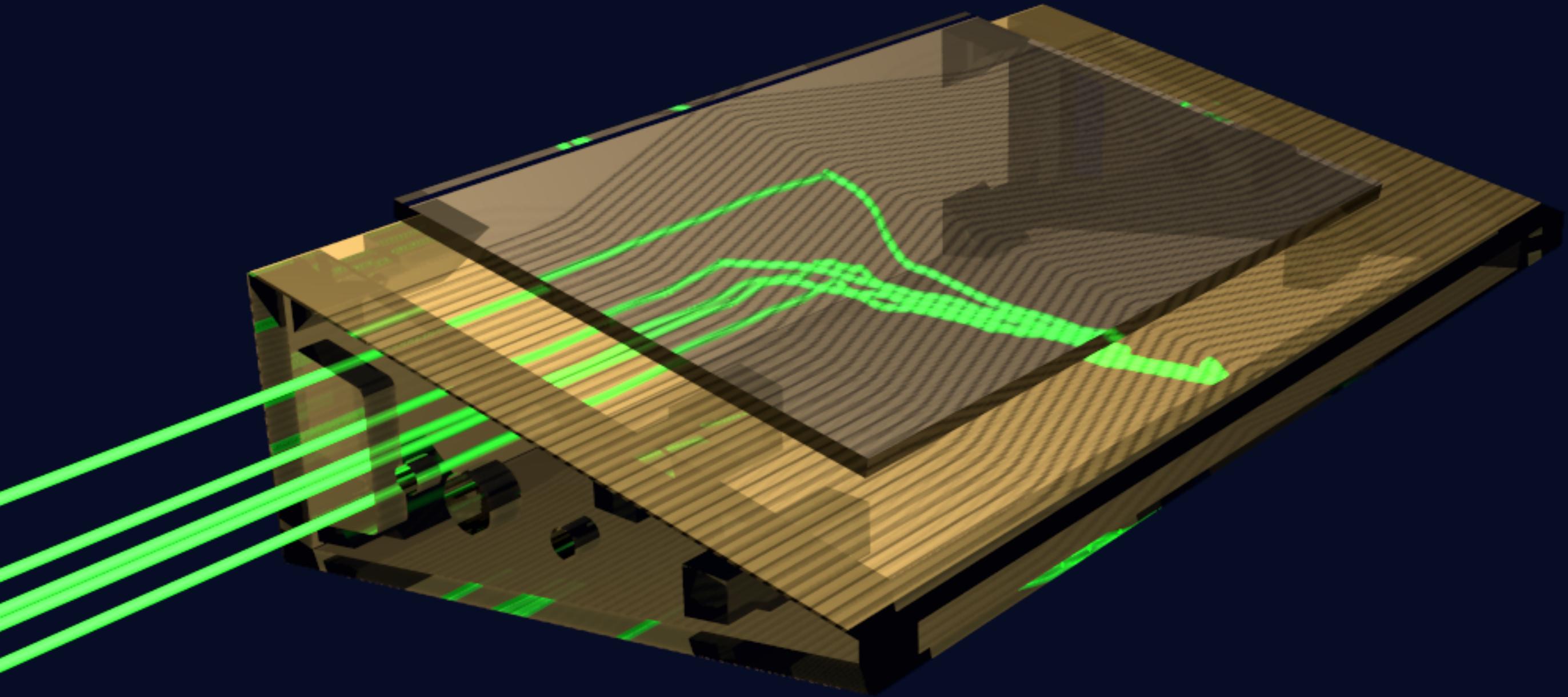
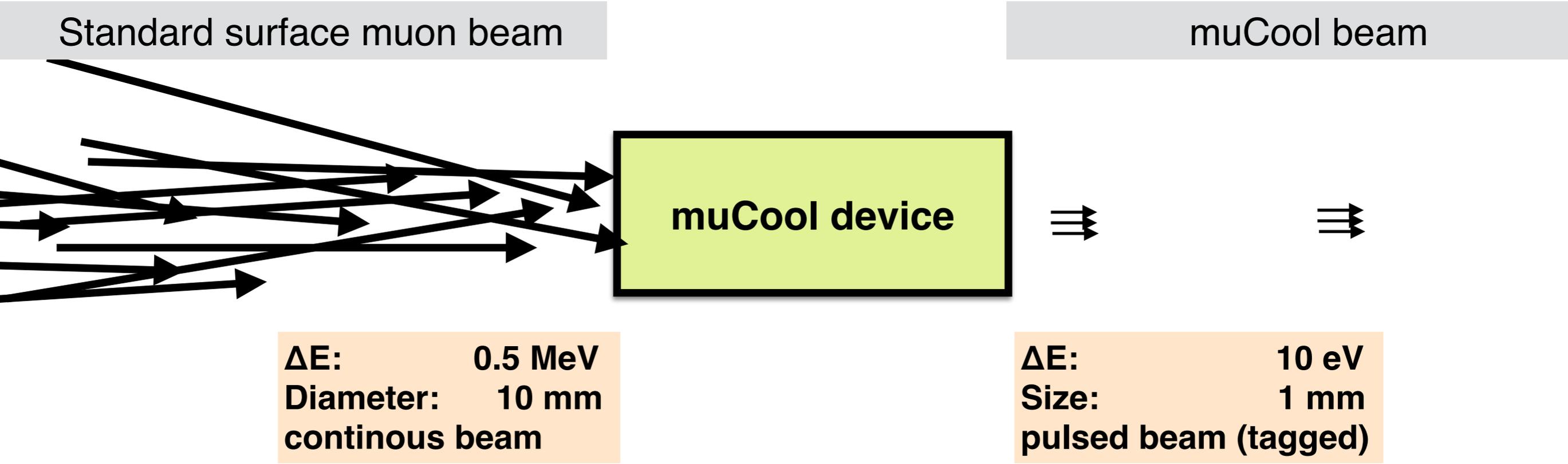


MuCool

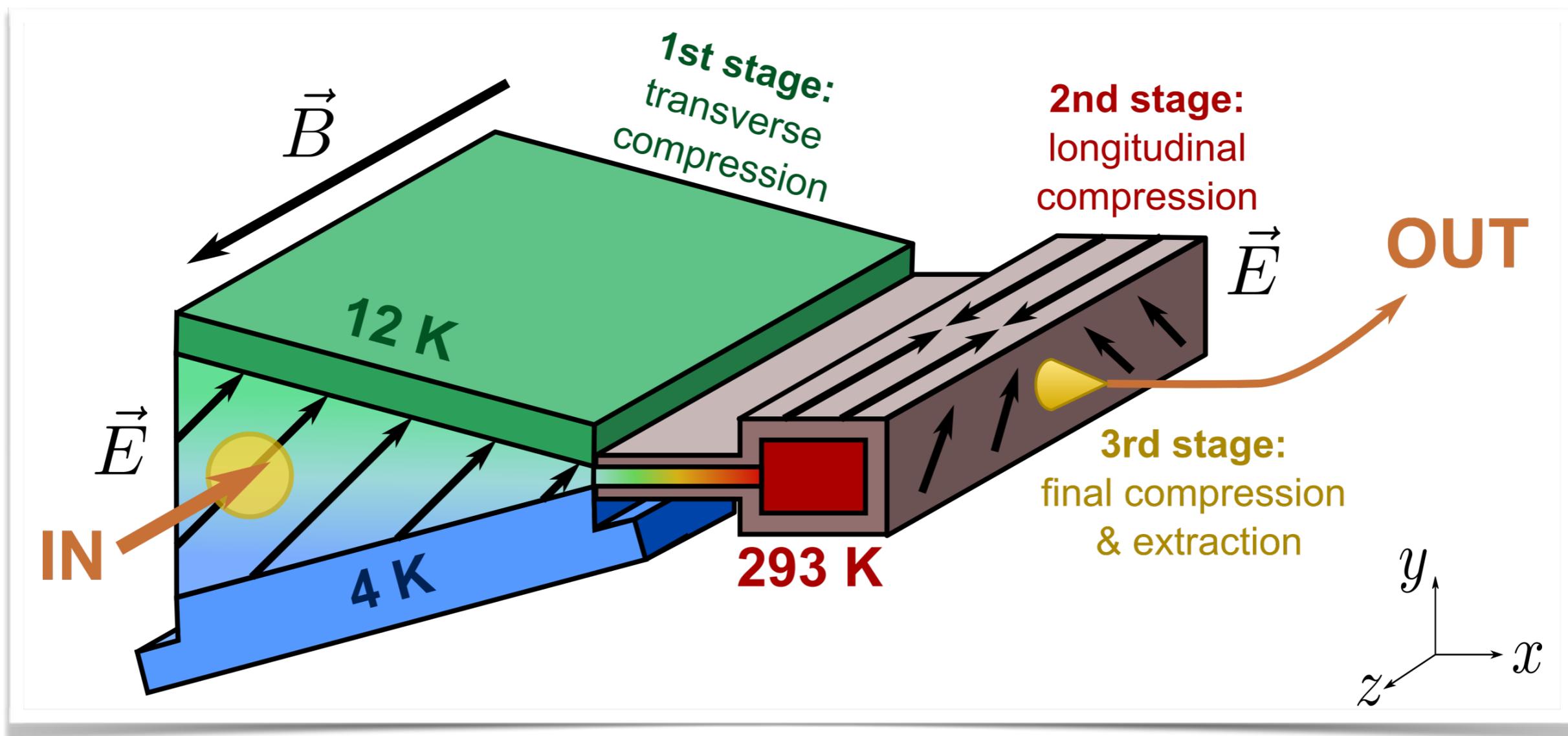
R-14-02.1



Goal of muCool project



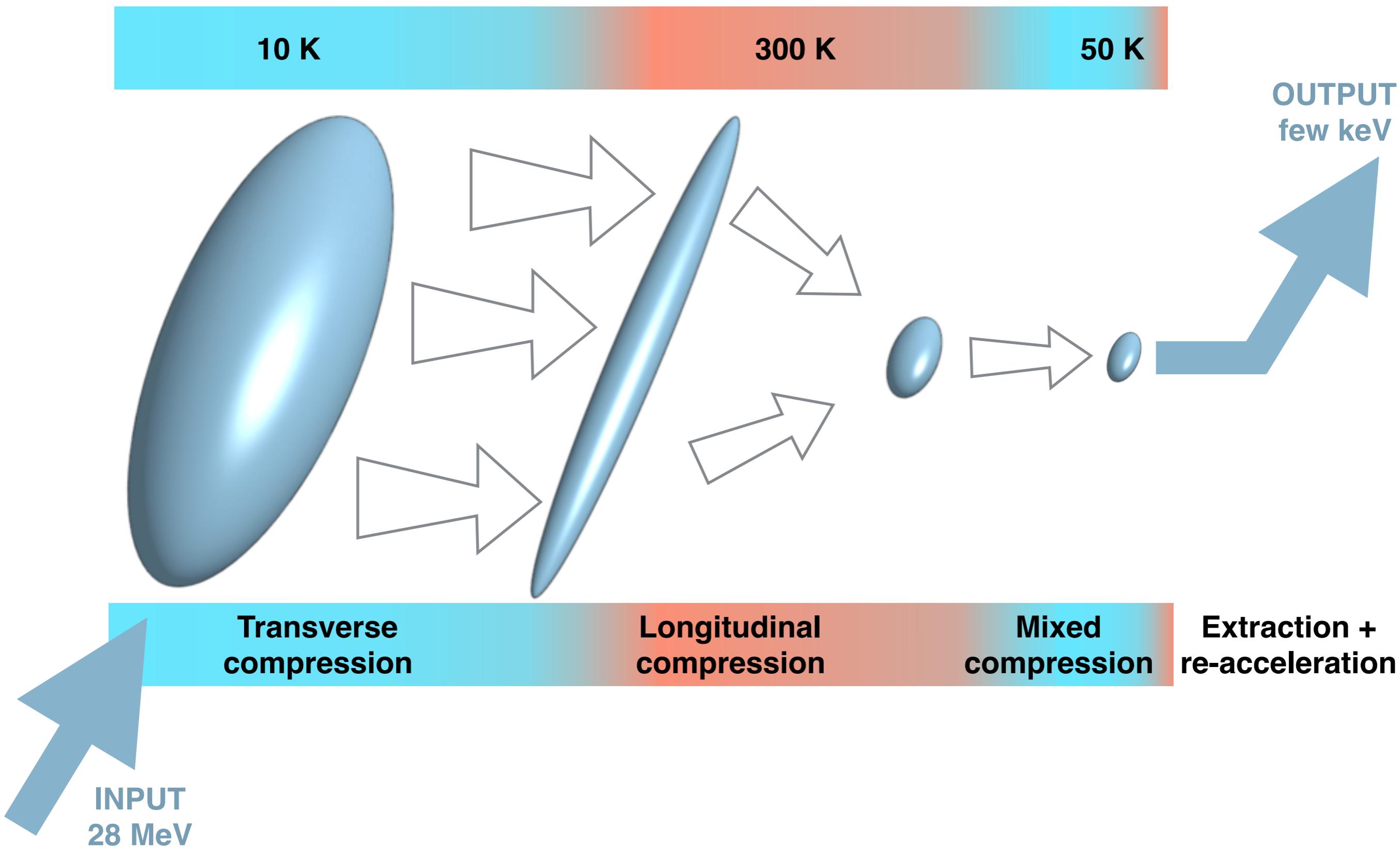
Improve phase space density of standard muon beams by 10 orders of magnitude with 10^{-3} efficiency



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

- ▶ τ_c : time between two μ^+ —He collisions
- ▶ ω : μ^+ cyclotron frequency

The various compressions stages Taqqu, PRL 97, 10 (2006)



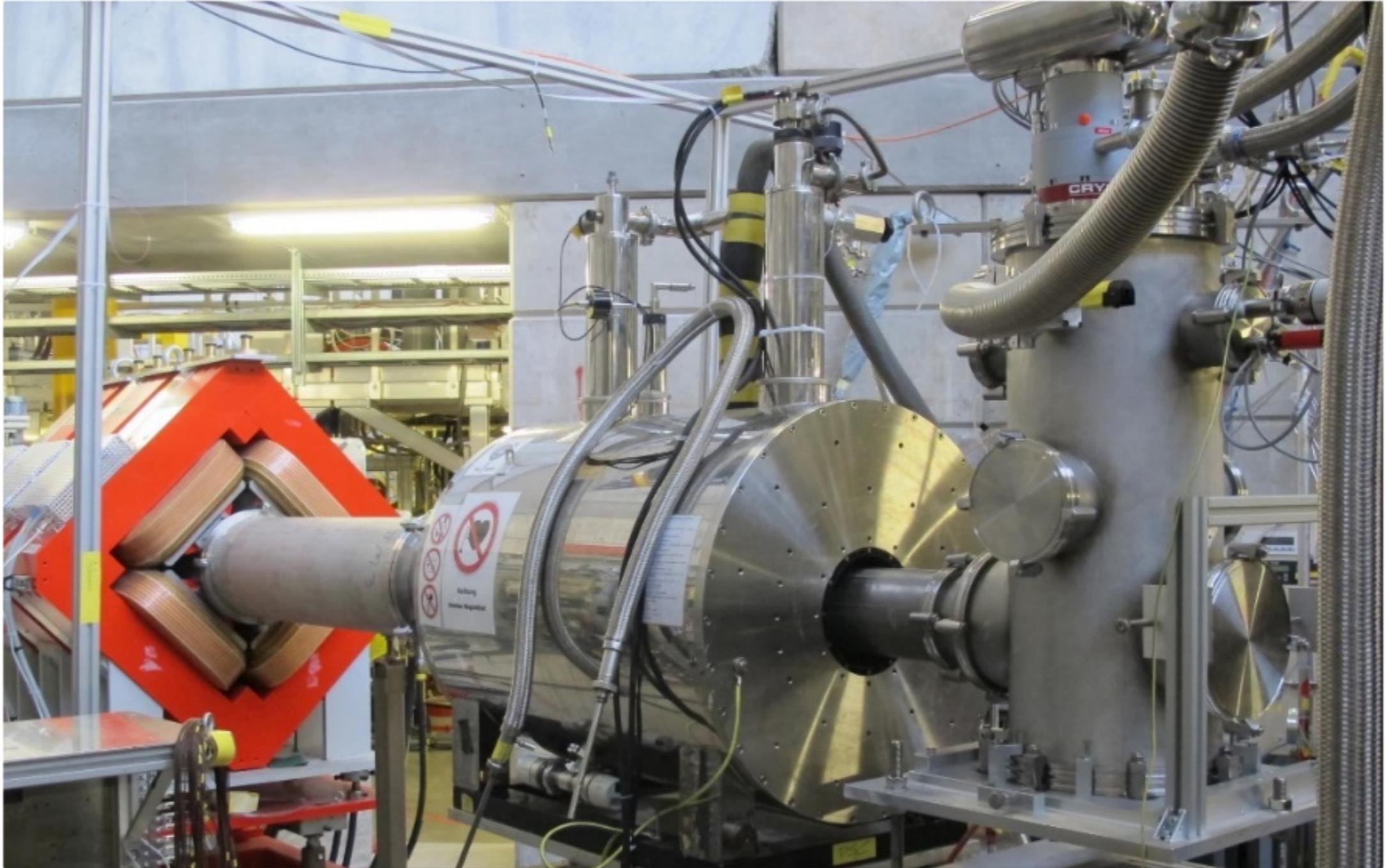
Beam-time history

- | | | |
|-------------|--|--|
| 2011 | <ul style="list-style-type: none">▶ Test of longitudinal compression.<ul style="list-style-type: none">⇒ Successful but limited by gas impurities and misalignments |  |
| 2013 | <ul style="list-style-type: none">▶ Measurement of density gradient using neutron imaging on He³ |  |
| 2014 | <ul style="list-style-type: none">▶ Improved test of longitudinal compression<ul style="list-style-type: none">⇒ Behaviour as expected from simulations▶ Engineering run of transverse compression stage<ul style="list-style-type: none">⇒ Detectors, cryostat, beam ok, but issues with the cryogenic target | 
 |
| 2015 | <ul style="list-style-type: none">▶ Improved test of longitudinal compression with ExB drift▶ Test of the transverse compression<ul style="list-style-type: none">⇒ Behaviour as expected from simulations | 
 |
| 2017 | <ul style="list-style-type: none">▶ Test of mixed longitudinal-transverse compression in a cryogenic target<ul style="list-style-type: none">⇒ Successful but limited by target issues |  |
| 2019 | | |

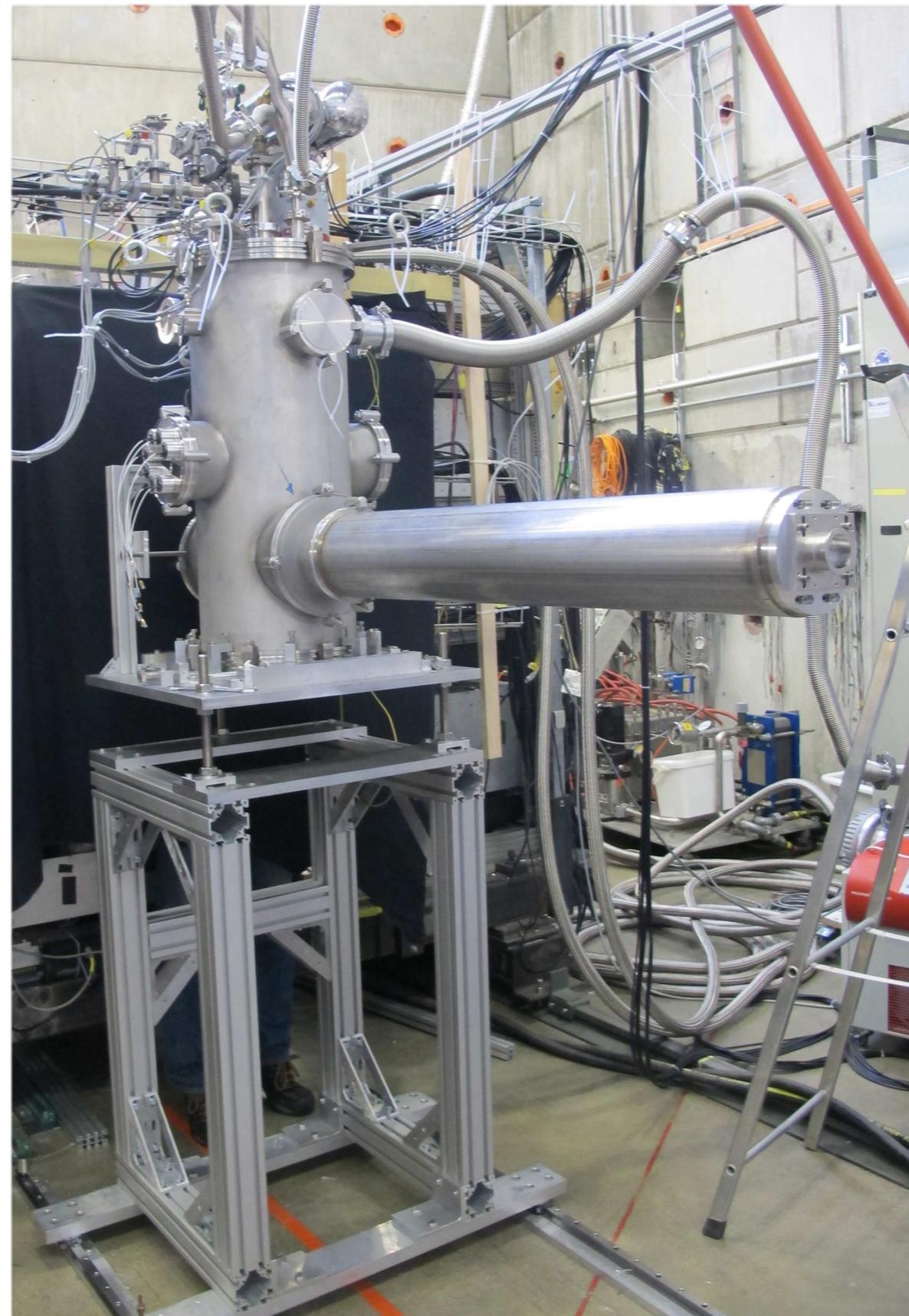
Beam-time history

- | | | |
|-------------|--|--|
| 2011 | <ul style="list-style-type: none">▶ Test of longitudinal compression.<ul style="list-style-type: none">⇒ Successful but limited by gas impurities and misalignments |  |
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 |
| 2017 | <ul style="list-style-type: none">▶ Test of mixed longitudinal-transverse compression in a cryogenic target<ul style="list-style-type: none">⇒ Successful but limited by target issues |  |
| 2019 | <ul style="list-style-type: none">▶ Improved test of mixed compression▶ Simplified extraction test | |

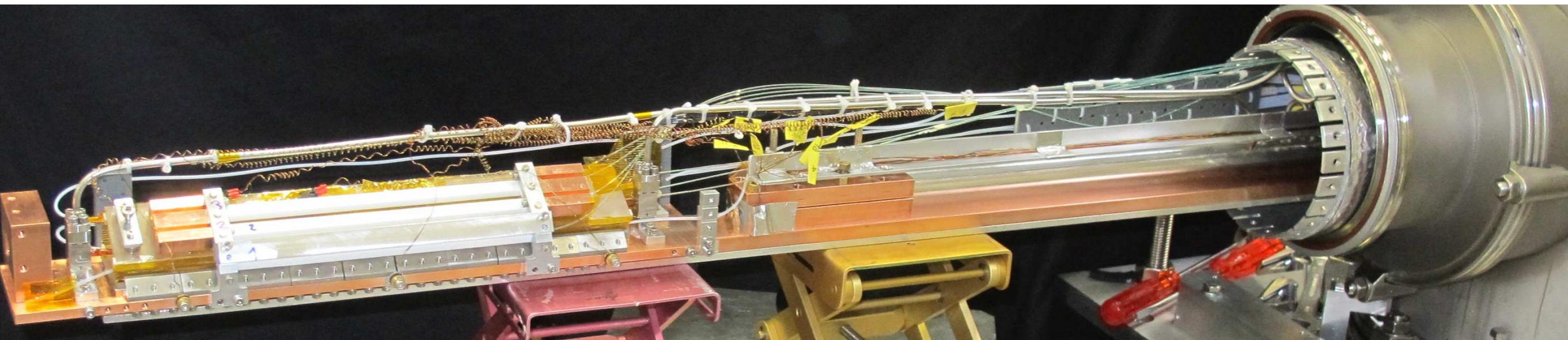
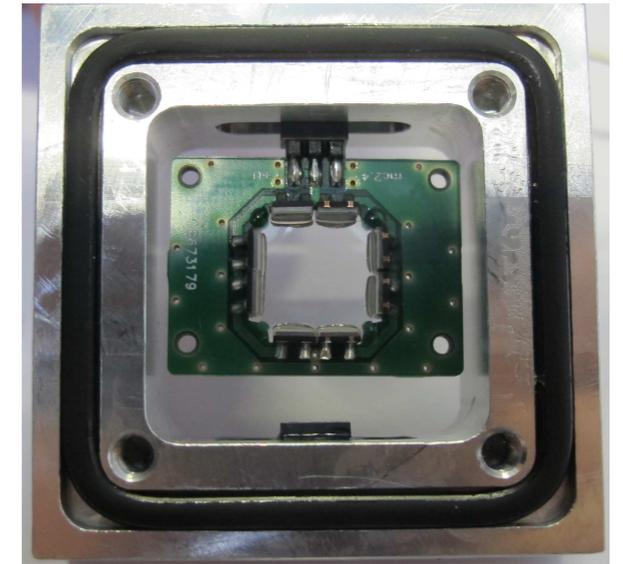
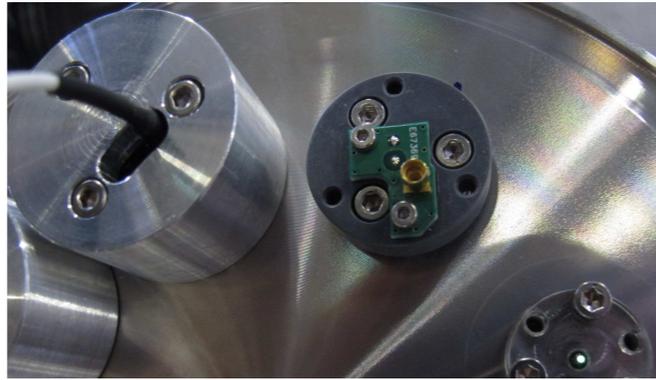
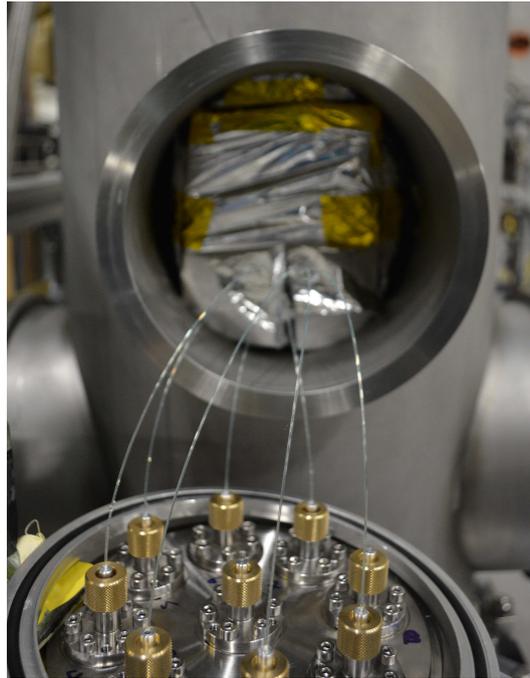
Transverse compression setup



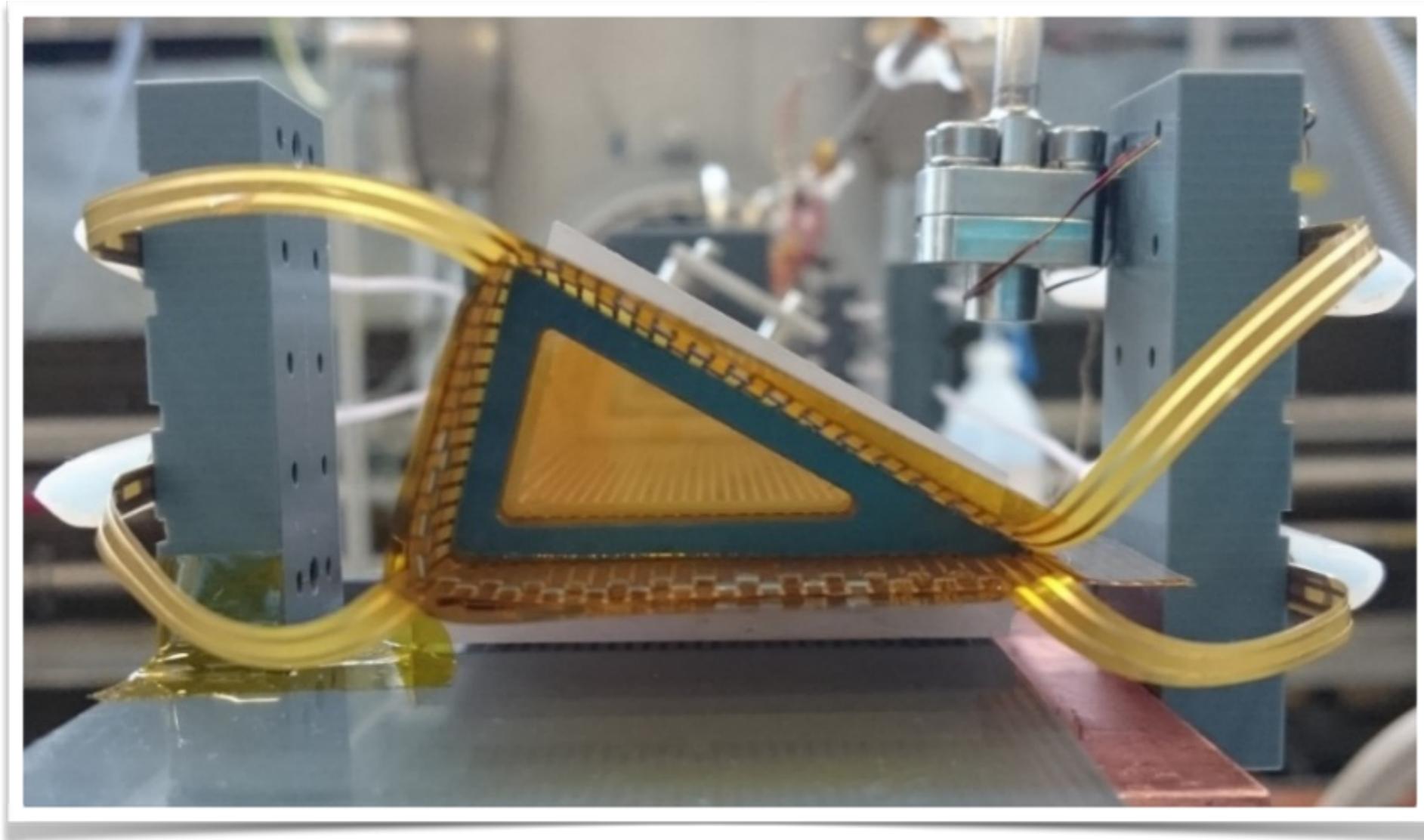
Transverse compression setup



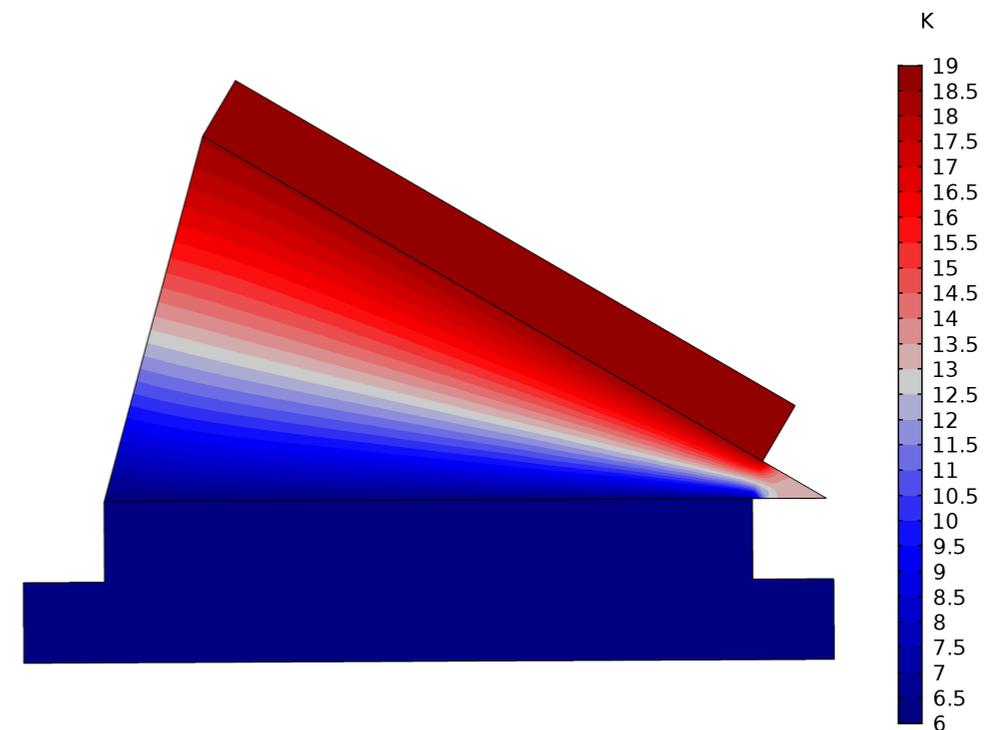
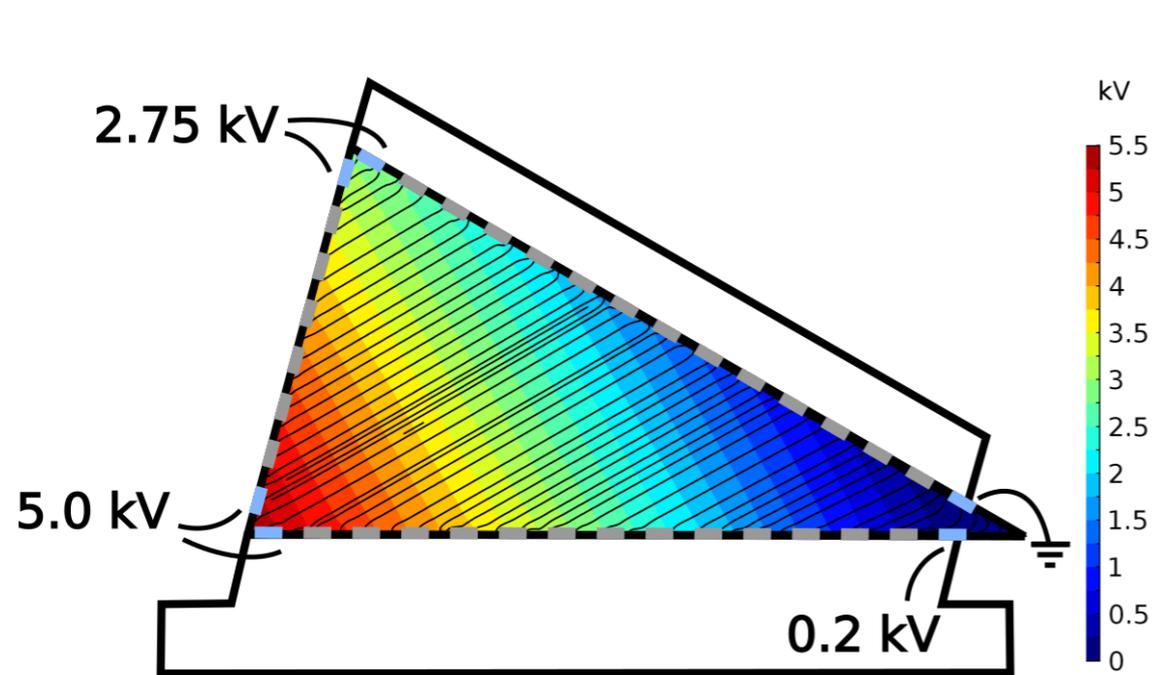
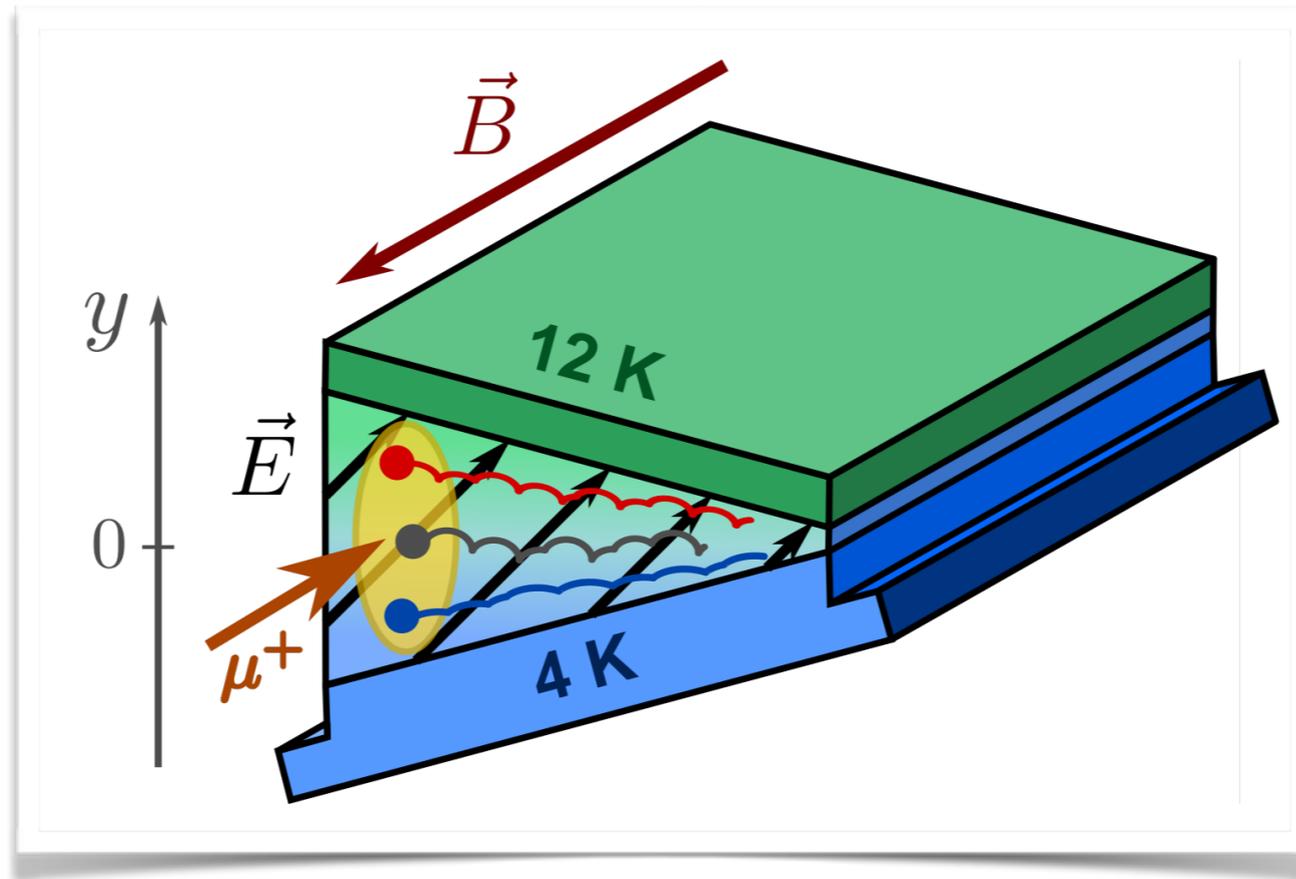
Transverse compression setup



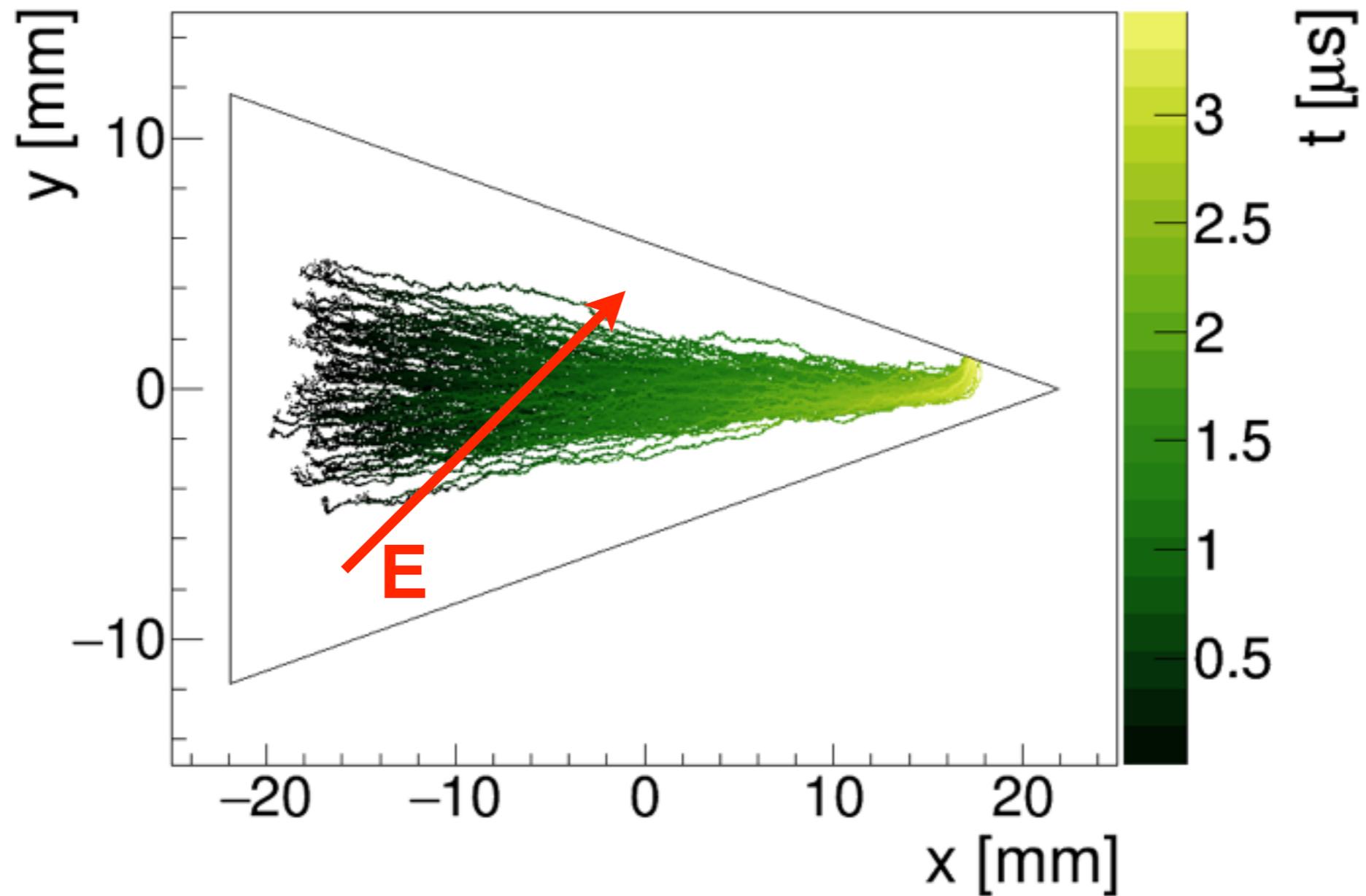
Transverse target



Transverse target

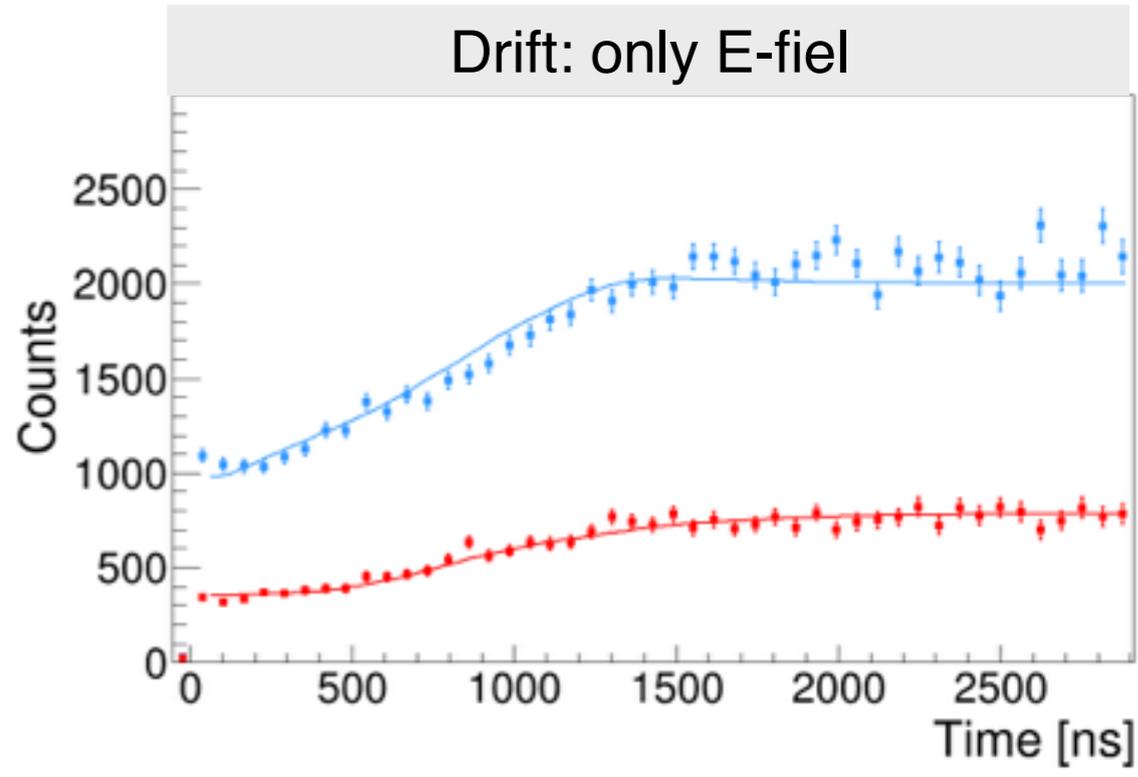
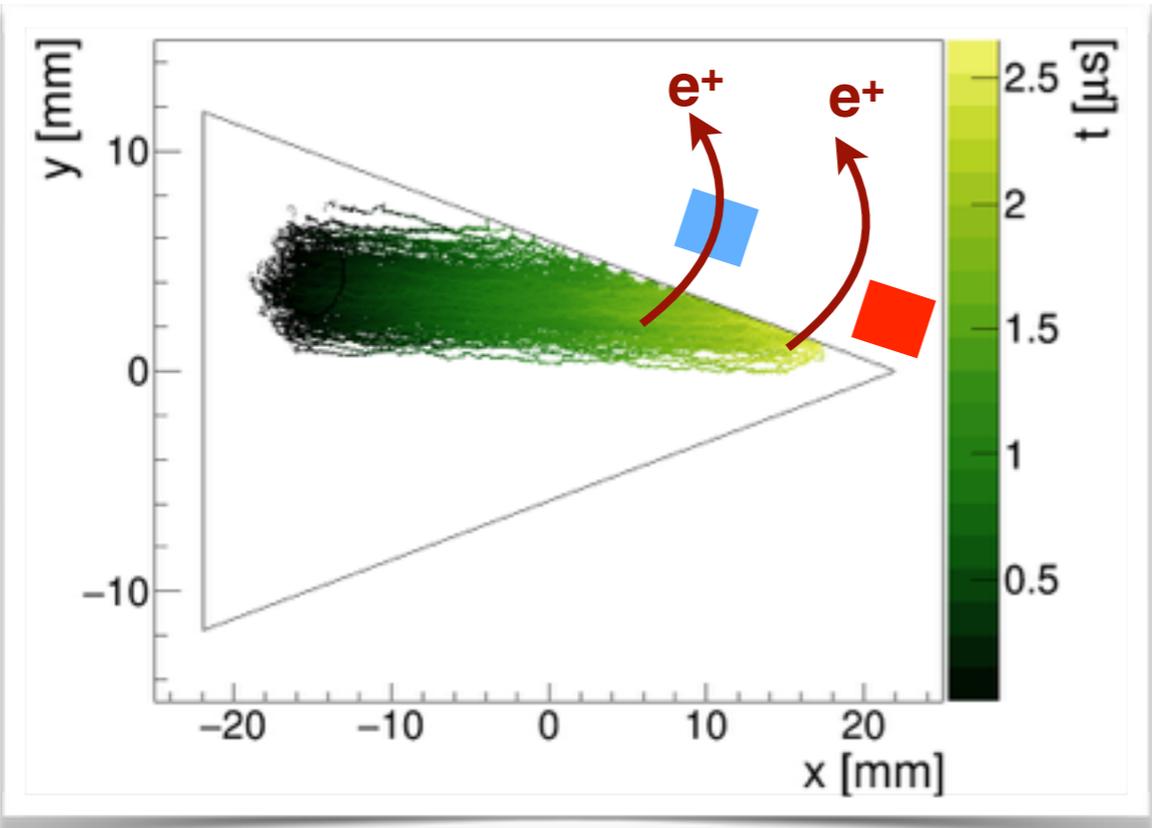
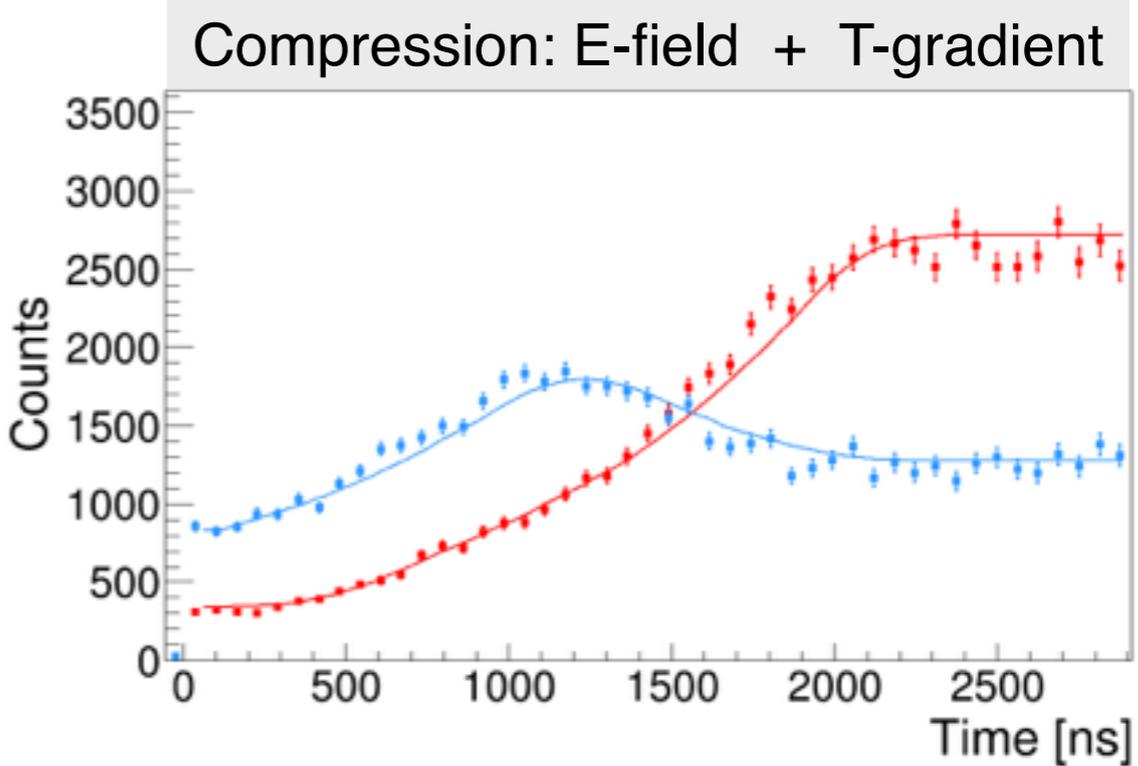
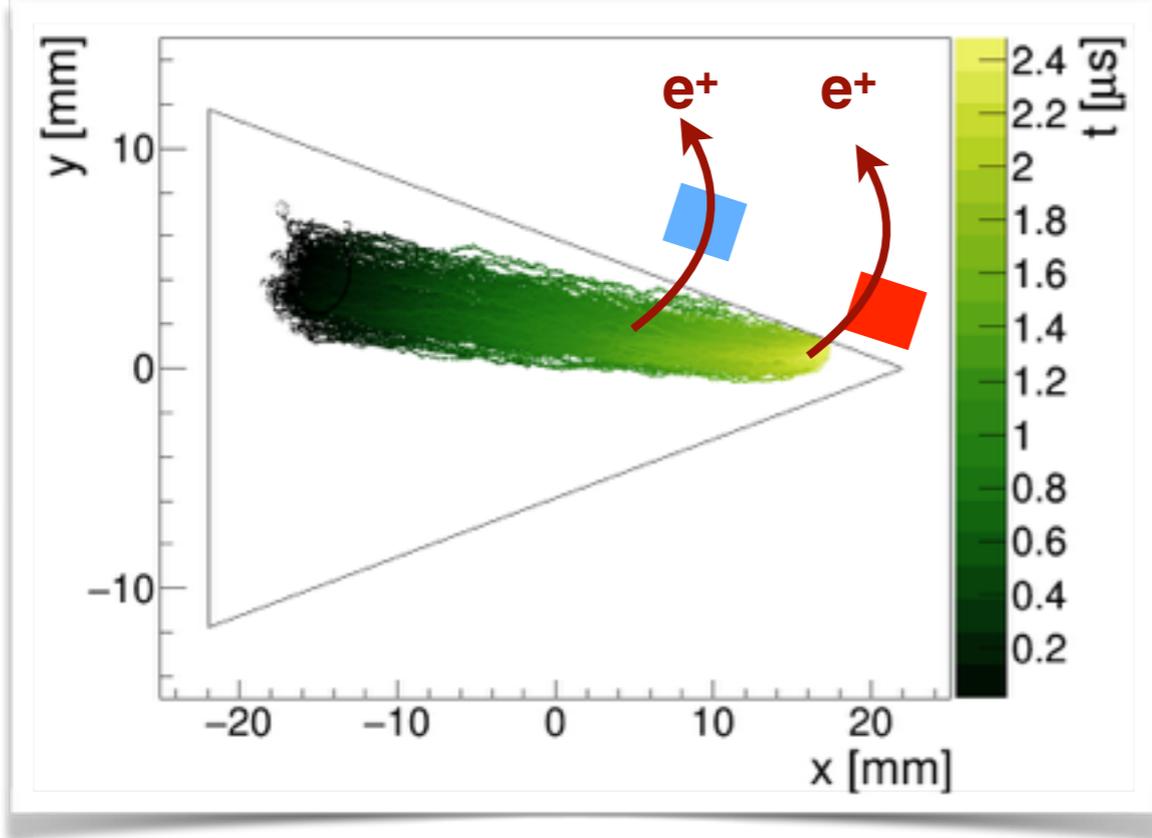


Transverse compression: simulations

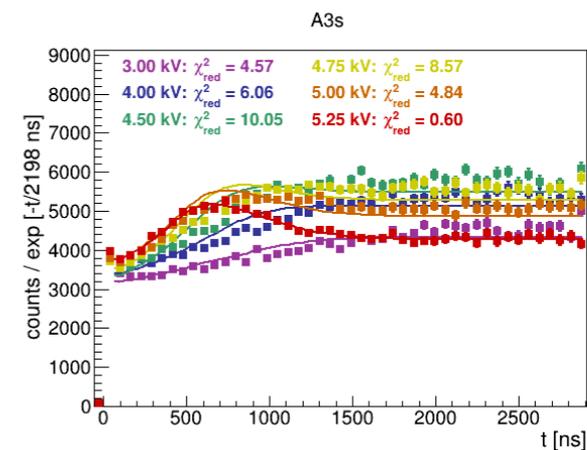
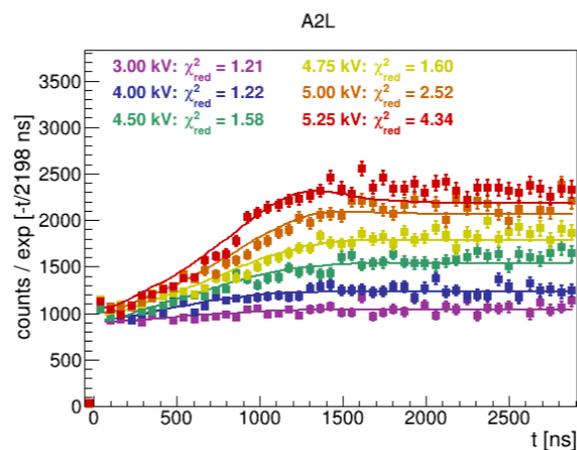
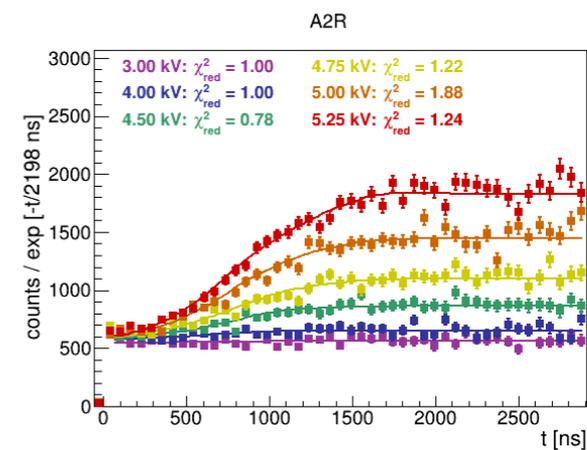
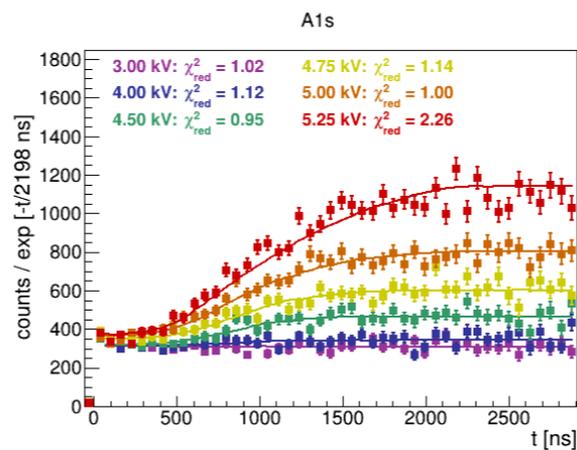
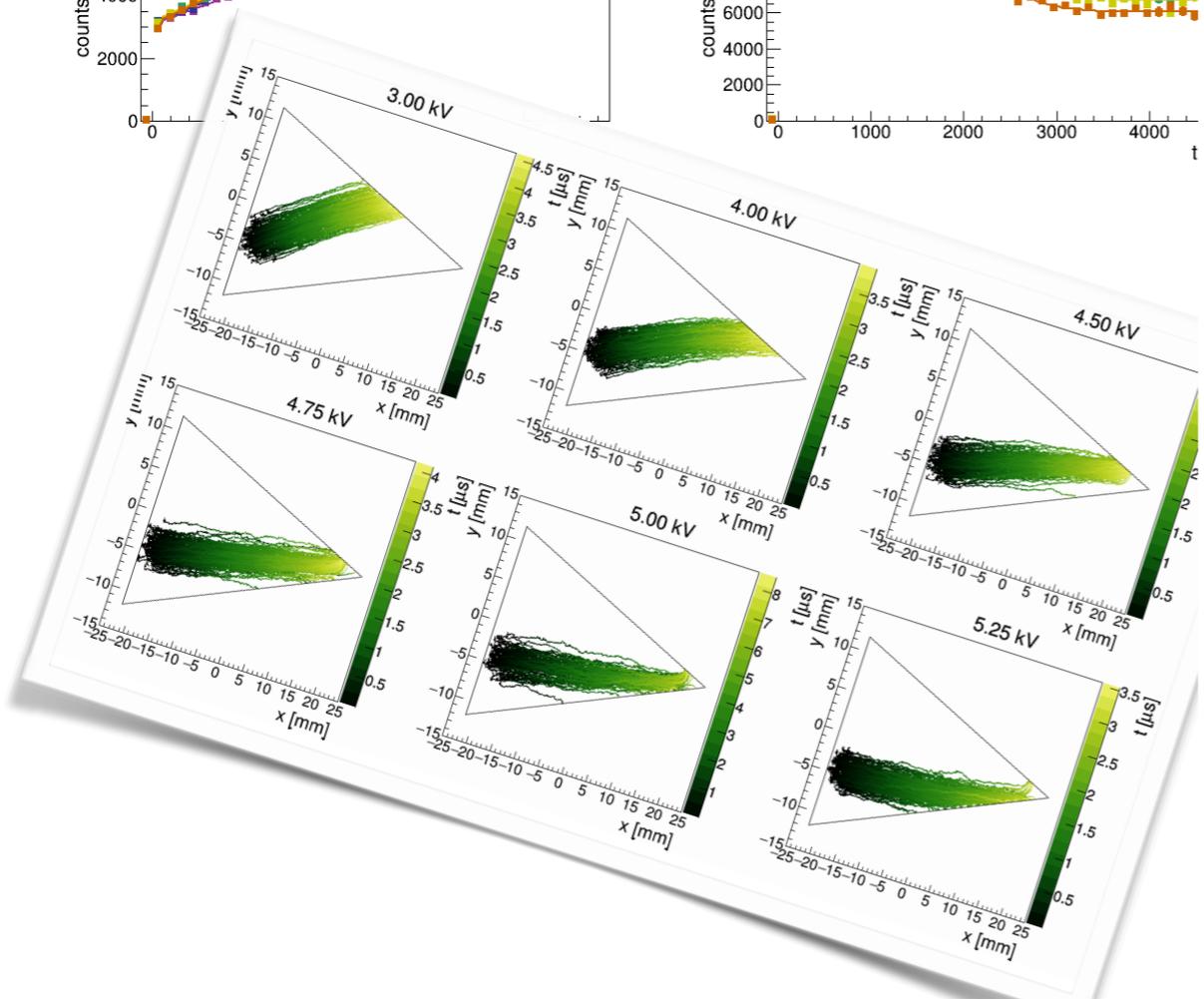
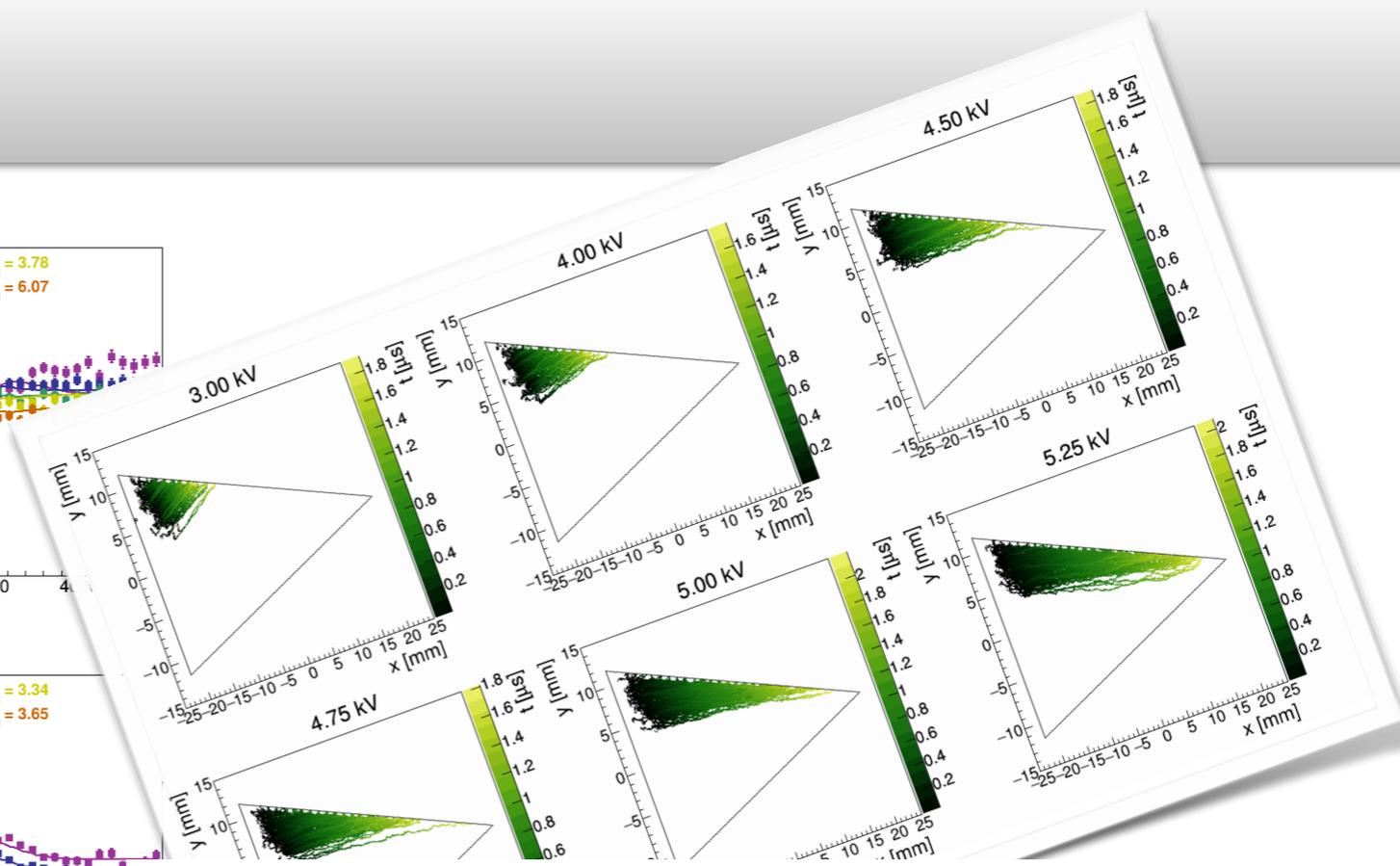
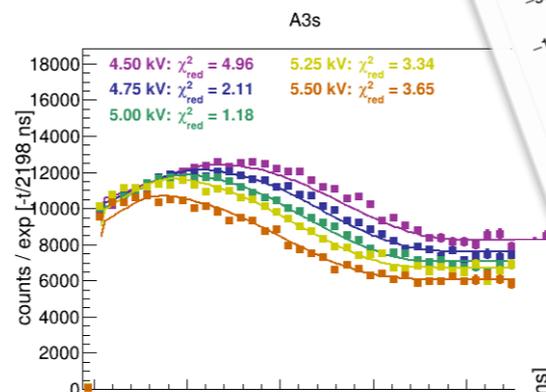
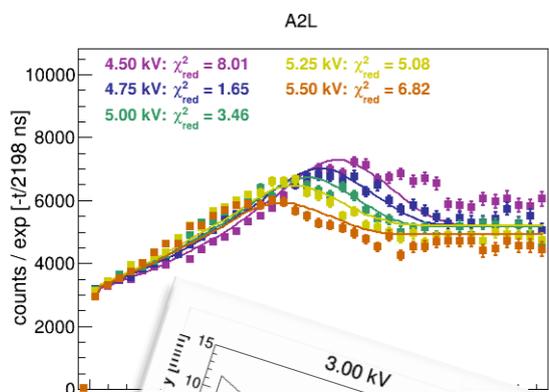
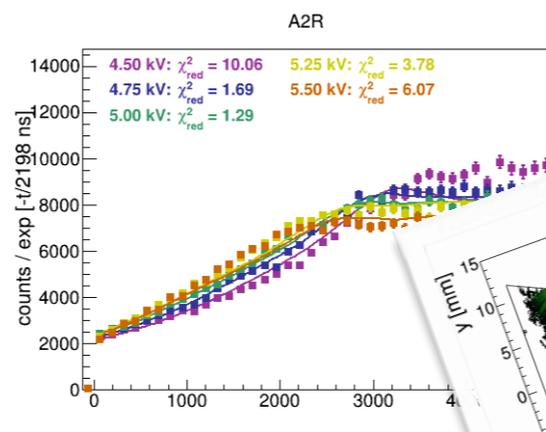
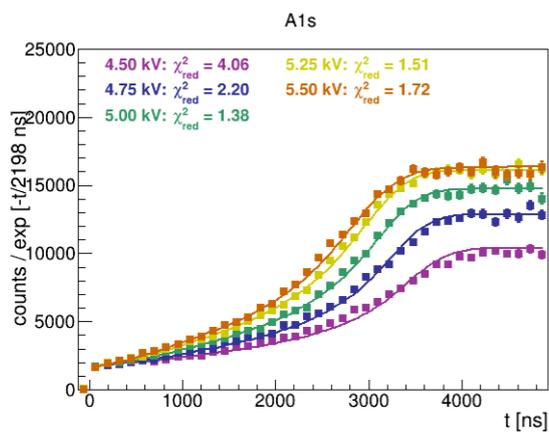


+ vertical density gradient

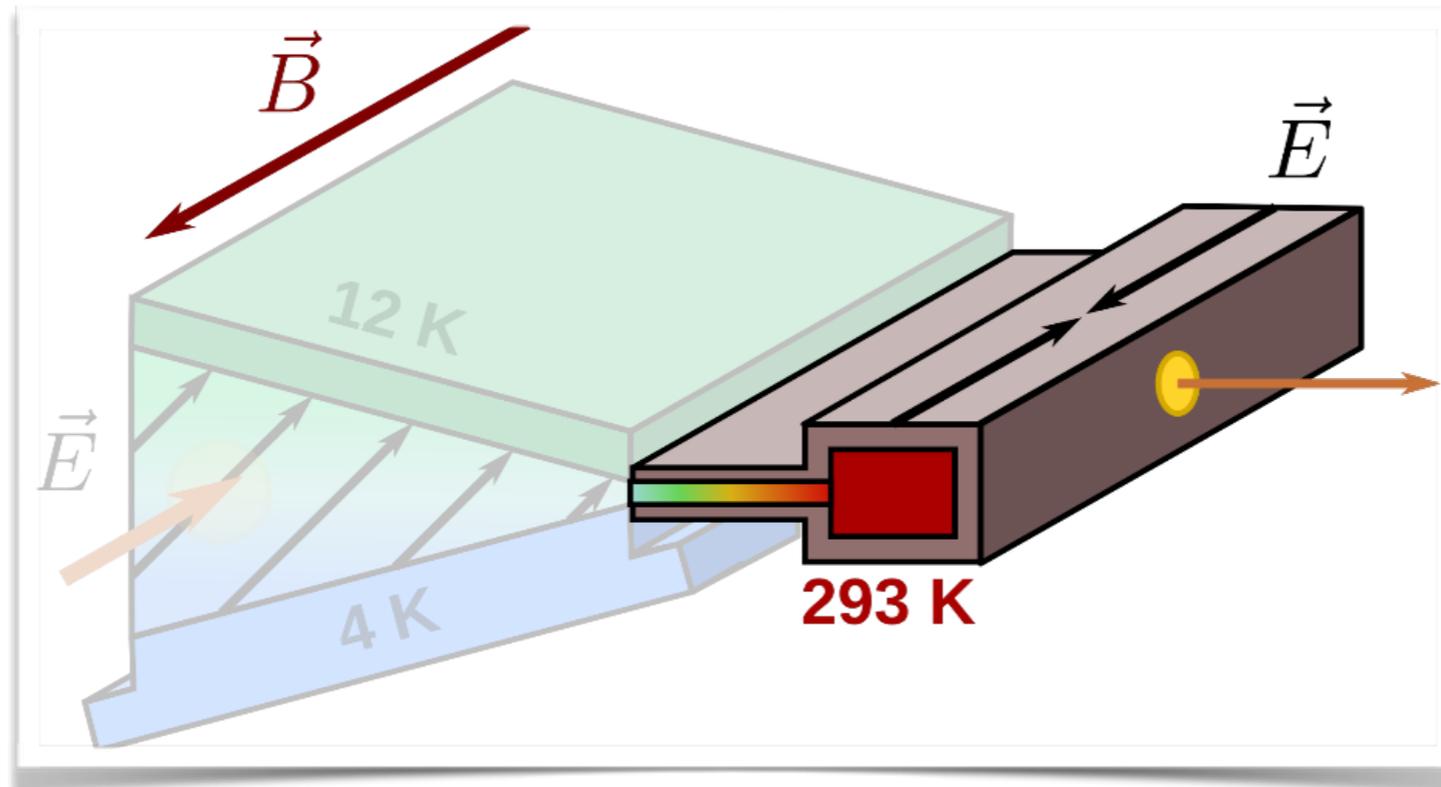
Simulated and measured transverse compression



Many more.....



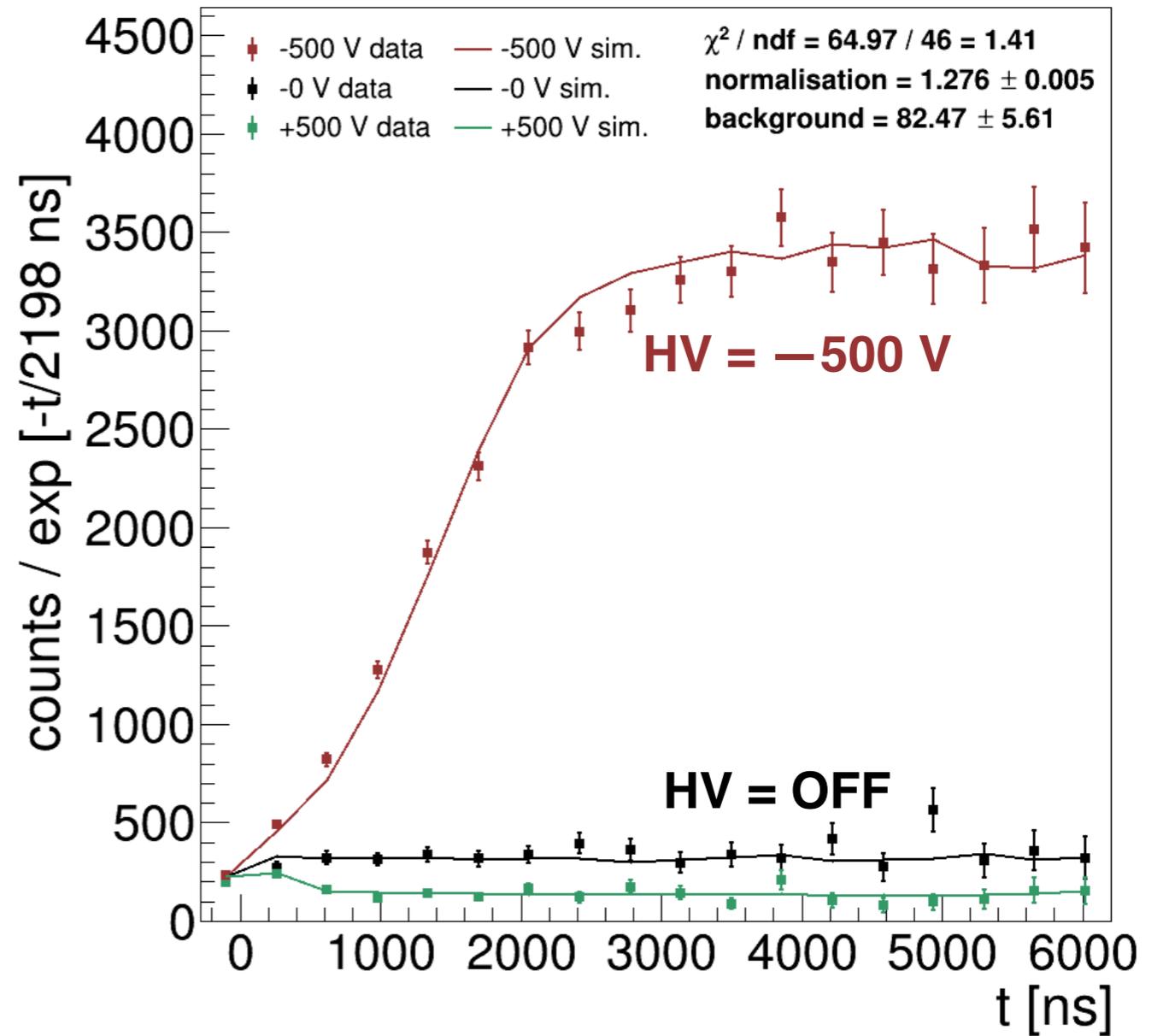
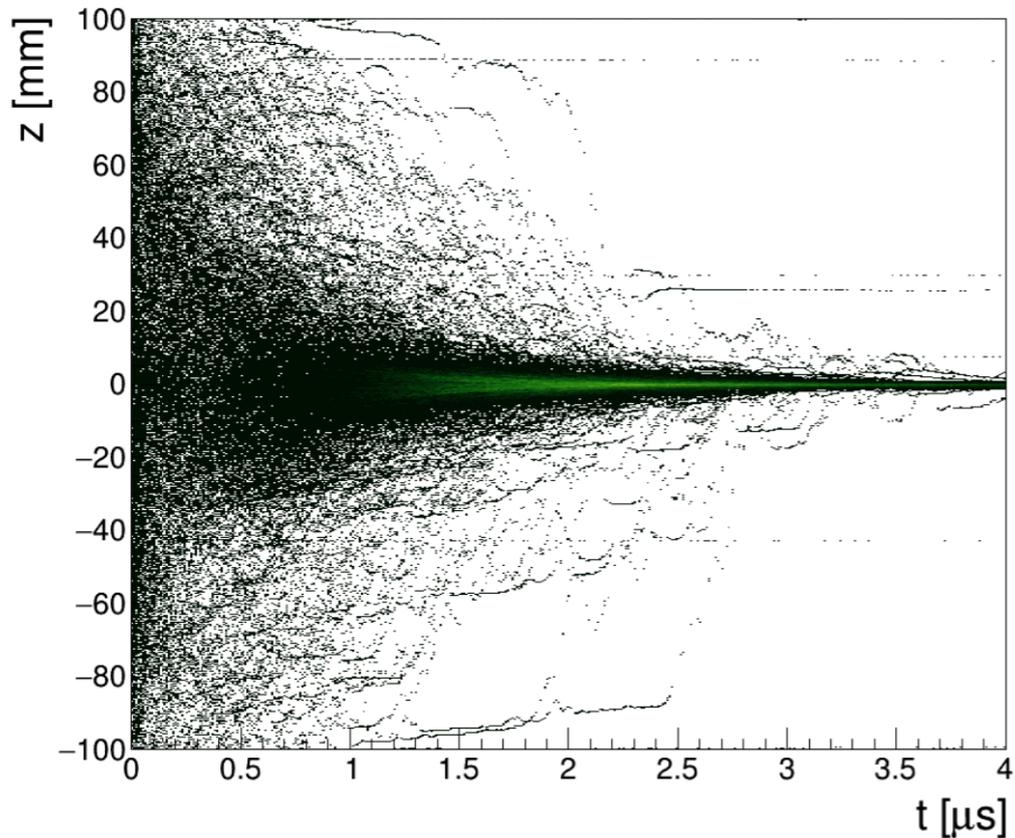
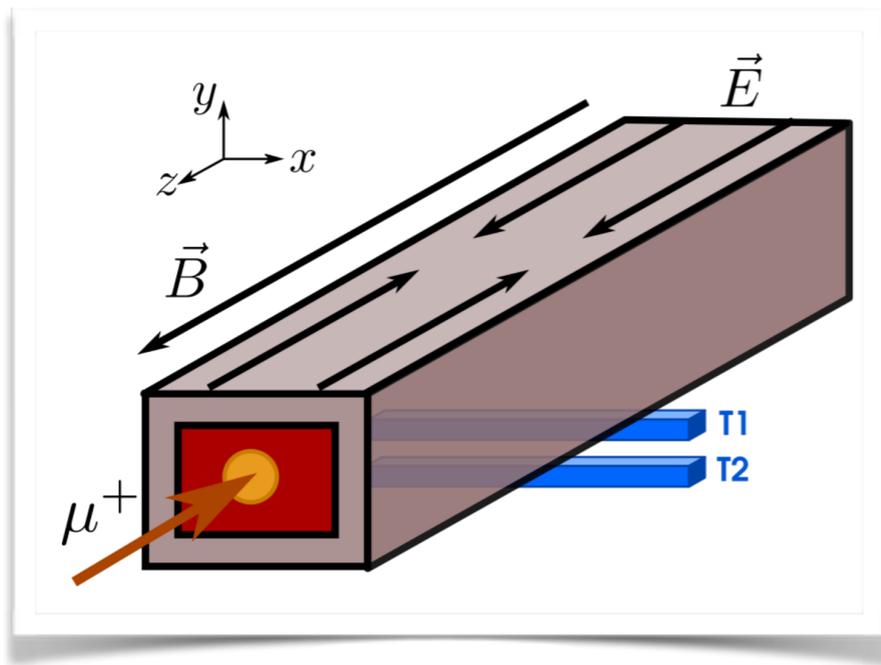
Longitudinal compression test



Y. Bao et al., PRL 224801 (2014)

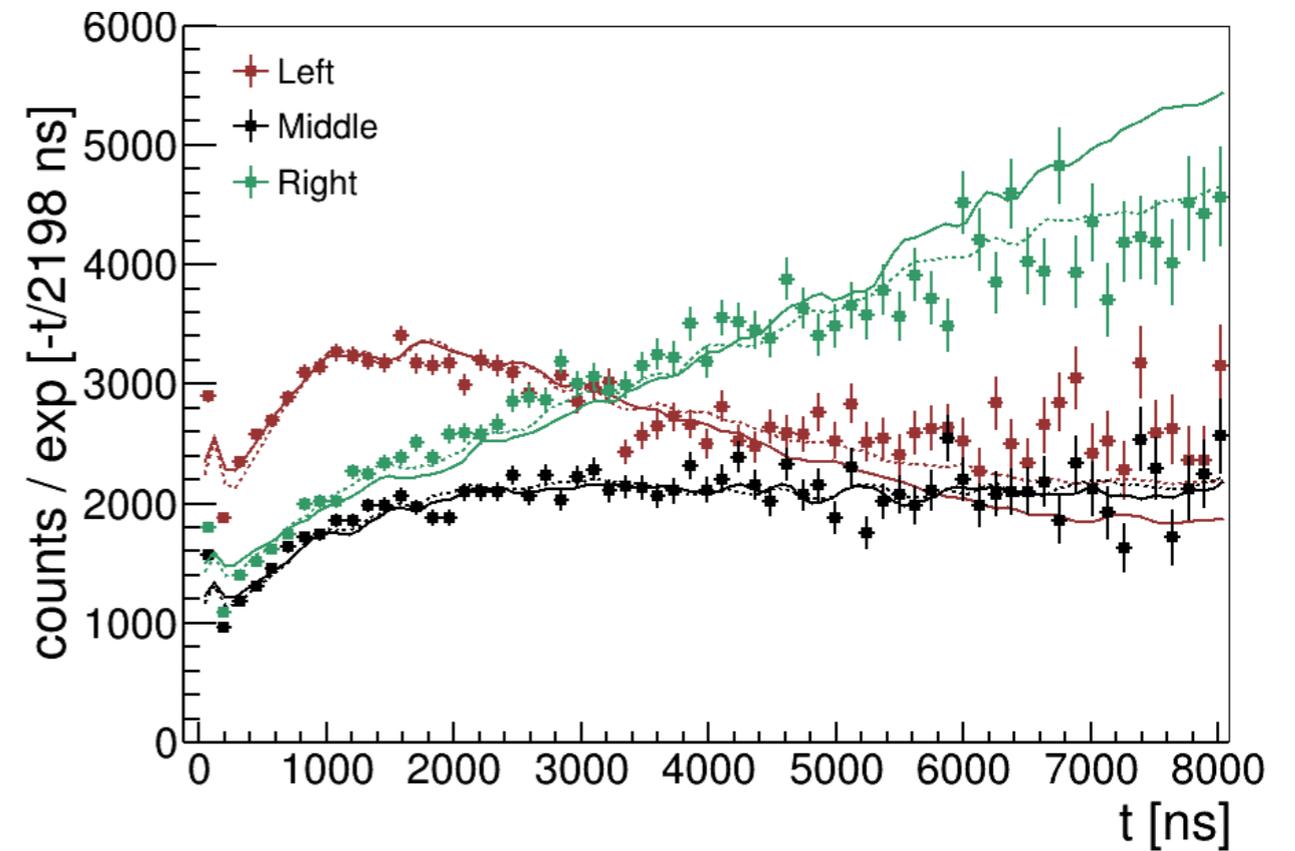
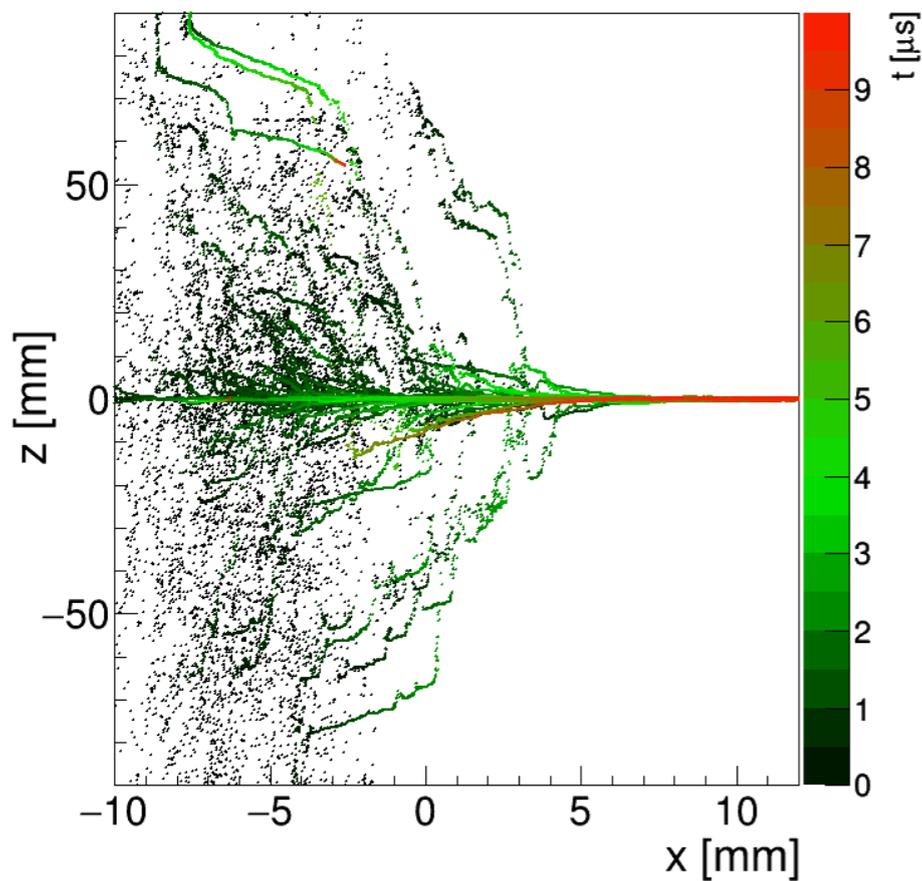
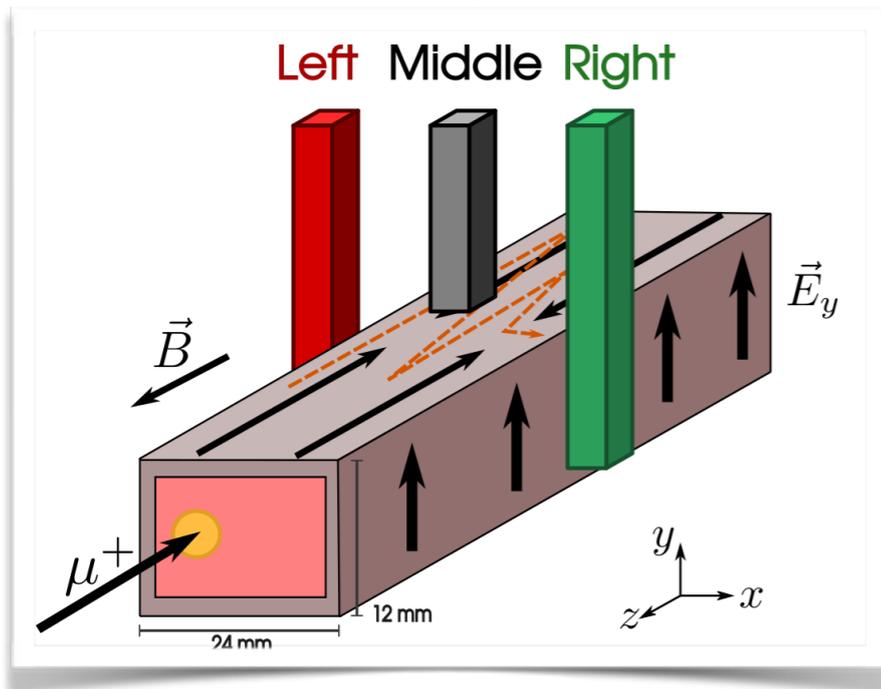
I. Belosevic et al., arXiv:1811.08332

Longitudinal compression test



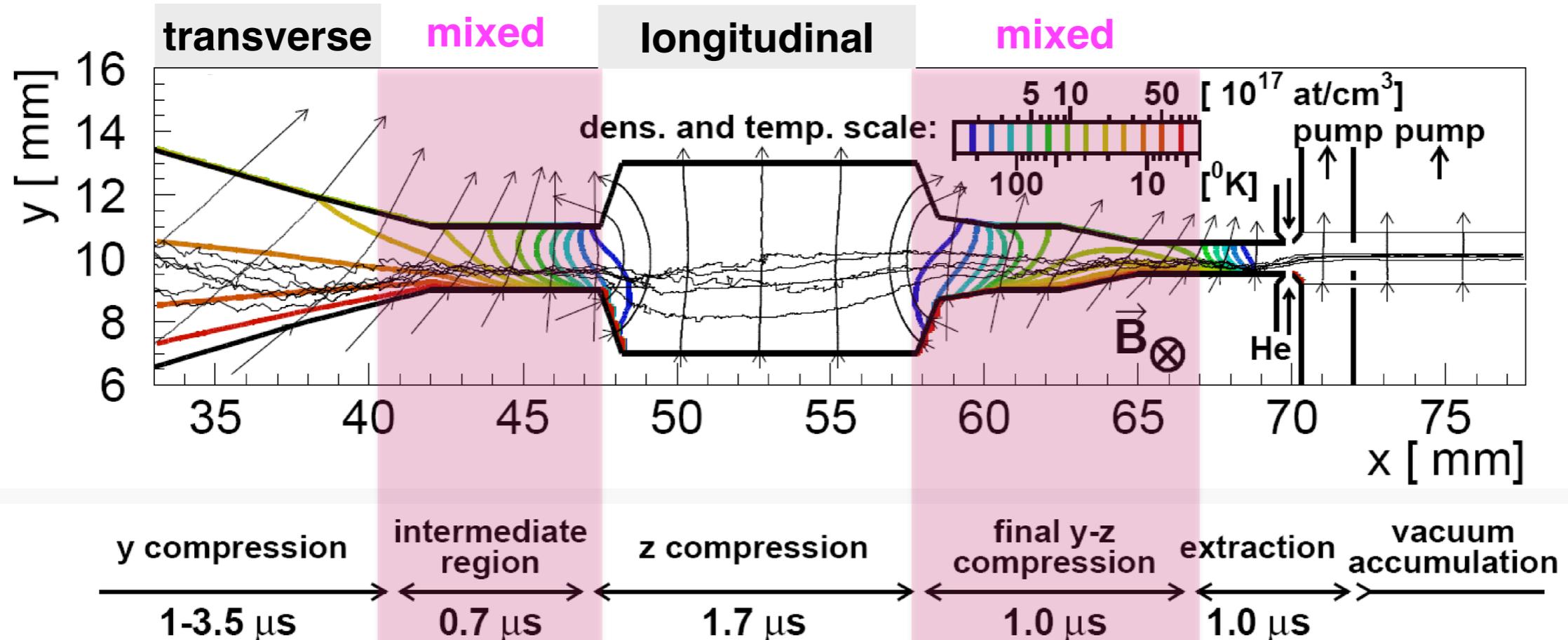
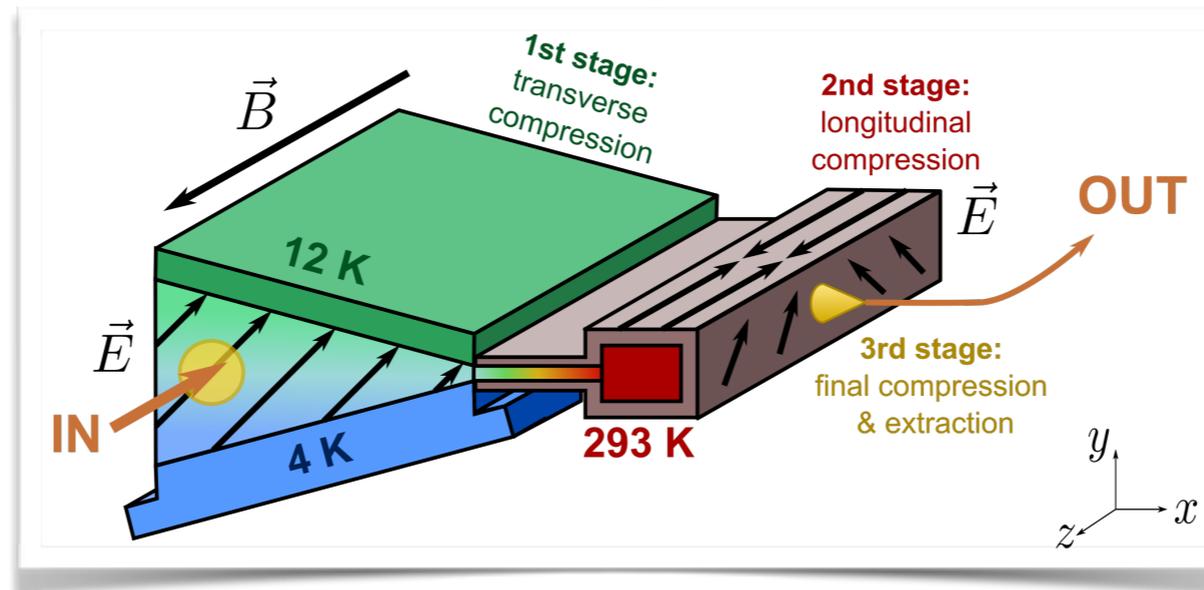
I. Belosevic et al., [arXiv:1811.08332](https://arxiv.org/abs/1811.08332)

Longitudinal compression with ExB drift

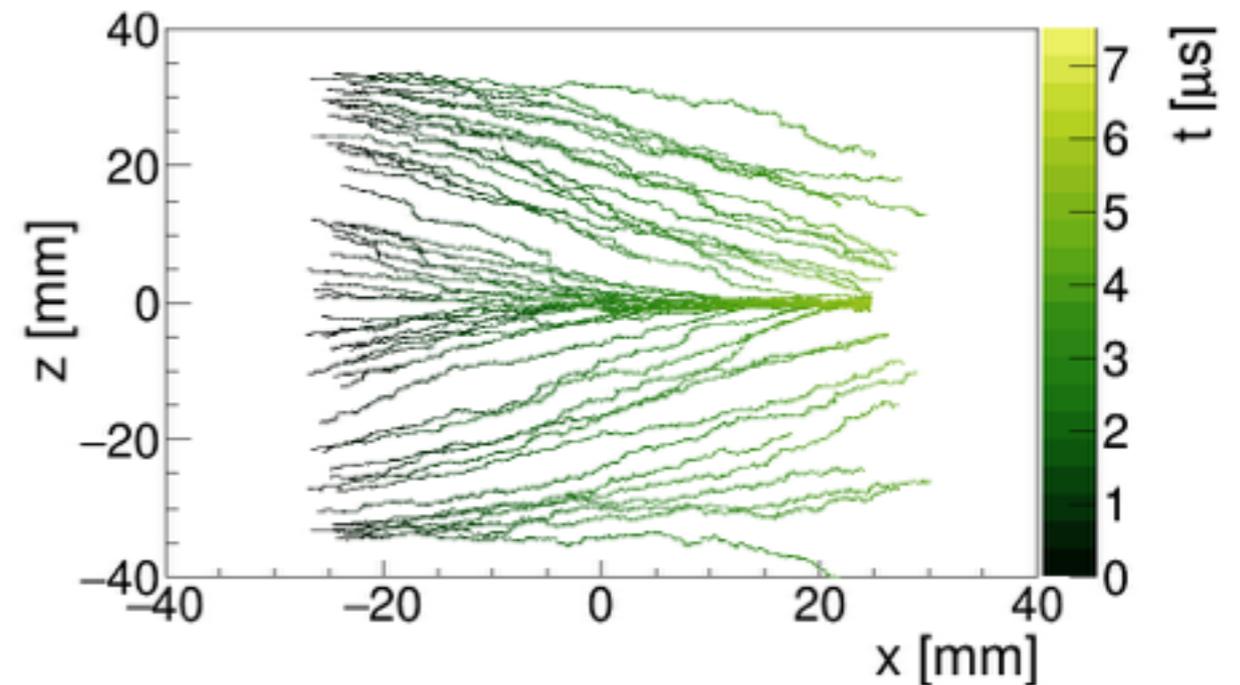
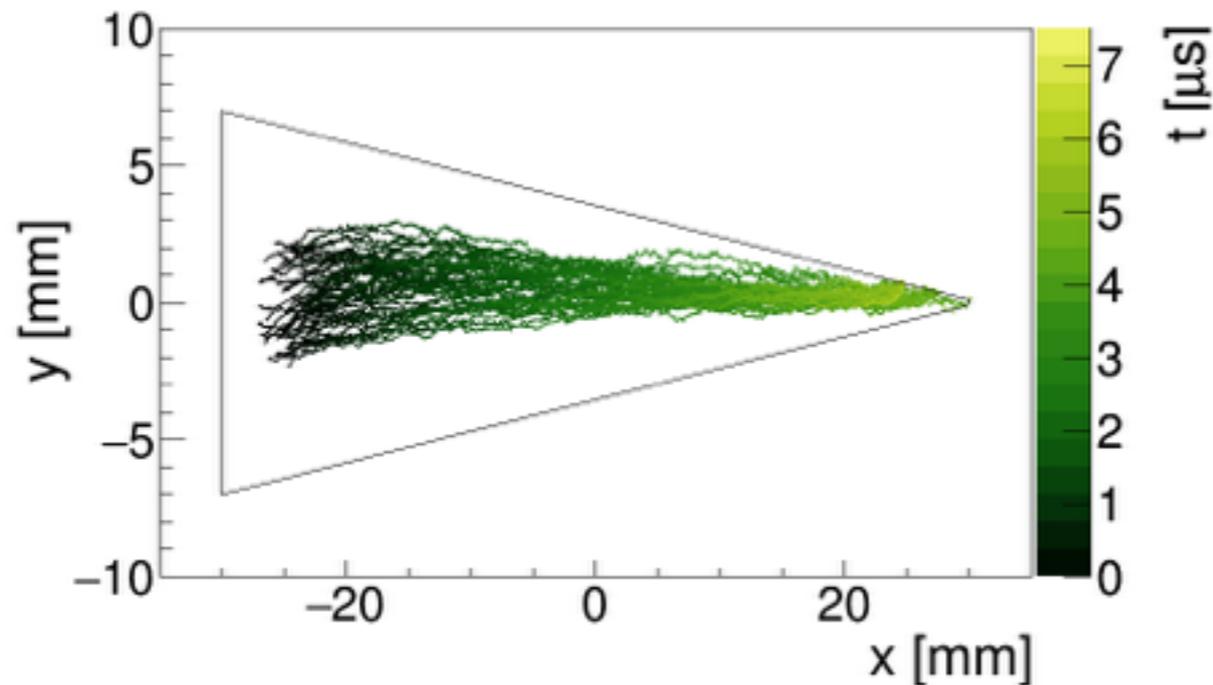
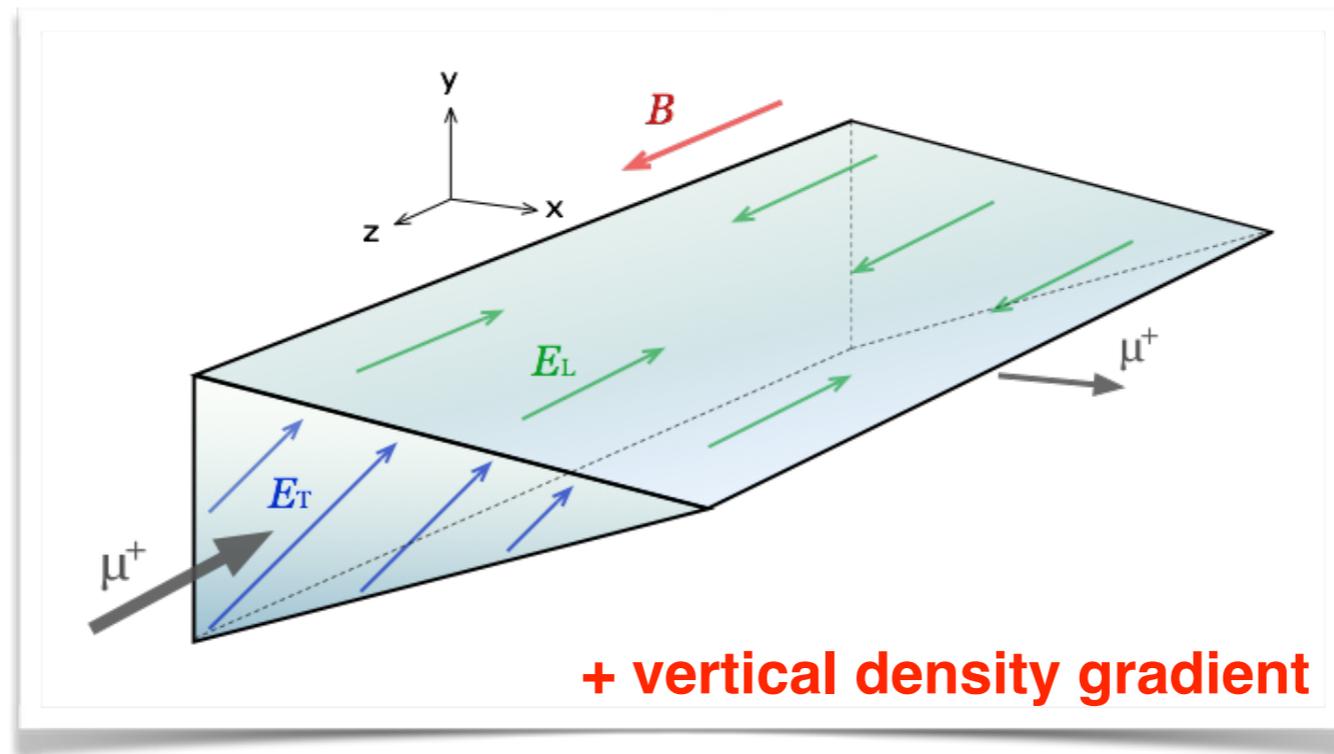


I. Belosevic et al., [arXiv:1811.08332](https://arxiv.org/abs/1811.08332)

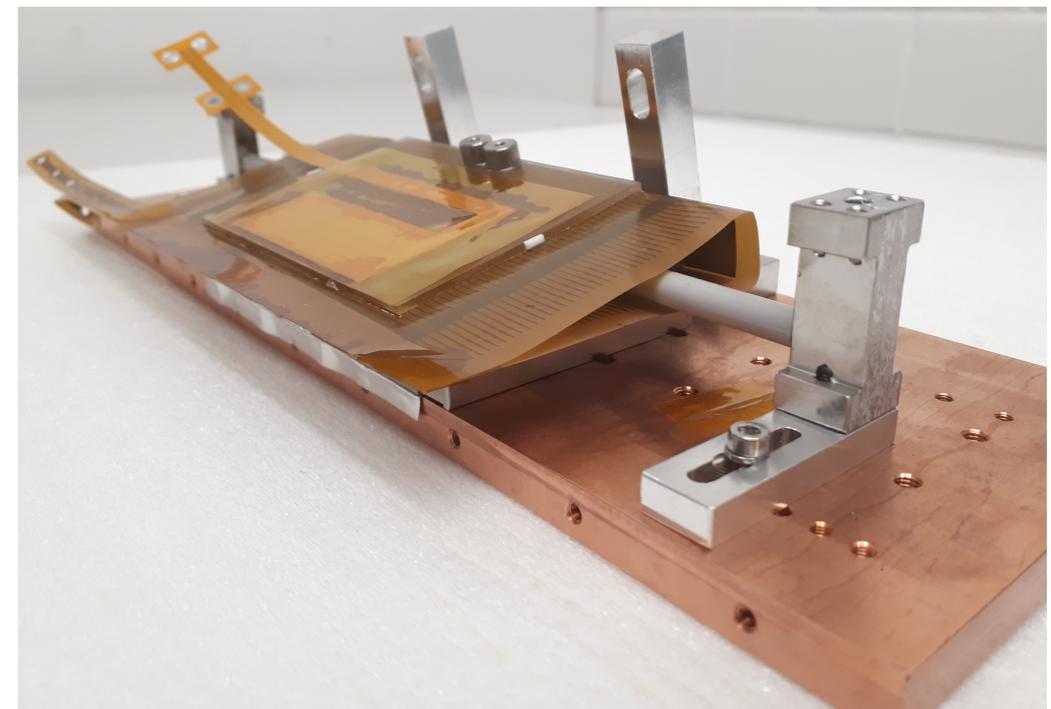
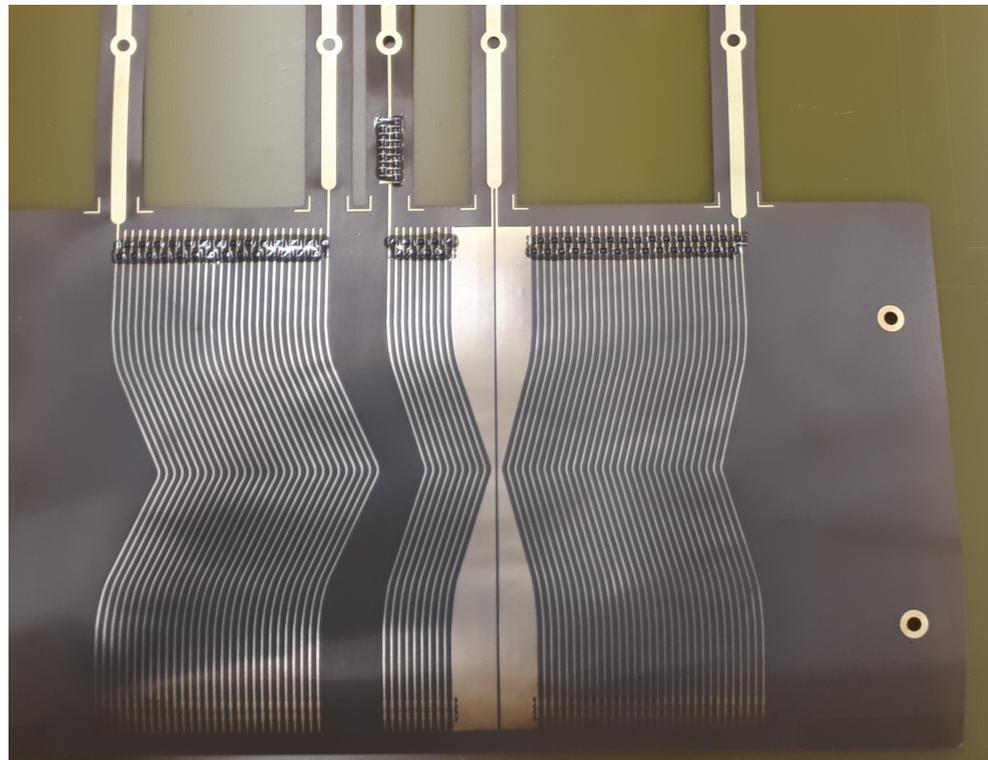
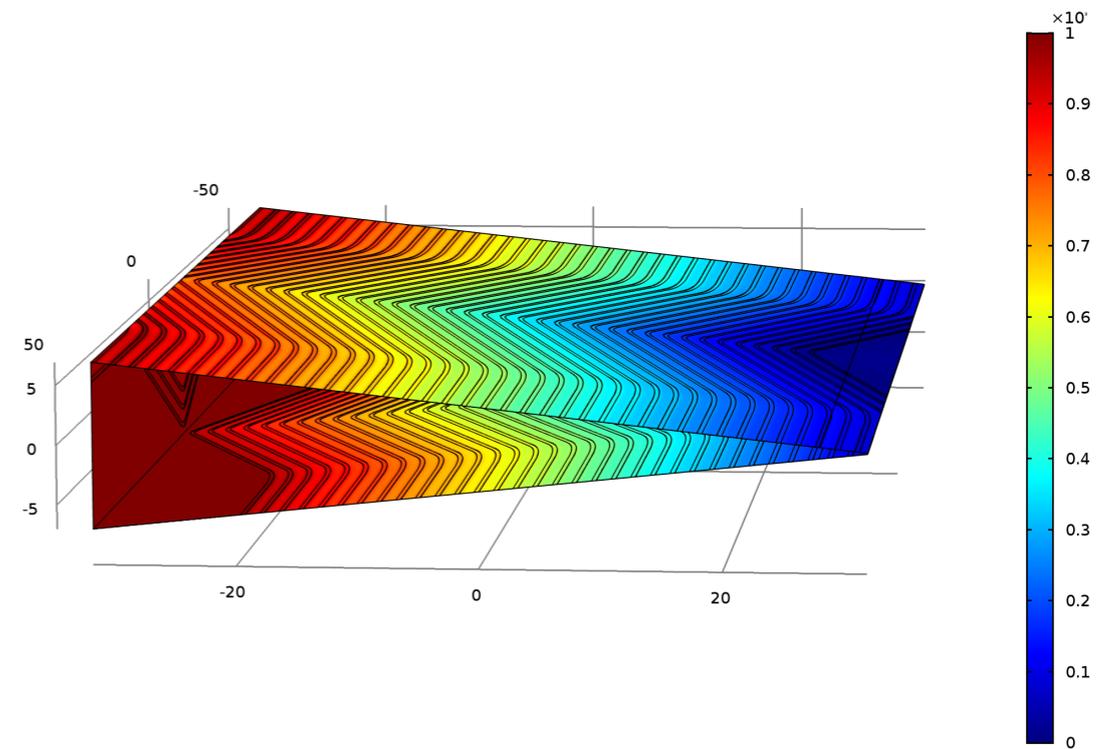
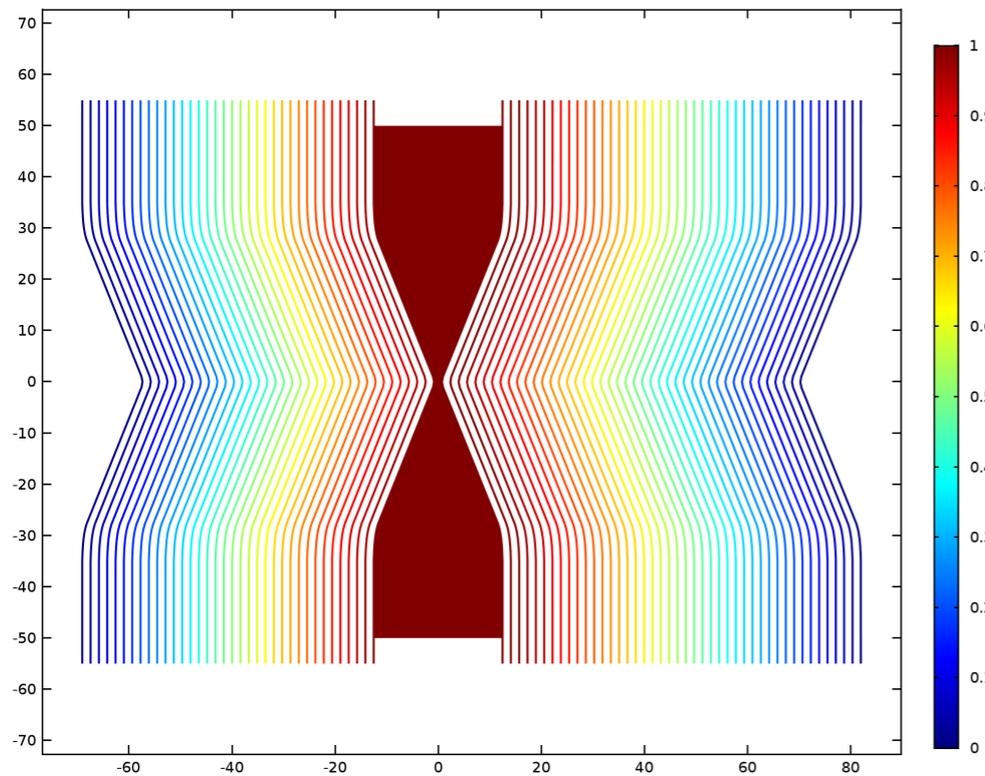
Mixed longitudinal-transverse compression



Target and simulations of mixed compression

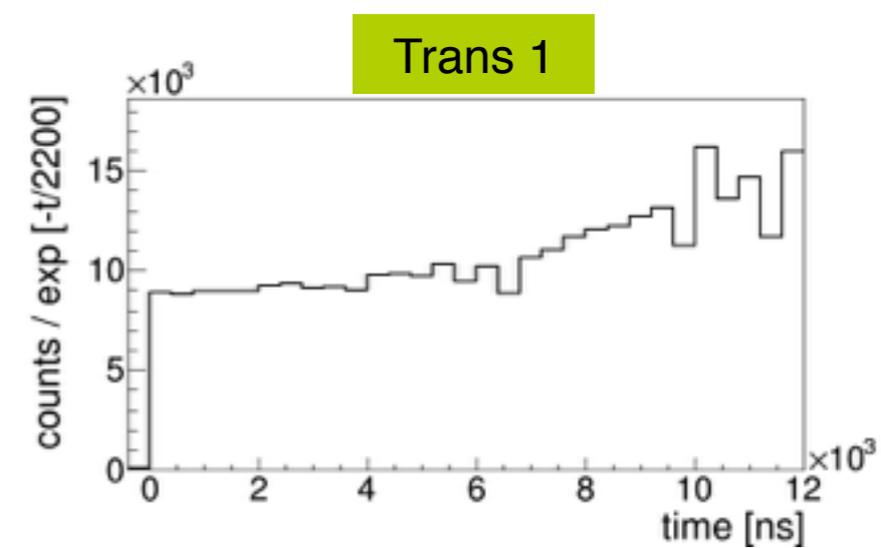
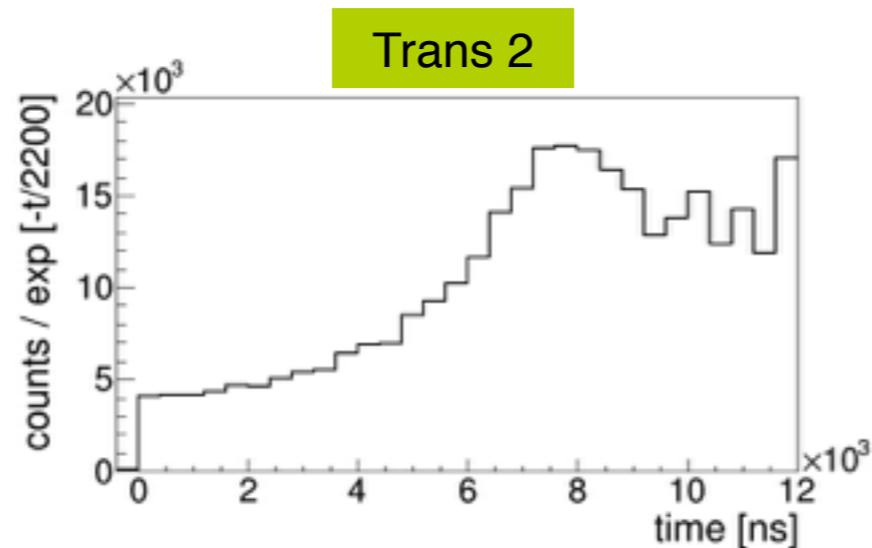
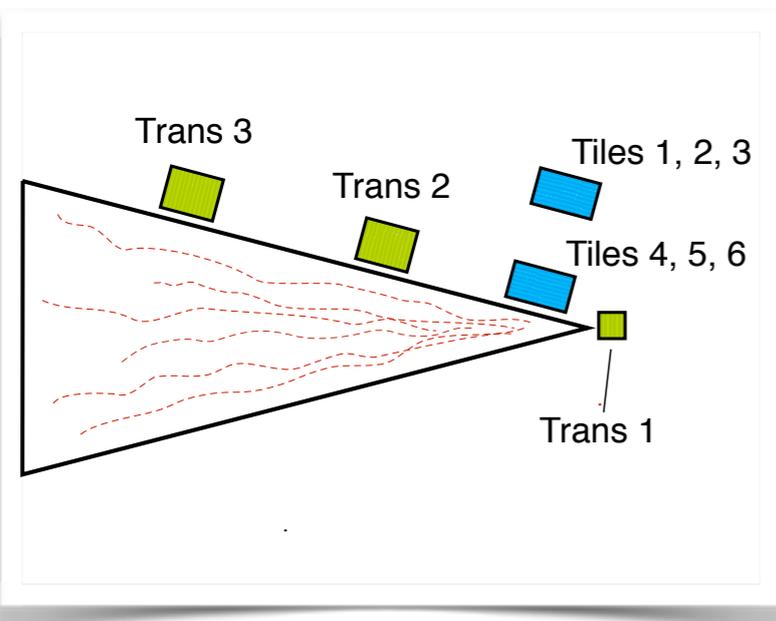


Target construction for mixed compression

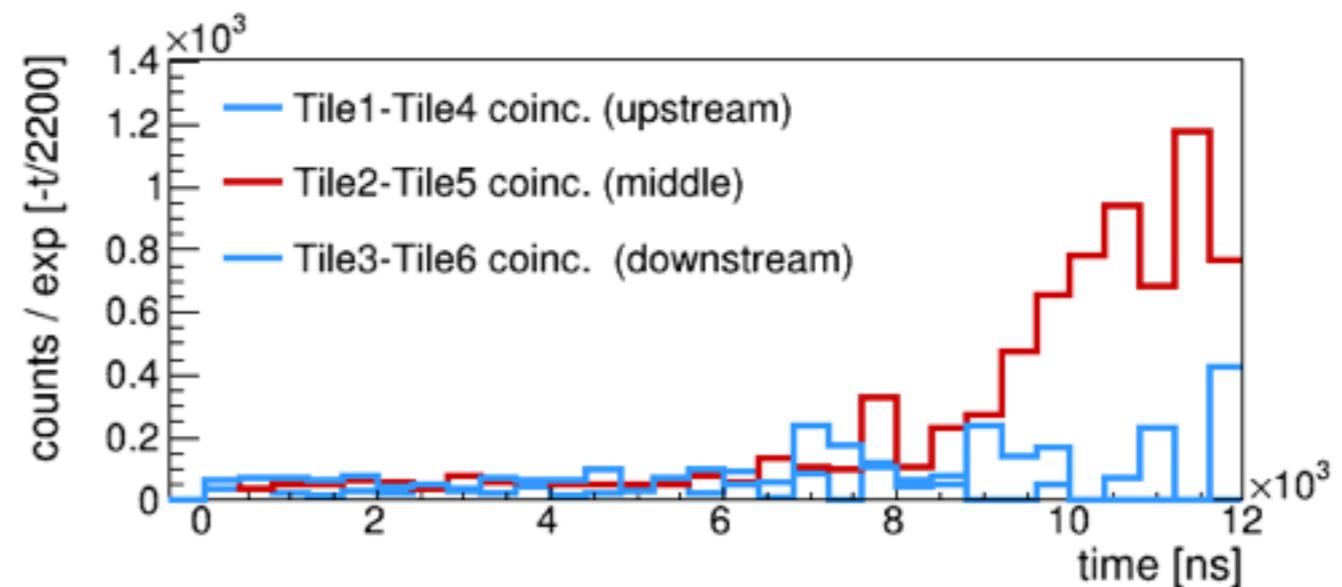
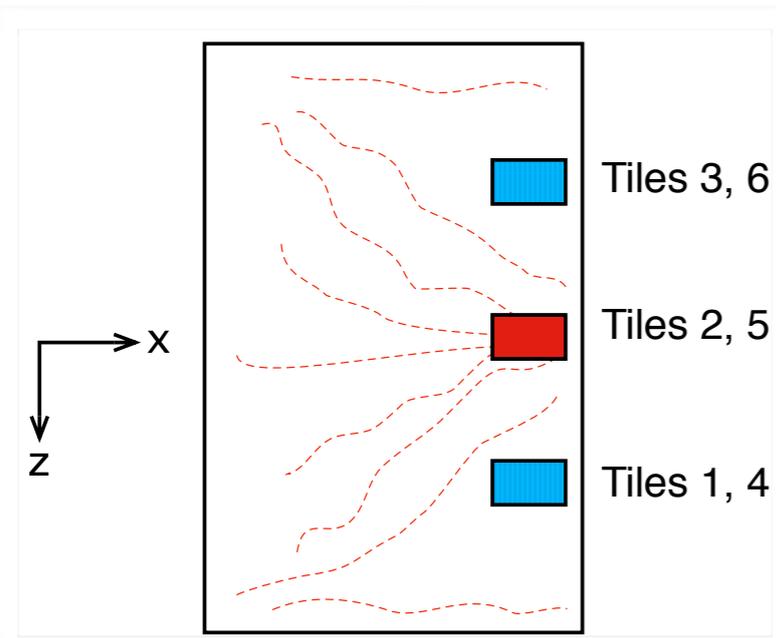


Measurement of mixed compression

Mixed compression in **transverse** direction



Mixed compression in **longitudinal** direction



Sub-optimal mixed compression observed

Sub-optimal compression due to target issues:

- ▶ $E_T = 0.7$ kV/cm instead of aimed $E_T = 1.1$ kV/cm
- ▶ motion of muon too close to target walls
 - ▶ slower motion
 - ▶ larger losses

$E_T = 0.7$ kV/cm

- ▶ According to simulations
 $\Delta y \times \Delta z = 5 \times 60 \text{ mm}^2$



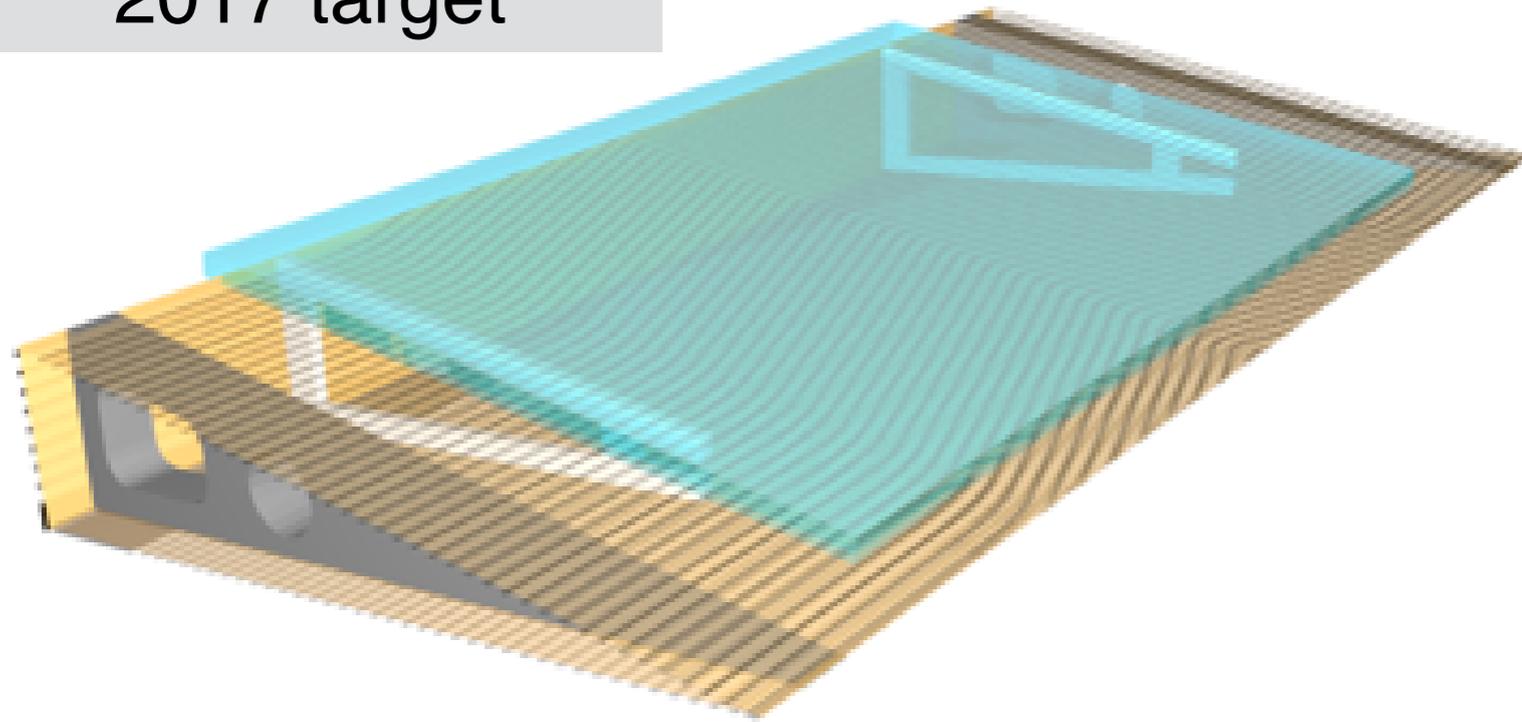
$E_T = 1.1$ kV/cm

- ▶ According to simulations
 $\Delta y \times \Delta z = 5 \times 60 \text{ mm}^2$

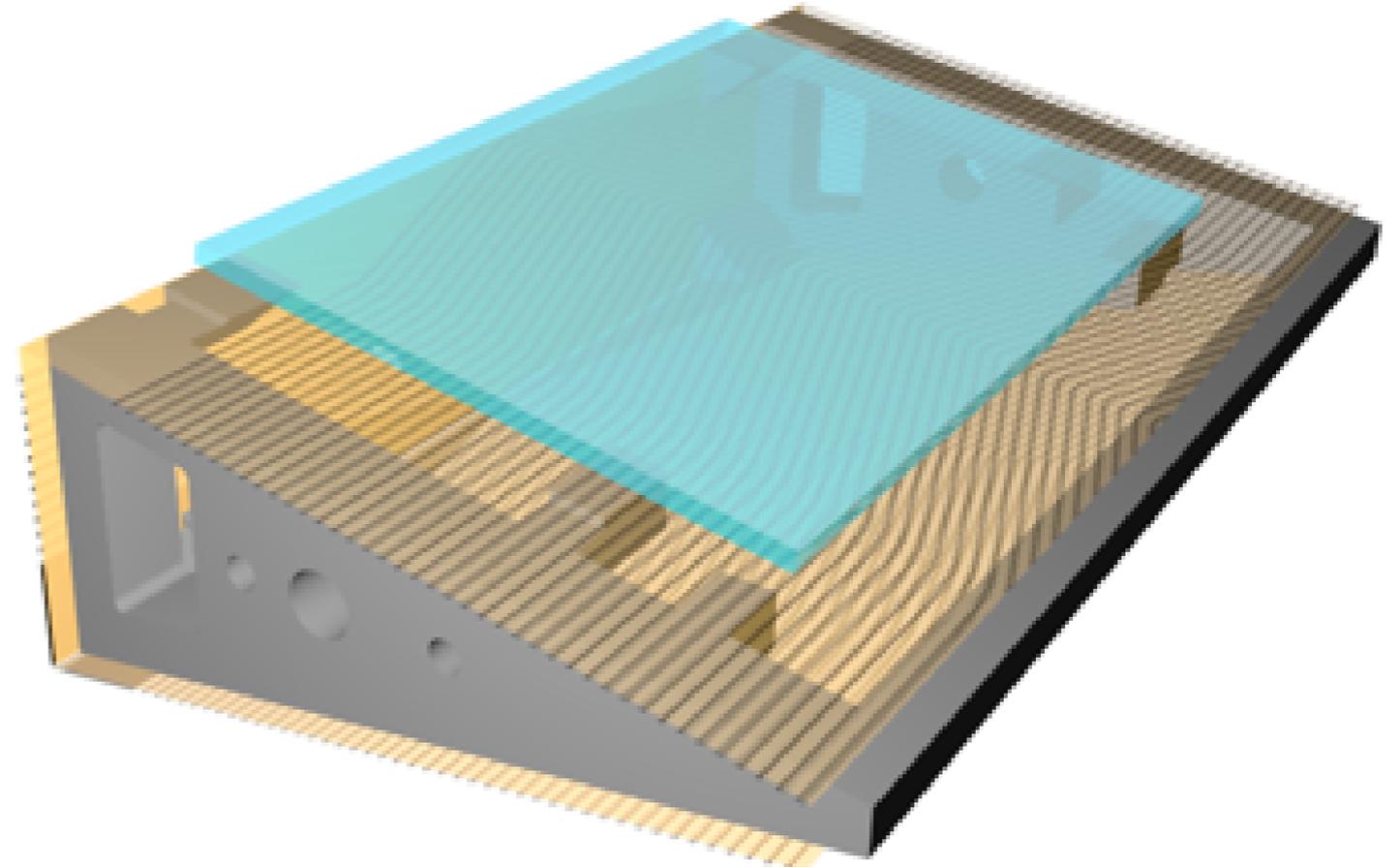


New target design

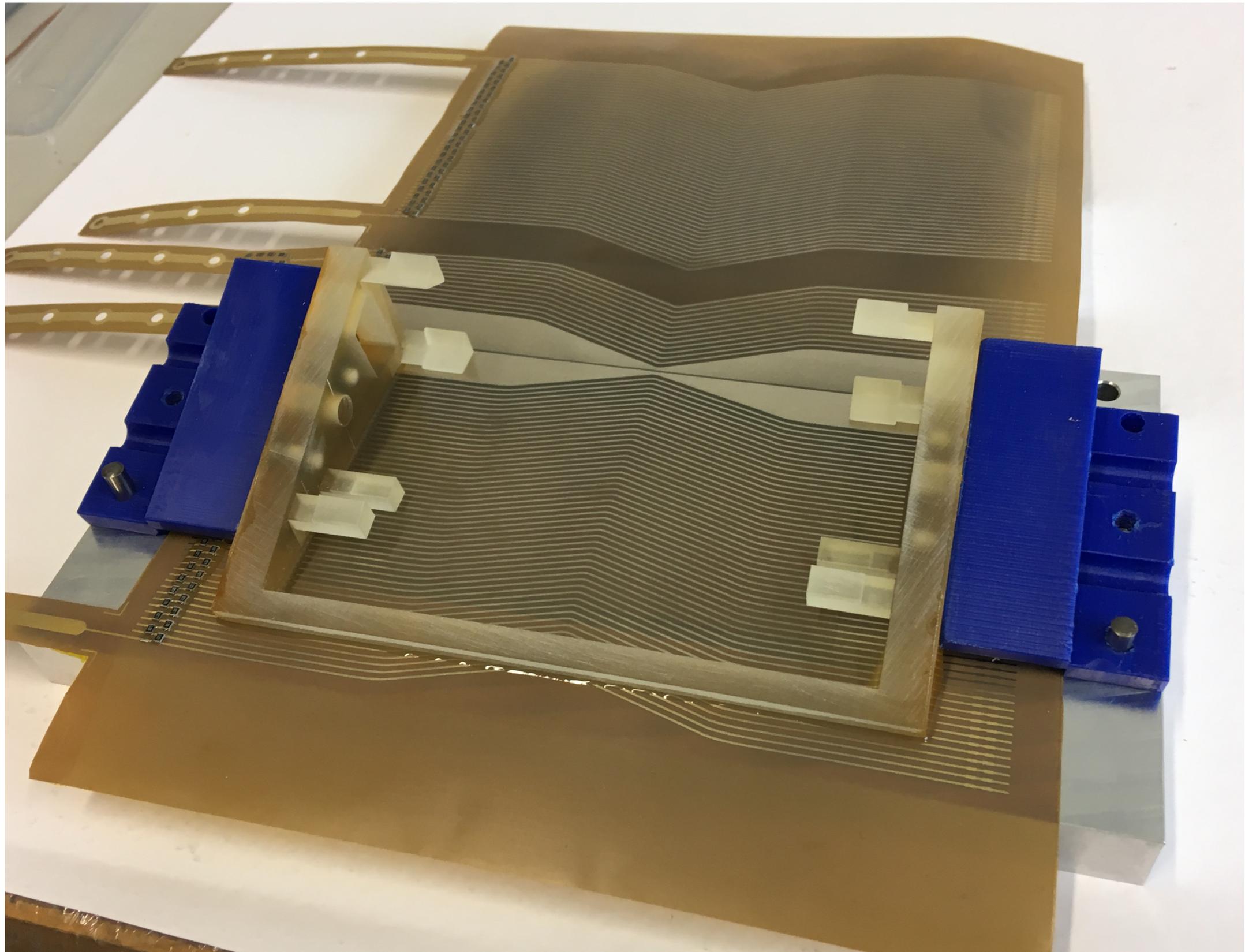
2017 target



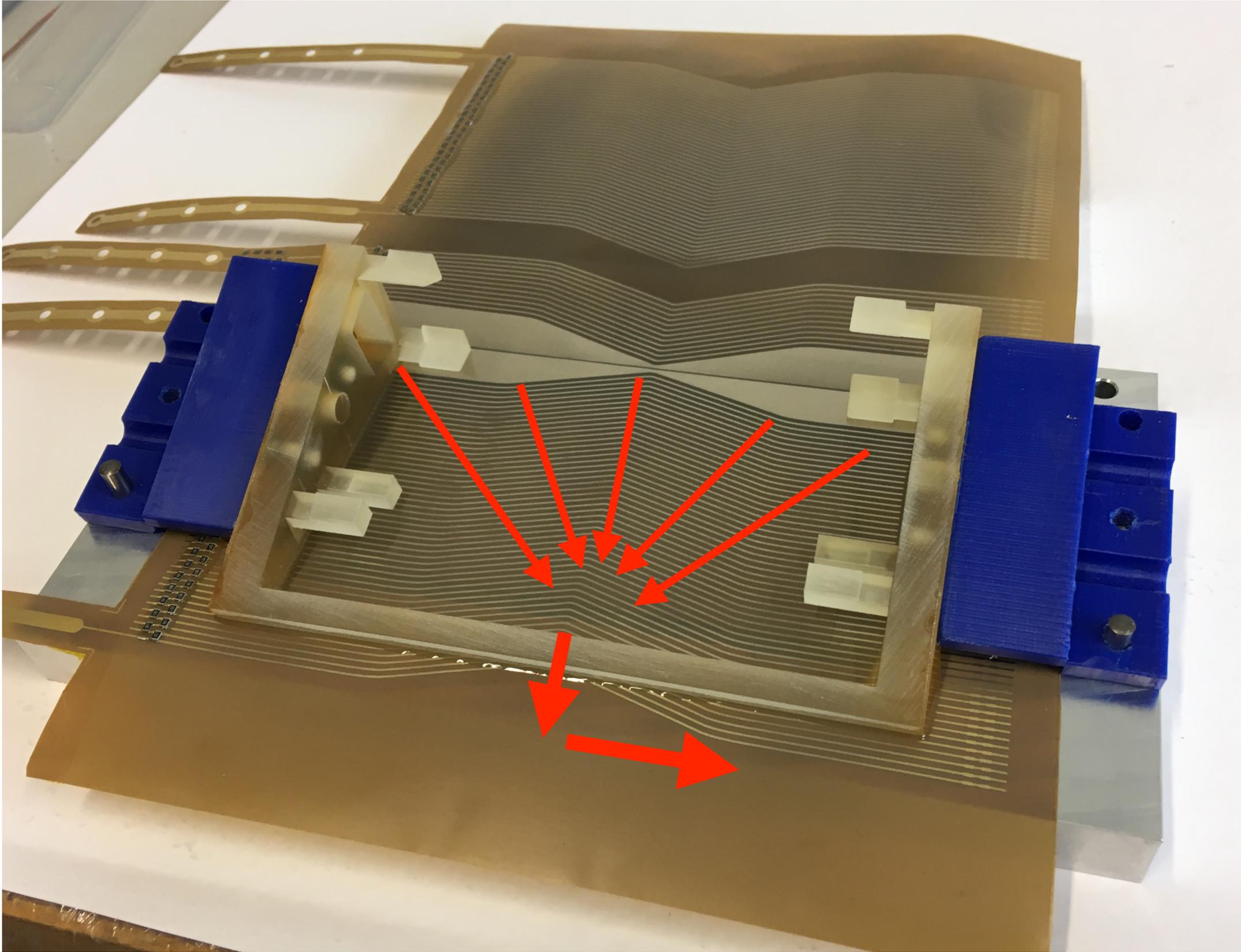
2018 target



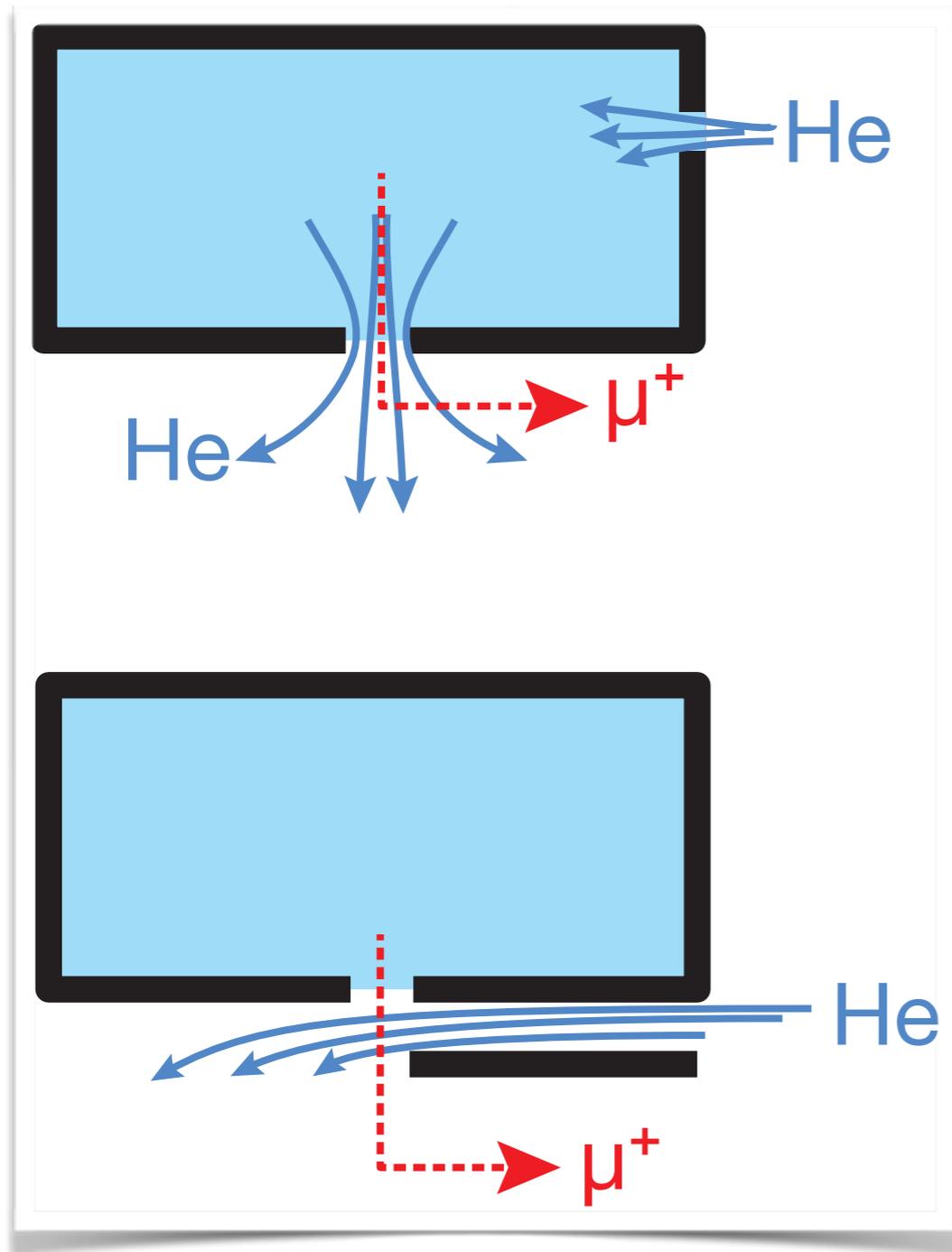
New target design



New target adaptable to extraction

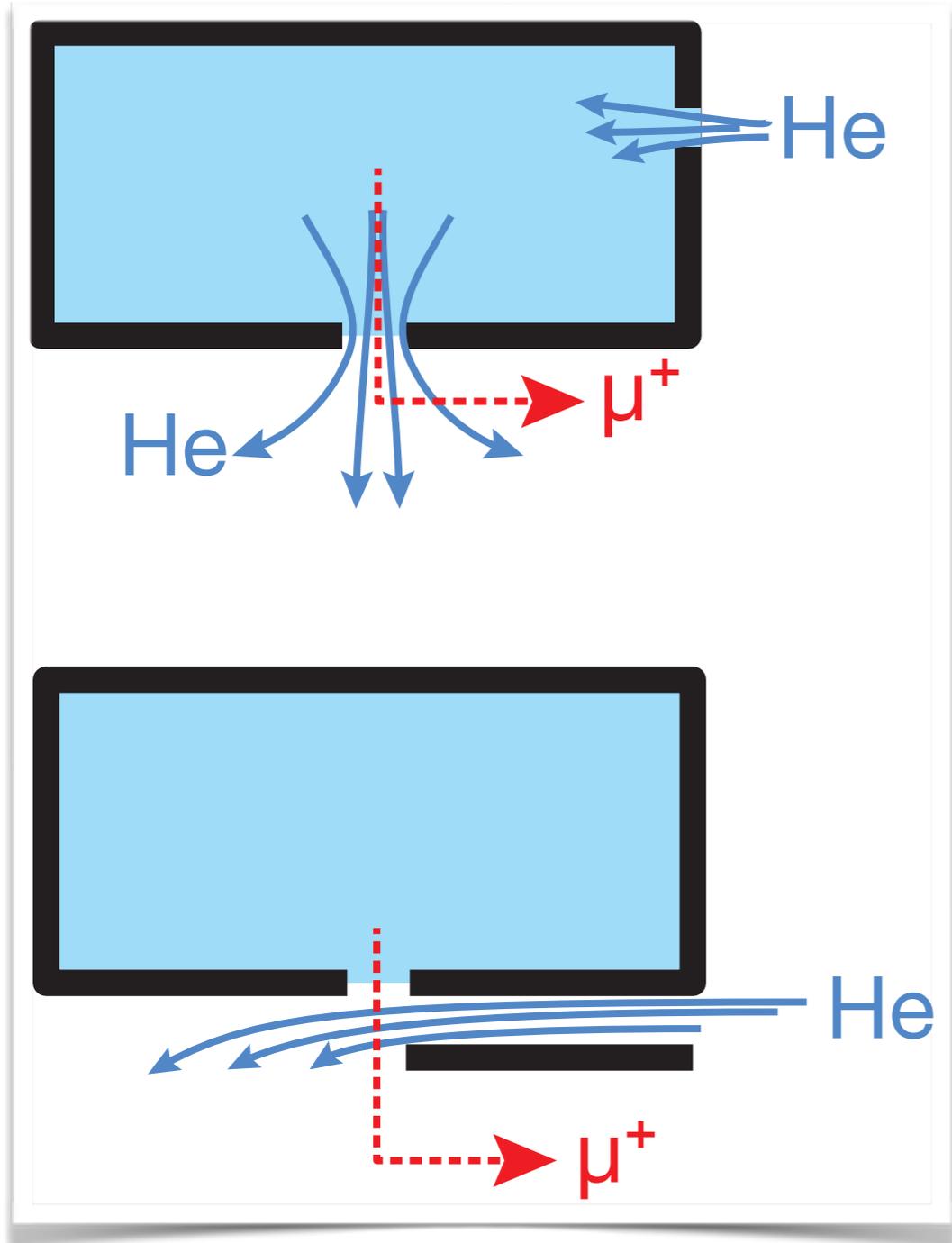


Gas injection for extraction

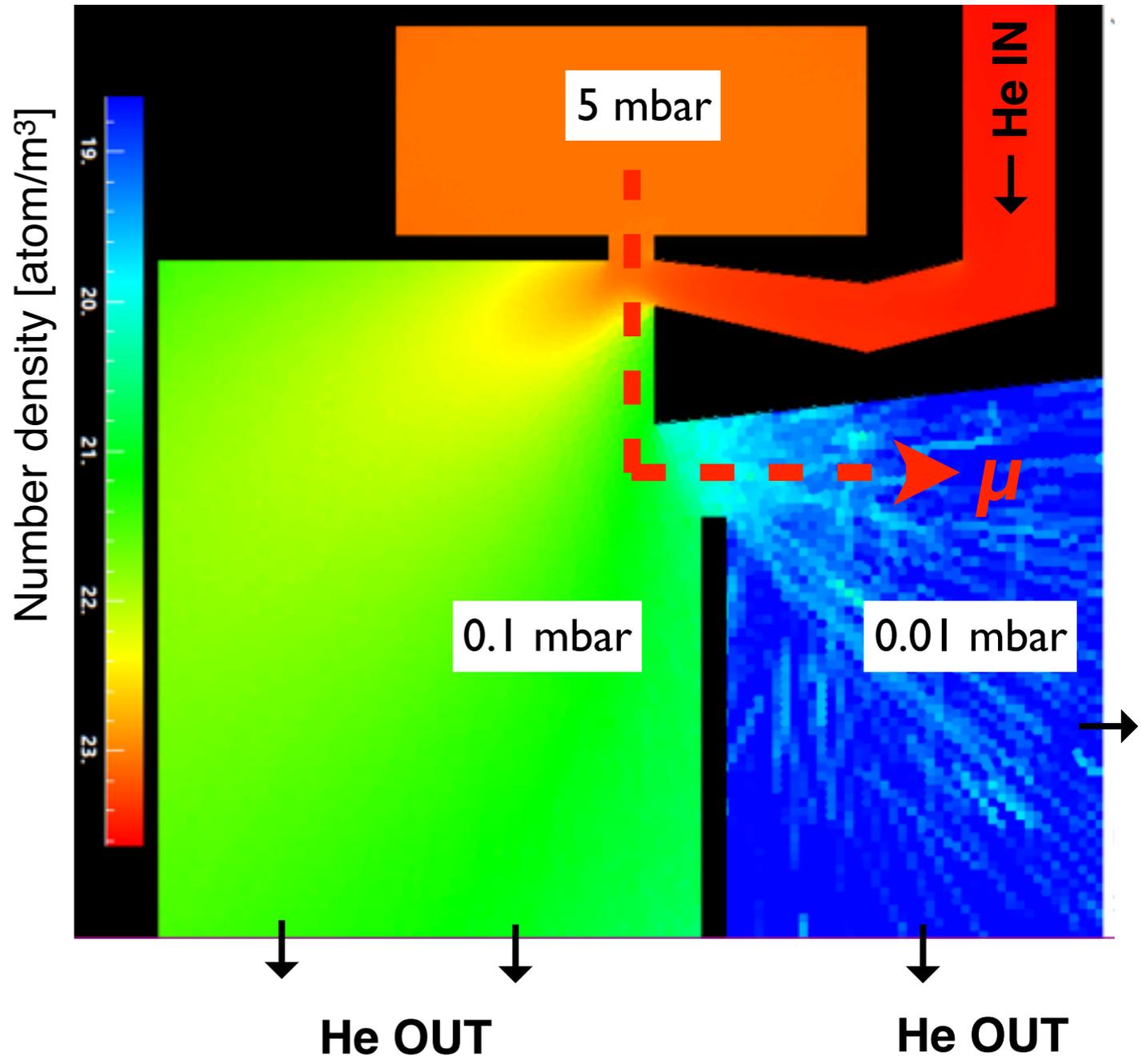


To avoid the disruption of the **vertical density gradient** a new gas injection scheme is needed

Gas injection for extraction

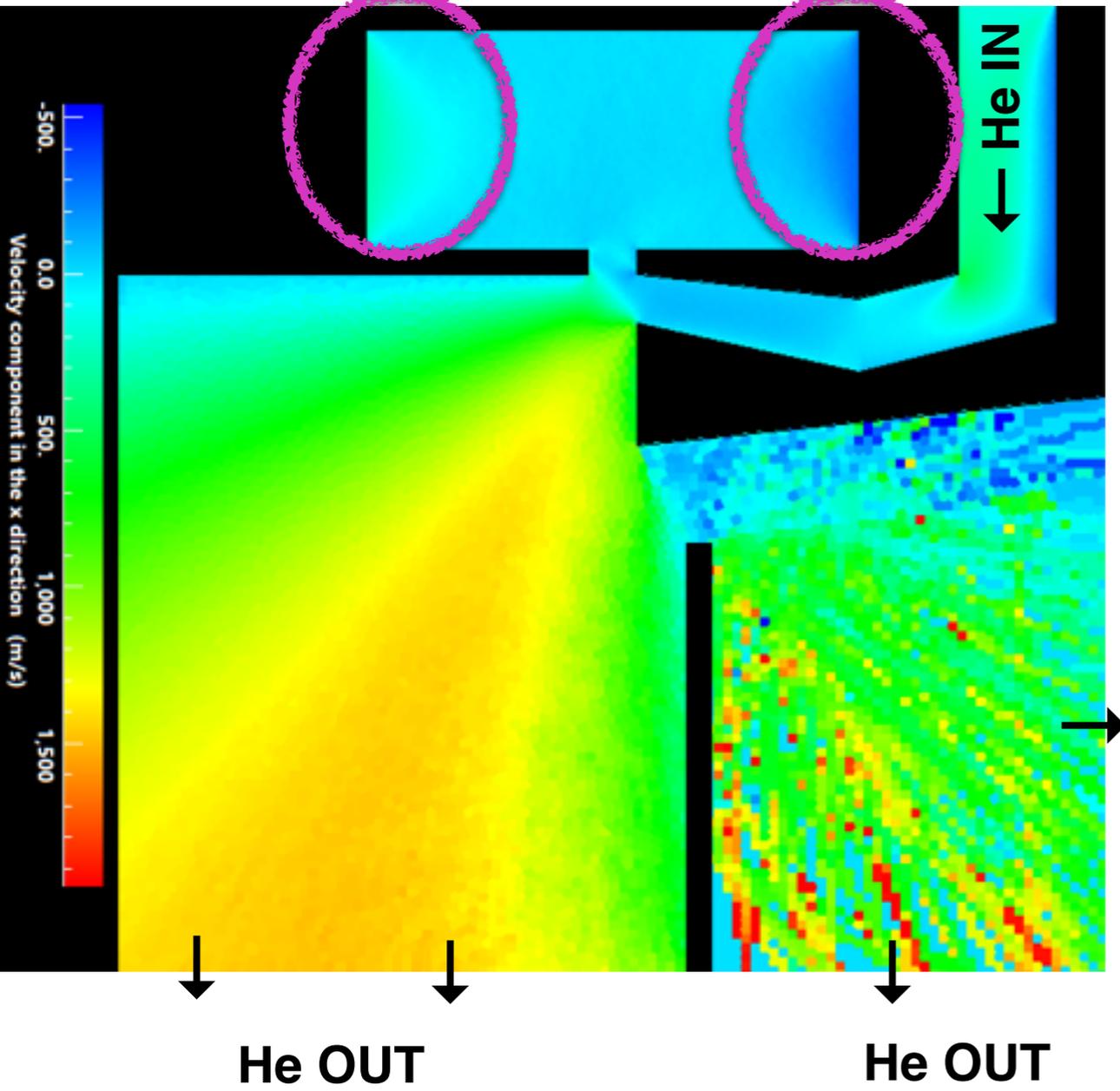


Pressure distribution in extraction region

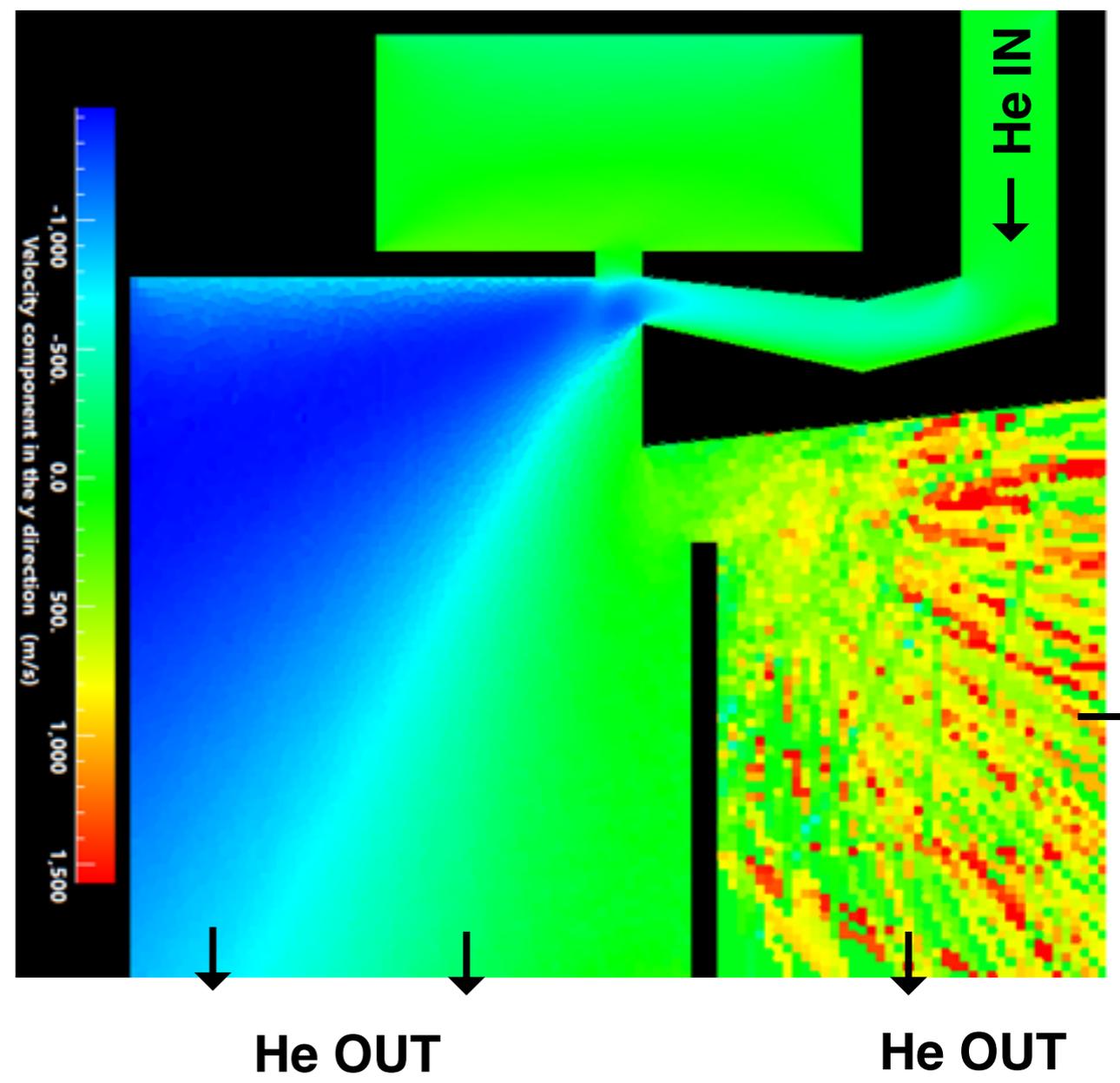


Gas injection for extraction

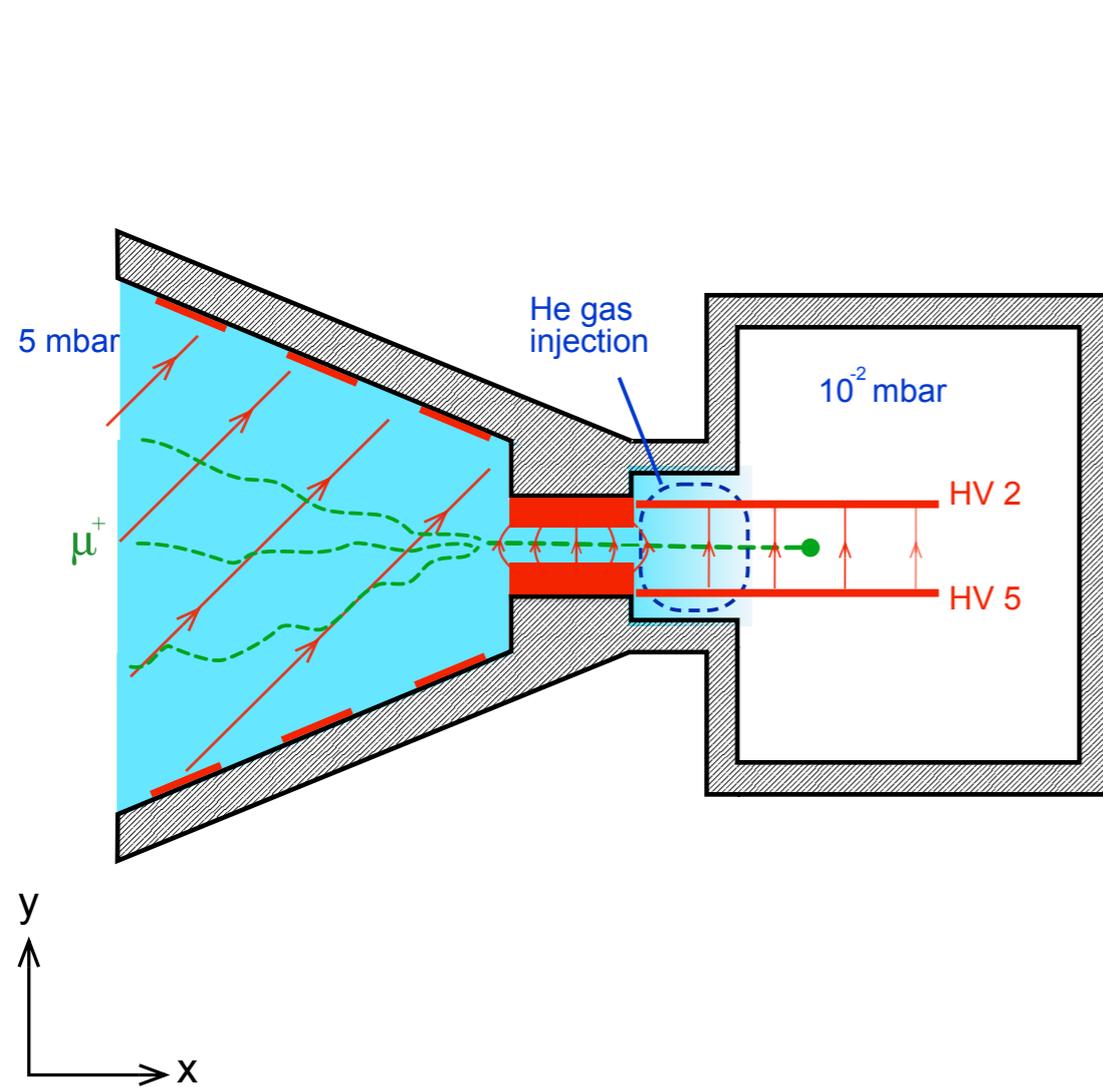
He velocity distribution in direction



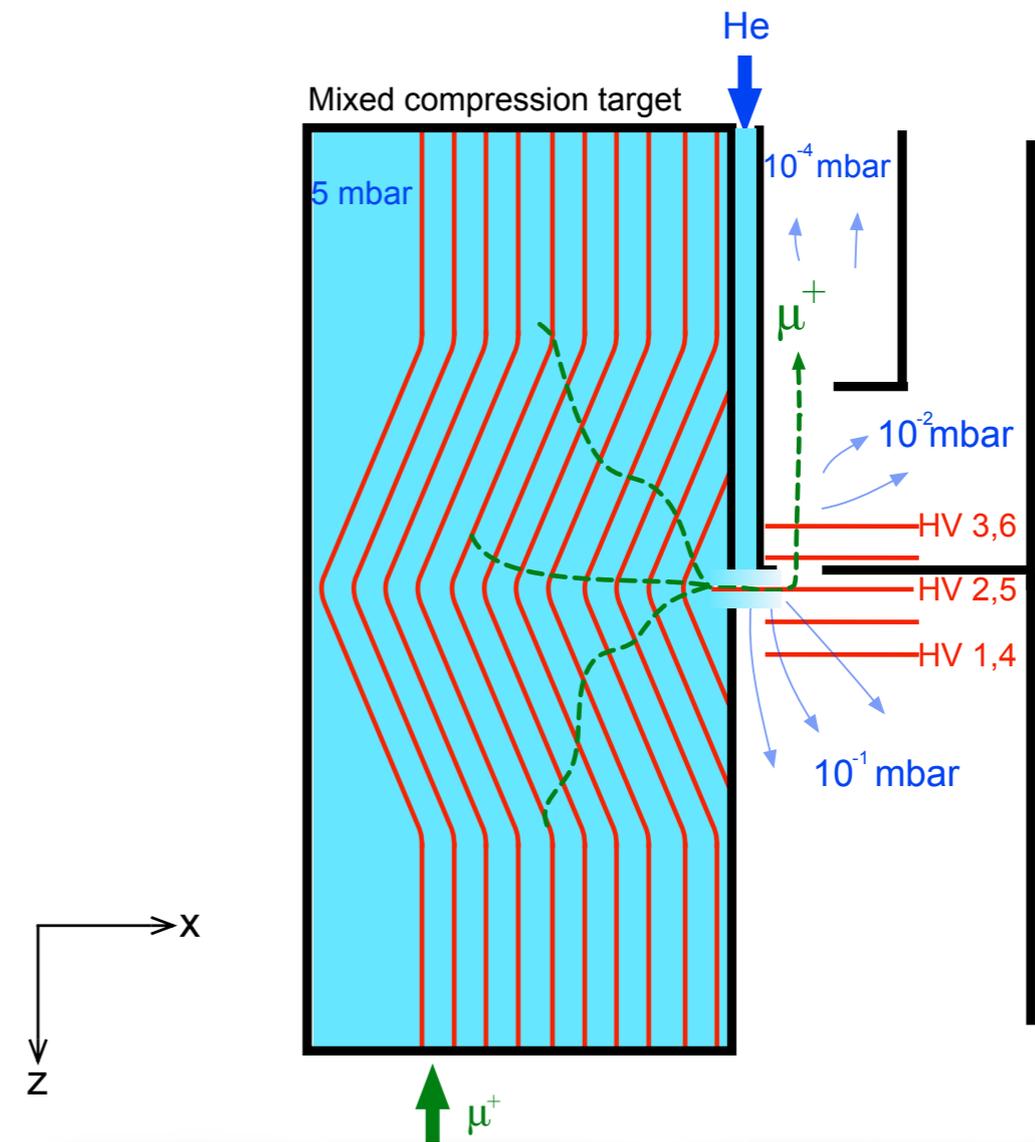
He velocity distribution in direction



Electrodes to guide muons out of gas target



- ▶ μ^+ guided out of target via ExB drift
- ▶ E-field defined by HV2 and HV5



- ▶ HV3,6 and HV1,4 to **confine** μ^+ in z-direction ($t < 0$)
- ▶ HV3,6 and HV1,4 to **re-accelerate** μ^+ in z-direction ($t > 0$)
- ▶ μ^+ moves in various differentially pumped regions

Beam time requests

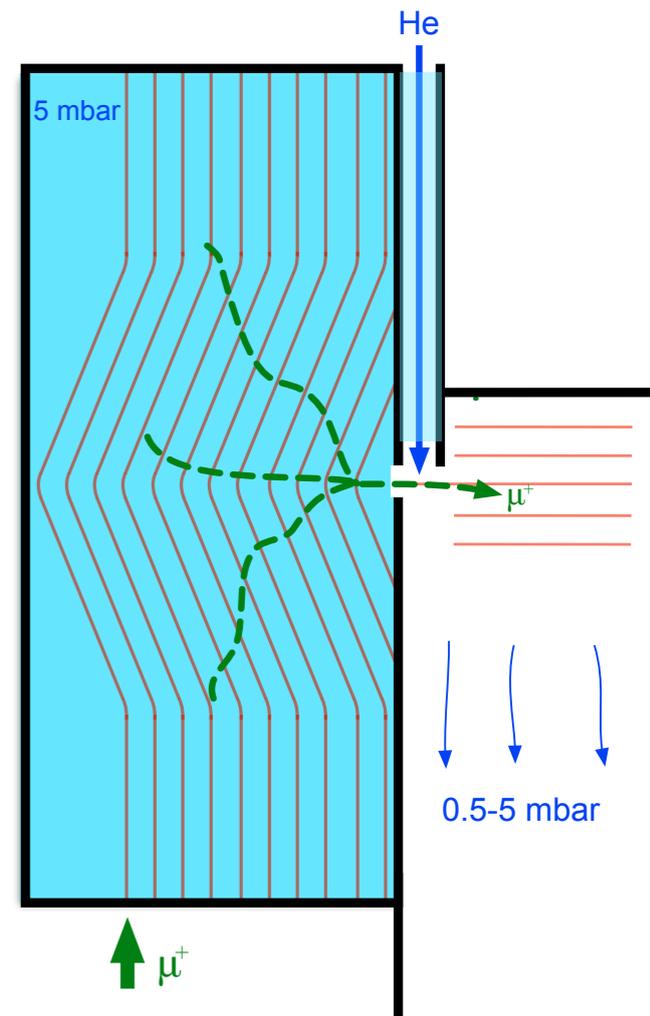
Improved test of mixed compression (2.5 weeks in $\pi E1$)

- ▶ various cryogenic targets need to be tested with various electric fields and temperature distributions.

Simplified test of extraction

(1 week in $\pi E1$)

- ▶ extract μ^+ through a small hole for various He flows:
 - ▶ test extraction
 - ▶ test disruption of mixed compression
- ▶ “vacuum” in the extraction region is strongly limited by mechanical constraints (bore diameter, thermal shields...)



If extraction successful....

A **single-stage** target with **mixed compression + extraction** could be used **alone** to deliver an interesting beam (without the need to develop the complete system)

Rate μ^+ ($\pi E5$, 11 MeV/c)	1 MHz
stopping efficiency: 60 mm, 10 K, 5 mbar	40%
mixed compression eff. : $\Delta y \times \Delta z = 1 \times 1 \text{ mm}^2$	2%
extraction through hole	30%
drift + accumulation time after extraction ($2.5 \mu\text{s}$)	30%
Total rate after extraction: eV, $1 \times 1 \text{ mm}^2$	700 Hz

Conservative estimate

The muCool collaboration

Antognini^{*}, N. Ayres, I. Belosevic, V. Bondar, R. Iwai,
K. Kirch^{*}, J. Nuber, F. Piegsa[‡] and D. Taqqu

Institute for Particle Physics and Astrophysics, ETH Zurich, 8093 Zurich, Switzerland

M. Hildebrandt, A. Knecht, A. Papa[§], C. Petitjean, S. Ritt 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 the PSI

‡ presently at university Bern

§ also at the INFN and university of Pisa



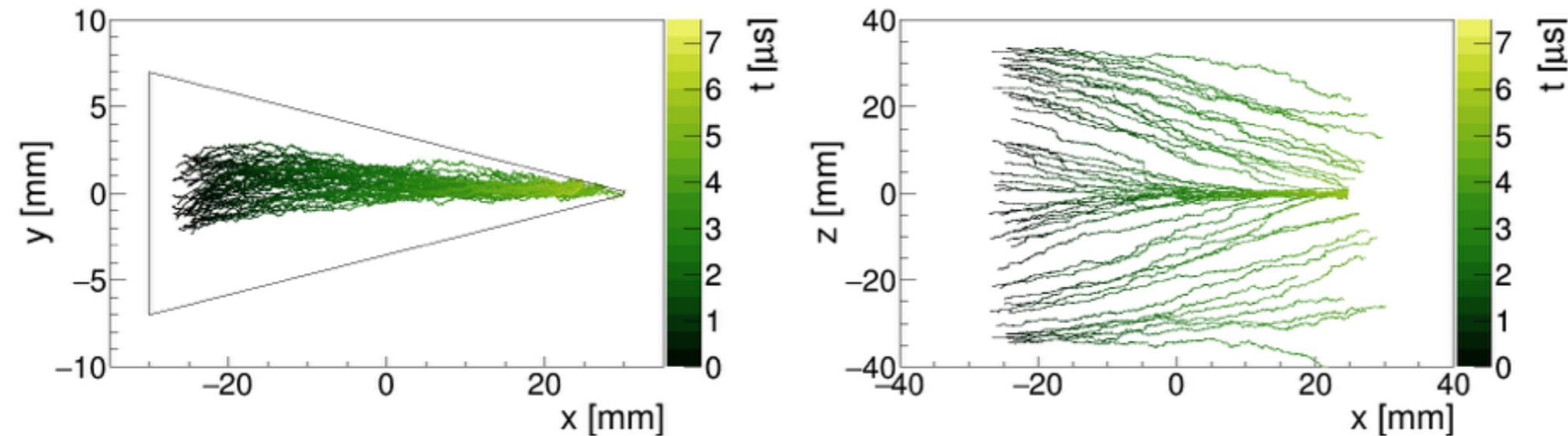
 PhD student

 40% of time, joined in 2019

Simulations of mixed compression

Aimed conditions

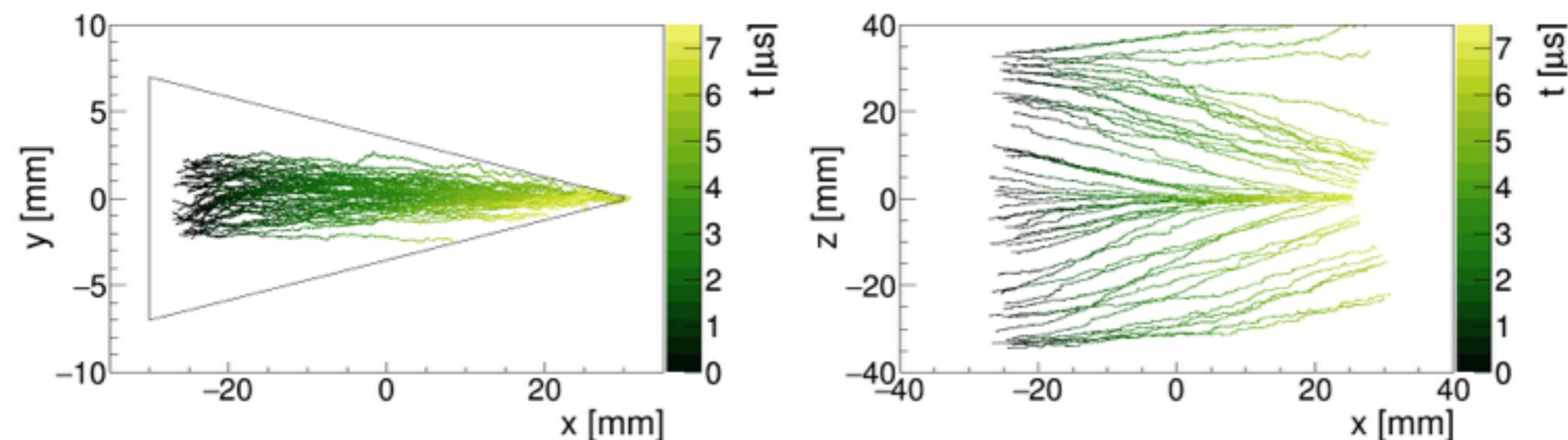
$E_T = 1.1$ kV/cm $E_T/E_L = 3.5$



3% of μ^+ starting from $\Delta y \times \Delta z = 5 \times 60$ mm² are compressed into $\Delta y \times \Delta z = 1 \times 1$ mm² (including decay)

2017 beam-time conditions

$E_T = 0.7$ kV/cm $E_T/E_L = 3.5$



1% of μ^+ starting from $\Delta y \times \Delta z = 5 \times 60$ mm² are compressed into $\Delta y \times \Delta z = 1 \times 1$ mm² (including decay)