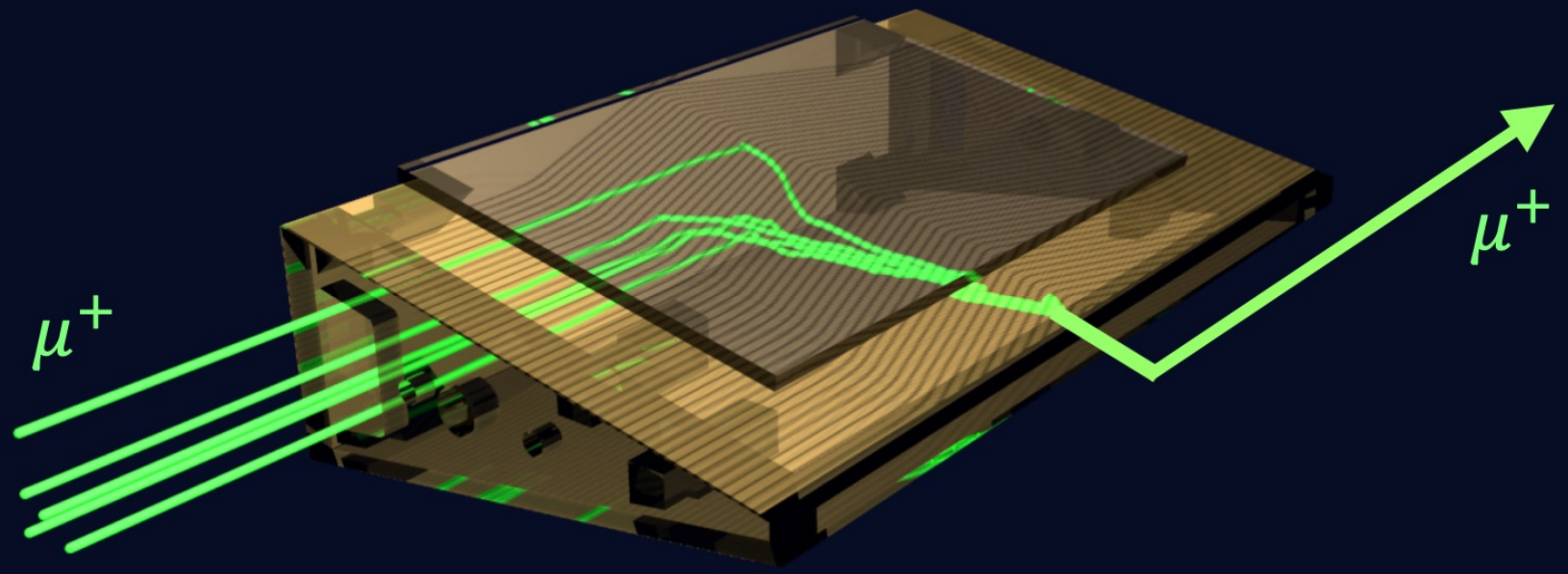


A muon beam of small phase space

Giuseppe Lospalluto (ETH Zürich)

Supervised by Prof. Aldo Antognini and Prof. Klaus Kirch

On the behalf of the muCool collaboration

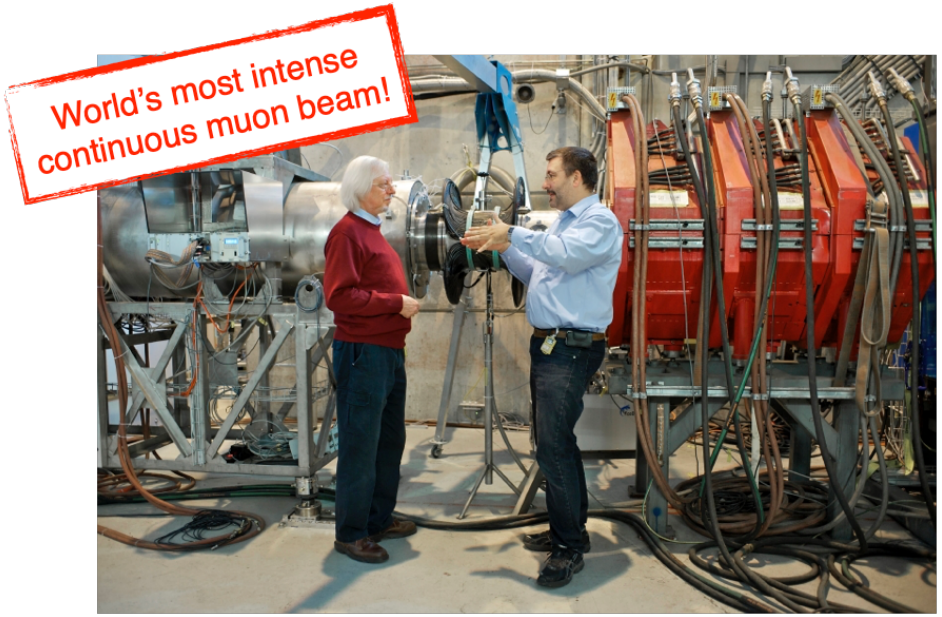
Zürich PhD seminar

27 Jan 2023

Muon beamline at PSI

- High intensity positive muon beam (4.1 MeV) at the Paul Scherrer Institut (PSI)

$$\underset{\text{(beam)}}{p} + \underset{\text{(target)}}{p} \rightarrow \pi^+ \ldots \rightarrow \mu^+ \ldots$$



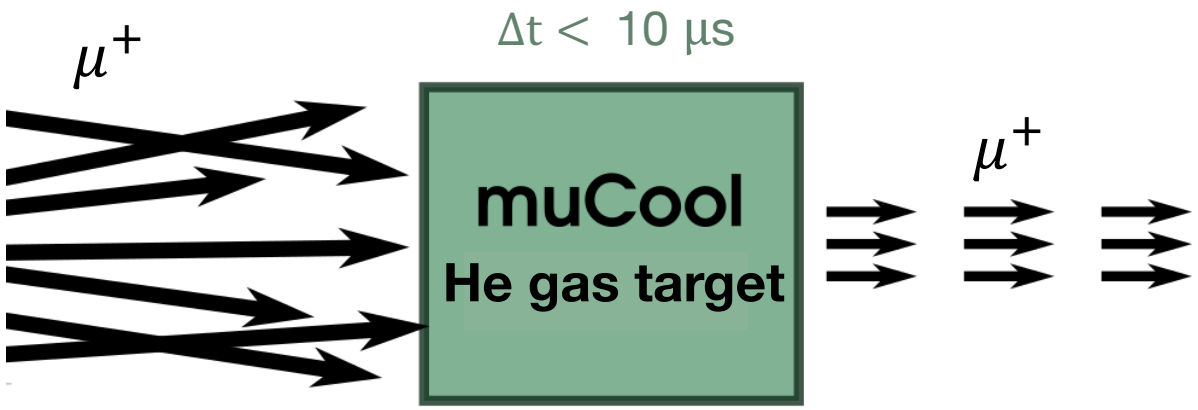
- What for?
  e.g. Rare muon decay searches ($\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^-e^+$)

High "rate", poor "quality"

- How can we cool a muon beam? (τ_μ = 2.2 μs)

muCool : “fast” phase space compression

E ~ 4 MeV
cm-size
MeV-energy spread

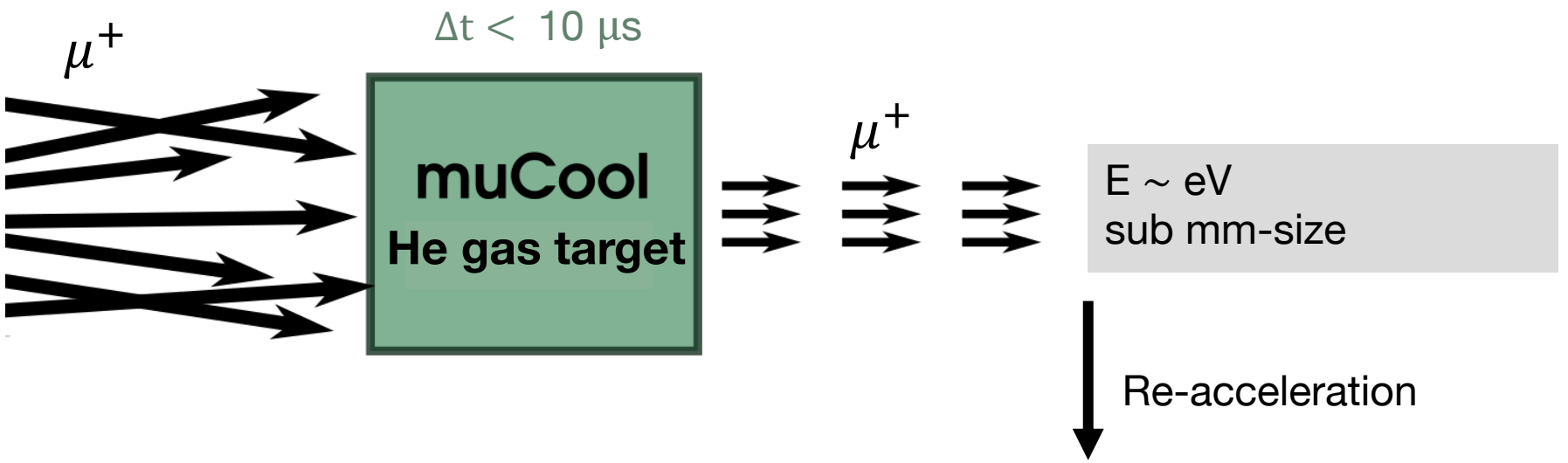


E ~ eV
sub mm-size

- Efficiency of $\sim 10^{-4}$
- Phase space improved by $> 10^8$

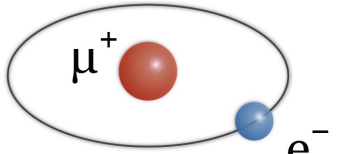
D. Taqqu. *Phys. Rev. Lett.* 97.194801 **(2006)**

muCool : “fast” phase space compression



- Efficiency of $\sim 10^{-4}$
- Phase space improved by $> 10^8$

keV energies



- Muonium spectroscopy, muonium gravity experiments
- Material Science (μSR)

MeV energies

- Muon g-2/EDM with storage ring

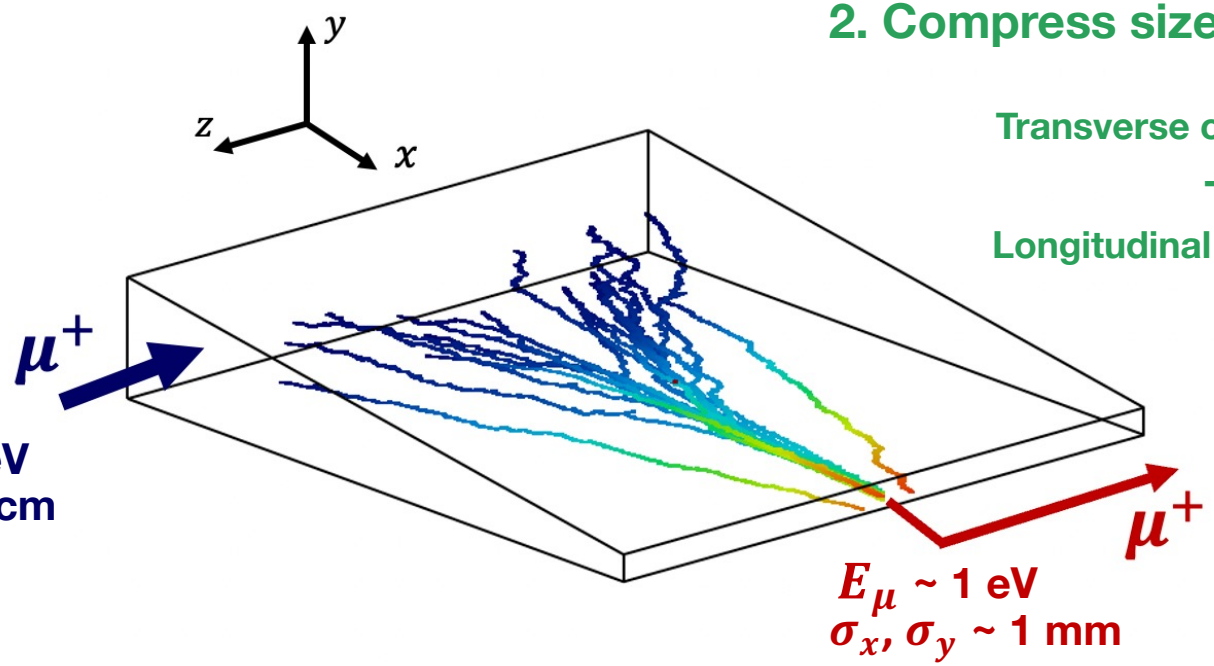
D. Taqqu. *Phys. Rev. Lett.* 97.194801 **(2006)**

muCool scheme

- Complex E-fields and B-field + density gradient compress the muon beam

1. Stop muon beam in He gas

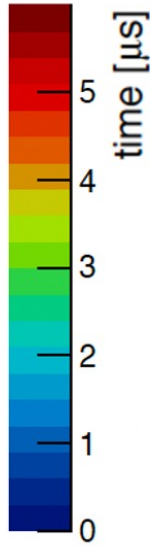
E_μ ~ 4 MeV
σ_x, σ_y ~ 1 cm



2. Compress size

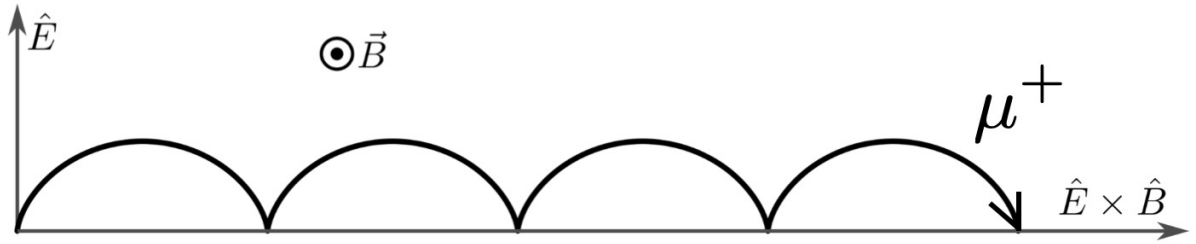
Transverse compression σ_y
+
Longitudinal compression σ_z

E_μ ~ 1 eV
σ_x, σ_y ~ 1 mm

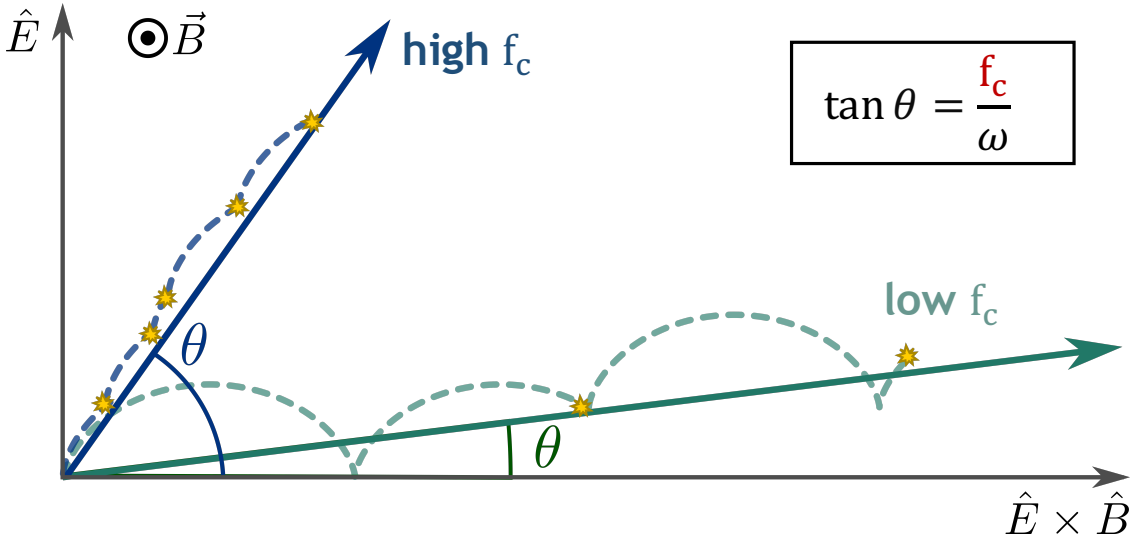


3. Extraction from He gas into vacuum

Muon drift in crossed E and B-fields



In vacuum



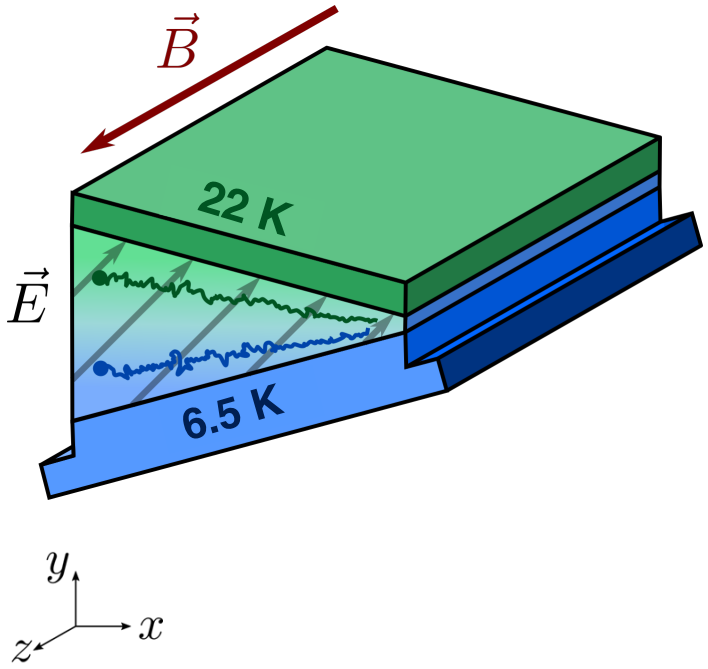
$$\tan\theta = \frac{f_c}{\omega}$$

In gas

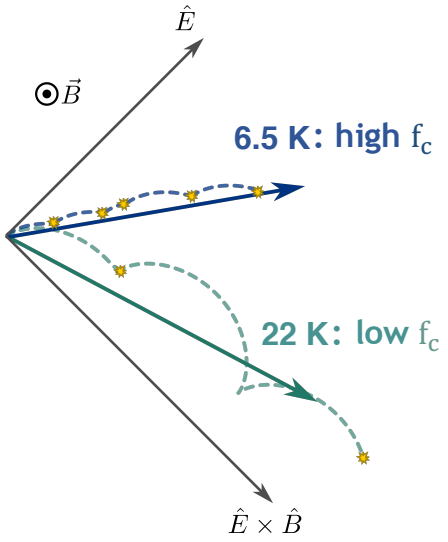
Collision with gas atoms at frequency f_c

muCool principle

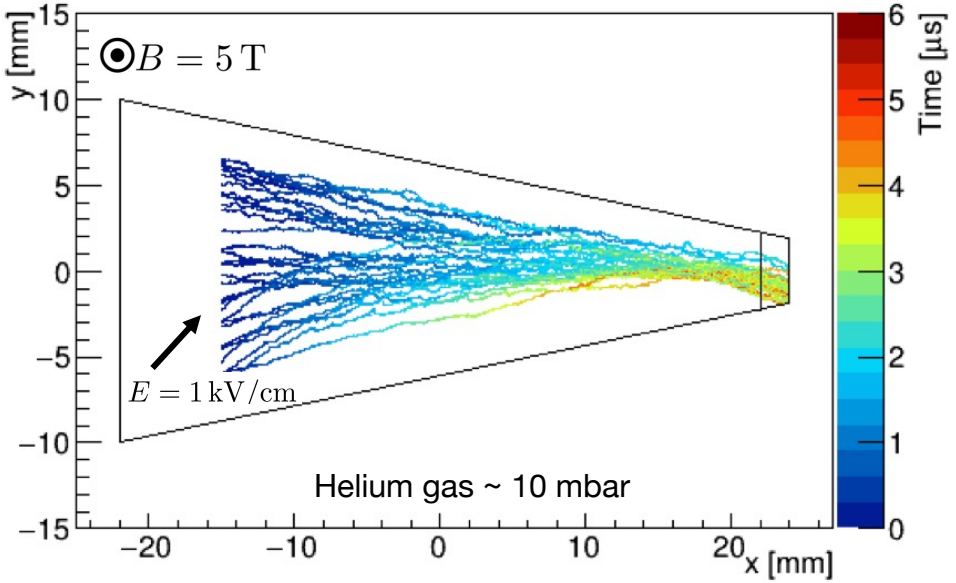
Transverse Compression



$f_c \propto$ gas density



Simulated muon trajectories



Drift velocity

$$\vec{v}_D = \frac{\mu E}{1+\frac{w^2}{f_c^2}}\left(\hat{E} + \frac{w}{f_c}\left(\hat{E}\times\hat{B}\right) + \frac{w^2}{f_c^2}\left(\hat{E}\cdot\hat{B}\right)\hat{B}\right)$$

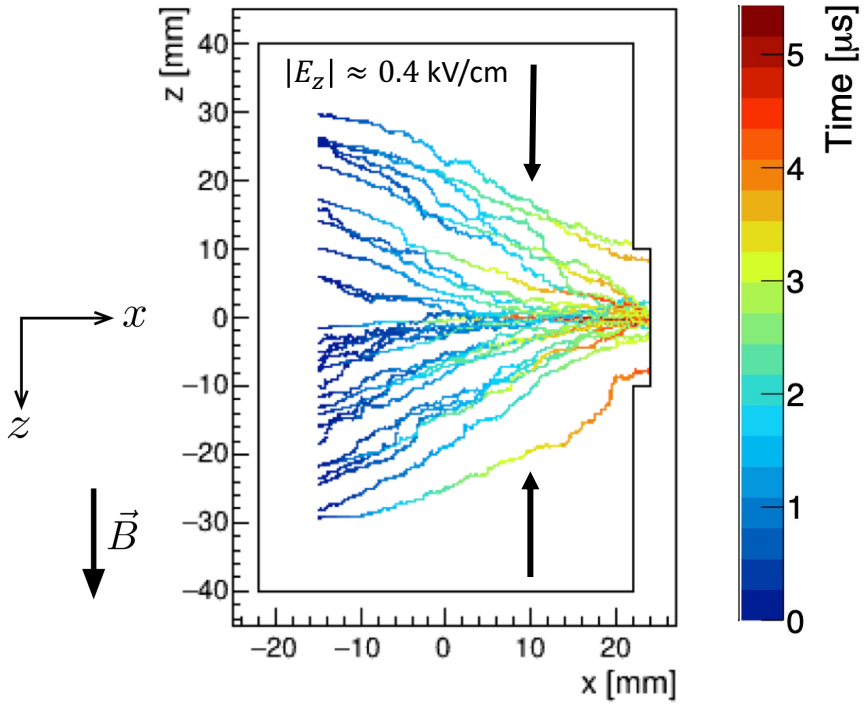
= 0

μ : muon mobility
w : cyclotron frequency
f_c : frequency of muon-He gas collisions

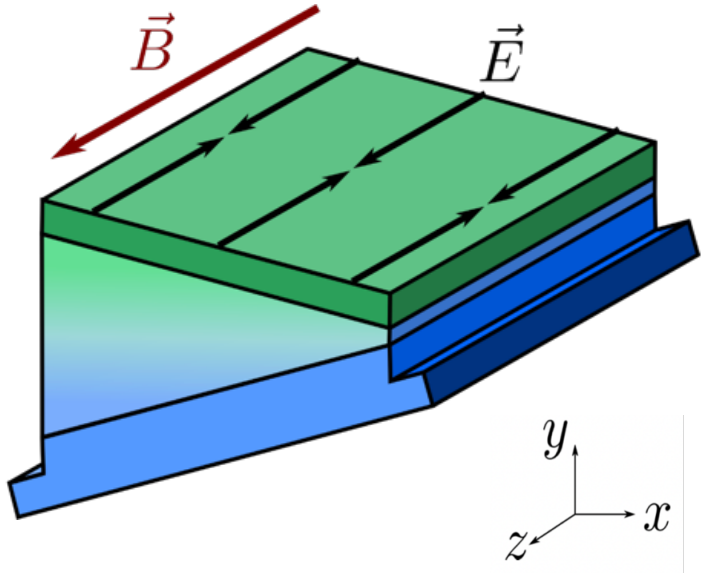
A. Antognini et al. *Phys. Rev. Lett.* 125.164802 **(2020)**

muCool principle

Simulated muon trajectories



Longitudinal Compression



Drift velocity

$$\vec{v}_D = \frac{\mu E}{1+\frac{w^2}{f_c^2}}\left(\hat{E} + \frac{w}{f_c}\left(\hat{E}\times\hat{B}\right) + \frac{w^2}{f_c^2}\left(\hat{E}\cdot\hat{B}\right)\hat{B}\right)$$

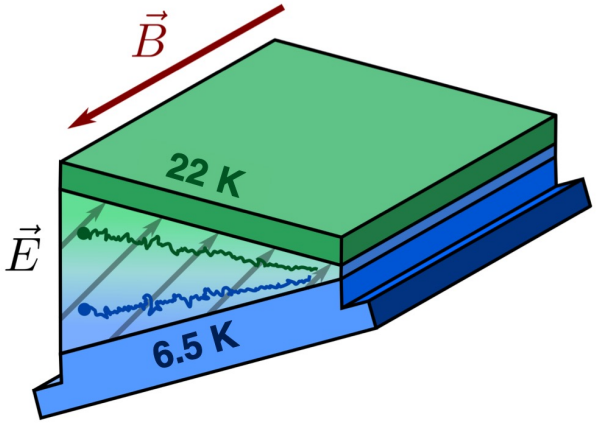
$= 0$

μ : muon mobility
w : cyclotron frequency
f_c : frequency of muon-He gas collisions

Belosevic, I. et al. *Eur. Phys. J. C* 79:430 **(2019)**
Y. Bao et al. *Phys. Rev. Lett.* 112.224801 **(2014)**

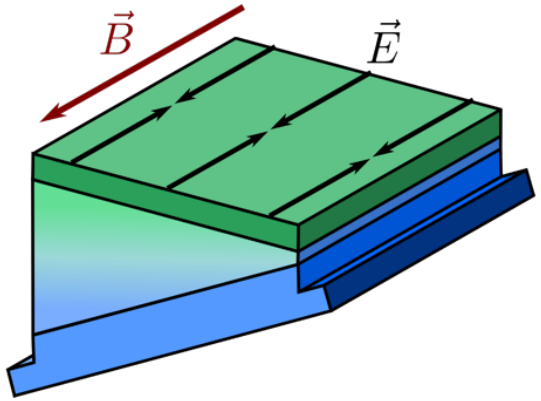
muCool principle

Transverse Compression



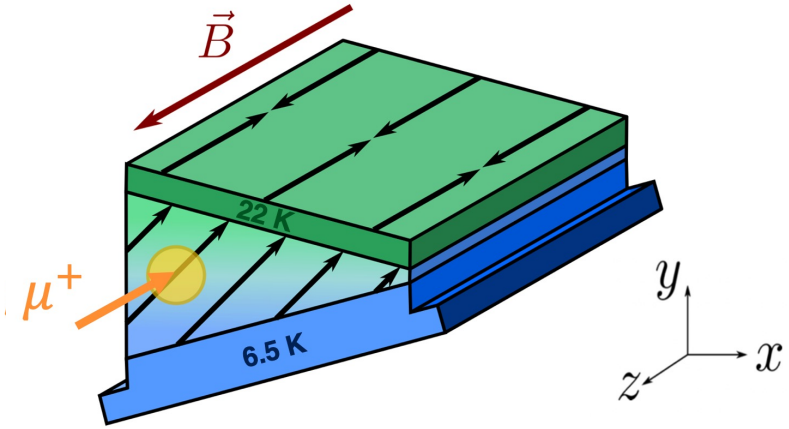
+

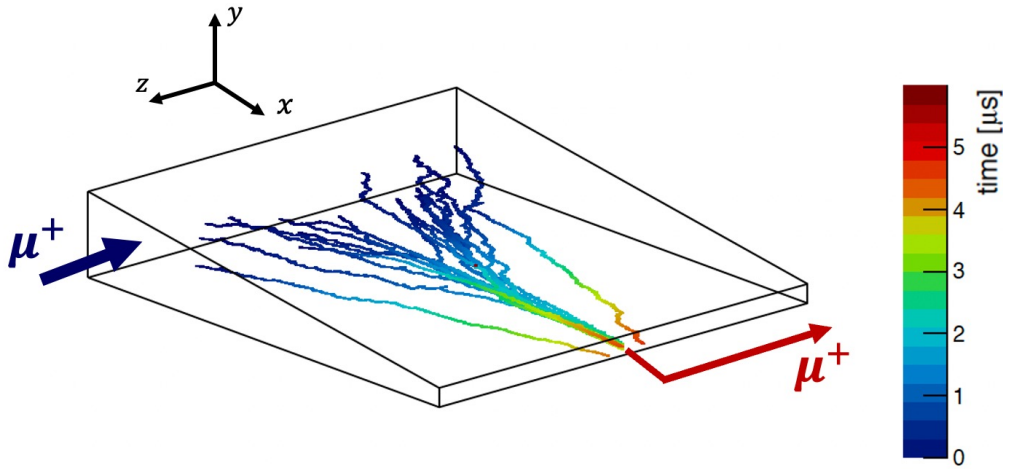
Longitudinal Compression



=

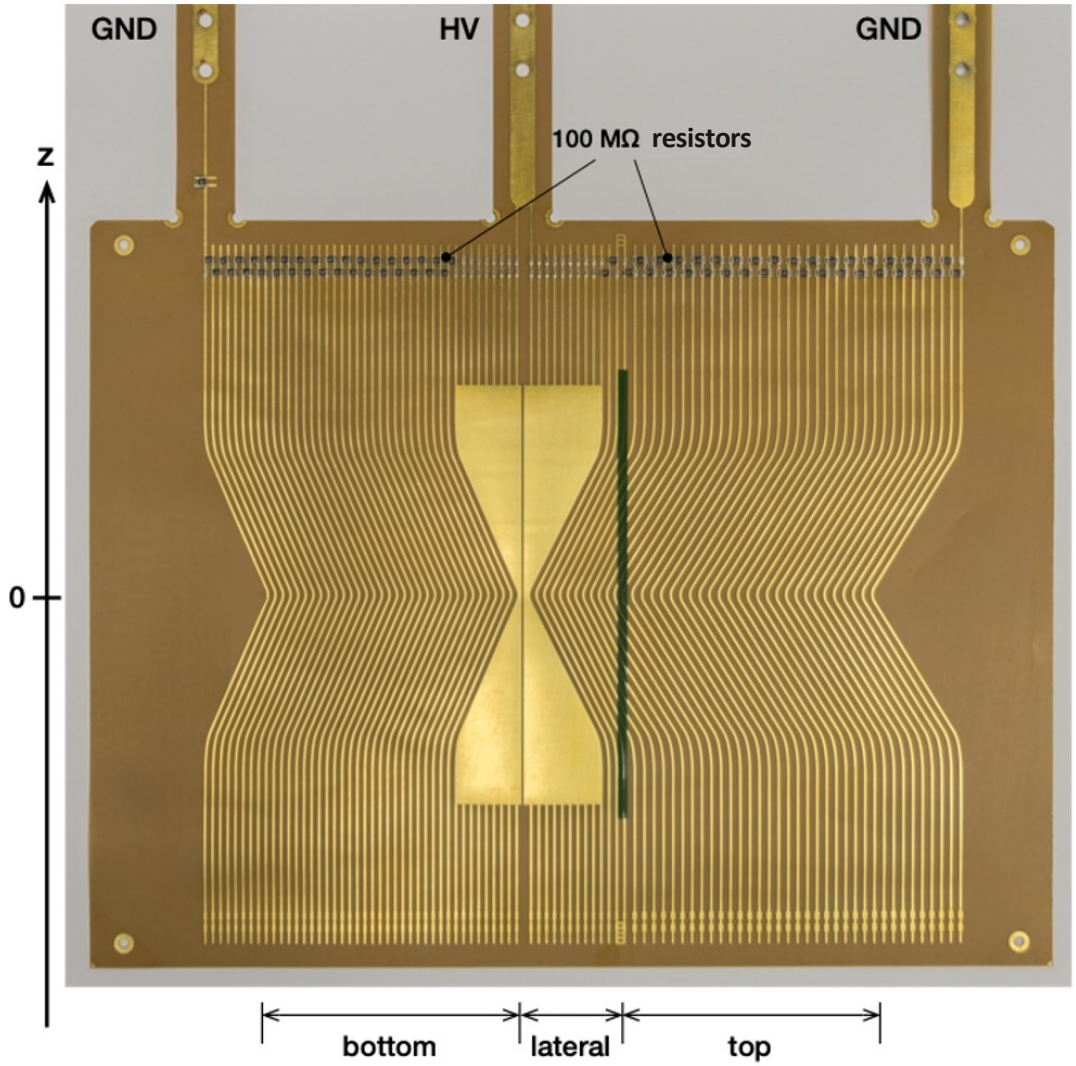
Mixed Compression





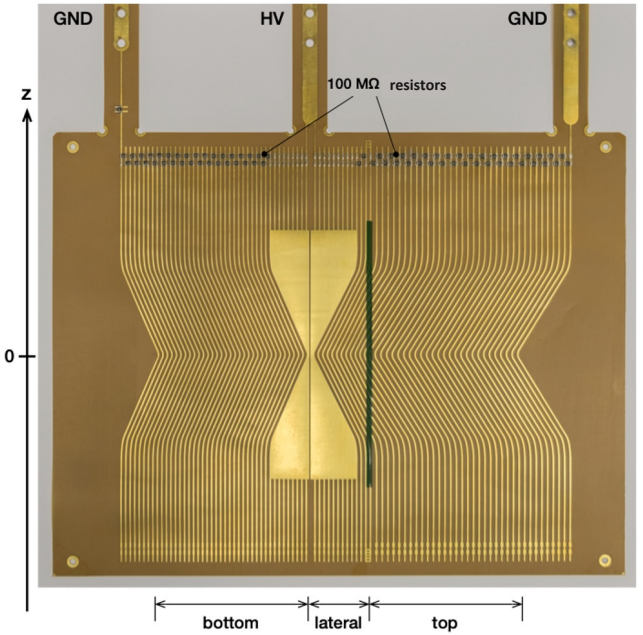
Target realisation

- Lined Kapton-foil: Electric field for mixed compression



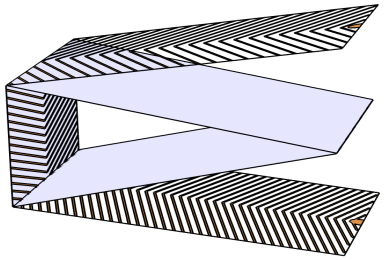
Target realisation

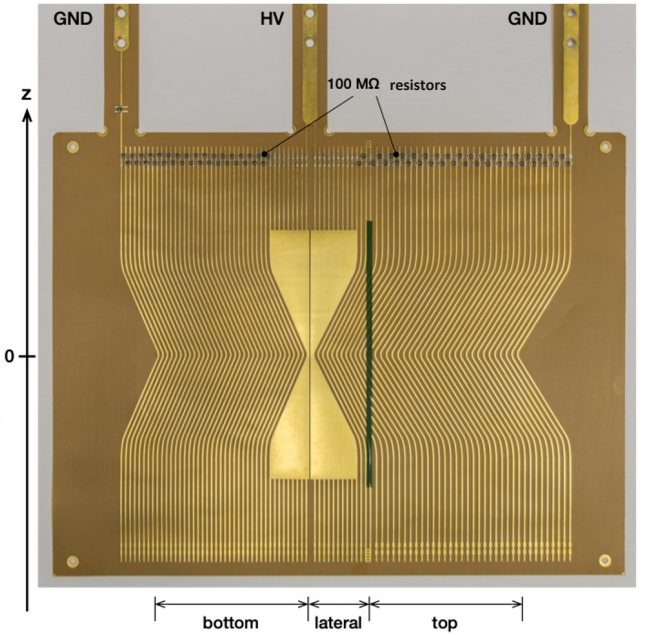
- Lined Kapton-foil: Electric field for mixed compression



Target realisation

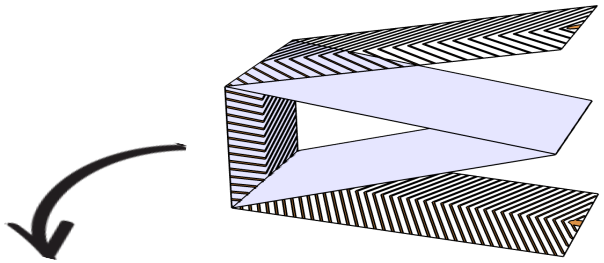
- Lined Kapton-foil: Electric field for mixed compression

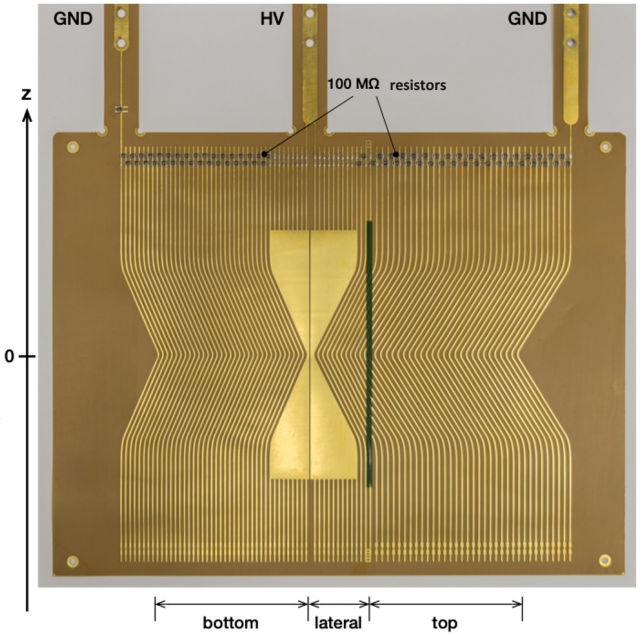


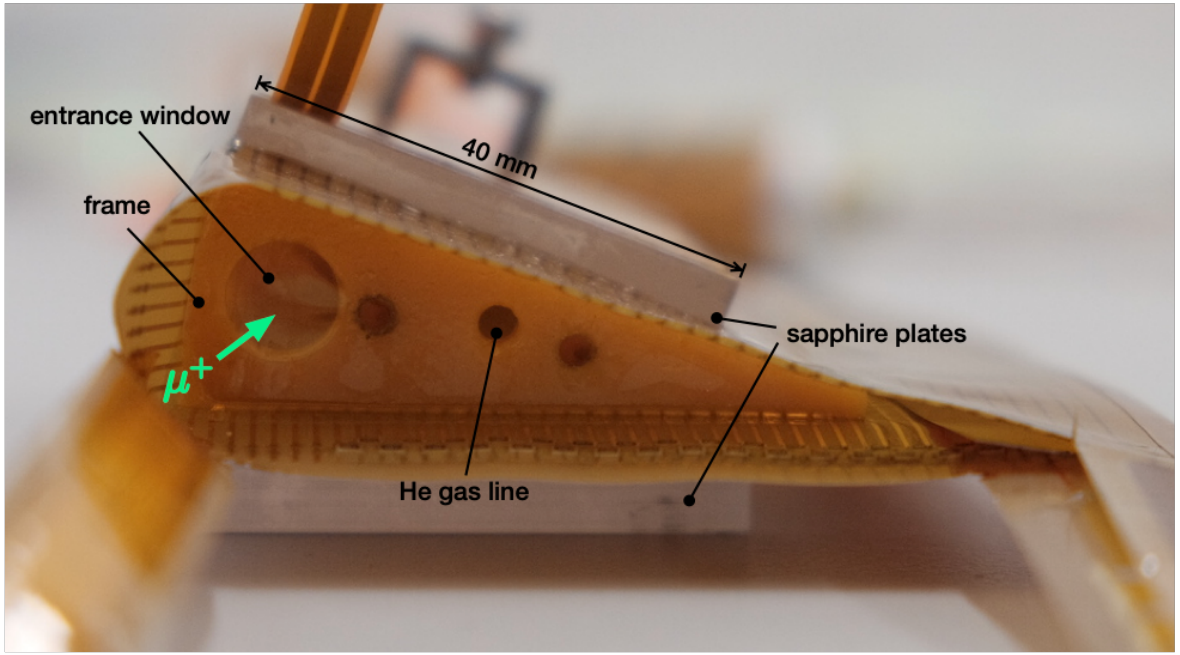


Target realisation

- Lined Kapton-foil: Electric field for mixed compression

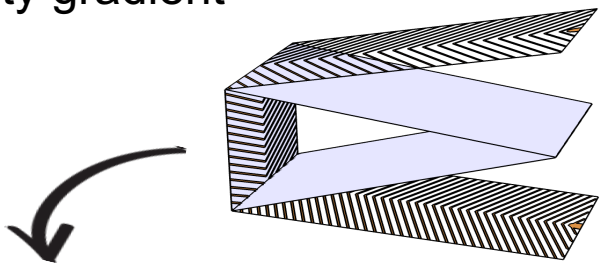


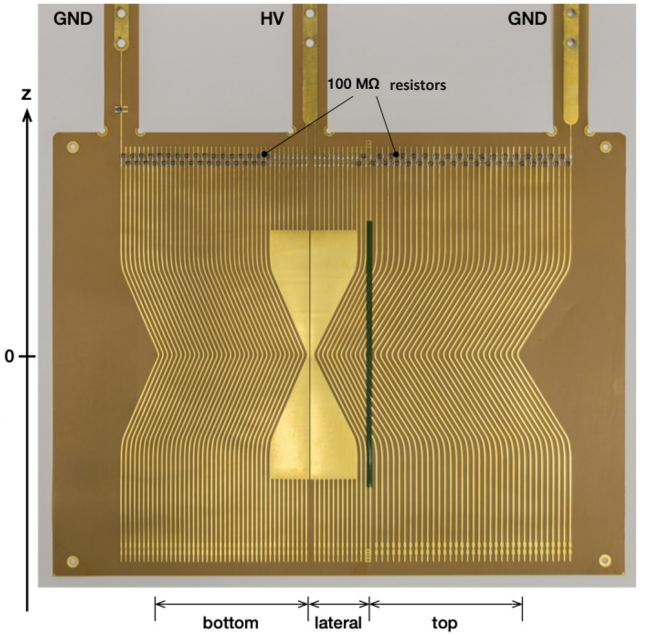


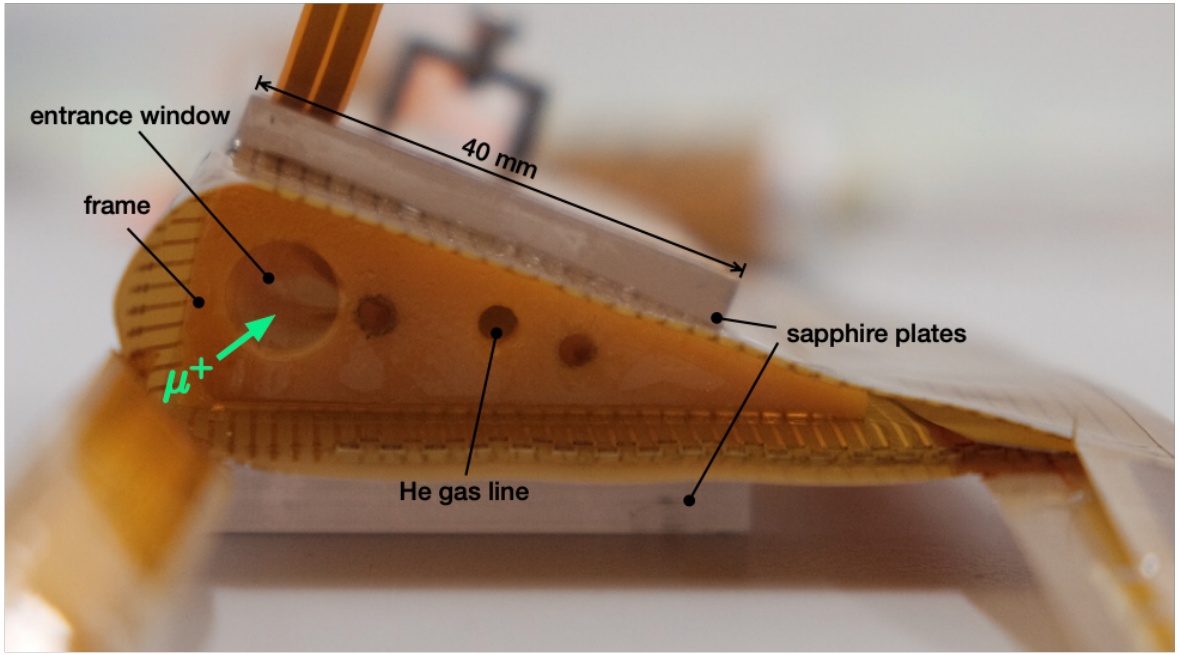


Target realisation

- Lined Kapton-foil: Electric field for mixed compression
- Sapphire plates: Vertical density gradient

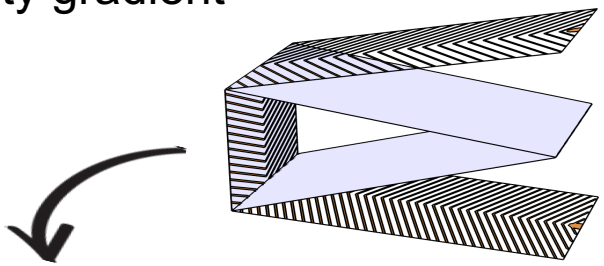


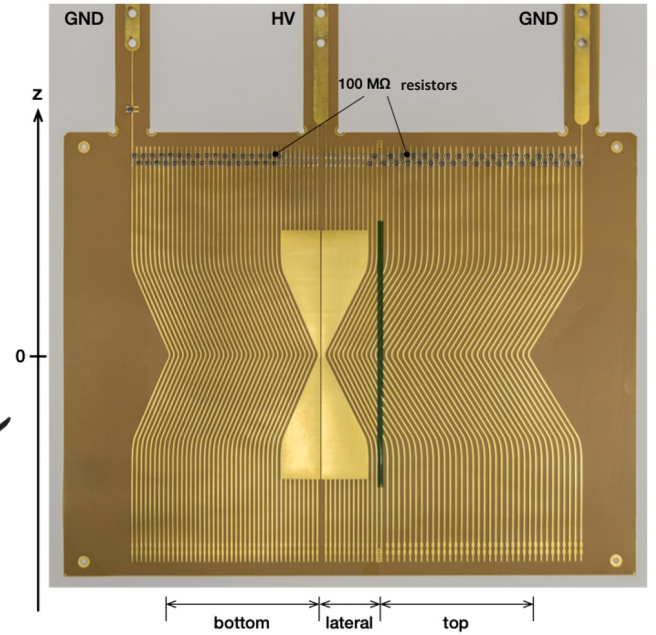


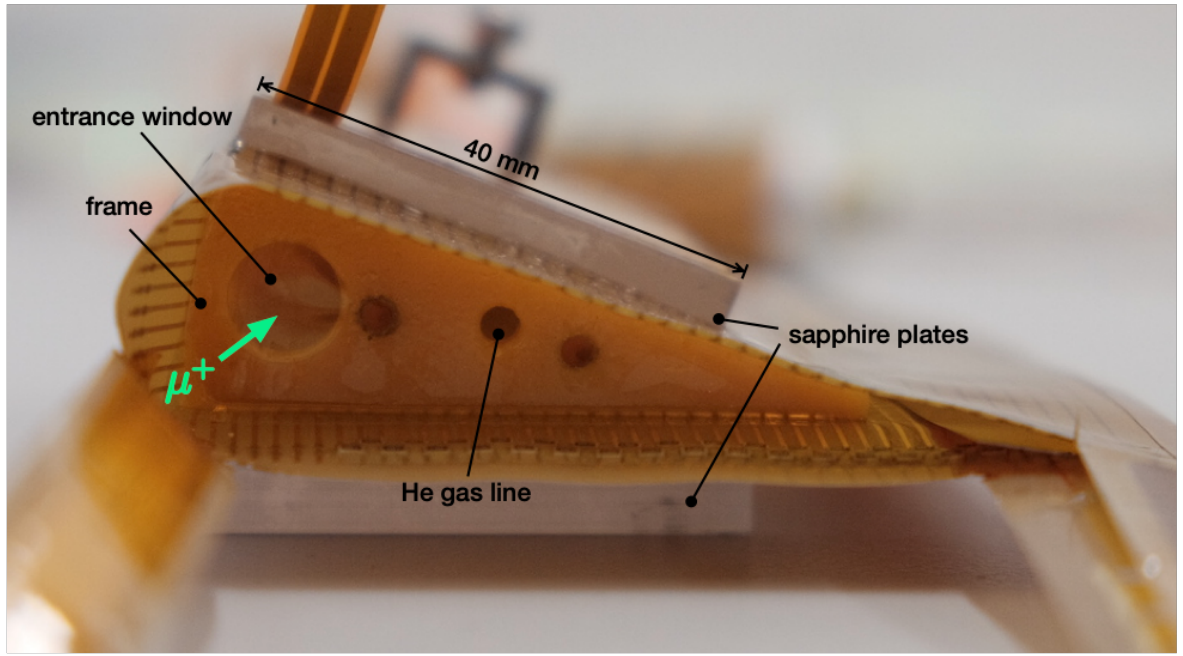


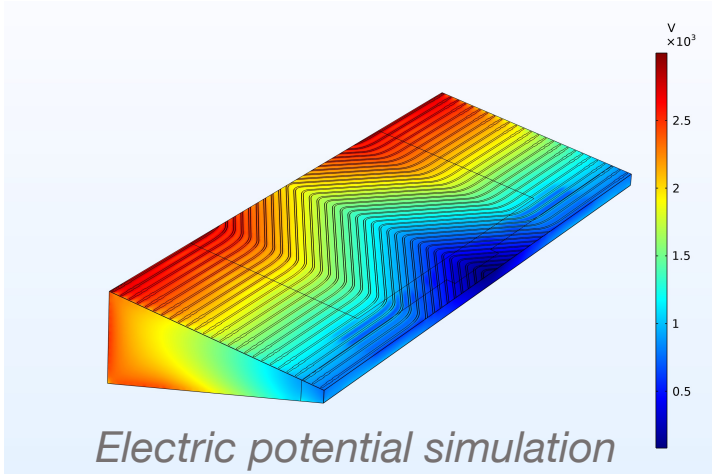
Target realisation

- Lined Kapton-foil: Electric field for mixed compression
- Sapphire plates: Vertical density gradient







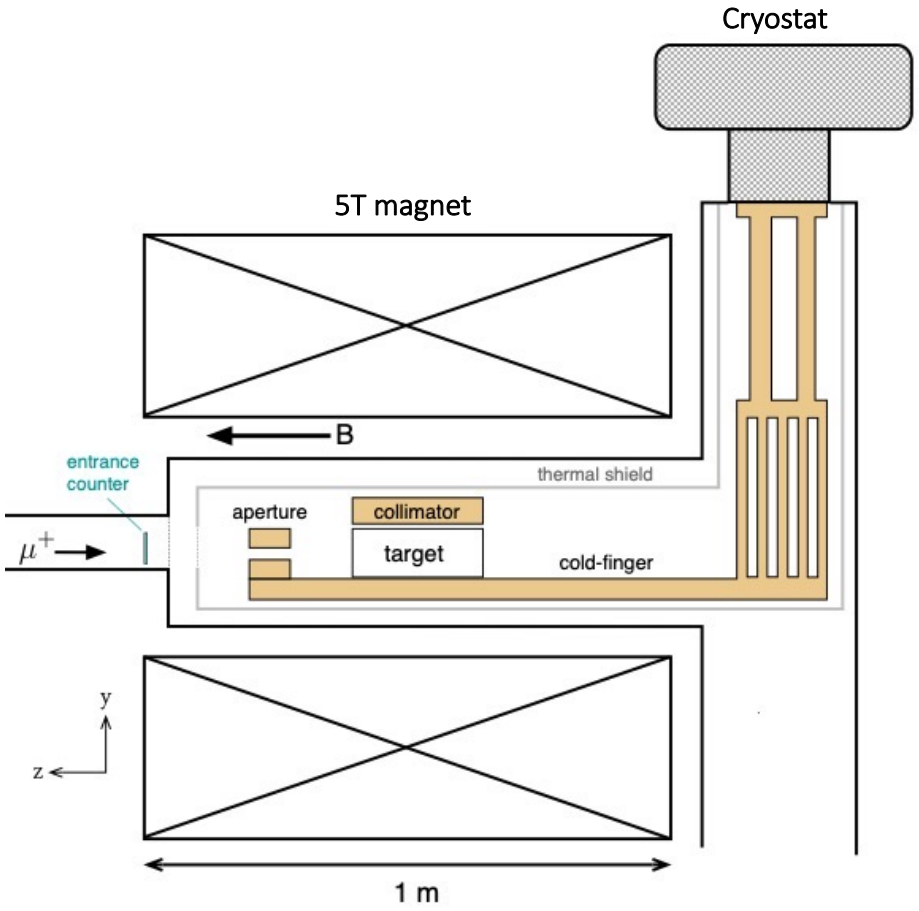


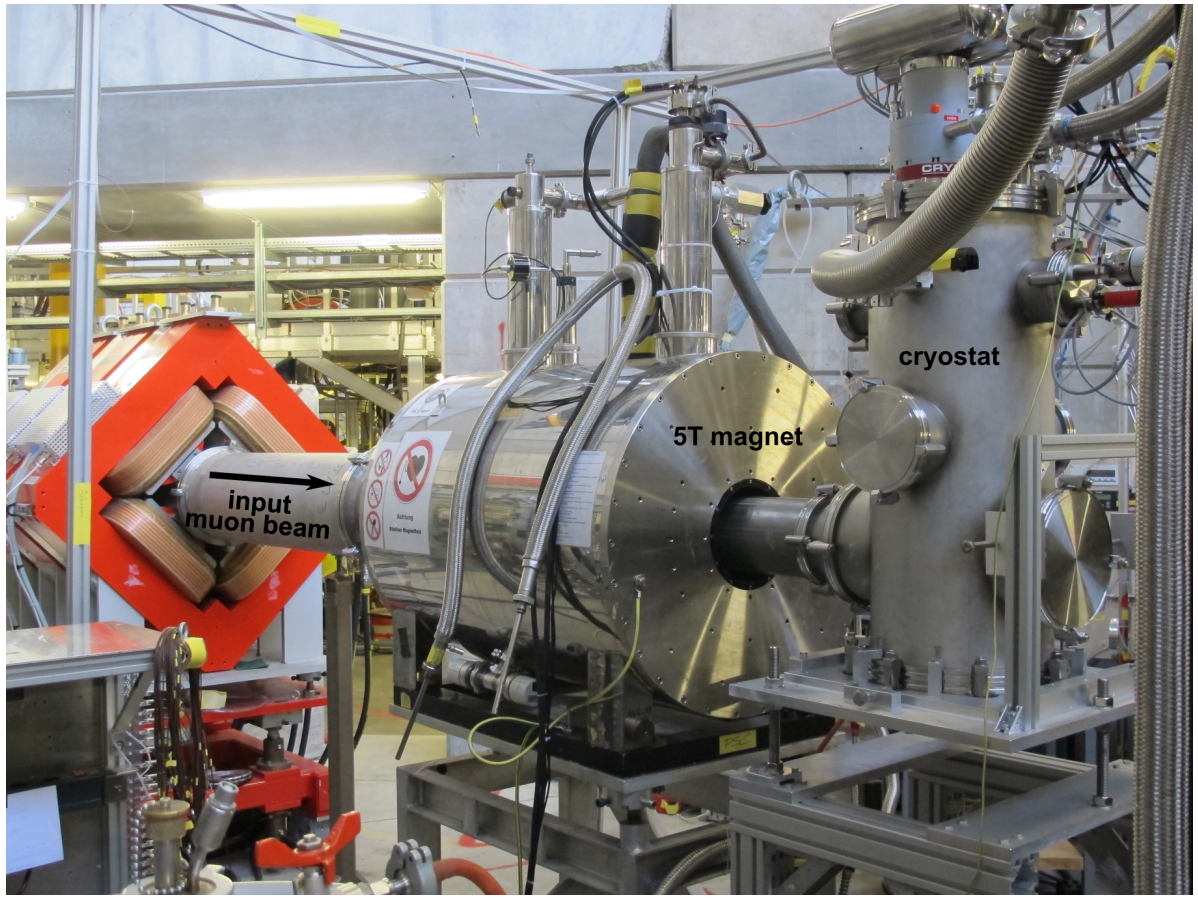
Electric potential simulation

Experiment

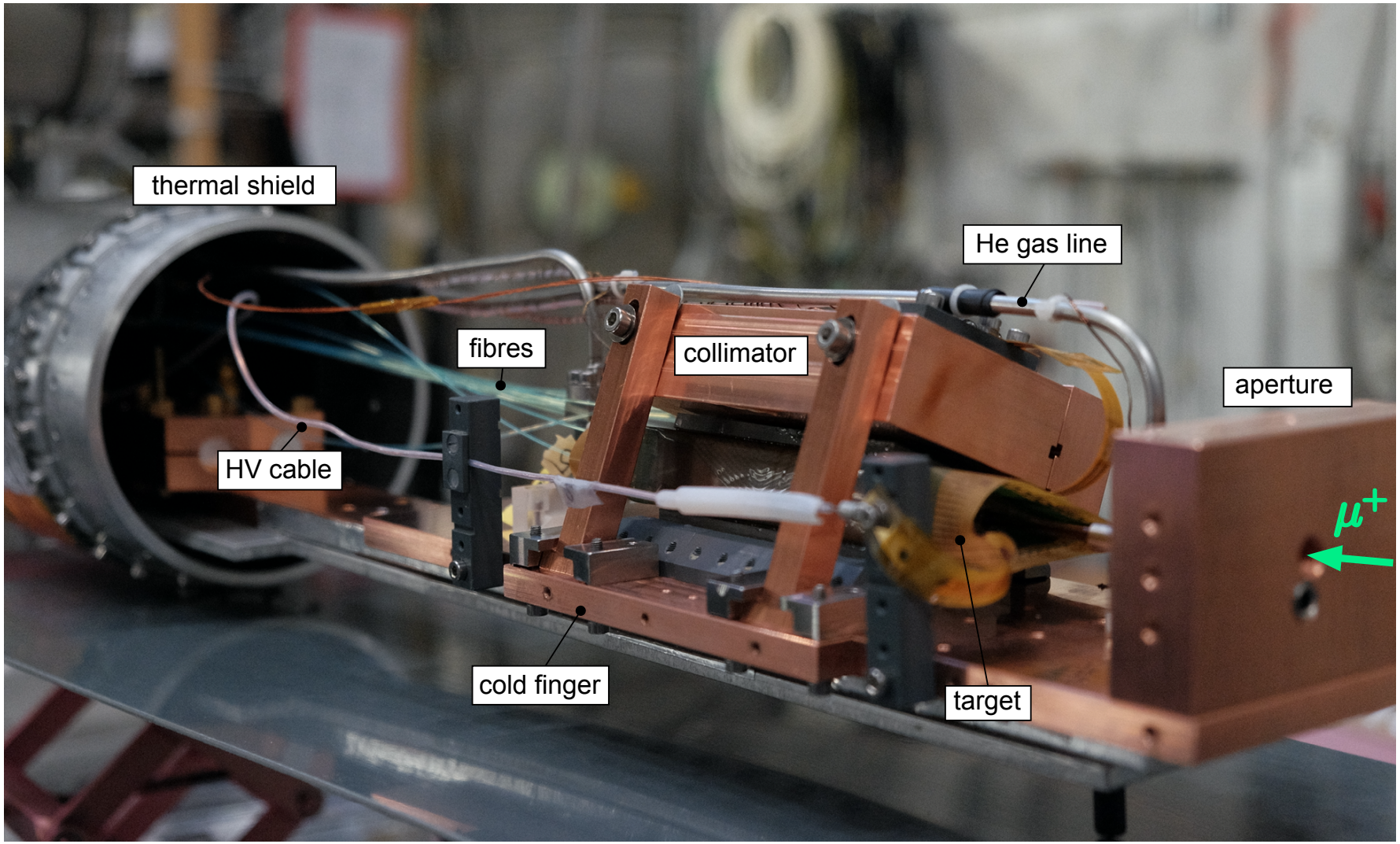
Test of mixed compression (2019)

- PSI πE1 beamline
- Momentum tuned ~15 MeV/c



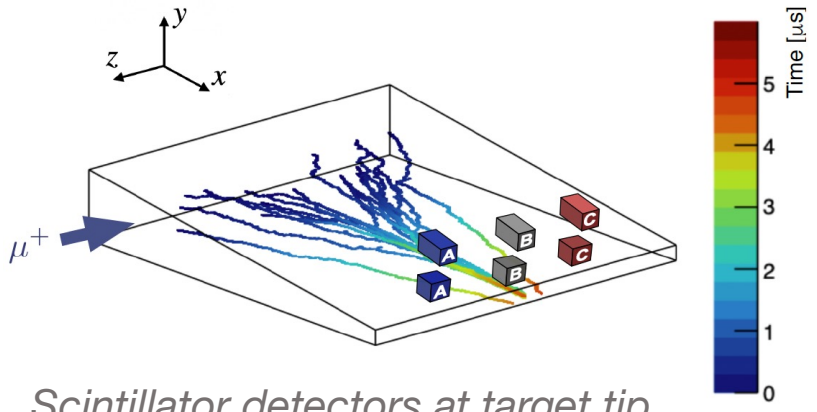


Experiment

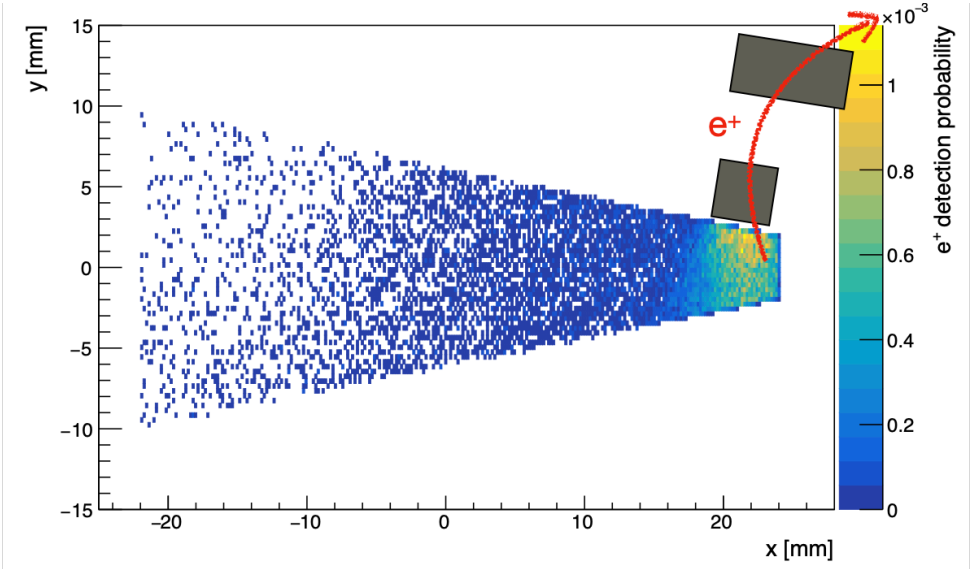

thermal shield
He gas line
fibres
collimator
aperture
HV cable
μ^+
cold finger
target

Test of mixed compression

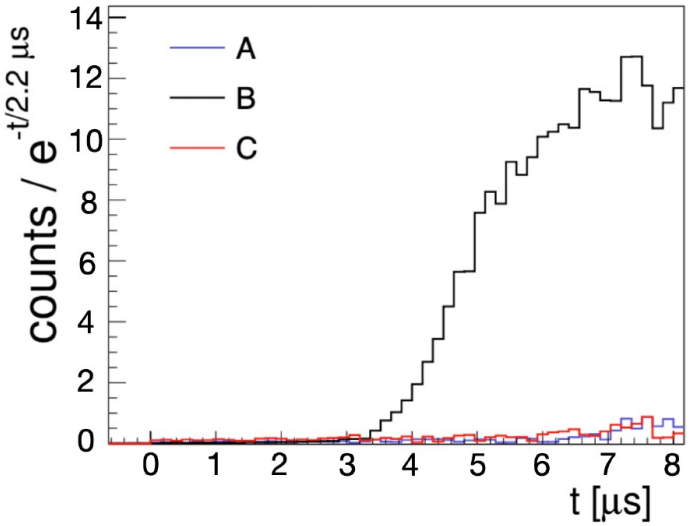
- "*Indirectly*" measure muon position by detecting decay positrons
- $t = 0$ given by entrance counter
- Large increase of counts: all muons reached target tip



Scintillator detectors at target tip



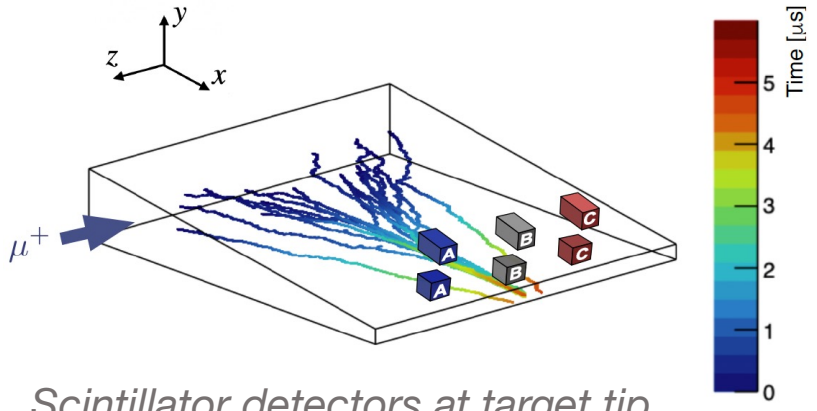
Detection simulation



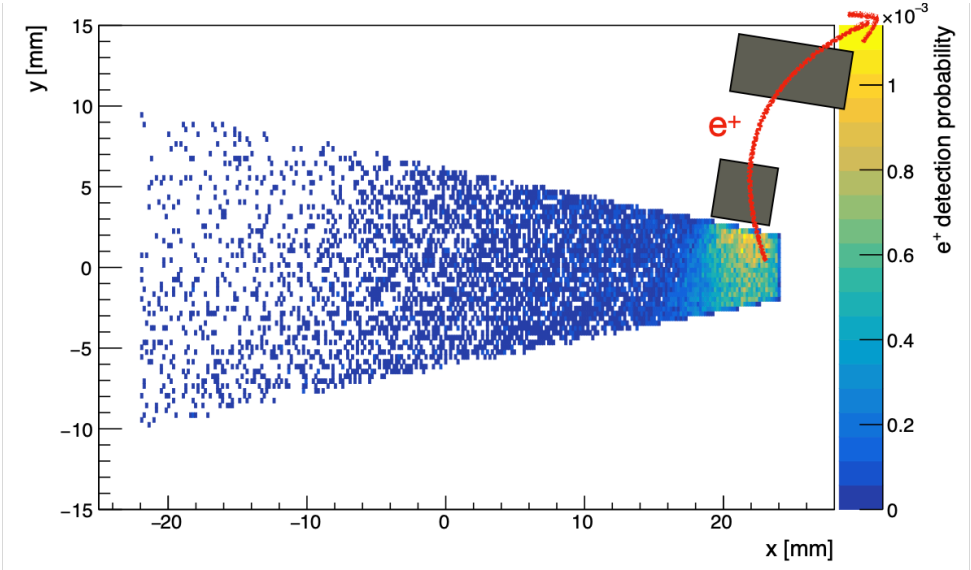
Measured time spectra (2019 beamtime)

Test of mixed compression

- "*Indirectly*" measure muon position by detecting decay positrons
- $t = 0$ given by entrance counter
- Large increase of counts: all muons reached target tip

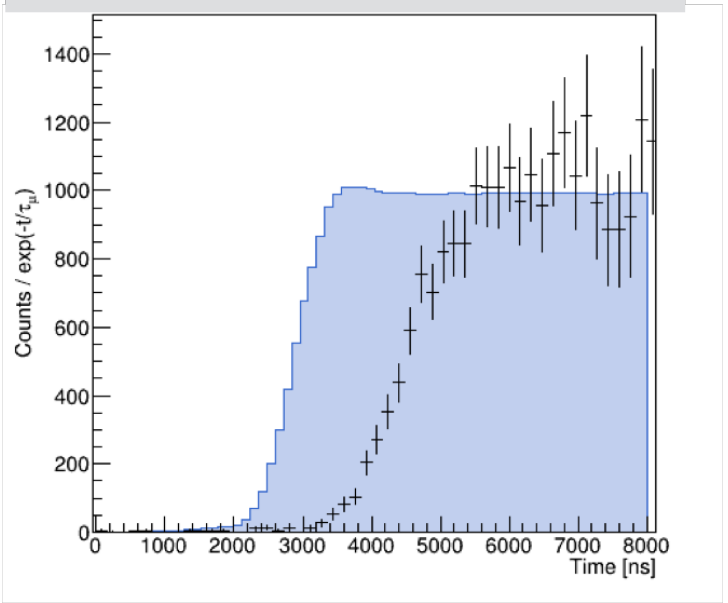


Scintillator detectors at target tip



Detection simulation

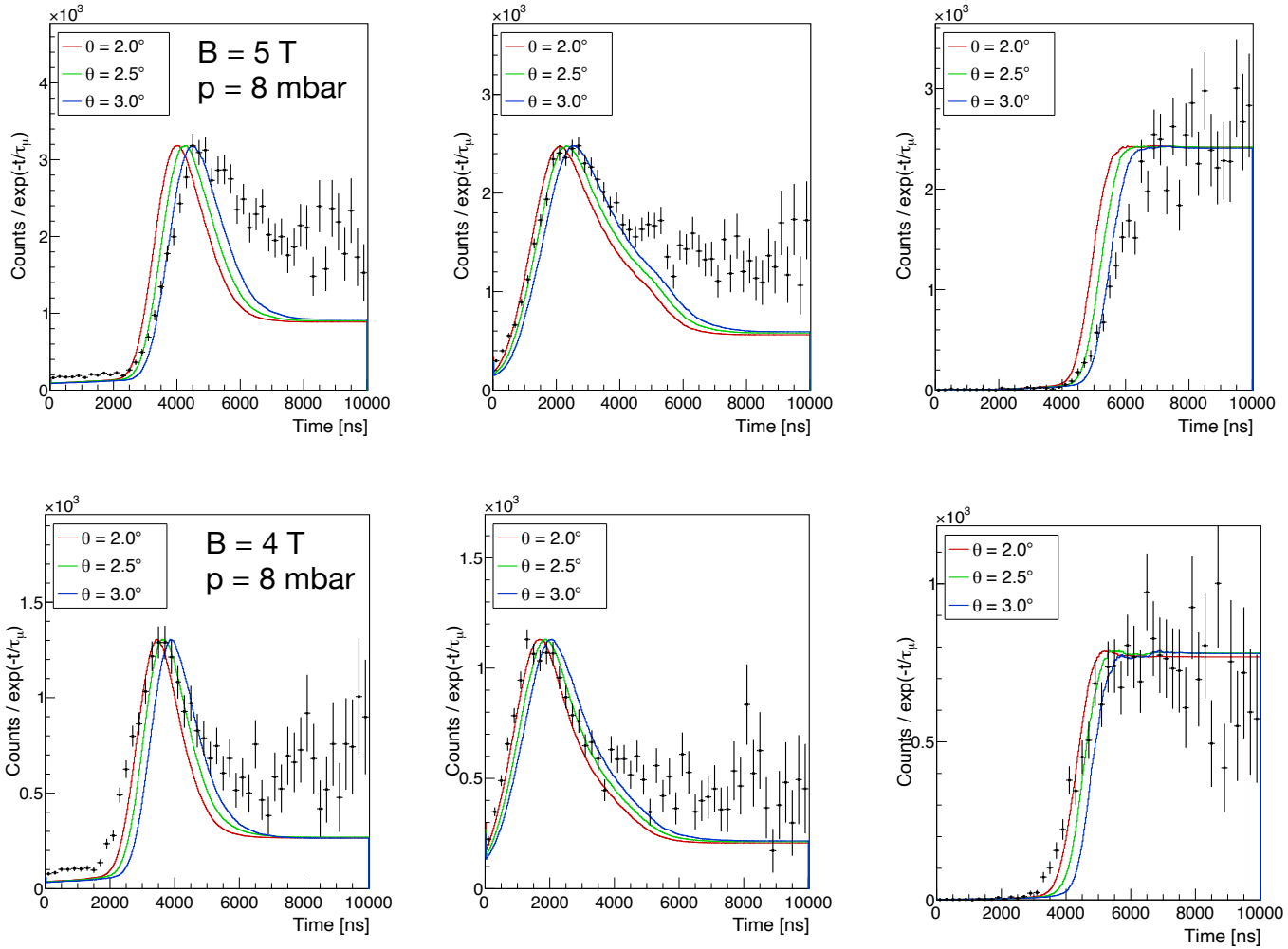
Simulations & measurements



observed tension?

Tuning target parameters

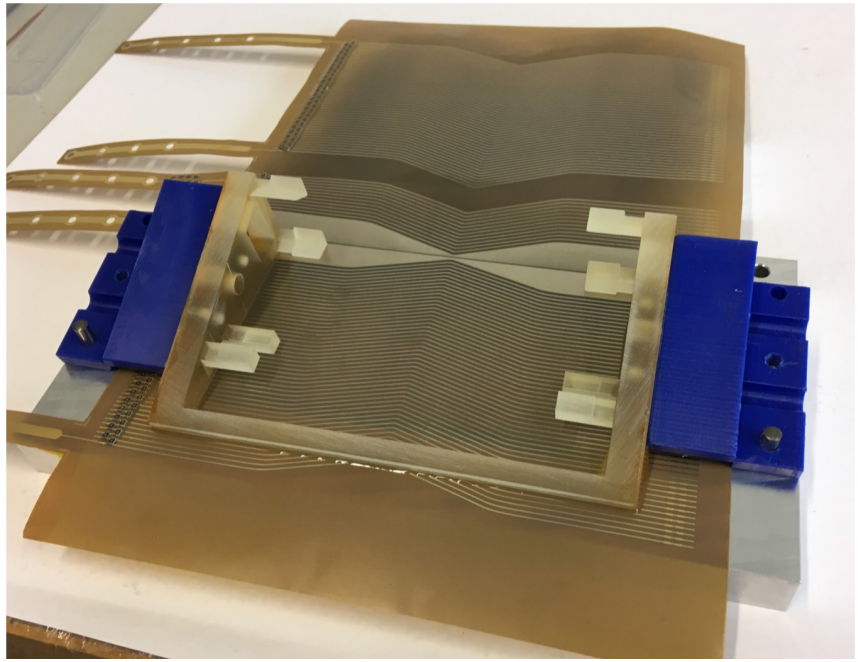
Trans 3 | Trans 2 | Tiles 2-5



Good agreement between simulations and measurements

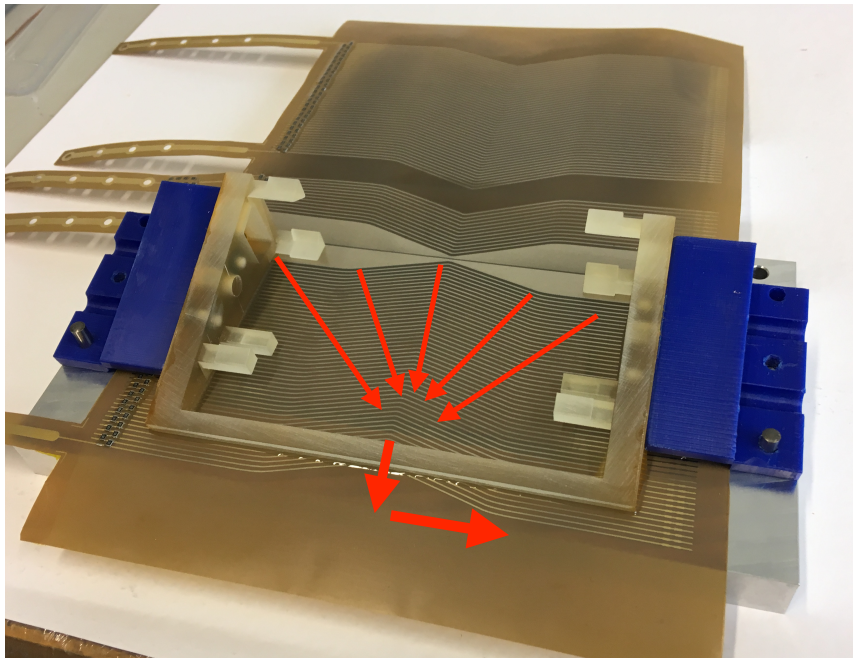
- For “realistic” tuning of the target conditions
- For several detectors
- For several conditions (*E, B, p*)

Next steps?



Open up muCool target

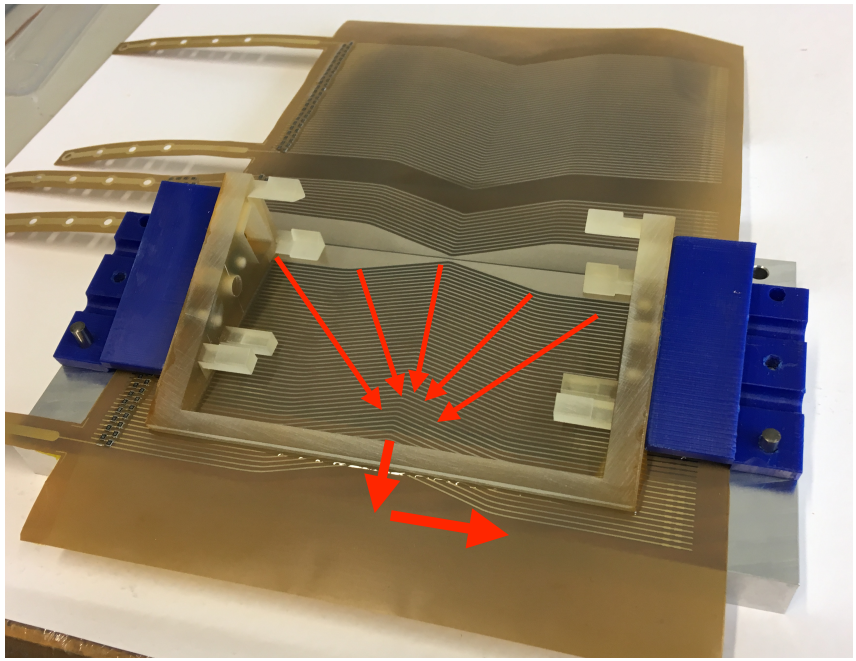
Next steps?



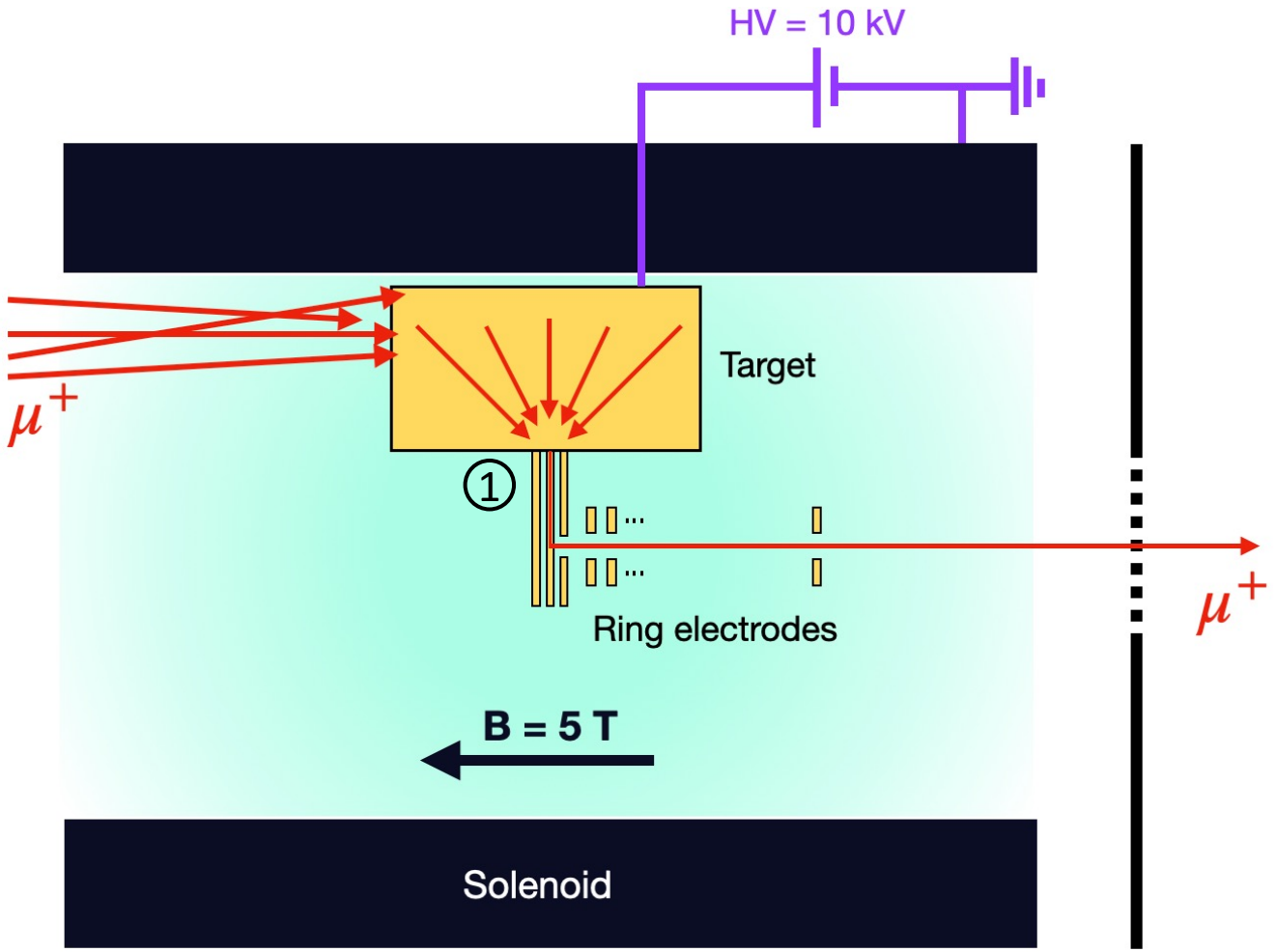
Make a hole and extract muons

Next steps?

① Muon extraction from gas target into vacuum



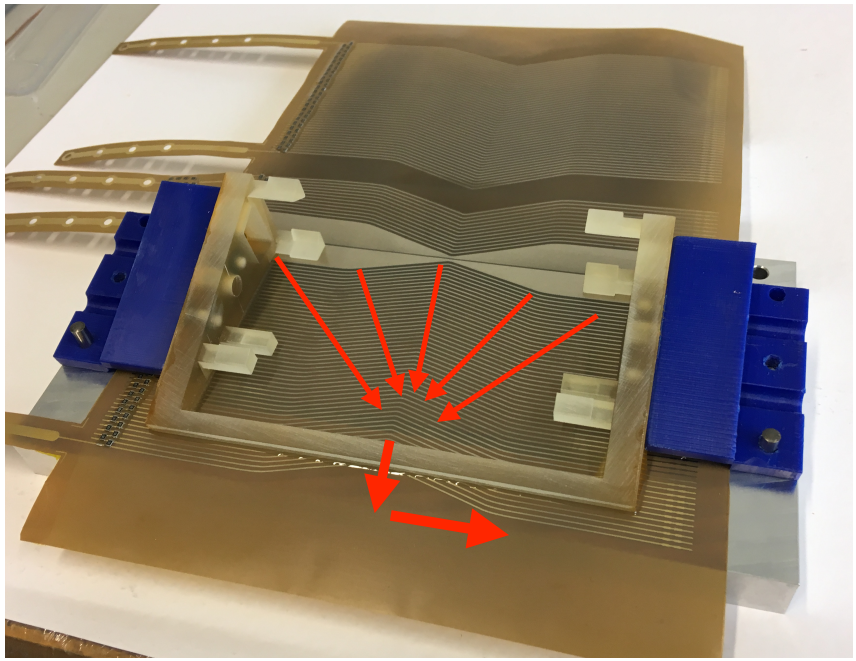
Make a hole and extract muons



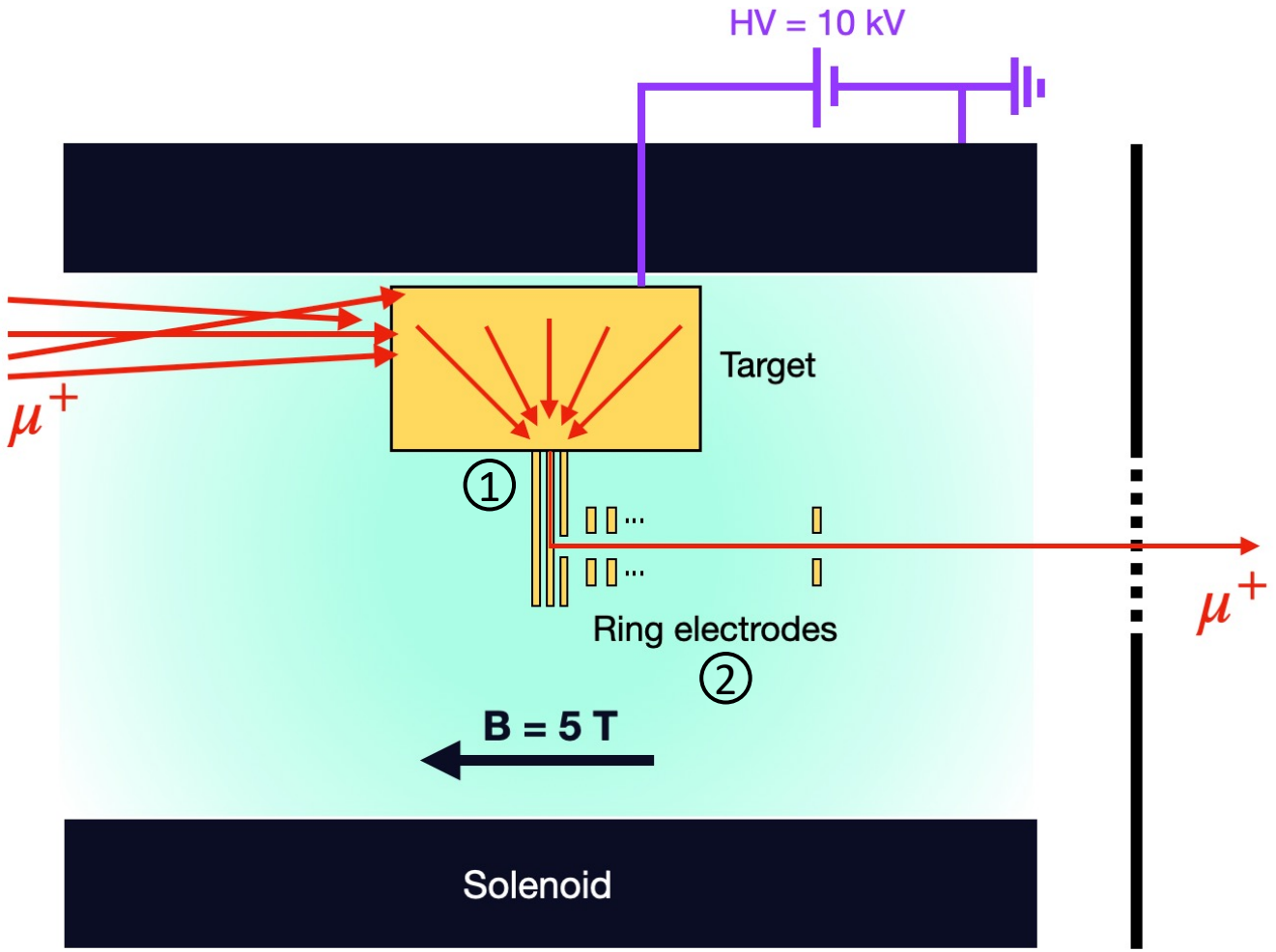
Next steps?

① Muon extraction from gas target into vacuum

② Re-acceleration to 10 keV



Make a hole and extract muons

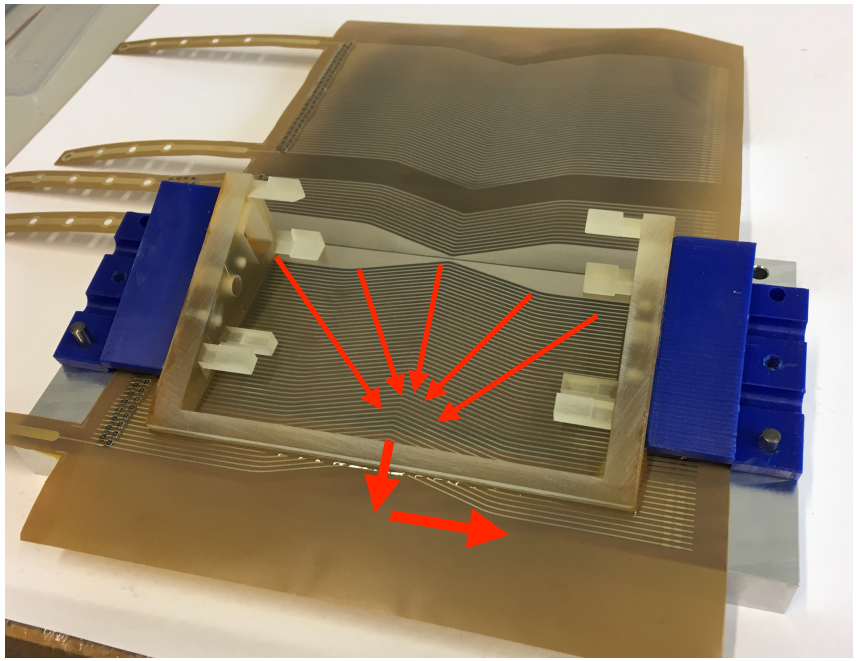


Next steps?

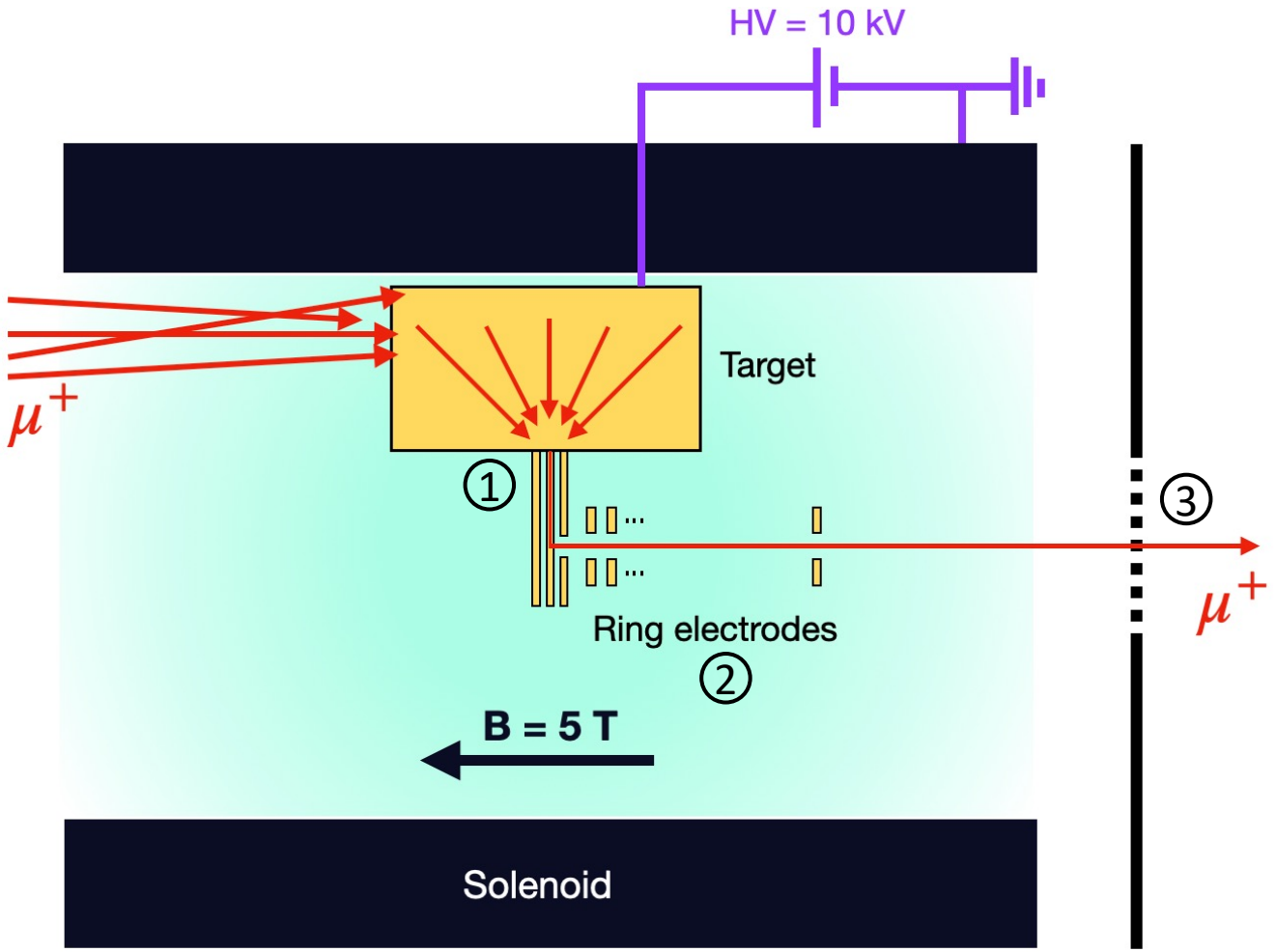
① Muon extraction from gas target into vacuum

② Re-acceleration to 10 keV

③ Extraction from 5T solenoid



Make a hole and extract muons

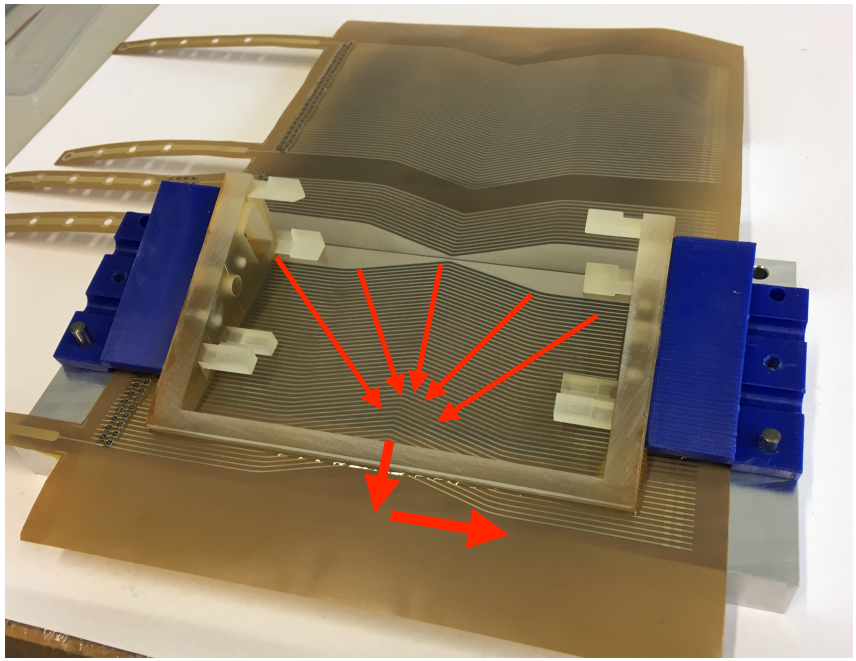


Next steps?

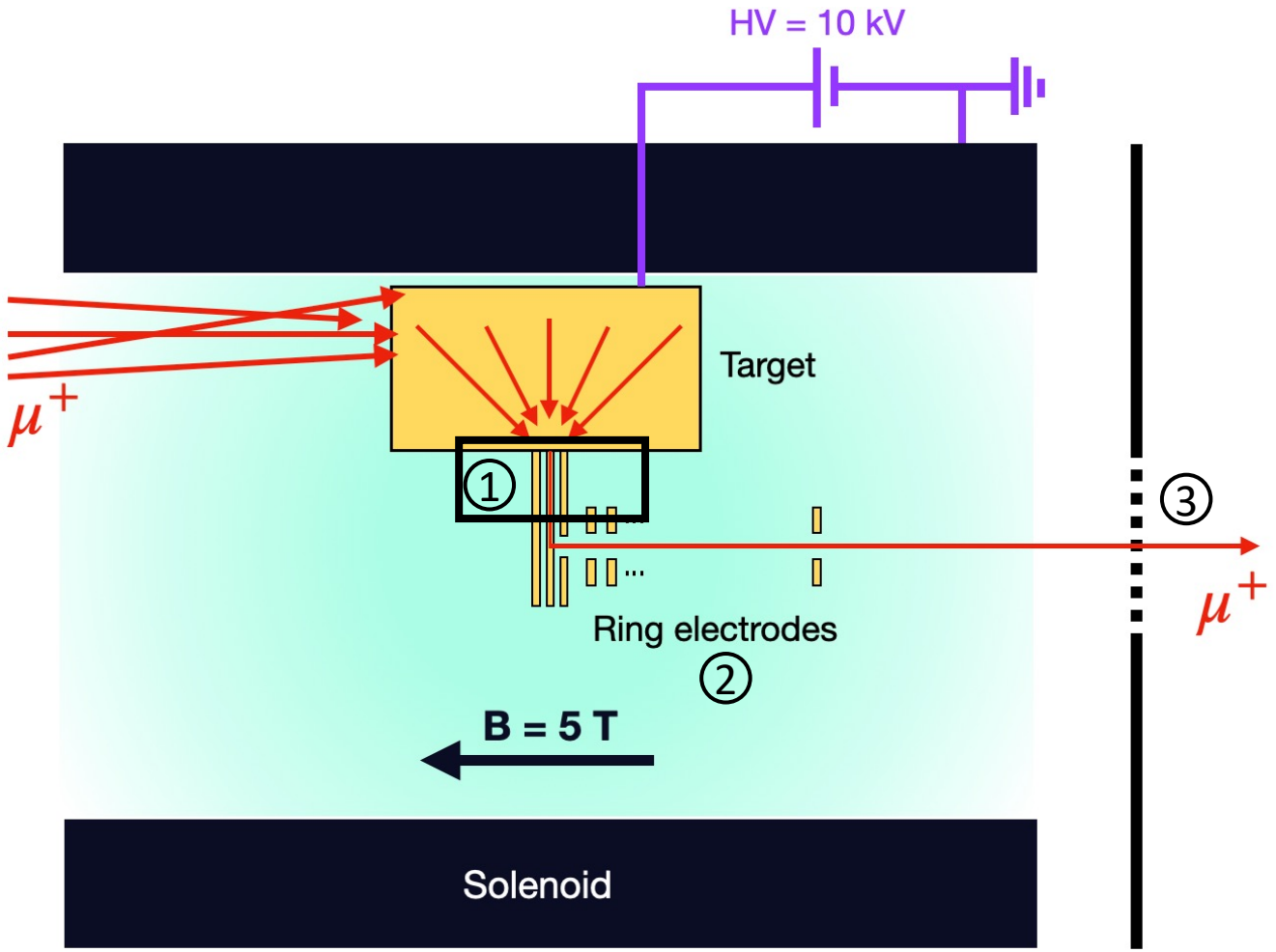
① **Muon extraction from gas target into vacuum**

② Re-acceleration to 10 keV

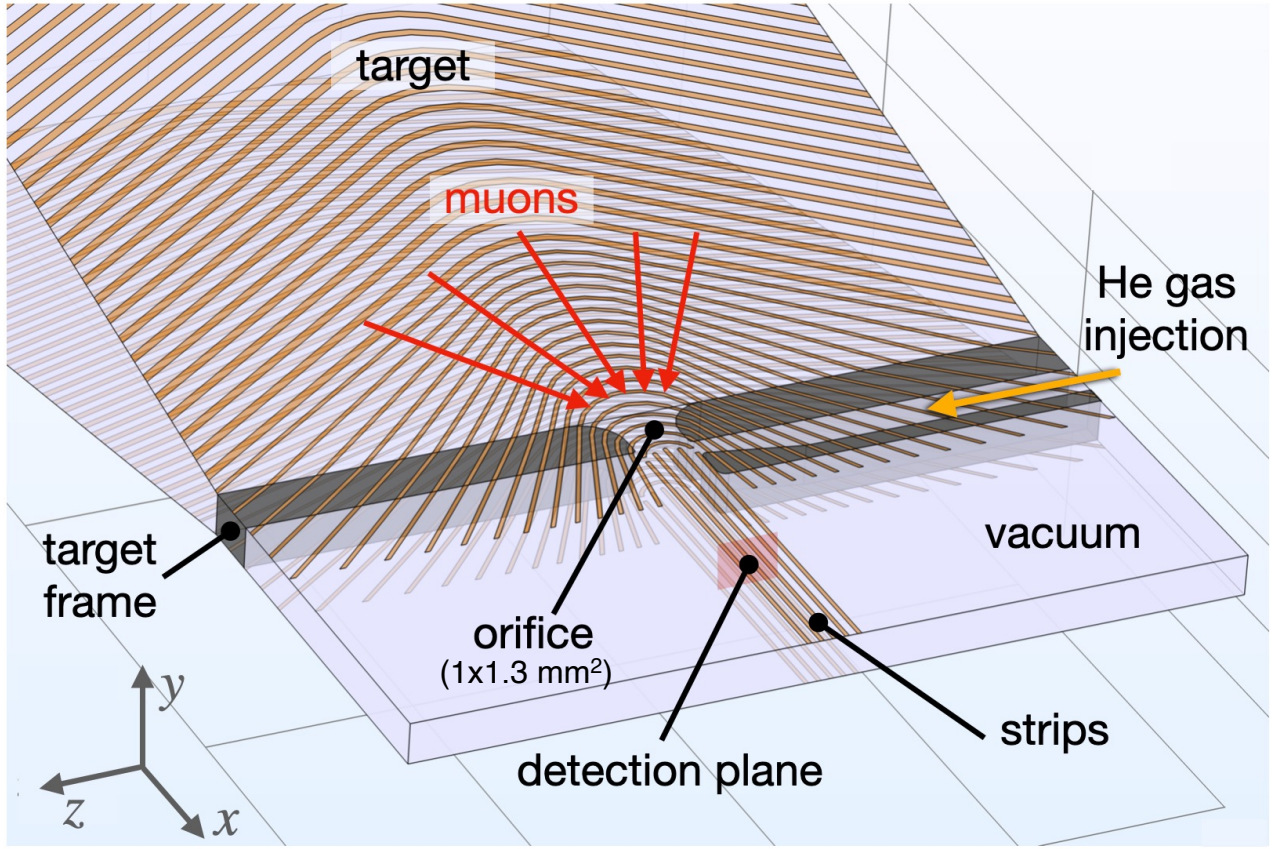
③ Extraction from 5T solenoid

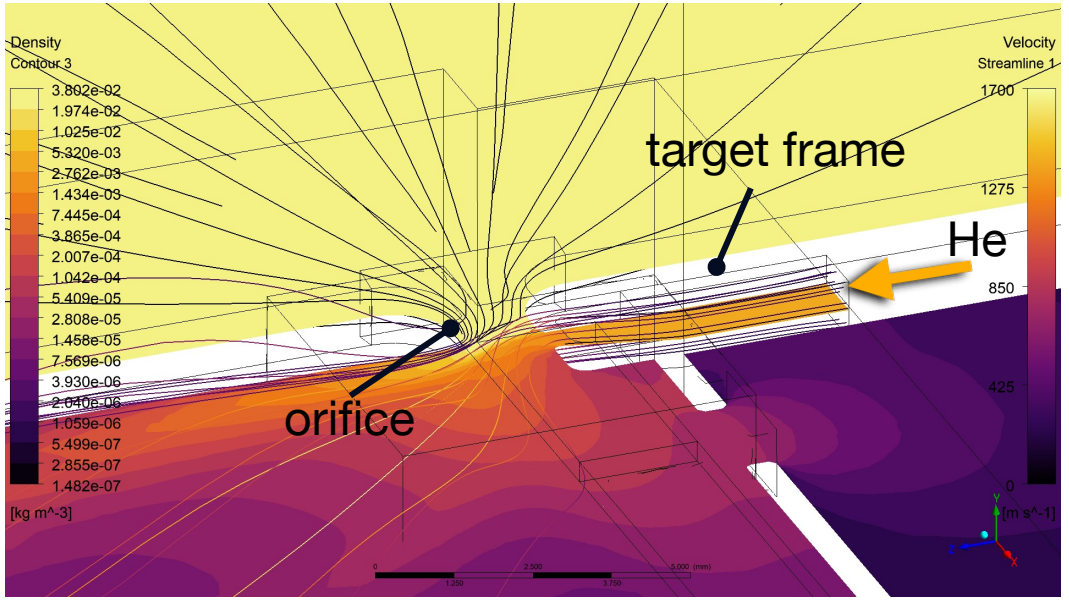


Make a hole and extract muons



Muon extraction from gas target into vacuum

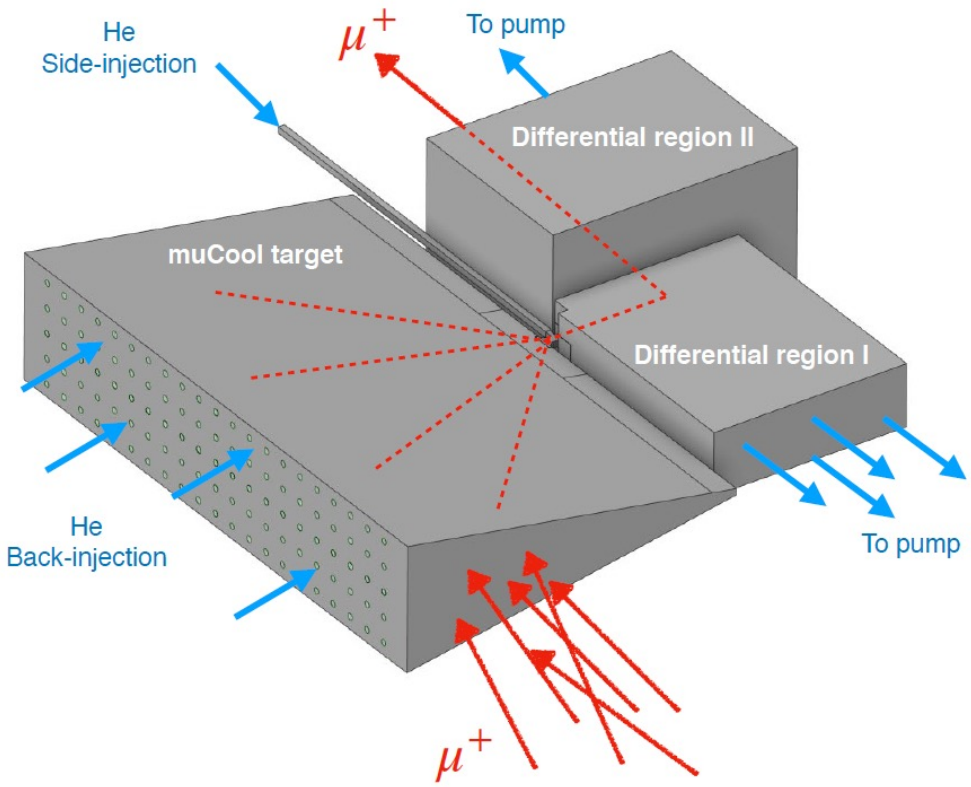


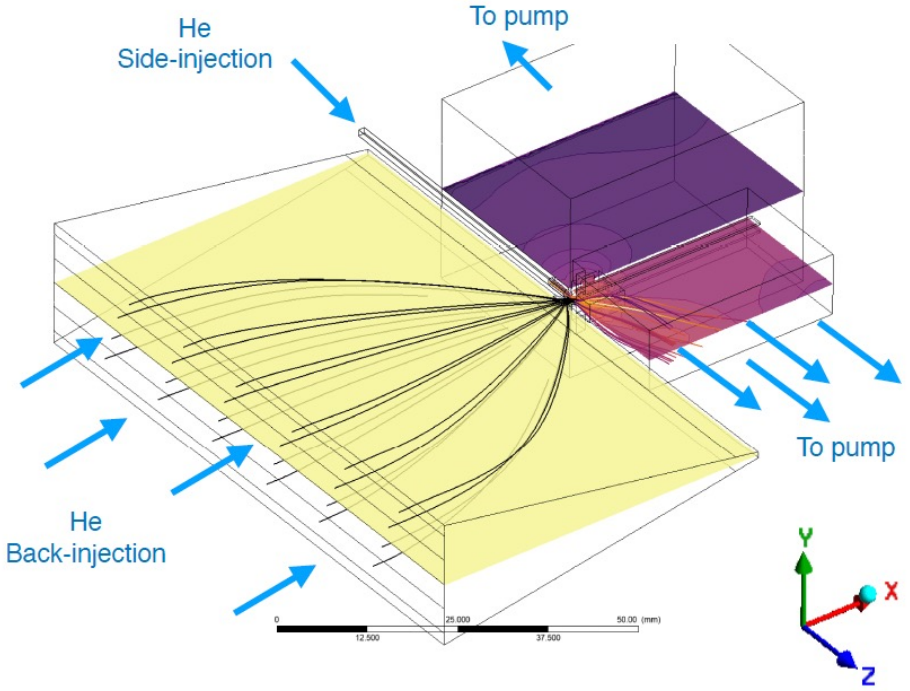


He gas density simulations

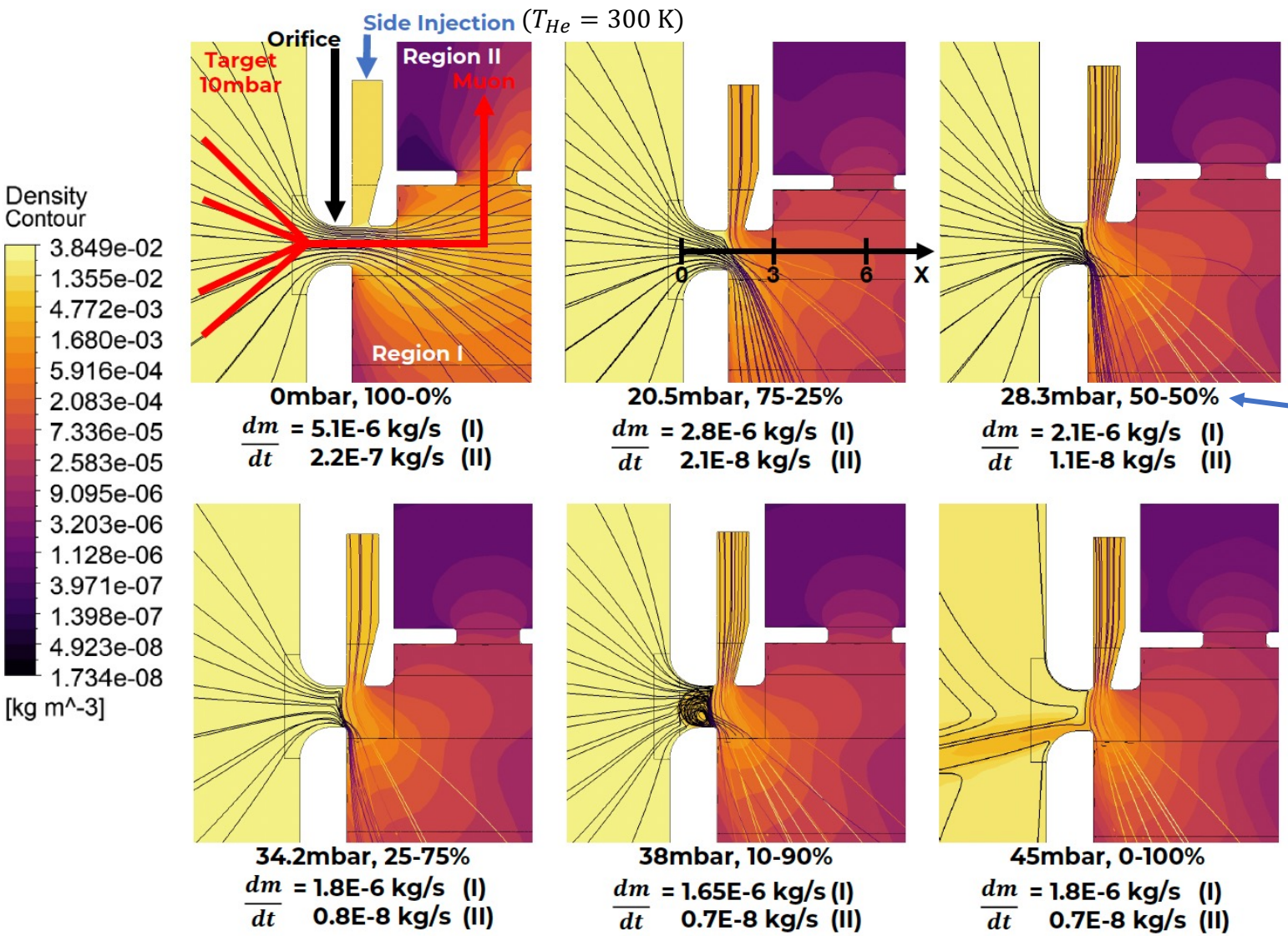
He gas injection schemes

- **Back injection***:* He injected through the back-wall of the muCool target.
- **Side injection***:* He injected at the orifice $\perp \vec{v}_D$ of muons exiting the target



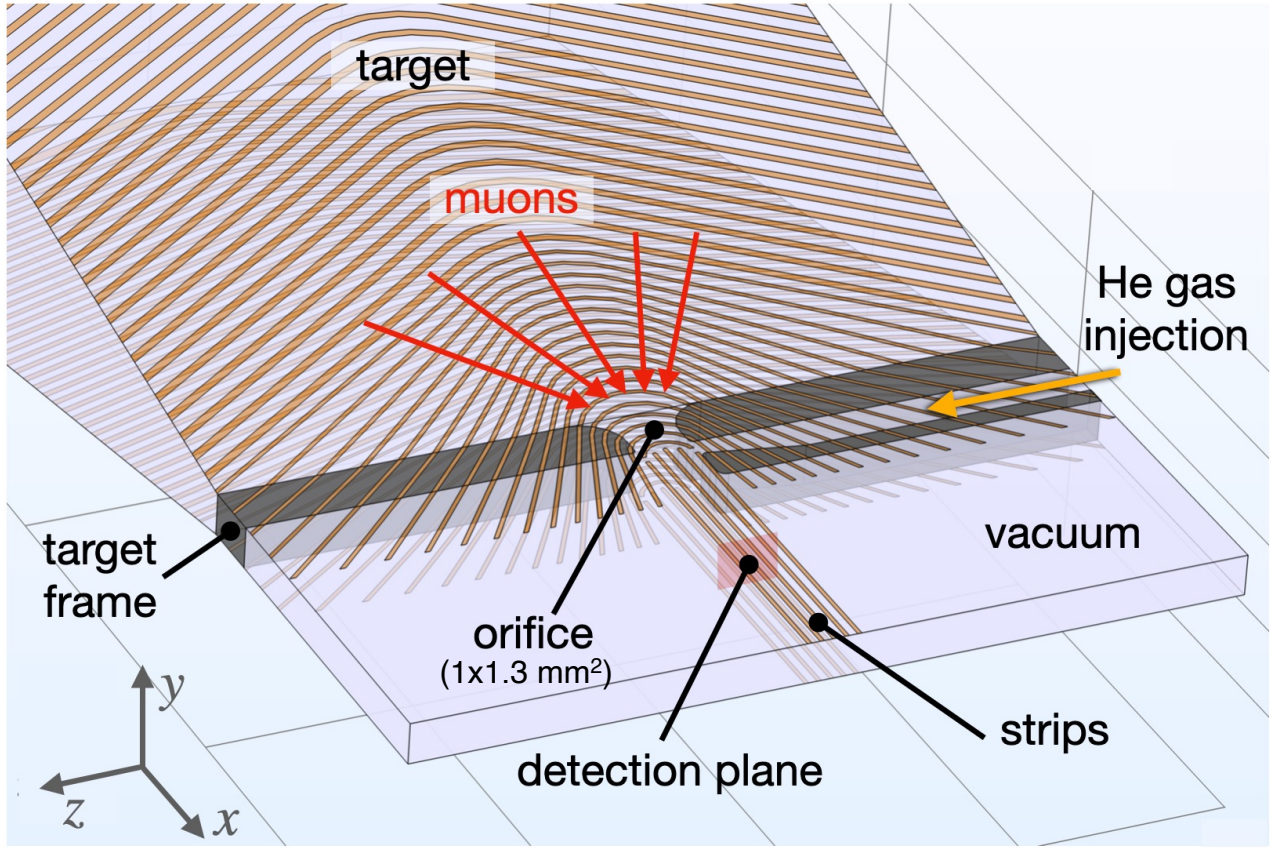


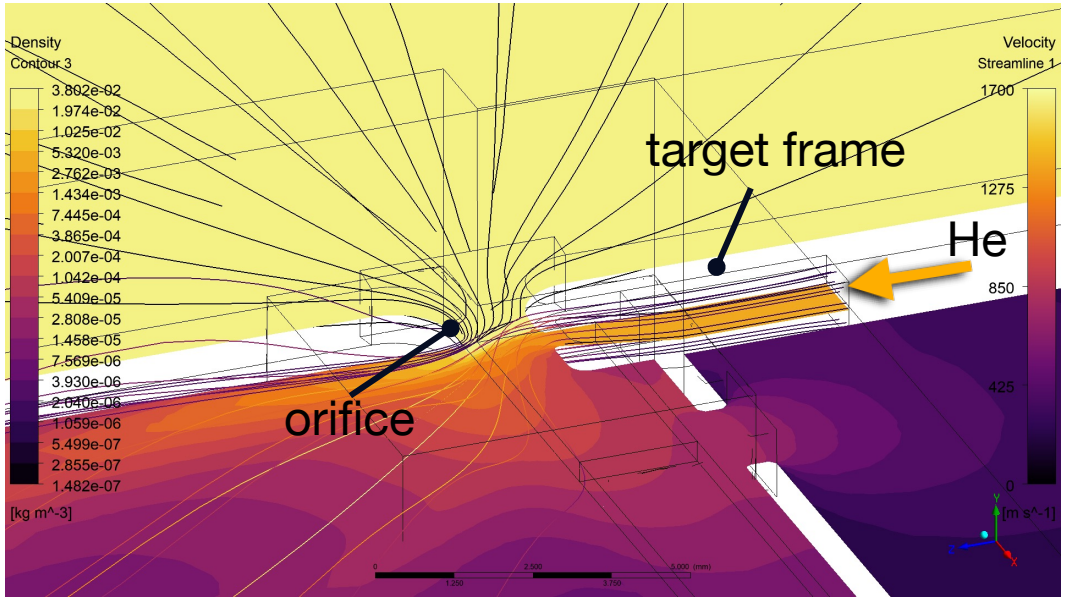
He gas injection schemes



different partitioning between back- and side-injections

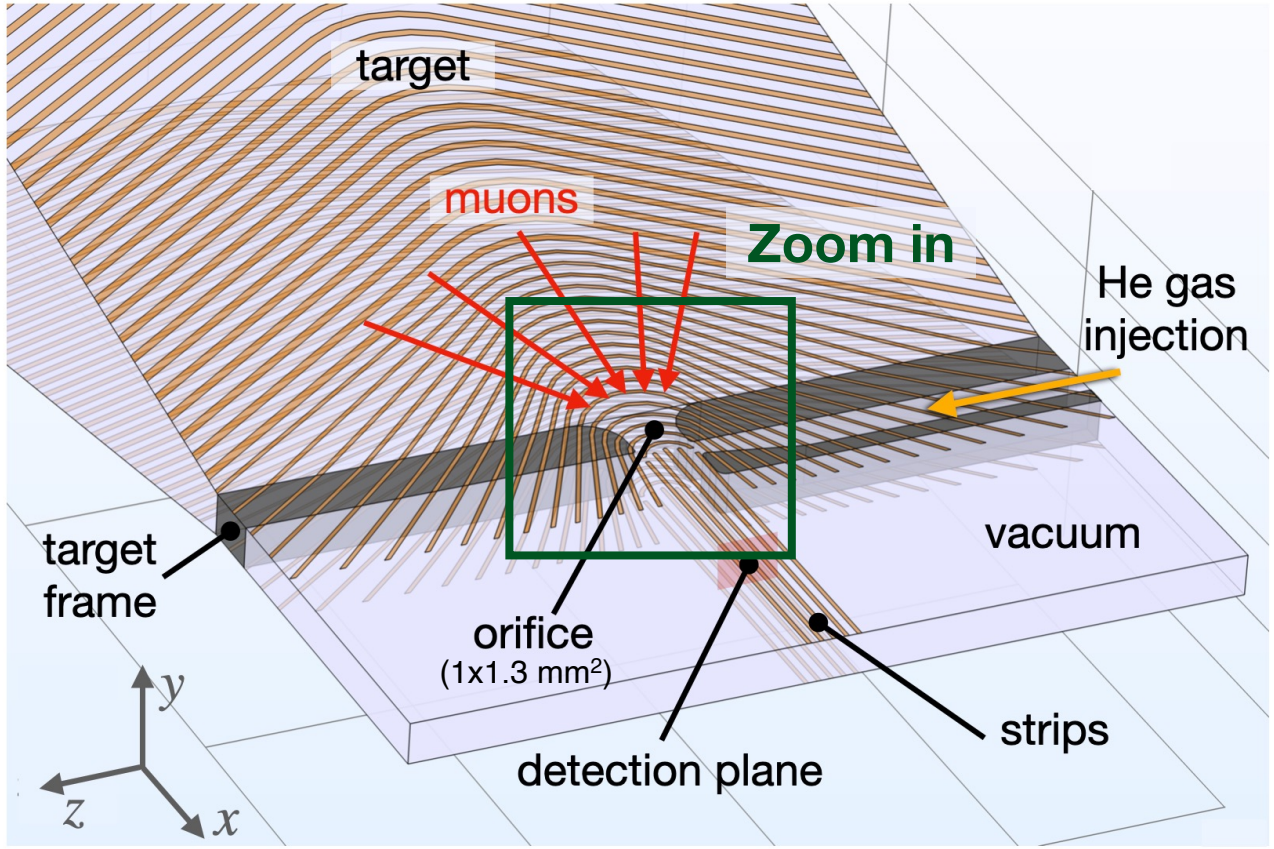
Muon extraction from gas target into vacuum

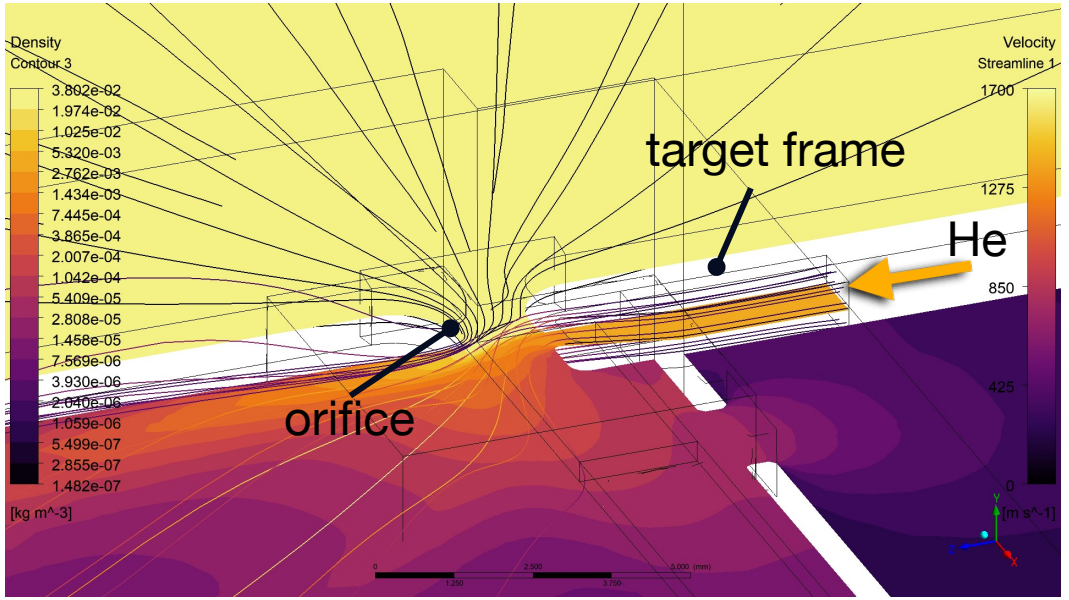




He gas density simulations with
65% back-injection and 35 % side-injection

Muon extraction from gas target into vacuum





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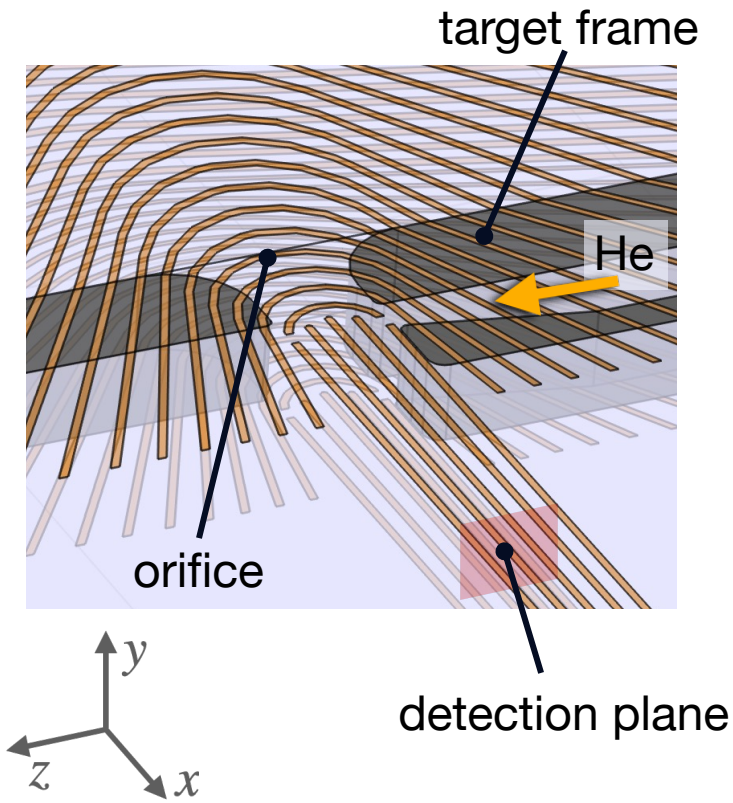
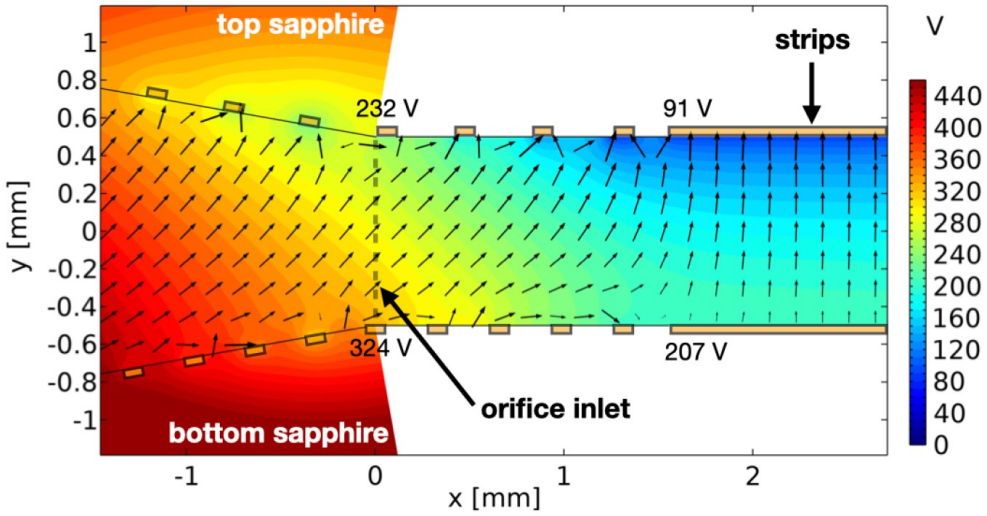
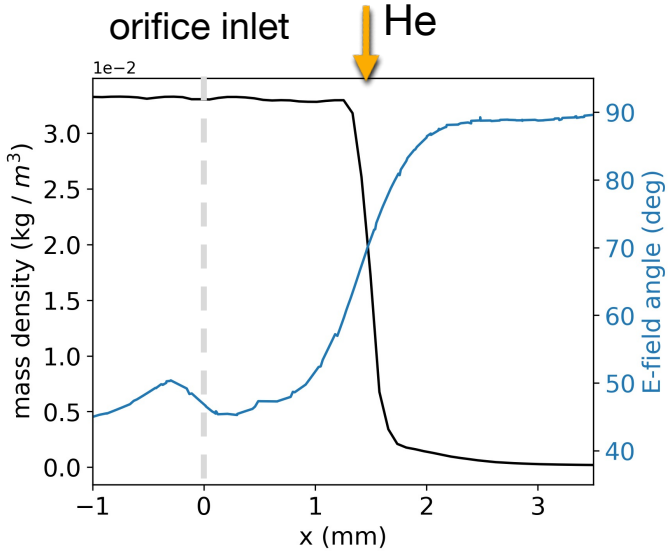
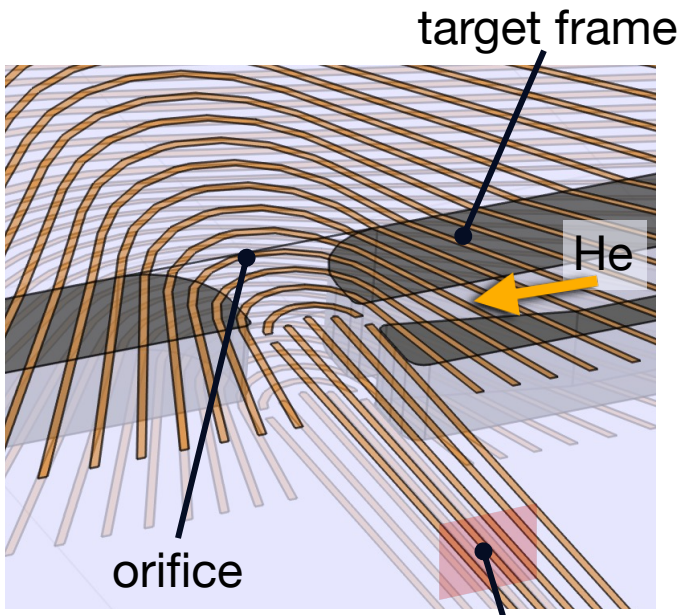
Electric field design

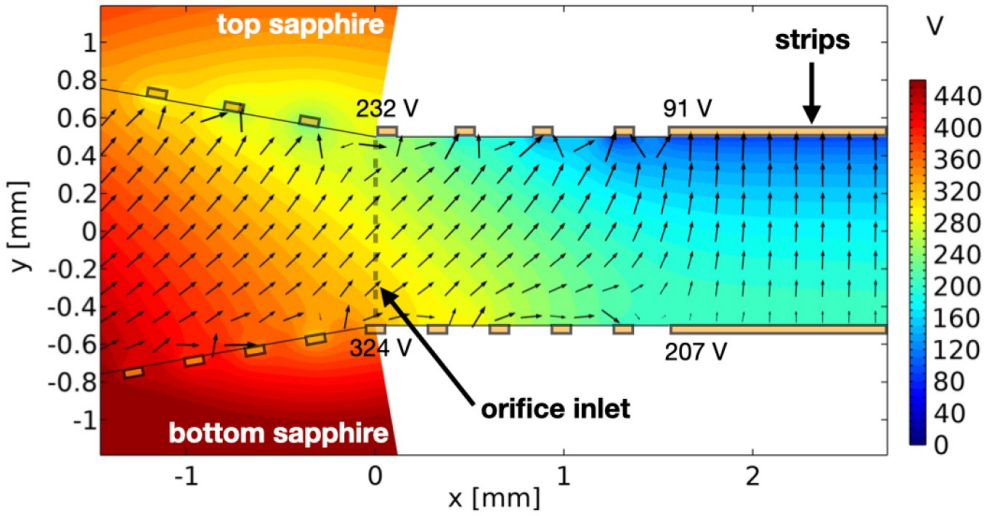


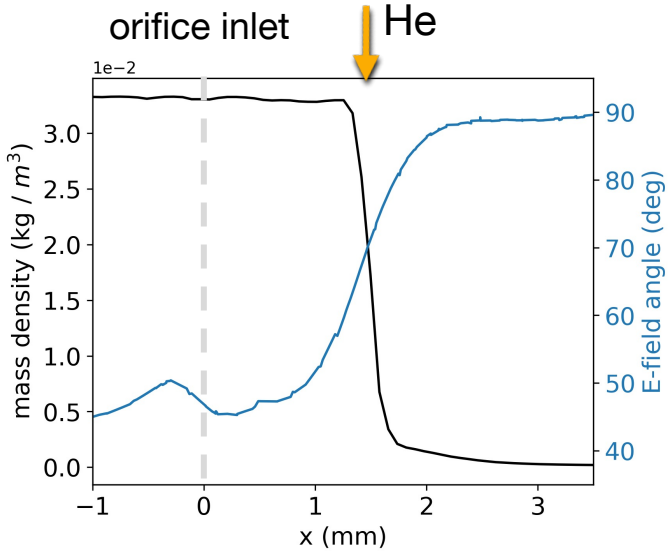


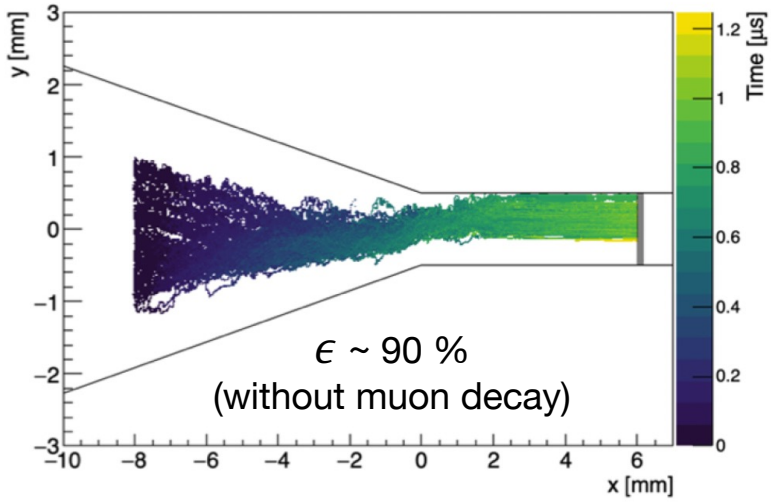


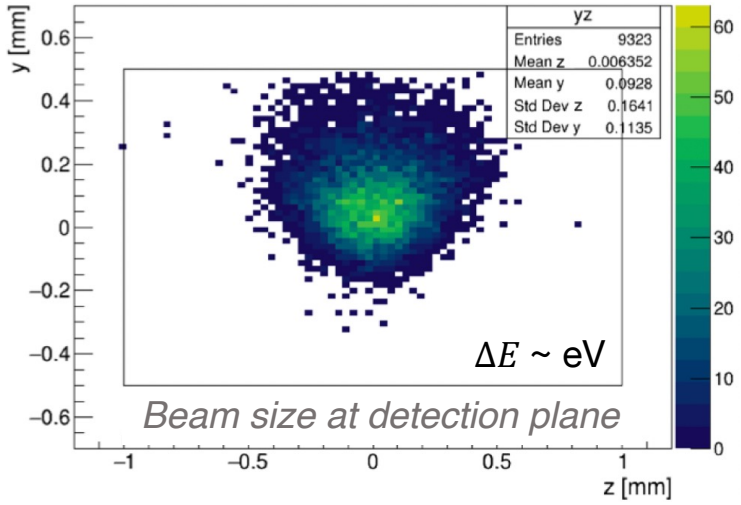
Electric field design and Geant4 simulations









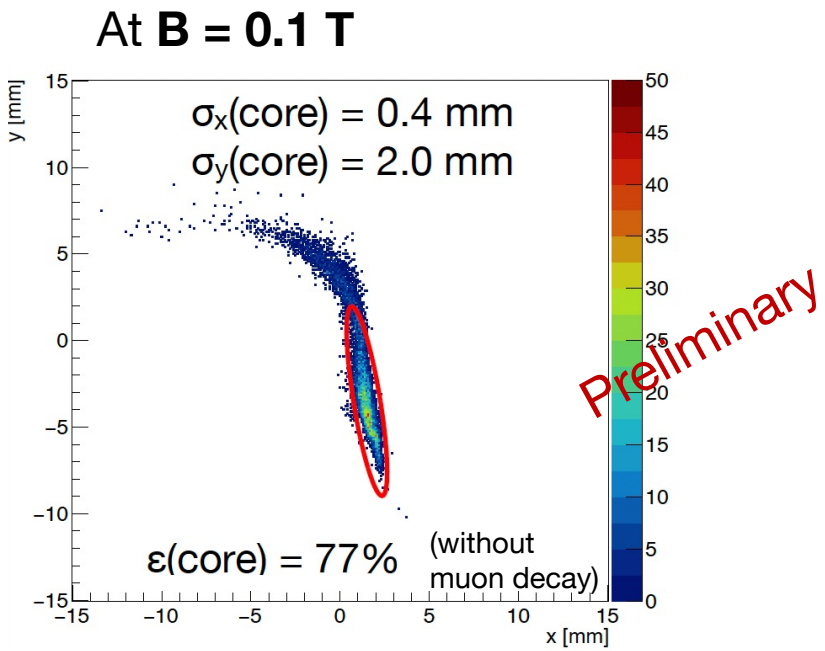


Next steps?

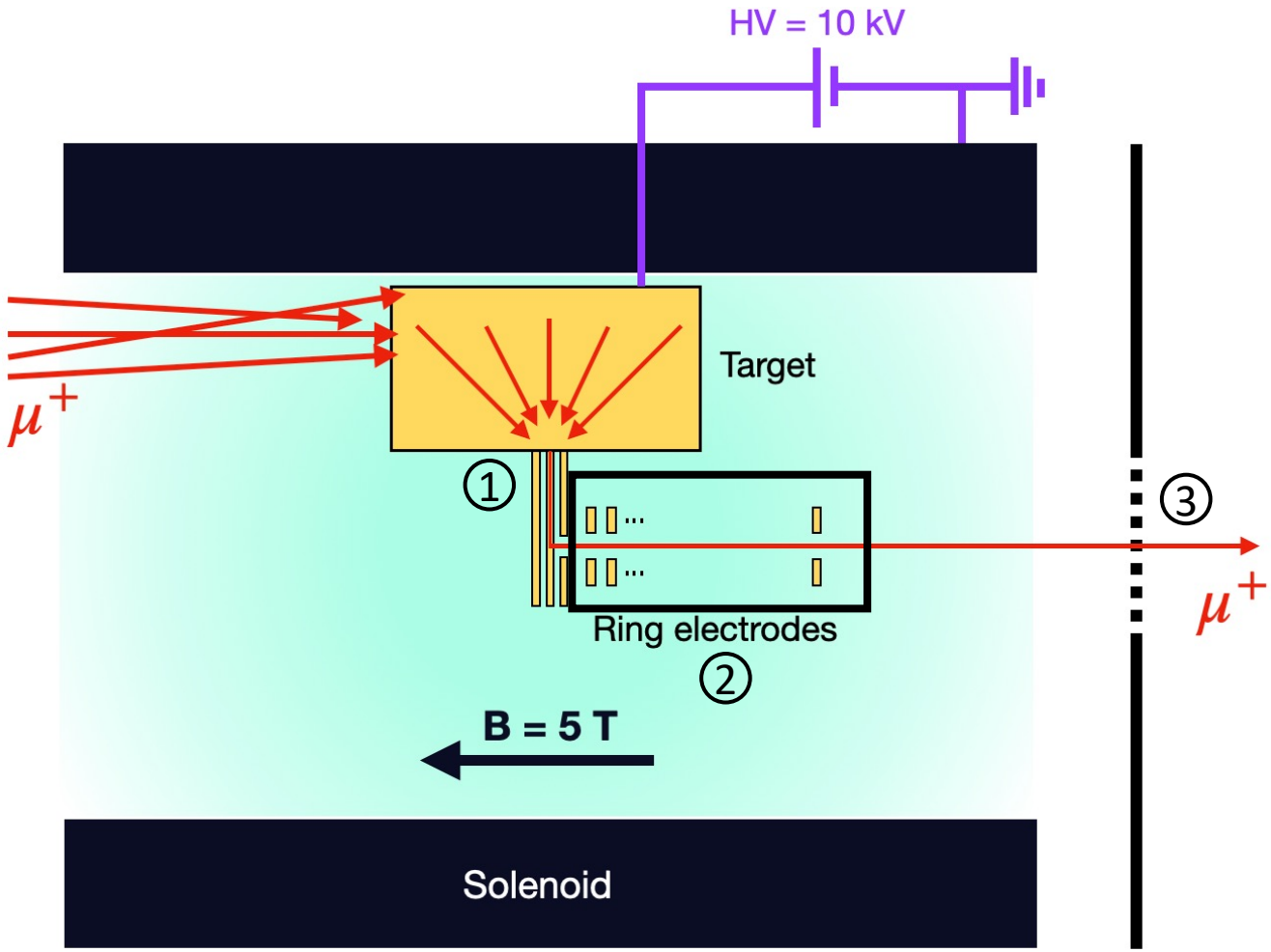
① Muon extraction from gas target into vacuum

② **Re-acceleration to 10 keV**

③ Extraction from 5T solenoid



$\Delta E \approx 20$ eV



Summary

- muCool proposes a “fast” phase space compression scheme for μ+ beam for future low energy experiments
- This is achieved with complex E-fields and B-field in combination with a He gas density gradient
- **Mixed compression stage successfully tested!**
- Performed simulations of muon extraction into vacuum and re-acceleration: experimental tests begin now

Summary

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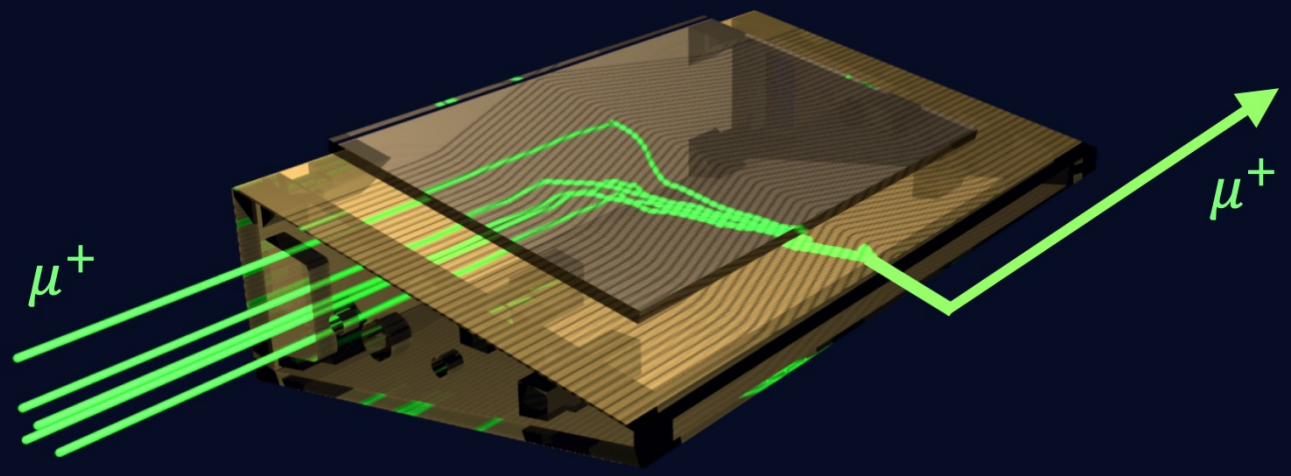
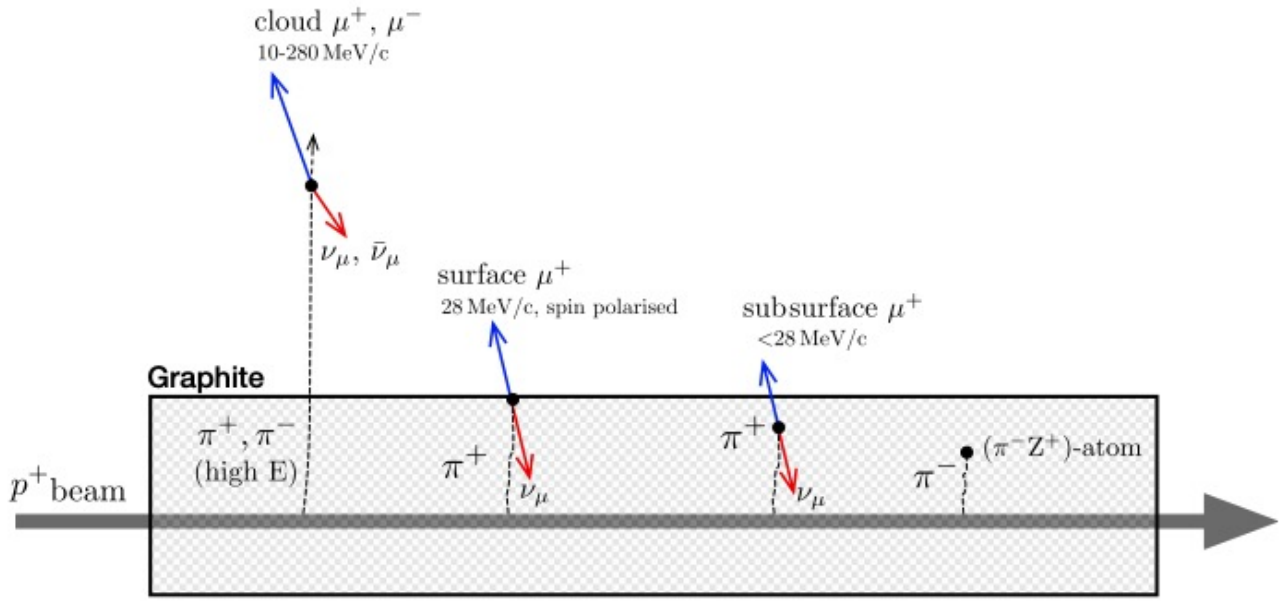
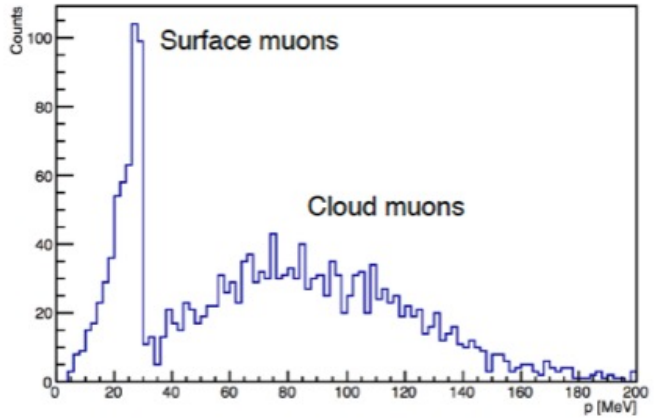


Thank you!

EXTRA SLIDES

Muon production

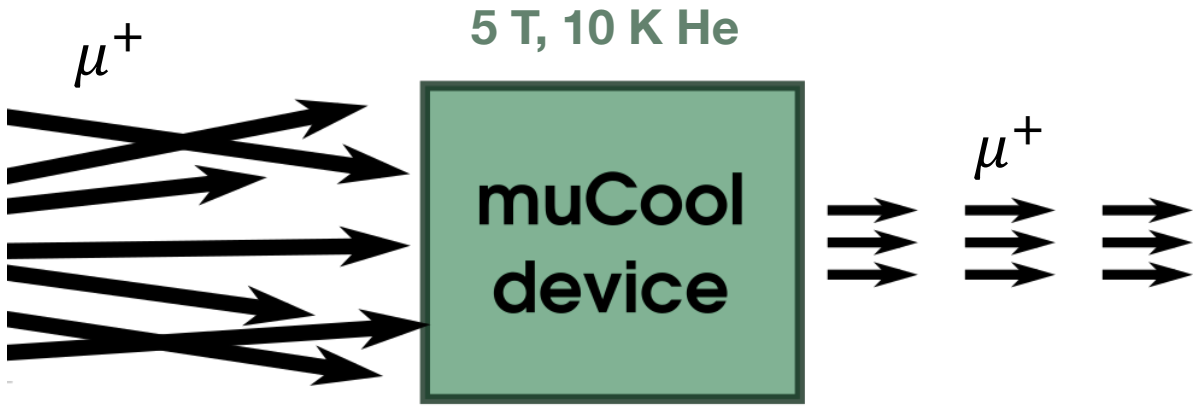




muCool : a phase space compressor

”Fast” compression scheme (within 10 μs)

E:	4 MeV
ΔE (FWHM):	800 keV
Diameter:	70 mm
Divergence:	200 mrad
cw beam	



E:	10 keV
ΔE:	100 eV
Diameter:	10 mm
Divergence:	2 mrad

$$\sigma_x \sigma_{\theta_x} = 1910 \text{ mm mrad}$$

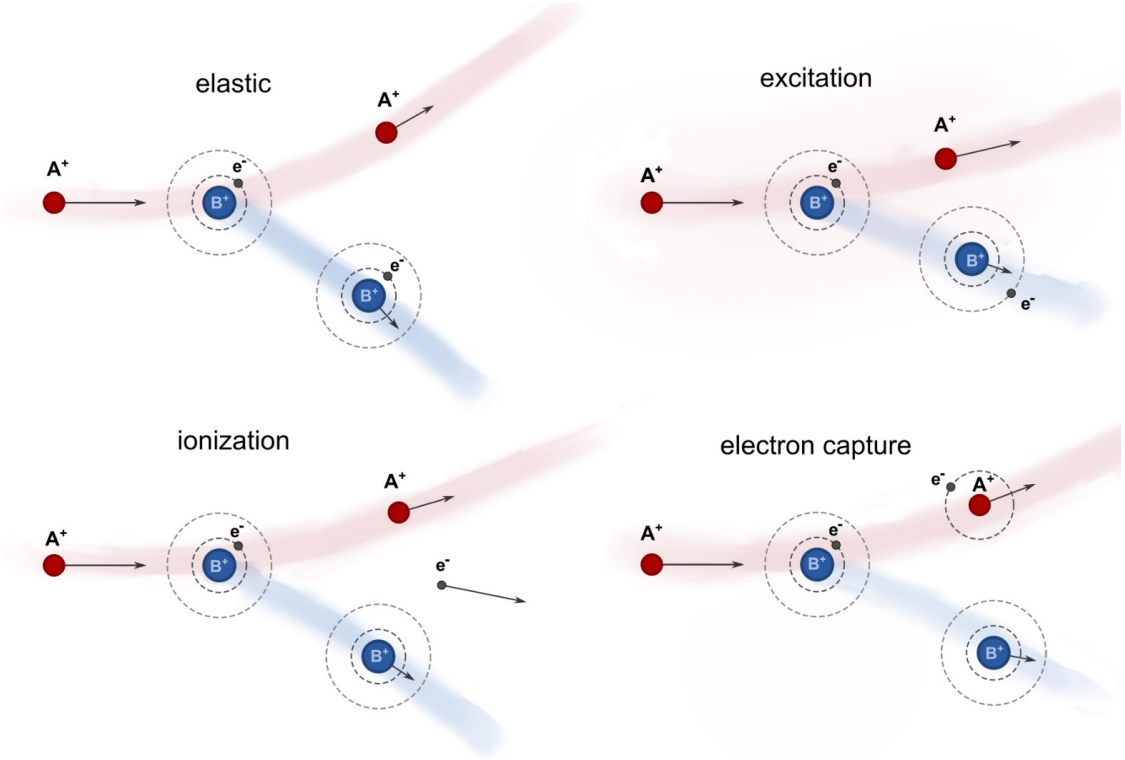
12.6% momentum bite.

$$\sigma_x \sigma_{\theta_x} \approx 20 \text{ mm mrad}$$

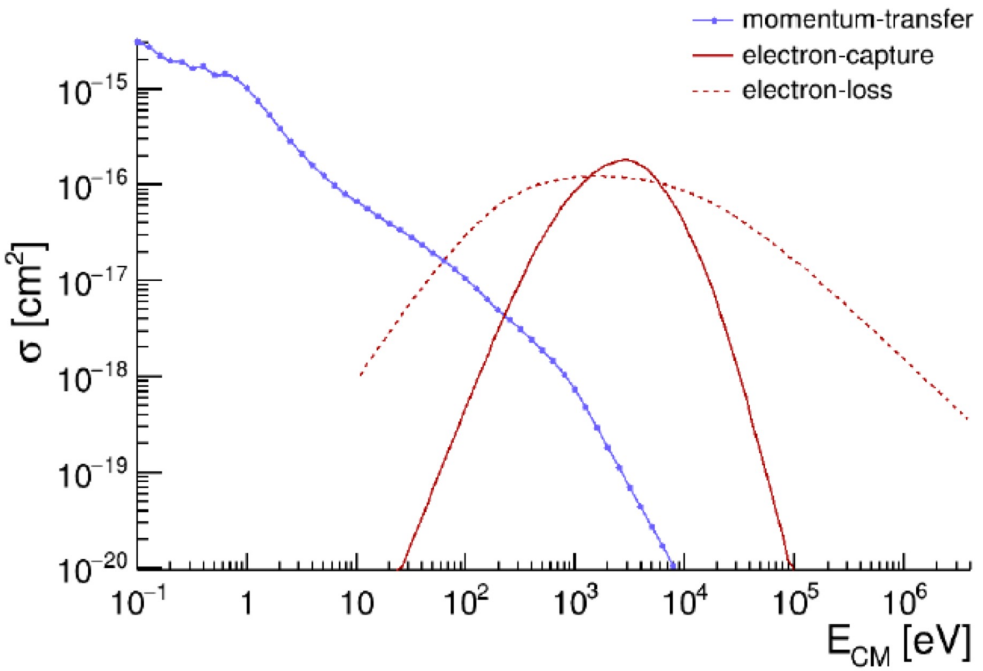
- Efficiency of 10^{-4} - 10^{-5}
- Phase space improved by 10^{9} - 10^{8}

D. Taqqu. *Phys. Rev. Lett.* 97.194801 **(2006)**

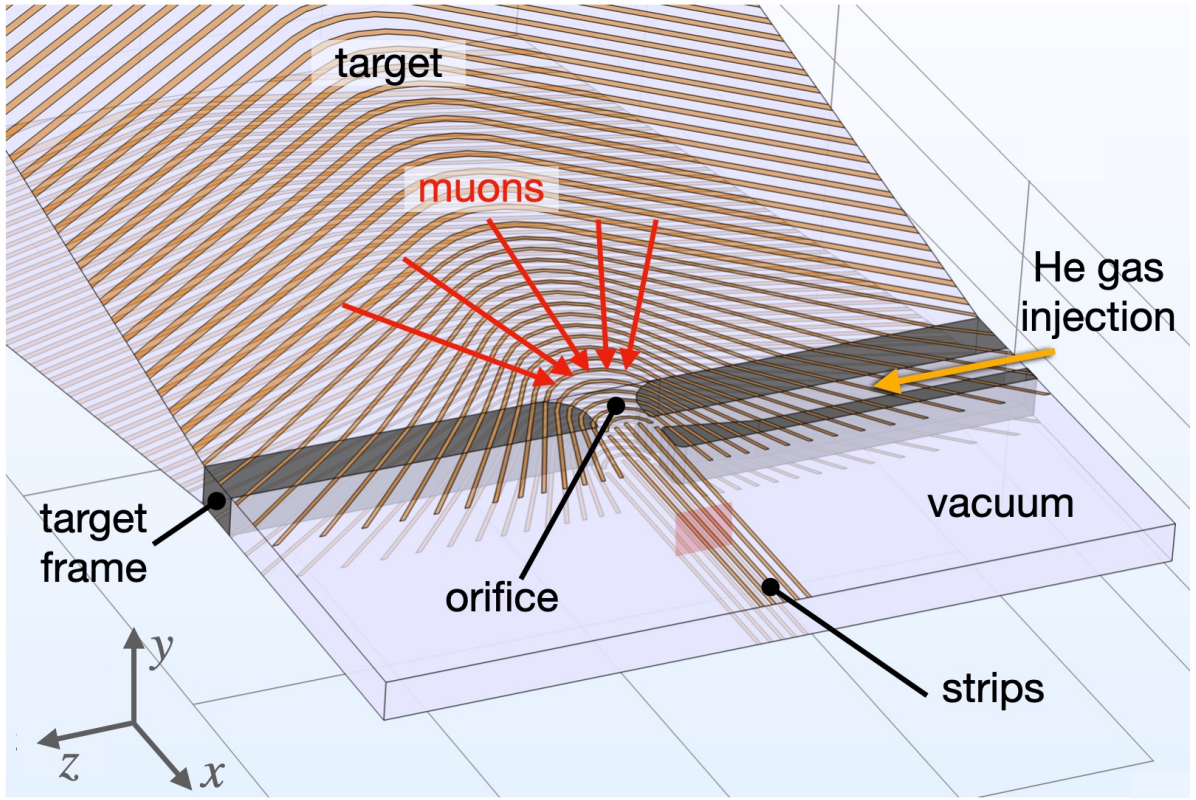
Muon-helium collisions

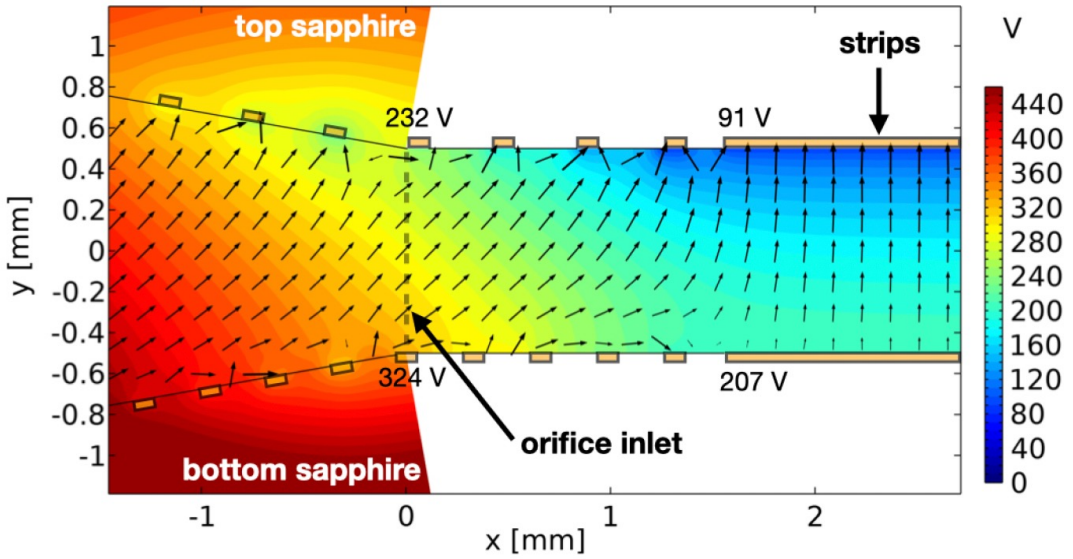


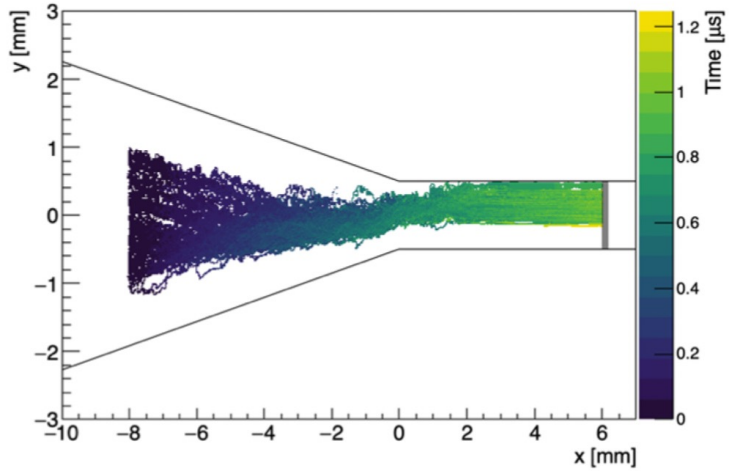
- collision type depends on muon energy
- consequences of the collisions:
  energy loss, direction change



Extraction: xy plane

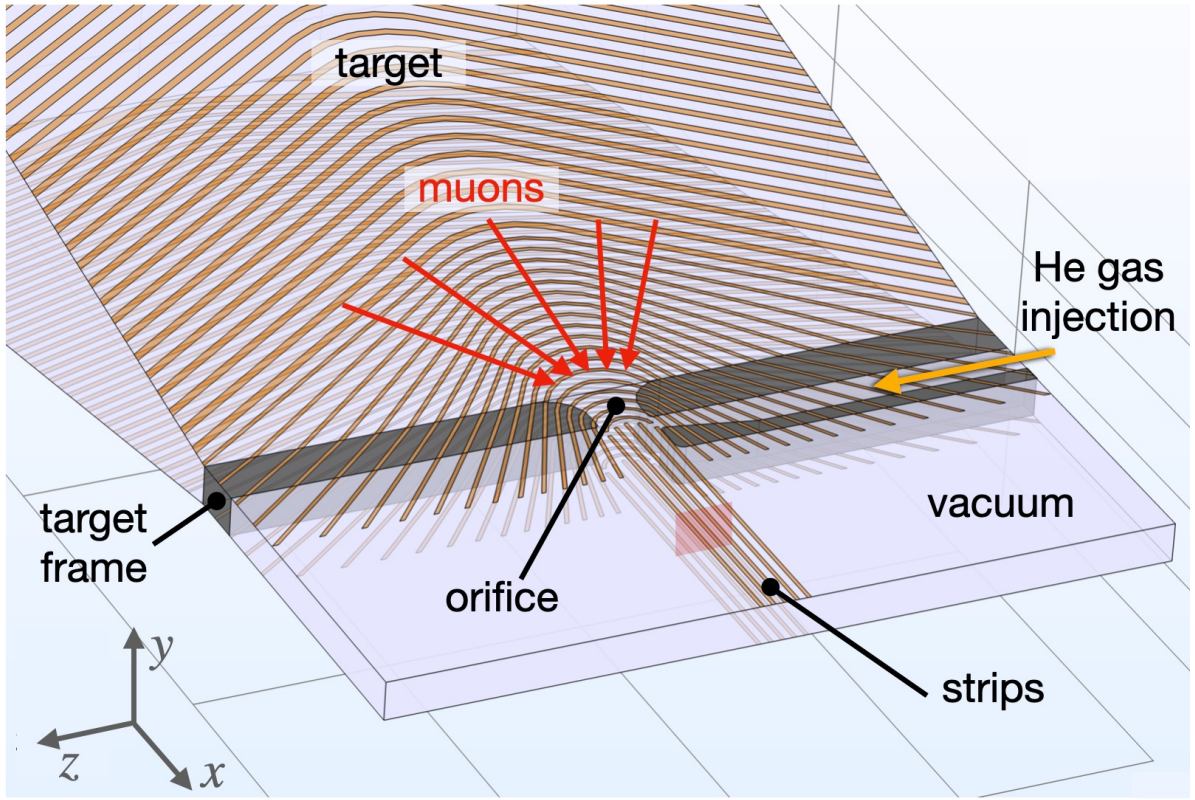


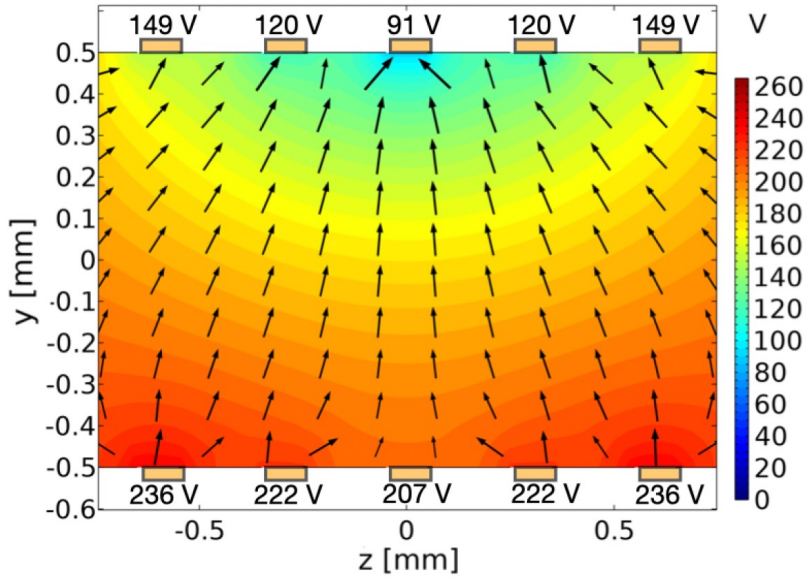


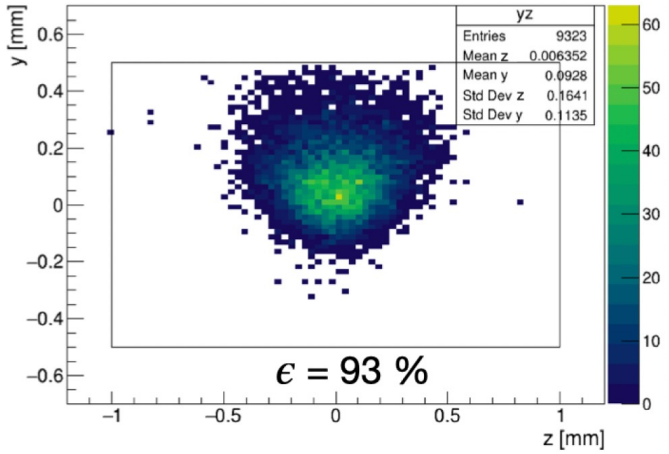


Position the parallel strips at x point where density drops sufficiently, i.e. drift angle in $\vec{E} \times \vec{B}$ *tends to 0*

Extraction: zy plane







Position the parallel strips at x point where density drops sufficiently, i.e. drift angle in $\vec{E} \times \vec{B}$ *tends to 0*

Preliminary conclusions

Baseline Efficiency	Possible Improvements	Description
$5.6 \cdot 10^{-1}$		Coupling to the 5 T solenoid with 60 mm coil diameter
$4.8 \cdot 10^{-1}$	$\times 2$	Impinging on the target entrance-face
$4.1 \cdot 10^{-3}$	$\times 1.6$	Stopping probability in active region of the target
$8 \cdot 10^{-2}$	$\times 1.5$	Compression towards the orifice (within 5 μs)
$4 \cdot 10^{-1}$	$\times 1.3$	Extraction from the orifice
$7 \cdot 10^{-1}$		Drift from orifice to re-acceleration region (in ~ 0.5 μs)
$8 \cdot 10^{-1}$		Re-acceleration and transport to the iron grid
$7 \cdot 10^{-1}$		Transmission through the iron grid terminating the B-field
$1.4 \cdot 10^{-5}$	$\times 6$	Total baseline compression efficiency (and possible improvement)

HIMB rate: $10^{10}\,\mu/s$

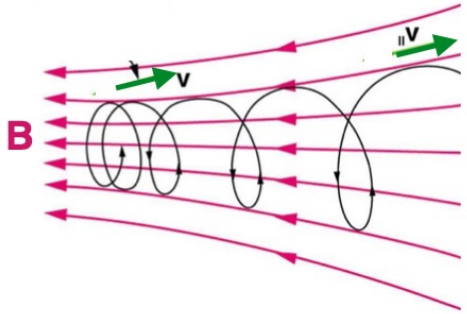
- ☑ Material science: distribute the muCool beam to several μSR setups at 40 kHz each
- ☑ Efficient Mu production: Mu-spectroscopy and Mu-gravity
- ☑ Re-accelerate to higher energies: e.g. 60 MeV for storage-ring-like experiments as μEDM or g-2

Extraction from B-field

- Charge particles follow magnetic field lines

$$r_i \sim r_0 \sqrt{\frac{B_0}{B_i}}$$

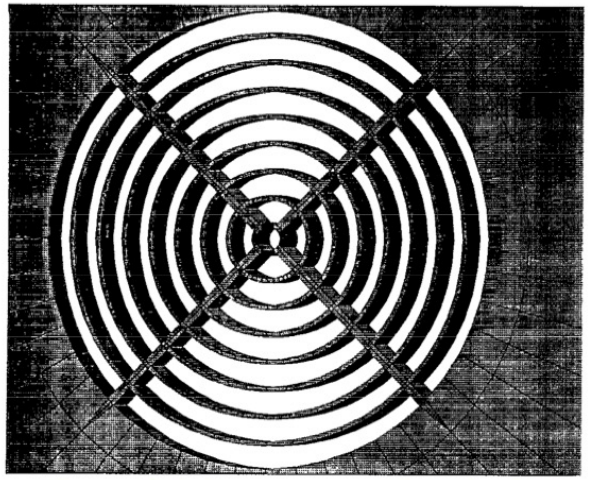
$$\Delta E_{\perp i} \sim \Delta E_{\perp 0} \frac{B_i}{B_0}$$



- The magnetic field can be terminated so that the beam transits from a region to another region with different field strengths. But in this process the charge particle receive an additional traverse momentum

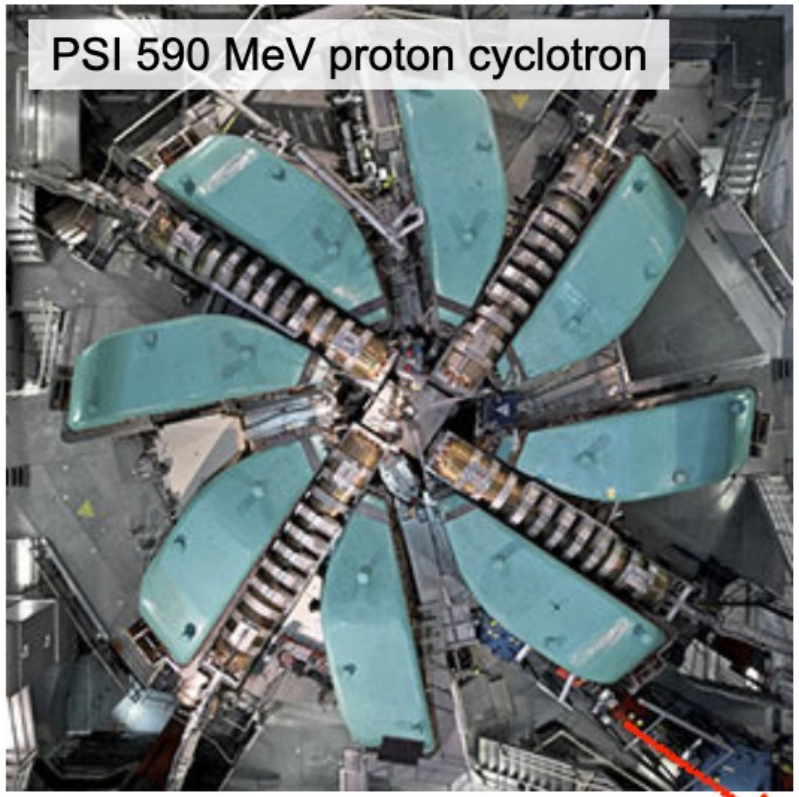
$$\Delta p_\perp = e \int_0^t v_z B_\perp dt \sim \frac{ewB_i}{2} \quad ,$$

$$\Delta E_\perp = \frac{e^2}{8m} w^2 B_i^2 \quad ,$$



Gerola et al., Rev. Sci. Instrum. 66 (7) 1995

Protons and muons at PSI



Muon beam

- Trade-off between *"rate"* and *"quality"*
- e.g. πE5 beamline at PSI

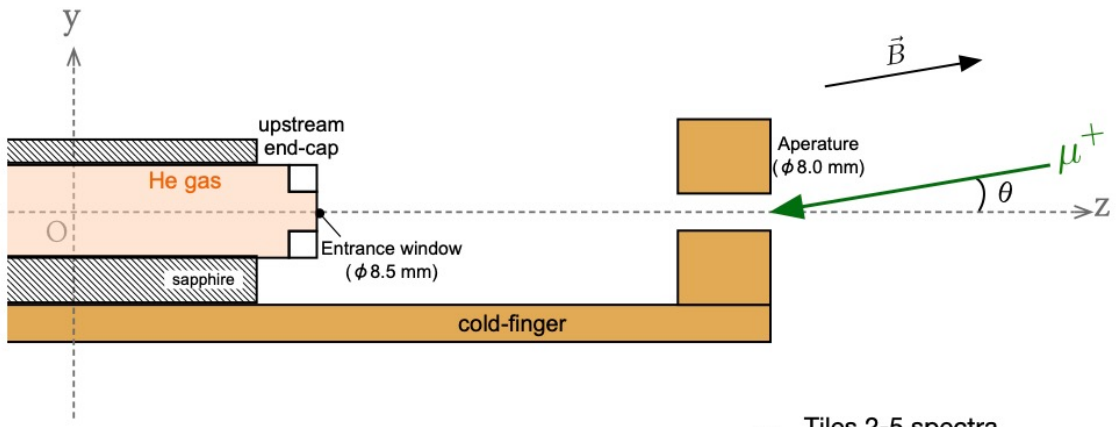
  100 MHz at 28 MeV/c

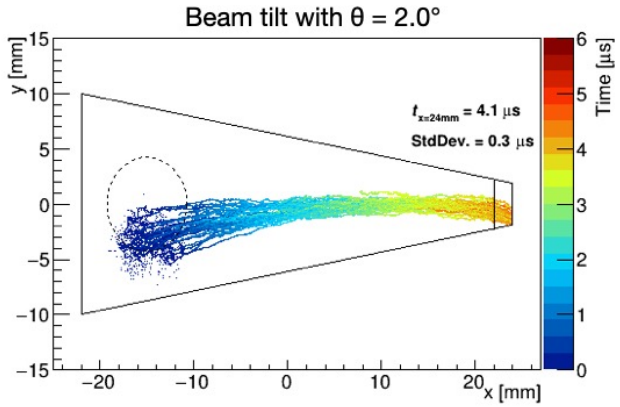
  σ_x ~ 1 cm

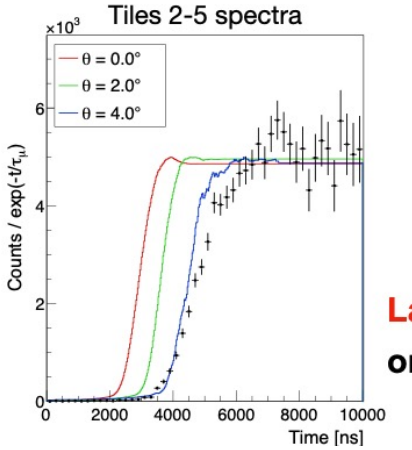
  σ_E ~ 0.5 MeV

Sensitivity to misalignment of incoming beam

- Misalignment between target axis and magnetic field
  - Maximum possible angle: $\theta_{MAX} \sim 4.5°$







Large effect on drift time

Scintillators position and data