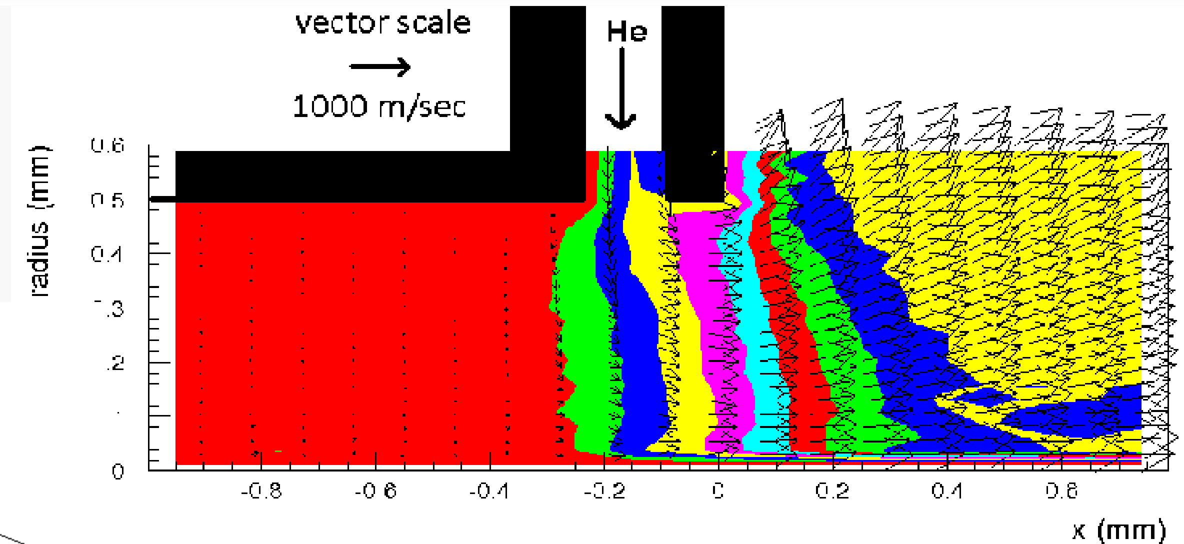
[Lin. et al., J. Phys. B **12**, 4179 (1979)]

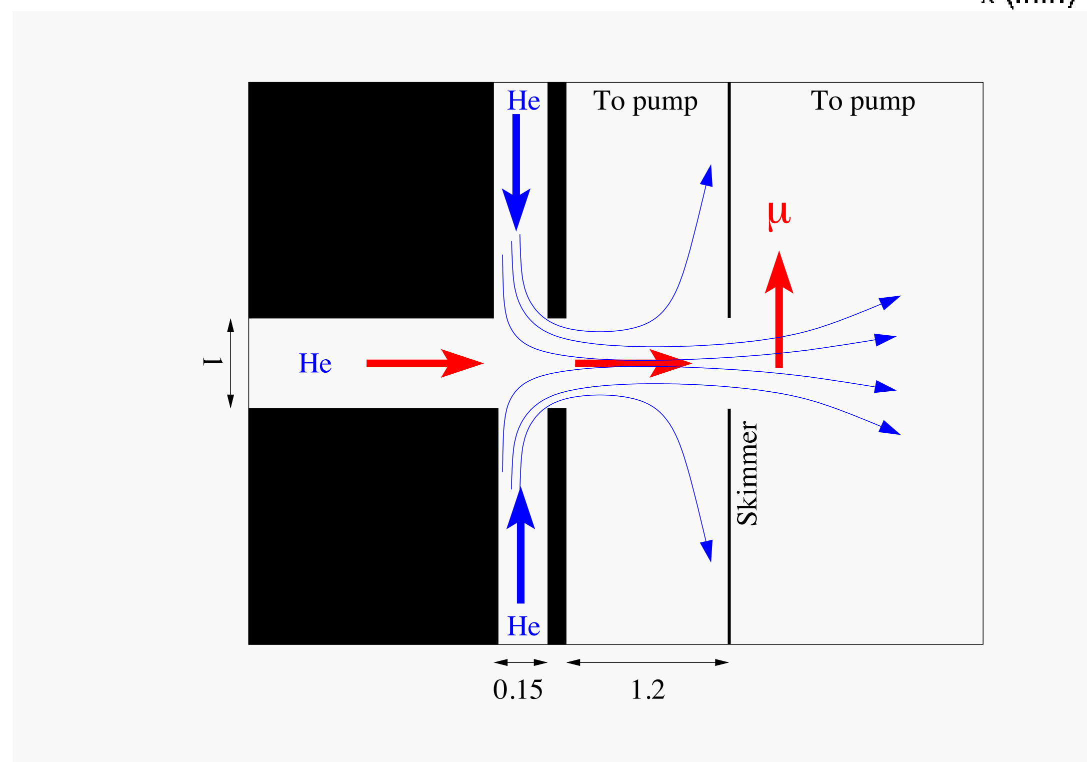
μ^+ cross sections at low energy are not know:

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

Extraction into Vacuum

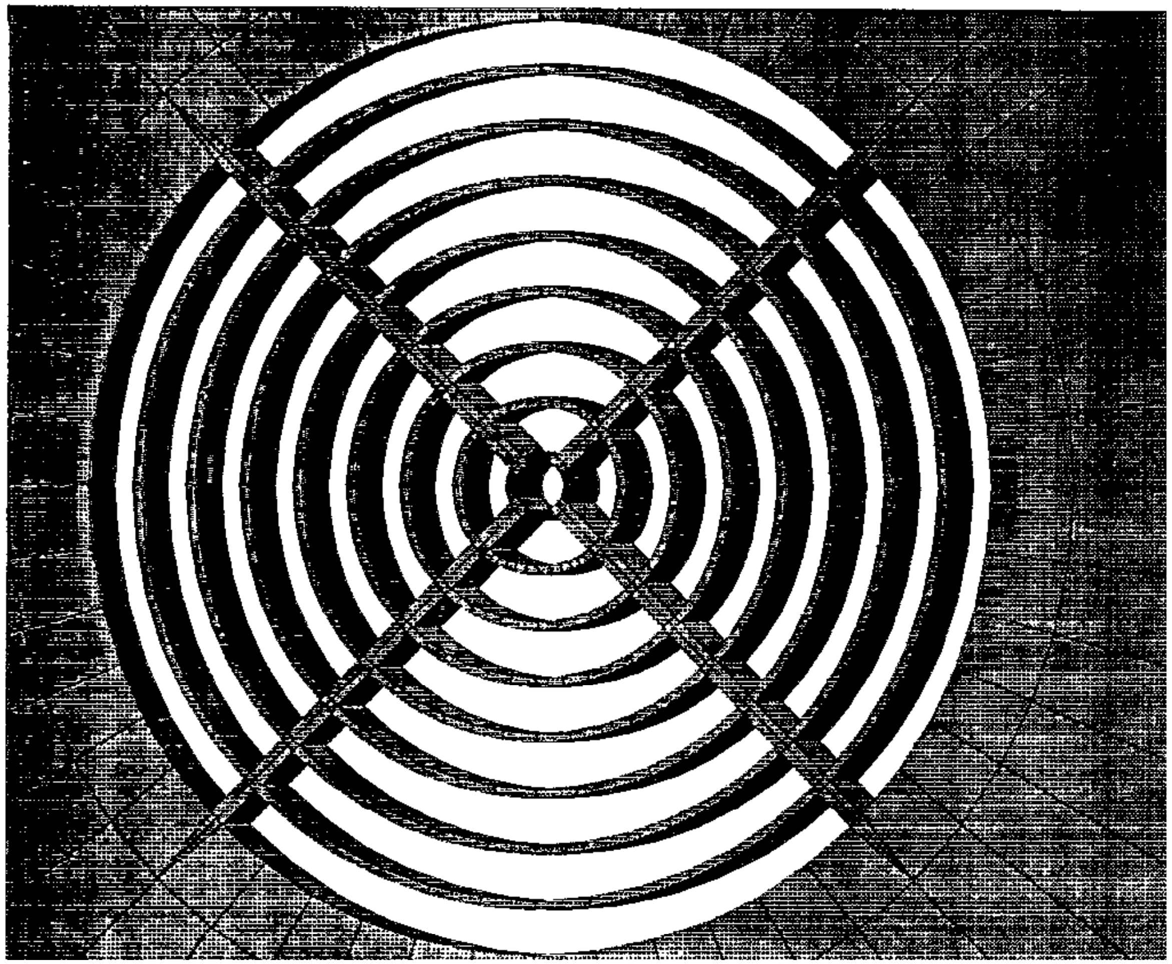




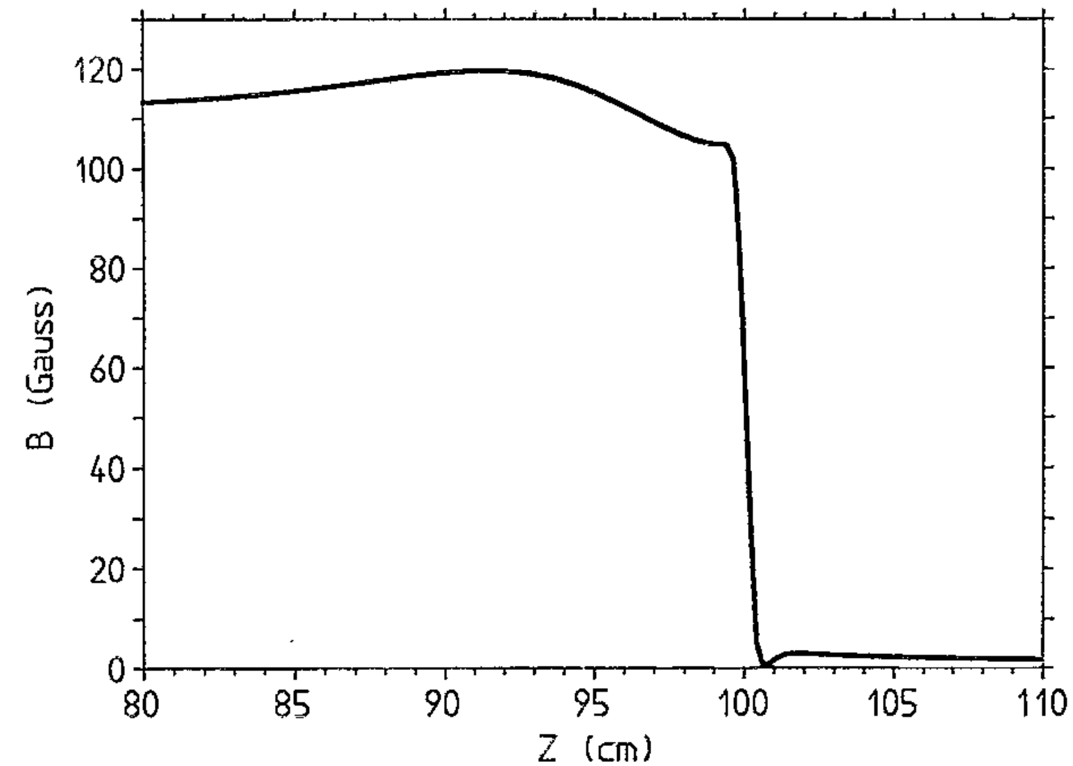


- No flow inside target!
- Reinjection of helium “blocks” outflow of helium from target cell and compensates losses

Extraction into Field Free Region

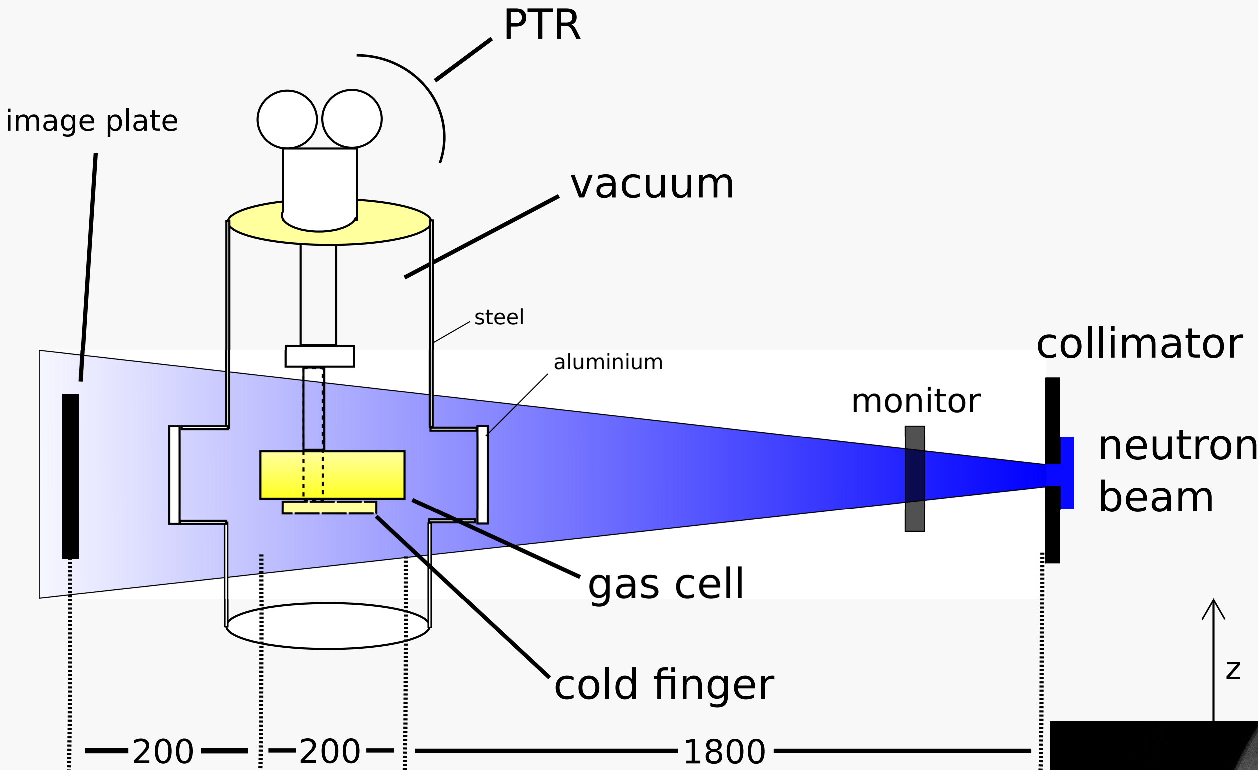


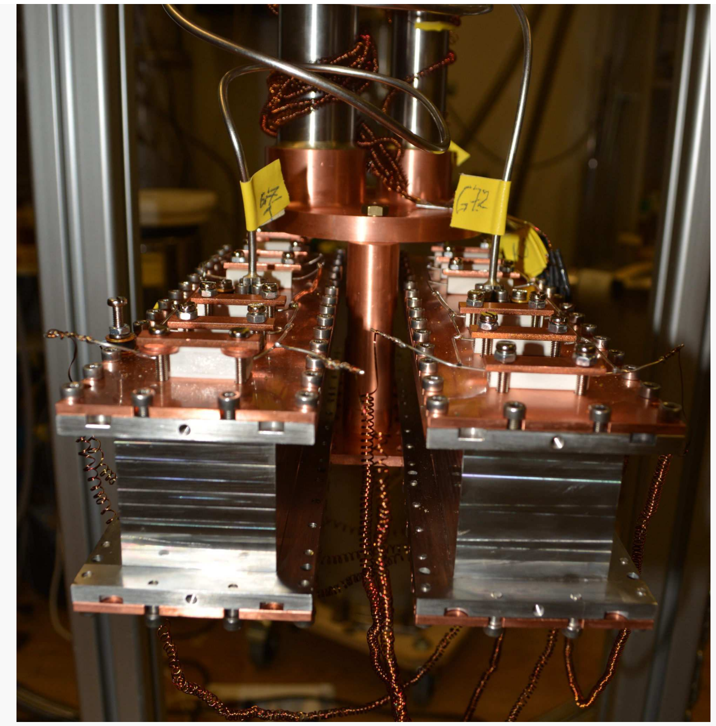
Gerola et al., Rev. Sci. Inst. **66**, 3819 (1995)



- Field termination with a magnetic grid
- Tested with electrons at a few keV
- ~50% transmission and increased transverse energy by O(10 eV)

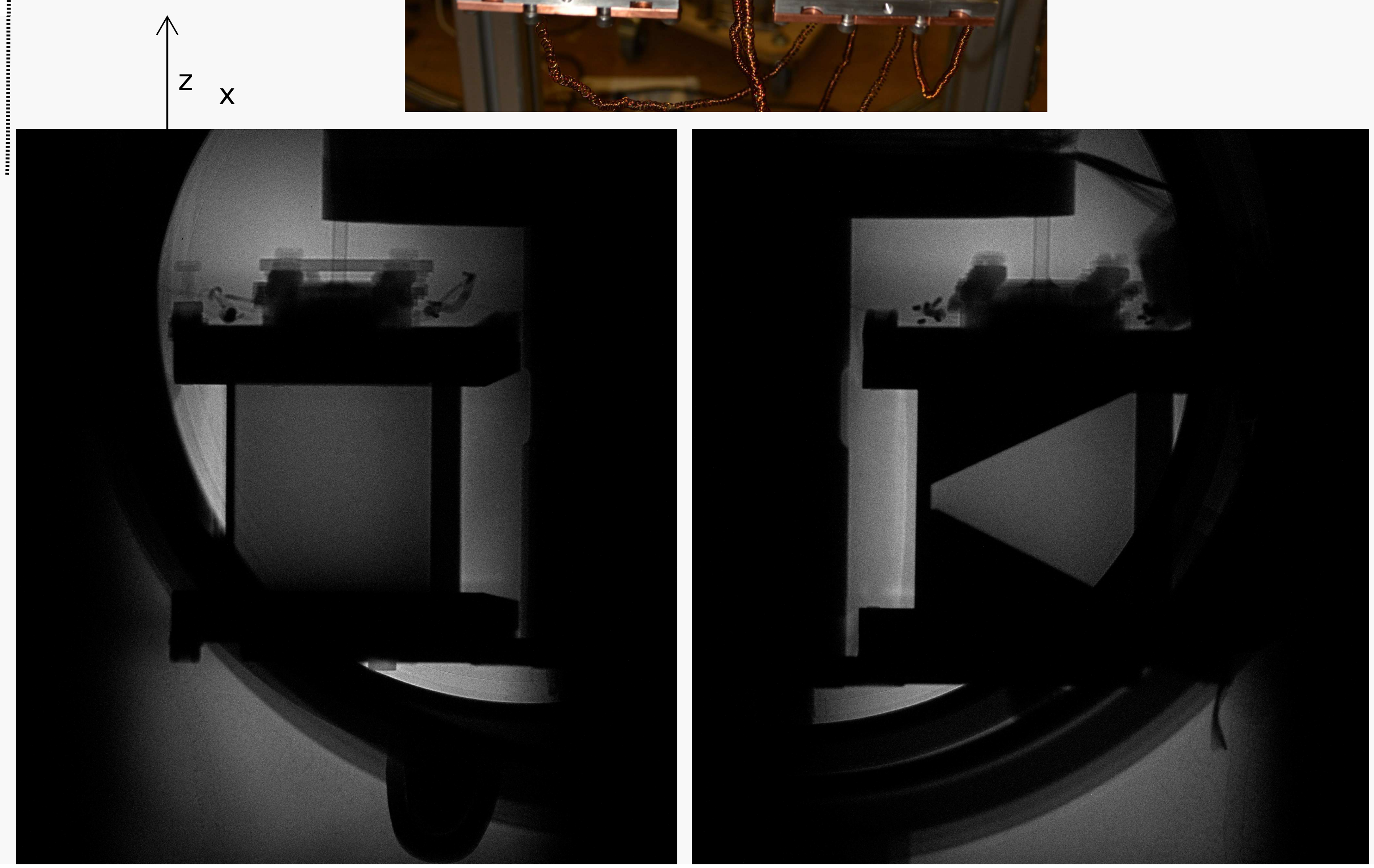
Measurement of Gas Density Gradient





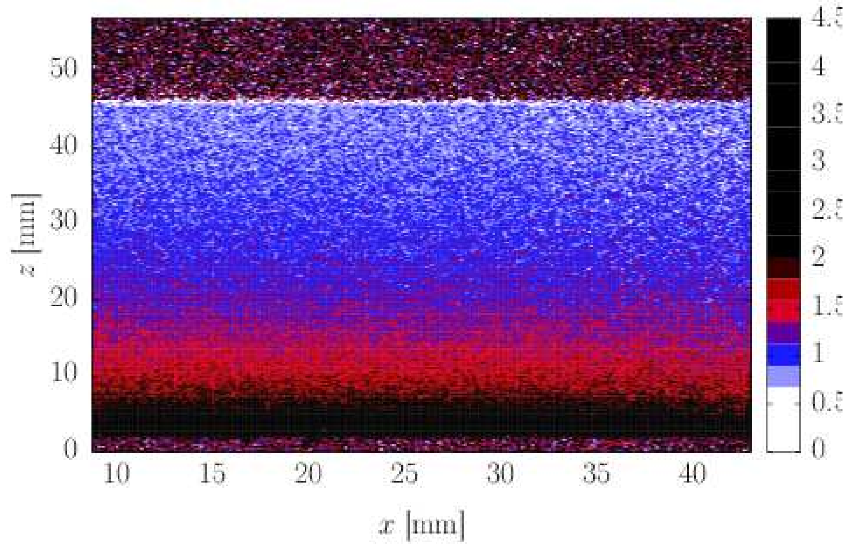
(Morpheus beam line, PSI)

(Raw data/images) →

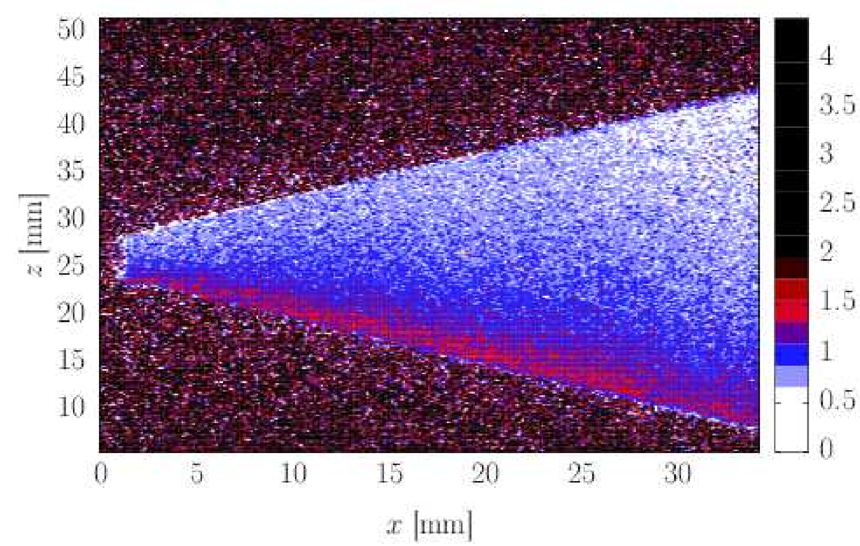


Measurement of Gas Density Gradient

Rectangular cell



Triangular cell

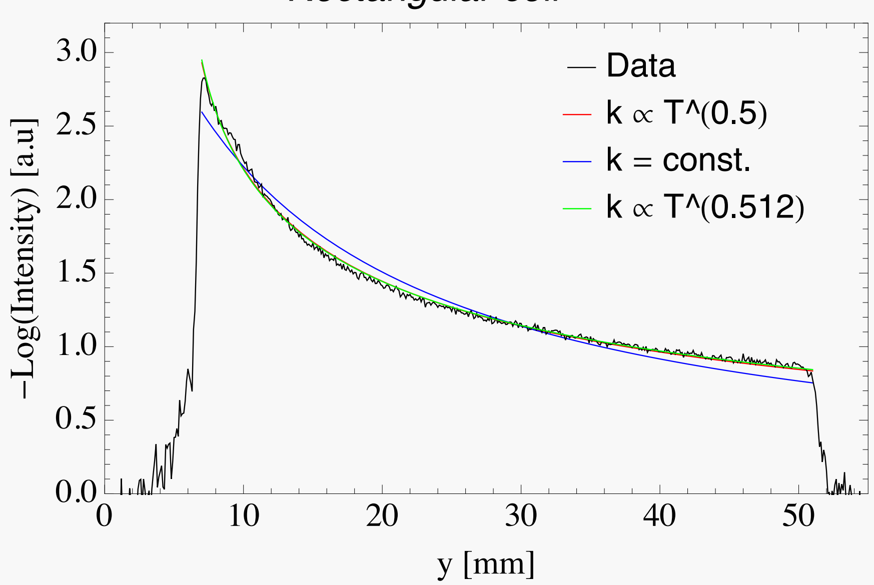


The color scales represent the exponential absorption coefficient.

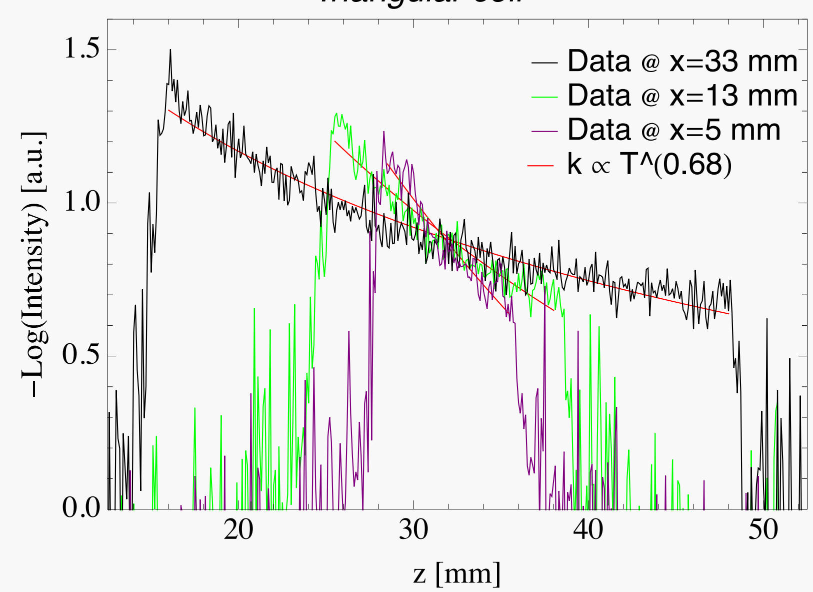
→ *The colors are proportional to the density* ρ

- Data normalized using a monitor detector and empty cell measurements.

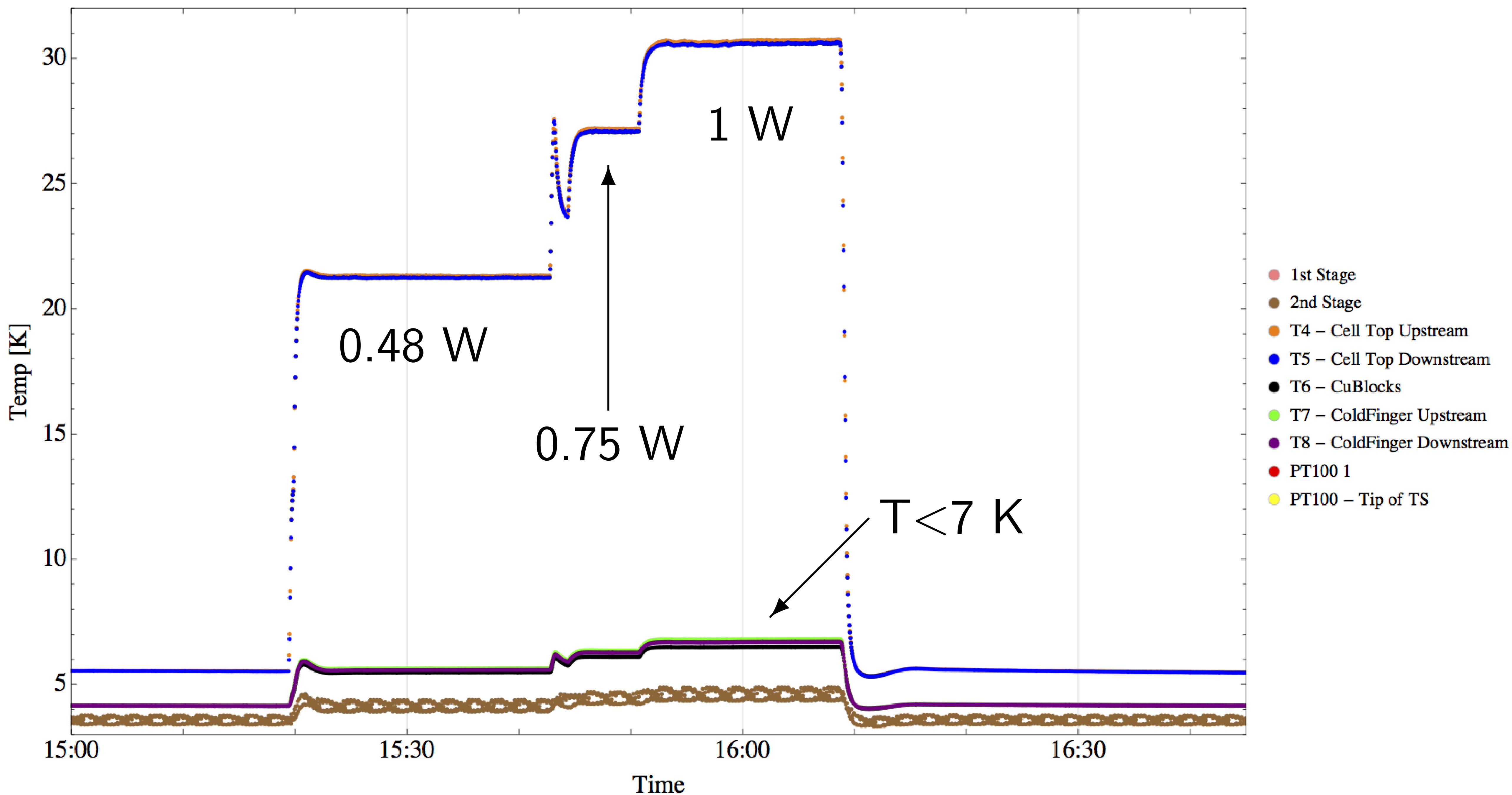
Rectangular cell



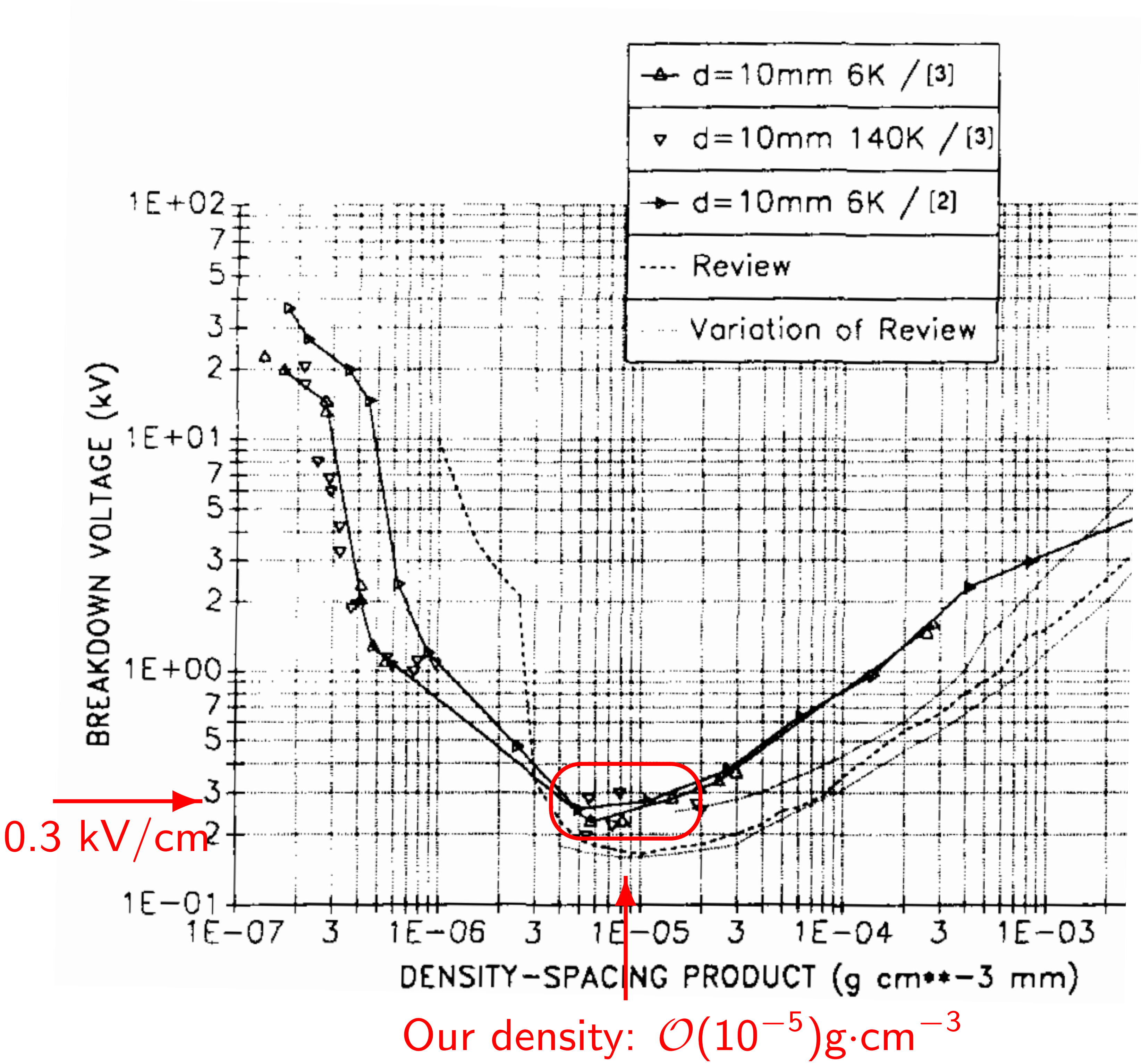
Triangular cell



Coldfinger Temperatures



Electric Discharges



- Require 2 kV/cm
- Strong B-field!
  - $\vec{E} \times \vec{B}$-drift
  - Increase effective density
  - Increase breakdown voltage

V_{BD} at cryogenic temperatures for He

M. Irmisch et al.; IEEE Trans. on E. I. Vol 28, No. 4, Aug 1993