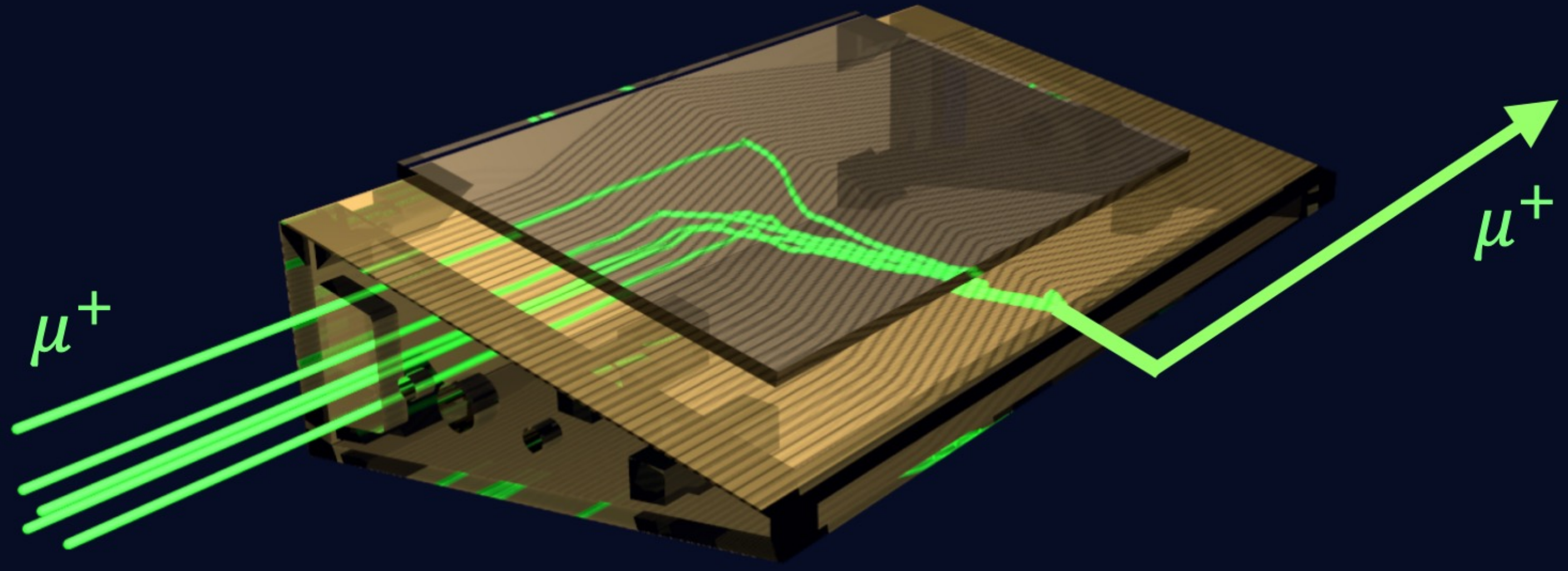


Muon cooling at PSI

Giuseppe Lospalluto (ETH Zürich)

On the behalf of the muCool collaboration

Muon4Future, Venice

29 May 2023

Muon beamline at PSI

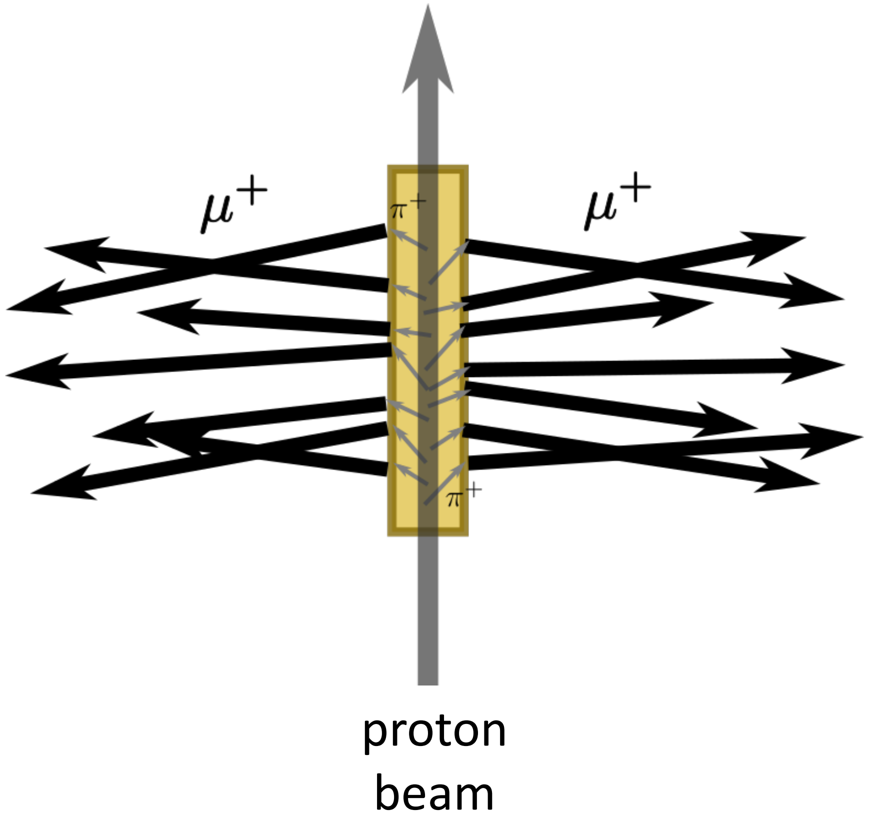
- High intensity cw positive muon beam (4.1 MeV) at the Paul Scherrer Institut (PSI)

$$p + p \rightarrow \pi^+ \ldots \rightarrow \mu^+ \ldots$$

(beam) (target)

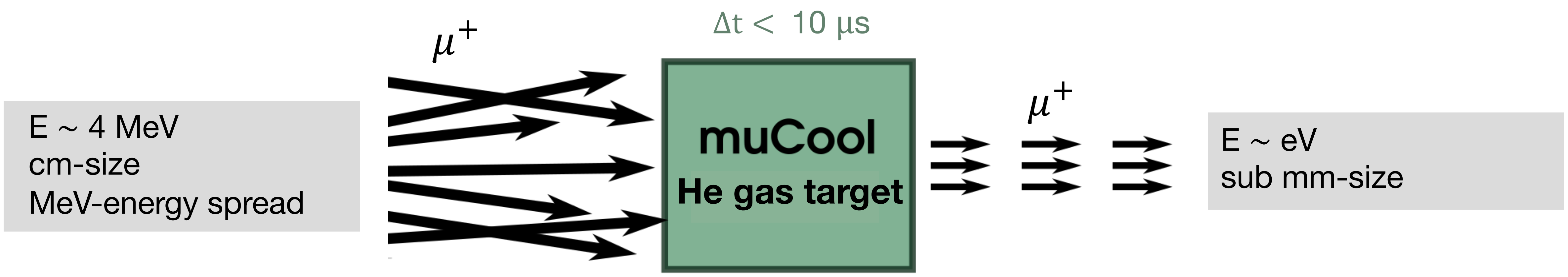
- What for?
  e.g. Rare muon decay searches ($\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^-e^+$)

High "rate", poor "quality"



- For several precision experiments "quality" is important
- How can we cool a muon beam? (τ_μ = 2.2 μs)

muCool : "fast" phase space compression

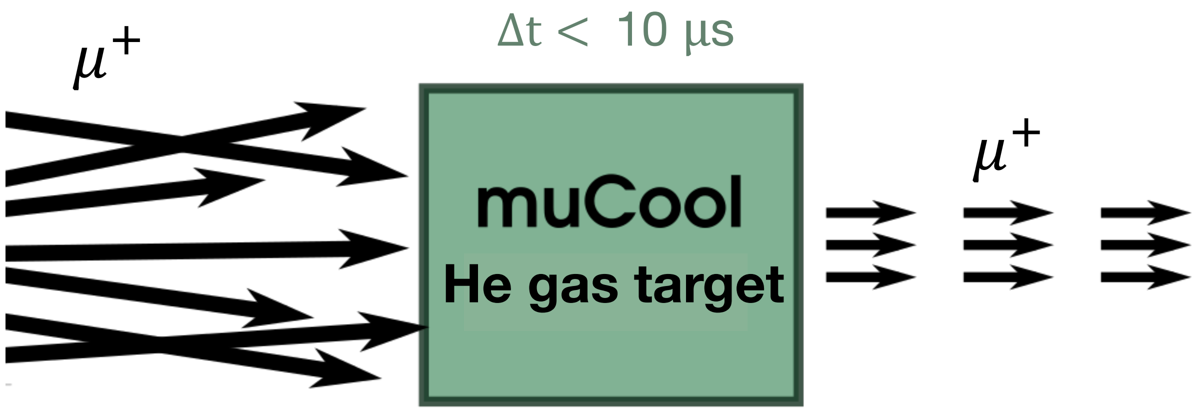


- Efficiency of 10^{-4} - 10^{-5}
- Phase space improved by $> 10^8$

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

muCool : “fast” phase space compression

E ~ 4 MeV
cm-size
MeV-energy spread

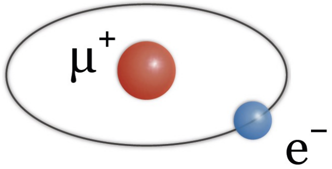


E ~ eV
sub mm-size

Re-acceleration

- ➢ Efficiency of 10^{-4} - 10^{-5}
- ➢ Phase space improved by $> 10^8$

keV energies



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

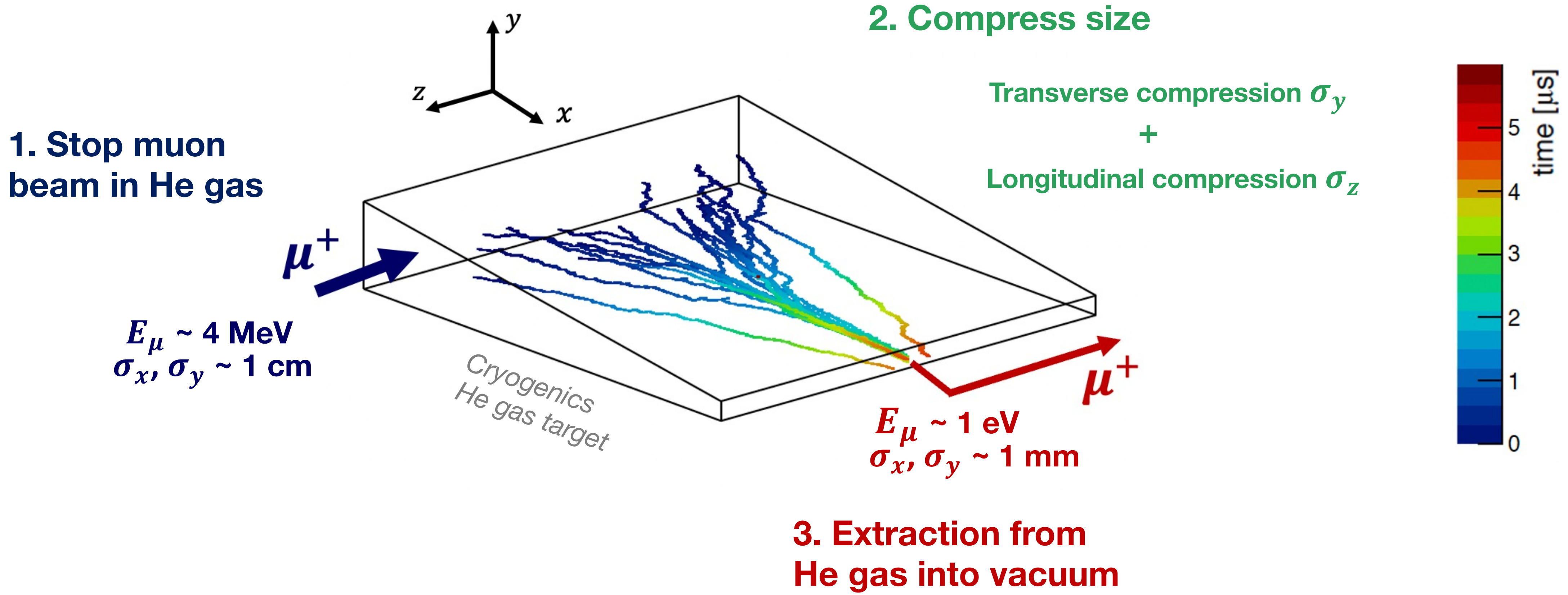
MeV energies

- ➢ Muon g-2/EDM with storage ring

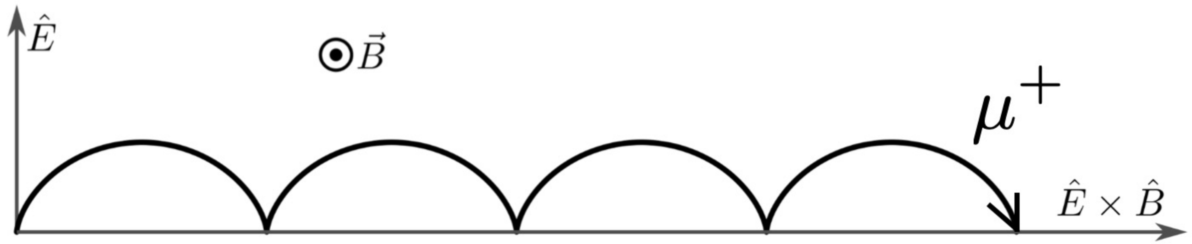
D. Taqqu. *Phys. Rev. Lett.* 97.194801 **(2006)**

muCool scheme

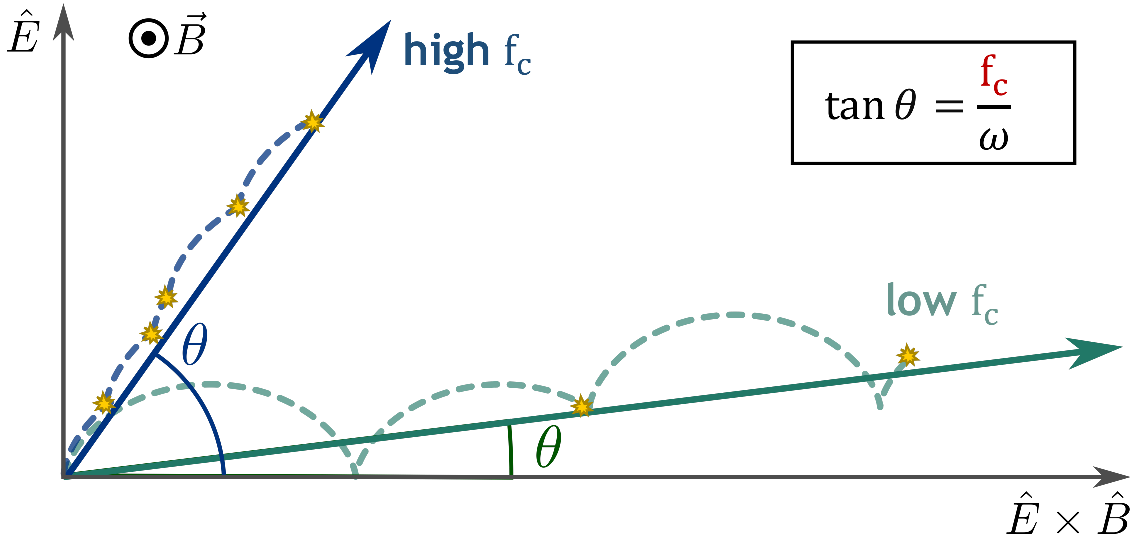
- Complex E-fields and B-field + density gradient compress the muon beam



Muon drift in crossed E and B-fields



In vacuum

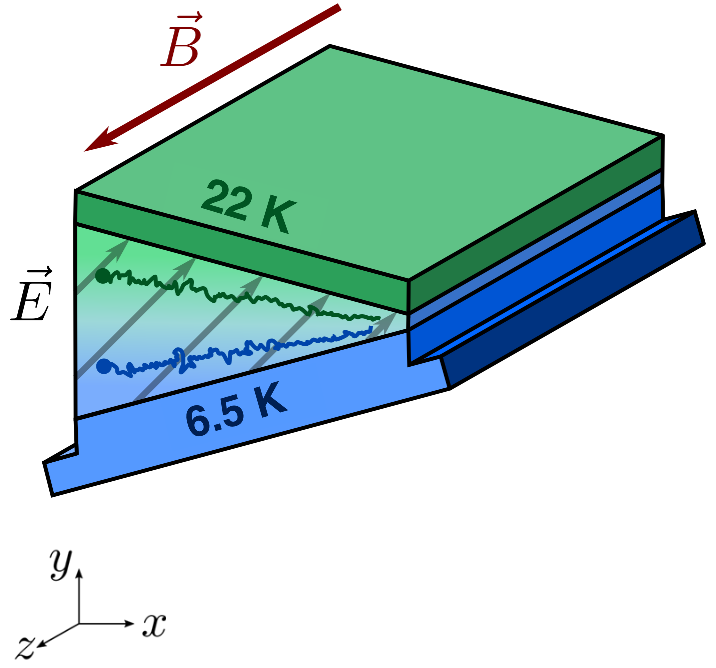


In gas

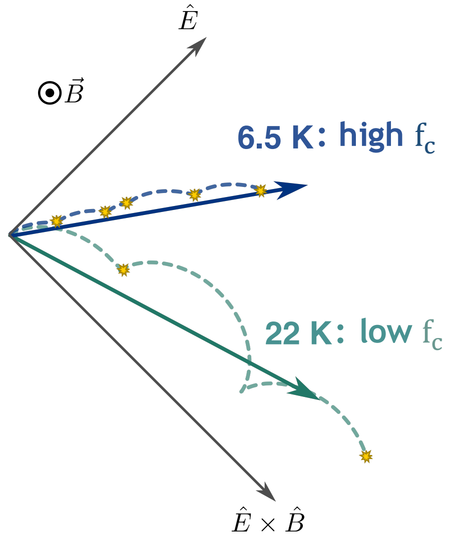
Collision with gas atoms at frequency f_c

muCool principle

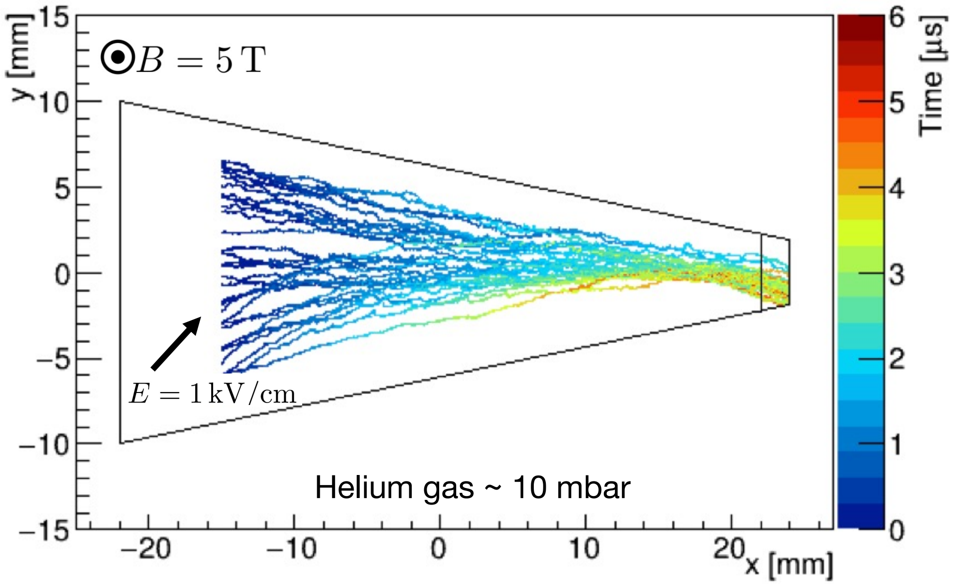
Transverse Compression



$f_c \propto$ gas density



Simulated muon trajectories



Drift velocity

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

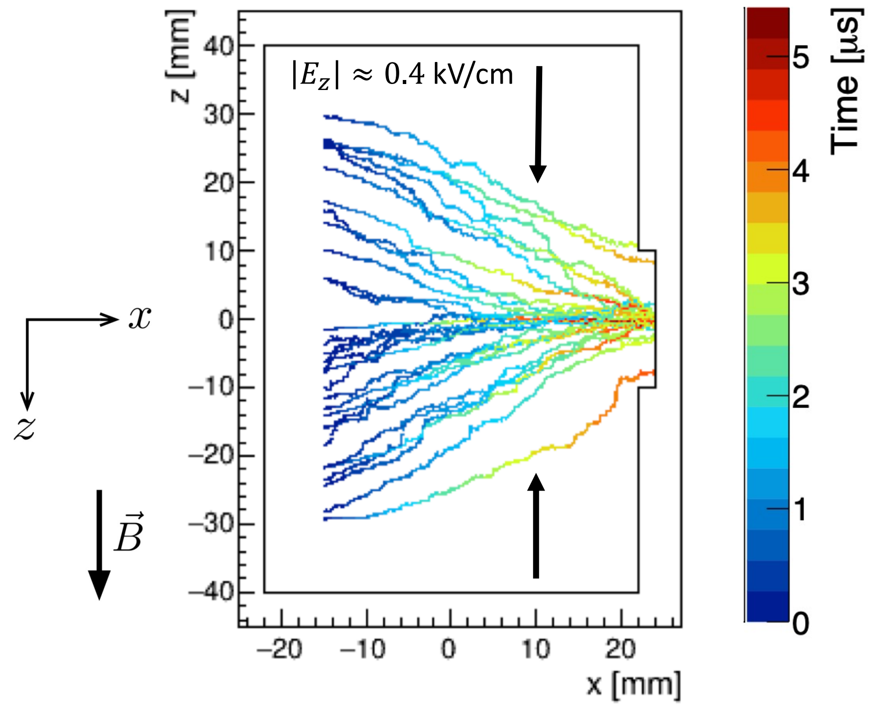
= 0 (for the $\left(\hat{E}\cdot\hat{B}\right)$ term)

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

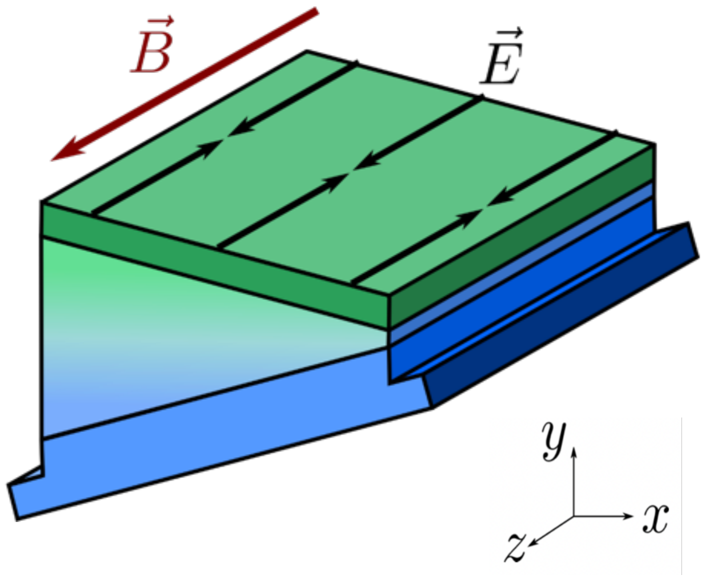
A. Antognini et al. *Phys. Rev. Lett.* 125.164802 **(2020)**

muCool principle

Simulated muon trajectories



Longitudinal Compression



Drift velocity

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

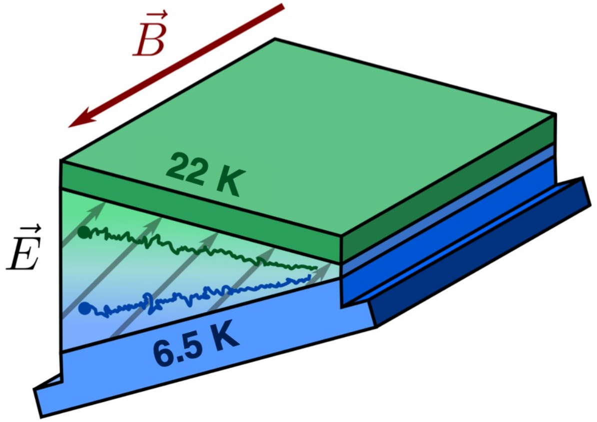
= 0

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)**

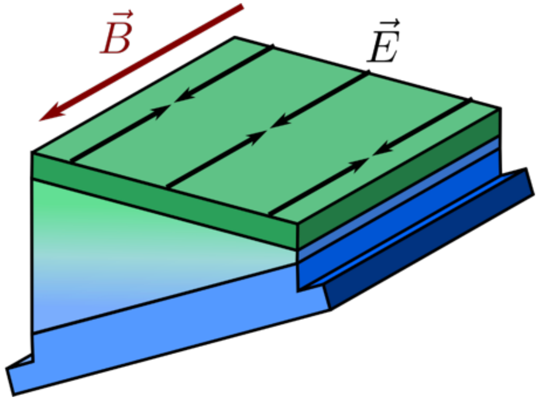
muCool principle

Transverse Compression



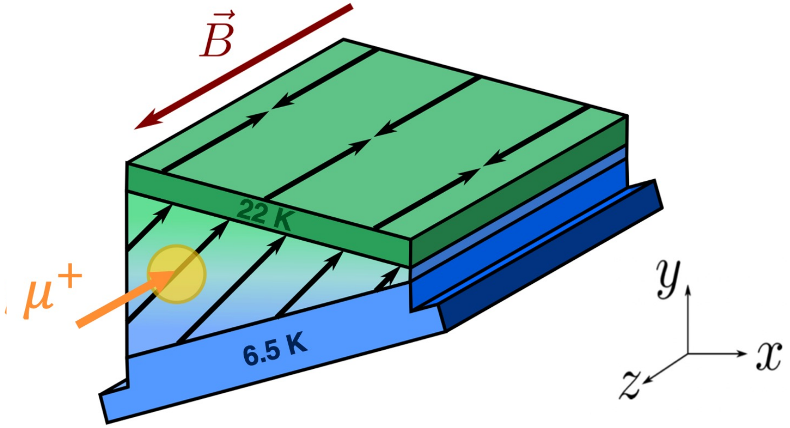
+

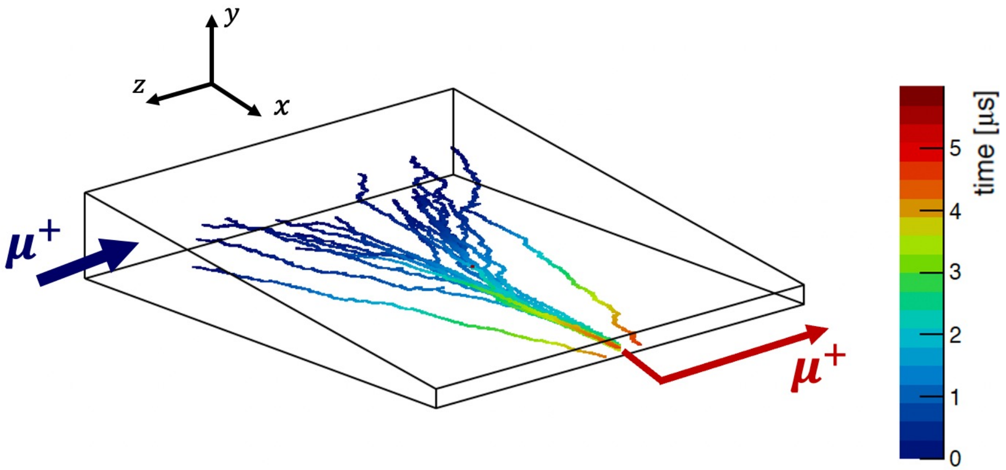
Longitudinal Compression



=

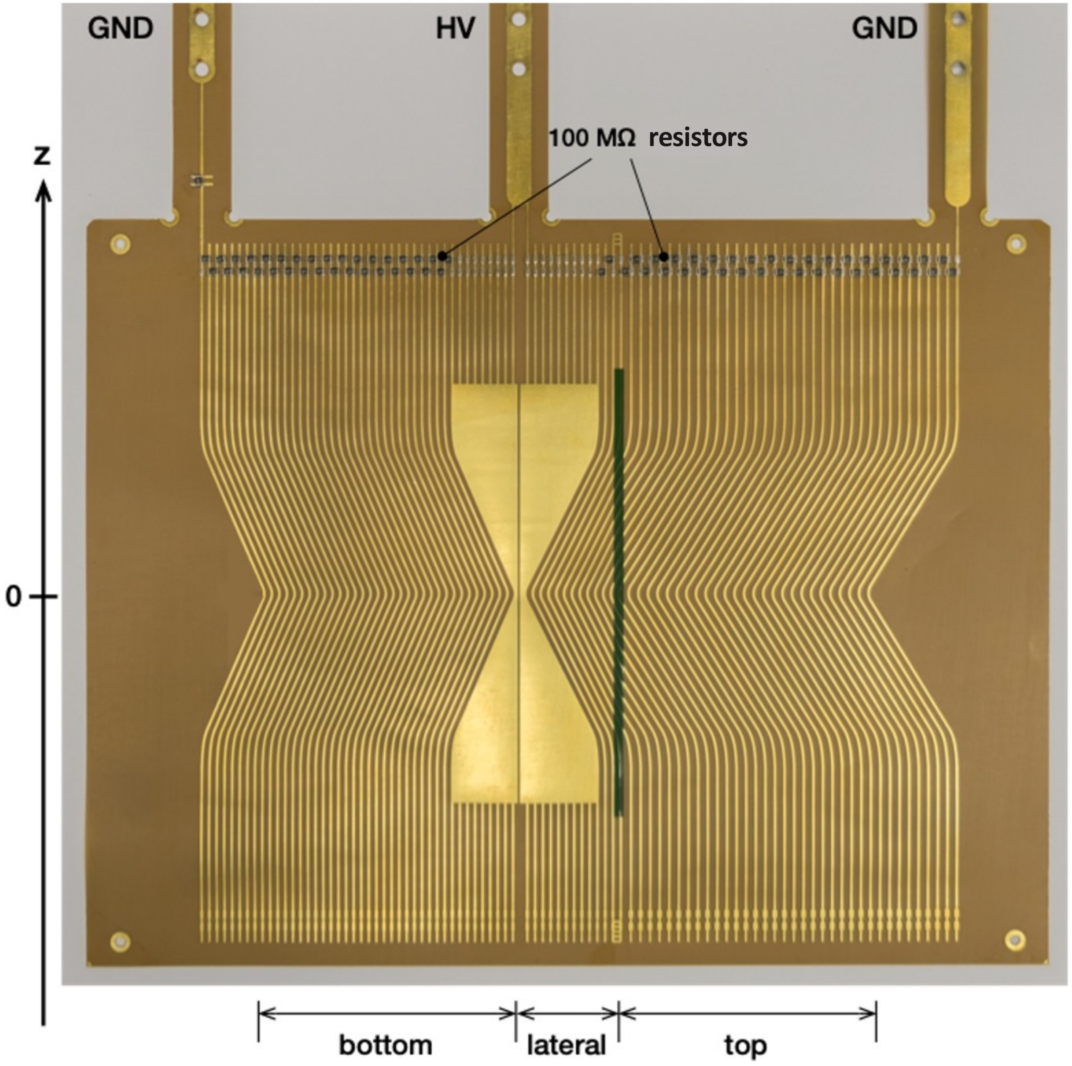
Mixed Compression





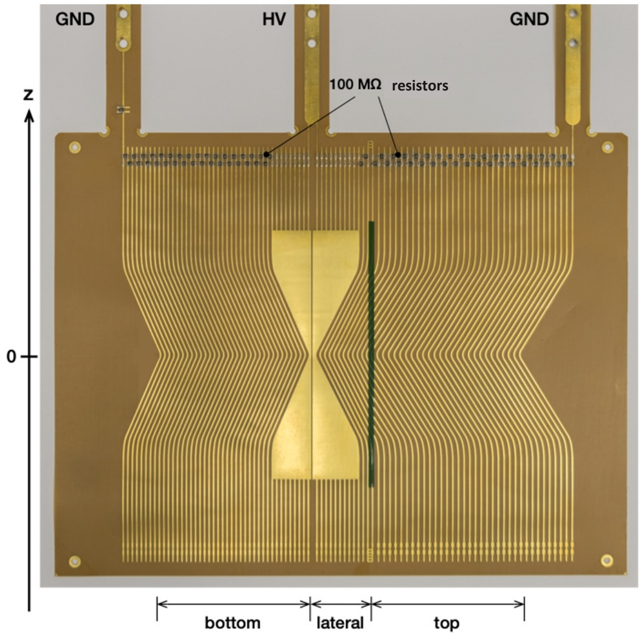
Target realisation

- Lined Kapton-foil: Electric field for mixed compression



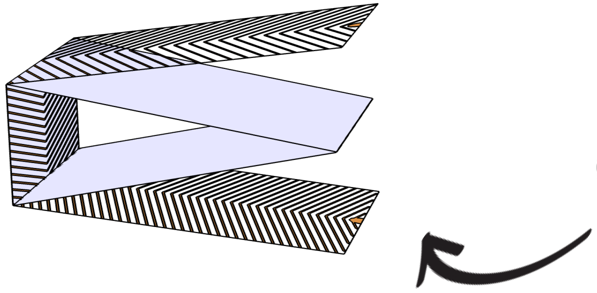
Target realisation

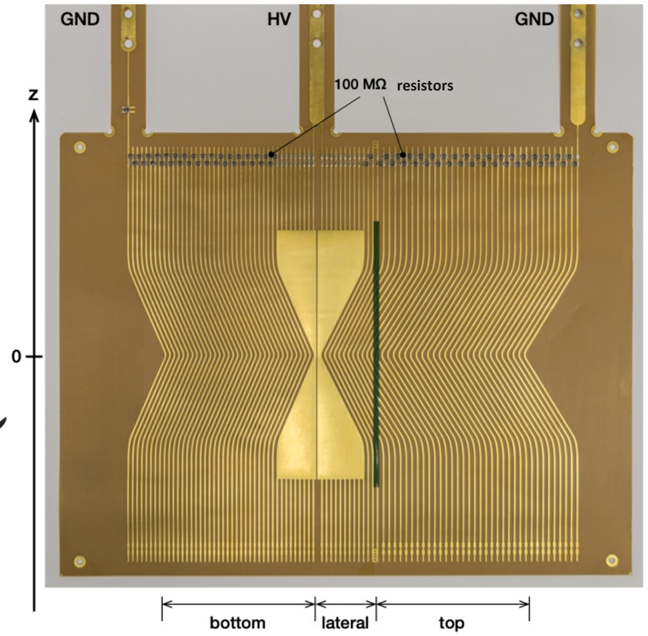
- Lined Kapton-foil: Electric field for mixed compression



Target realisation

- Lined Kapton-foil: Electric field for mixed compression





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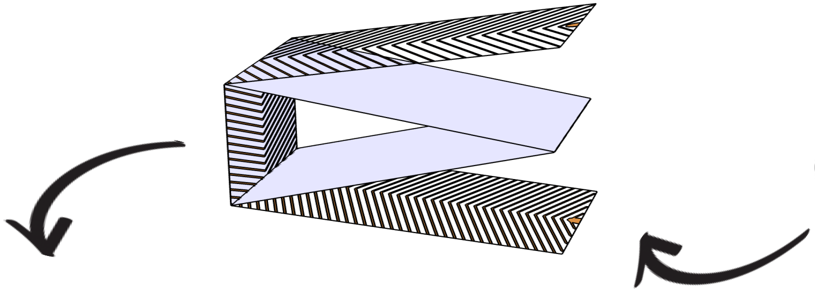
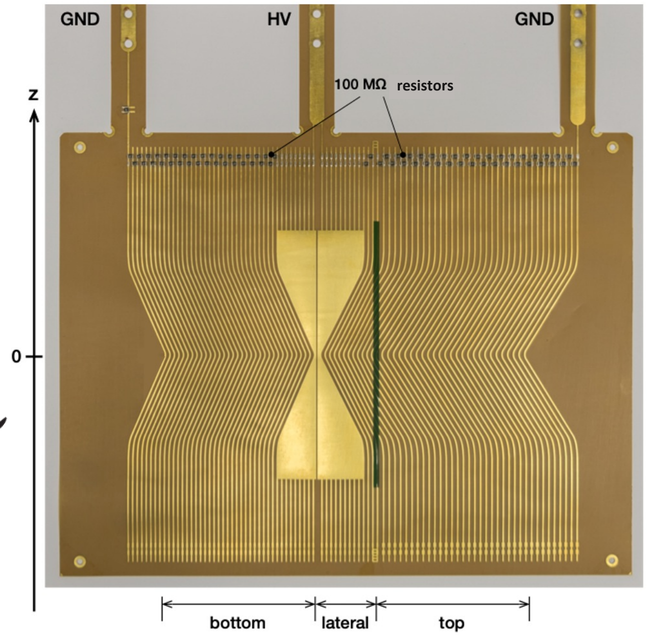
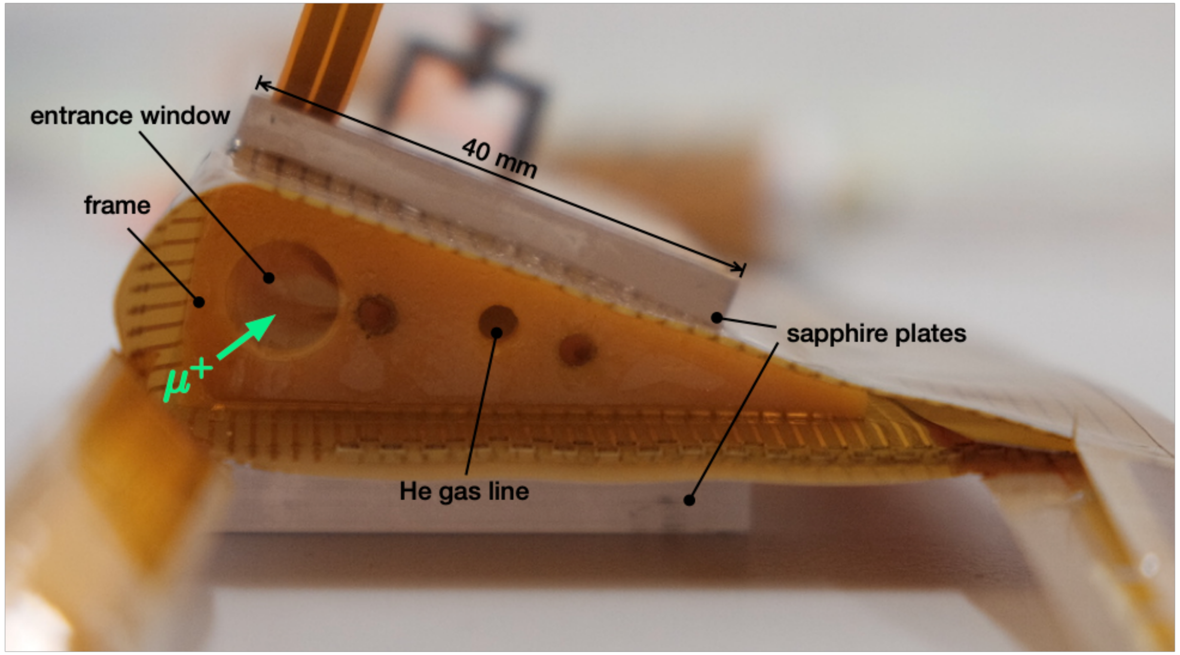
- Lined Kapton-foil: Electric field for mixed compression

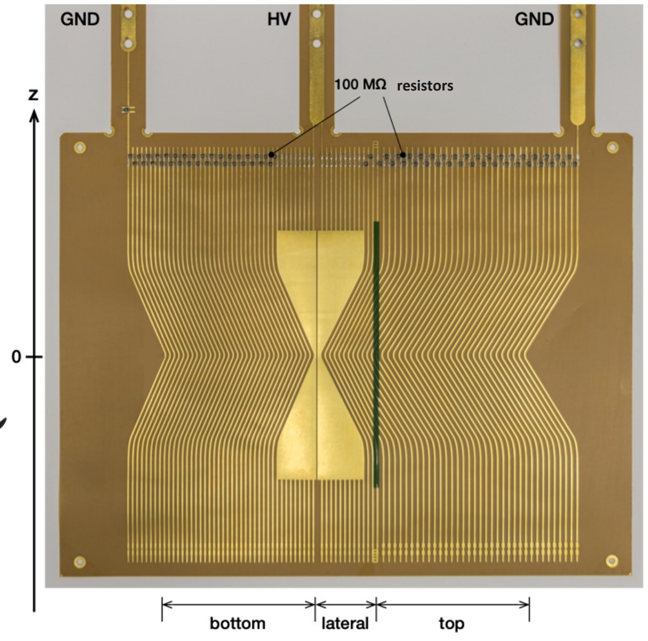


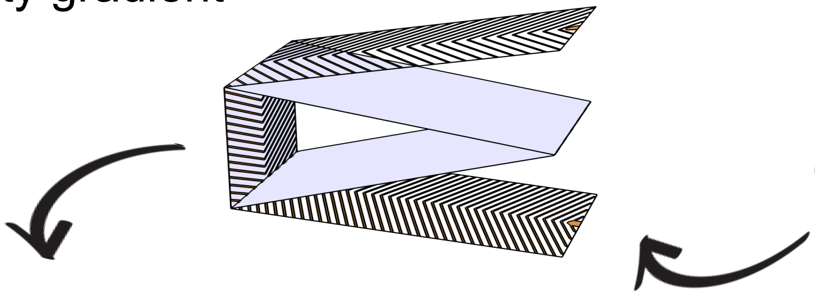


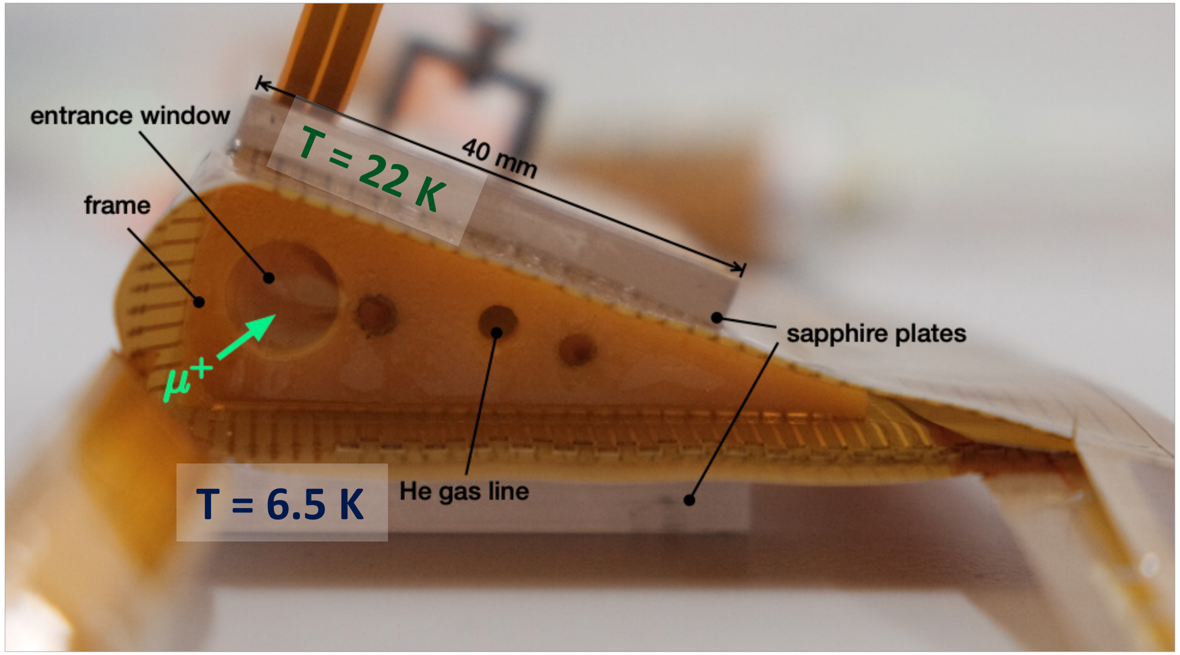


Target realisation

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

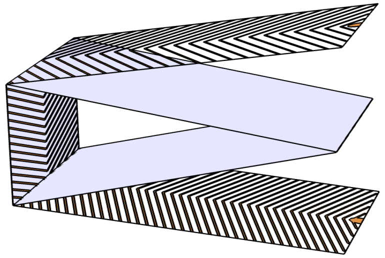


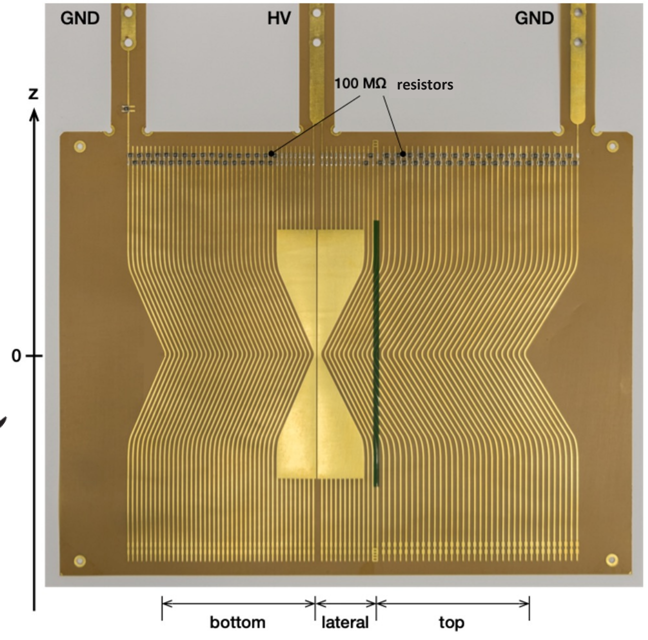


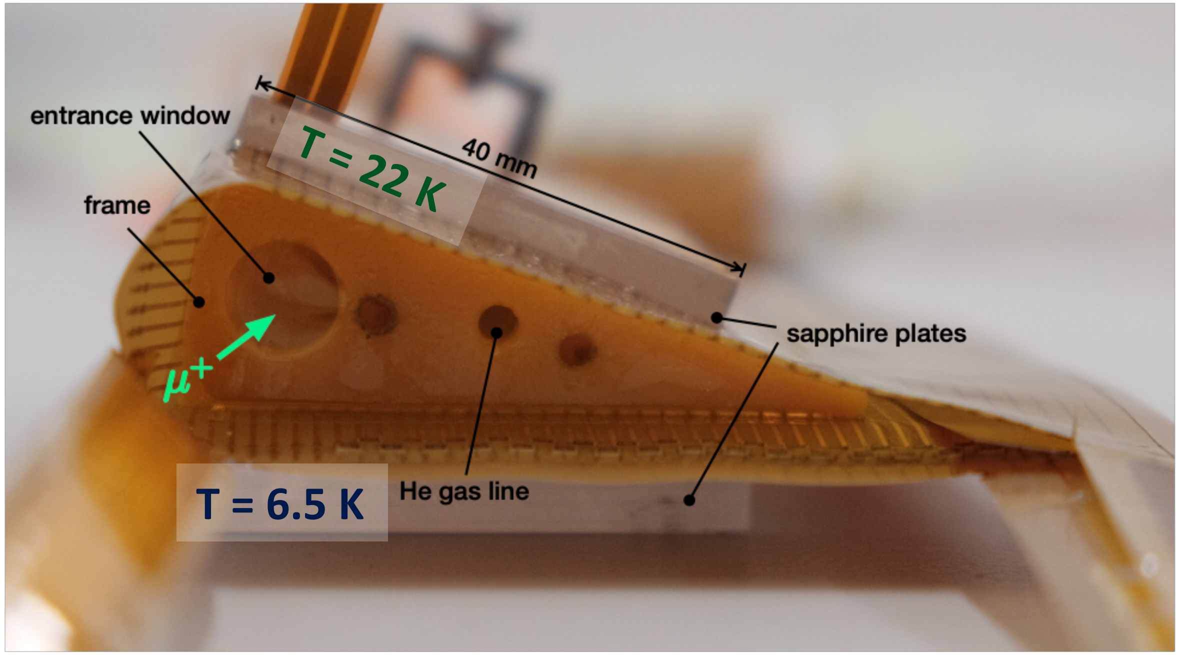


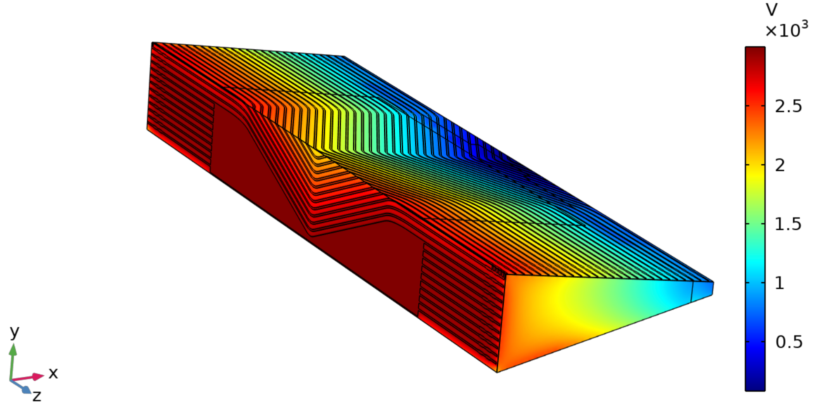
Target realisation

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







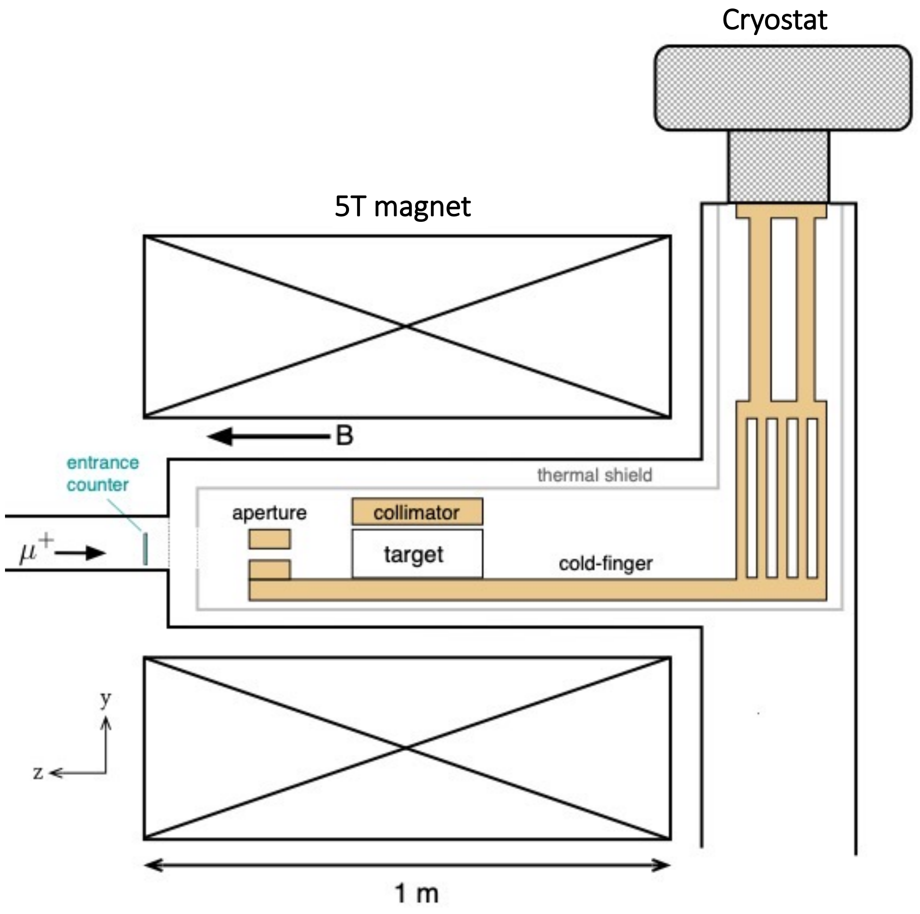


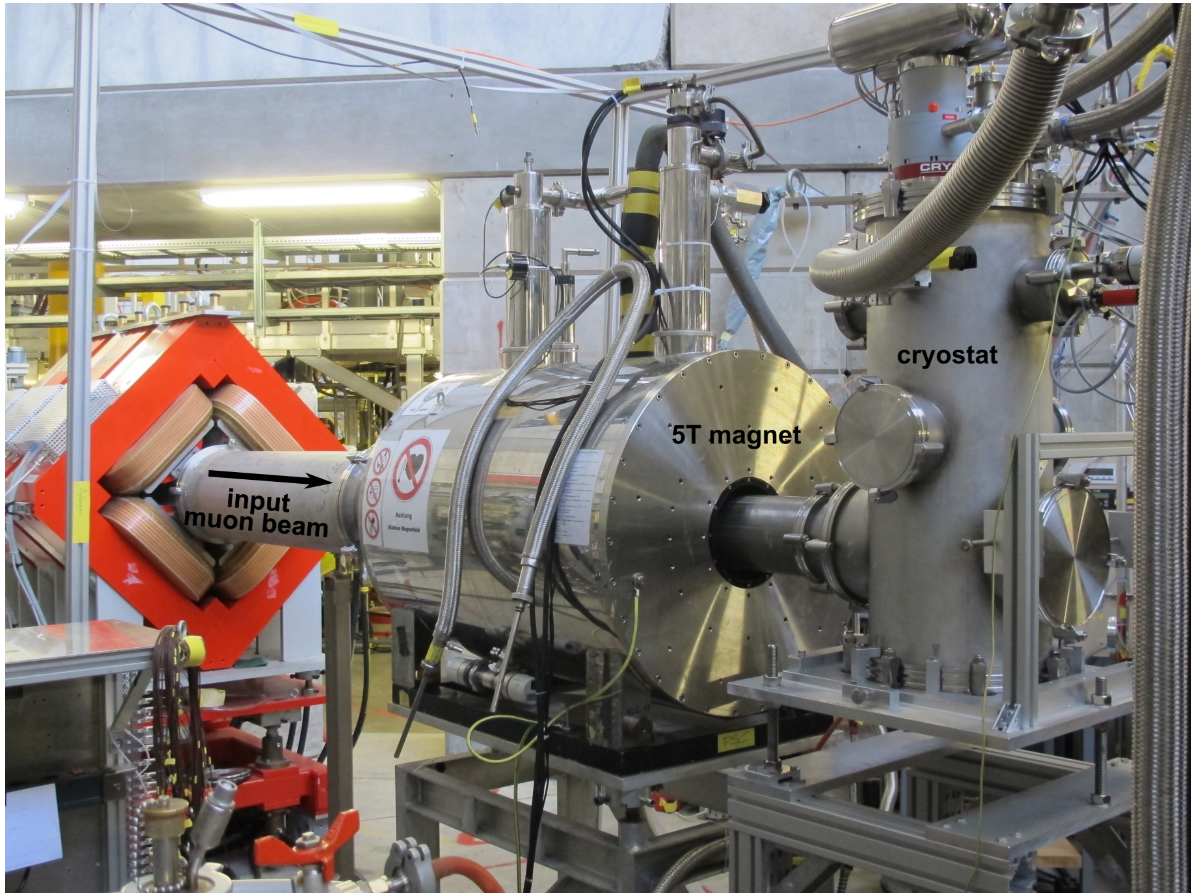
Electric potential simulation

Experiment

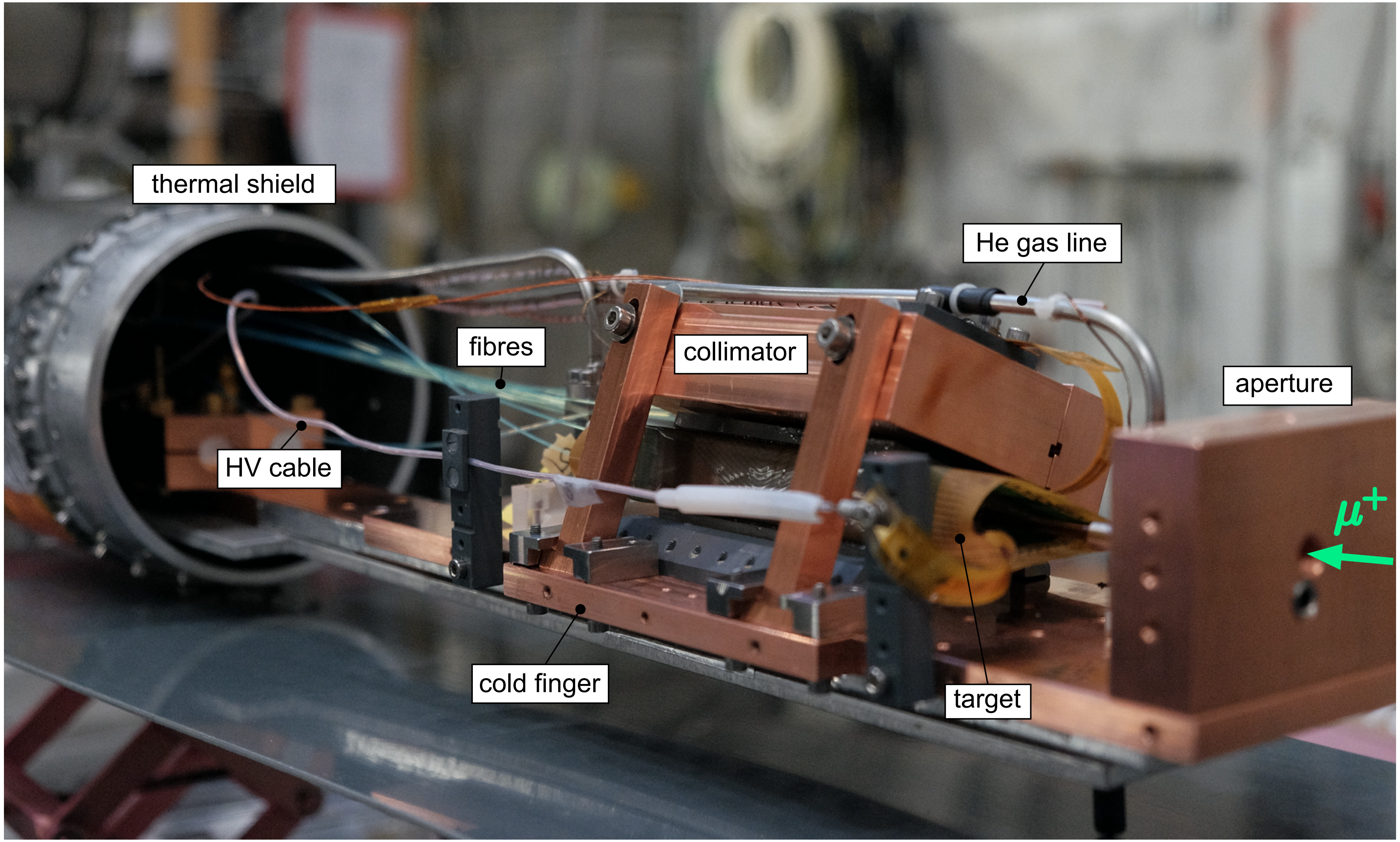
Test of mixed compression (2019)

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



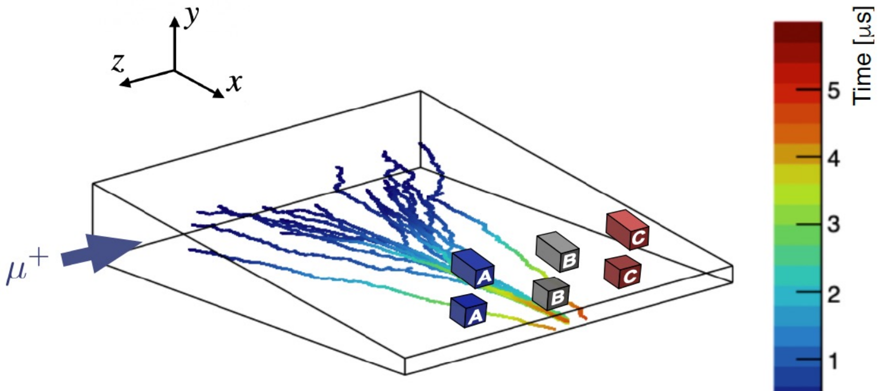


Experiment

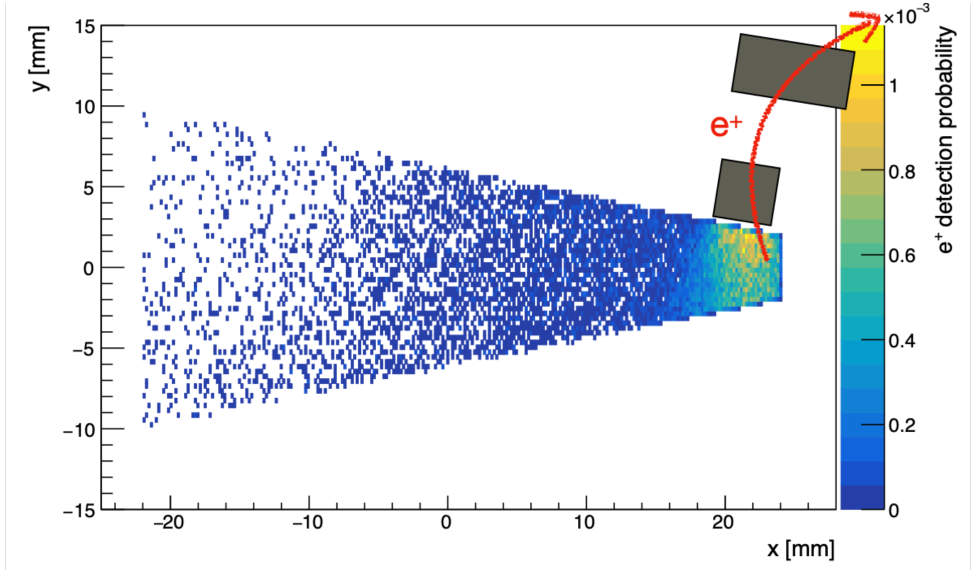

thermal shield
He gas line
fibres
collimator
aperture
HV cable
μ^+
cold finger
target

Test of mixed compression

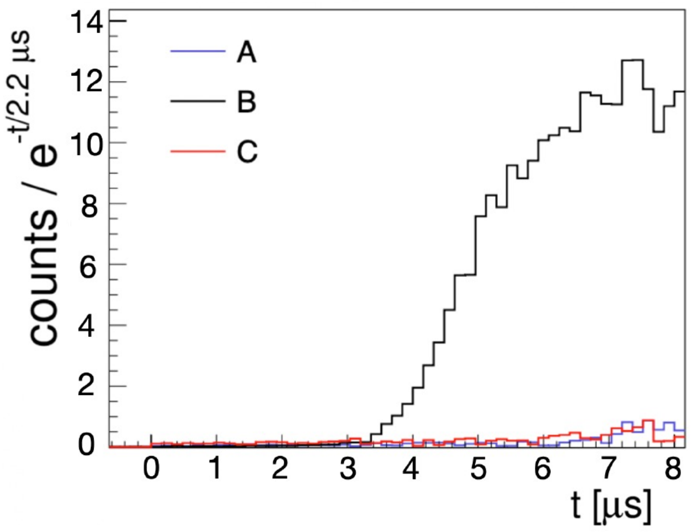
- "*Indirectly*" measure muon position by detecting decay positrons
- t = 0 given by entrance counter
- Large increase of counts: all muons reached target tip



Scintillator detectors at target tip



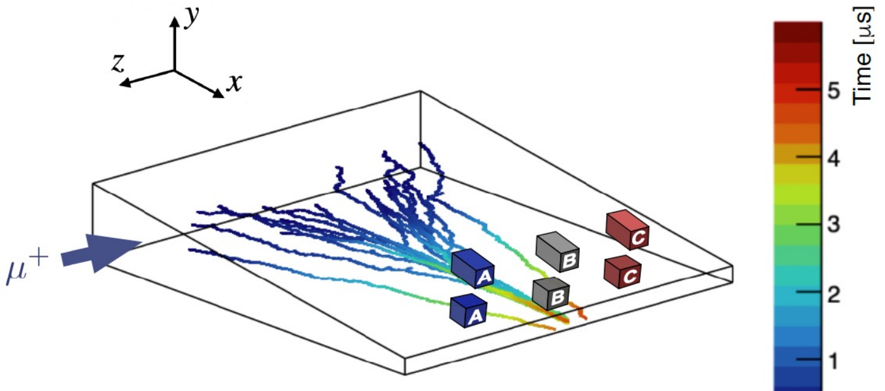
Detection simulation



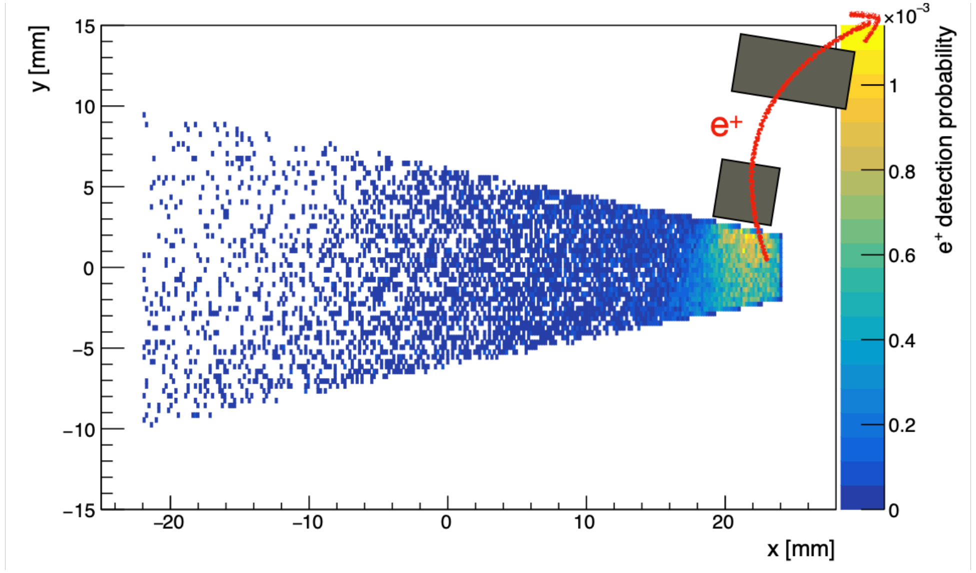
Measured time spectra (2019 beamtime)

Test of mixed compression

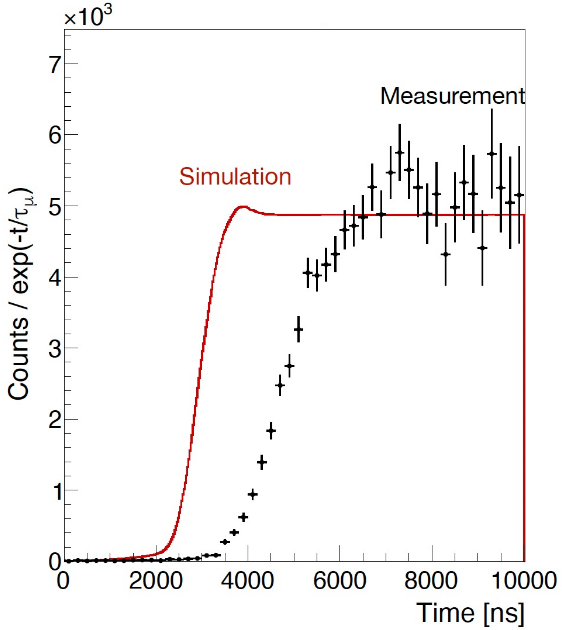
- "*Indirectly*" measure muon position by detecting decay positrons
- t = 0 given by entrance counter
- Large increase of counts: all muons reached target tip



Scintillator detectors at target tip



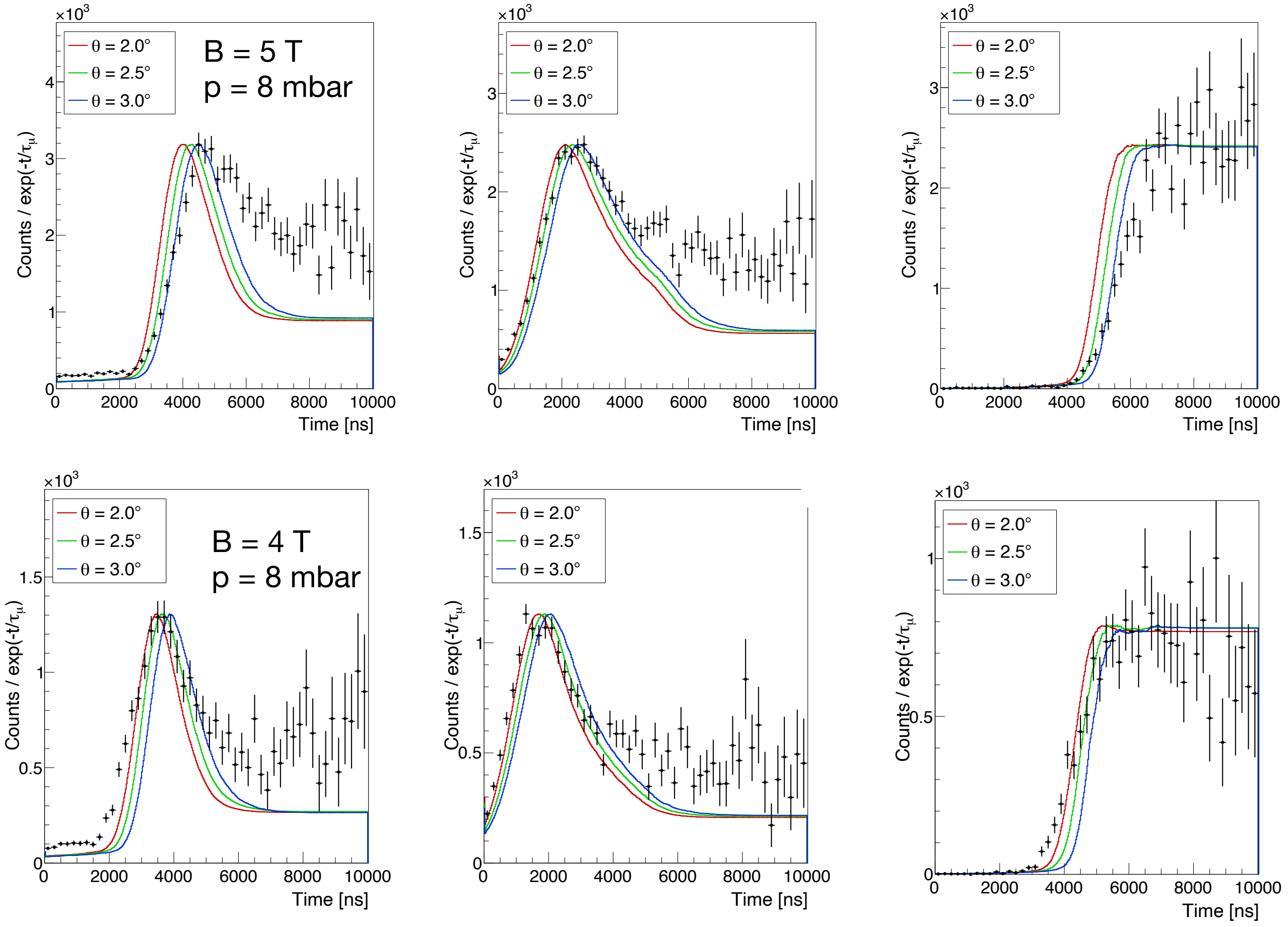
Detection simulation

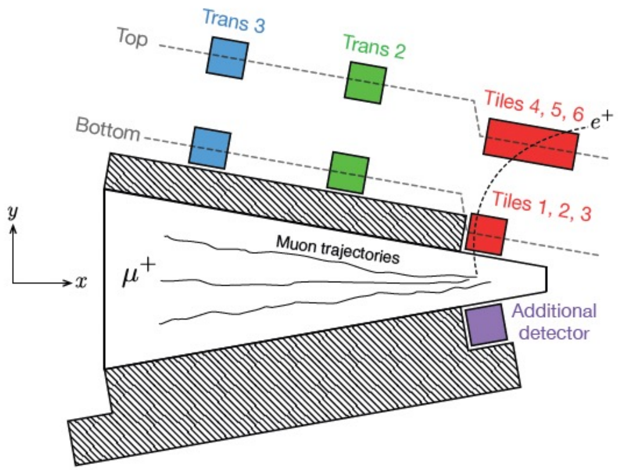


observed tension?

Tuning target parameters

Trans 3 | Trans 2 | Tiles 2-5



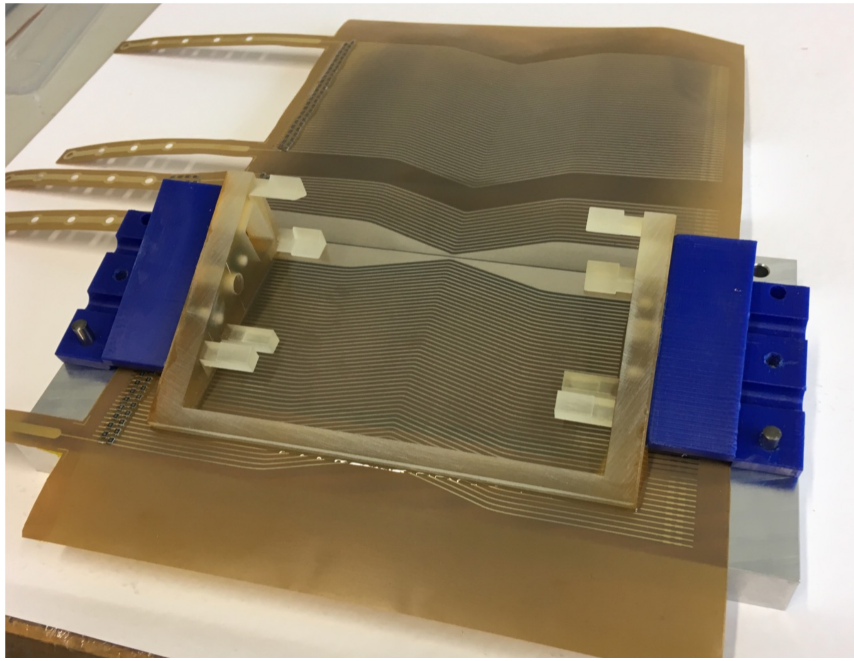


Good agreement between simulations and measurements

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

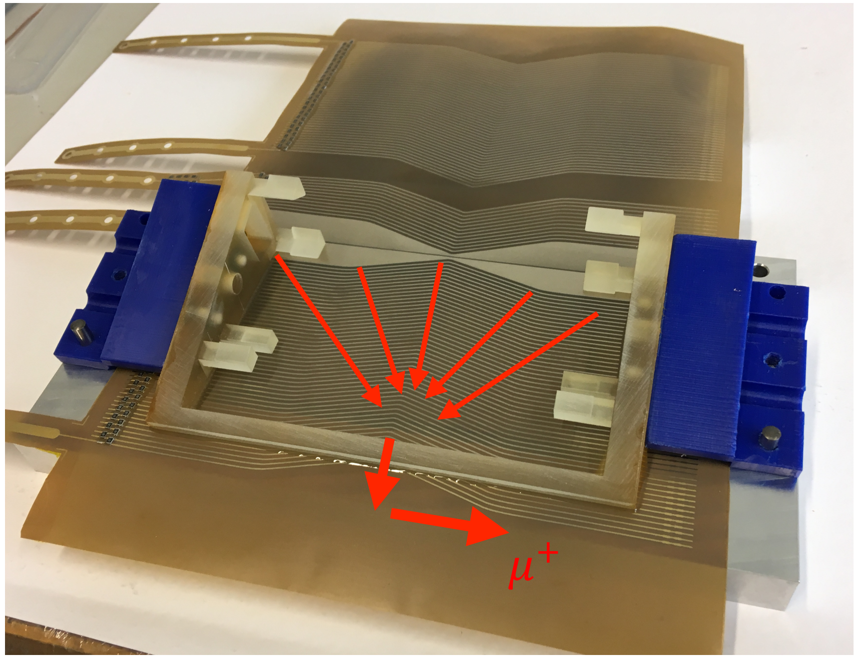
R. Iwai. *PhD thesis (ETH Zurich)* **(2022)**

Next steps?



Open up muCool target

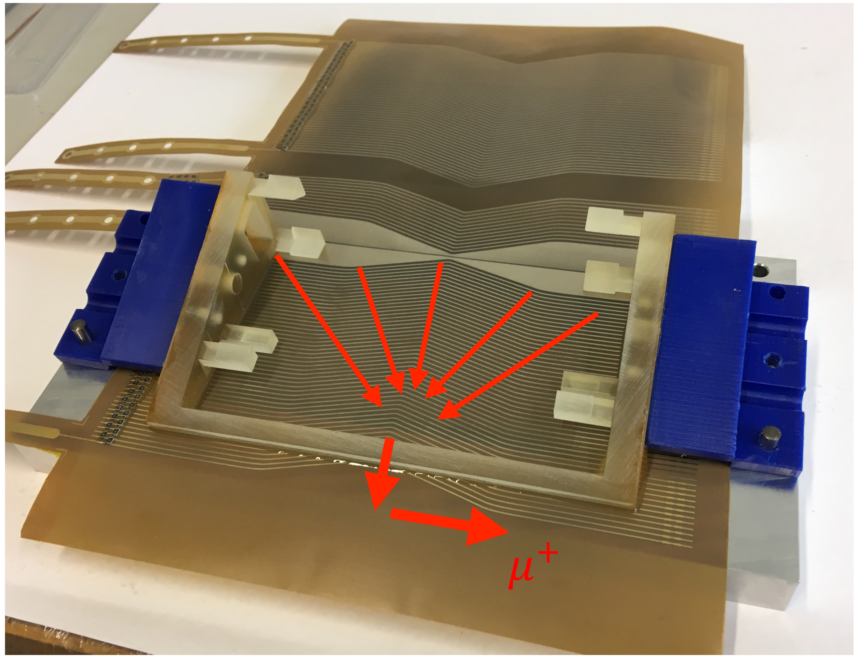
Next steps?



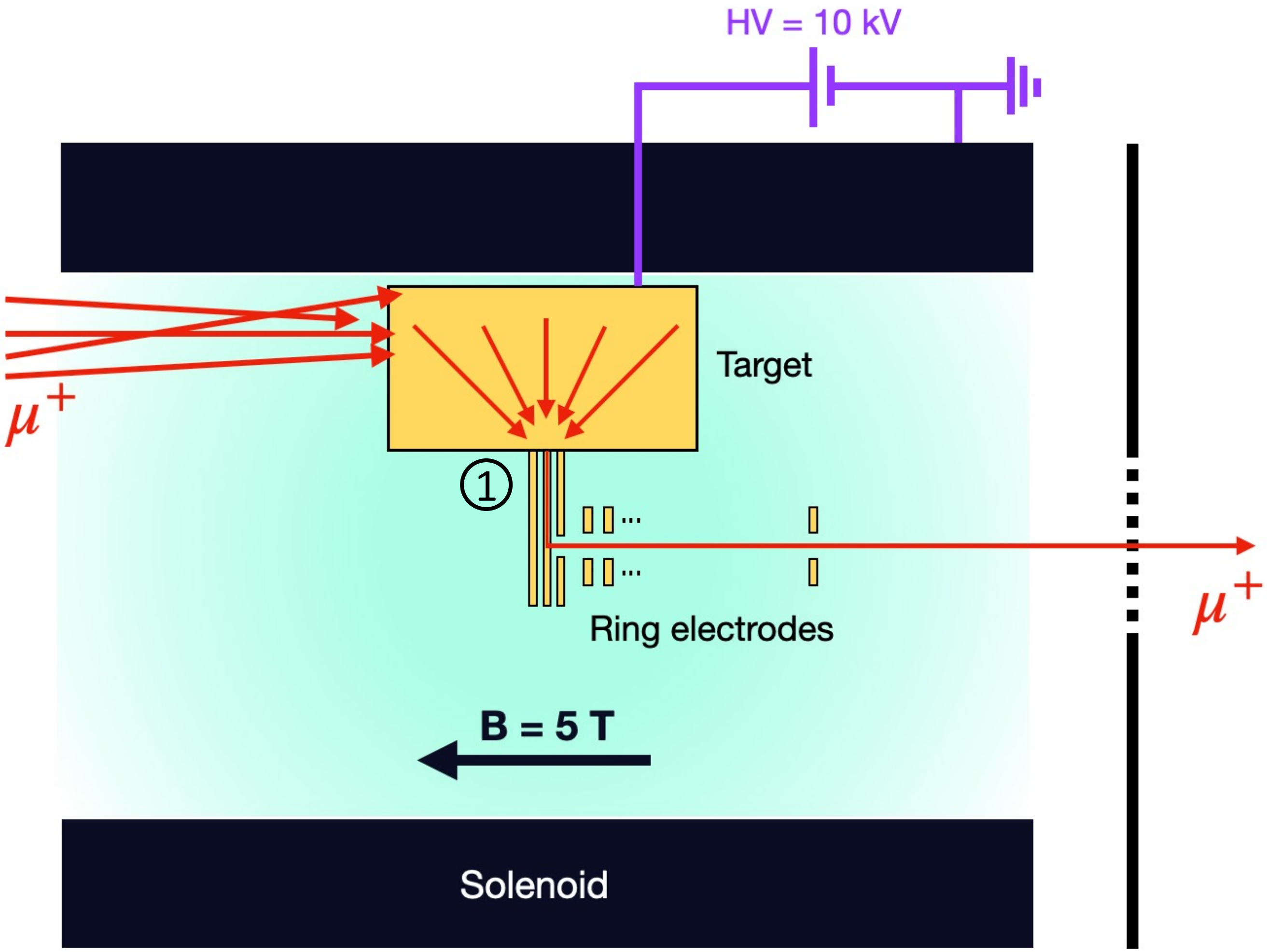
Make a hole and extract muons

Next steps?

① Muon extraction from gas target into vacuum via tiny orifice (eV energy muons)



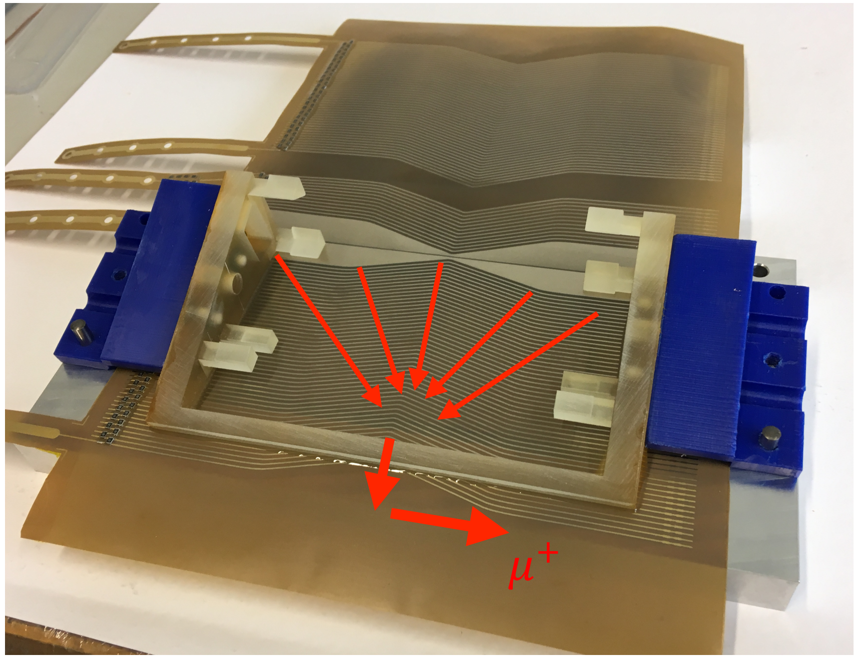
Make a hole and extract muons



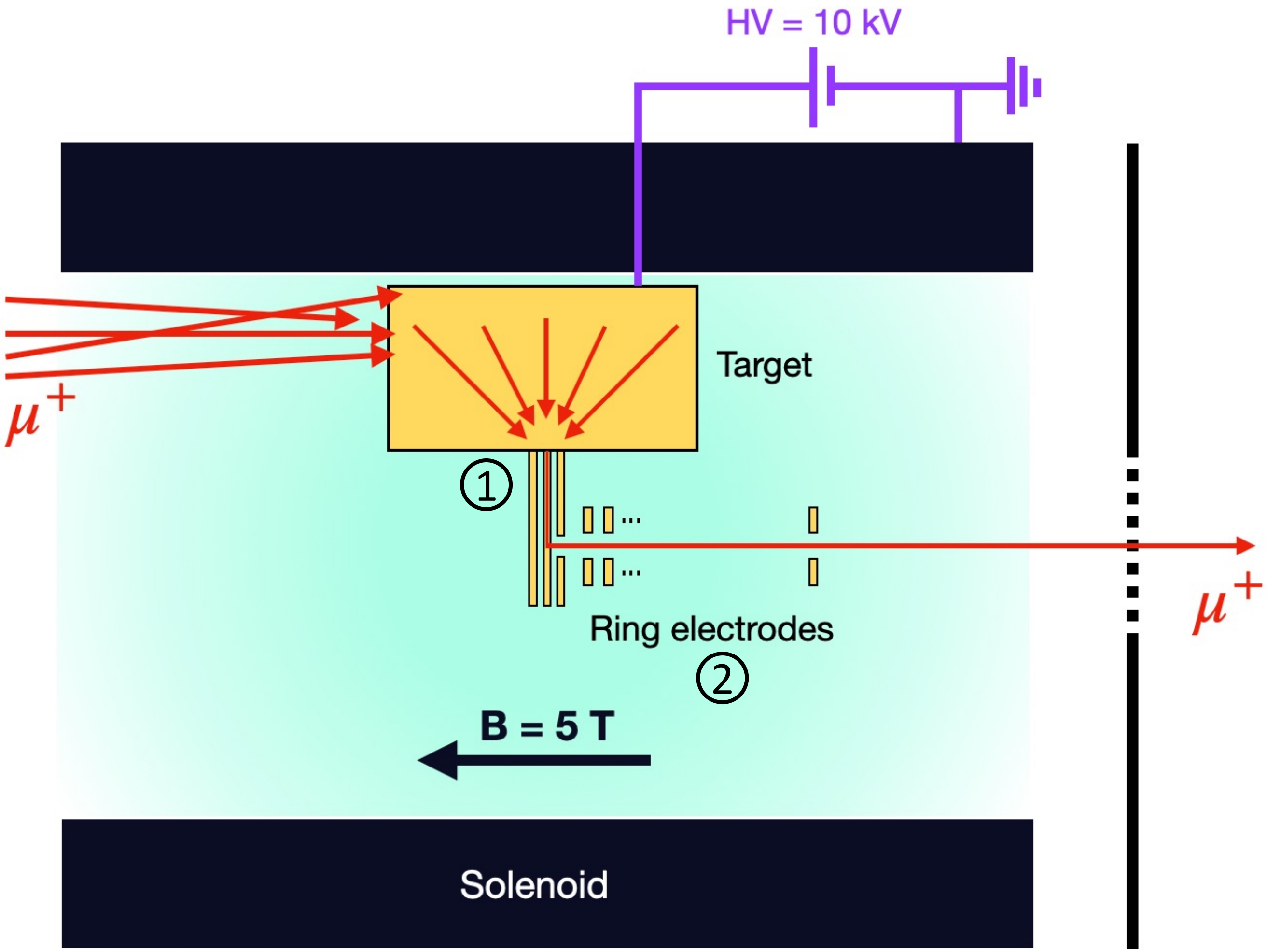
Next steps?

① Muon extraction from gas target into vacuum via tiny orifice (eV energy muons)

② Re-acceleration to 10 keV



Make a hole and extract muons

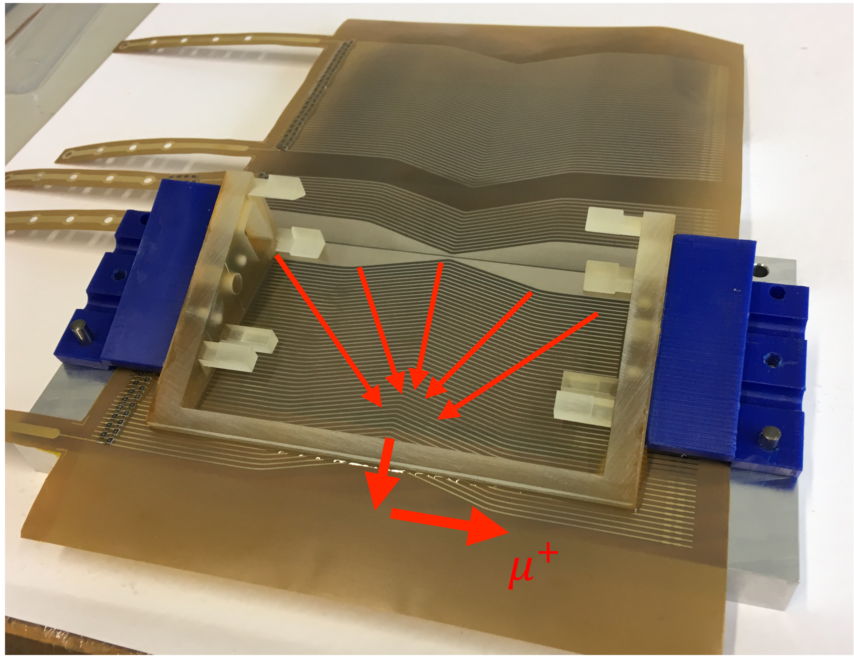


Next steps?

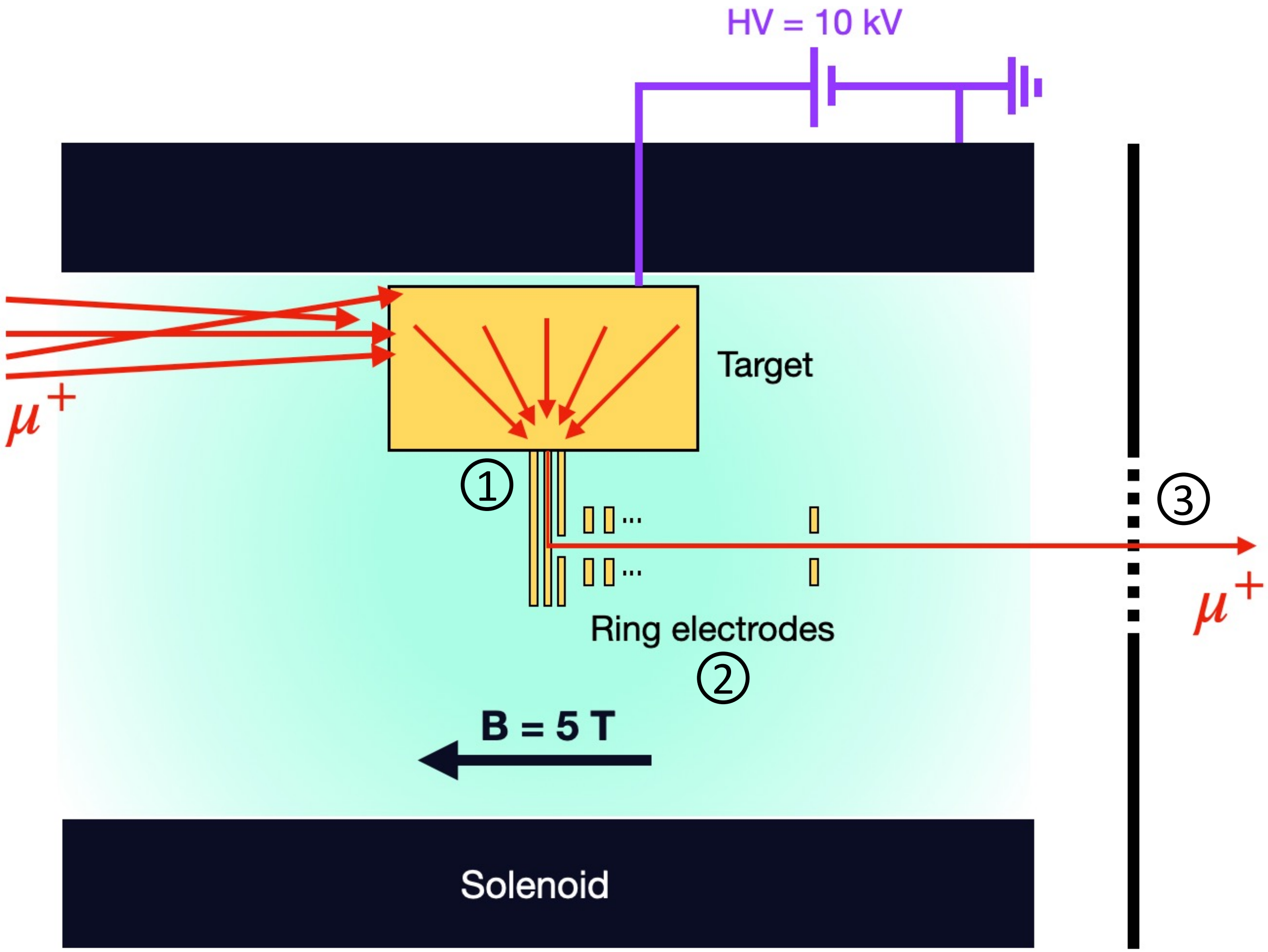
① Muon extraction from gas target into vacuum via tiny orifice (eV energy muons)

② Re-acceleration to 10 keV

③ Extraction from 5T solenoid



Make a hole and extract muons

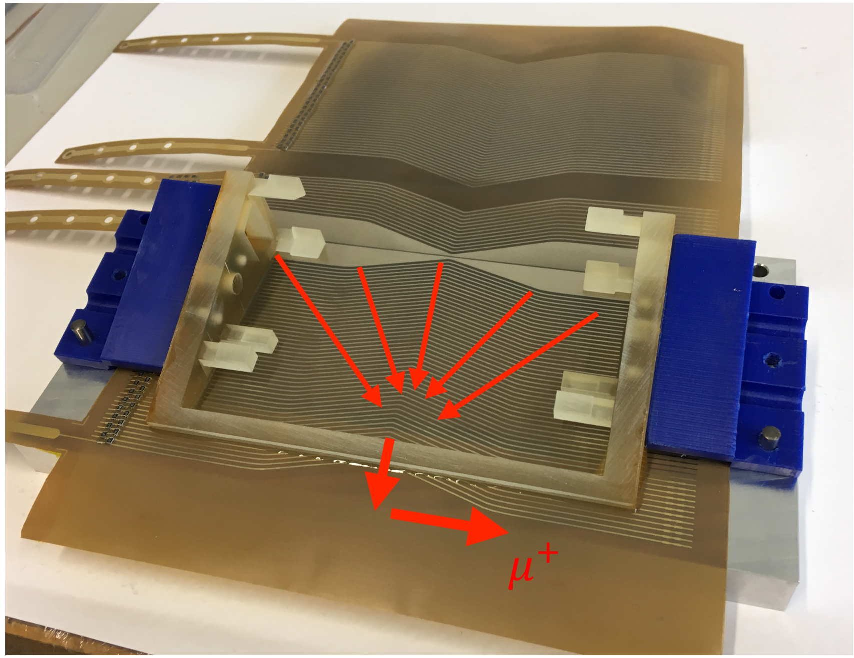


Next steps?

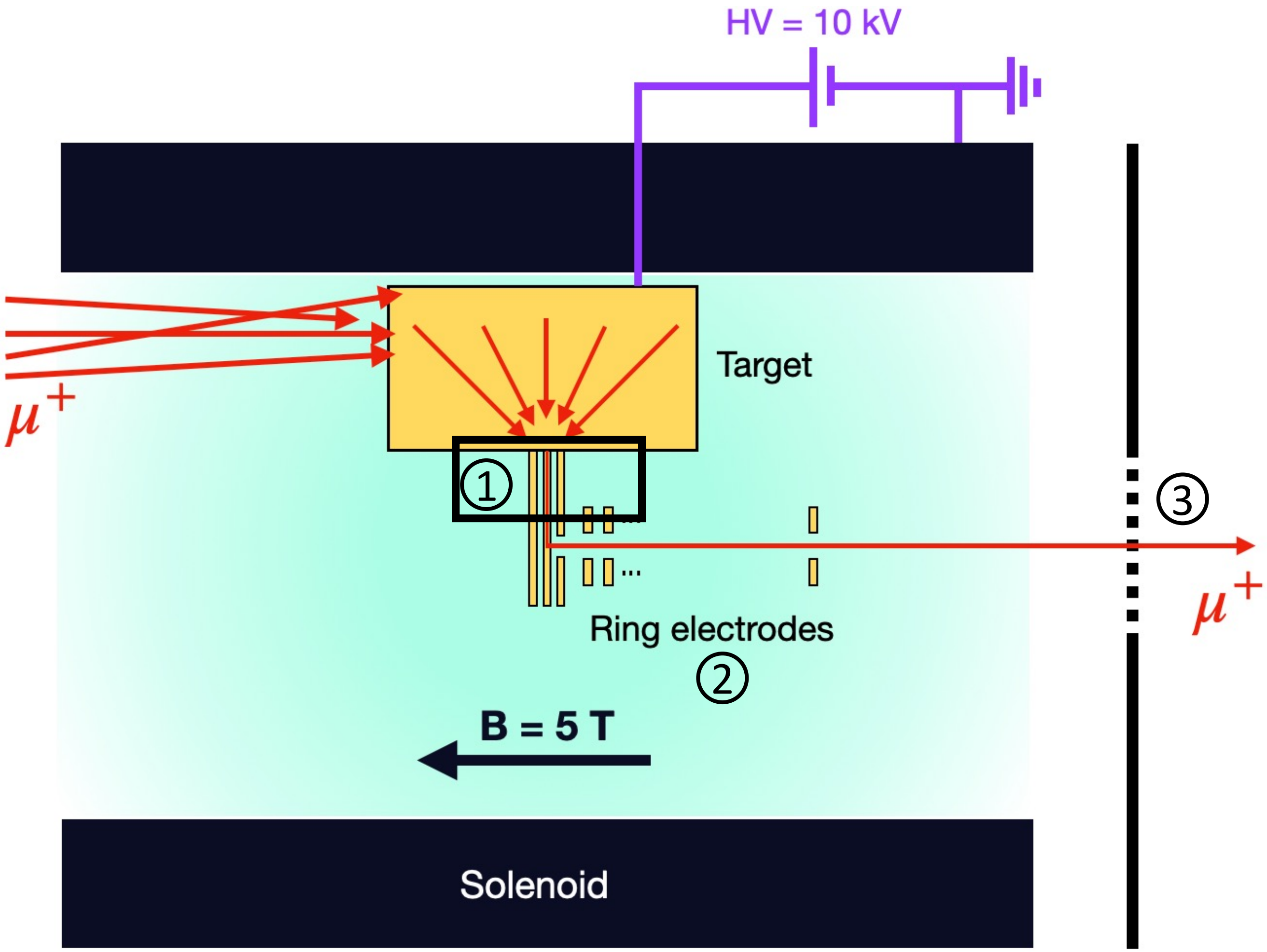
① **Muon extraction from gas target into vacuum via tiny orifice (eV energy muons)**

② Re-acceleration to 10 keV

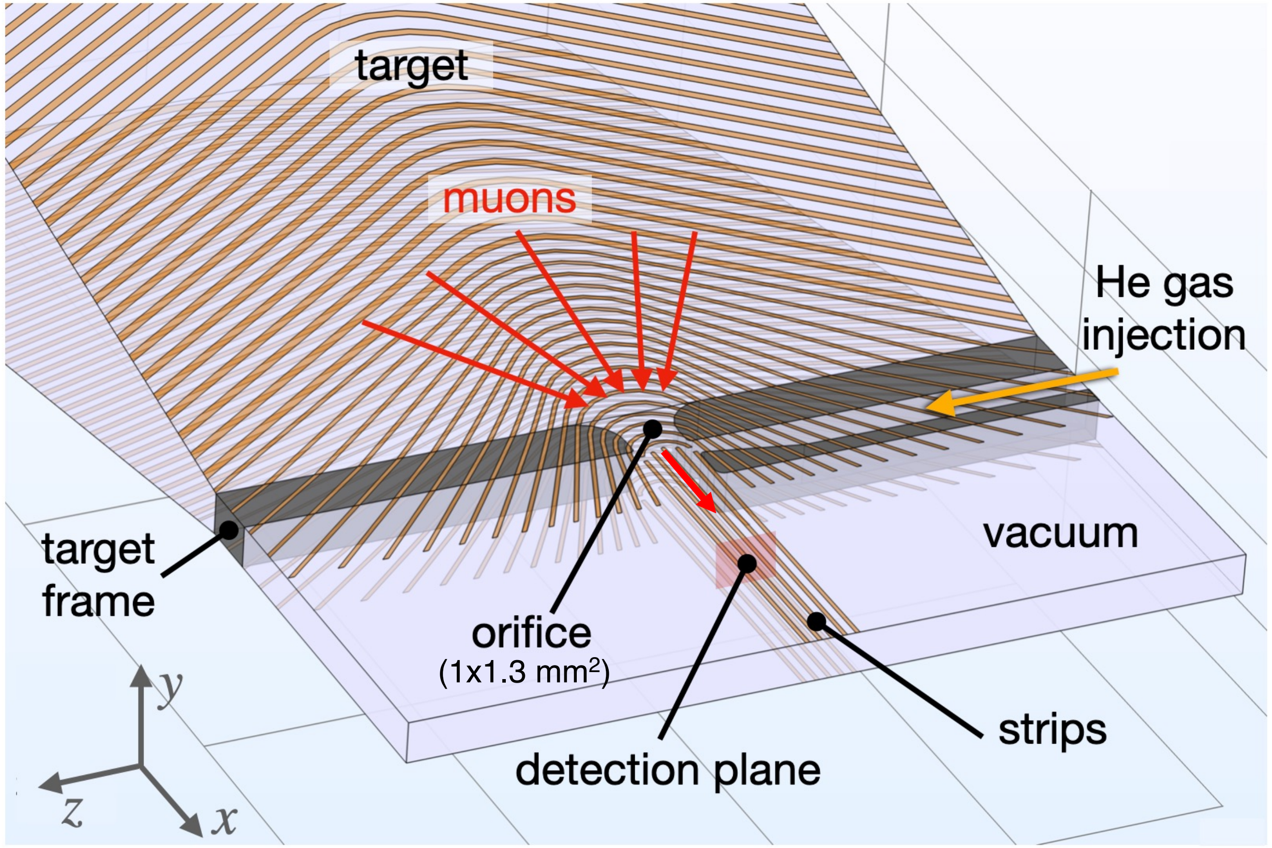
③ Extraction from 5T solenoid

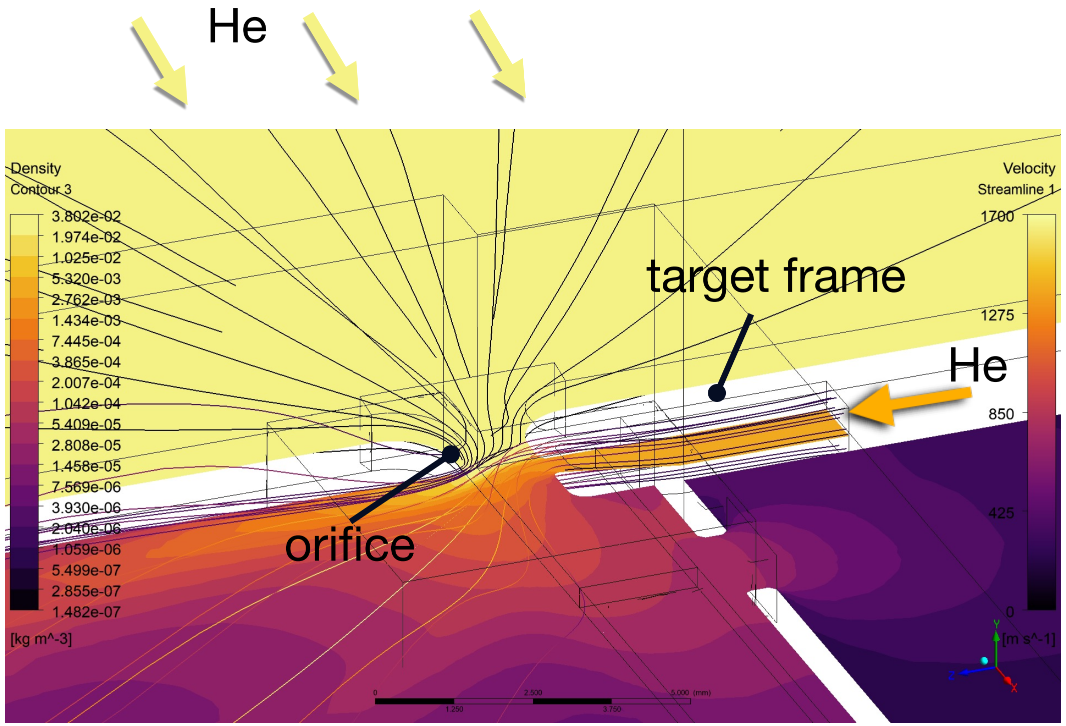


Make a hole and extract muons



Muon extraction from gas target into vacuum

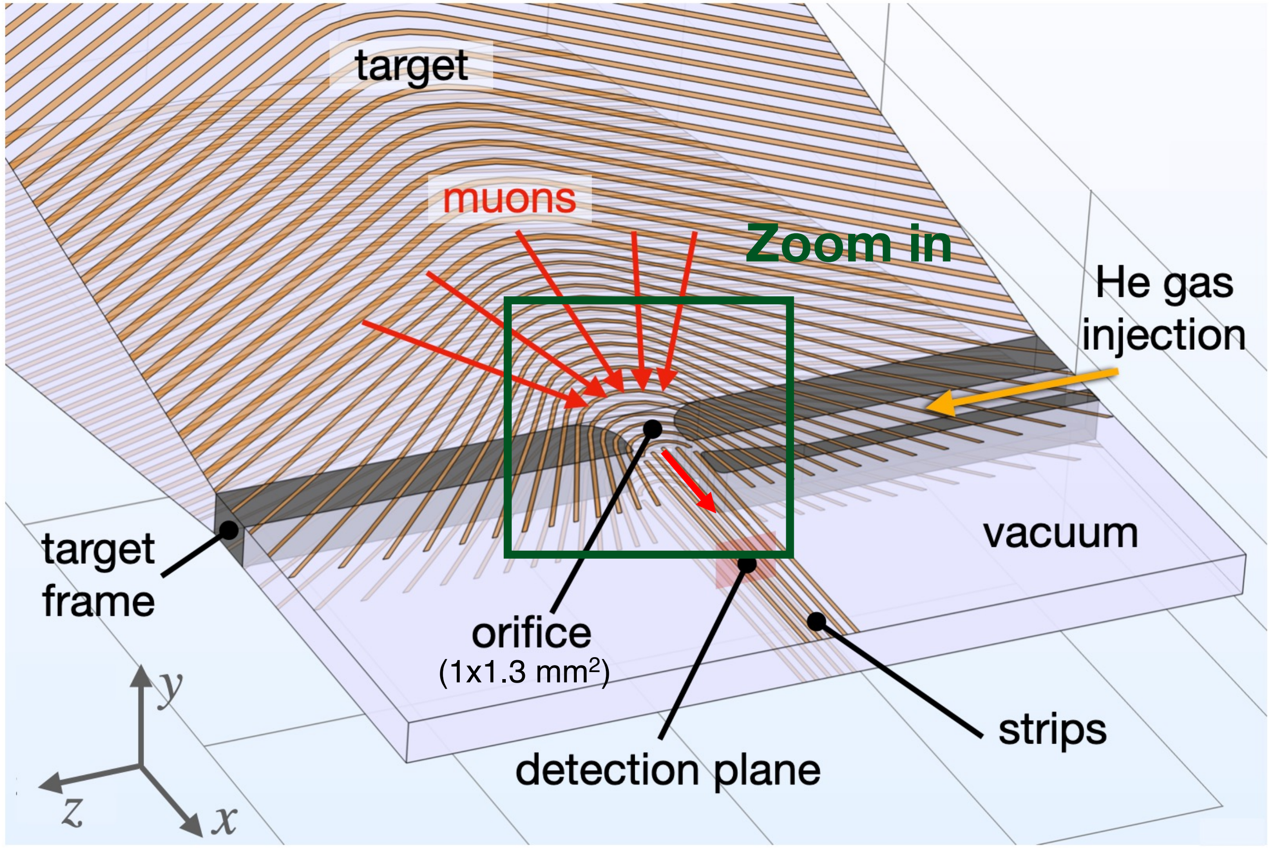


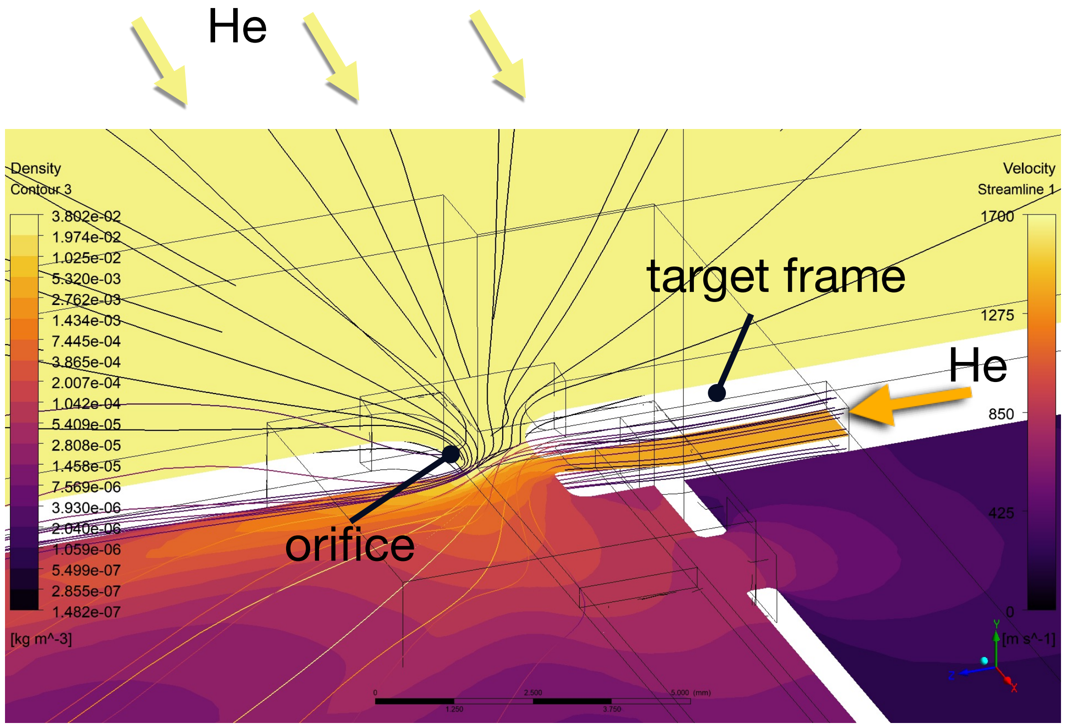


He gas injected from

- *the back-wall of the target*
- *the side: $\perp$ to $\vec{v}_D$ of muons*

Muon extraction from gas target into vacuum

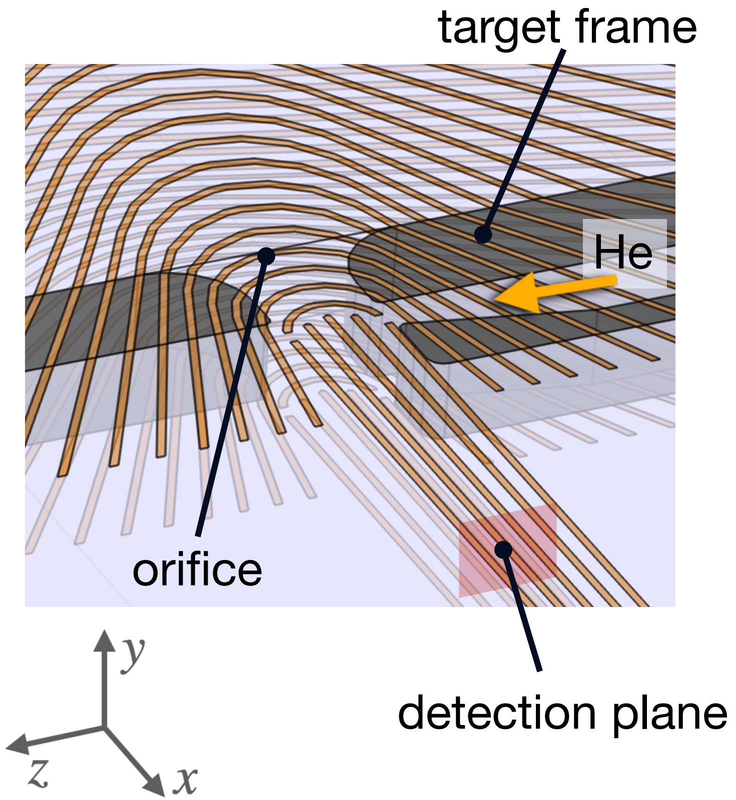


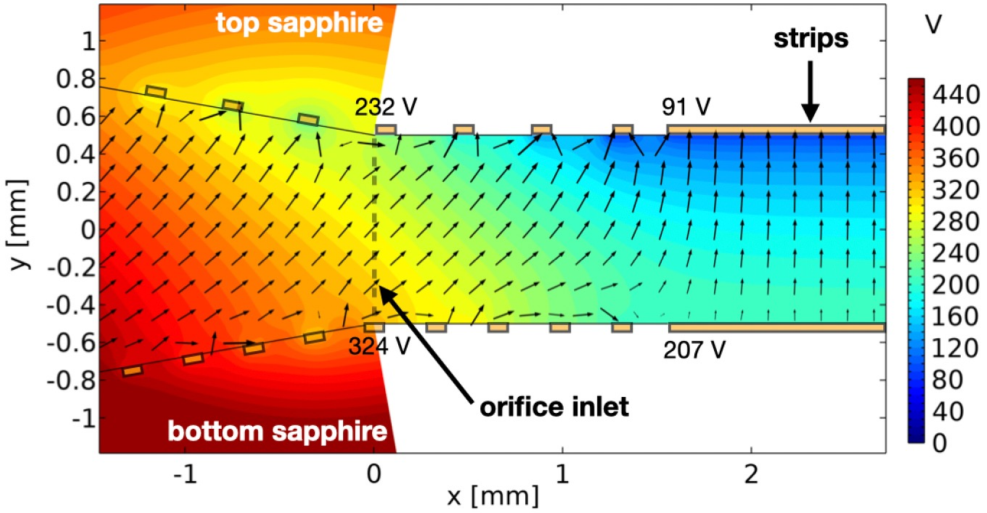


He gas injected from

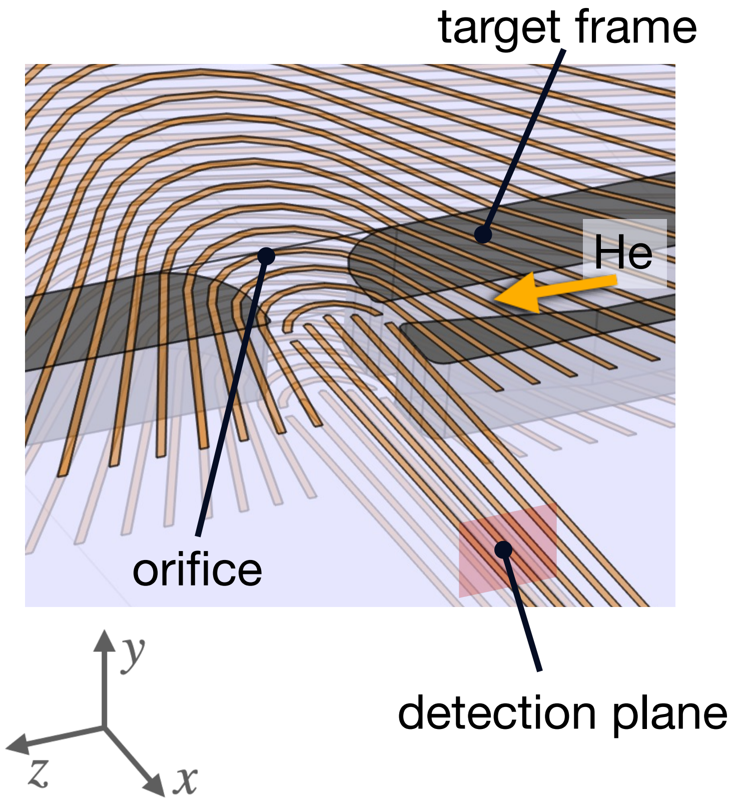
- *the back-wall of the target*
- *the side: ⊥ to $\vec{v}_D$ of muons*

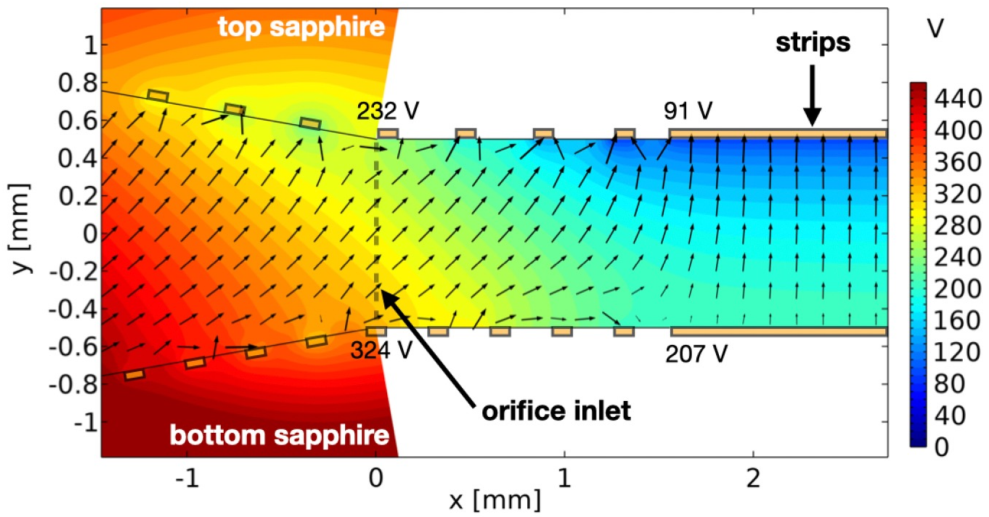
Electric field design

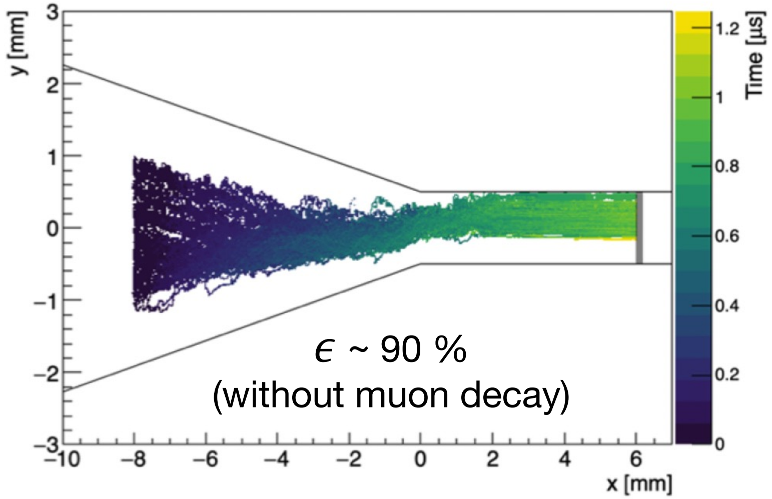


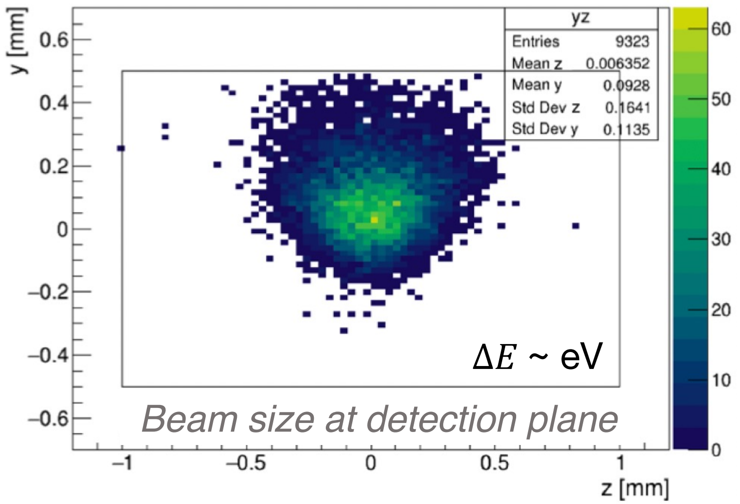


Electric field design and Geant4 simulations

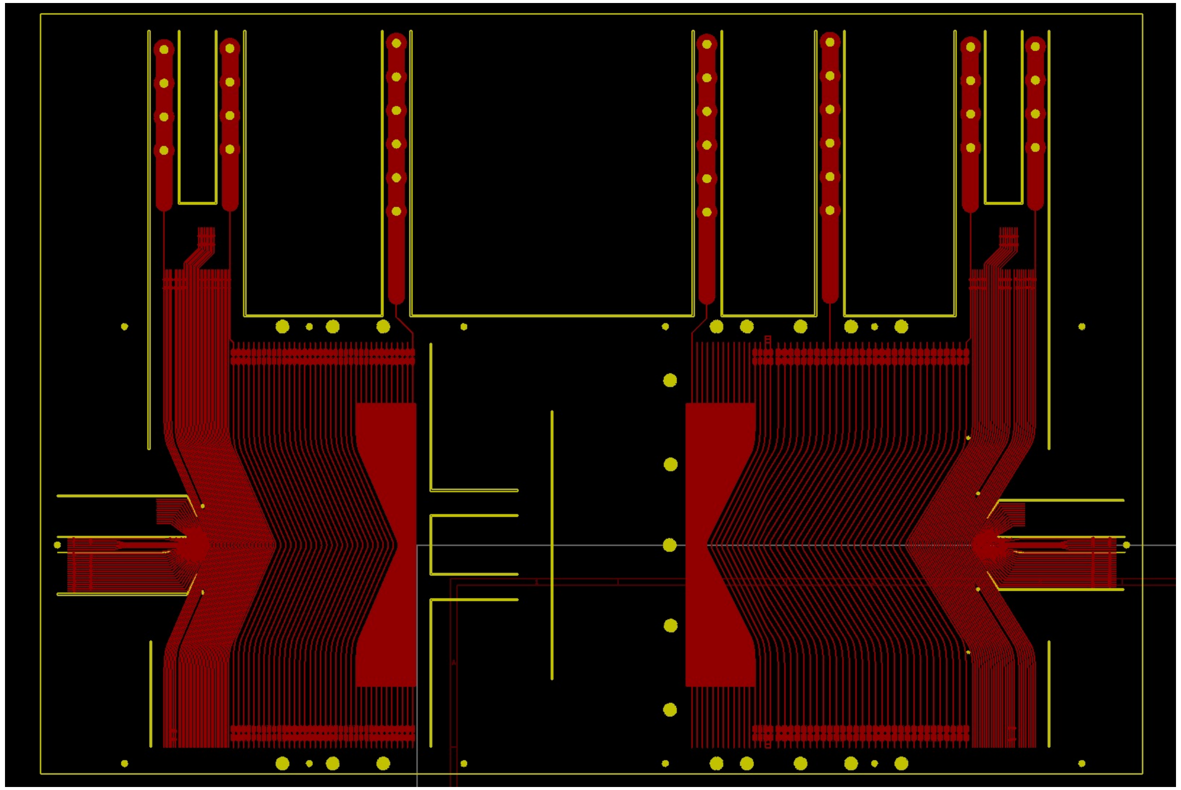




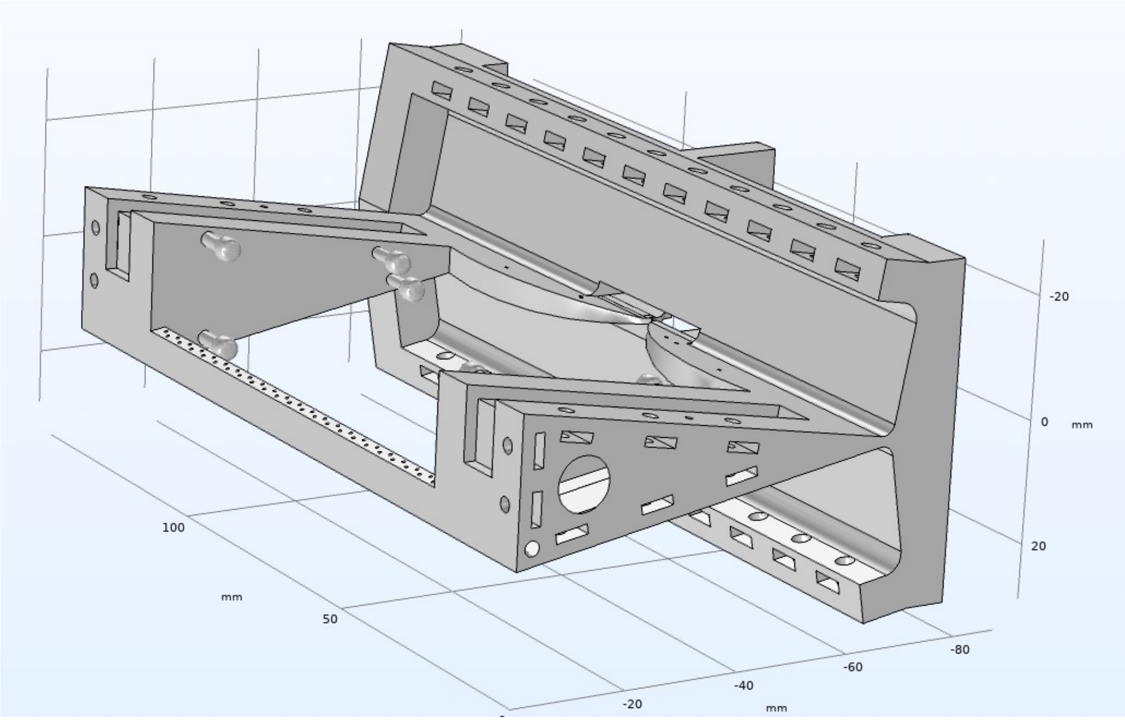




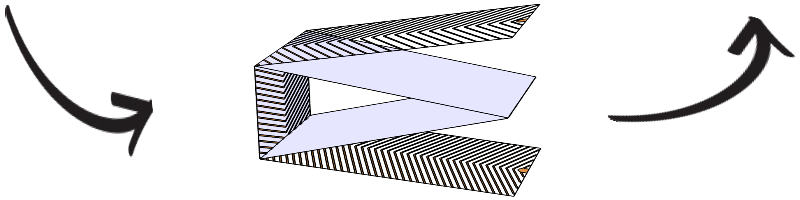
Target production



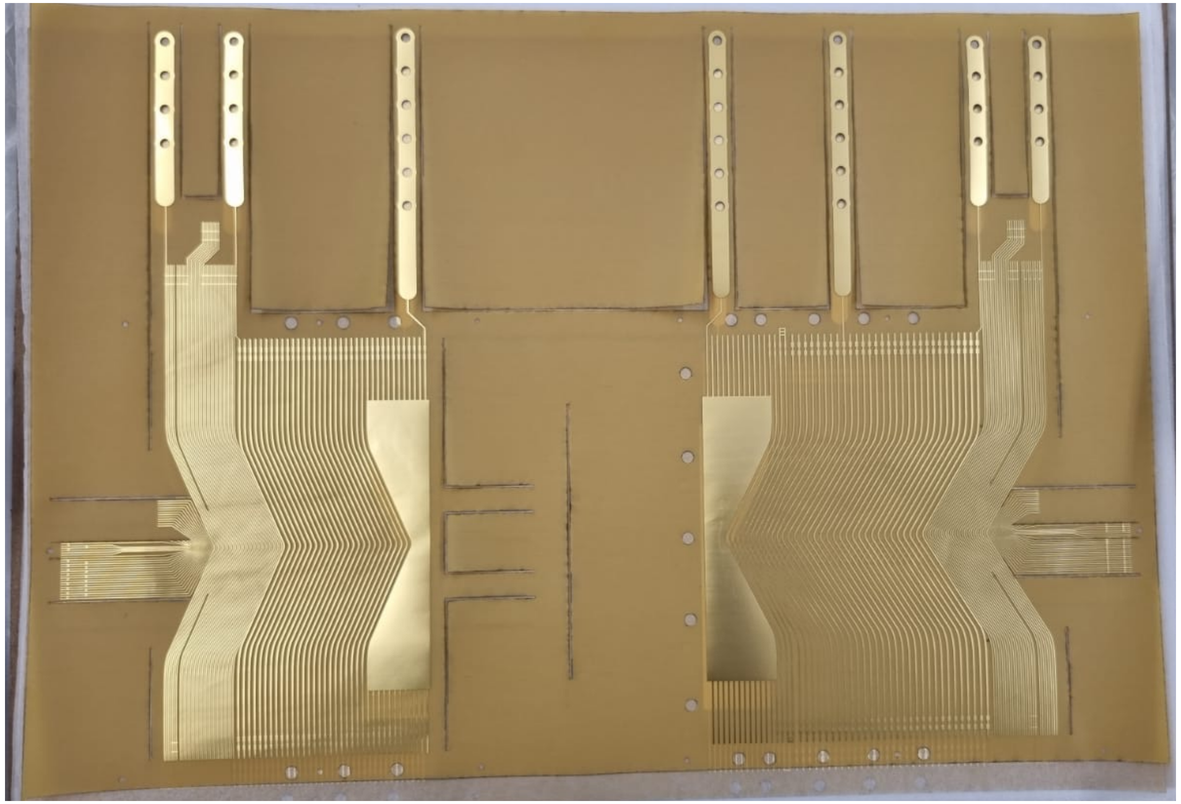
Electrode lines on Kapton foil



Target frame



Target production



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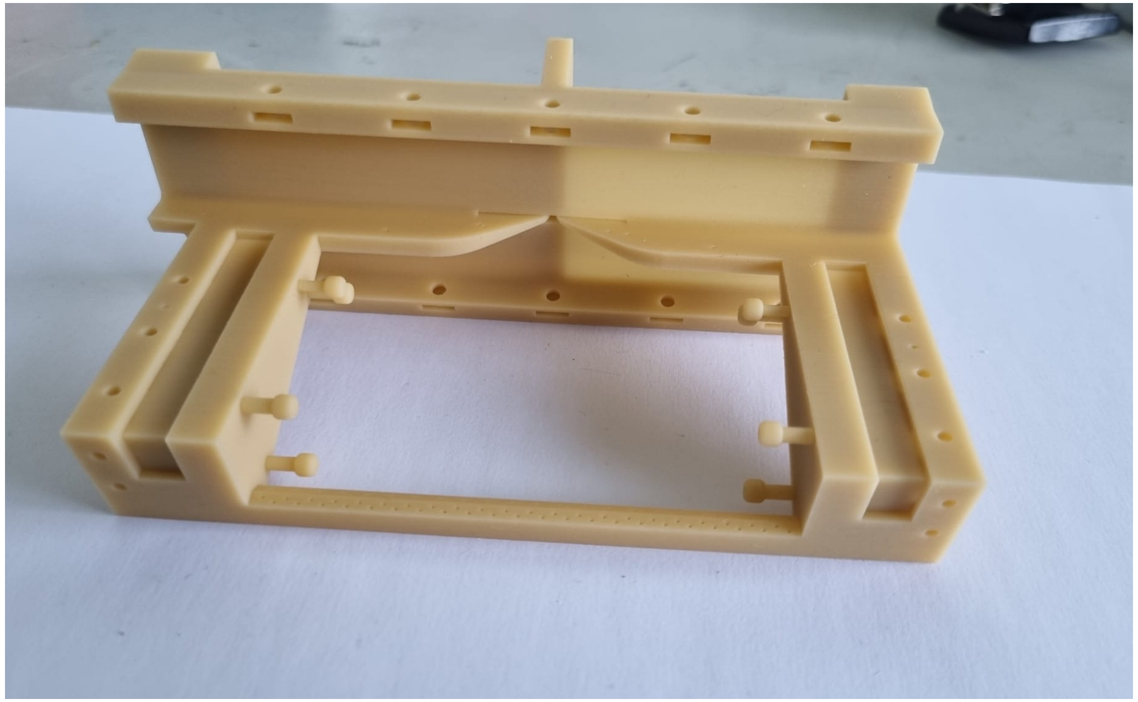
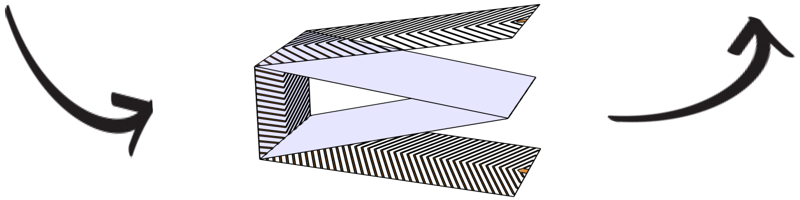


Target frame



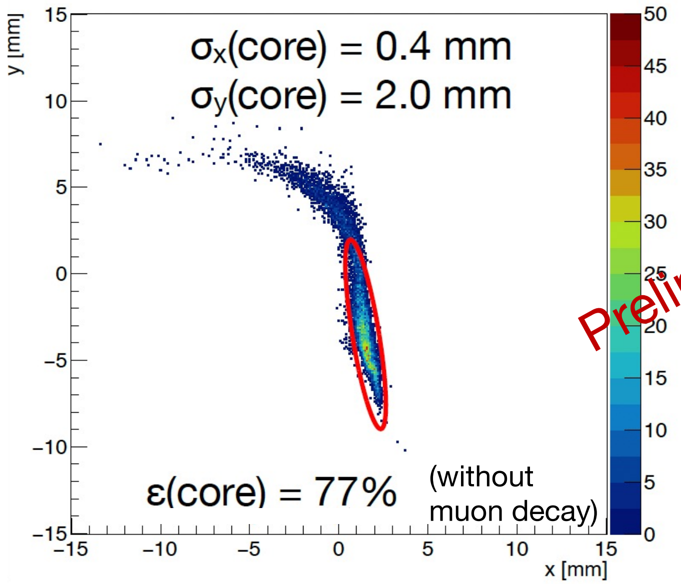
Next steps?

① Muon extraction from gas target into vacuum

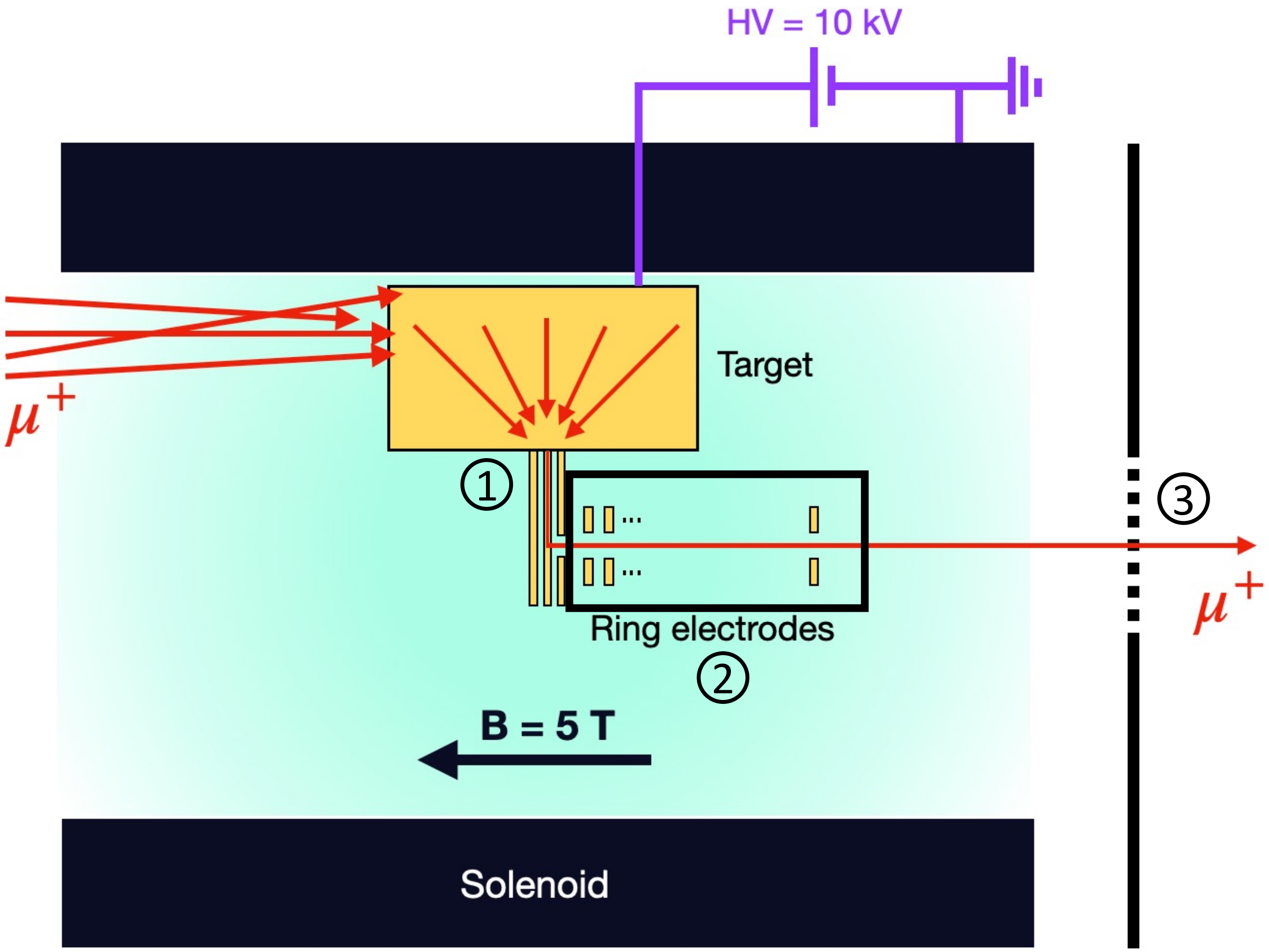
② **Re-acceleration to 10 keV**

③ Extraction from 5T solenoid

At **B = 0.1 T**



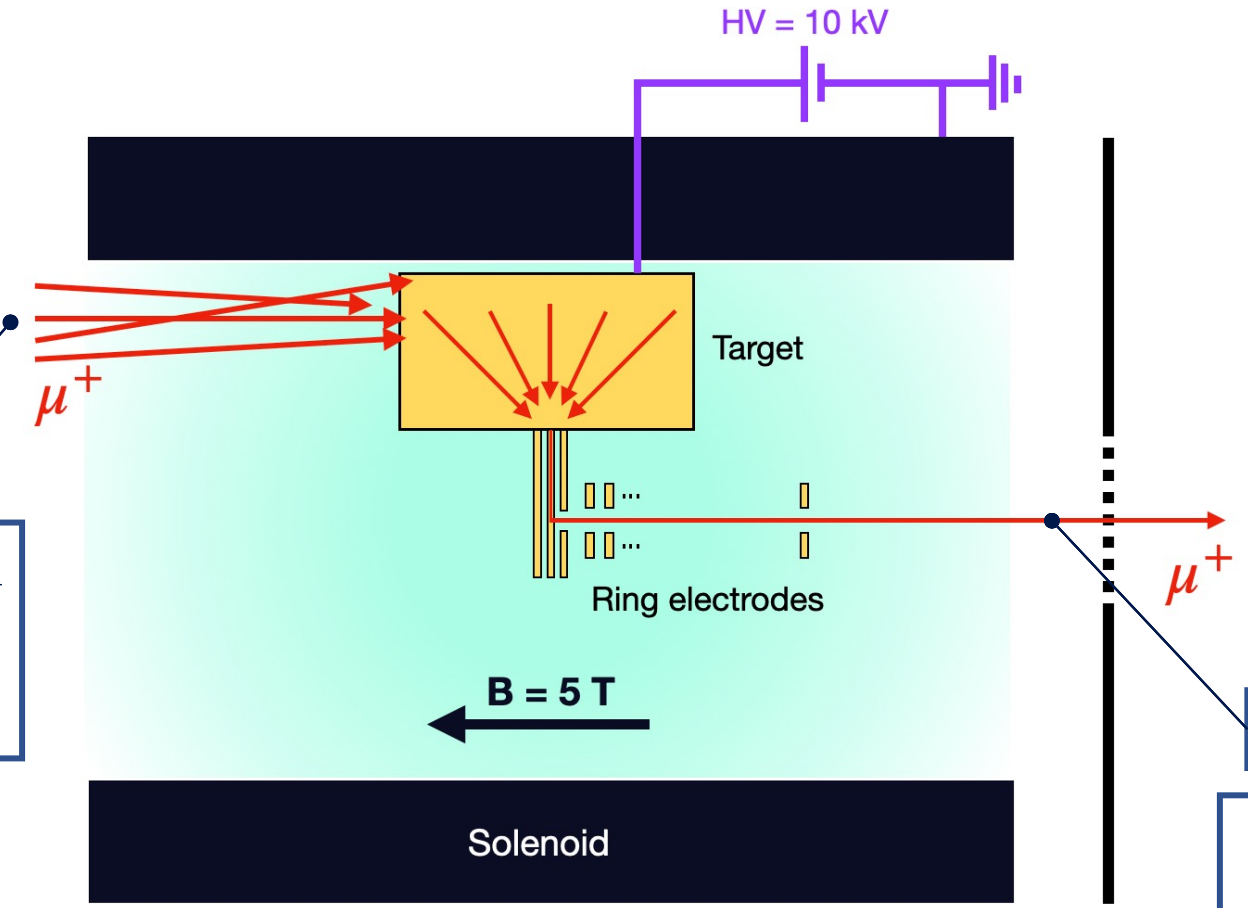
$\Delta E \approx 50$ eV



M. Sakurai. *PhD thesis (ETH Zurich)* **(2023)**

Efficiency estimates

HIMB rate $10^{10}\ \mu^+$/s



IN

$\sigma_x\sigma'_x \approx \sigma_y\sigma'_y \approx 2000\ \text{mm}\cdot\text{mrad}$

$E = 3.6$ MeV

$\Delta E = 0.34$ MeV $(1\ \sigma)$

OUT

$\sigma_x\sigma'_x \approx 1.3\ \text{mm}\cdot\text{mrad}$

$\sigma_y\sigma'_y \approx 11.3\ \text{mm}\cdot\text{mrad}$

$E = 10$ keV

$\Delta E \leq 100$ eV $(1\ \sigma)$

Preliminary

Efficiency $\geq \mathbf{3 \cdot 10^{-5}}$

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: target development ongoing

Summary

- muCool proposes a “fast” phase space compression scheme for μ+ beam for future low energy experiments
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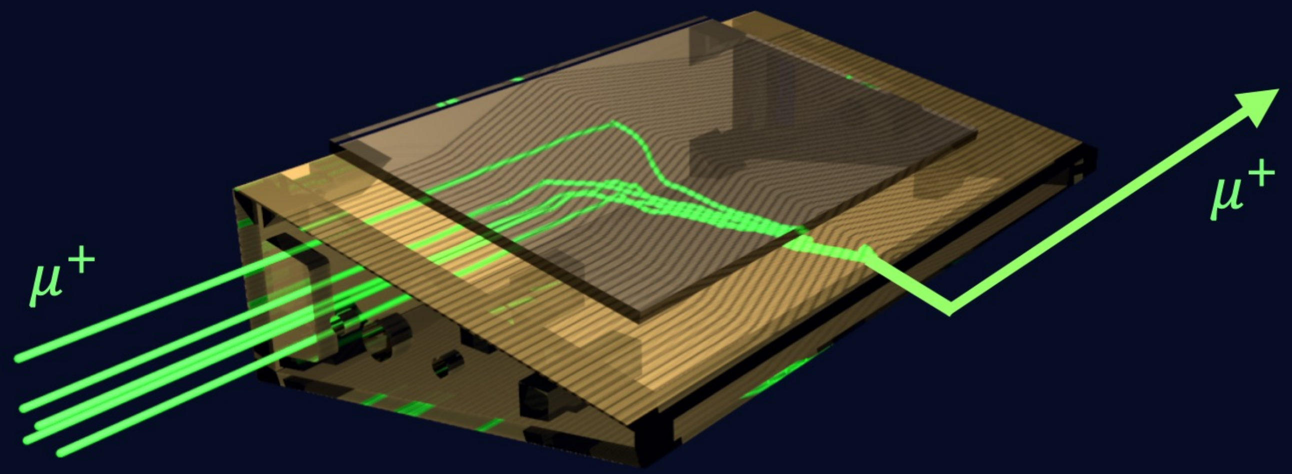
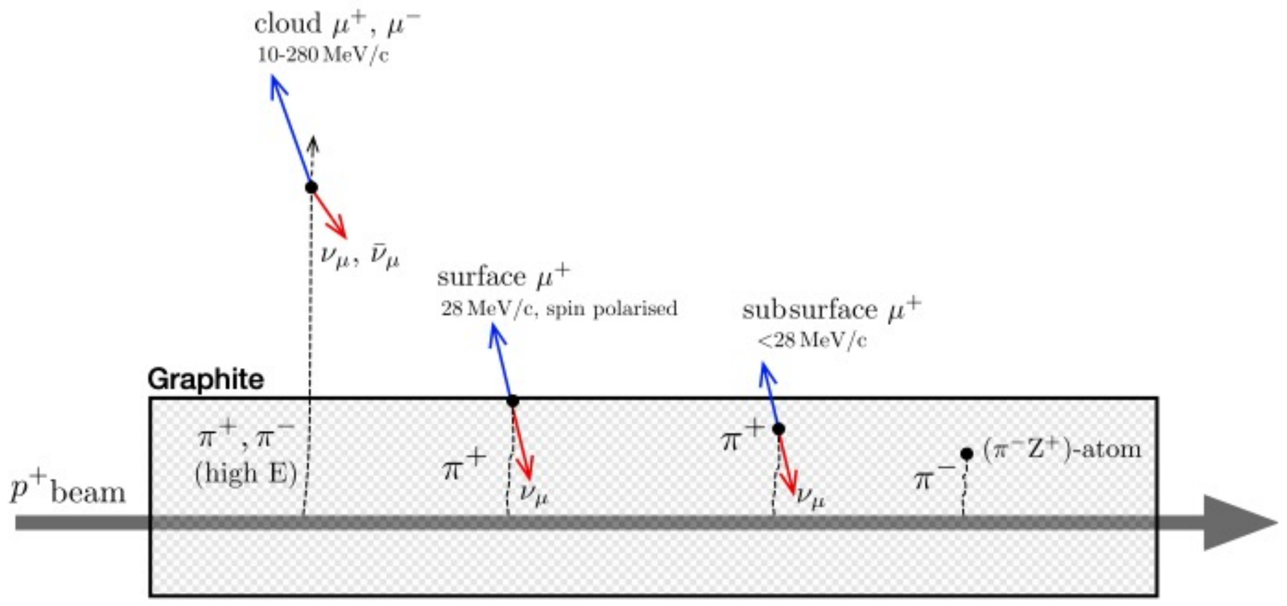
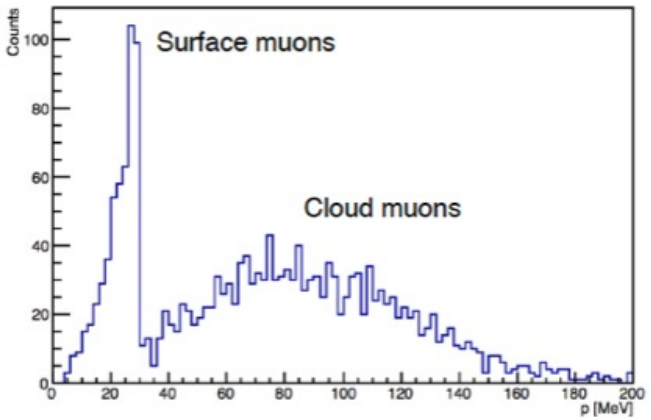


Thank you!

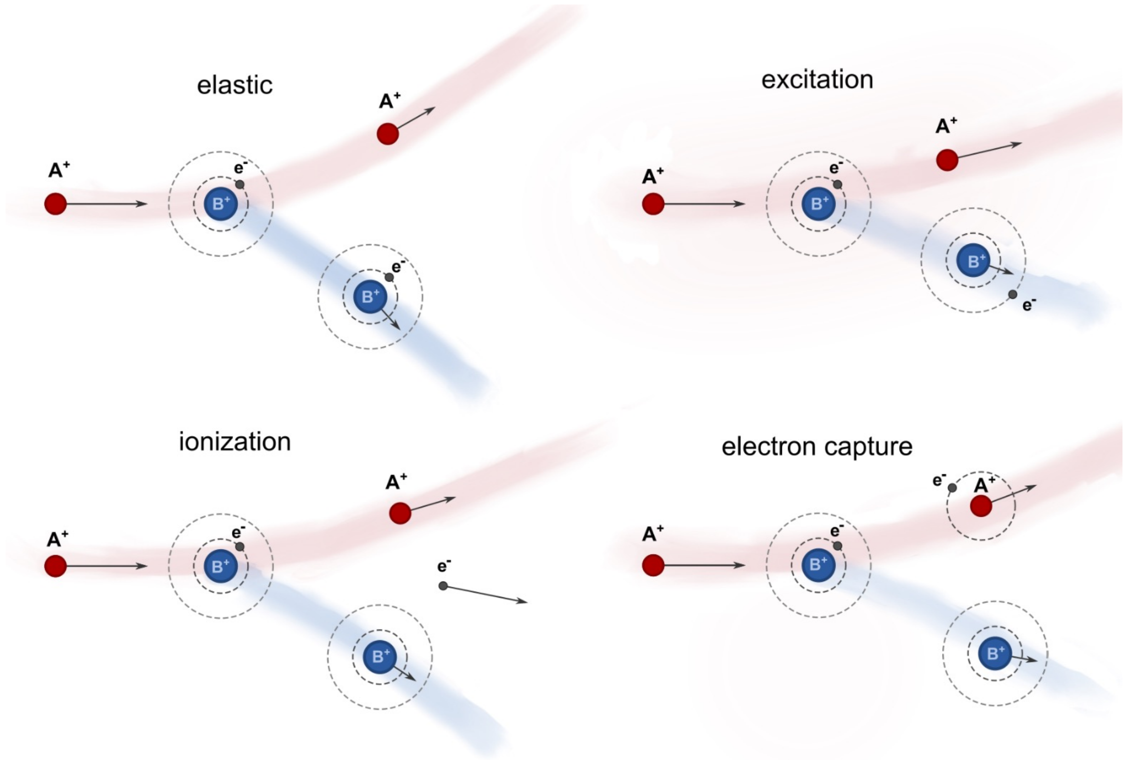
EXTRA SLIDES

Muon production

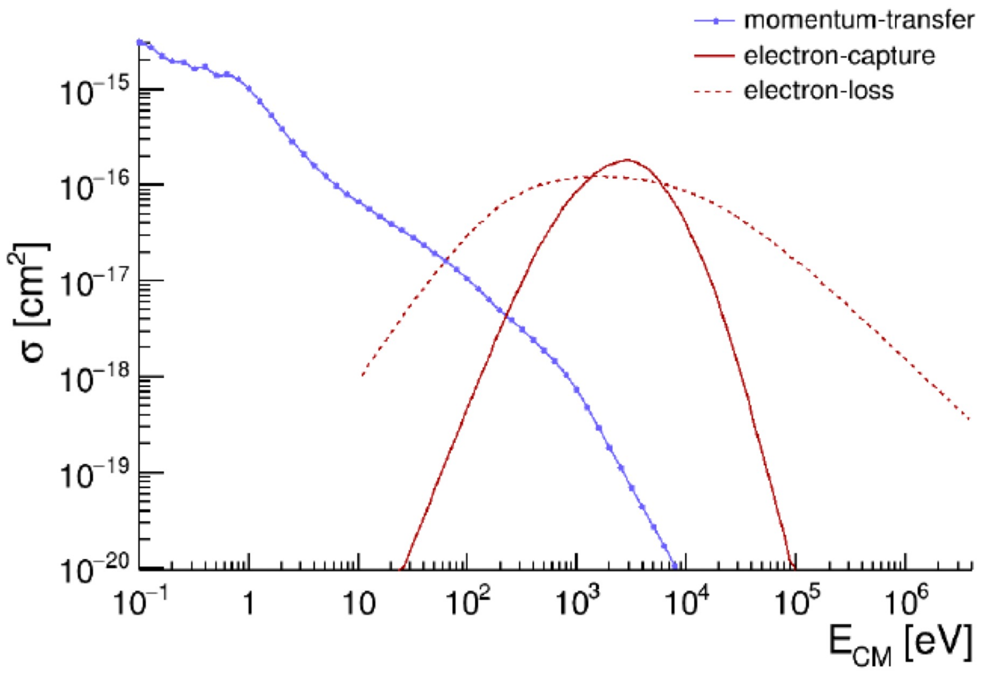




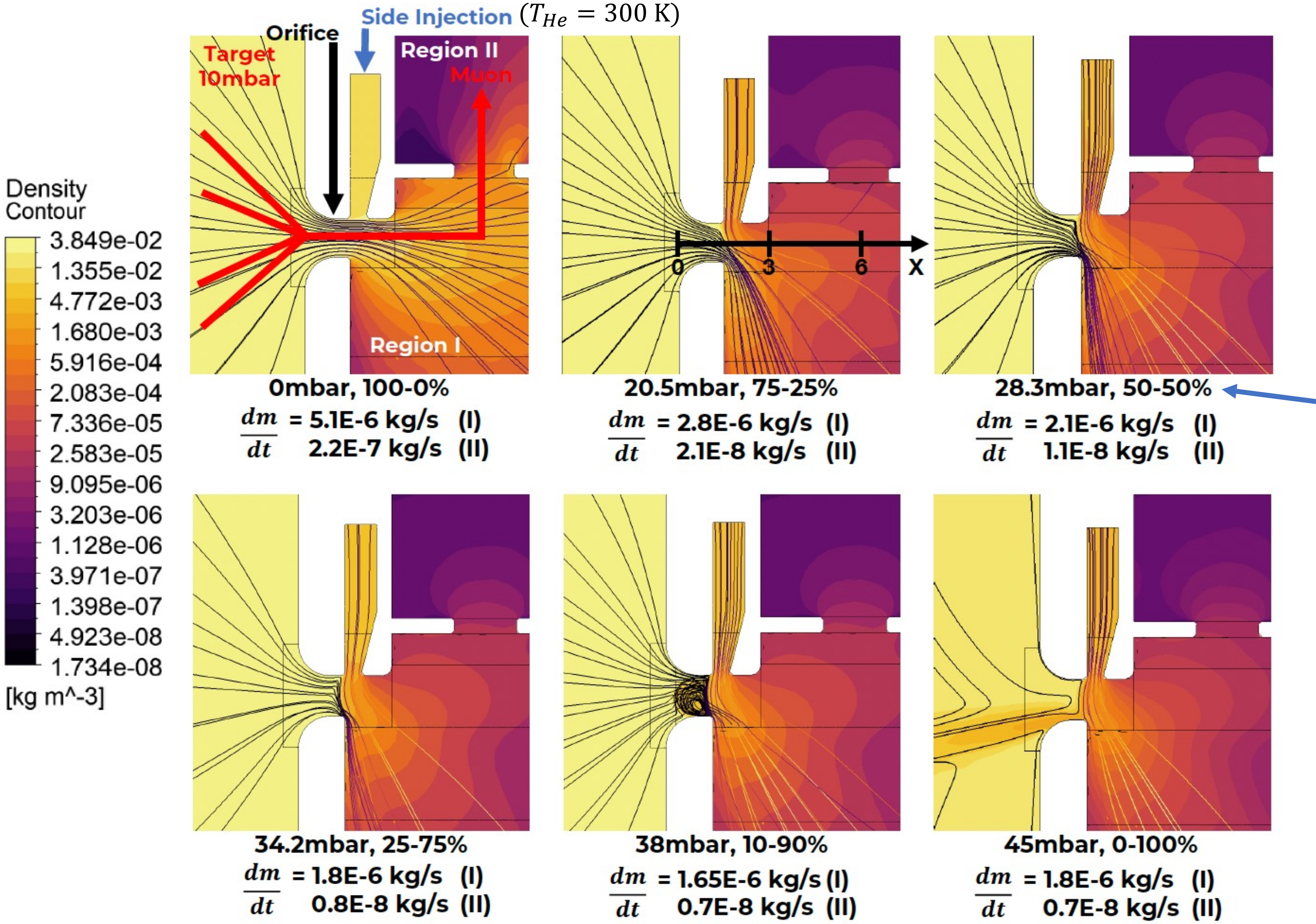
Muon-helium collisions



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

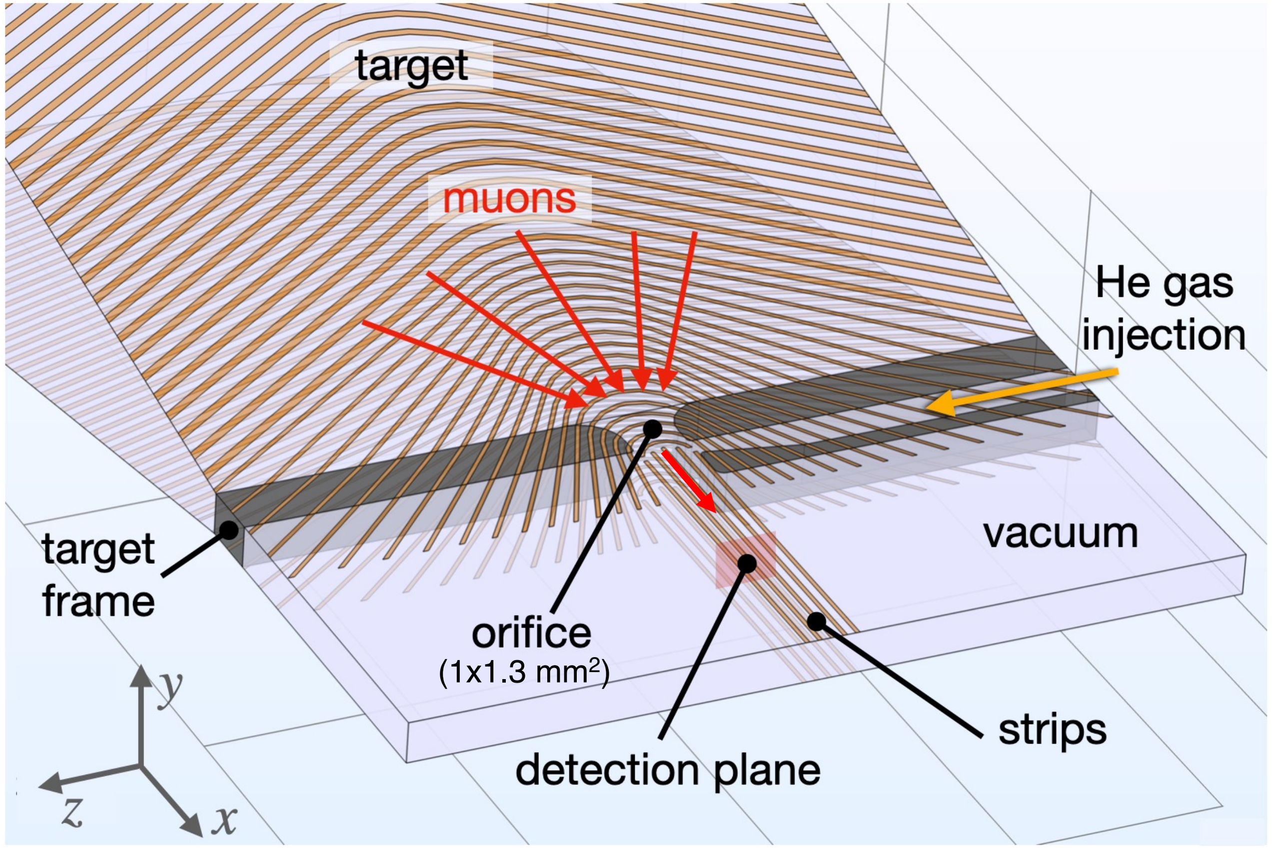


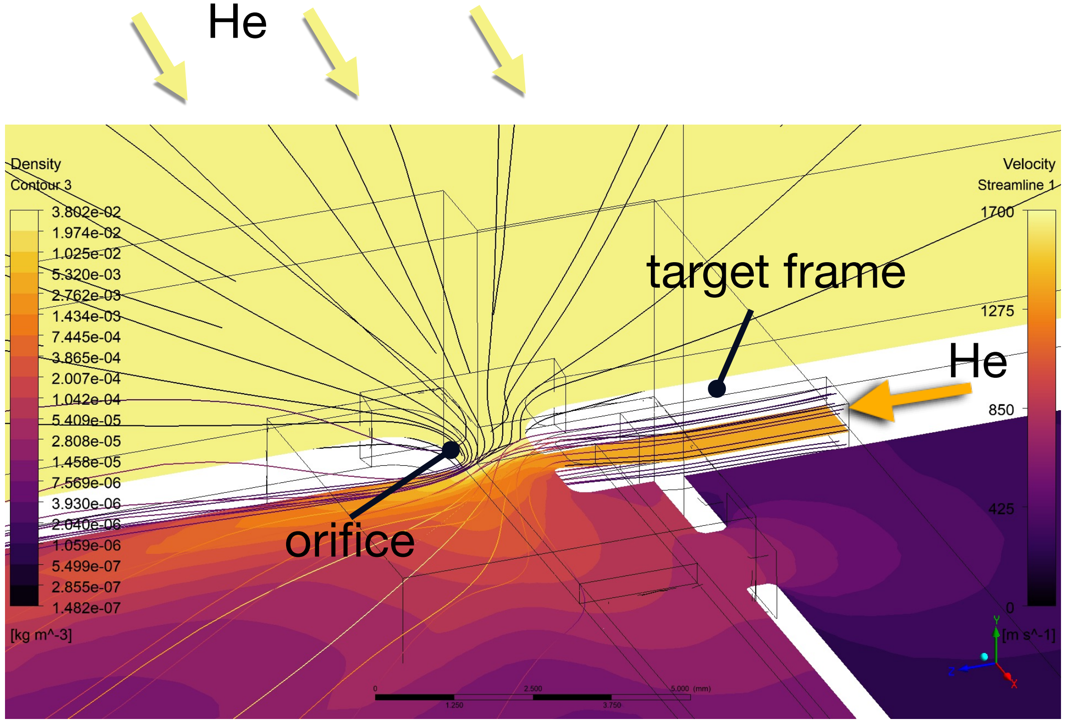
He gas injection schemes



different partitioning between back- and side-injections

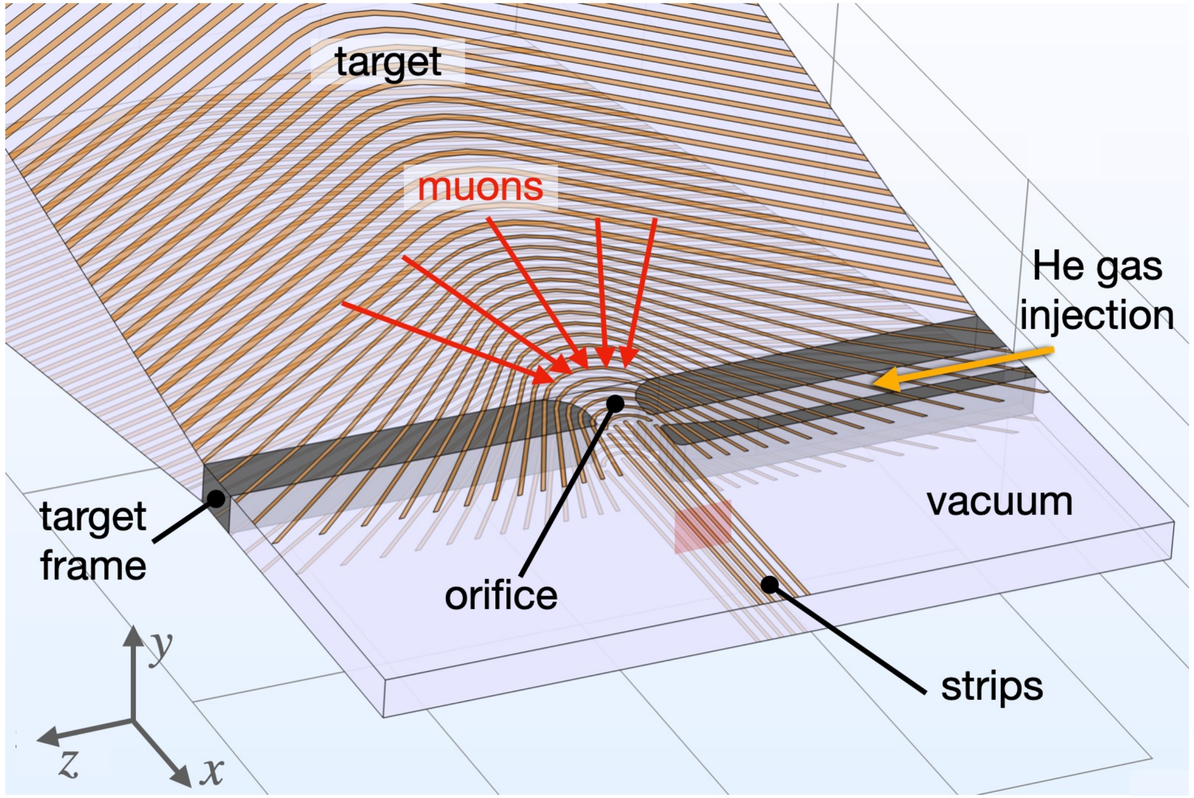
Muon extraction from gas target into vacuum

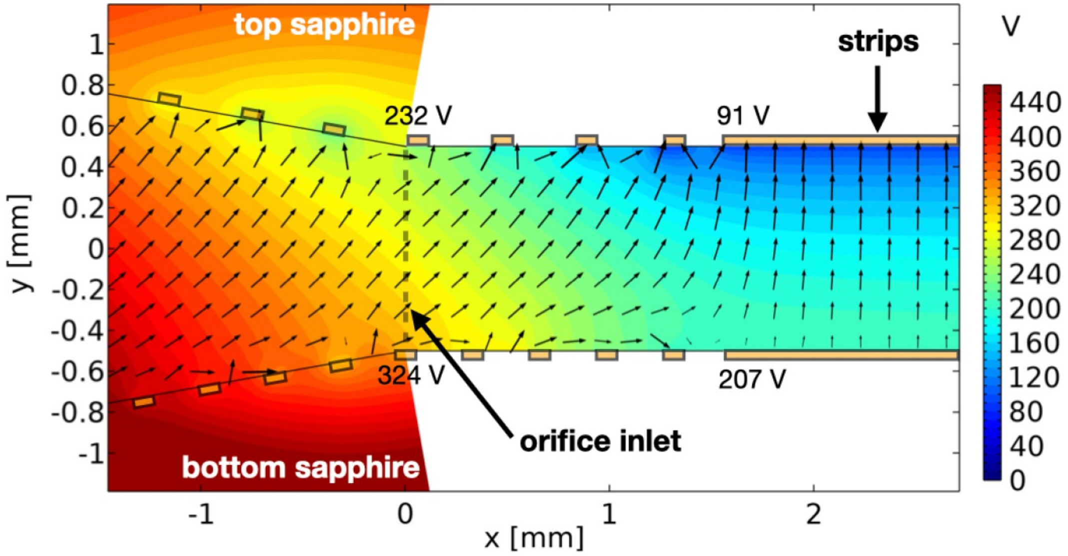


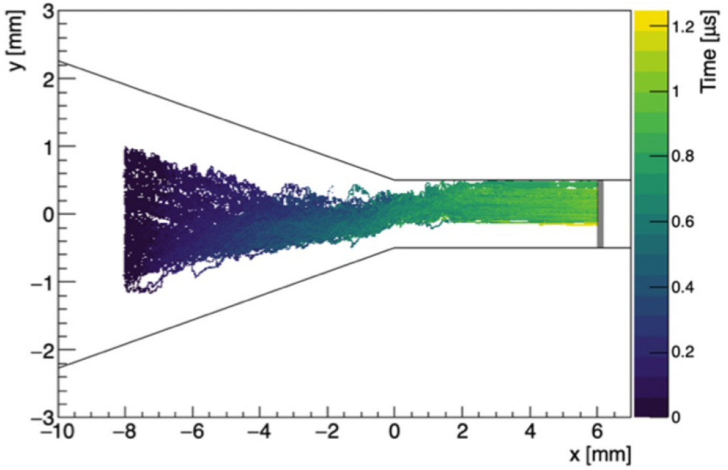


He gas density simulations with 65% back-injection and 35% side-injection

Extraction: xy plane

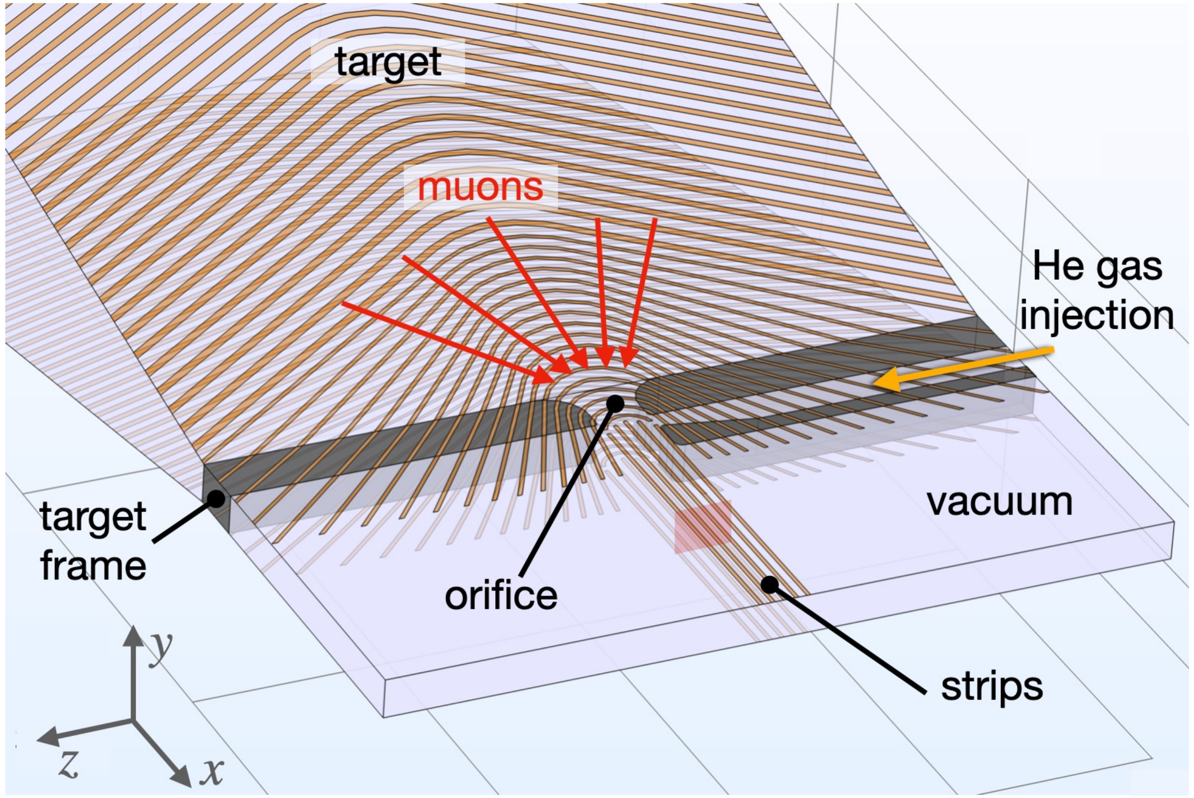


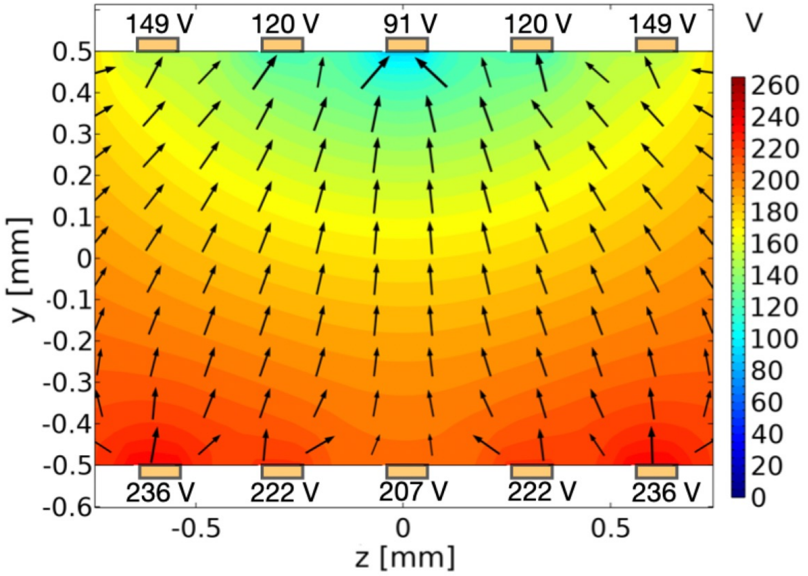


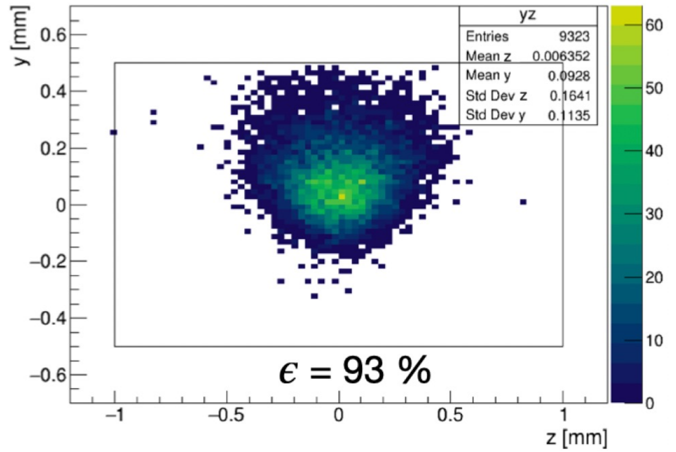


Position the parallel strips at x point where density drops sufficiently, i.e. drift angle in $\vec{E} \times \vec{B}$ *tends to 0*

Extraction: zy plane







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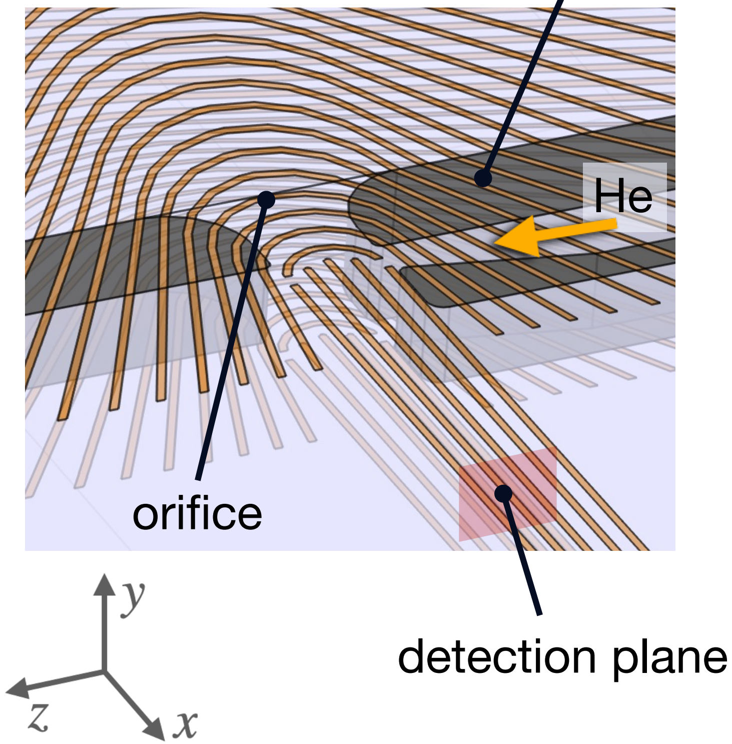
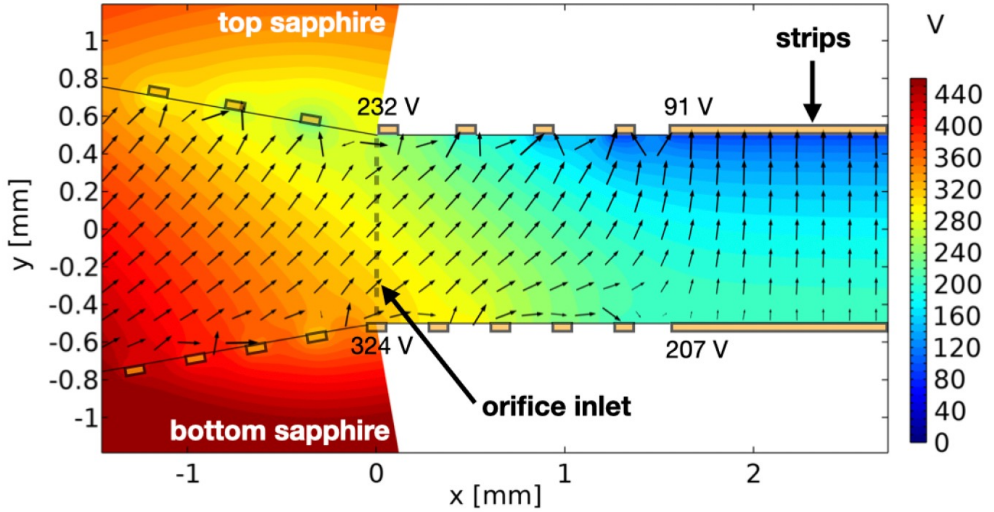
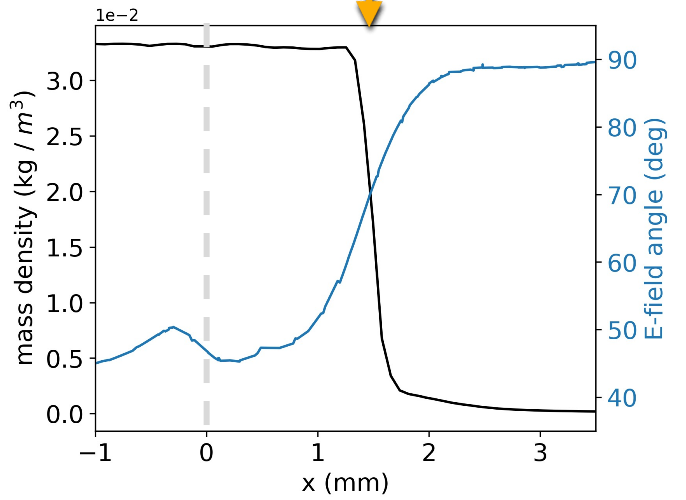
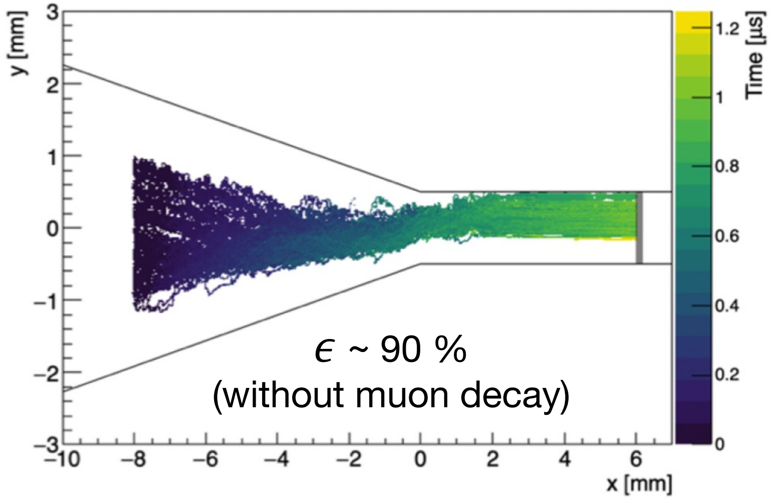
Electric field design and Geant4 simulations

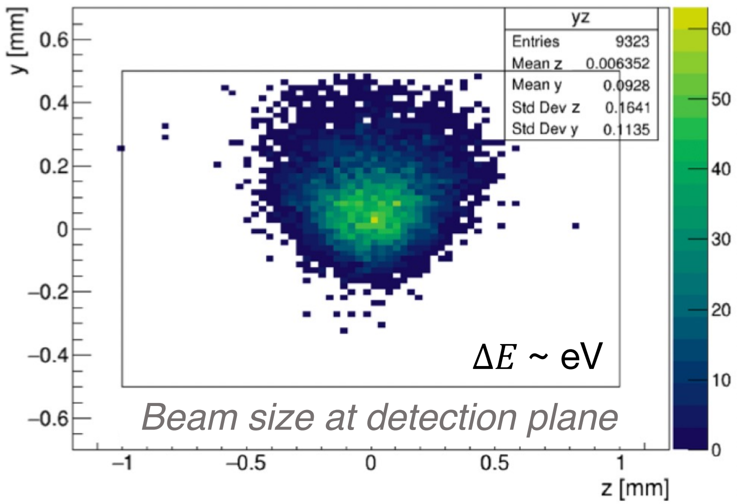








ϵ ~ 90 %
(without muon decay)



ΔE ~ eV

Beam size at detection plane

Preliminary conclusions

Baseline Efficiency	Possible Improvements	Description
$5.5 \cdot 10^{-1}$		Coupling to 5T solenoid
$4.6 \cdot 10^{-1}$	$\times 2$	Into target entrance
$6 \cdot 10^{-3}$	$\times 1.6$	Stopping in He gas
$8 \cdot 10^{-2}$	$\times 1.5$	Compression towards orifice ($5\ \mu s$)
$9 \cdot 10^{-1}$		Extraction from orifice
$5 \cdot 10^{-1}$		Drift to re-acceleration region ($0.5\ \mu s$)
$8 \cdot 10^{-1}$		Re-acceleration up to iron grid
$7 \cdot 10^{-1}$		Transmission to B-field free region
$\mathbf{3 \cdot 10^{-5}}$	$\times 4.8$	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

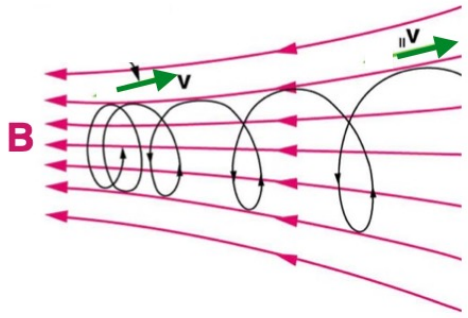
M. Sakurai. *PhD thesis (ETH Zurich)* **(2023)**

Extraction from B-field

- Charge particles follow magnetic field lines

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

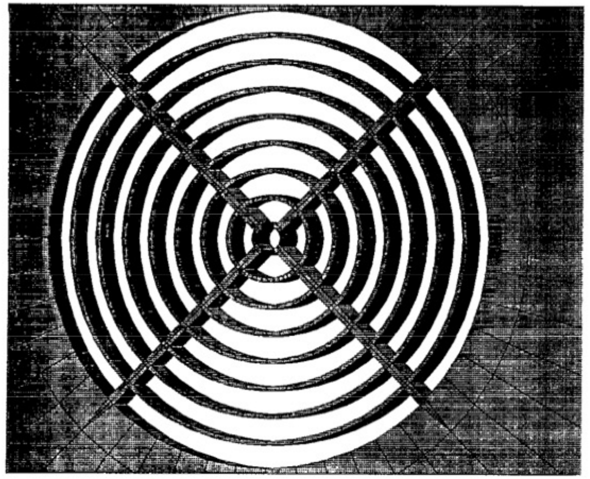
$$\Delta E_{\perp i} \sim \Delta E_{\perp 0} \frac{B_i}{B_0}$$



- 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

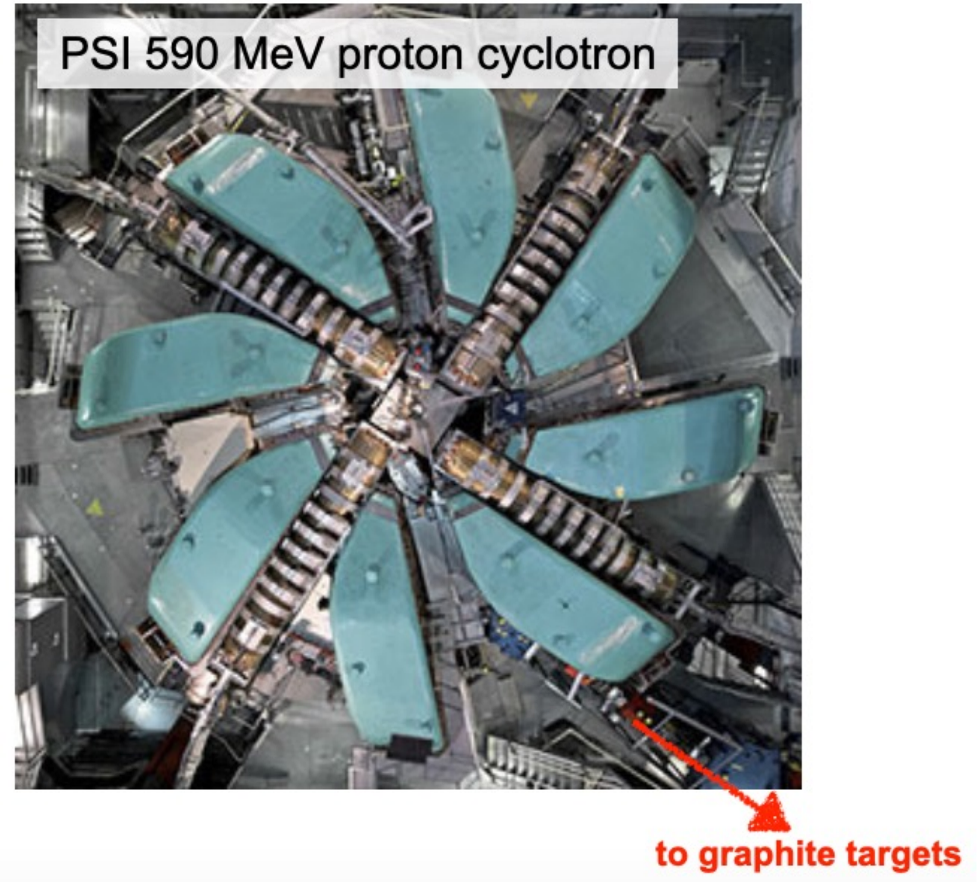
$$\Delta p_\perp = e \int_0^t v_z B_\perp dt \sim \frac{ewB_i}{2} \quad ,$$

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



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

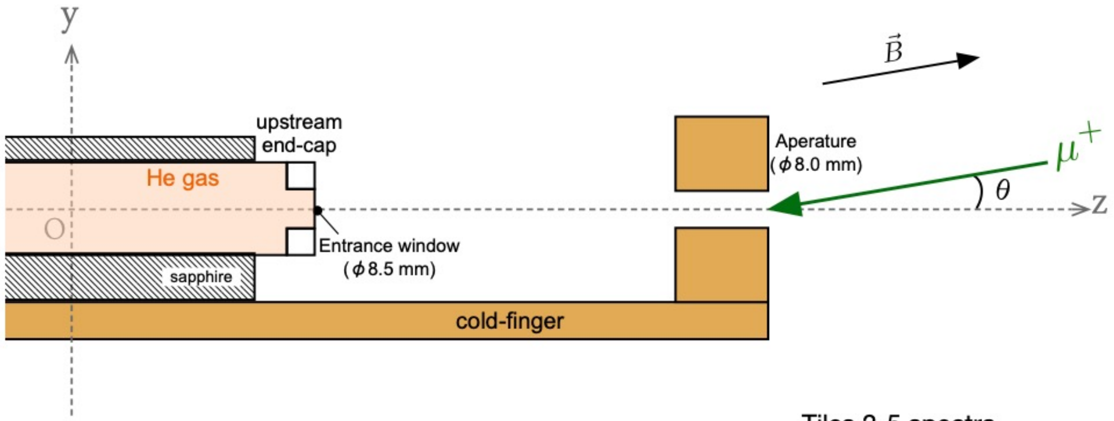
  100 MHz at 28 MeV/c

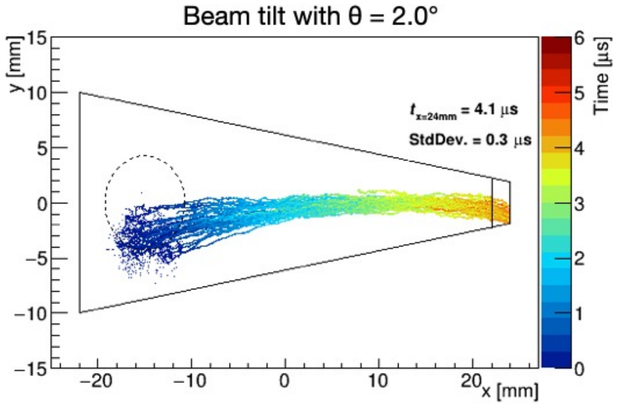
  $\sigma_x \sim 1$ cm

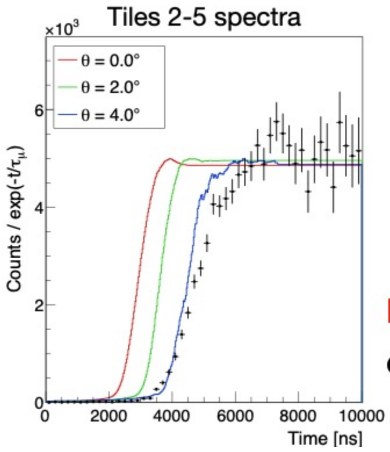
  $\sigma_E \sim 0.5$ MeV

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