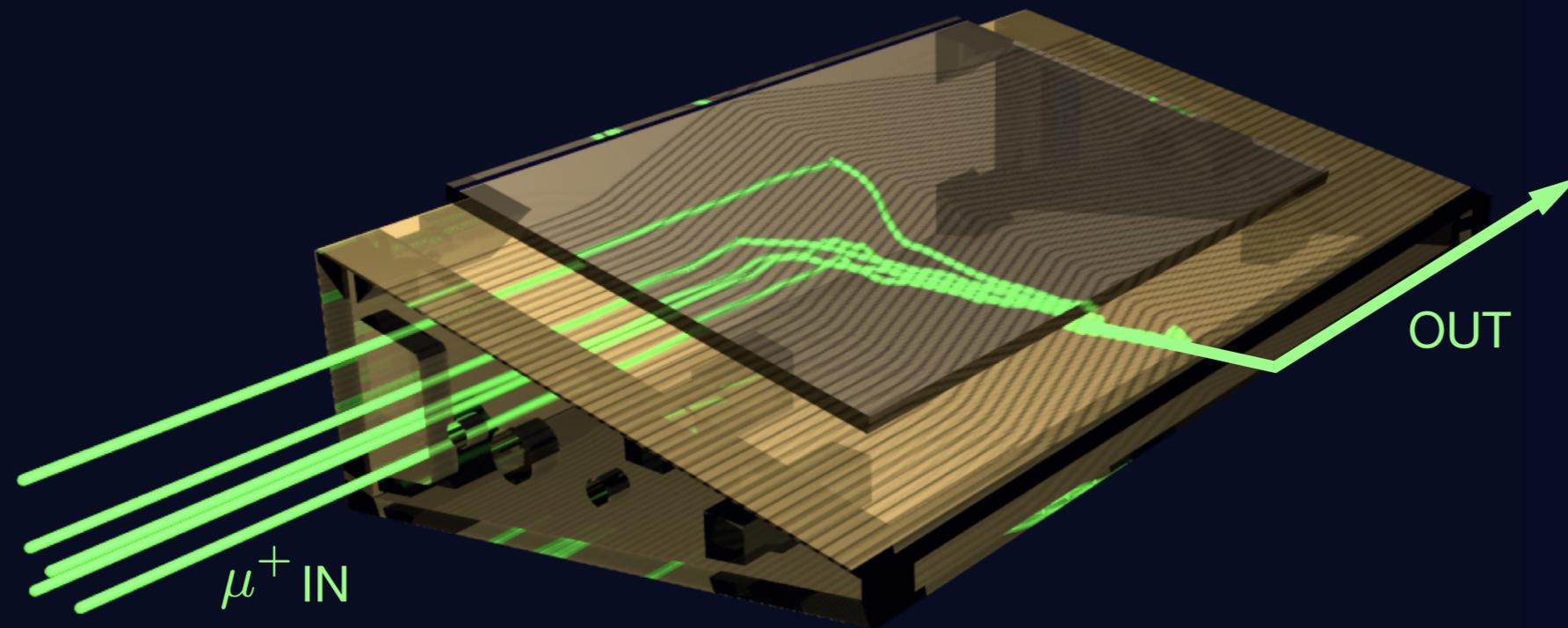


# muCool: simulation studies on the HIMB-muCool coupling and re-acceleration



1

Mikio Sakurai

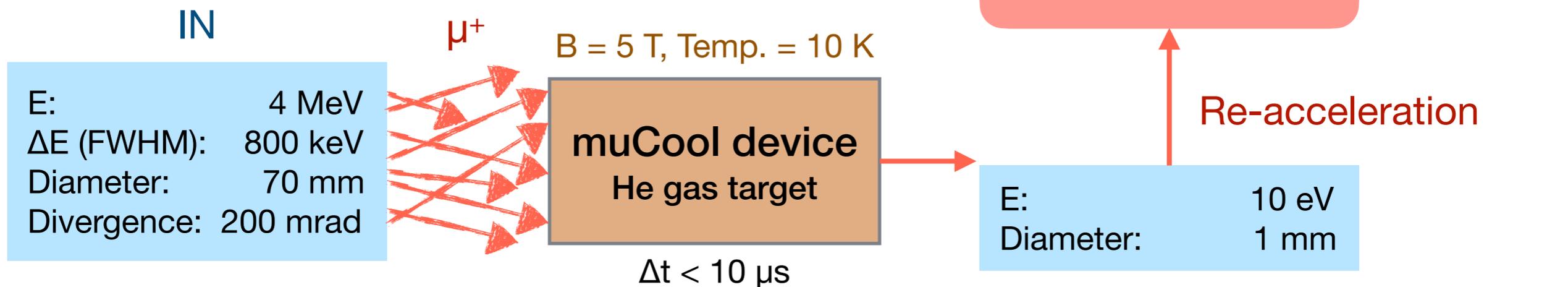
on behalf of the muCool collaboration

**ETH** zürich /

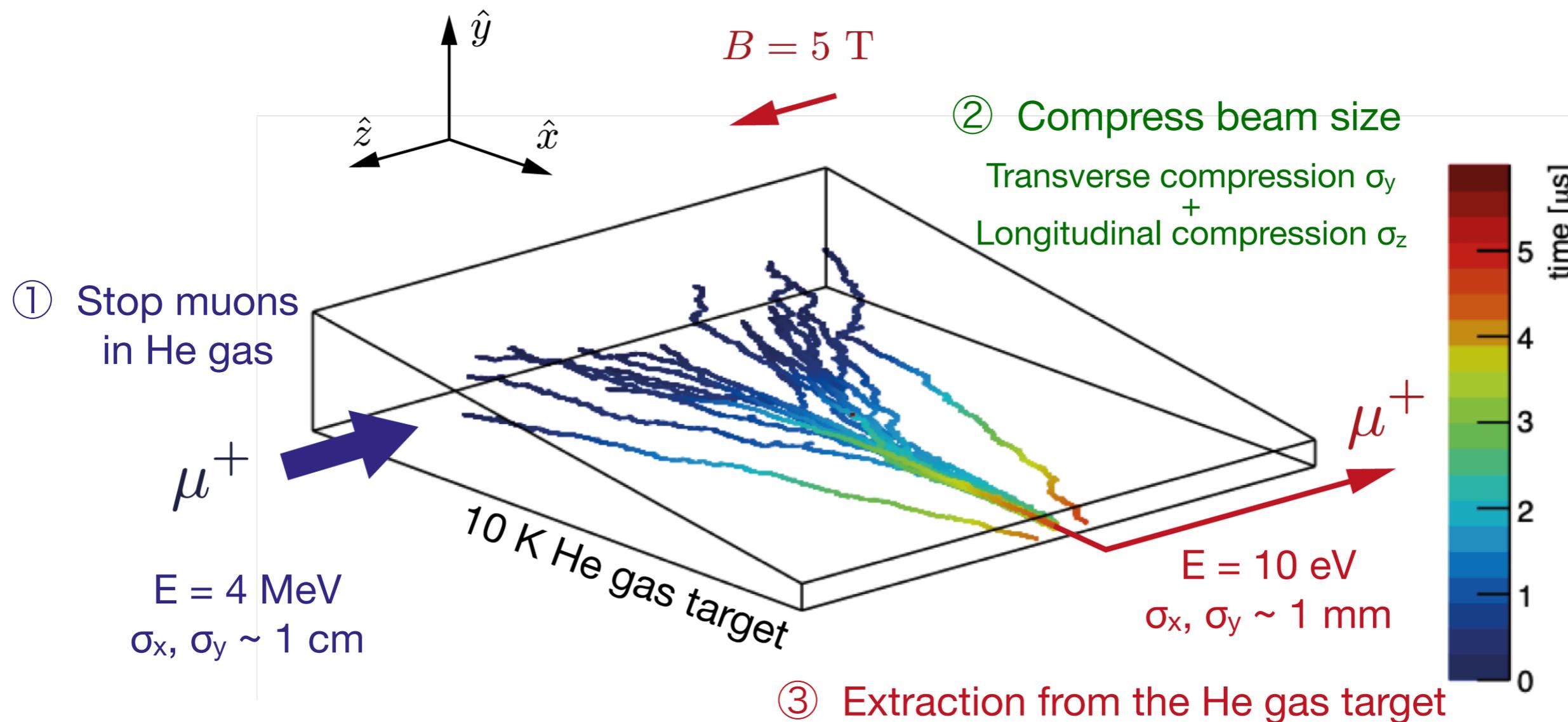
PAUL SCHERRER INSTITUT  
**PSI**

[msakurai@phys.ethz.ch](mailto:msakurai@phys.ethz.ch)

- Efficiency:  $\sim 10^{-4}$
- Phase space improvement in 6D:  $> 10^8$
- Applications:
  - keV energies: Mu spectroscopy, Mu gravity experiment,  $\mu$ SR experiment
  - MeV energies: muon EDM, g-2

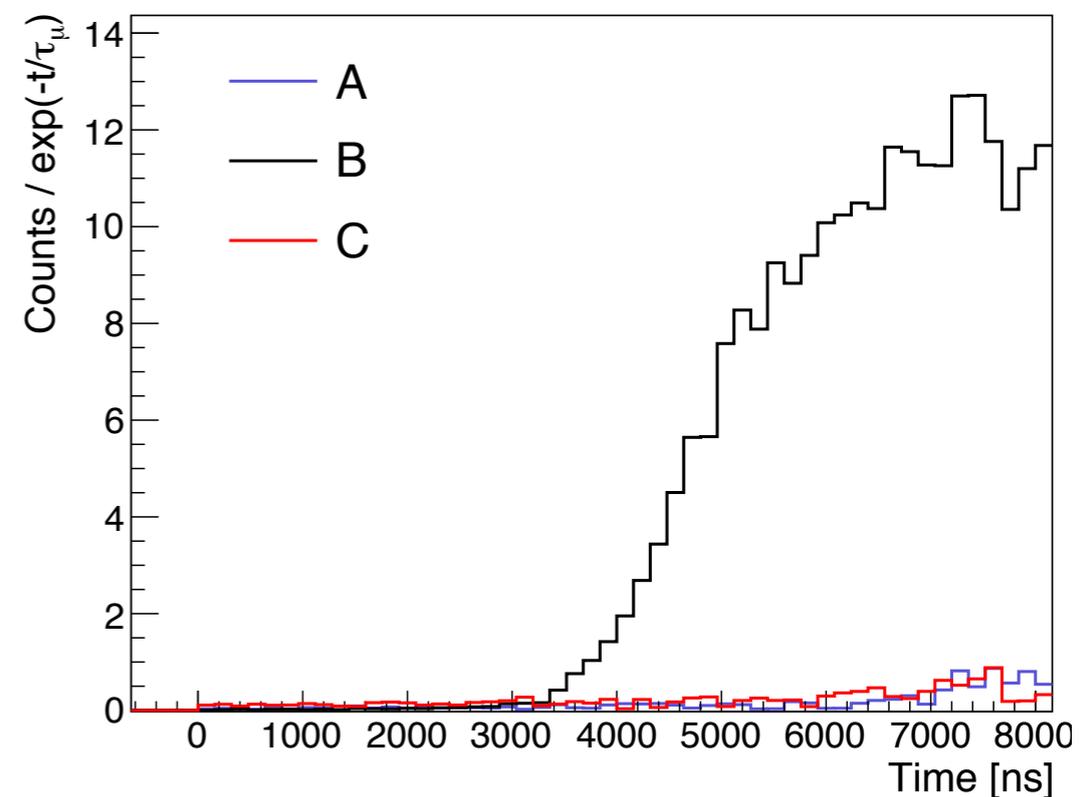
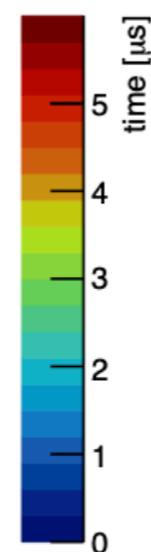
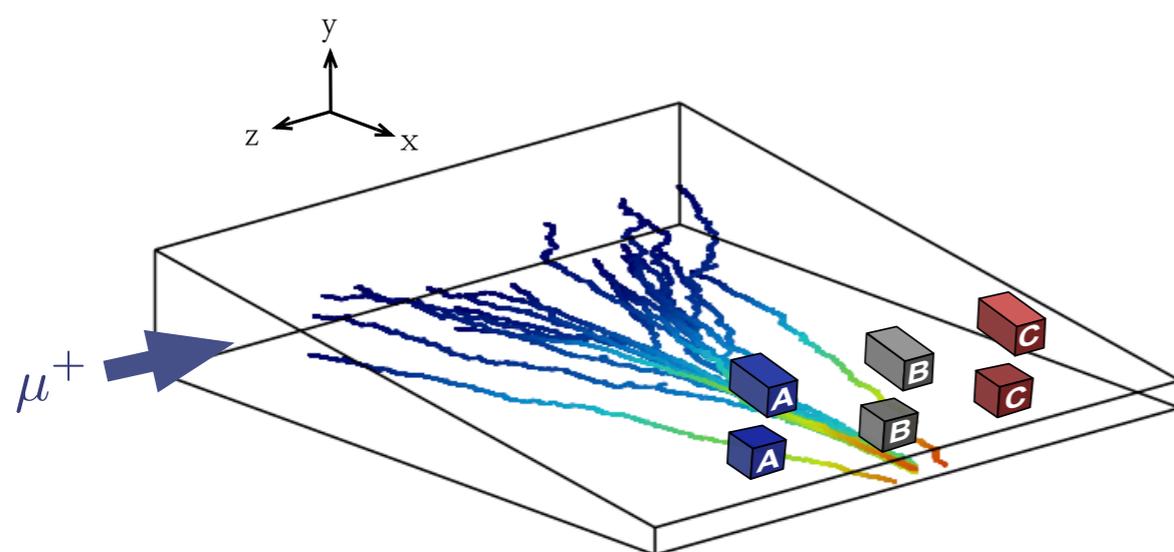


D. Taqqu., Phys. Rev. Lett. 97 (2006), p. 194801

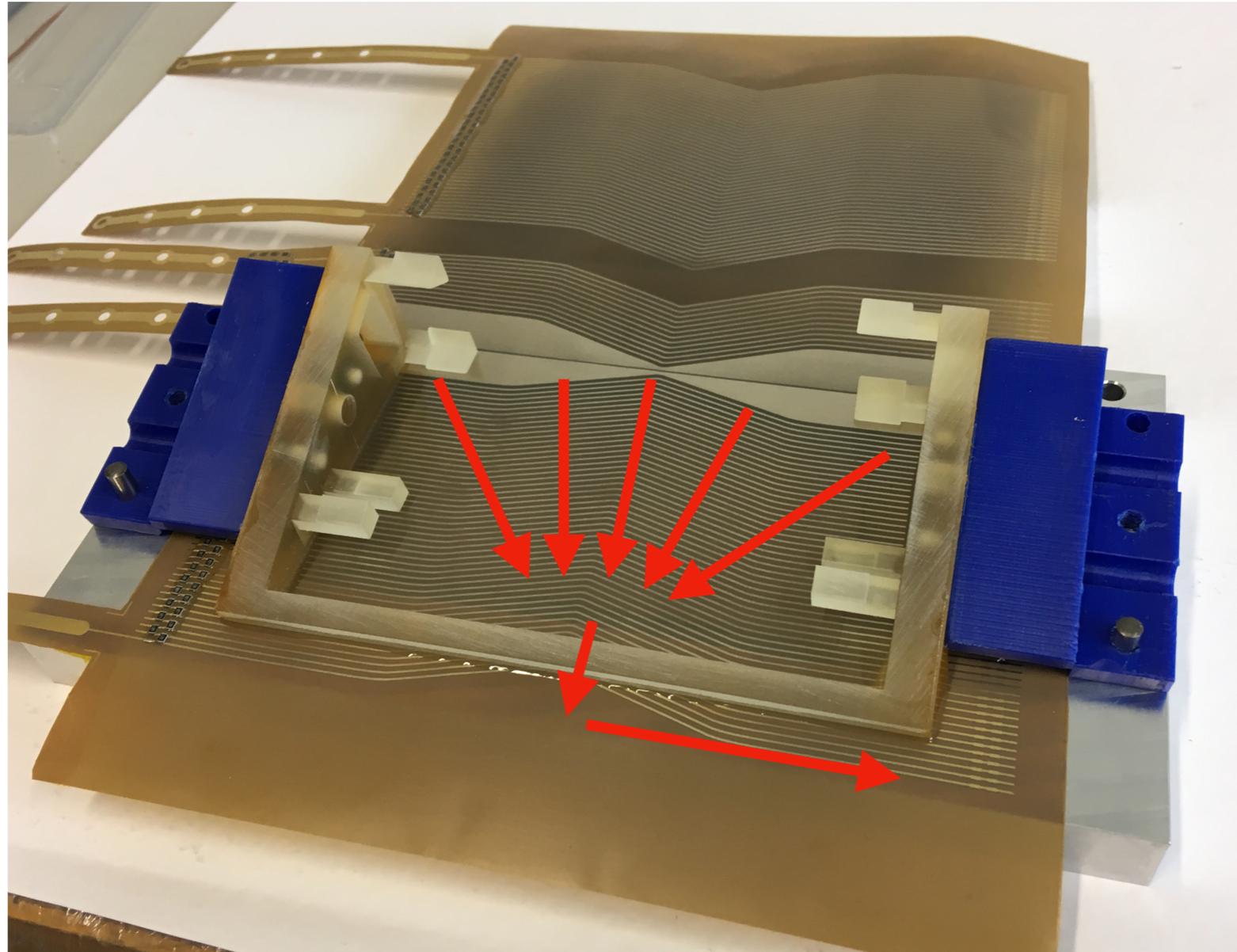


- Transverse, Longitudinal and Mixed compression

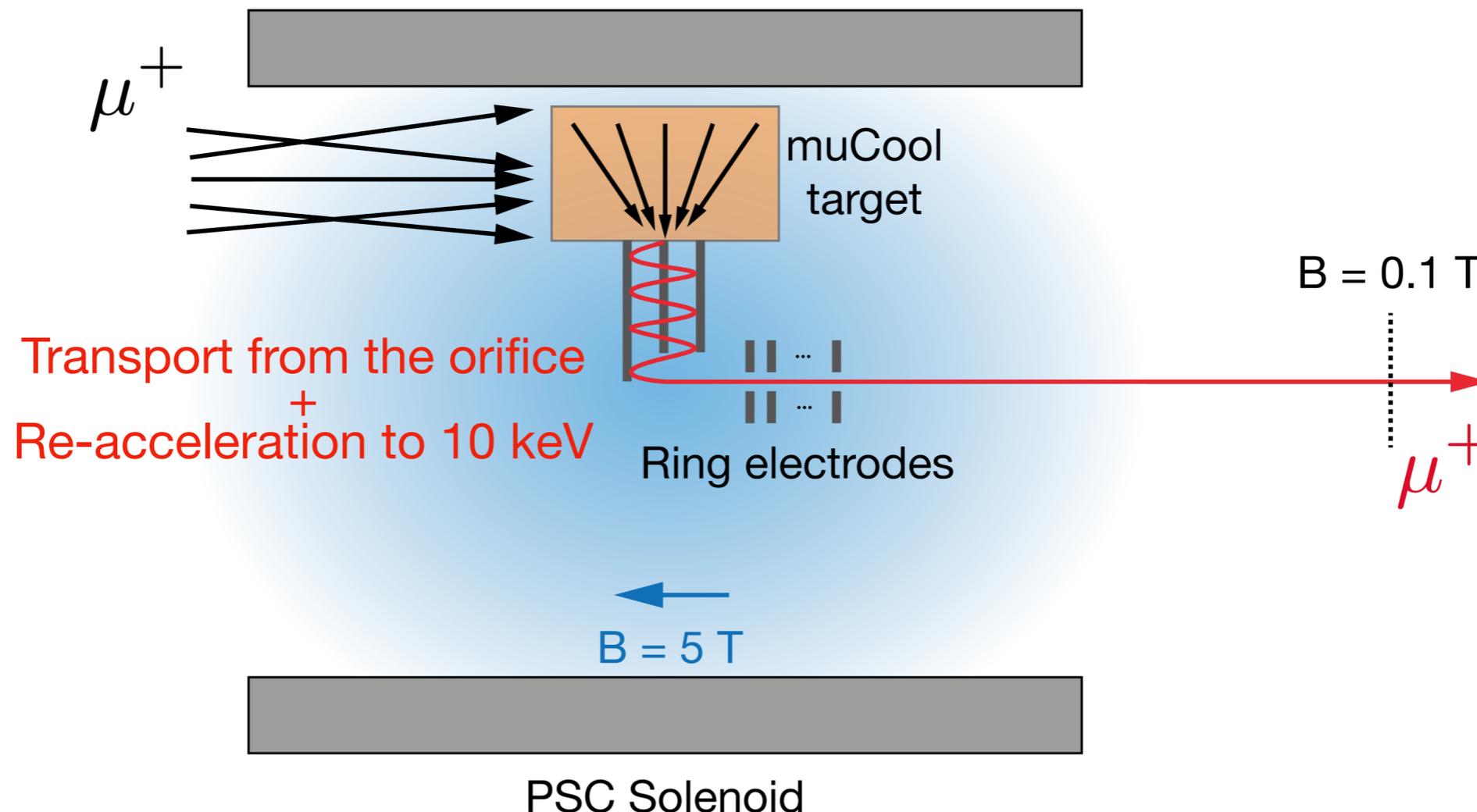
A. Antognini *et al.*, PRL 125, 164802 (2020)  
 Y. Bao *et al.*, PRL 112, 224801 (2014)  
 R. Iwai, PhD Thesis, ETH Zurich (2021)



- “Indirect” muon position measurement by detecting decay positrons
- Demonstrated successful simultaneous transverse and longitudinal compressions 

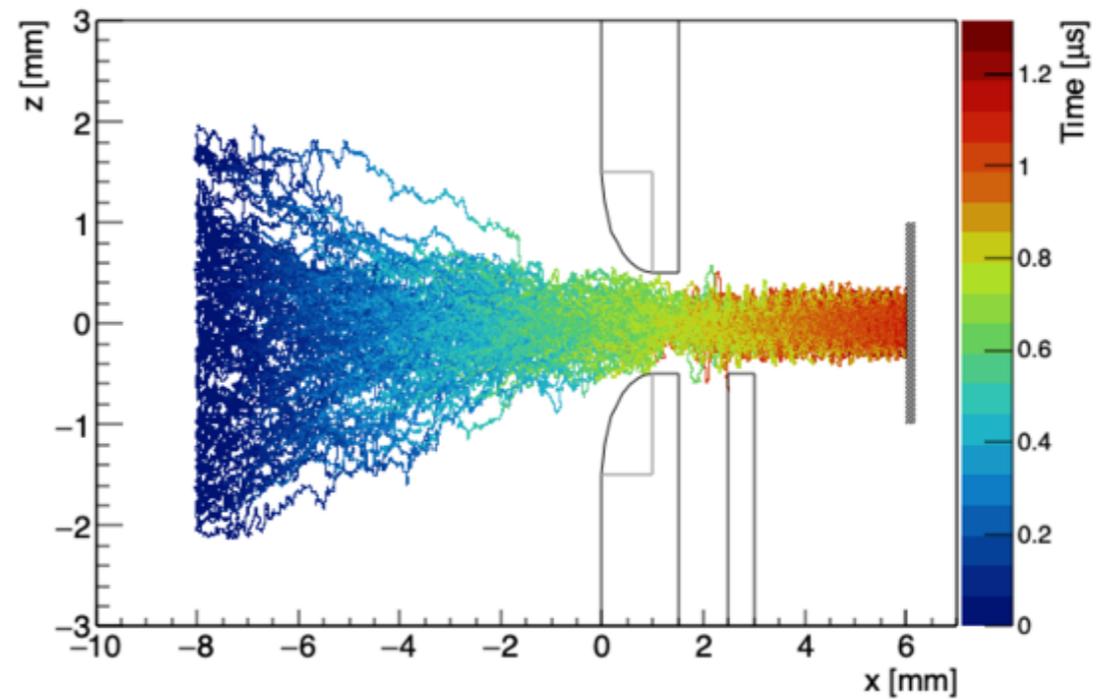
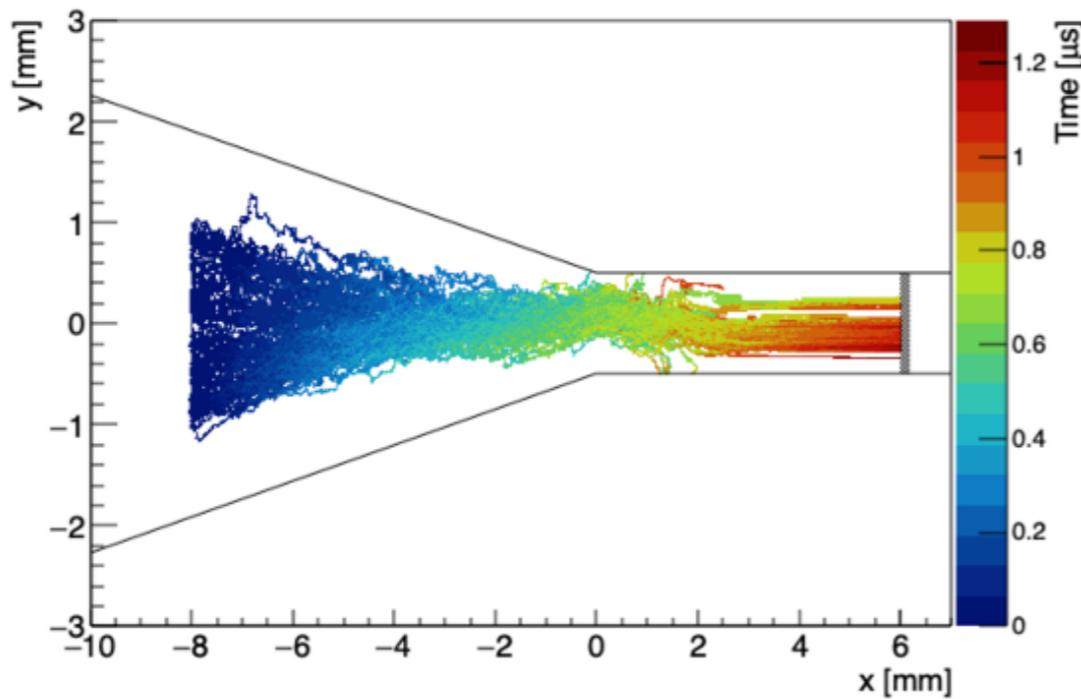
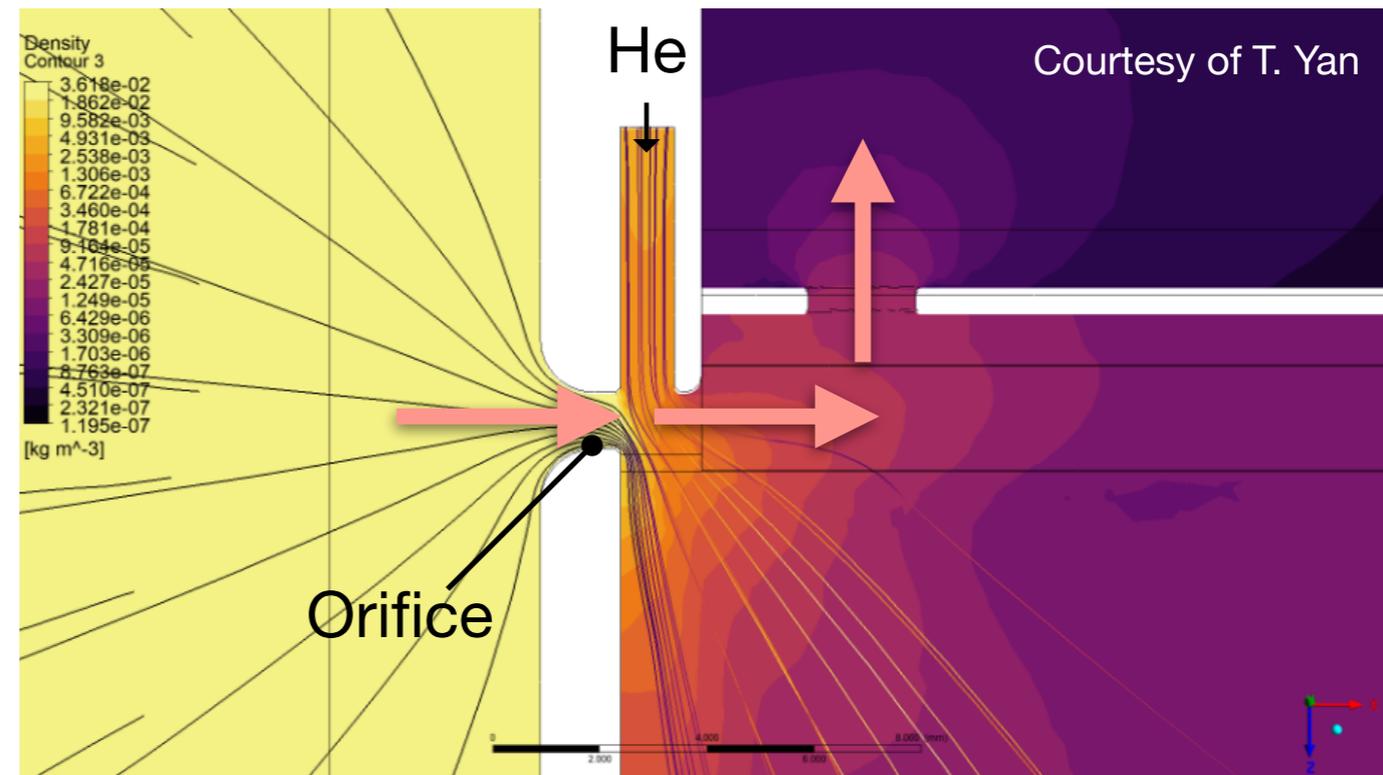
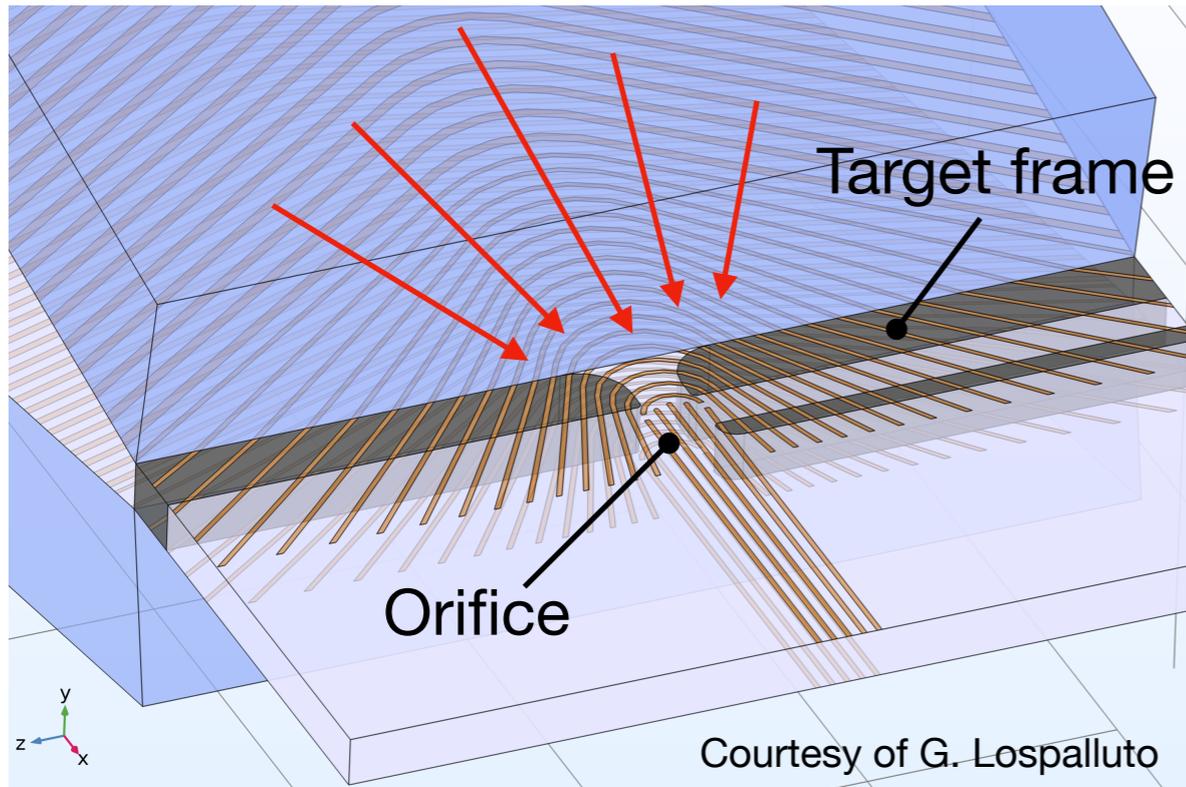


- Lined Kapton-foil to achieve complex E-fields for the mixed compression
- Next step: Develop the post-compression schemes

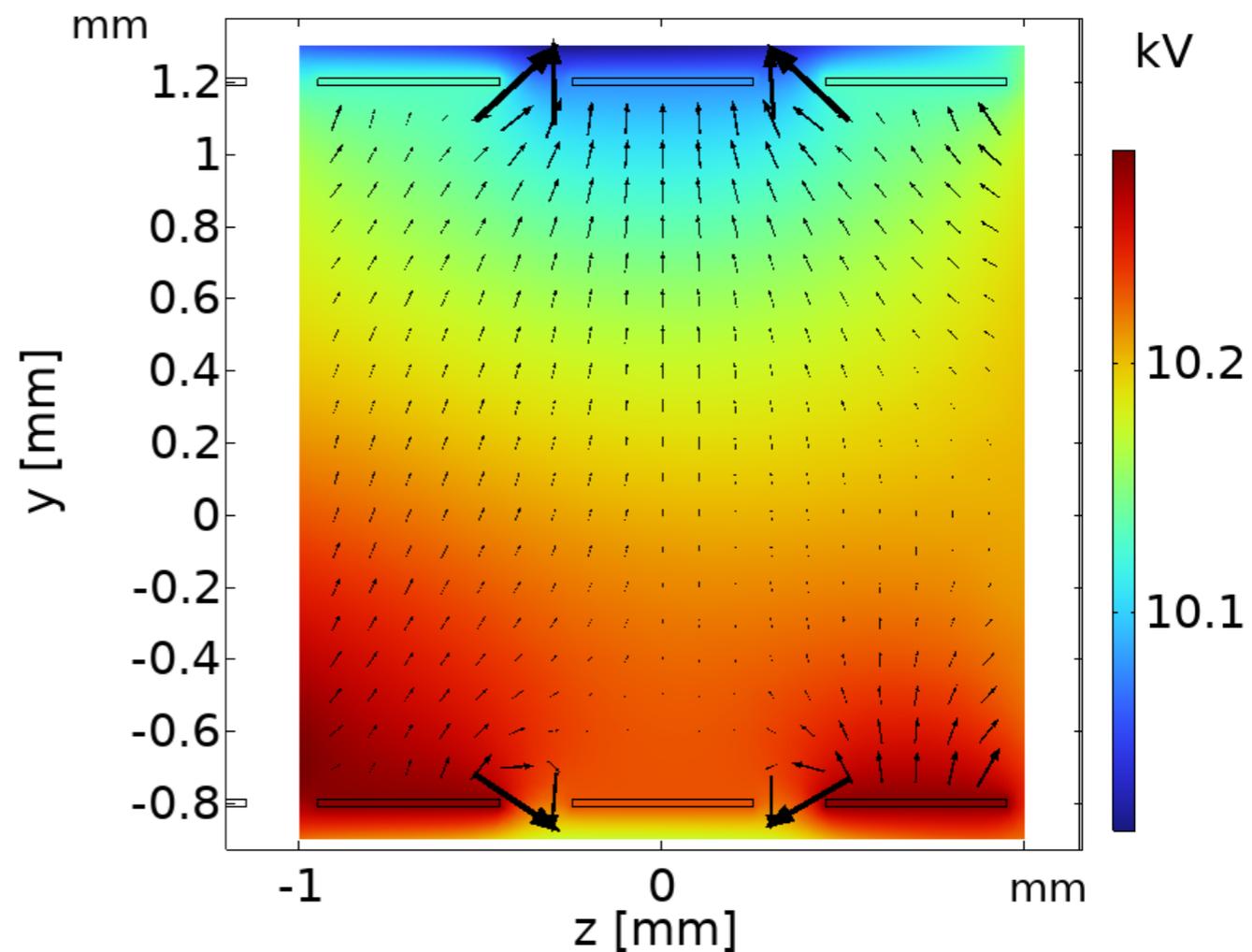
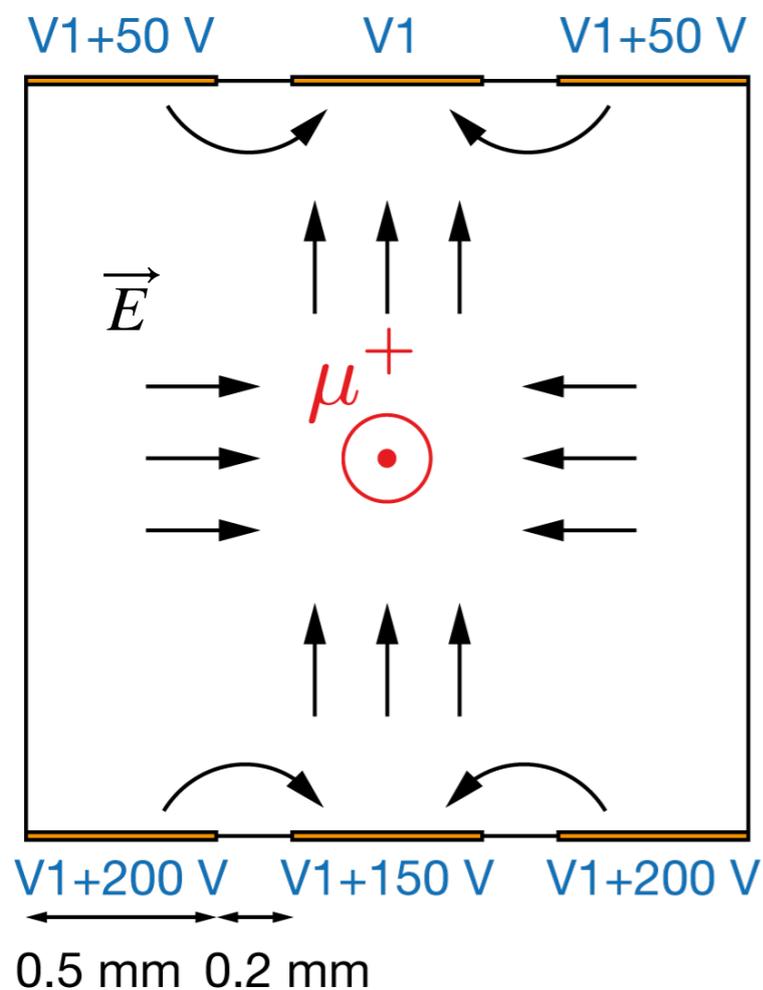


- Next steps:
  - Muon extraction from the muCool target through an orifice
  - Transport muons from the orifice and re-acceleration to 10 keV
  - Extraction from the solenoid magnetic field
- For the HIMB development: Coupling the HIMB beam into the muCool target

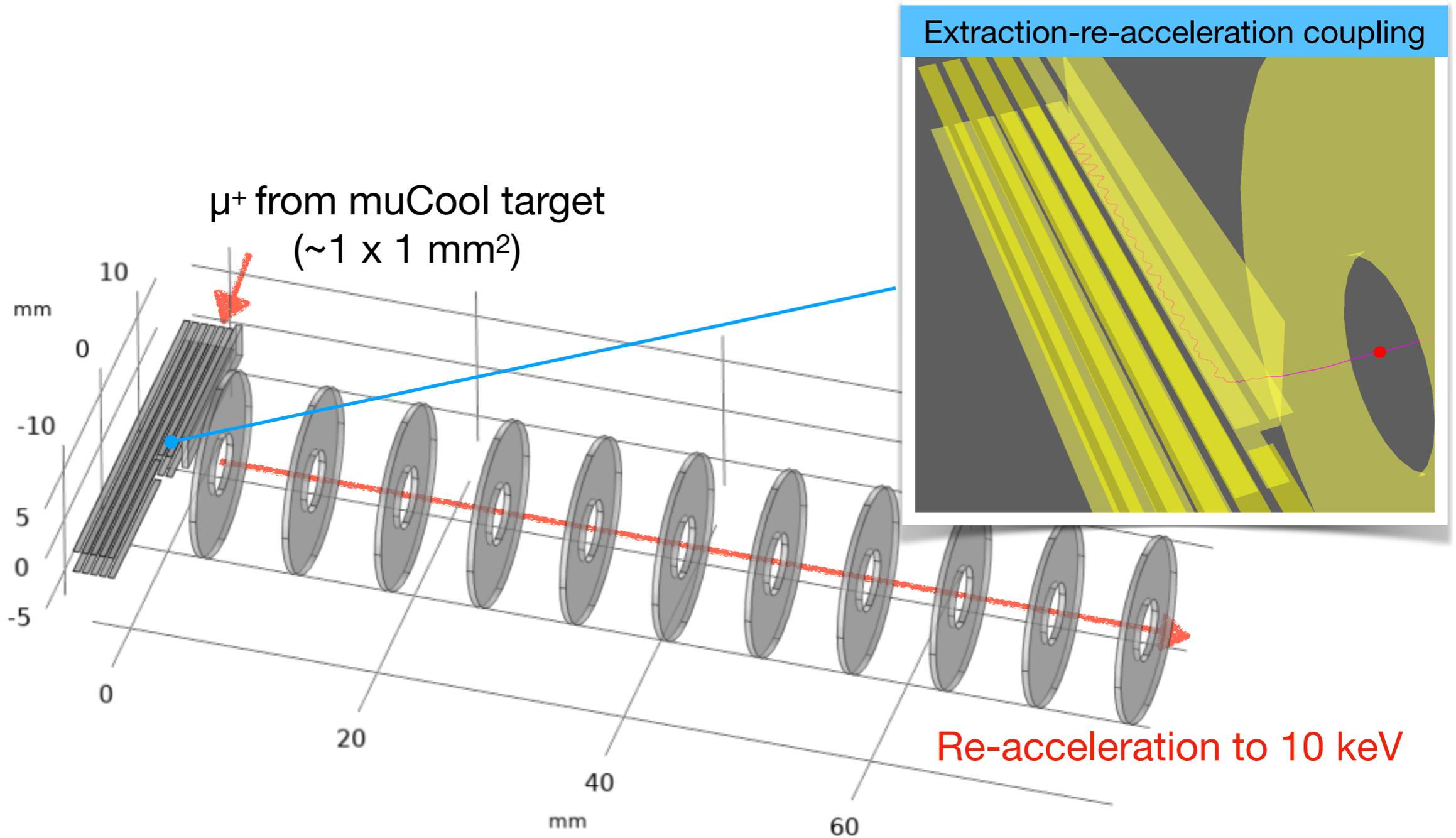
# Extraction from the target



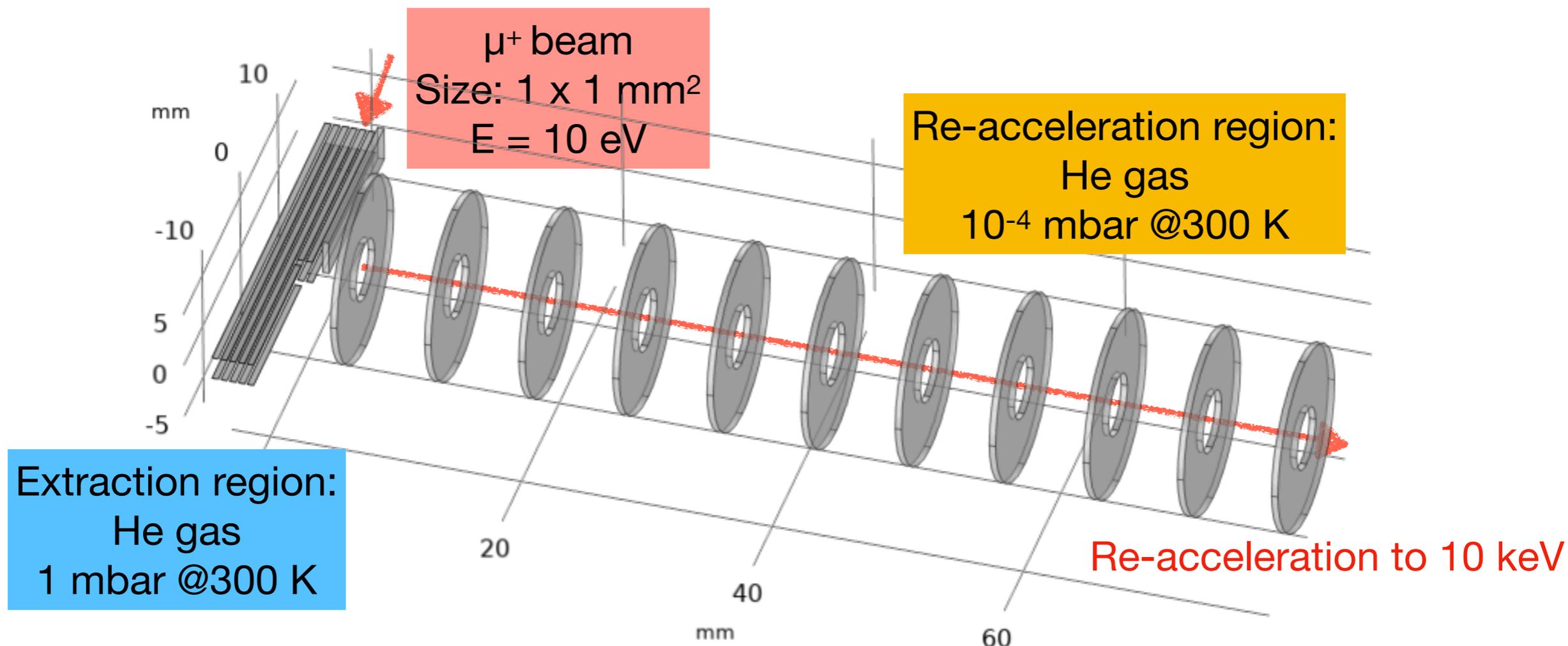
- Preliminary simulation shows 90% transmission efficiency



- 3 pairs of strip electrodes to confine and guide muons



- Electrostatic acceleration with a series of ring electrodes

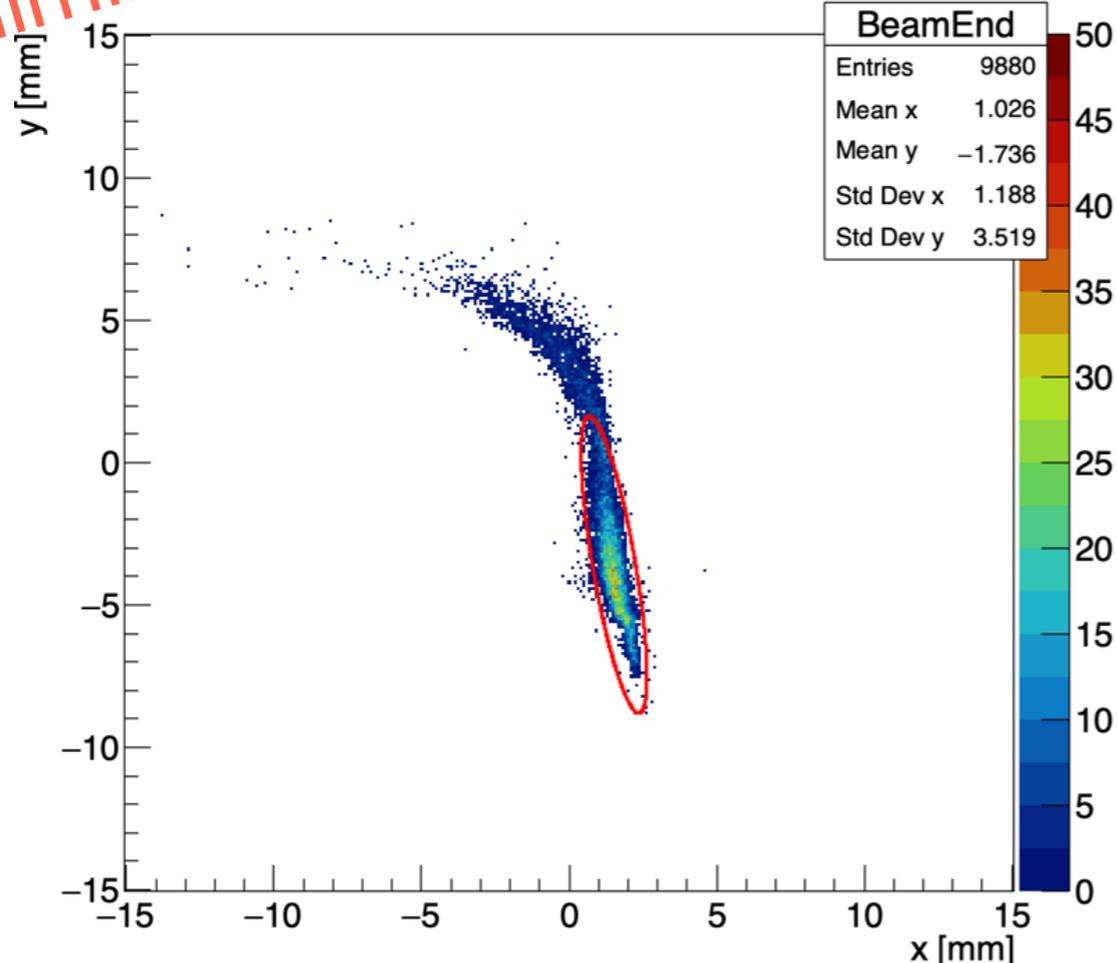


- Study beam quality including low-energy mu-He interactions
- Physics processes in Geant4:
  - Extraction region ( $E < 1 \text{ keV}$ )  
Custom low-energy mu-He elastic scattering, Mu-formation/ionisation
  - Re-acceleration region ( $E > 1 \text{ keV}$ )  
Geant4-standard Coulomb scattering, Ionisation, Bremsstrahlung, Pair production

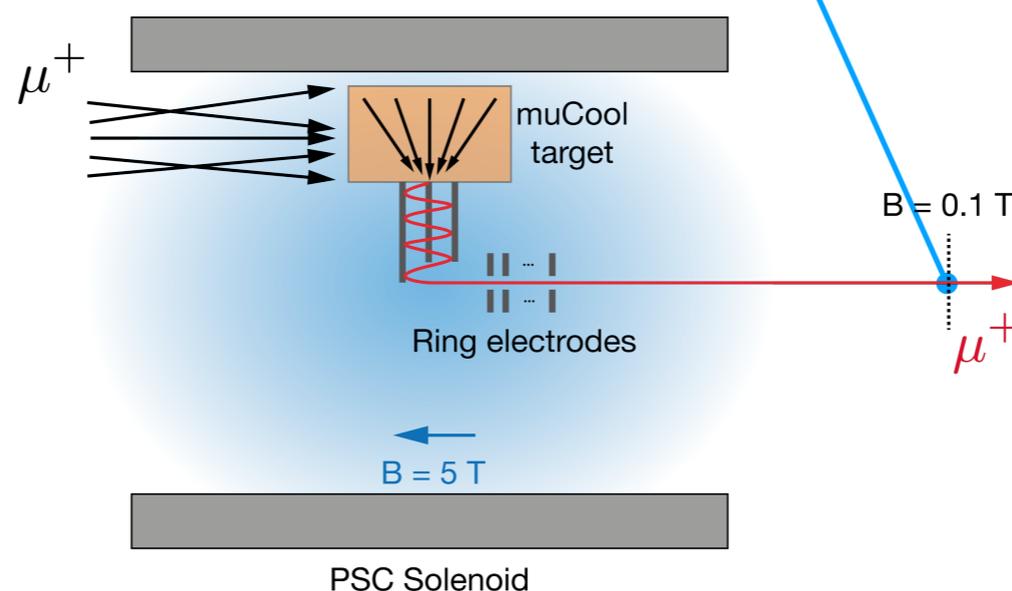
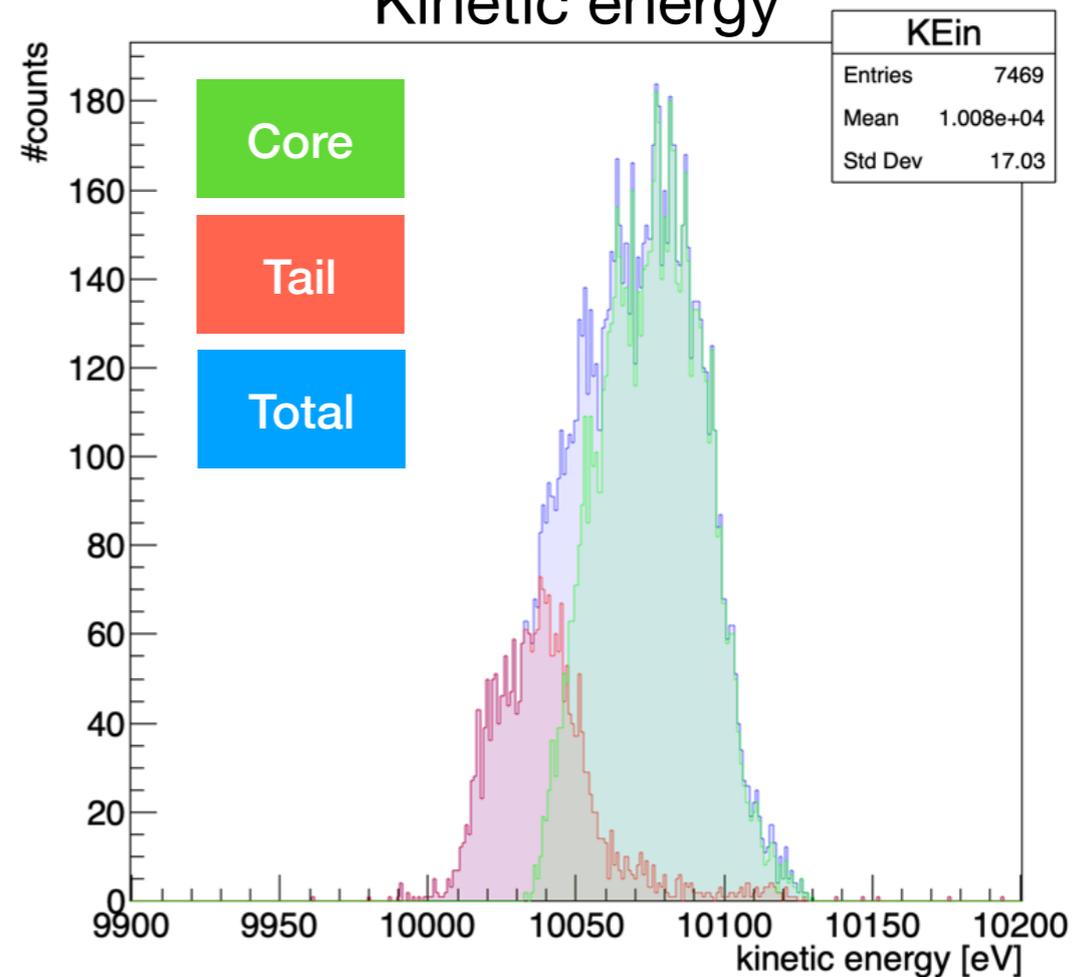
# Simulated beam properties at 0.1 T field

Preliminary

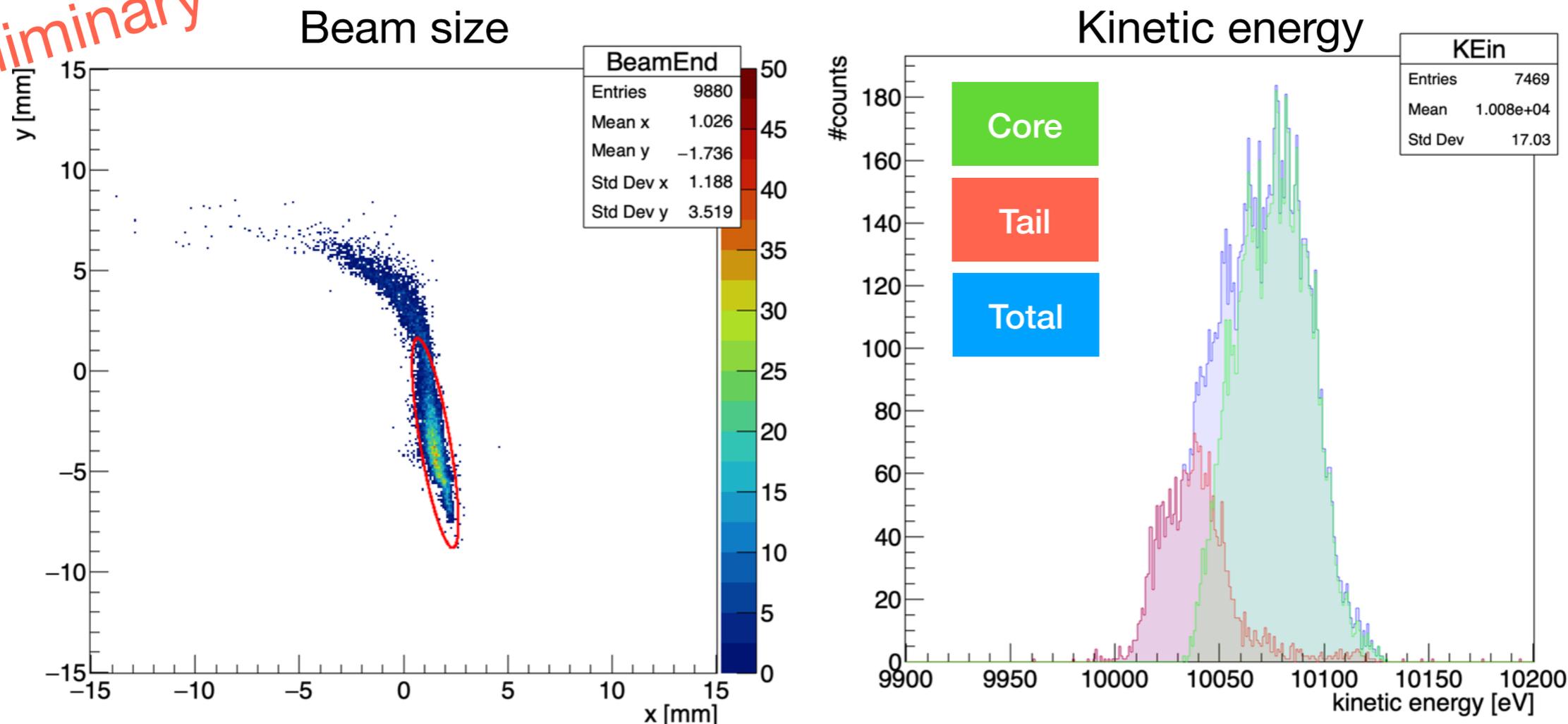
### Beam size



### Kinetic energy



Preliminary



- Transport efficiency (orifice-0.1 T field): ~75% w/o  $\mu^+$  decay
- Time (orifice-0.1 T field): ~1  $\mu$ s to travel 1.6 m
- Muonium formation: ~0.1%
- ToDo: Improve scattering & energy loss treatment of Geant4

@B = 0.1 T

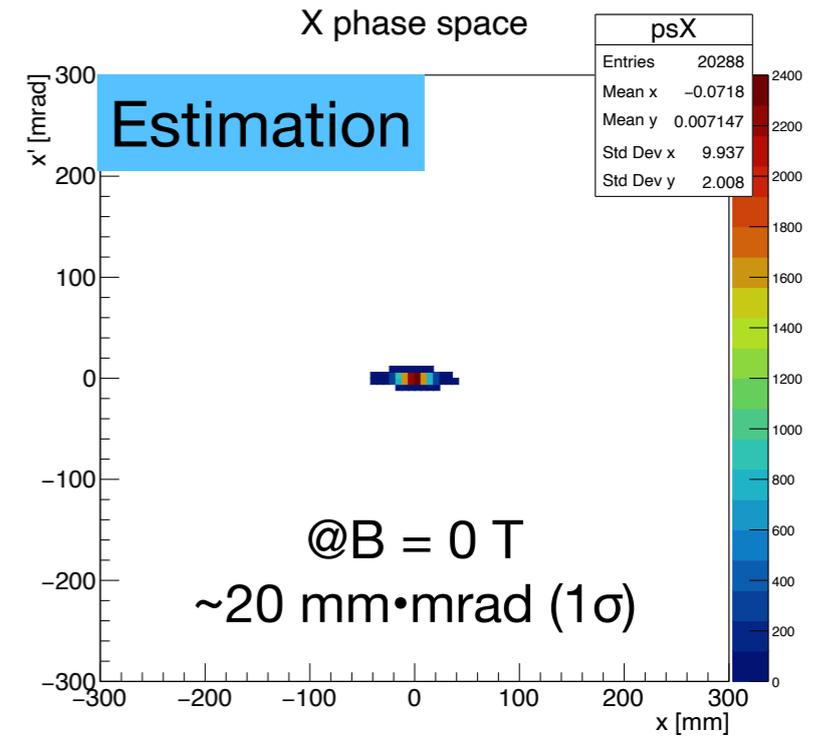
$\sigma_x$ : 0.4 mm

$\sigma_y$ : 1.9 mm

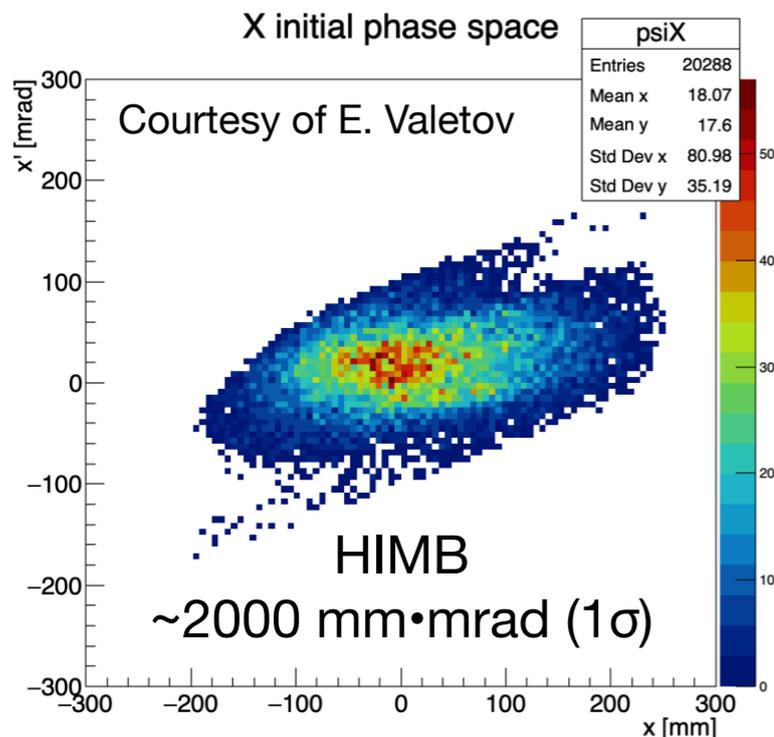
E: ~10 keV

$\Delta E$  ( $1\sigma$ ): ⚠ 17 eV

- Promising phase space @B = 0.1 T
- Likely to achieve better phase space @B = 0 T than initial estimation
- Now:  
How can we couple HIMB beam into muCool target efficiently?

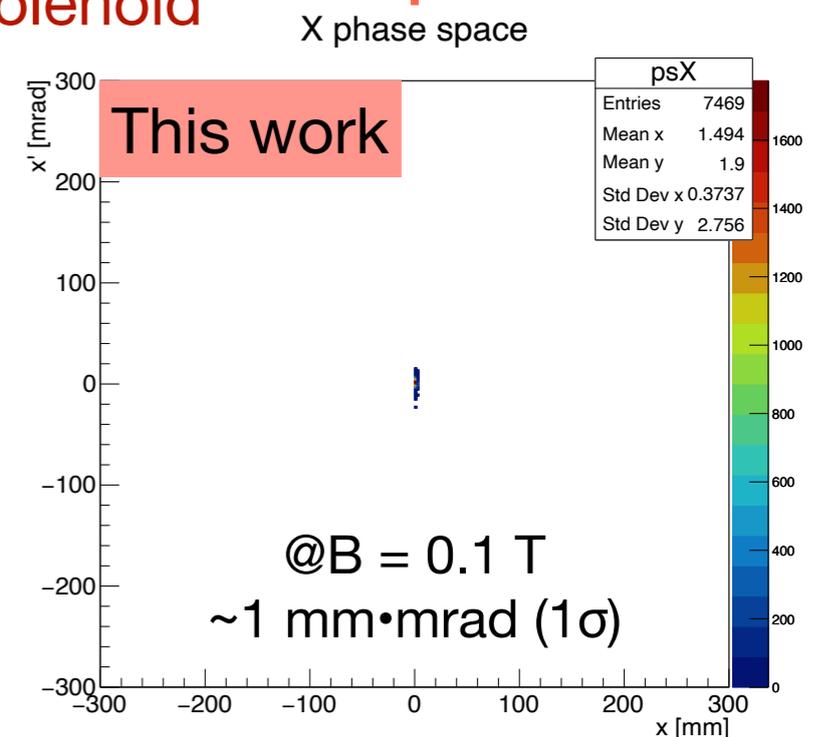


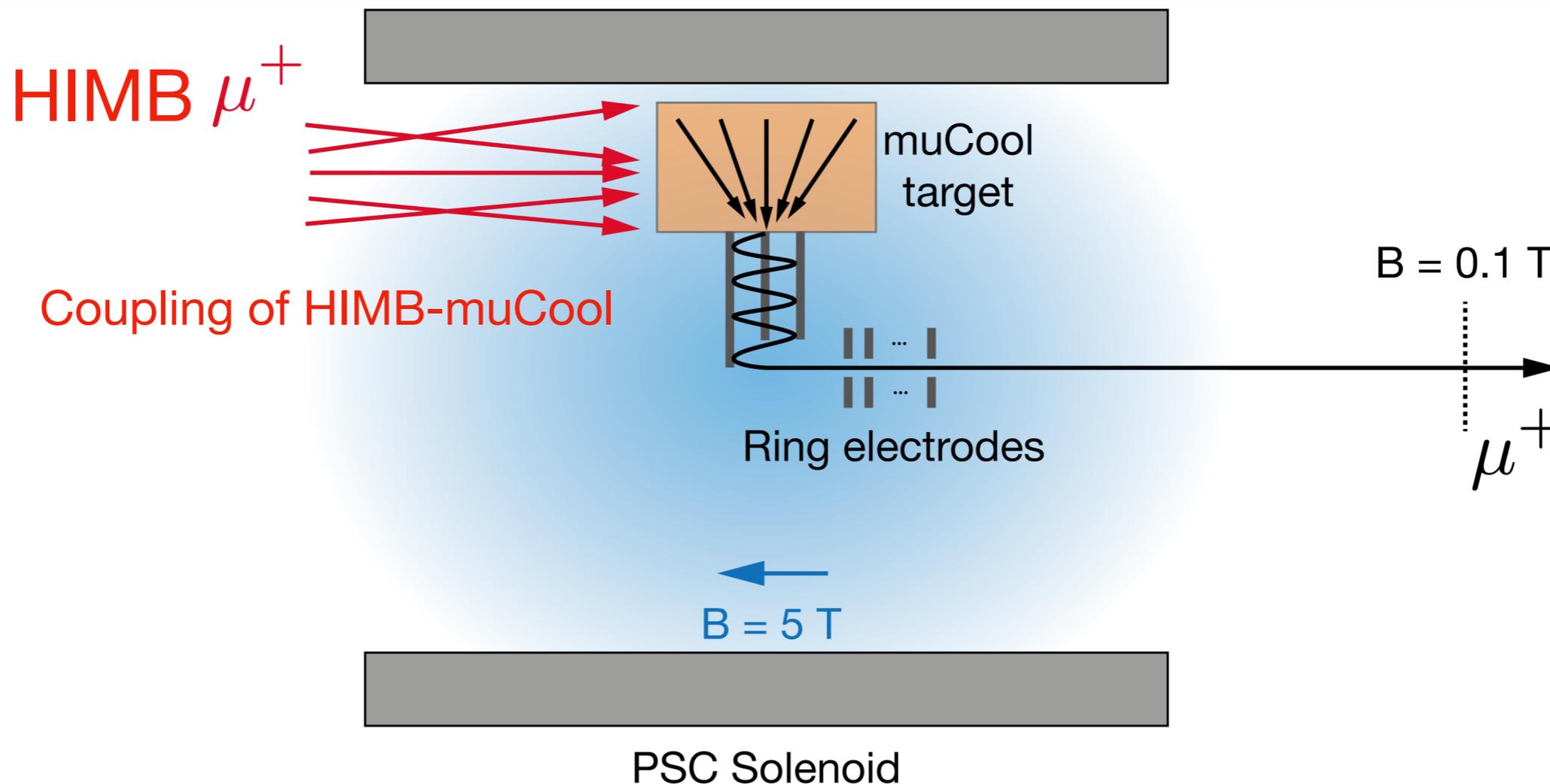
M. Aiba et al., arXiv:2111.05788 [hep-ex]



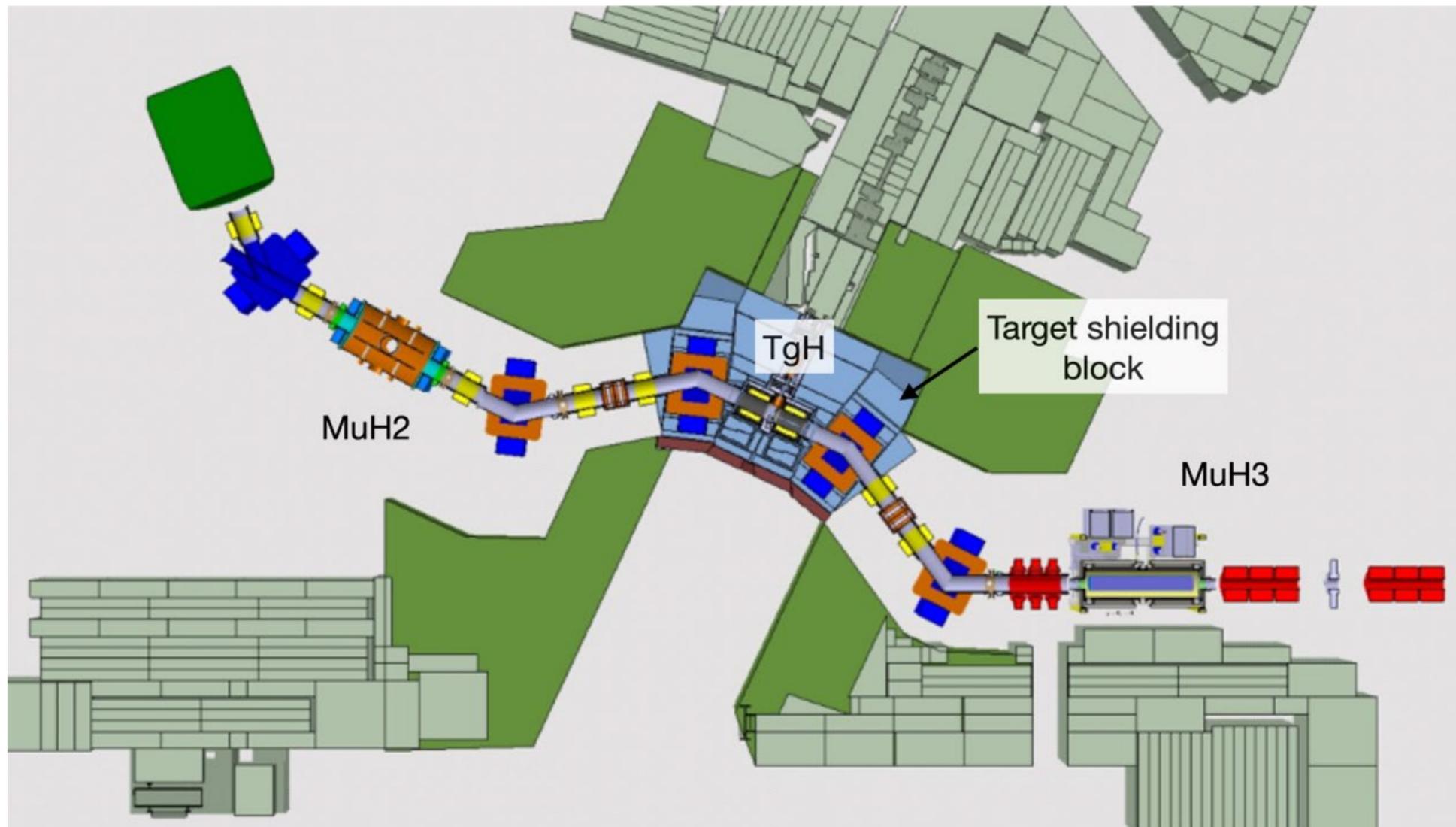
Re-acceleration

Extraction from solenoid



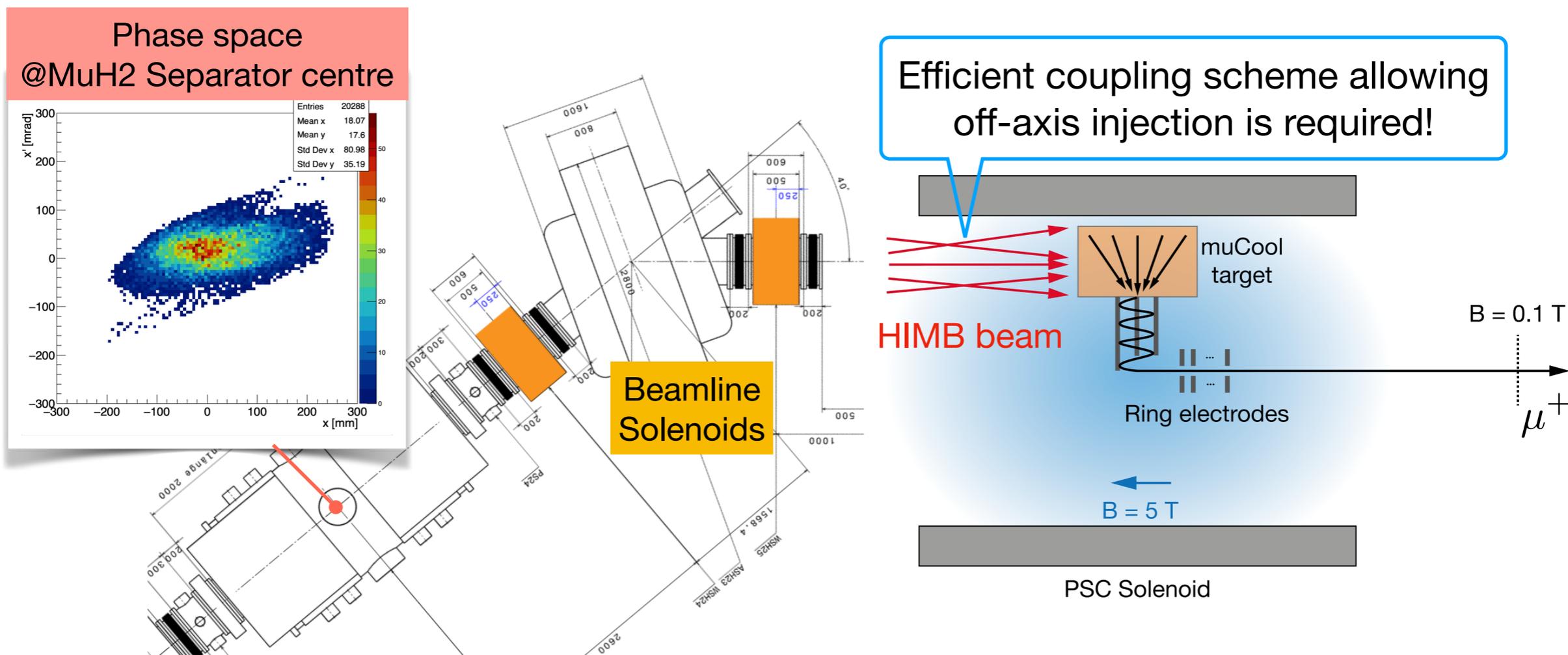


- Next steps:
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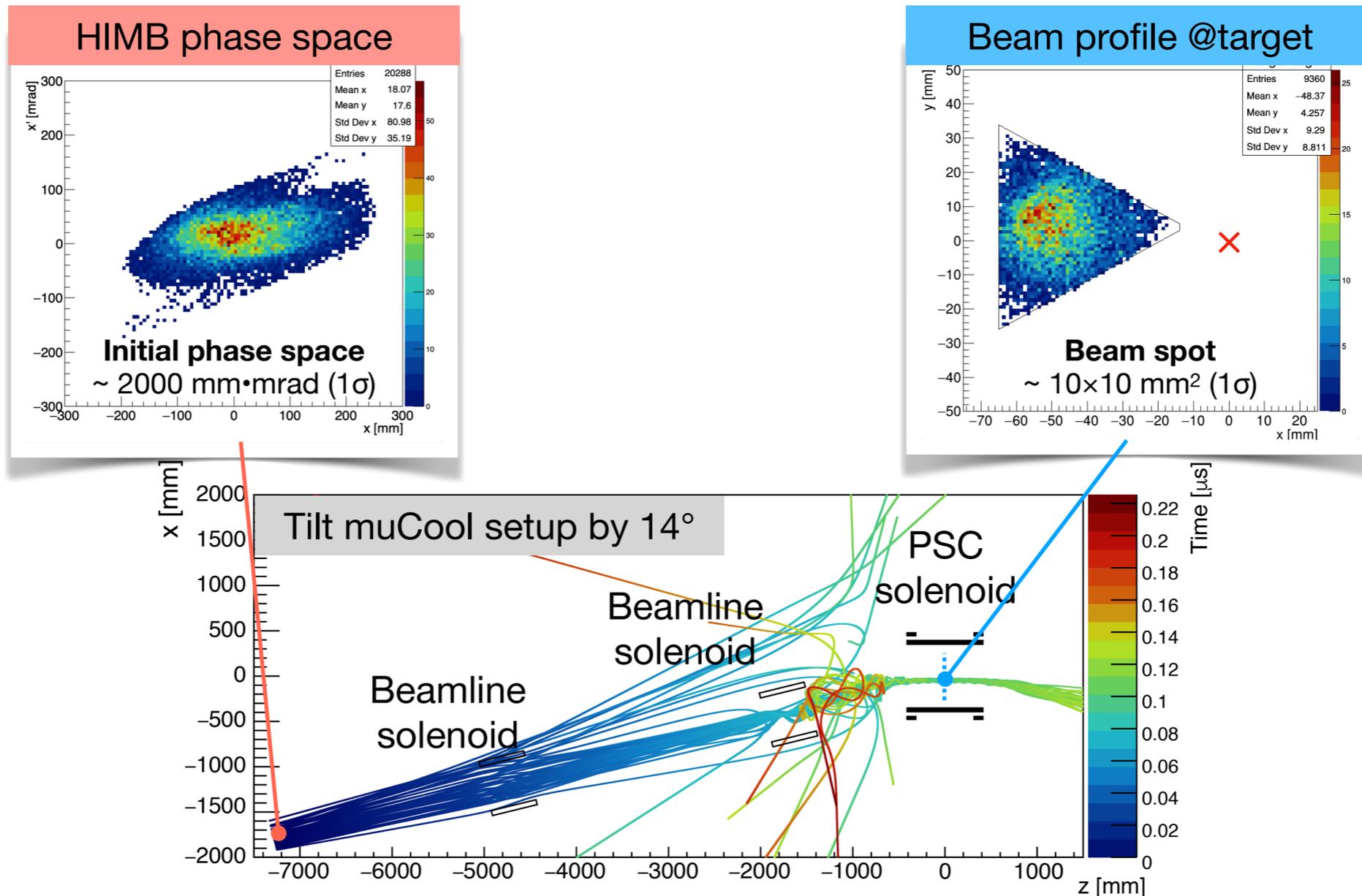


R. Eichler *et al.*, IMPACT conceptual design report (2022)

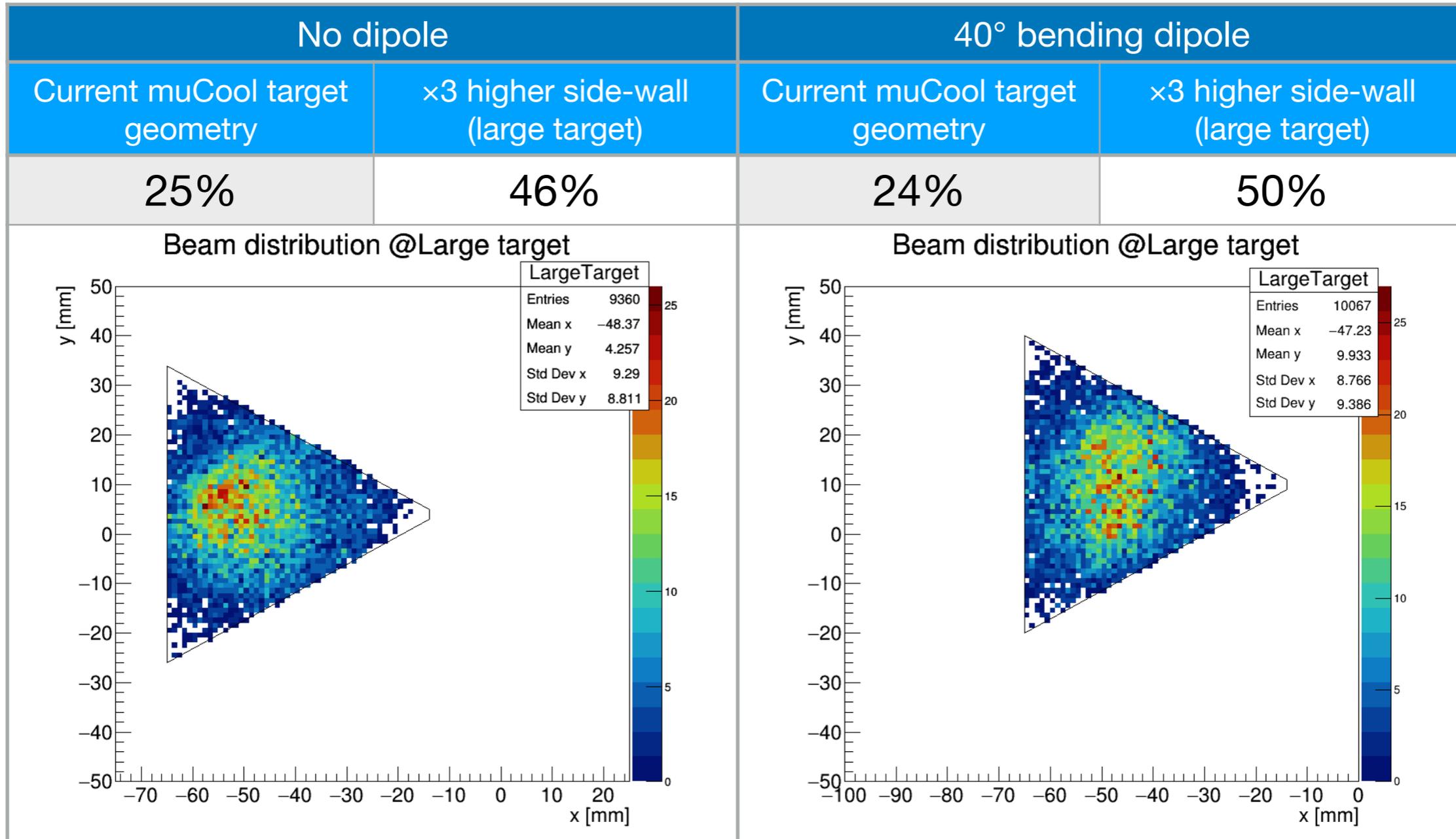
- Construction of new TgH by replacing the existing TgM
- New solenoid-based beamlines to deliver  $10^{10}$  surface  $\mu/s$
- Exciting opportunities for particle physics and  $\mu$ SR experiments



- Off-axis injection → On-axis re-acceleration
- Multi-parameter optimisation simulations by changing...
  - Focusing strength of beamline solenoids
  - Layout: w/ and w/o beamline dipole, shifting and tilting the muCool setup w.r.t the beamline



- A large phase space of the HIMB beam is not easy to handle...
- 45% of muons are back-reflecting when coupling into 5 T PSC solenoid
- Off-axis injection works



- Off-axis injection works for both beamline layouts
- A dipole might help to reduce a large  $\Delta p = 3.5 \text{ MeV}/c$  (FWHM) and to improve the target stopping efficiency

- muCool is a phase space compression scheme for  $\mu^+$  beam
- Mixed transverse-longitudinal compression is successfully tested
- The post-compression schemes are being studied with simulations
  - Showed the feasibility of the extraction-re-acceleration concept
  - Promising  $\sim 1 \text{ mm}\cdot\text{mrad}$  phase space ( $1\sigma$ ) at  $B = 0.1 \text{ T}$
- A possible beamline configuration to couple the HIMB beam into the muCool target was studied with simulations
  - 45% of the HIMB beam is back-reflected when coupling to a 5 T solenoid
  - Off-axis injection for the muCool target is possible

# Thank you!

## The muCool collaboration

A. Antognini\*, N. Ayres, I. Belosevic, V. Bondar, R. Iwai, G. Lospalluto  
K. Kirch\*, F. Piegsa<sup>‡</sup>, T. Yan, M. Sakurai and D. Taqqu

*Institute for Particle Physics and Astrophysics, ETH Zurich, Switzerland*

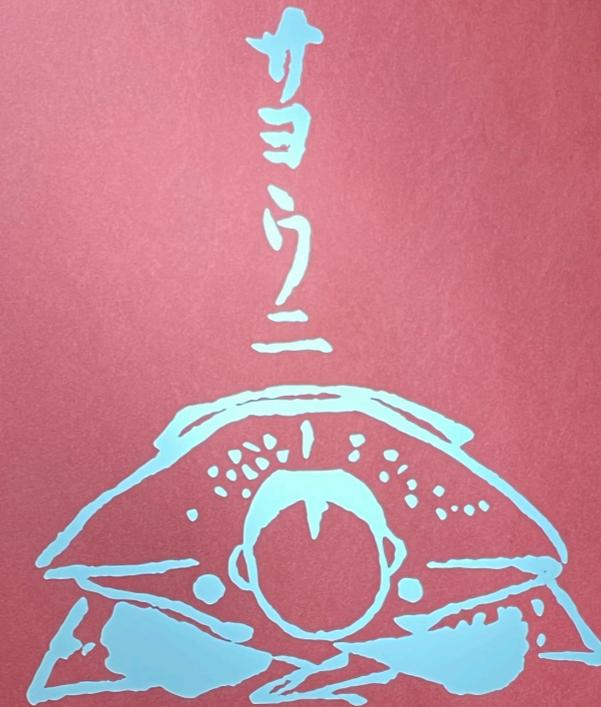
M. Hildebrandt, A. Knecht, J. Nuber, A. Papa<sup>§</sup>, C. Petitjean, and A. Stoykov

*Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland*

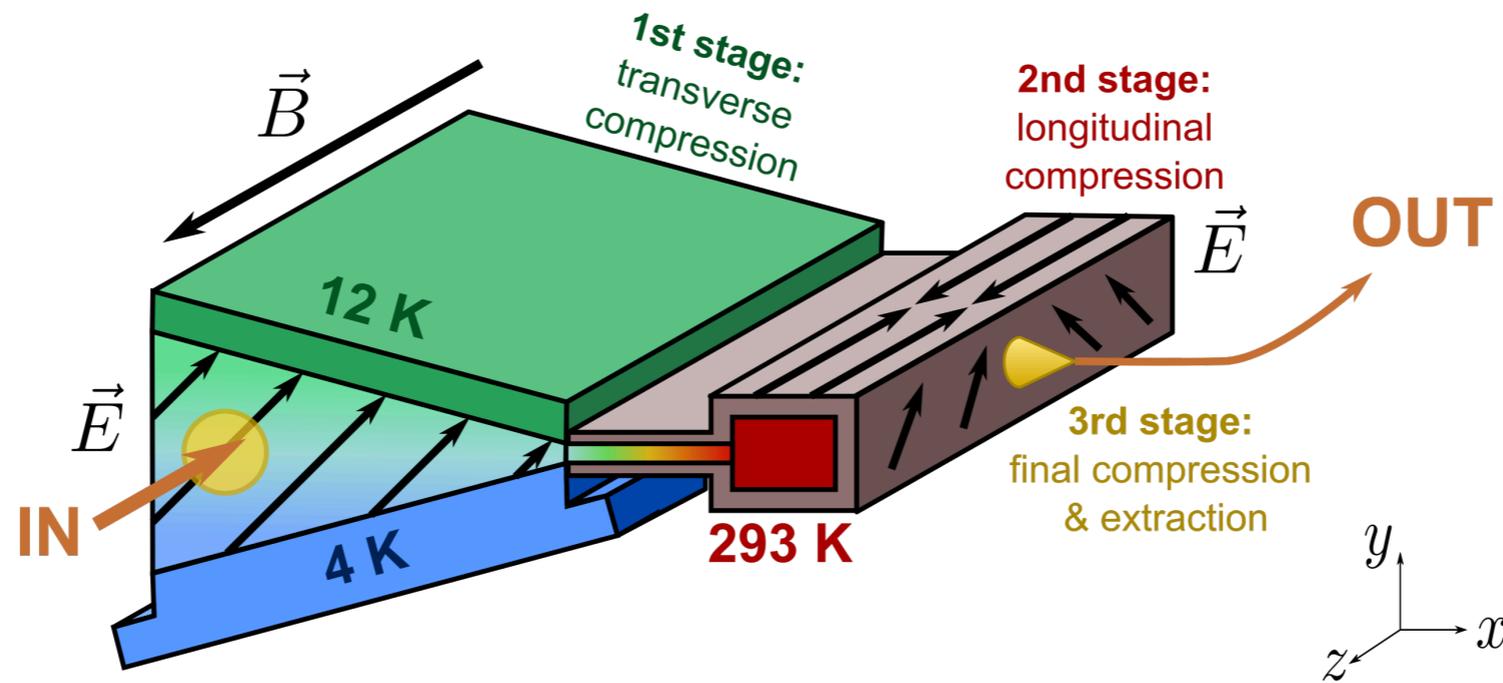
D. M. Kaplan and T. J. Phillips

*Illinois Institute of Technology, Chicago, IL 60616 USA*

\* also at PSI    ‡ presently at University of Bern    § also at University of Pisa and INFN

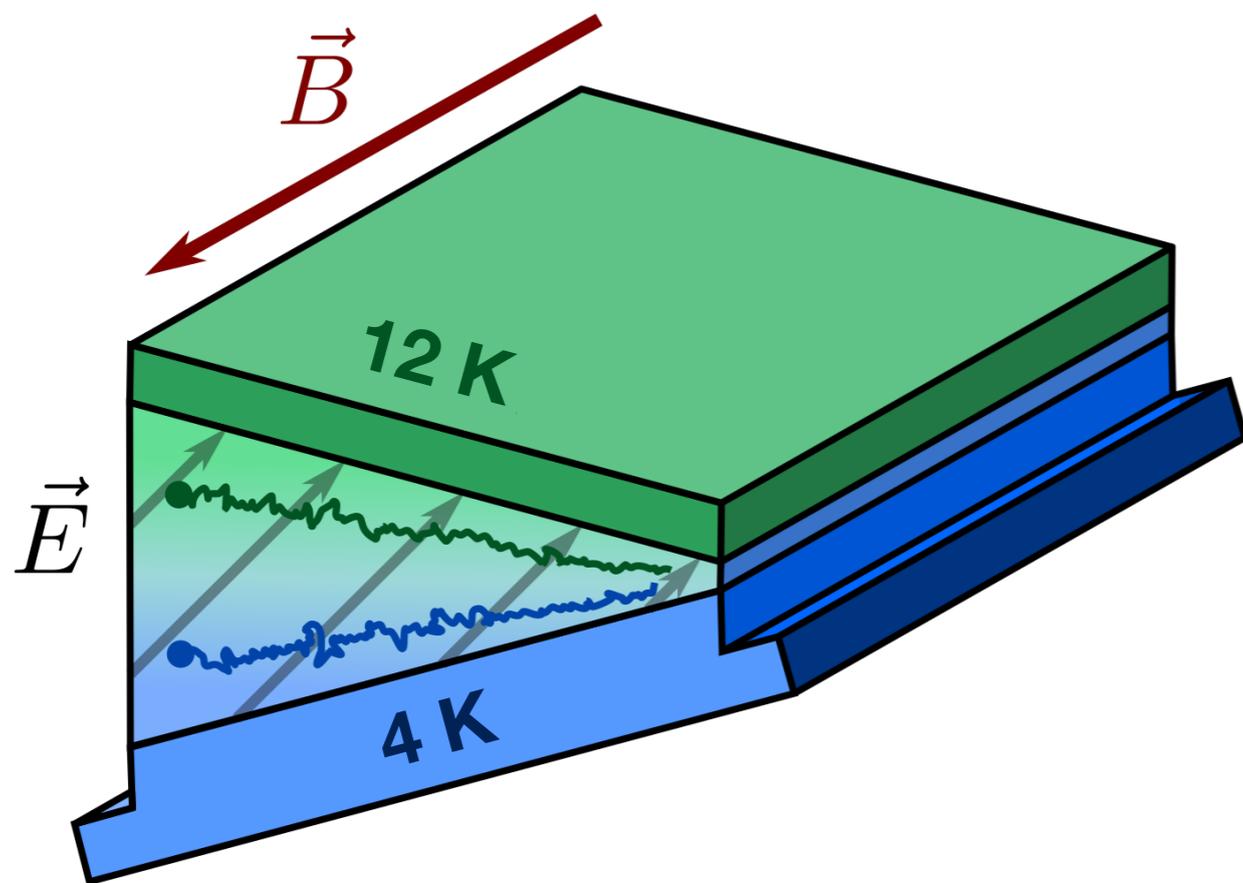


# Backup



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

- $\tau_c$ : mean time between two  $\mu^+$ -He collisions
- $\omega$ :  $\mu^+$  cyclotron frequency



$\mu^+$ -He collision frequency  $\propto$  Gas density

