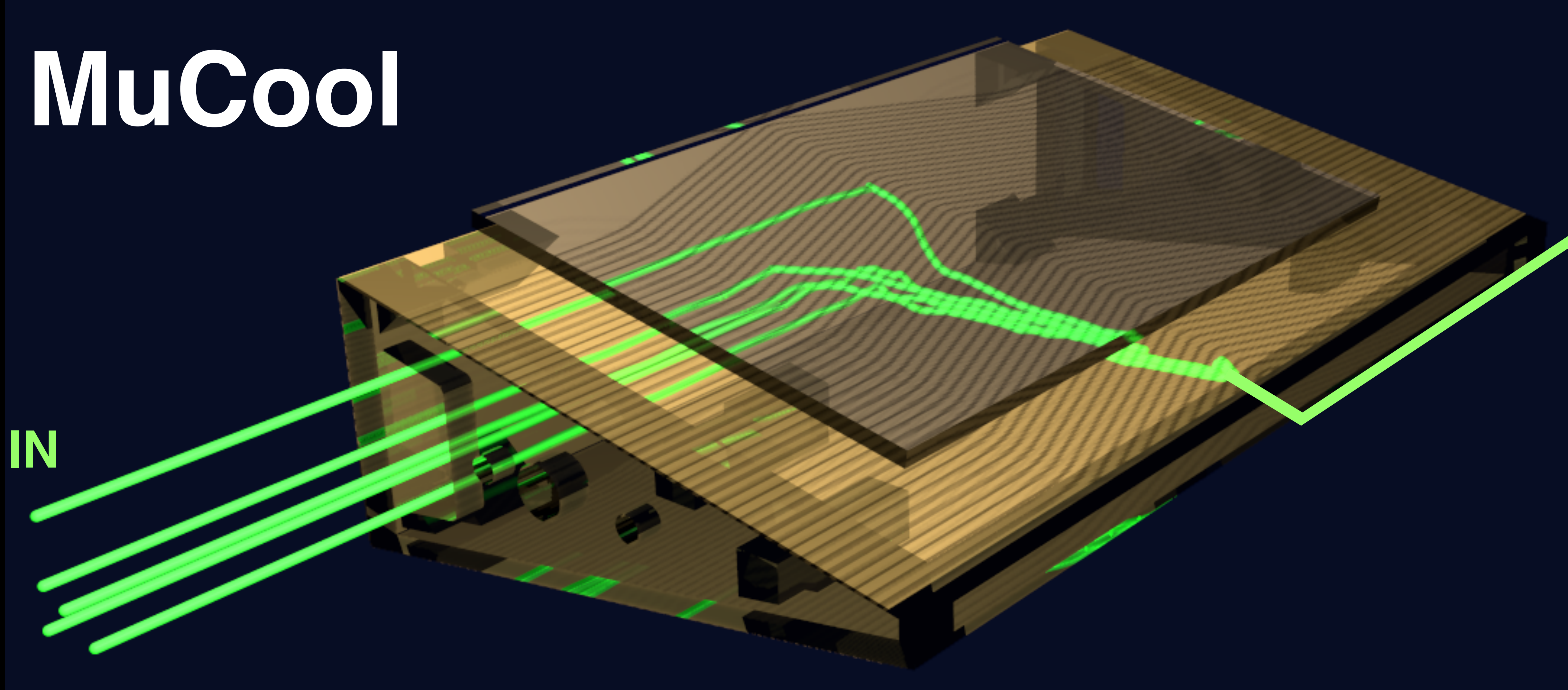

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muCool: a phase-space compressor

E:	10 keV
ΔE:	100 eV
Diameter:	20 mm
Divergence:	2 mrad

OUT
B=0

extraction from solenoid

E:	10 keV
ΔE:	100 eV
Diameter:	20 mm
E_T:	< 5 eV

OUT
B=0.01T

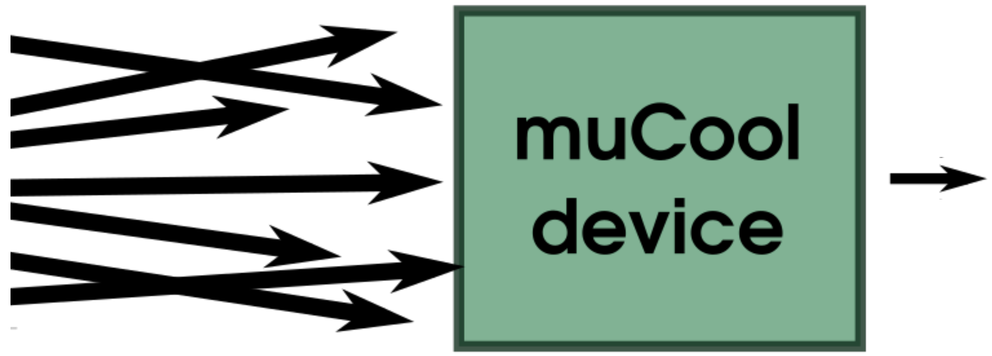
μ^+

IN

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

μ^+

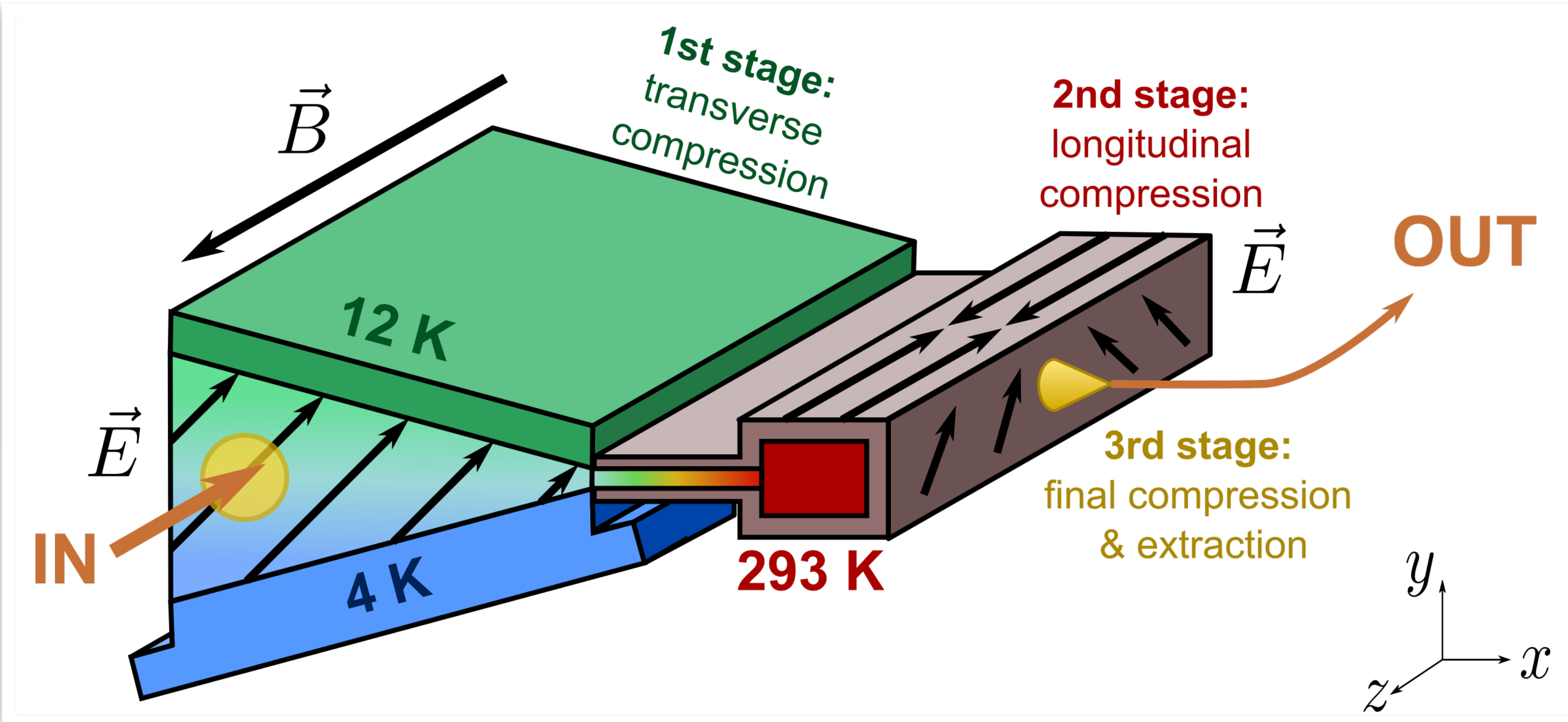
5T, 10 K He



degradation & compression

re-acceleration

E:	10-100 eV
Diameter:	1 mm
Divergence:	-
cw beam	

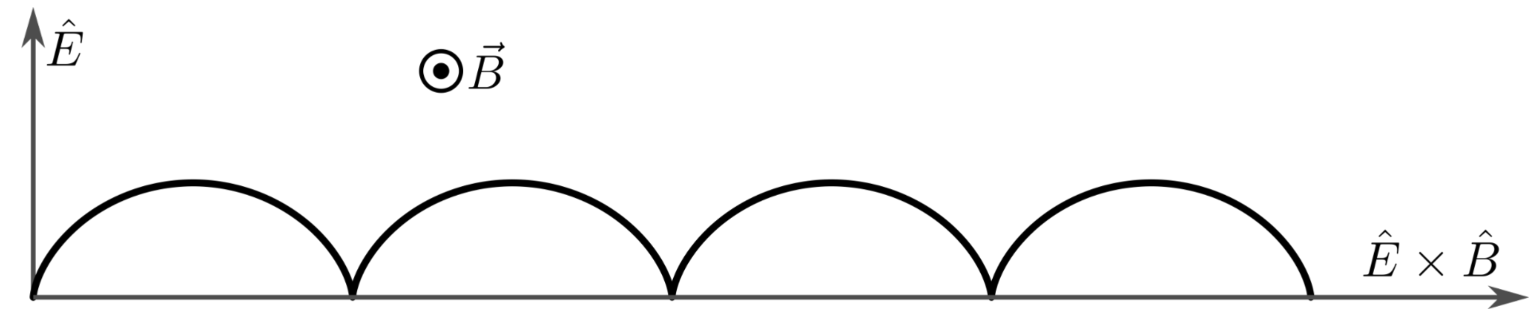


$$\vec{v}_D = \frac{\mu E}{1+\omega^2\tau_c^2}\left[\hat{E} + \omega\tau_c\left(\hat{E}\times\hat{B}\right) + \omega^2\tau_c^2(\hat{E}\cdot\hat{B})\hat{B}\right]$$

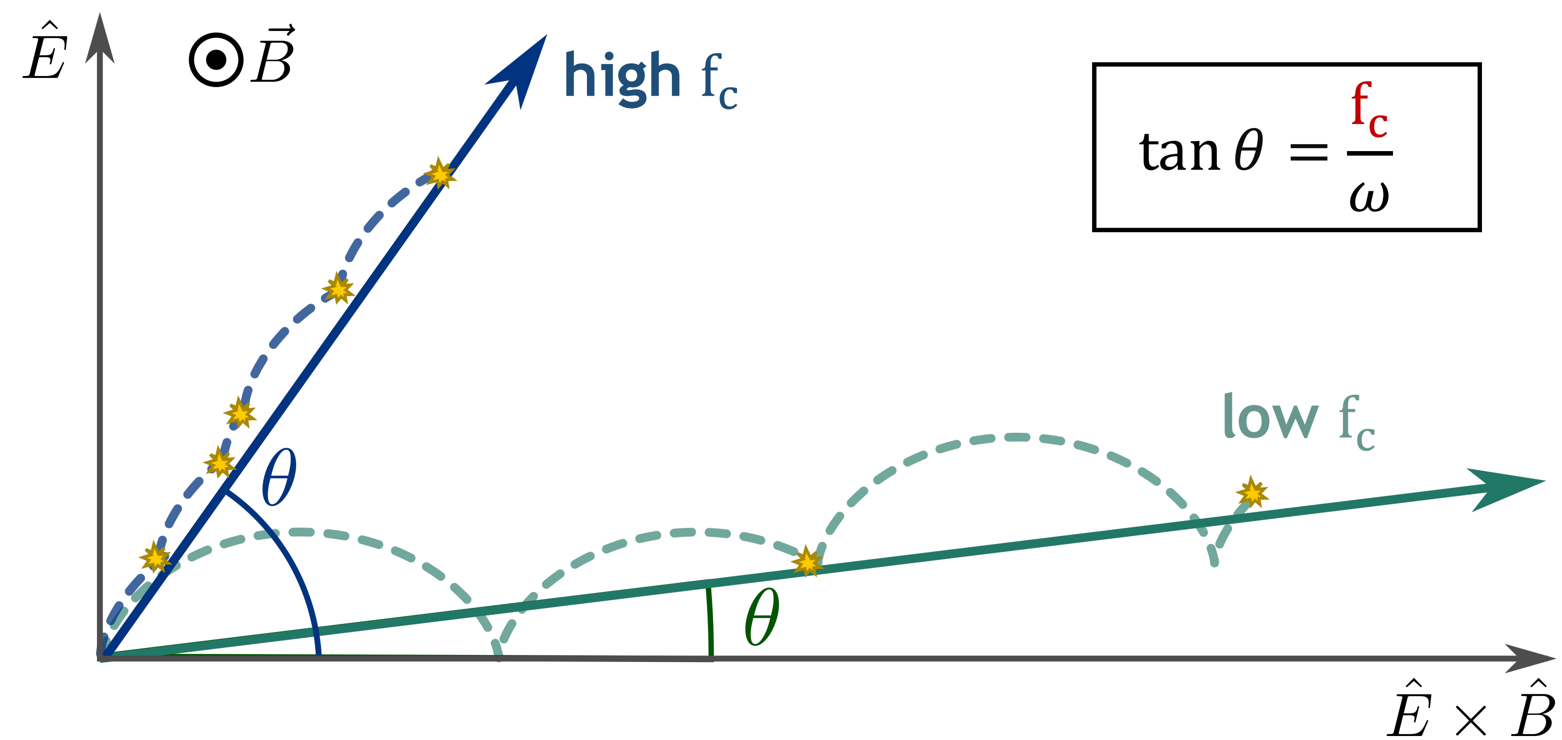
- τ_c : mean time between two μ^+—He collisions
- ω : μ^+ cyclotron frequency

Trajectories in E- and B-fields with and without gas

In vacuum



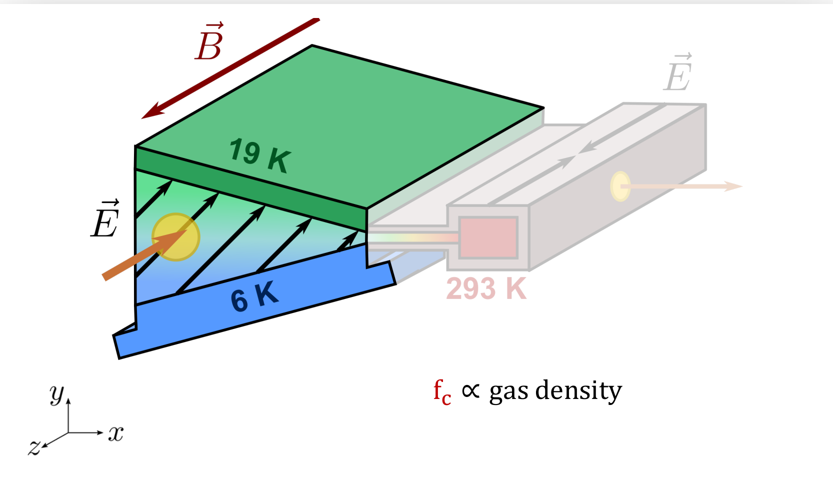
In gas



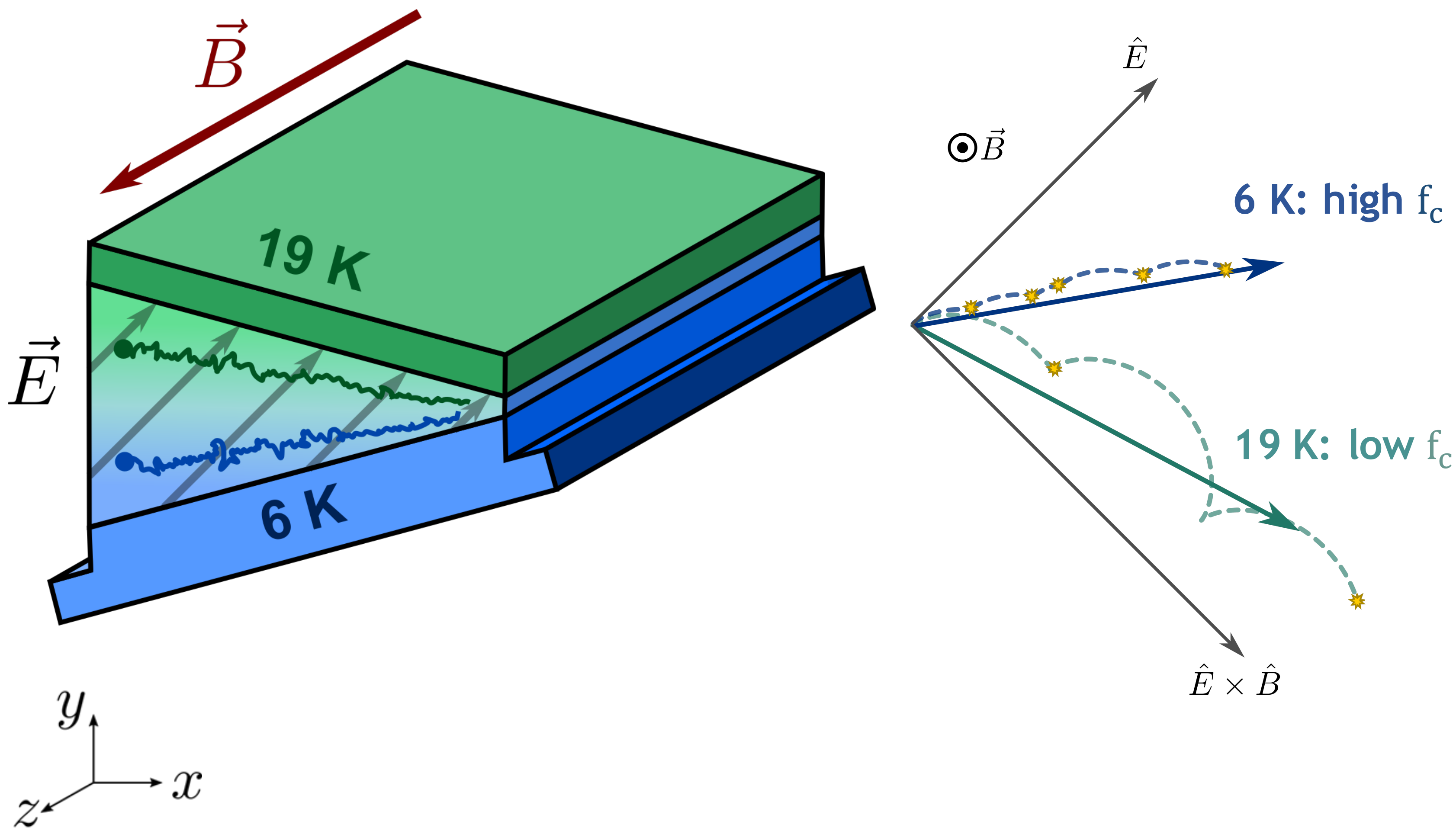
$$\tan\theta = \frac{f_c}{\omega}$$

- Collisions with gas atoms with frequency f_c

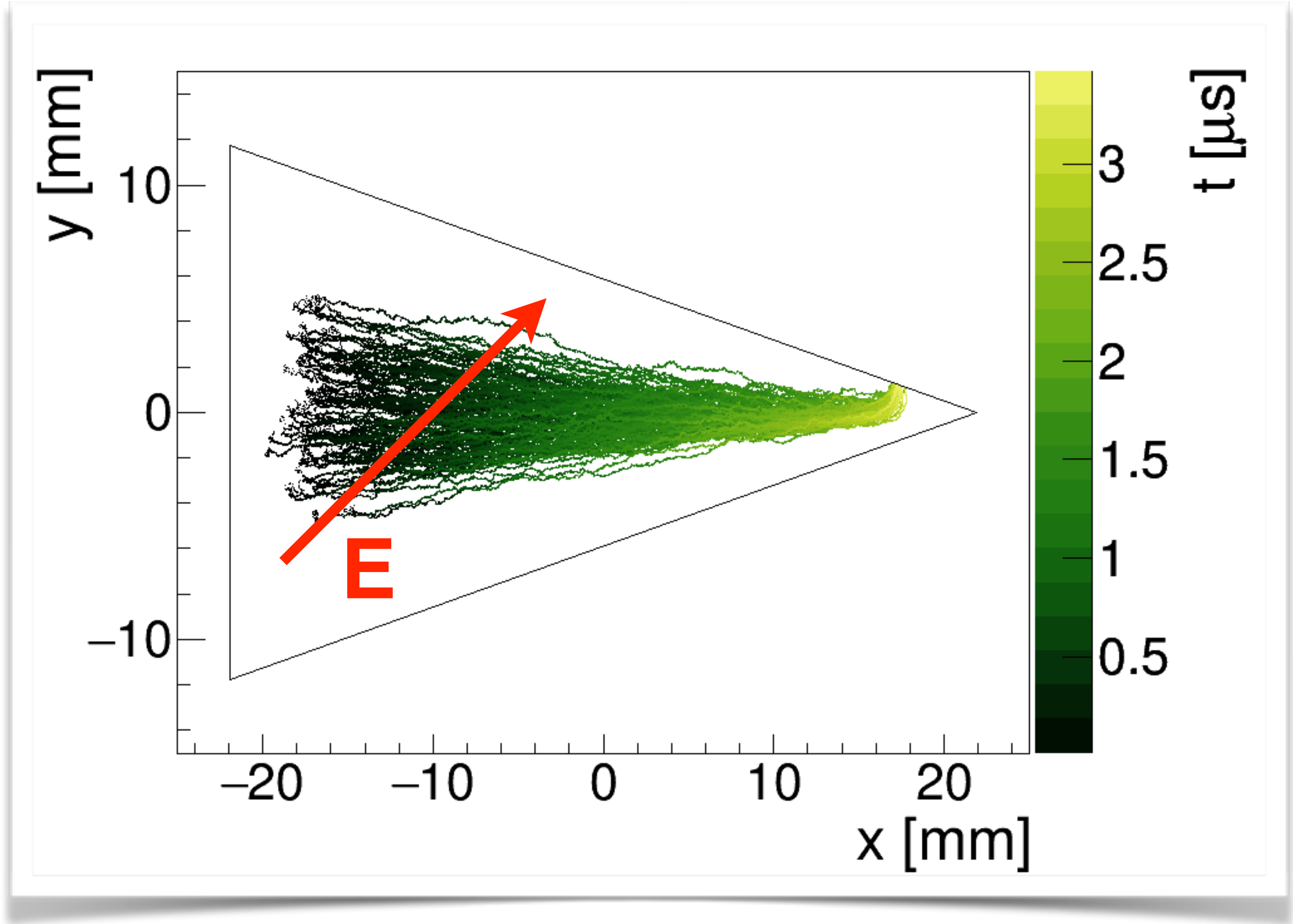
Transverse compression: working principle



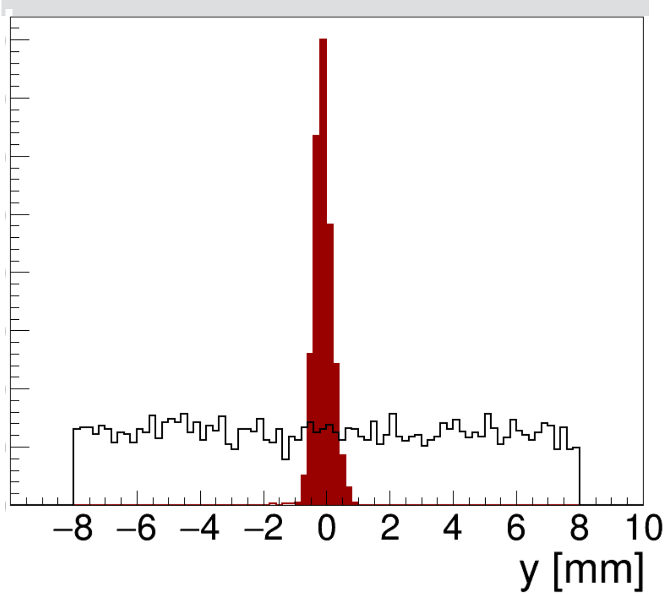
$f_c \propto$ gas density



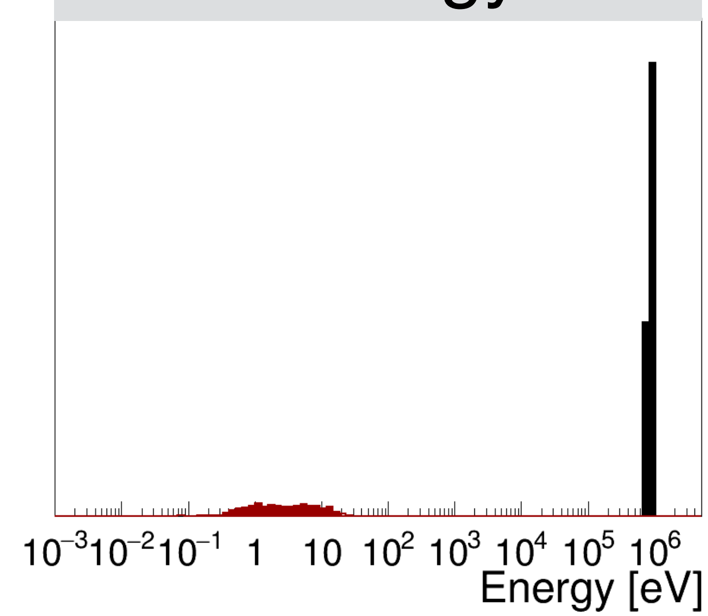
Transverse compression: simulations



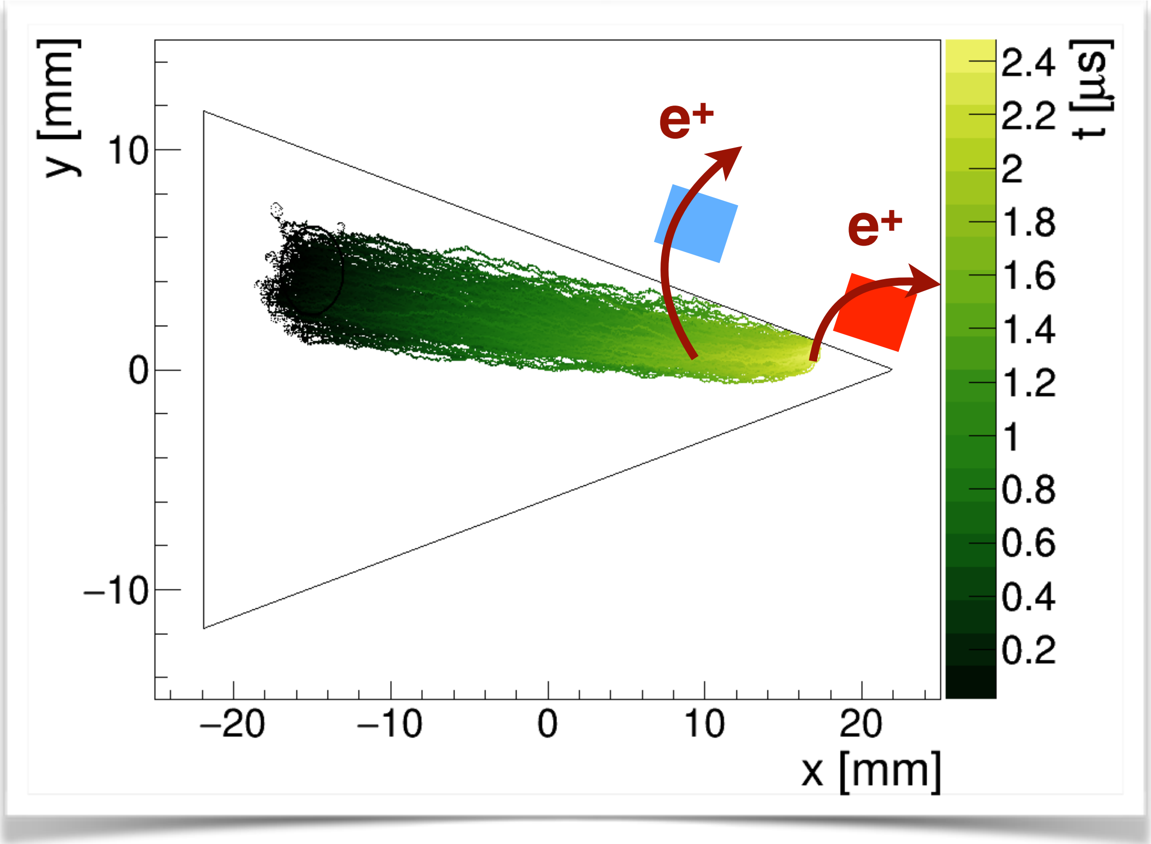
Extension

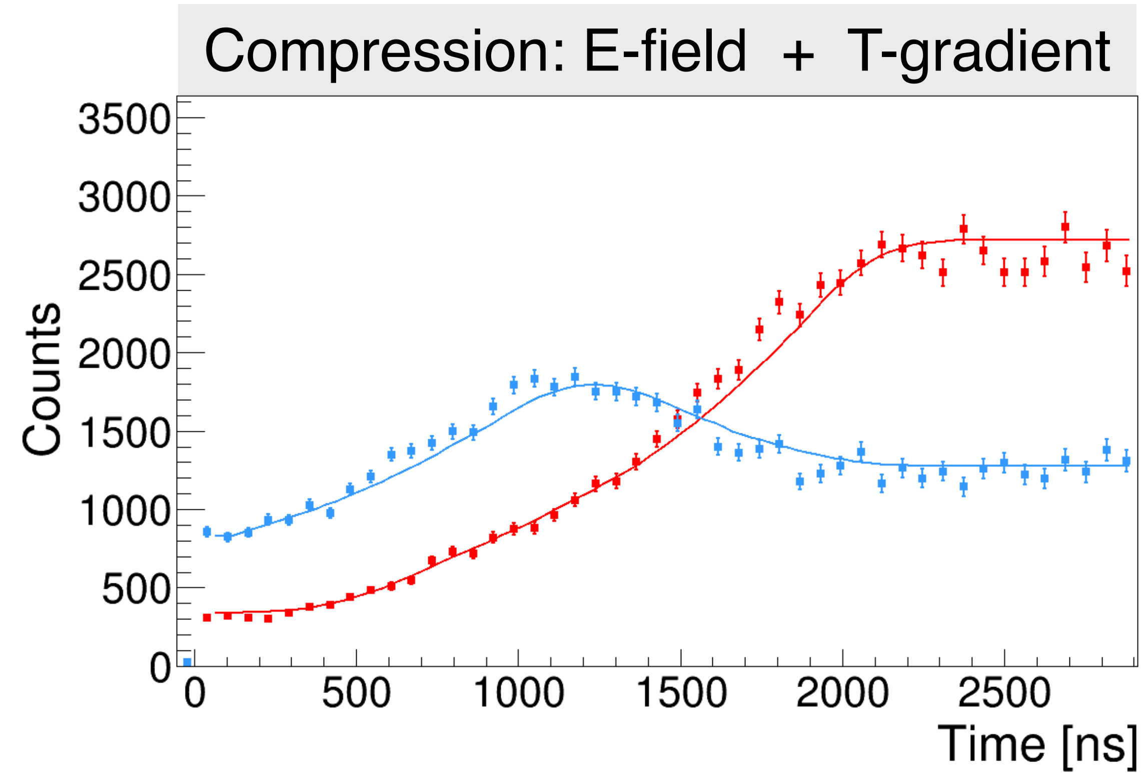


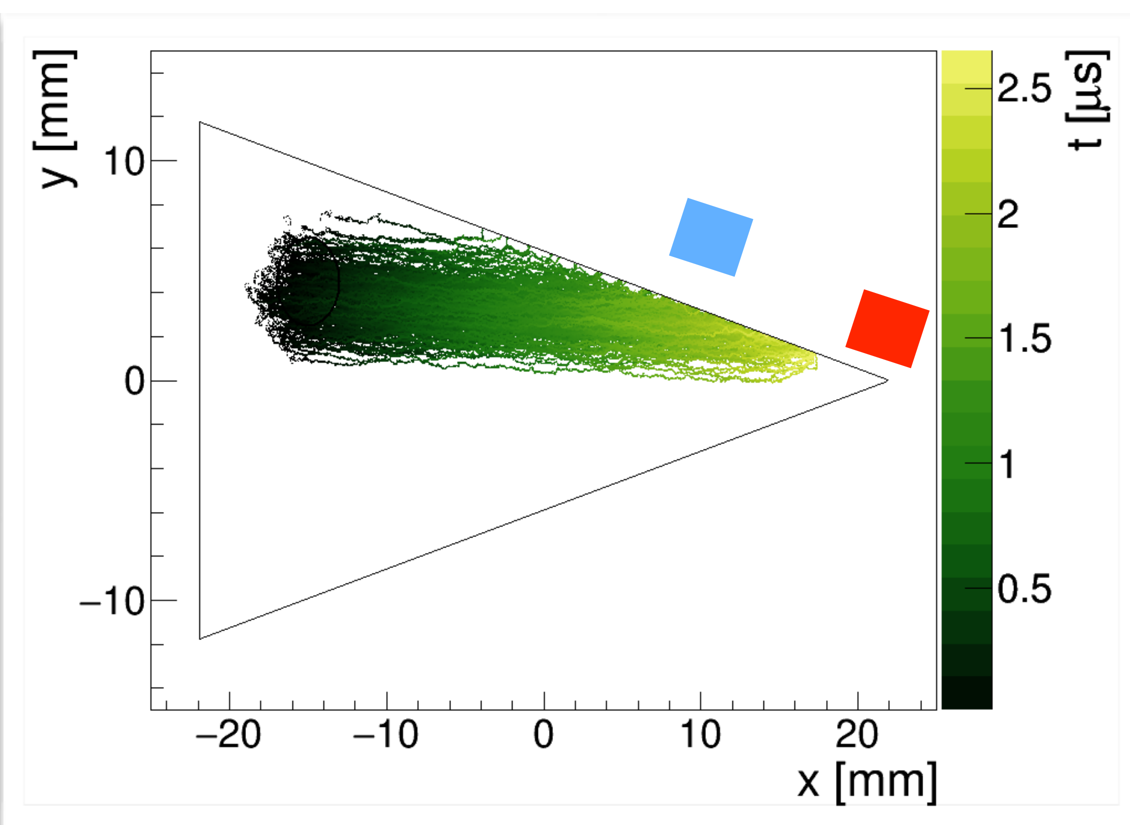
Energy

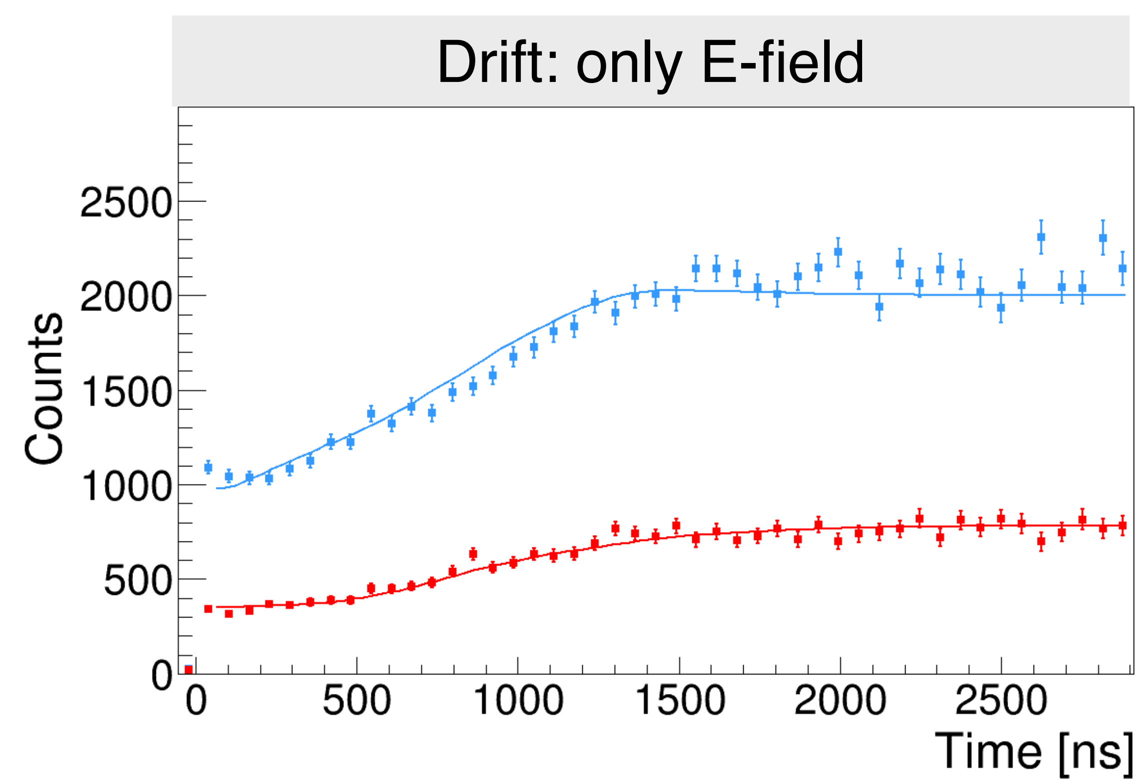


Transverse compression: simulations & measurements

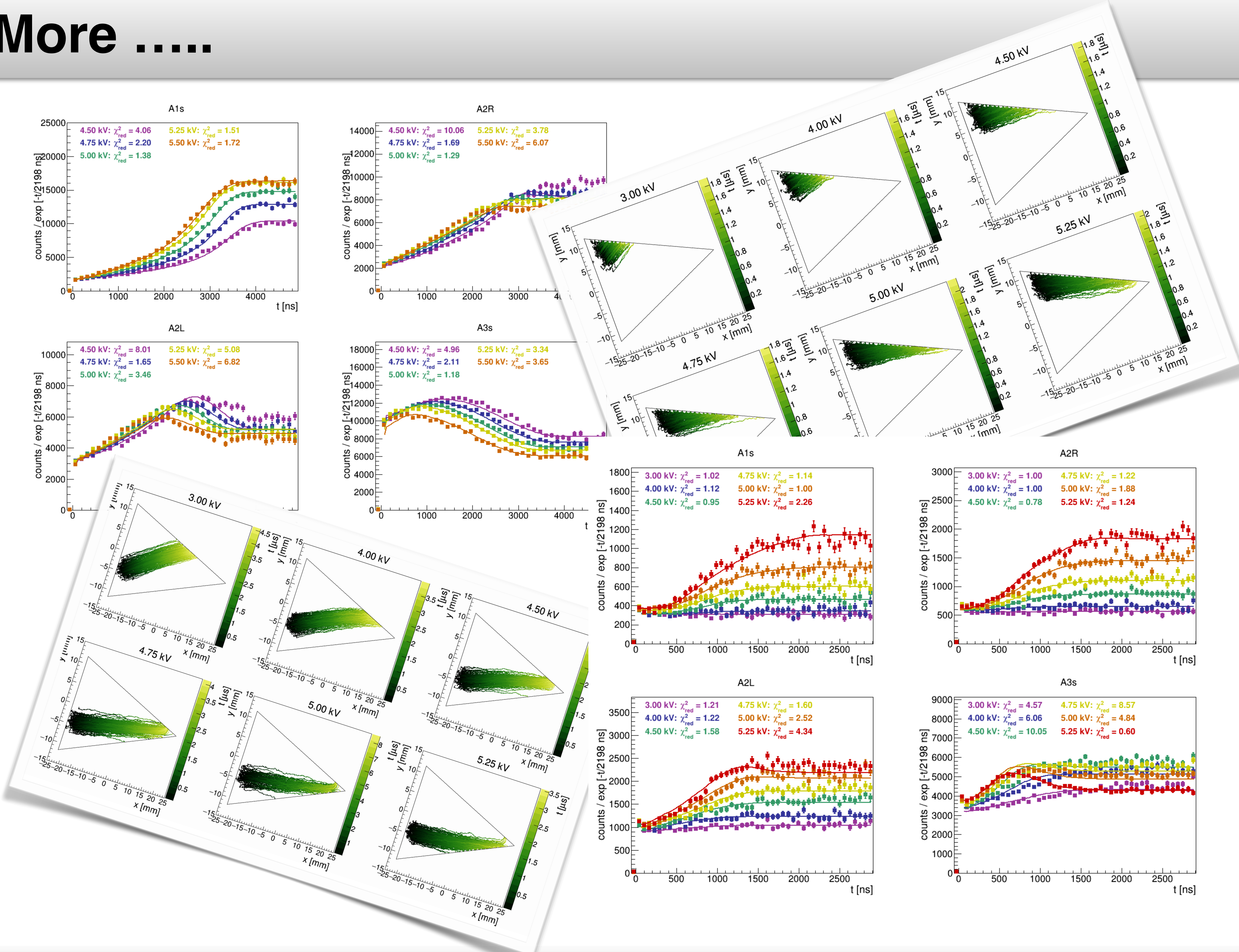




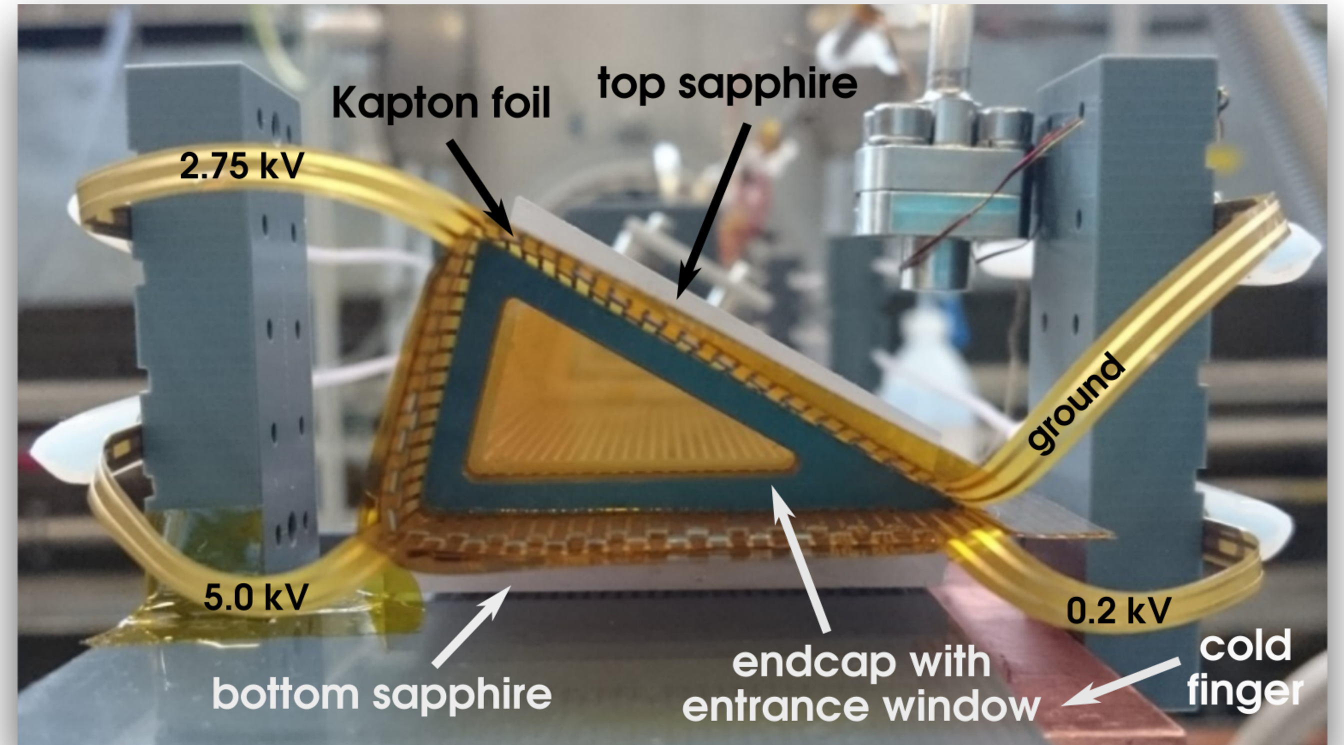




More .....

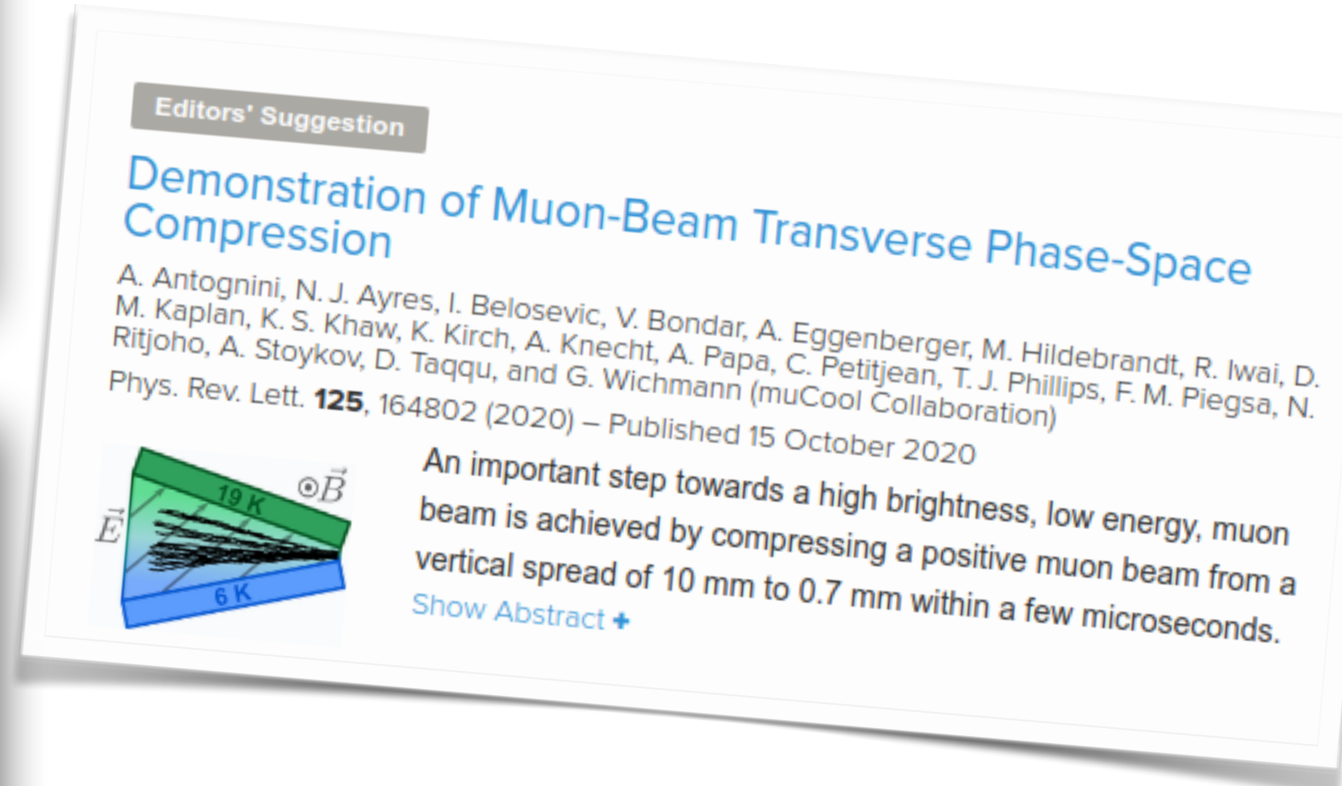

A1s
4.50 kV: χ^2_{red} = 4.06
4.75 kV: χ^2_{red} = 2.20
5.00 kV: χ^2_{red} = 1.38
5.25 kV: χ^2_{red} = 1.51
5.50 kV: χ^2_{red} = 1.72
A2R
4.50 kV: χ^2_{red} = 10.06
4.75 kV: χ^2_{red} = 1.69
5.00 kV: χ^2_{red} = 1.29
5.25 kV: χ^2_{red} = 3.78
5.50 kV: χ^2_{red} = 6.07
A2L
4.50 kV: χ^2_{red} = 8.01
4.75 kV: χ^2_{red} = 1.65
5.00 kV: χ^2_{red} = 3.46
5.25 kV: χ^2_{red} = 5.08
5.50 kV: χ^2_{red} = 6.82
A3s
4.50 kV: χ^2_{red} = 4.96
4.75 kV: χ^2_{red} = 2.11
5.00 kV: χ^2_{red} = 1.18
5.25 kV: χ^2_{red} = 3.34
5.50 kV: χ^2_{red} = 3.65
counts / exp [-t/2198 ns]
t [ns]
3.00 kV
4.00 kV
4.50 kV
4.75 kV
5.00 kV
5.25 kV
x [mm]
y [mm]
t [µs]
A1s
3.00 kV: χ^2_{red} = 1.02
4.00 kV: χ^2_{red} = 1.12
4.50 kV: χ^2_{red} = 0.95
4.75 kV: χ^2_{red} = 1.14
5.00 kV: χ^2_{red} = 1.00
5.25 kV: χ^2_{red} = 2.26
A2R
3.00 kV: χ^2_{red} = 1.00
4.00 kV: χ^2_{red} = 1.00
4.50 kV: χ^2_{red} = 0.78
4.75 kV: χ^2_{red} = 1.22
5.00 kV: χ^2_{red} = 1.88
5.25 kV: χ^2_{red} = 1.24
A2L
3.00 kV: χ^2_{red} = 1.21
4.00 kV: χ^2_{red} = 1.22
4.50 kV: χ^2_{red} = 1.58
4.75 kV: χ^2_{red} = 1.60
5.00 kV: χ^2_{red} = 2.52
5.25 kV: χ^2_{red} = 4.34
A3s
3.00 kV: χ^2_{red} = 4.57
4.00 kV: χ^2_{red} = 6.06
4.50 kV: χ^2_{red} = 10.05
4.75 kV: χ^2_{red} = 8.57
5.00 kV: χ^2_{red} = 4.84
5.25 kV: χ^2_{red} = 0.60

Transverse compression: setup & target



A. Antognini et al., PRL 125, 164802 (2020)

I. Belosevic, PhD Thesis ETH Zurich (2019)



Editors' Suggestion

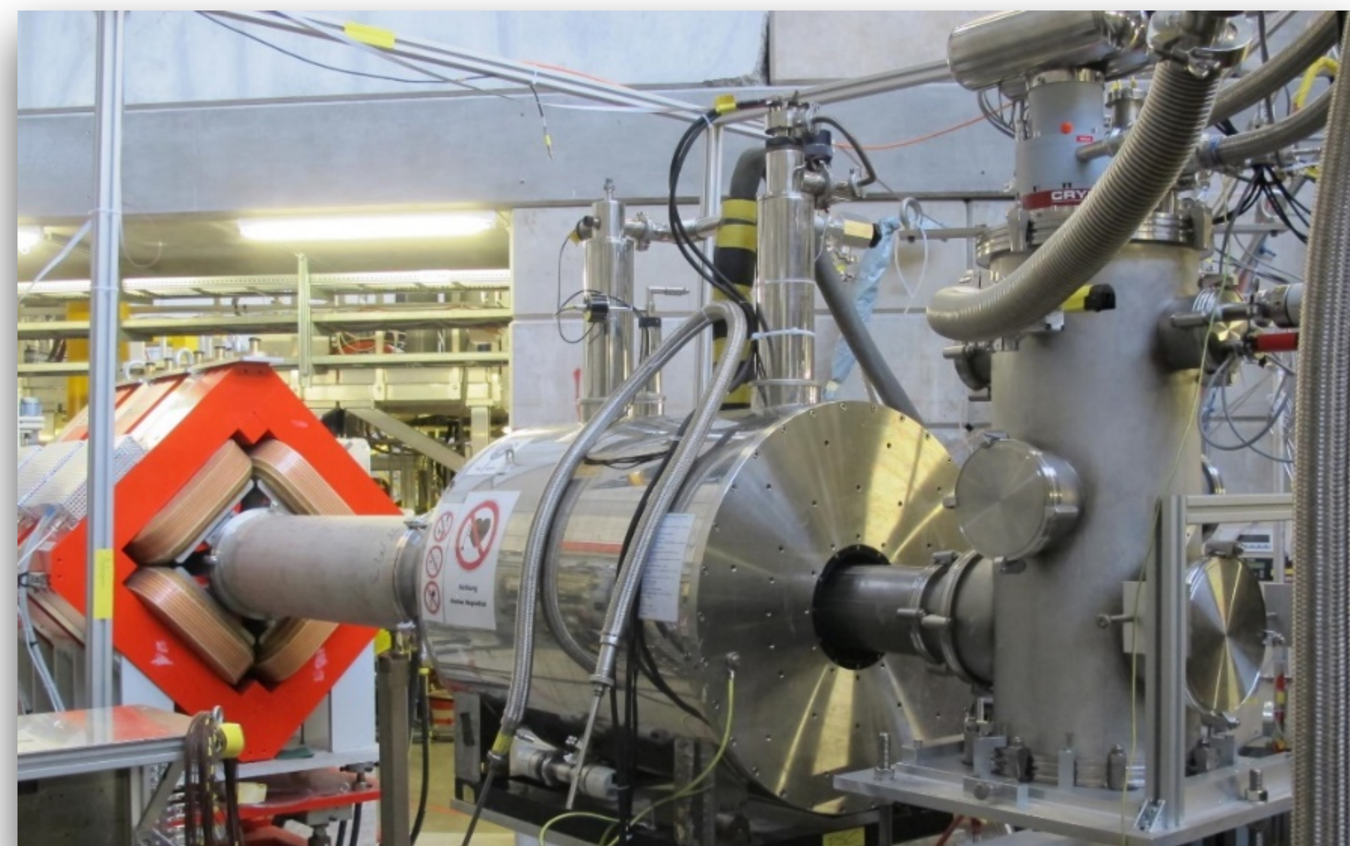
Demonstration of Muon-Beam Transverse Phase-Space Compression

A. Antognini, N. J. Ayres, I. Belosevic, V. Bondar, A. Eggenberger, M. Hildebrandt, R. Iwai, D. M. Kaplan, K. S. Khaw, K. Kirch, A. Knecht, A. Papa, C. Petitjean, T. J. Phillips, F. M. Piegsa, N. Ritjoho, A. Stoykov, D. Taqqu, and G. Wichmann (muCool Collaboration)

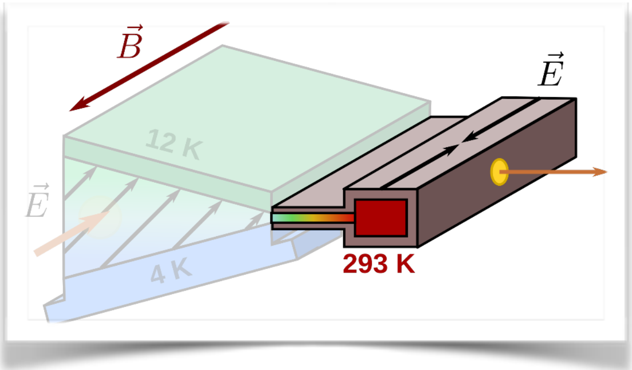
Phys. Rev. Lett. **125**, 164802 (2020) – Published 15 October 2020

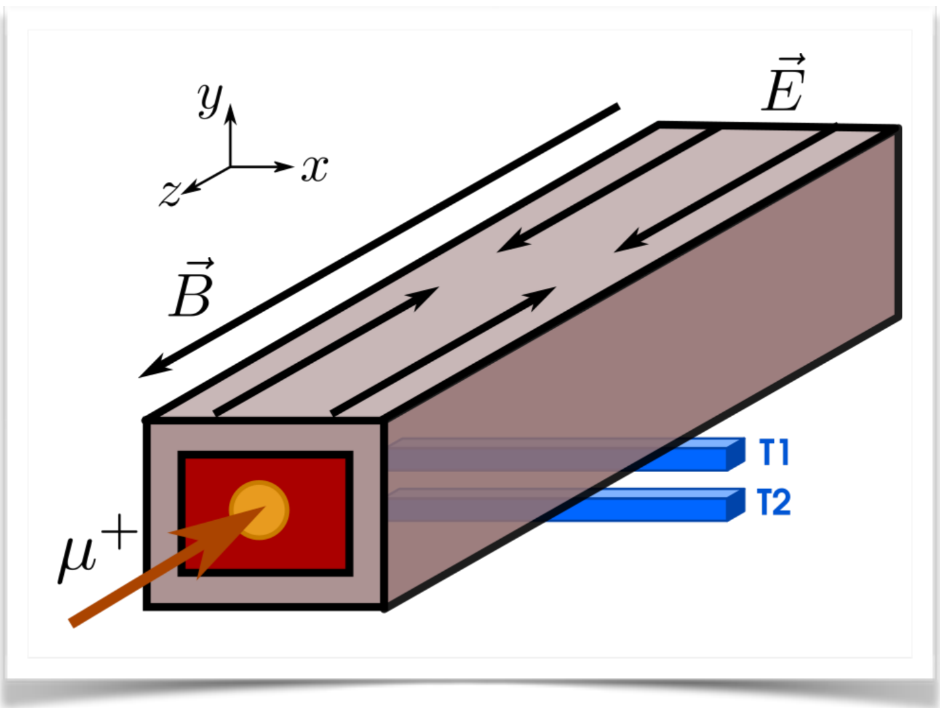
An important step towards a high brightness, low energy, muon beam is achieved by compressing a positive muon beam from a vertical spread of 10 mm to 0.7 mm within a few microseconds.

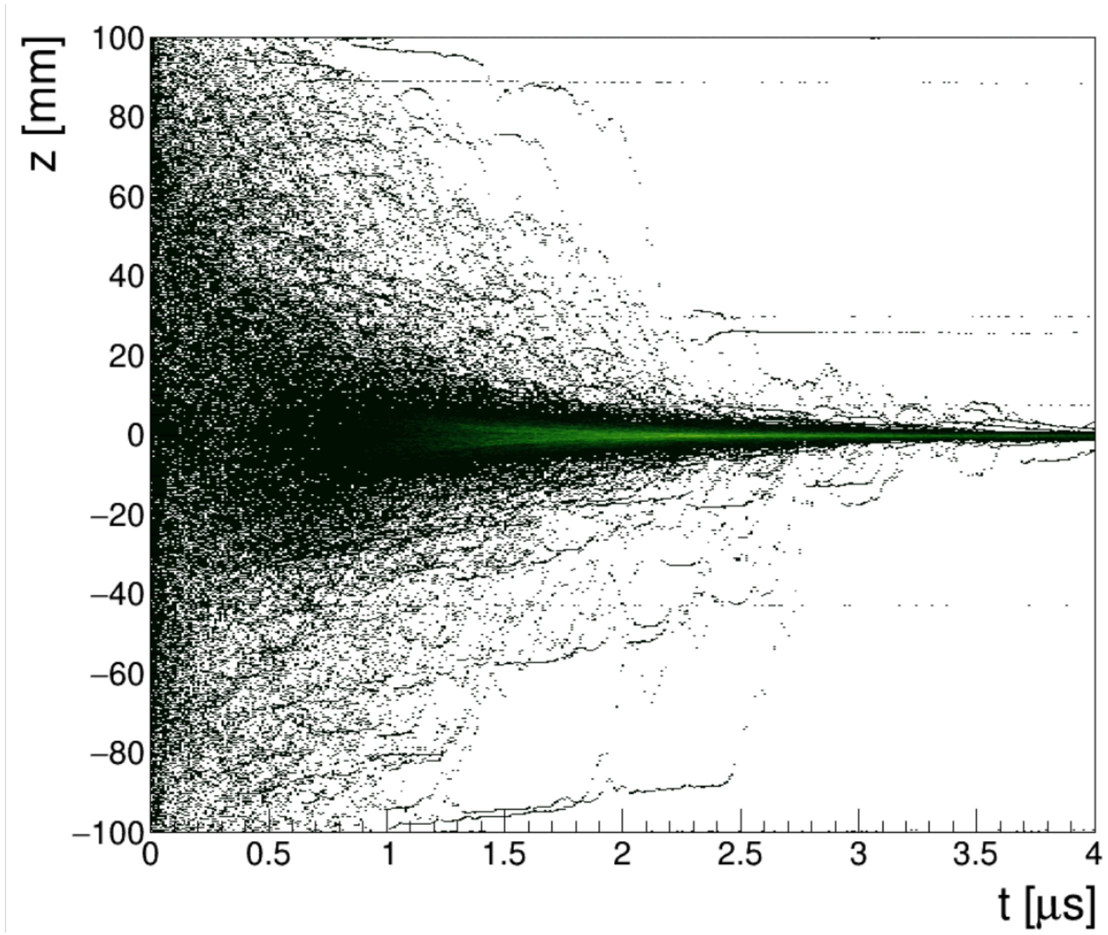
Show Abstract +



Longitudinal compression: simulation



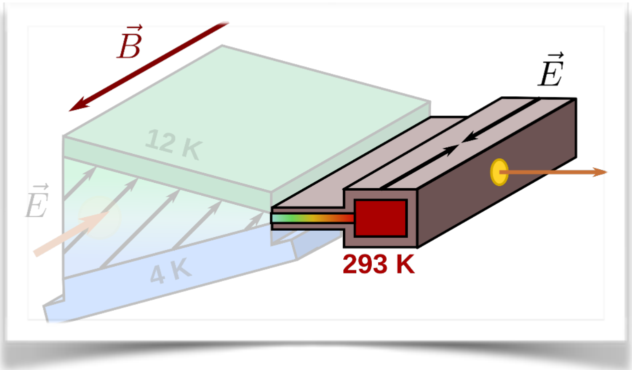


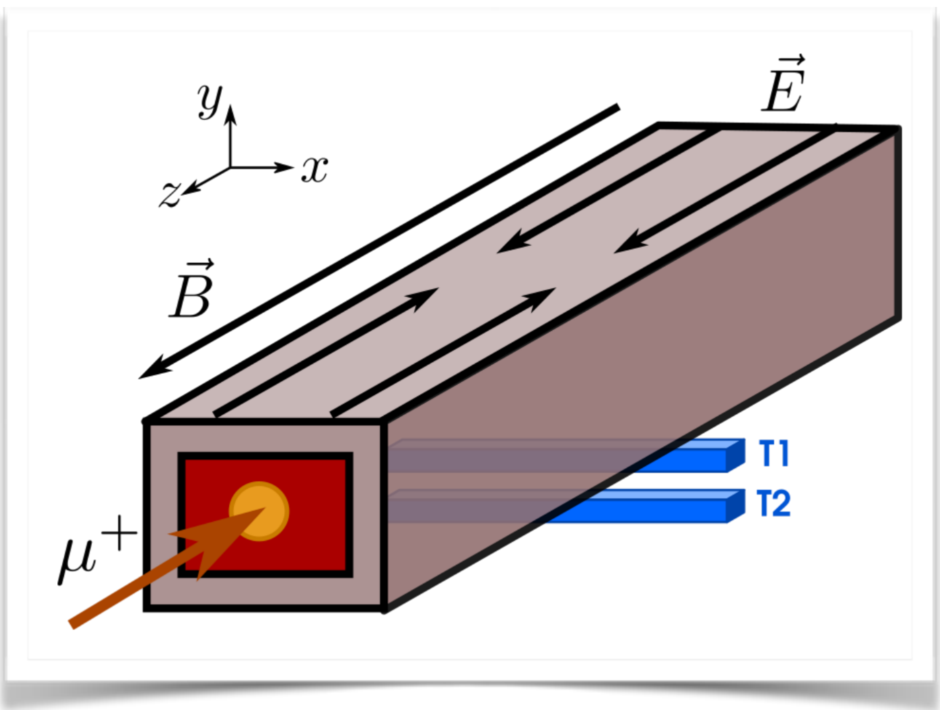


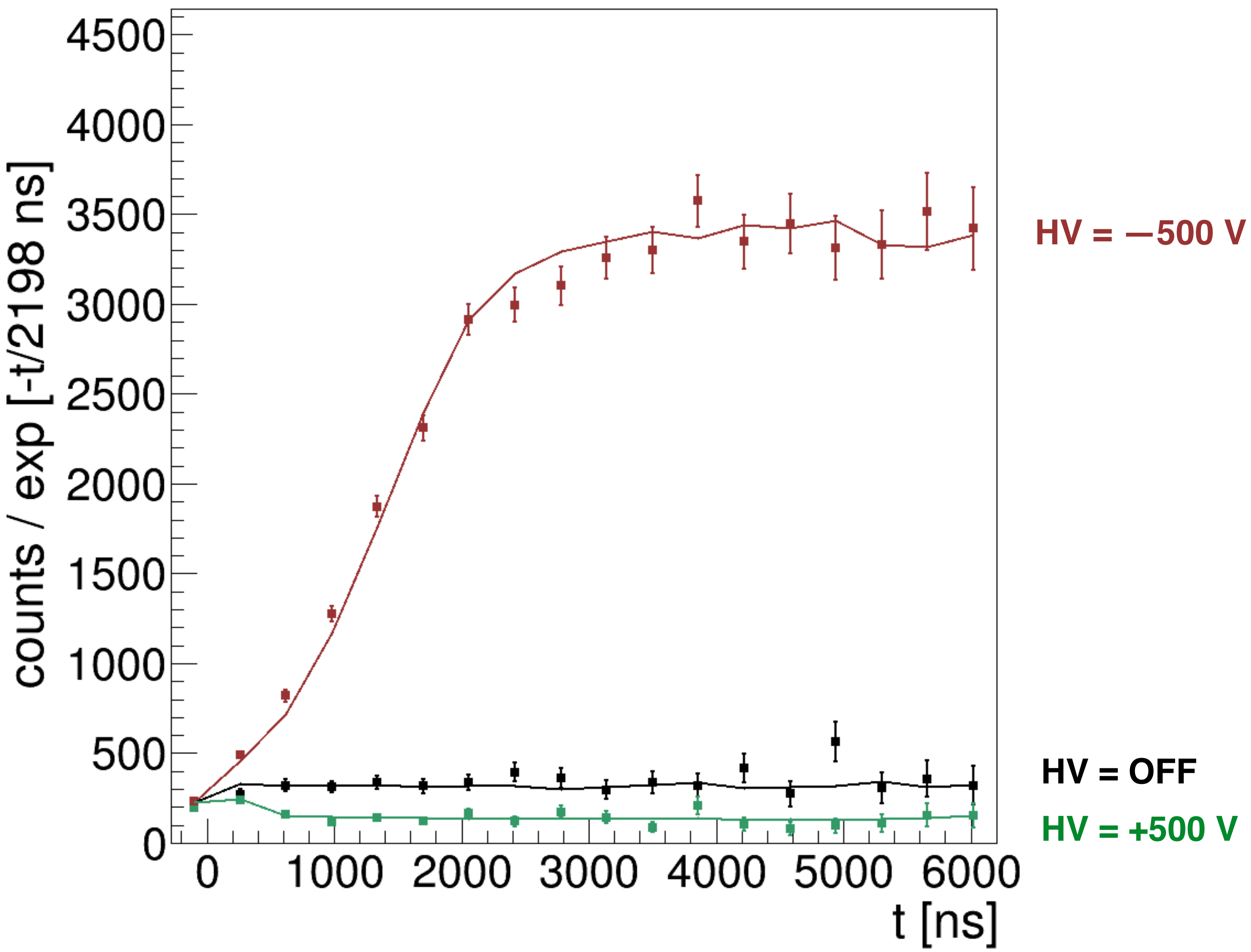
Longitudinal compression: measurements

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

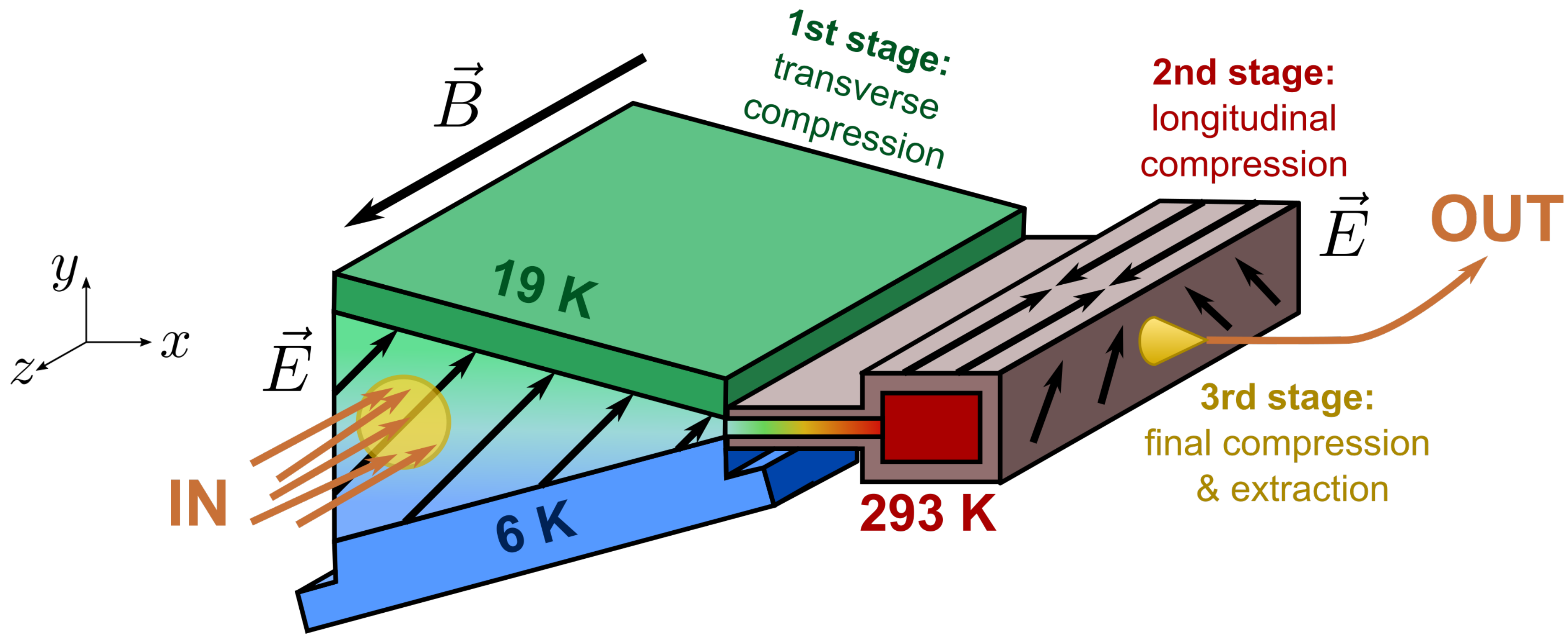
I. Belosevic et al., EPJC 79, 430 (2019)



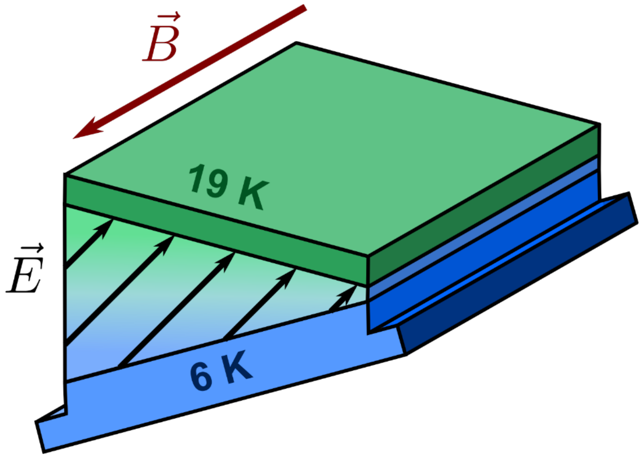




The general scheme

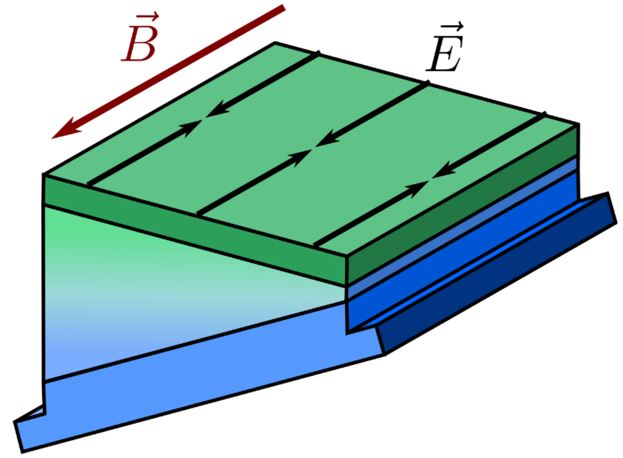


Mixed transverse-longitudinal compression



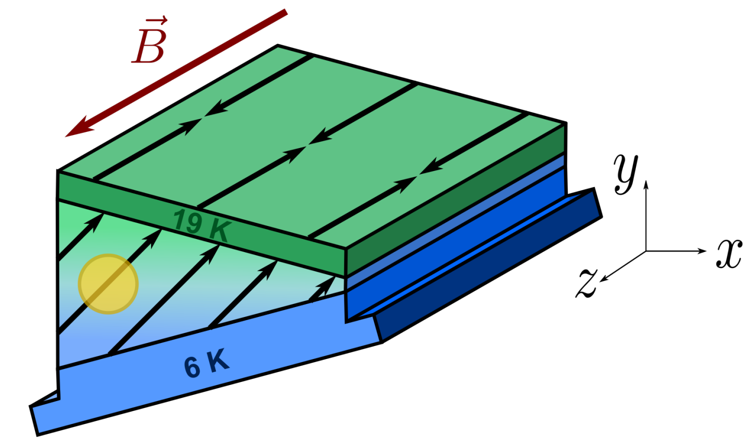
Transverse

+

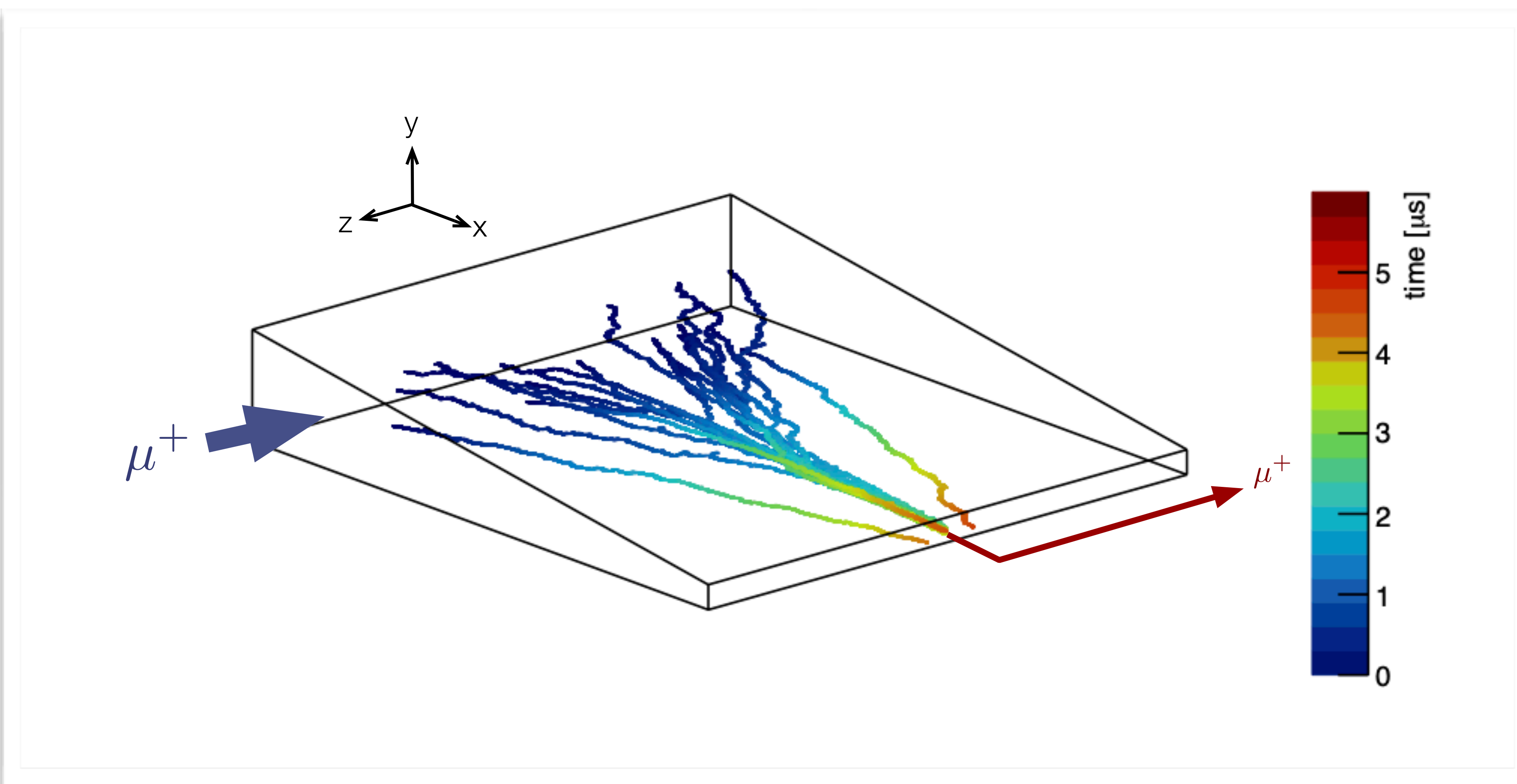


Longitudinal

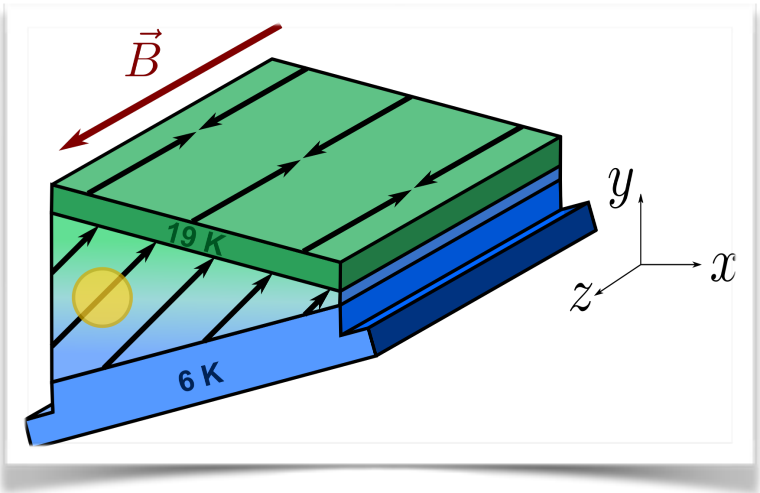
=

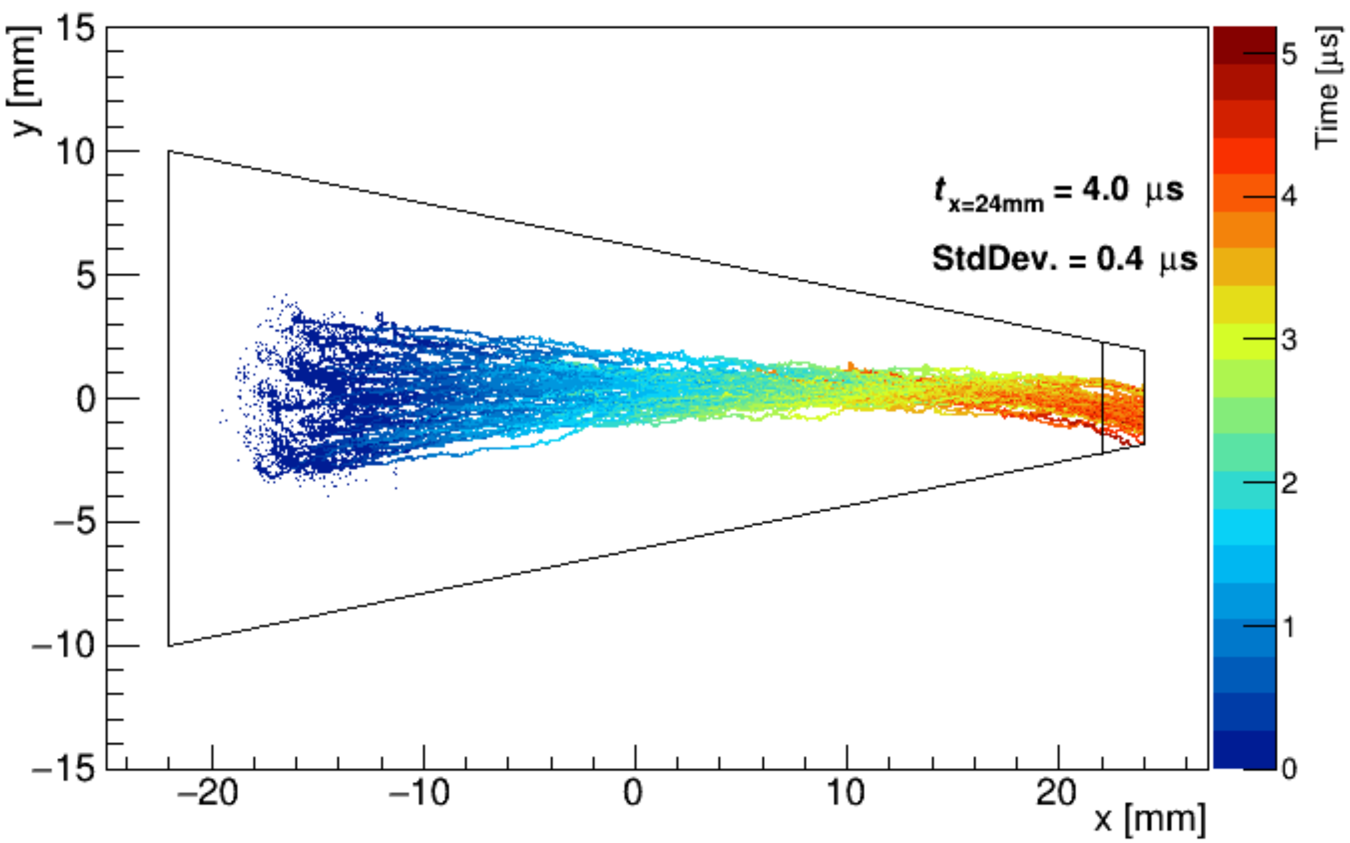


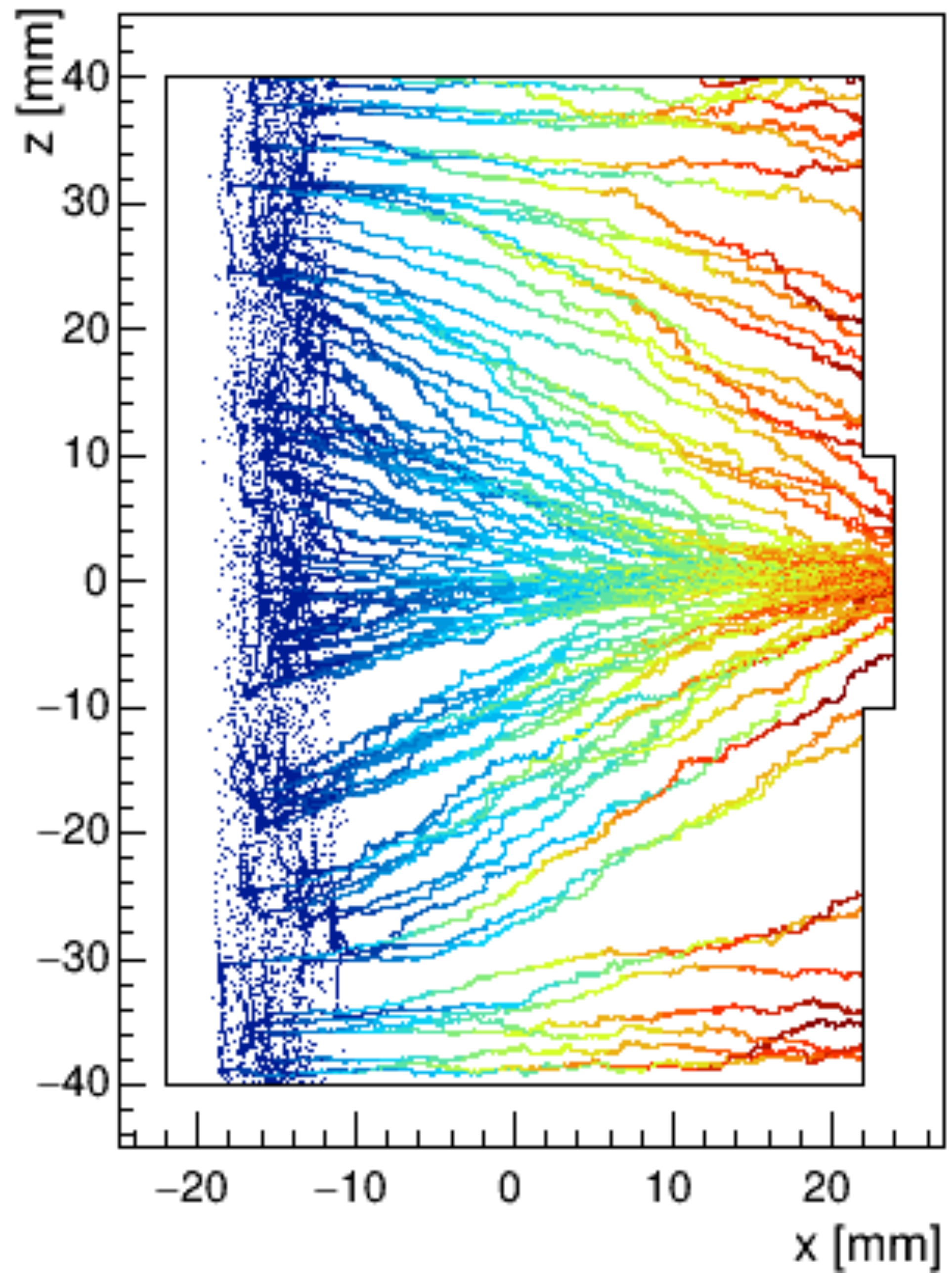
Mixed



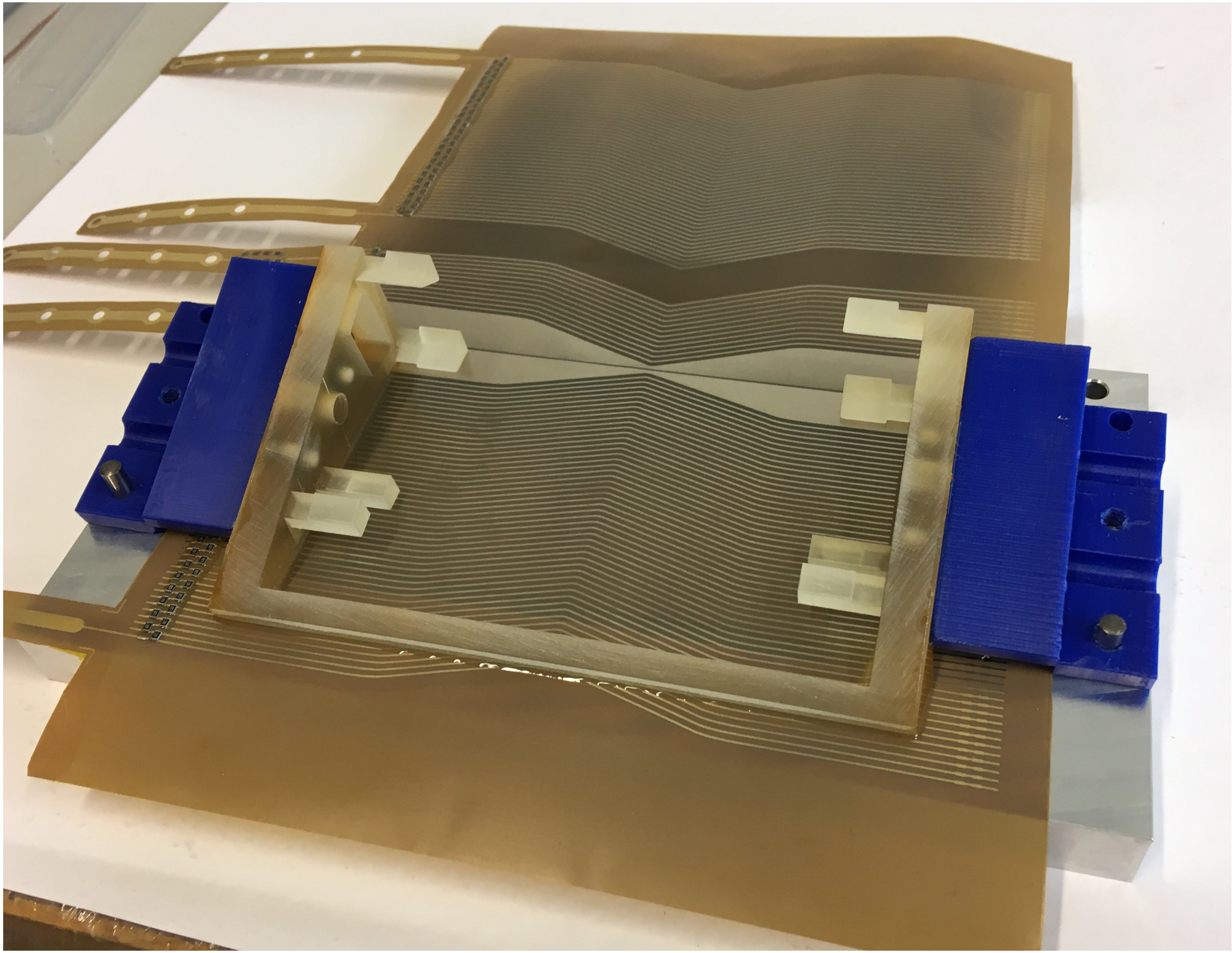
Mixed compression: simulations



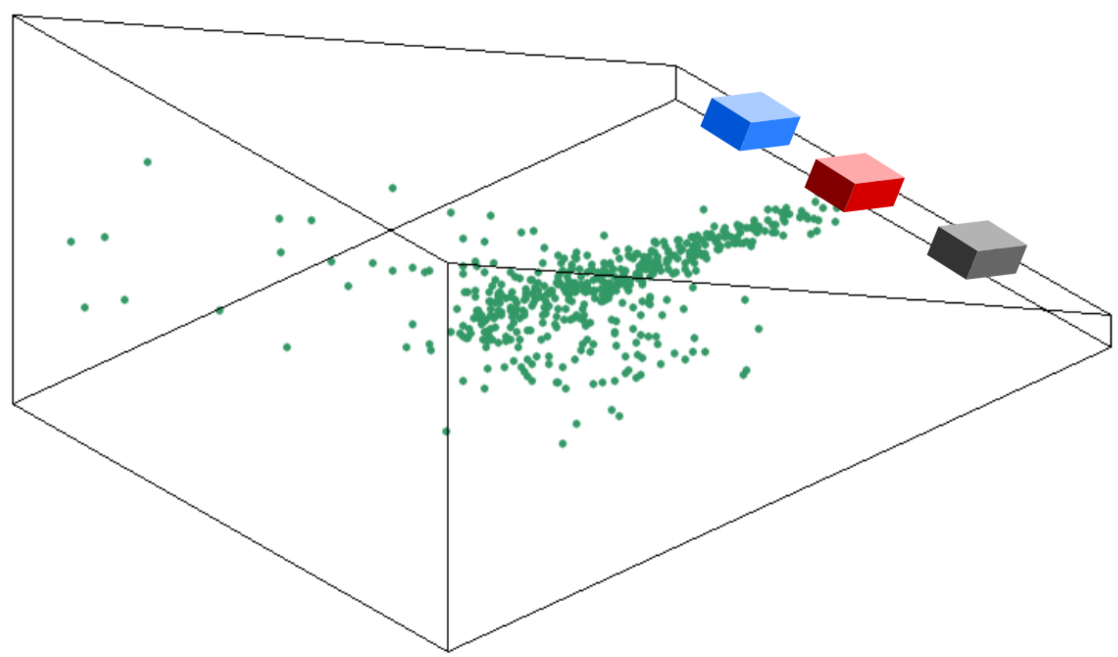


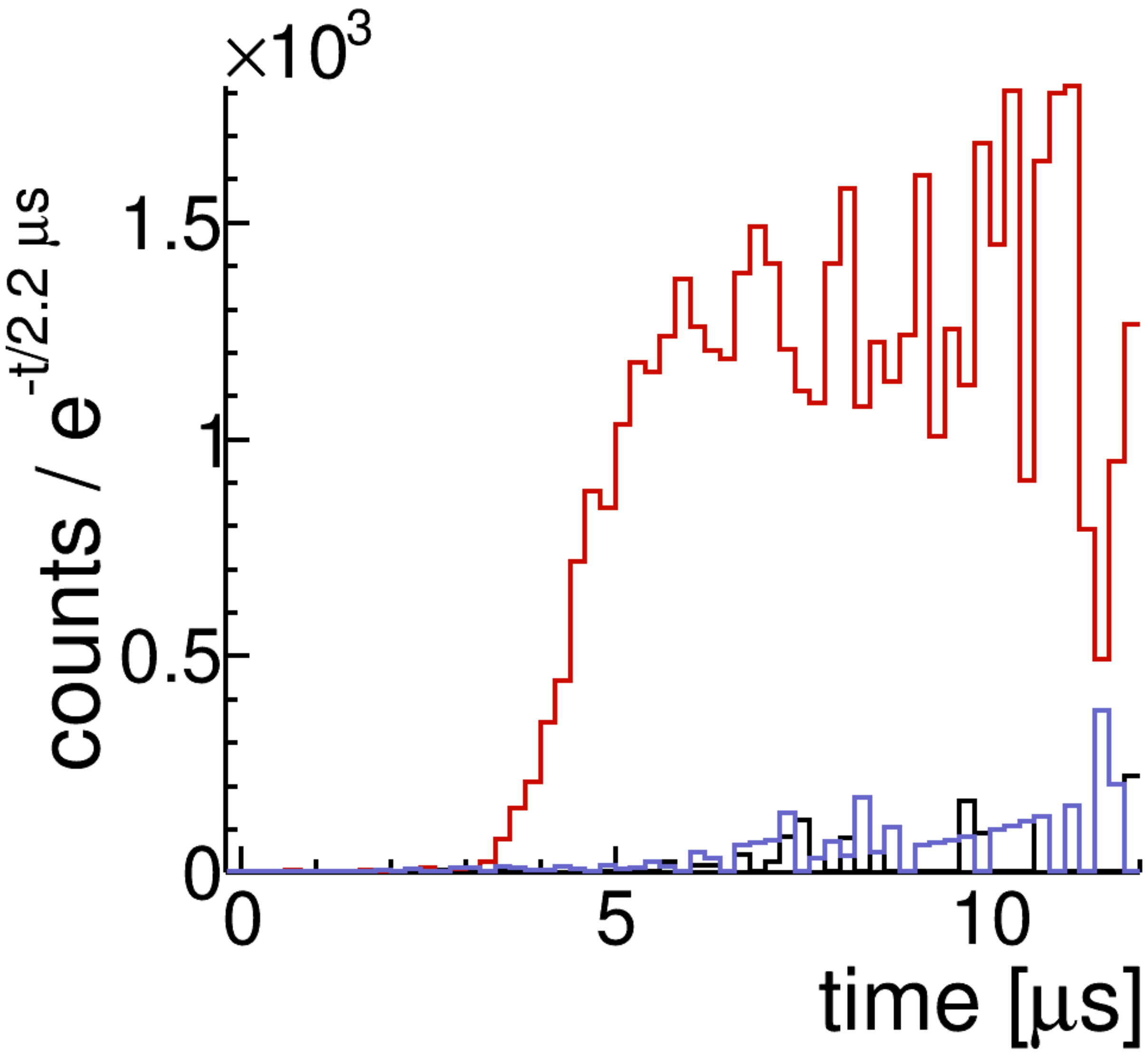


New target design

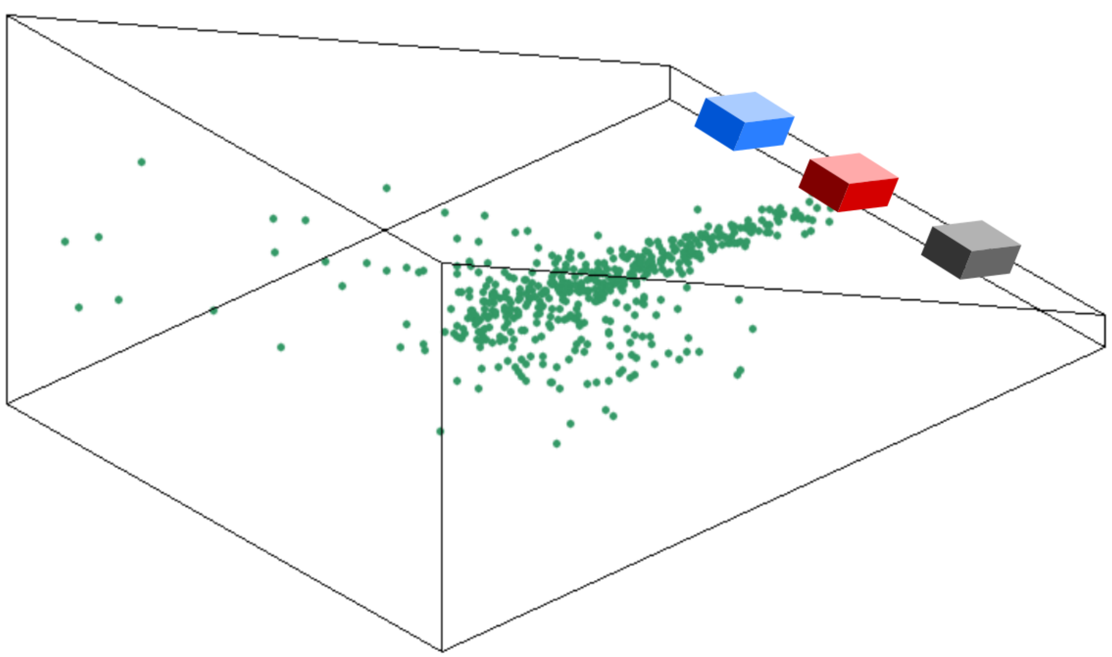


Mixed compression: measurements

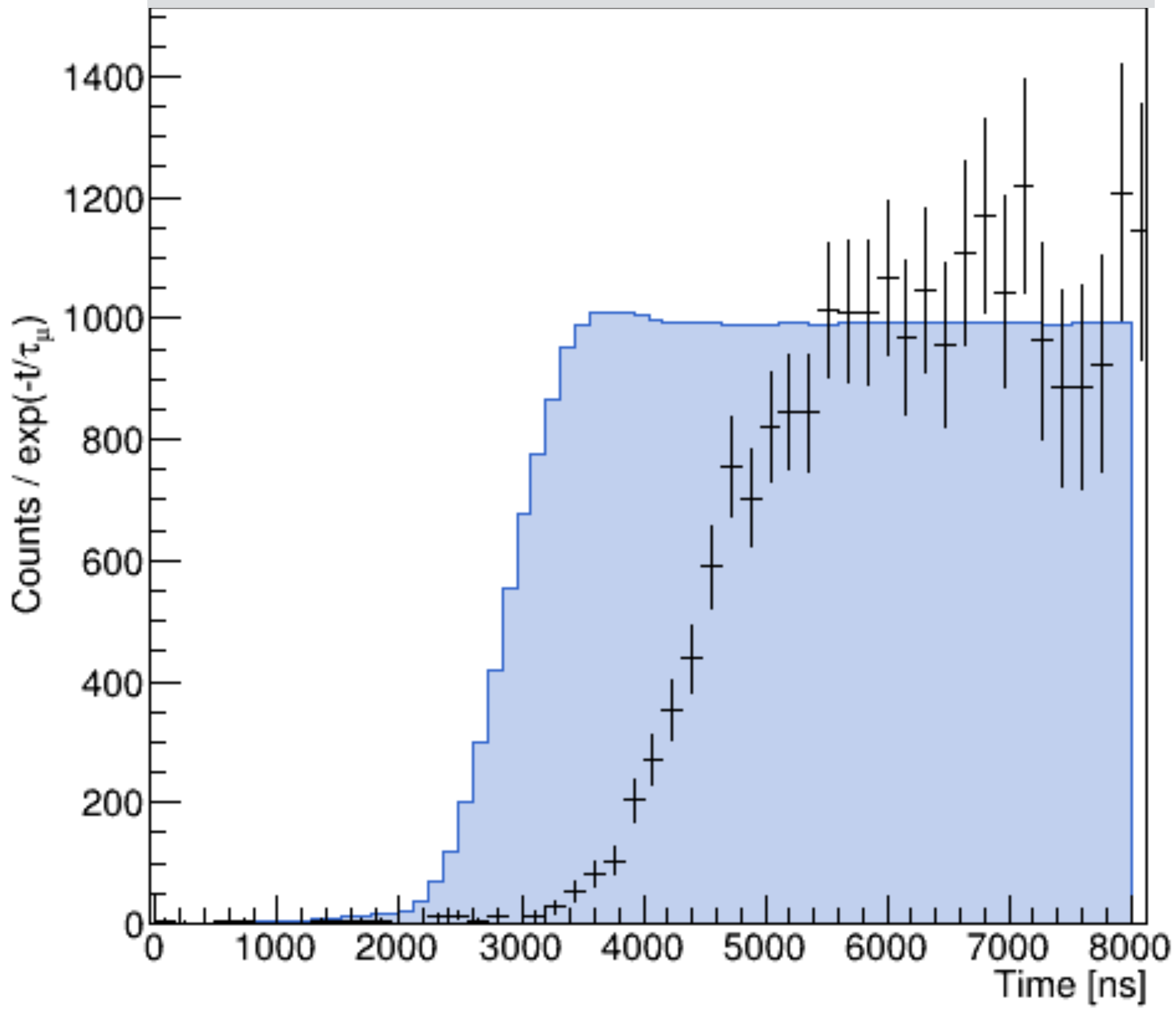




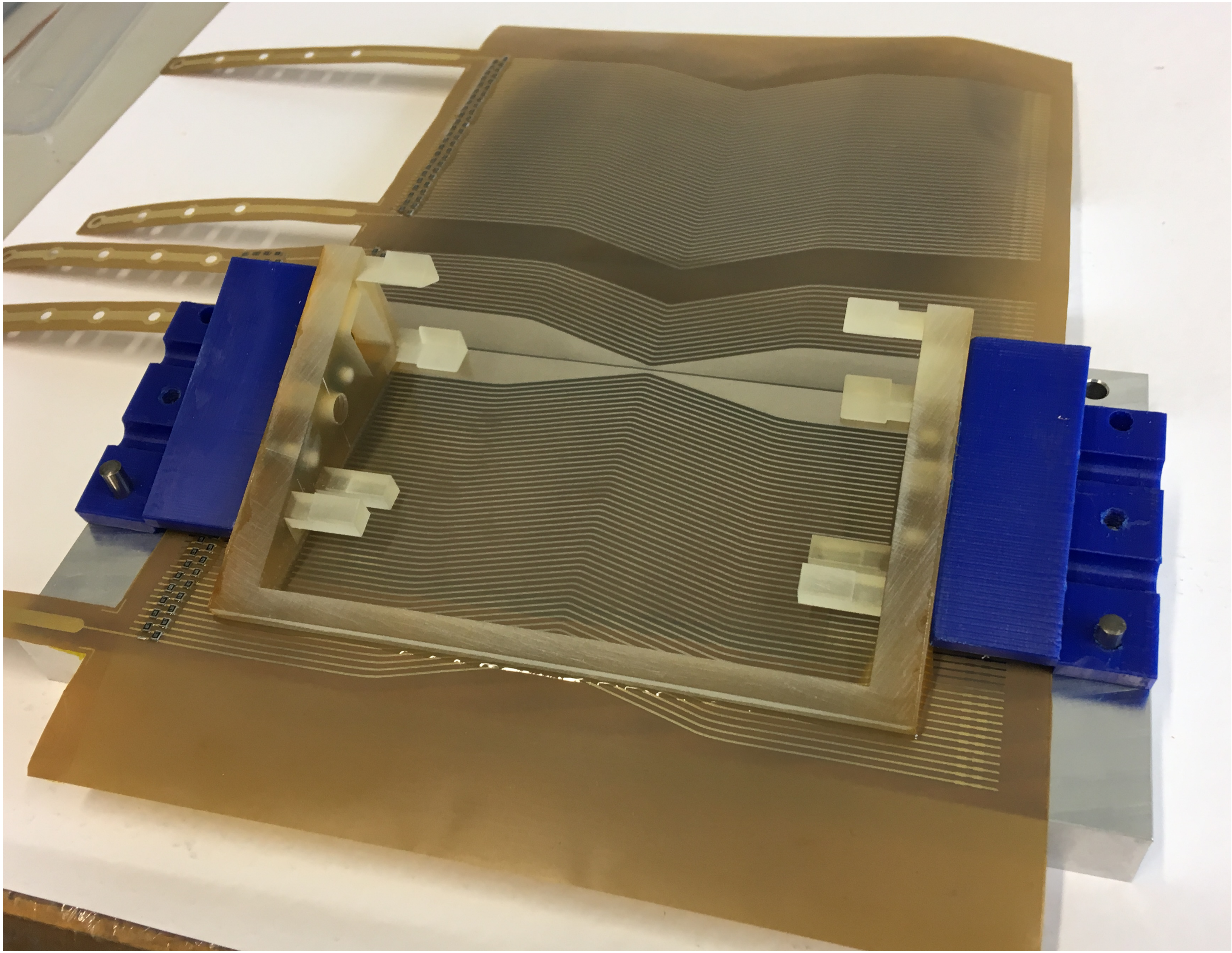
Mixed compression: discrepancy



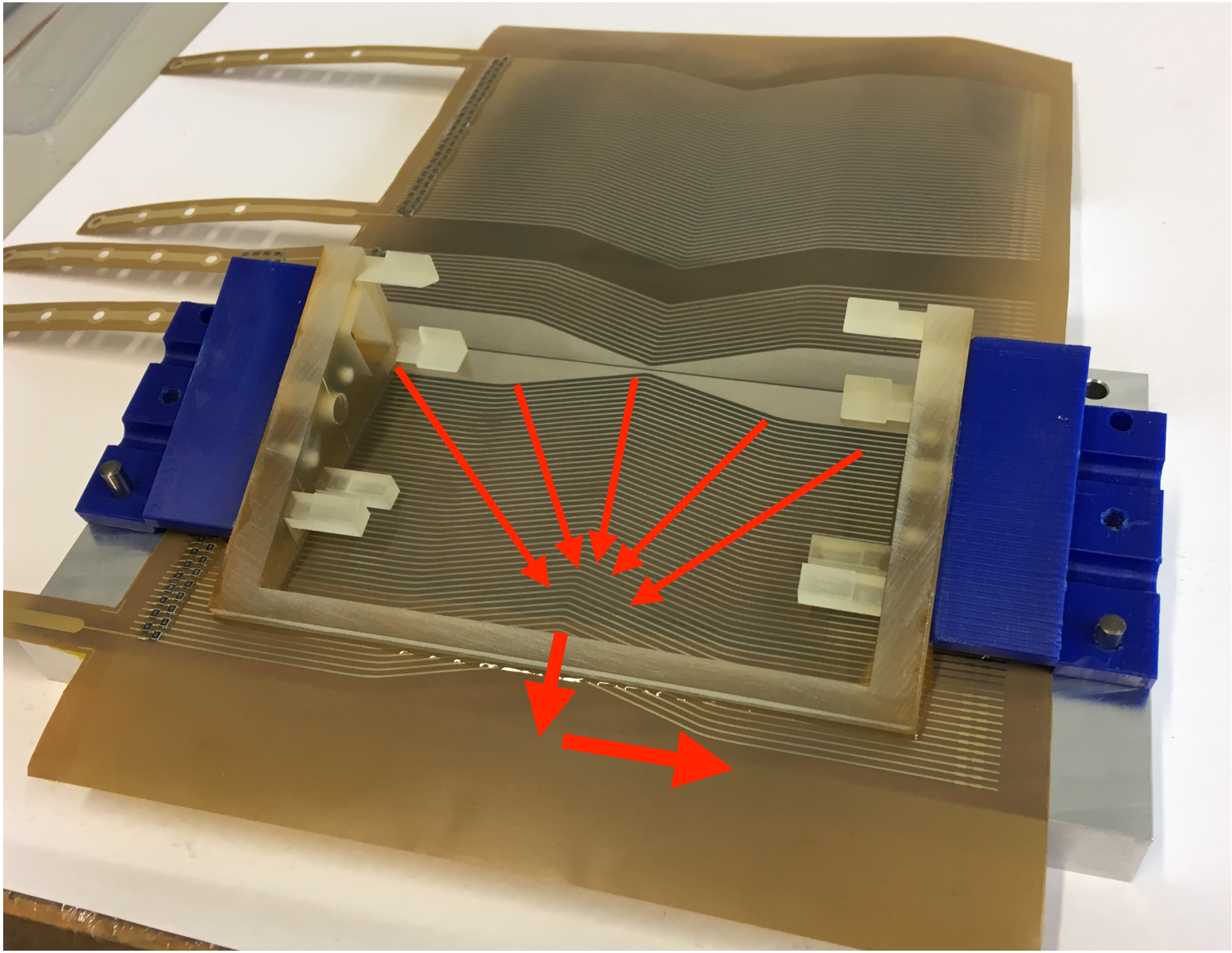
Simulations &
measurements



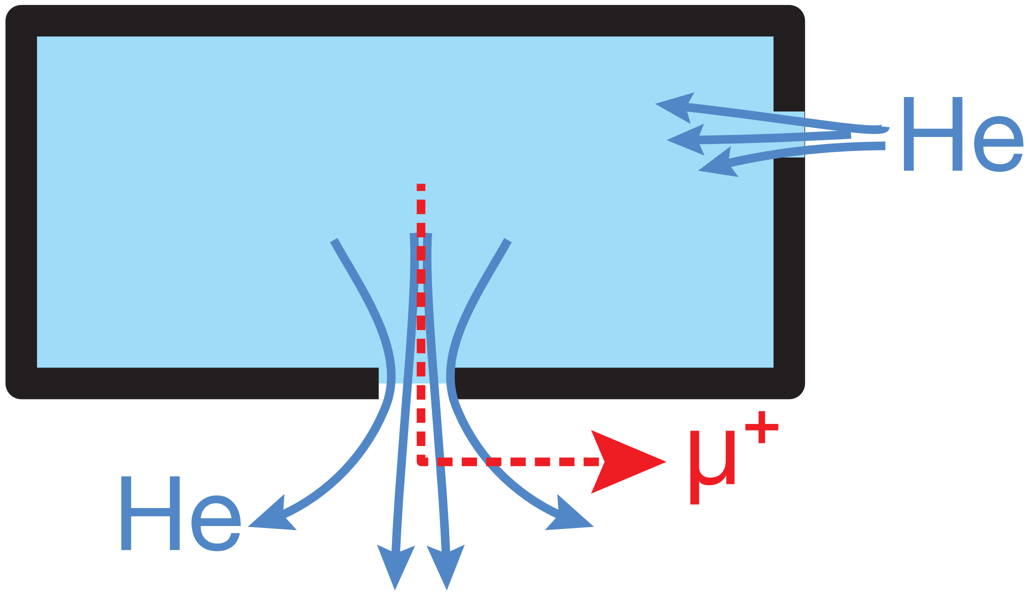
New target design



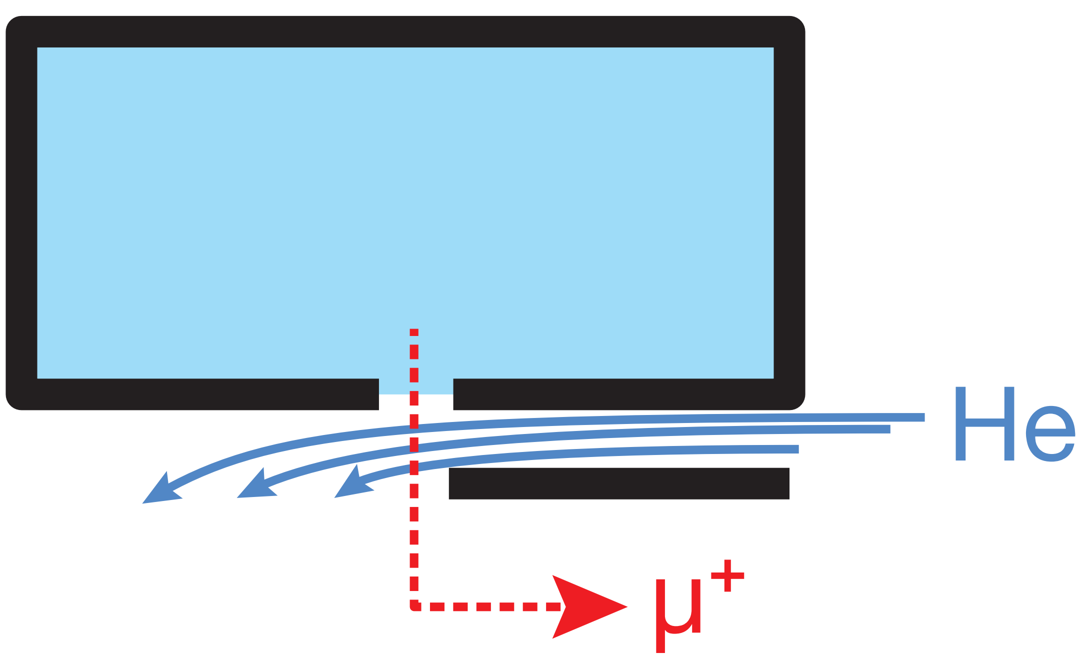
New target adaptable to extraction



Gas injection for extraction

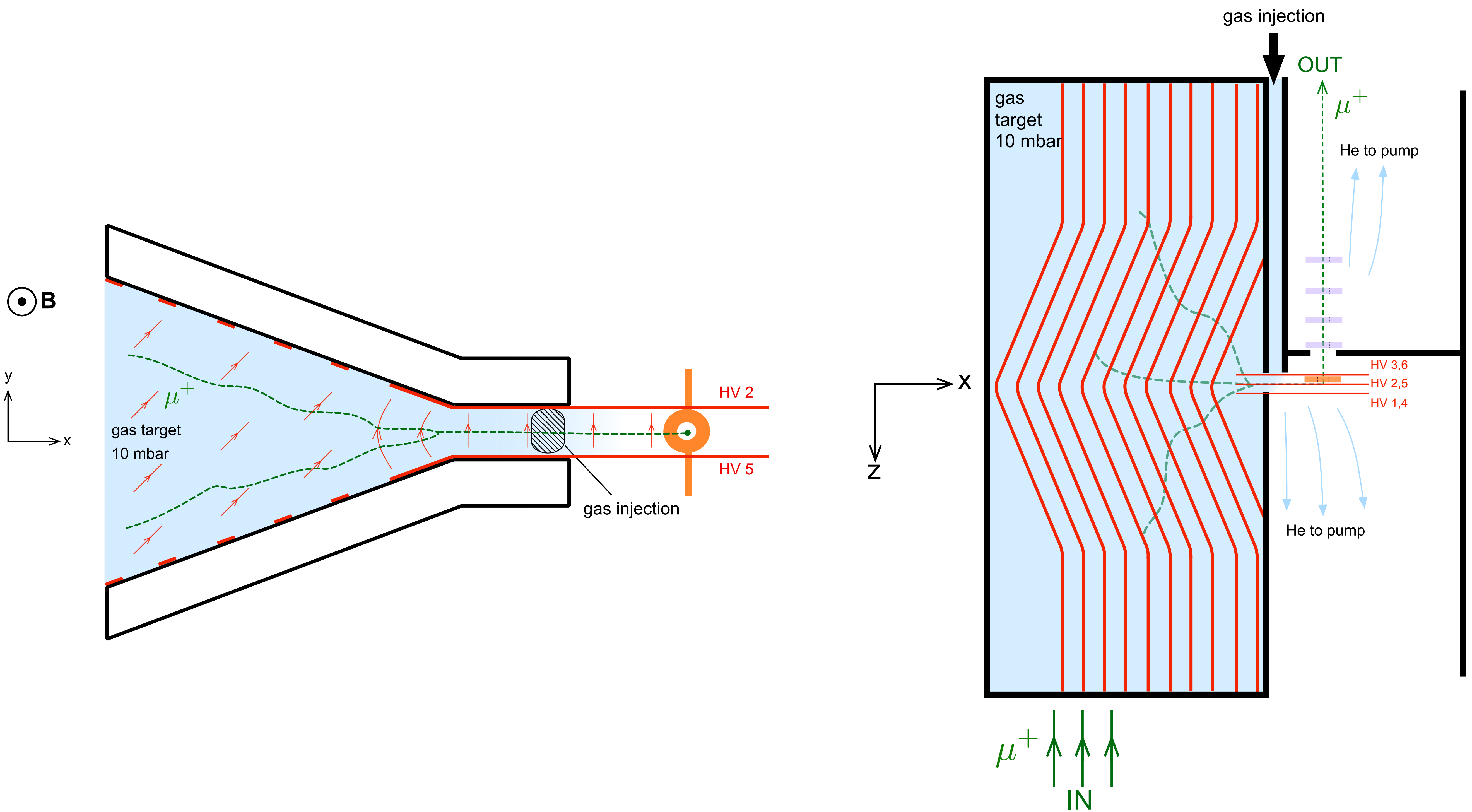


destroy the vertical density gradient

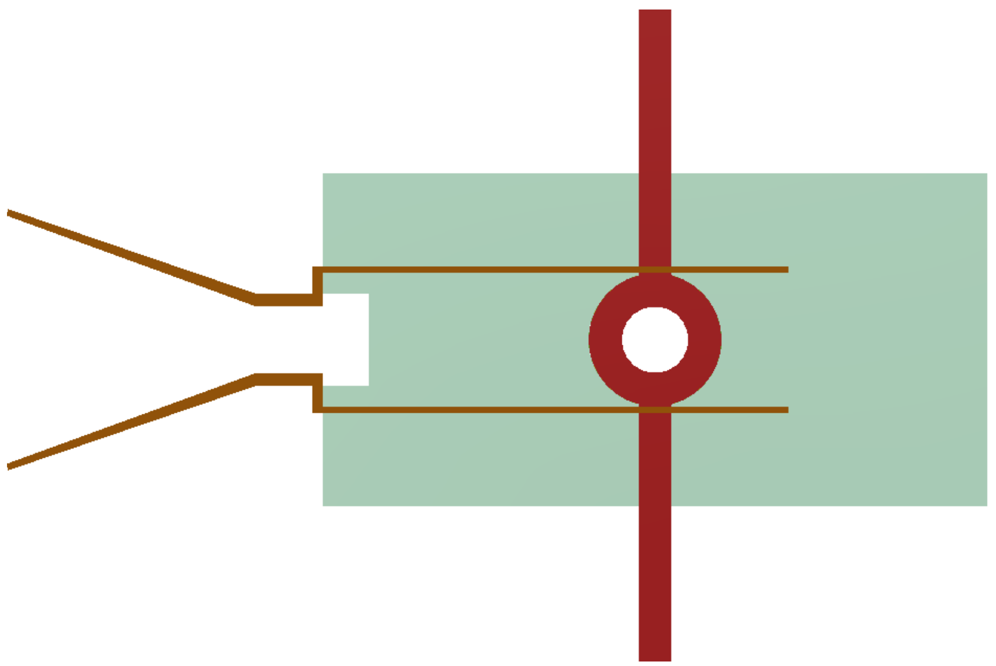


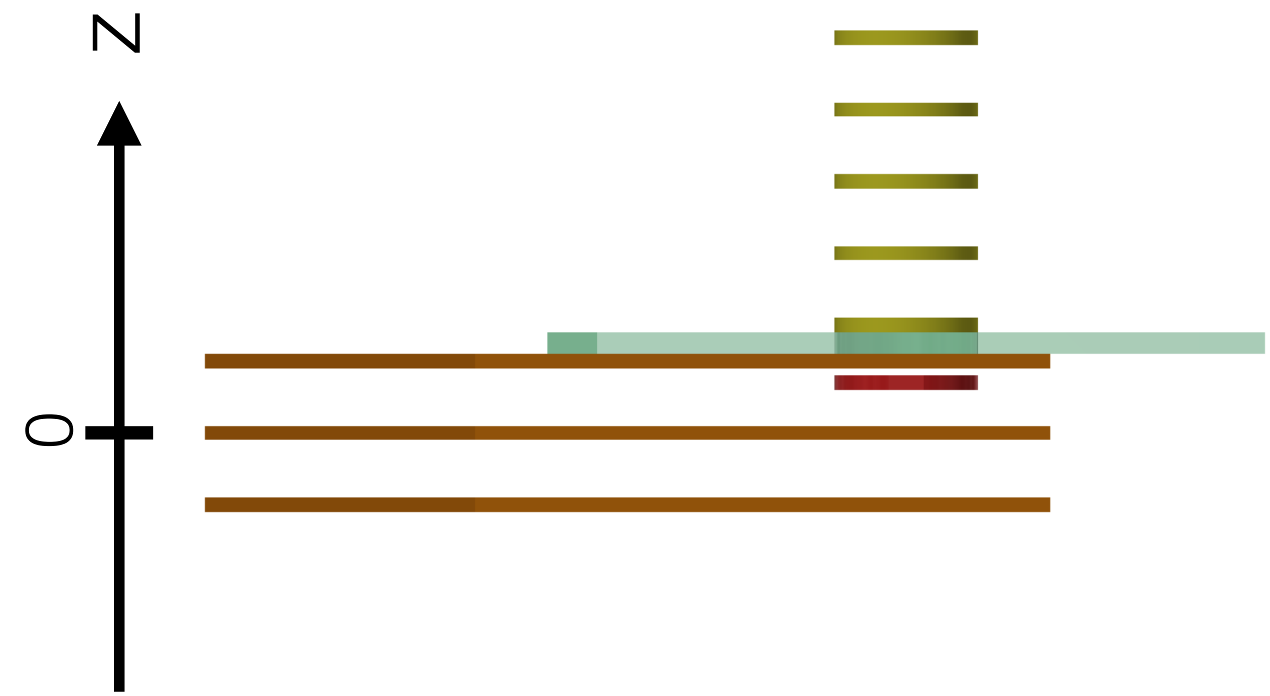
Gas barrier for the target

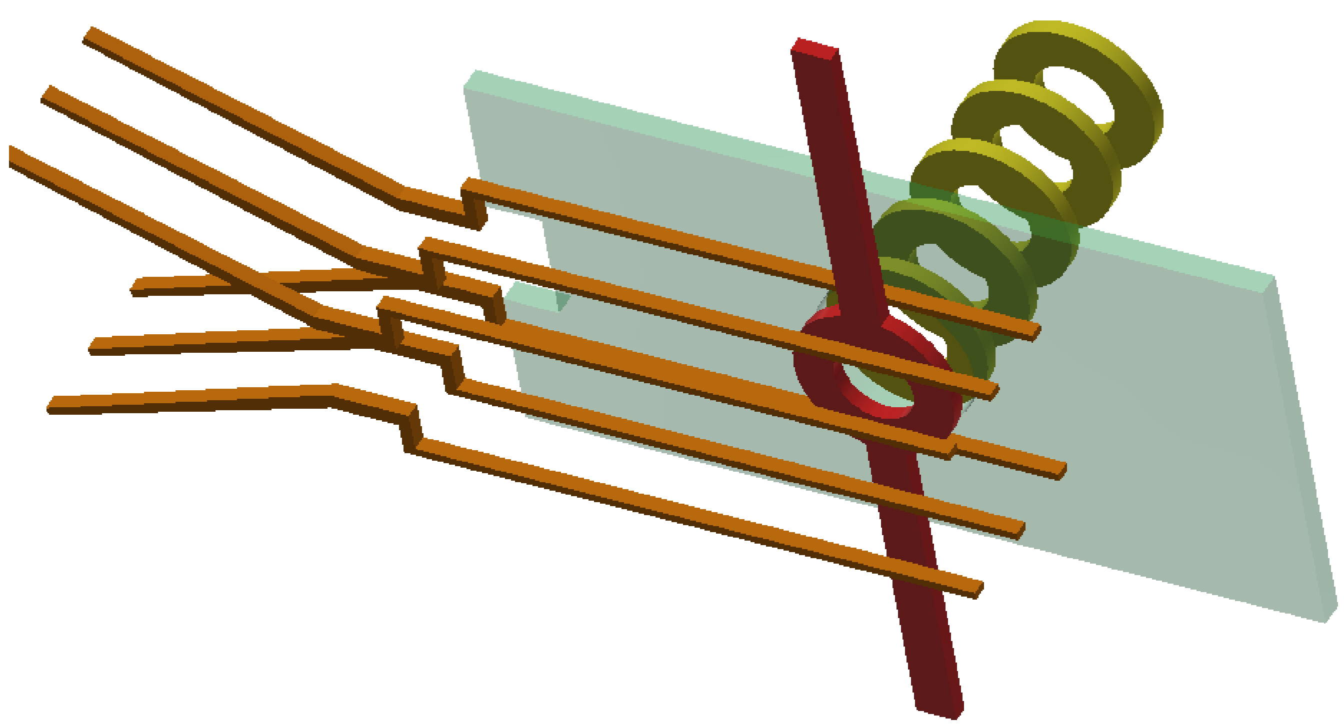
Extraction (base scheme)

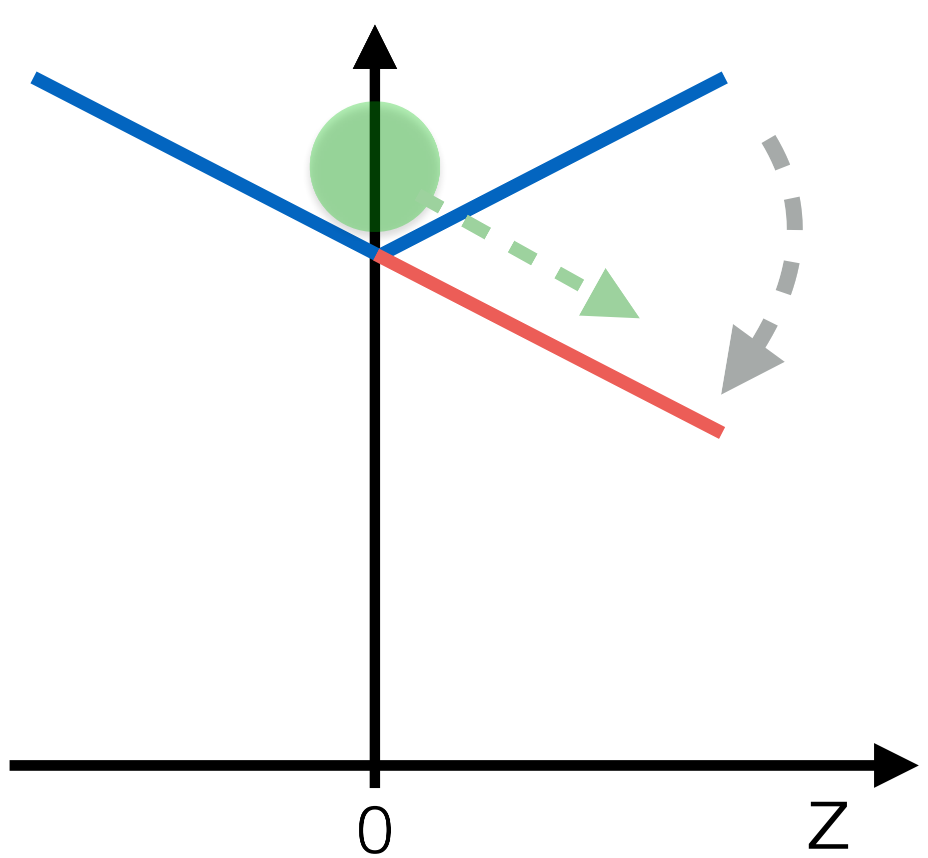


Extraction — pulsed re-acceleration

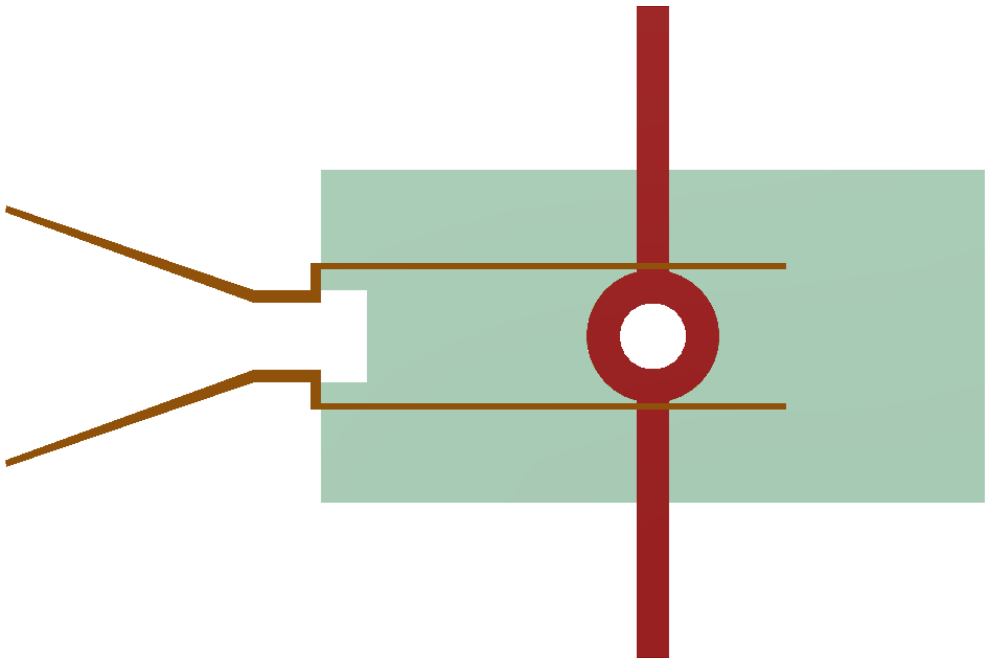


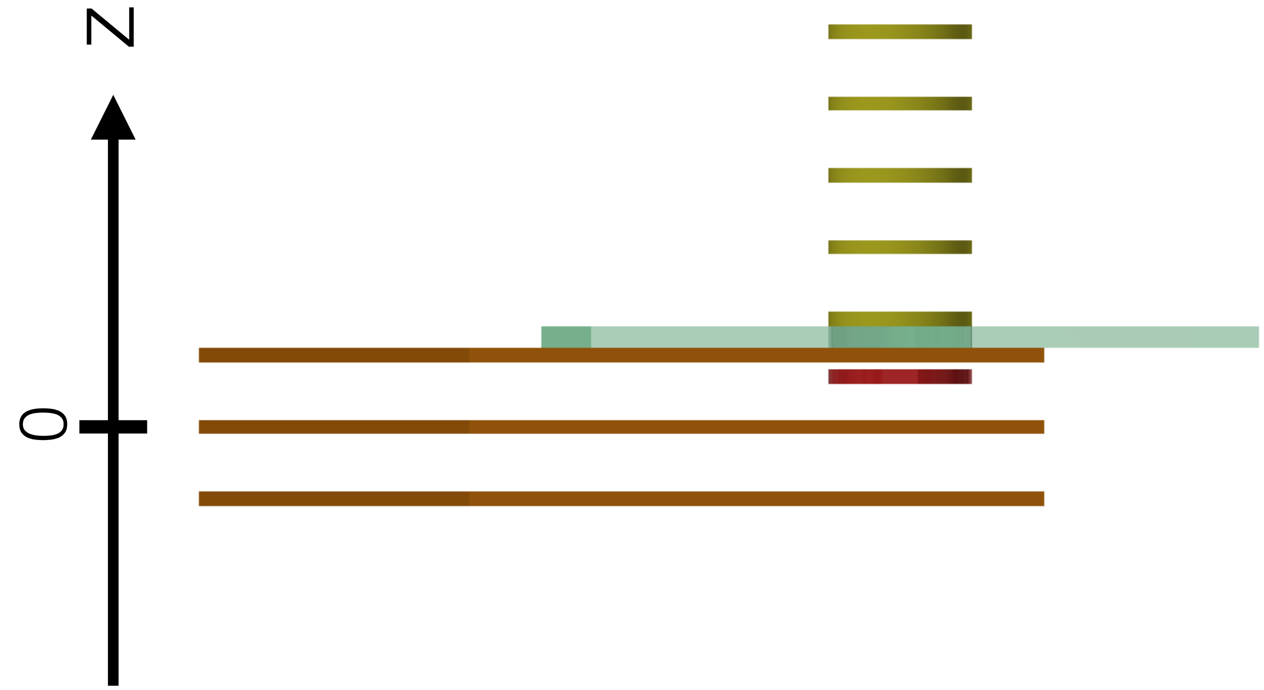


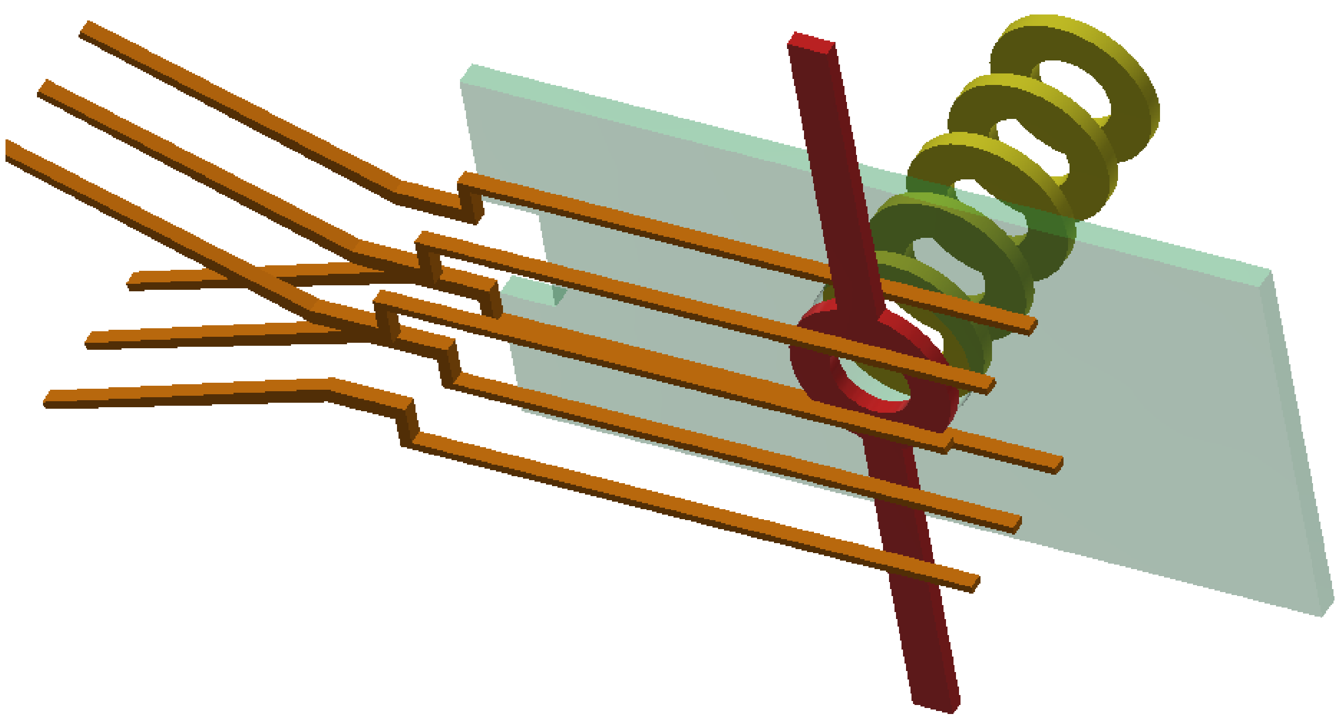




Extraction — pulsed re-acceleration



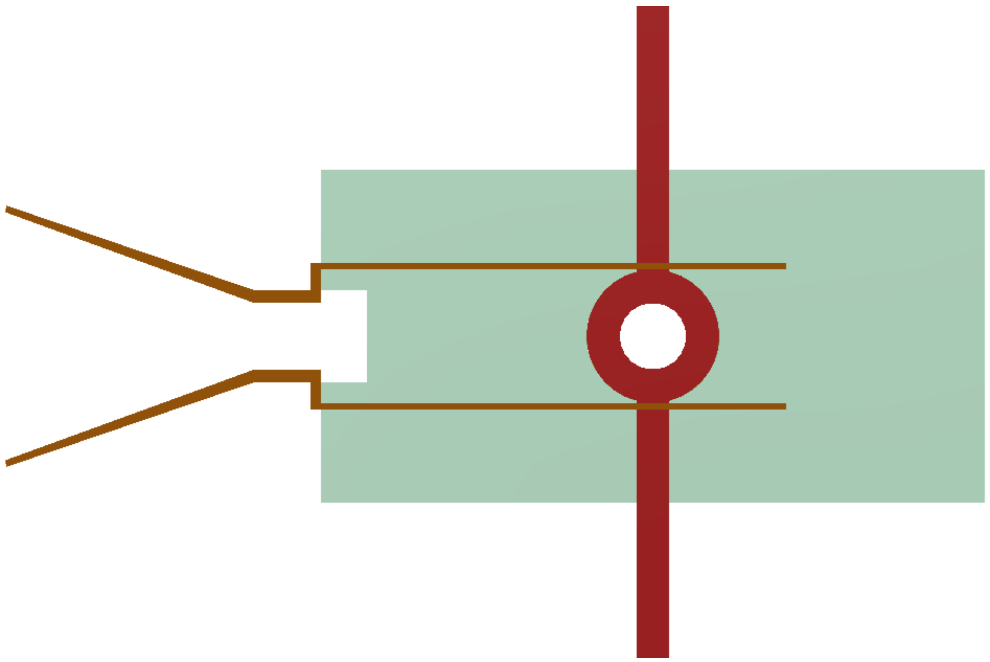


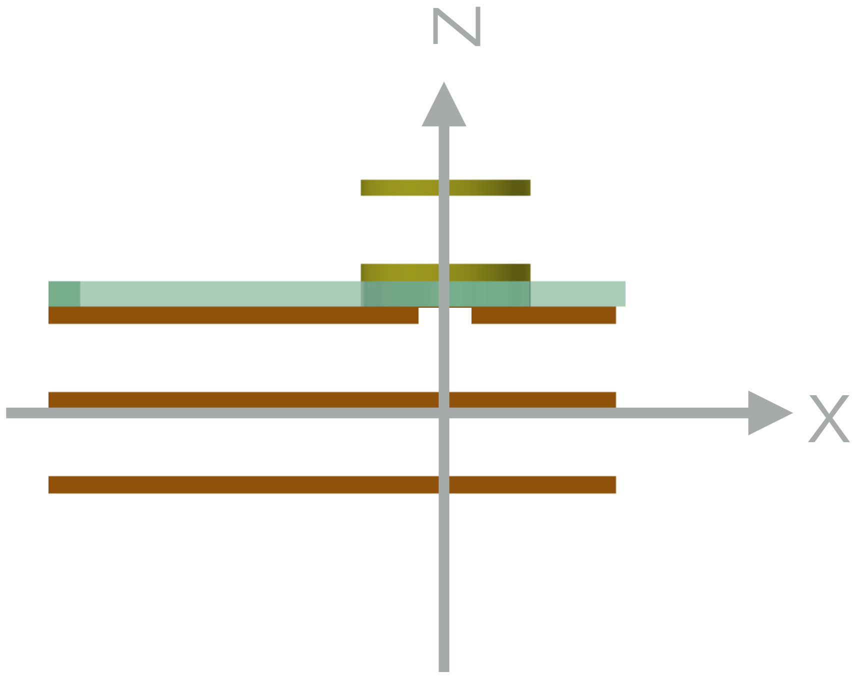


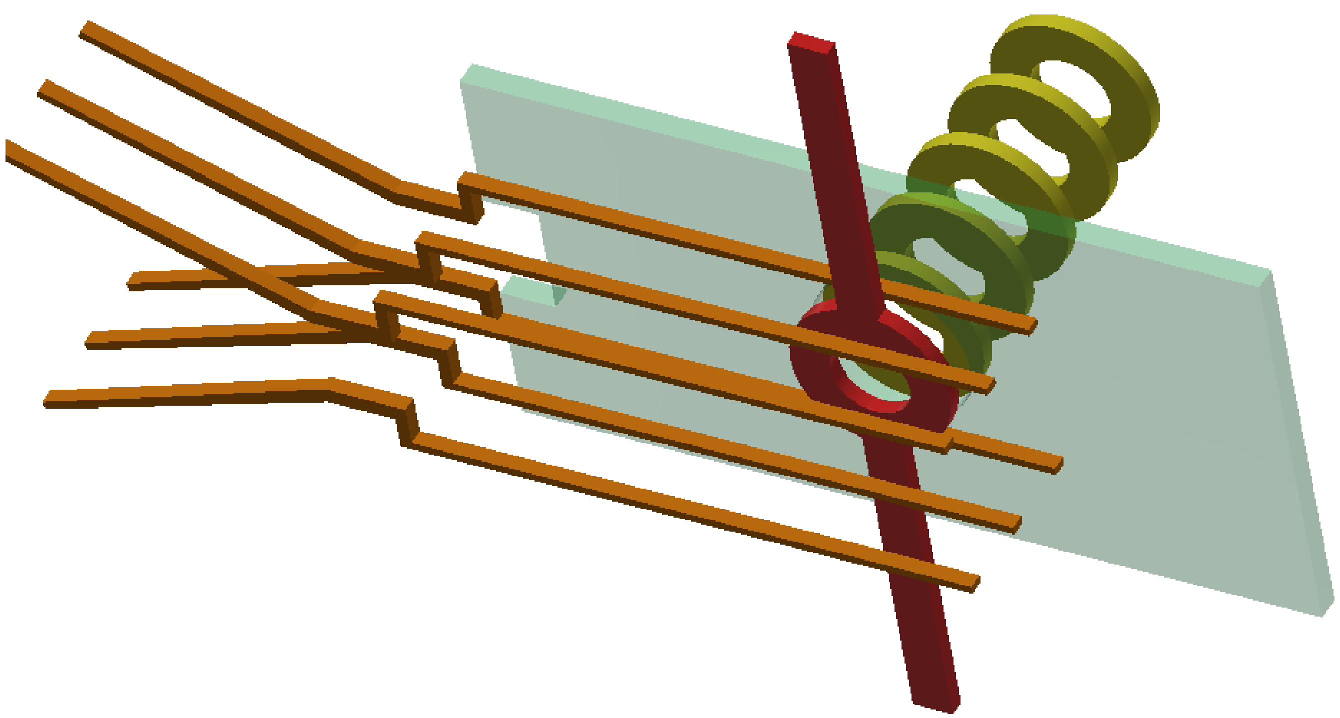
Accumulation can be very complicated:

- degradation of beam quality
- muon decay

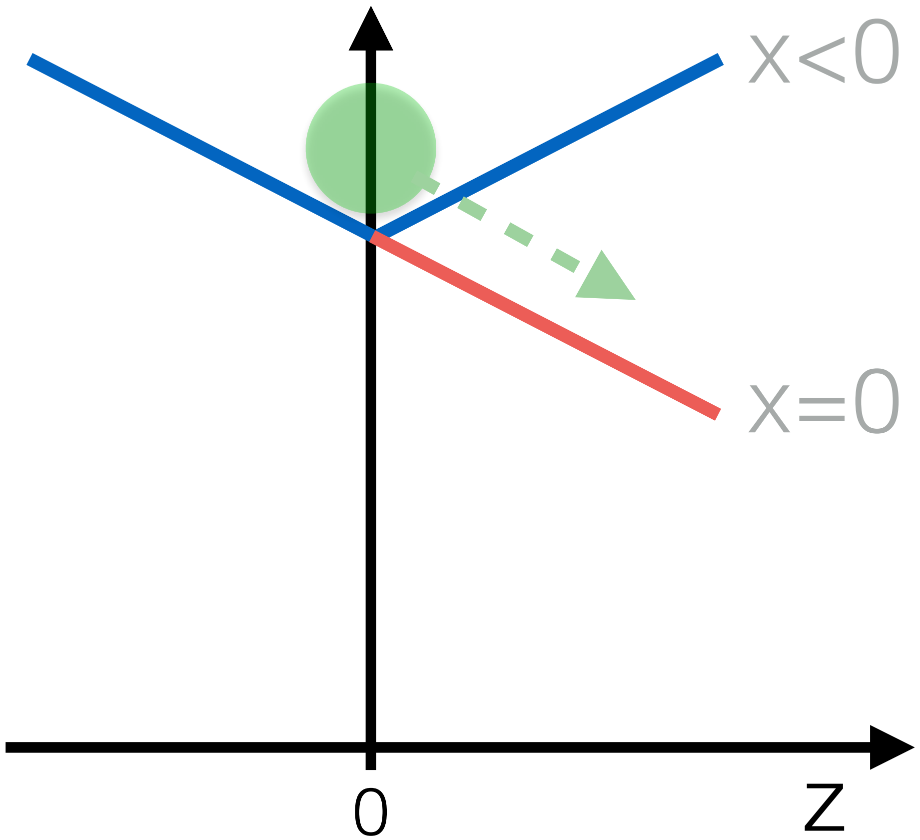
Extraction — cw re-acceleration



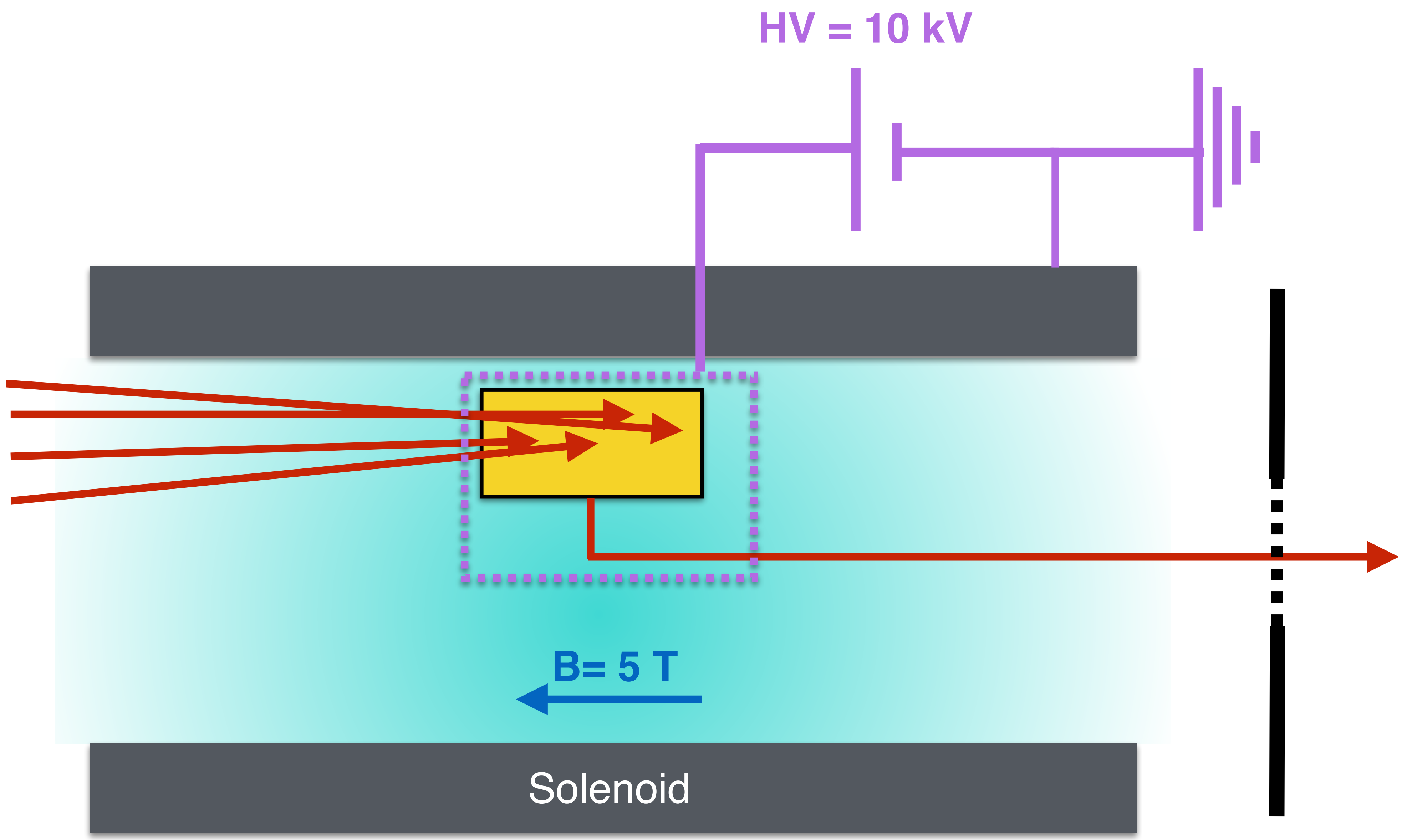


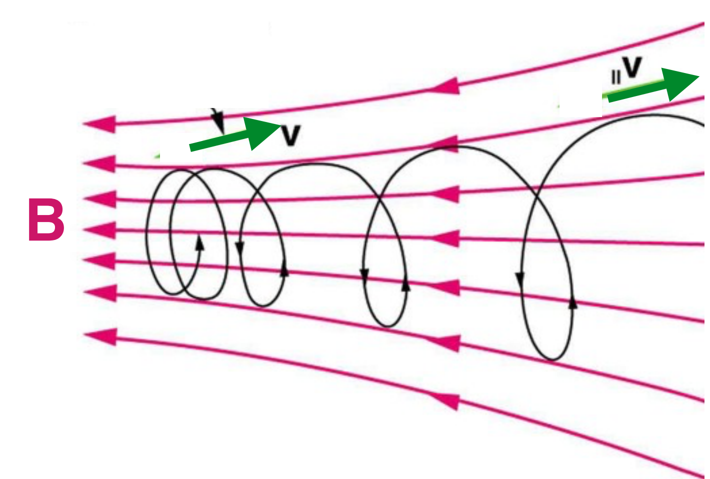


Potential



The muCool setup





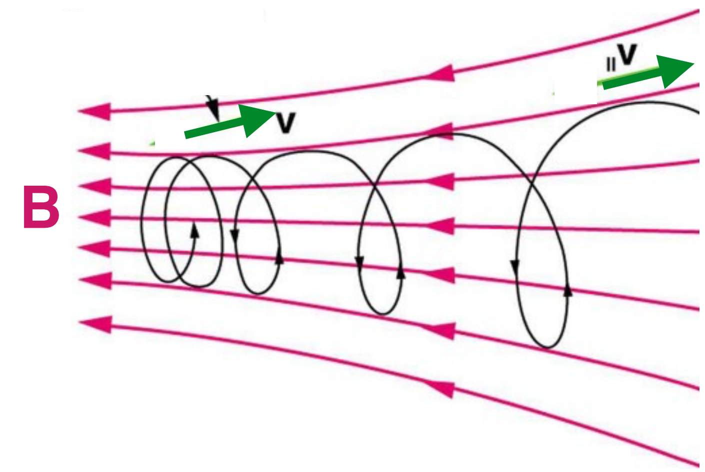
The muCool setup has an overall bias needed for acceleration

Extraction from B-field

- Charge particles follow magnetic field lines

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

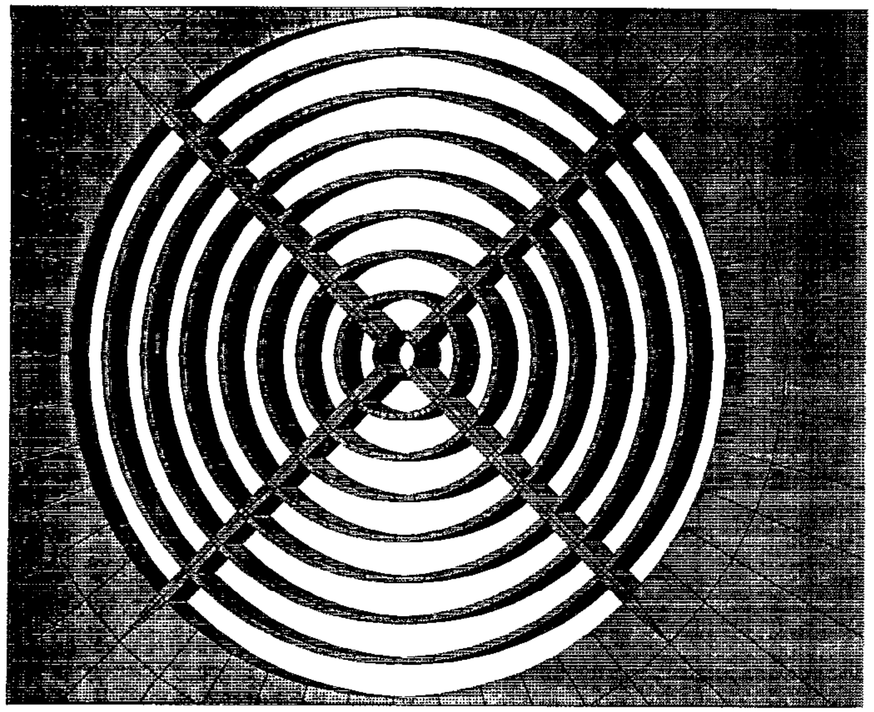
$$\Delta E_{\perp i} \sim \Delta E_{\perp 0} \frac{B_i}{B_0}$$



- 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

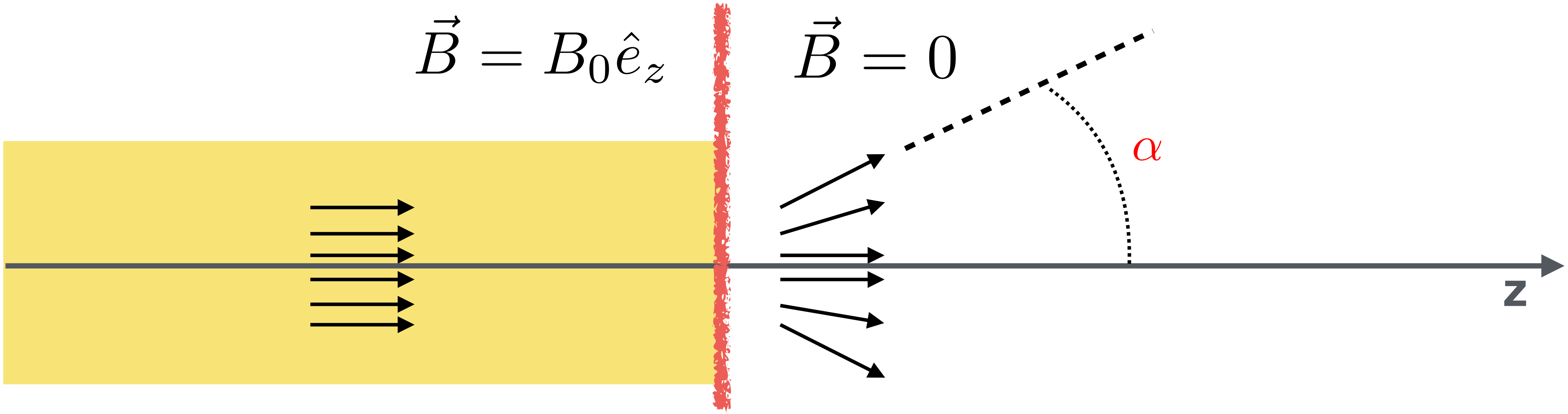
$$\Delta p_\perp = e \int_0^t v_z B_\perp dt \sim \frac{ewB_i}{2} \quad ,$$

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

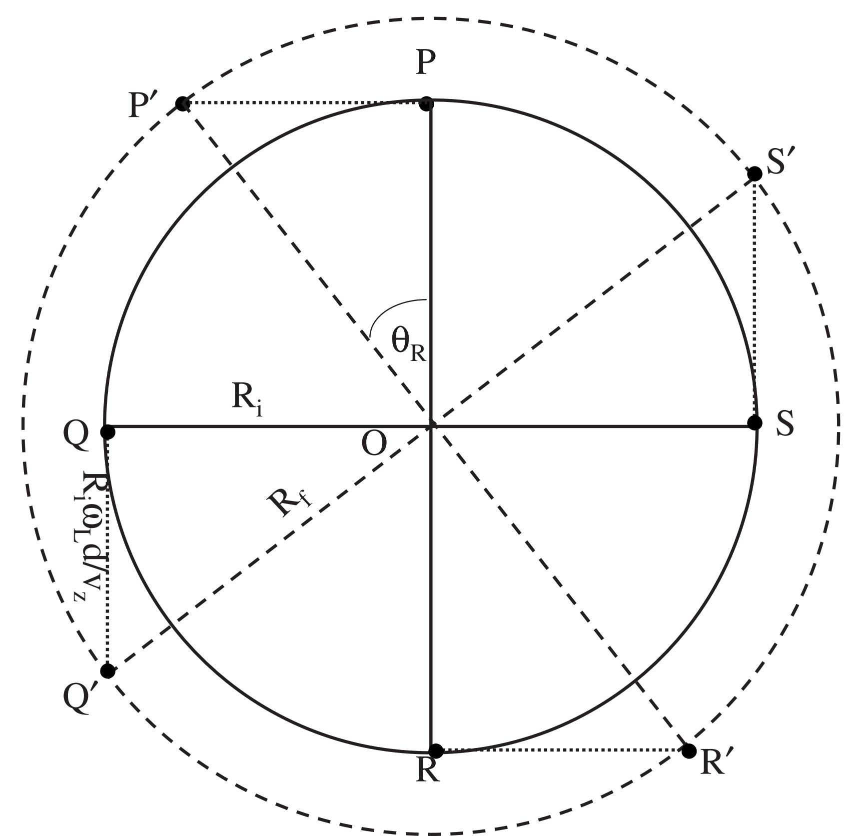


Gerola et al., Rev. Sci. Instrum. 66 (7) 1995

Extraction from B-field



$$B_r = \frac{r}{2} B_0 \, \delta(z)$$



- Terminate B-field
- The radial component produces an azimuthal force
  $$F_\theta = -e v_z B_r(z)$$
- The azimuthal force produces a divergence

$$\alpha = \frac{e B_0}{2 m \gamma} \frac{R}{v}$$

Extraction from B-field

- At B = 4 T : beam diameter of 1mm

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

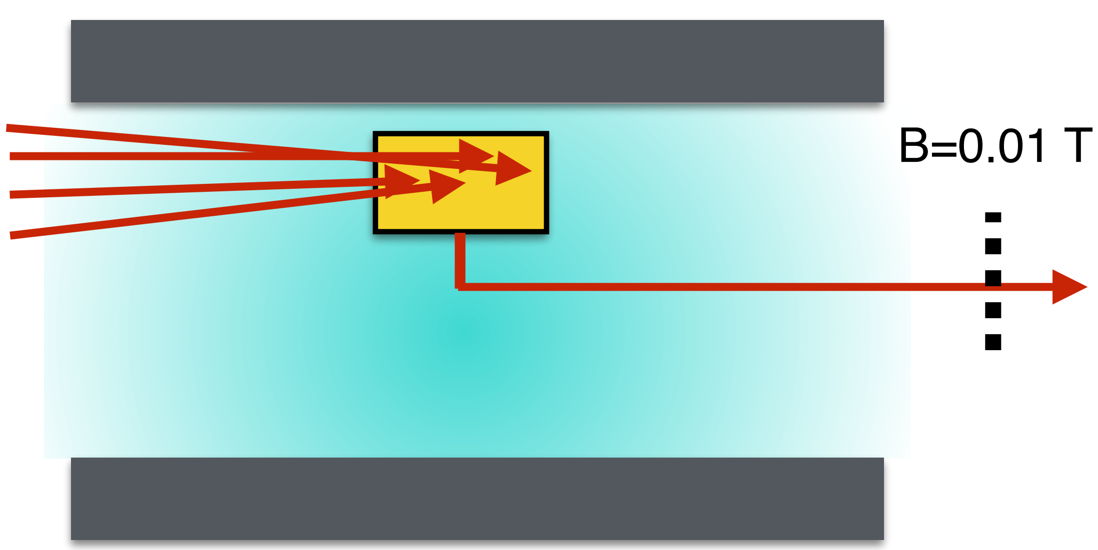
$$\Delta E_{\perp i} \sim \Delta E_{\perp 0} \frac{B_i}{B_0}$$

- Terminate B-field at B=0.01 T with 2 mm grid spacing

  Far field divergence 2 mrad

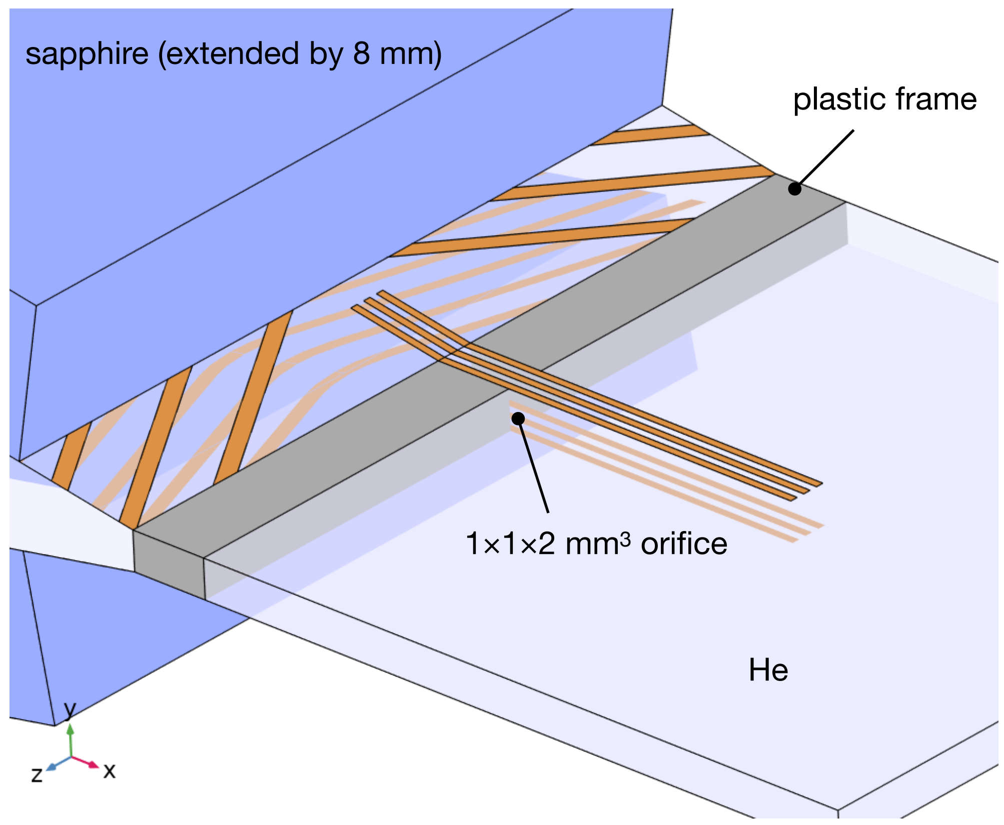
  Beam diameter is 20 mm

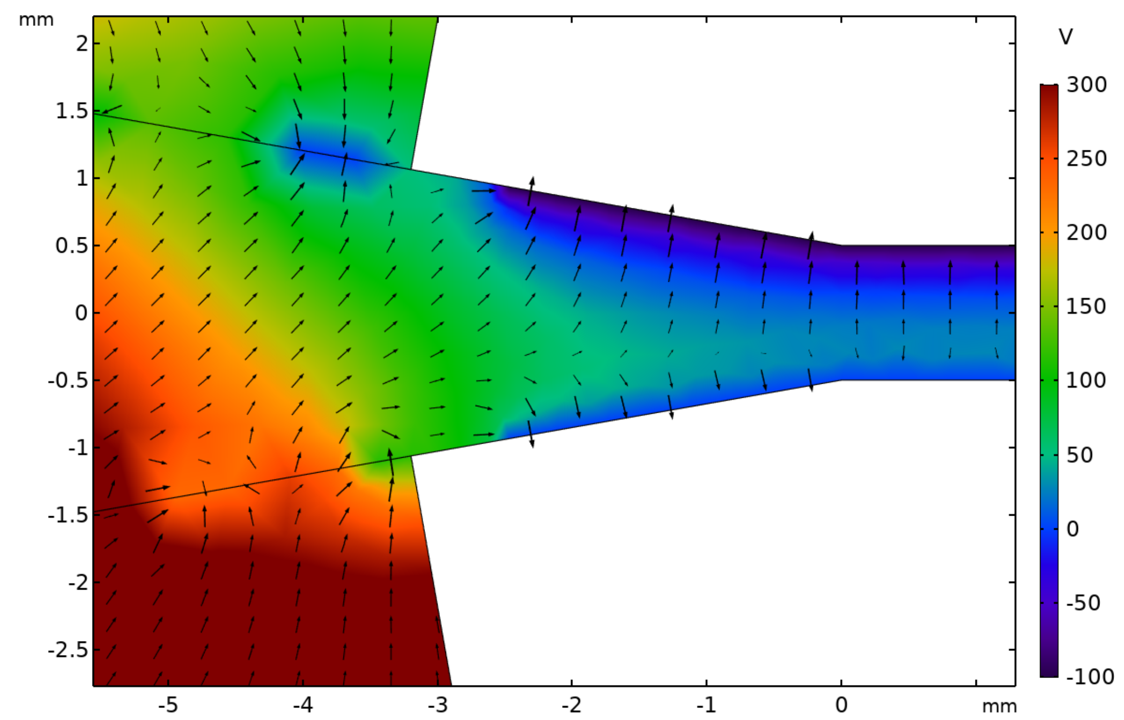
  Transmission 70%

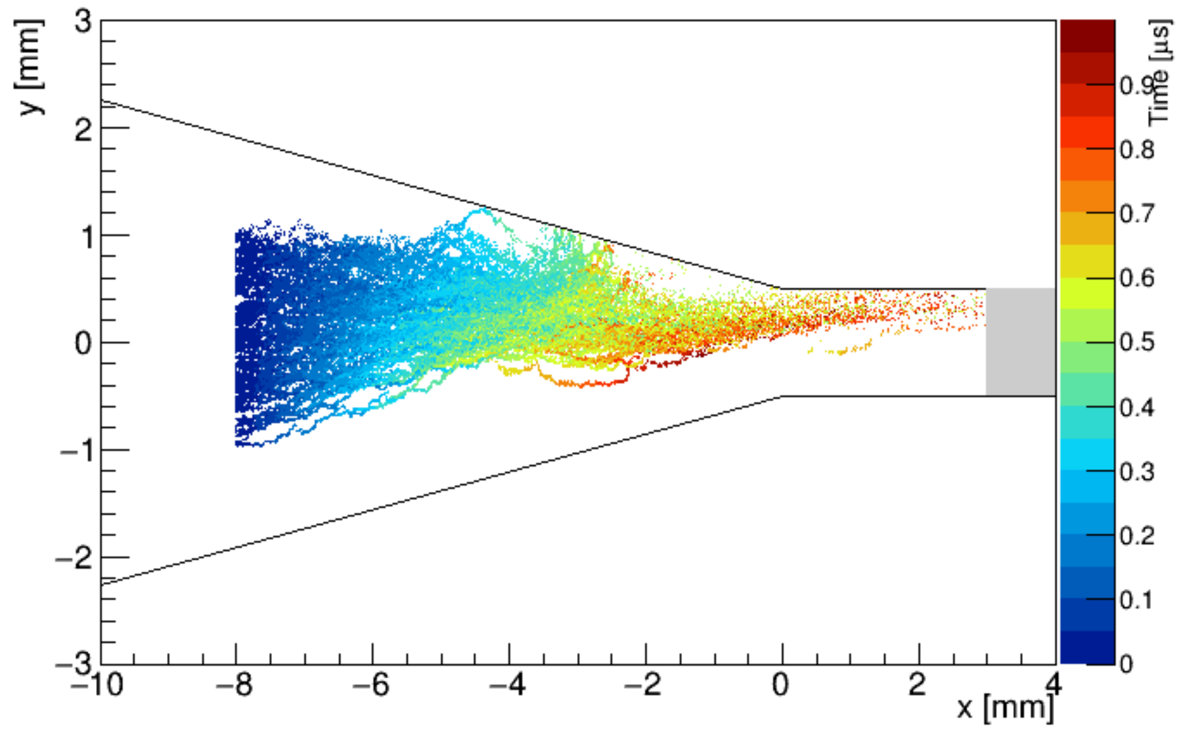


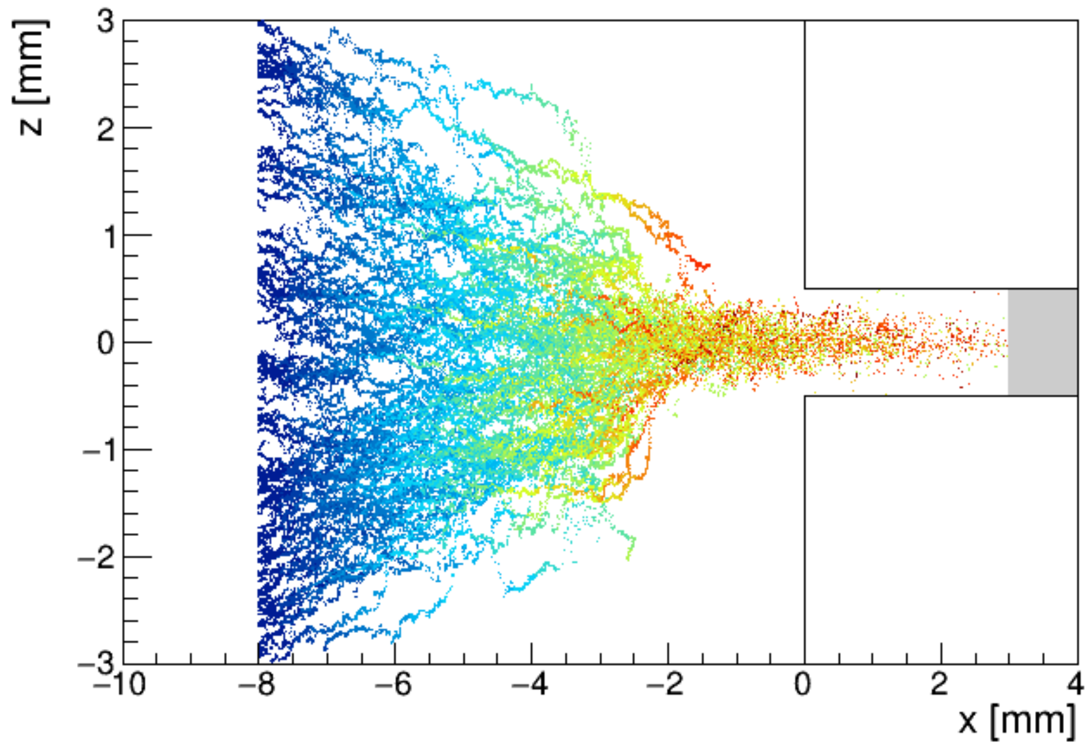
E:	10 keV
ΔE:	100 eV
Diameter:	20 mm
Divergence:	2 mrad

Preliminary simulations of extraction



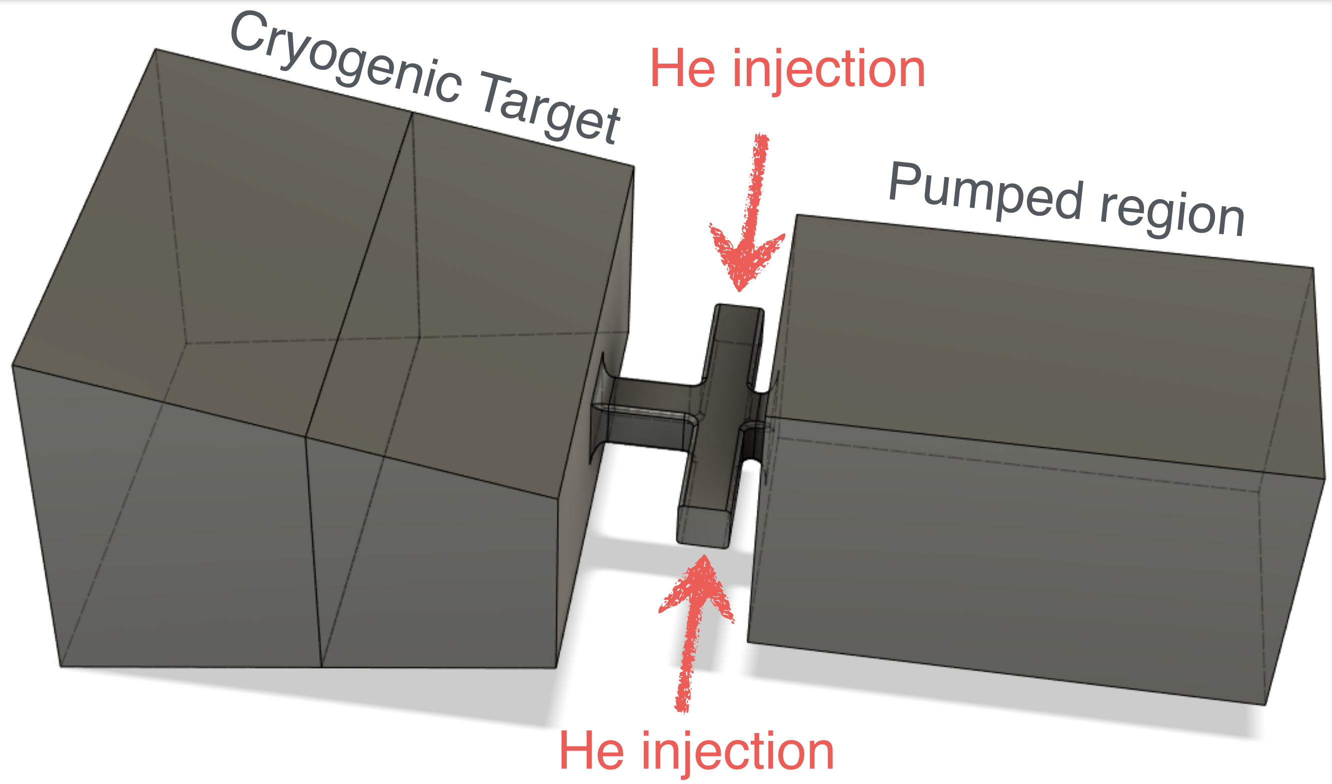


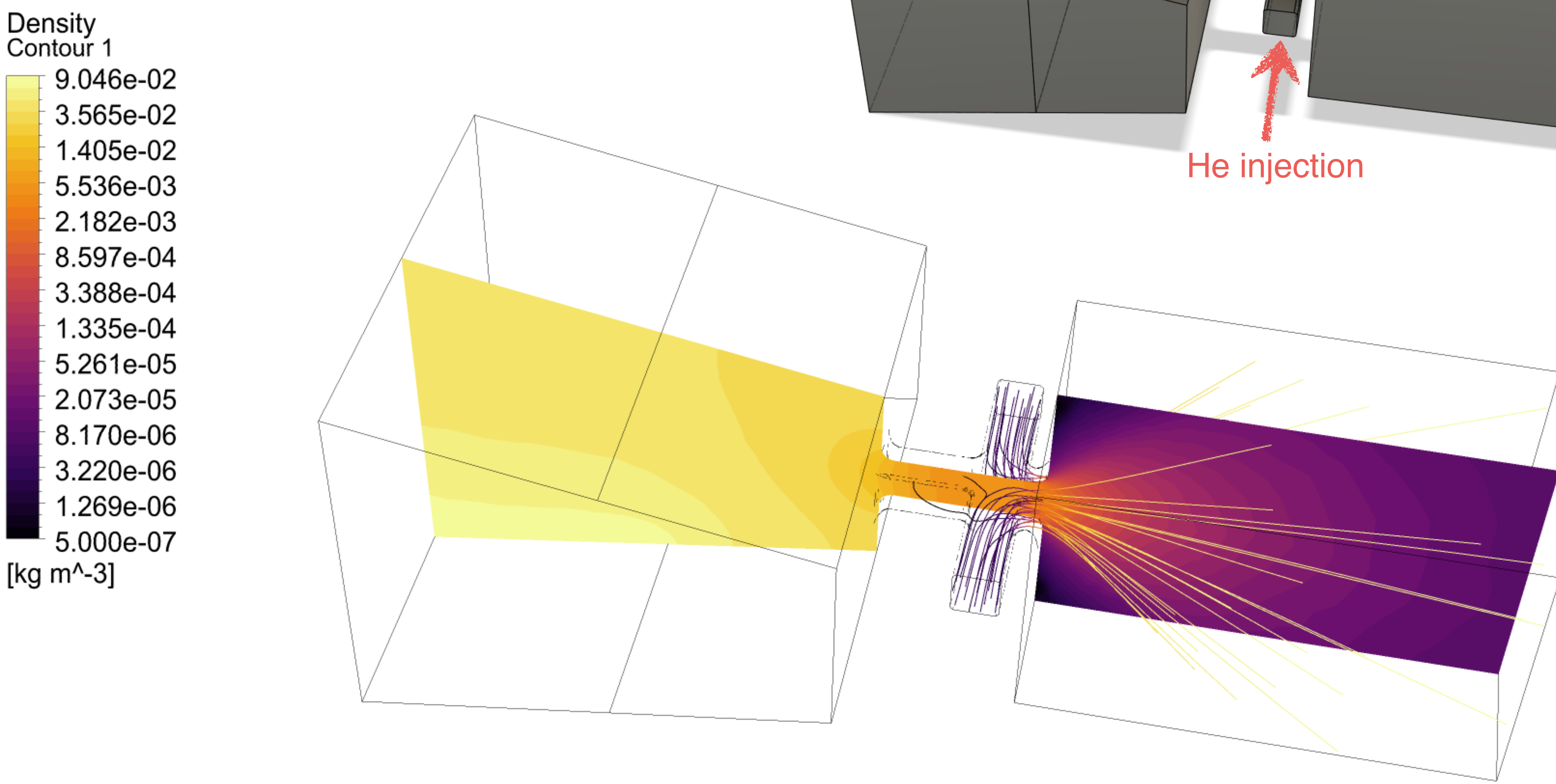




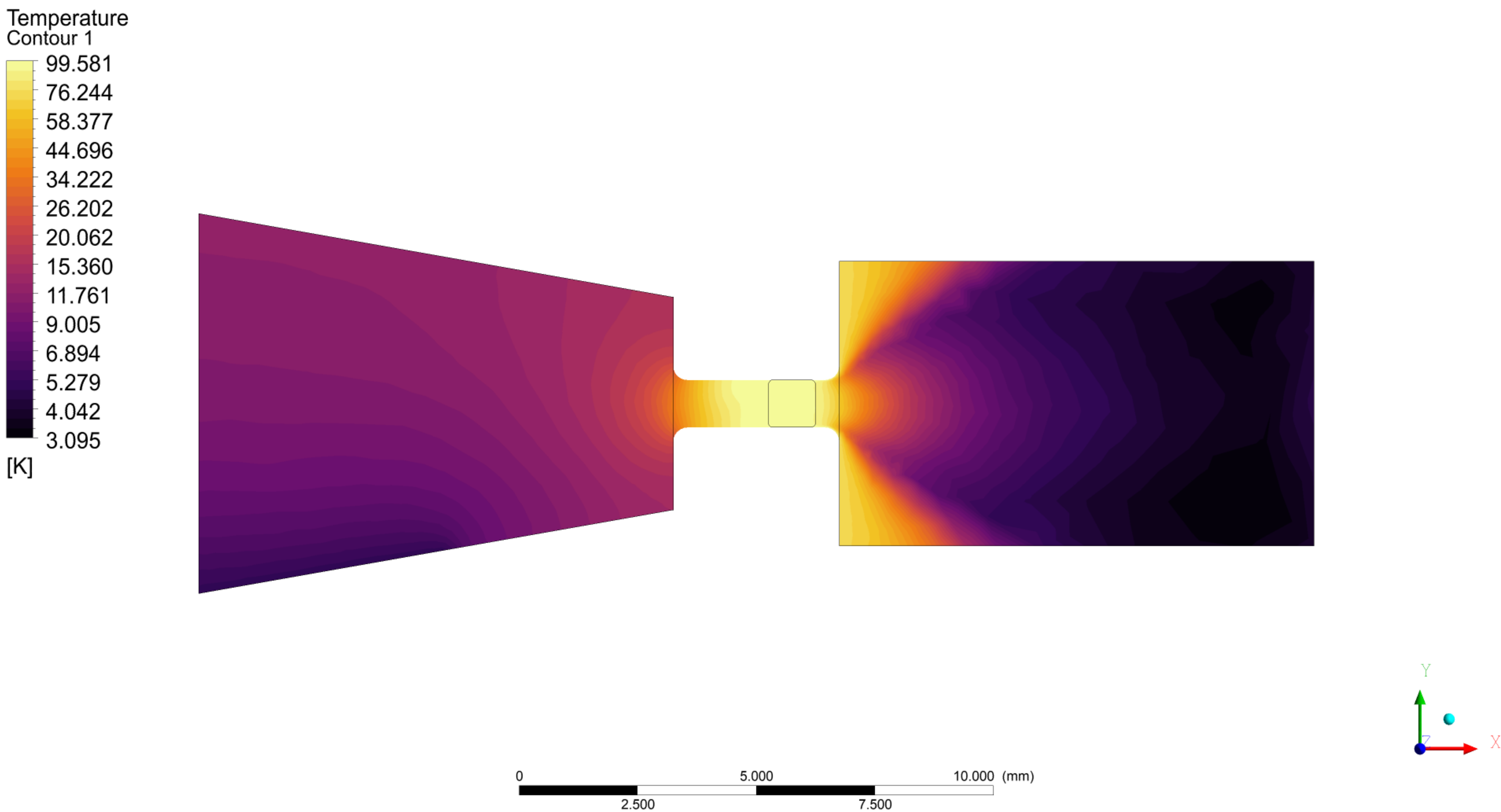
Preliminary simulations: density

- Continuous flow simulations with ANSYS (accurate till 5 mm from last wall)
- Differentially pumped region will be simulated with Monte Carlo approaches

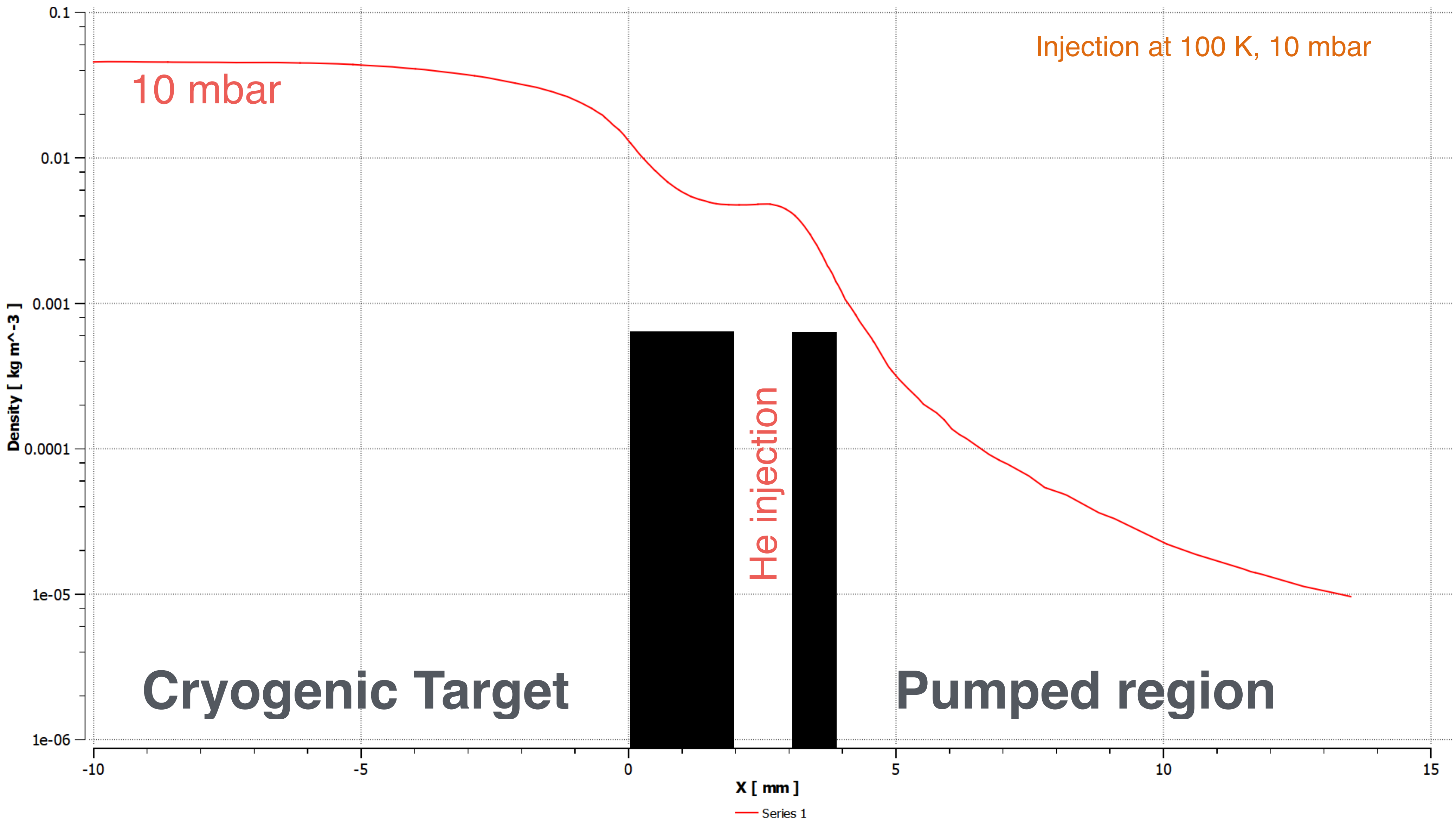




Preliminary simulations: temperature



Preliminary simulations: density



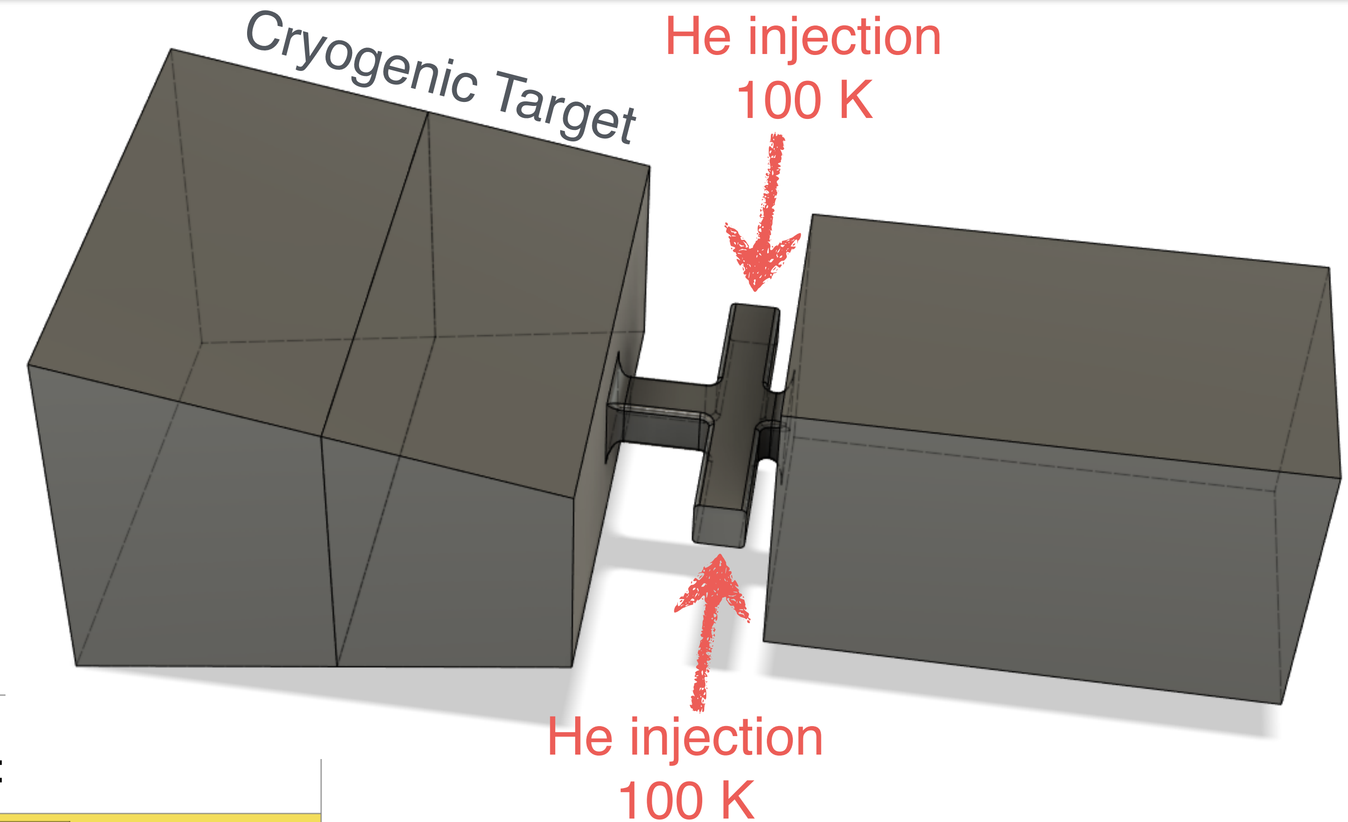
optimistic configuration !!

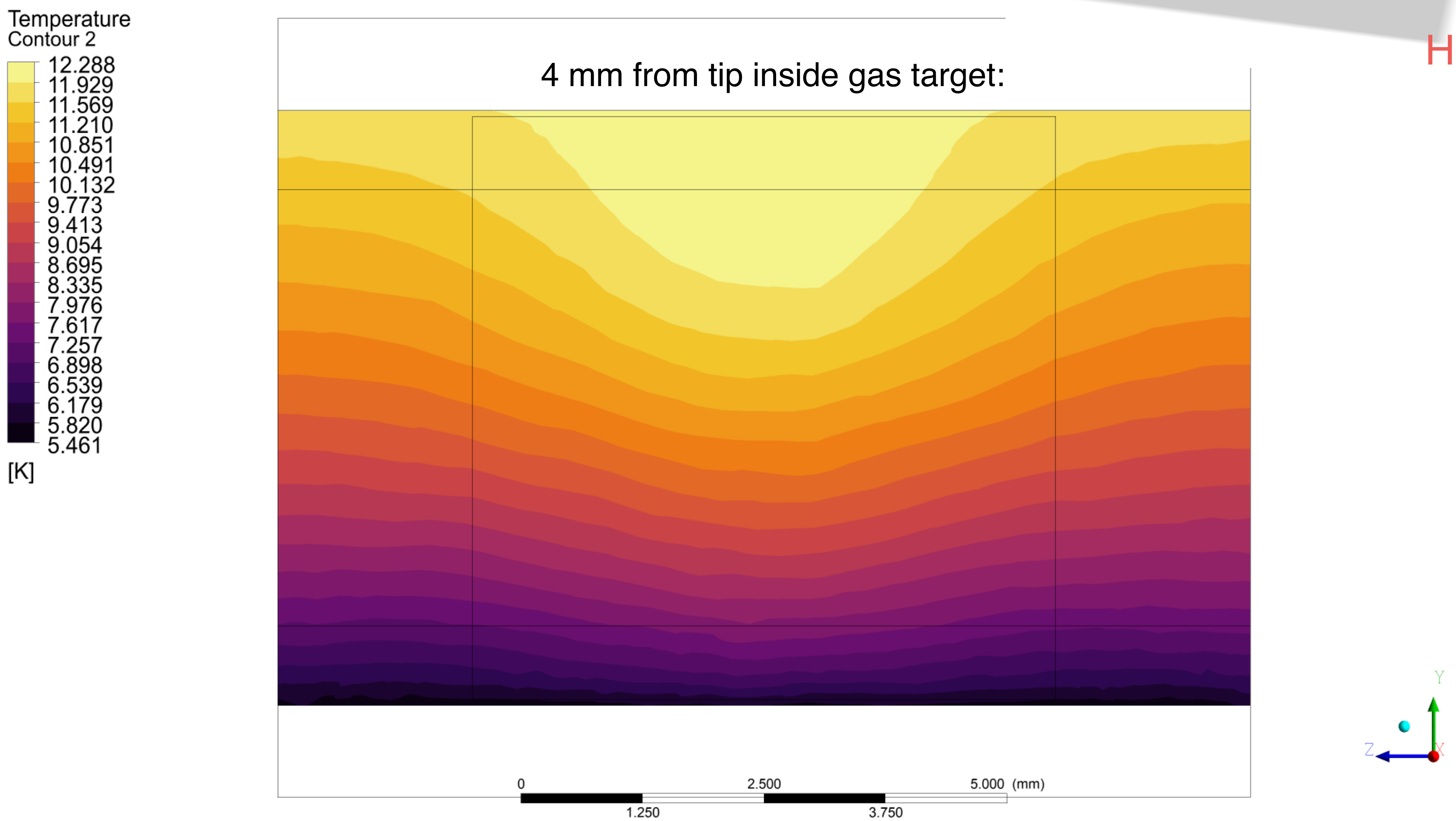
5 mm inside pumped region:

500x smaller density relative to target

Preliminary simulations: density gradient in target

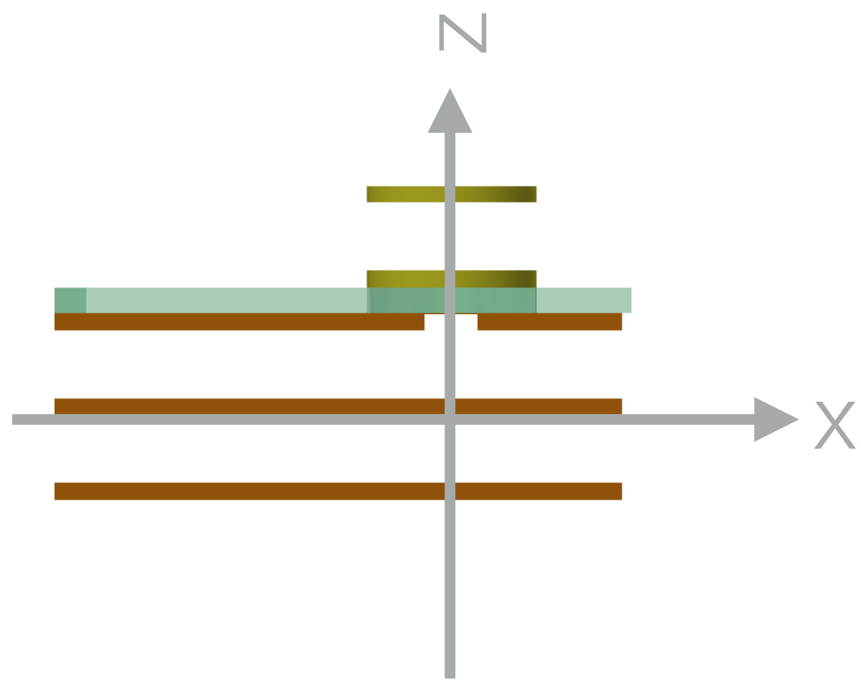
Density gradient is only minimally affected by gas injection



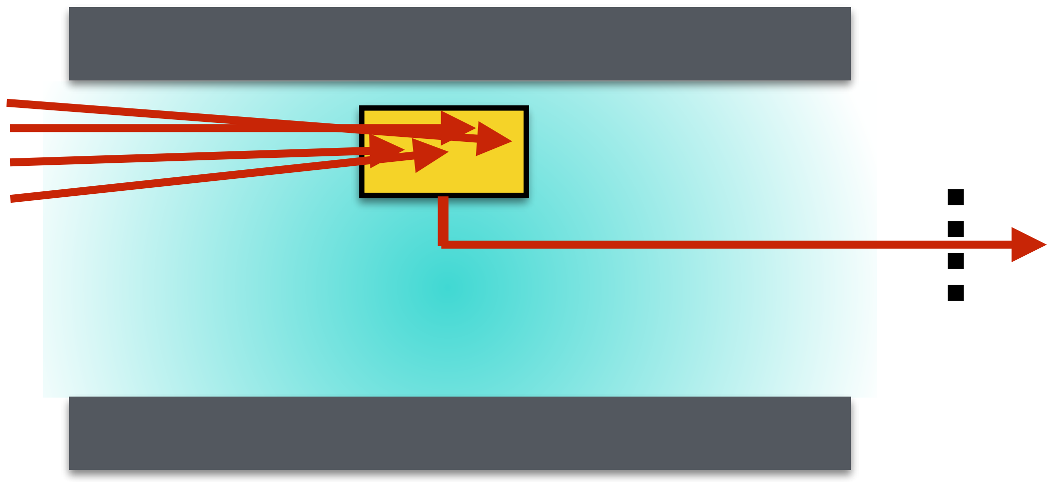


Efficiency for cw acceleration using mixed target

HIMB	3 x 10^{-1}	Injection into solenoid and coupling into gas target
HIMB	6 x 10^{-3}	Stopping in active region of gas target (10 mbar, 14 K)
	1.0 x 10^{-1}	Compression towards orifice (in about 5 µs)
	6 x 10^{-1}	Extraction from orifice
	4 x 10^{-1}	Drift from orifice to re-acceleration region
		~~Accumulation and pulsing~~
	8 x 10^{-1}	Muon decay till end of solenoid
	7 x 10^{-1}	Transmission through grid
	2.5 x 10^{-5}	**Total efficiency**



Using demonstrated mixed target



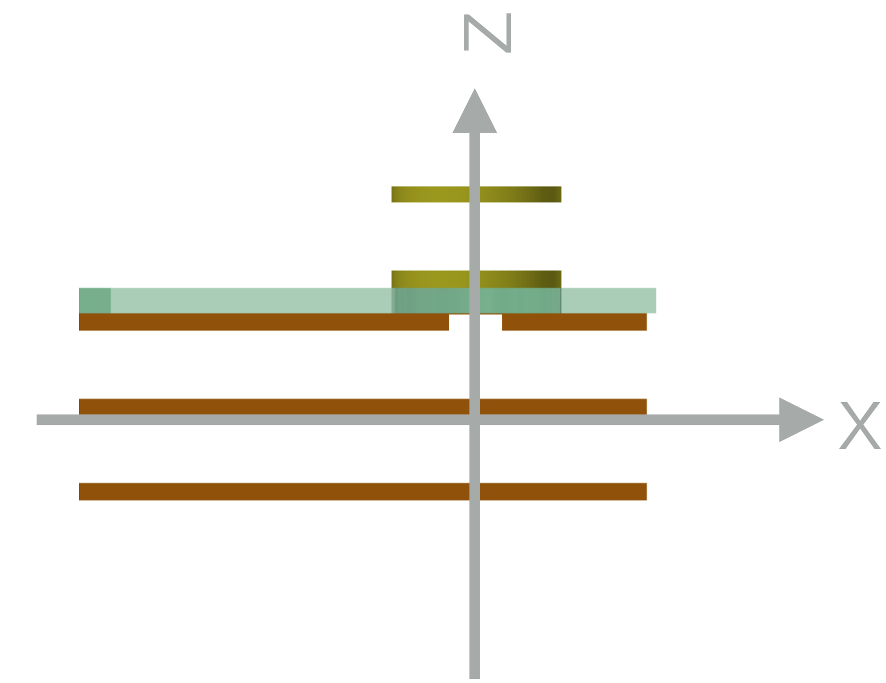
- 10% (FWHM) momentum bite is a big problem
- Stopping probability in 10 mbar He @ 14 K, 5 T:
  - 2.1% FWHM= 1%
  - 1.6% FWHM= 3%
  - 0.6% FWHM= 10%

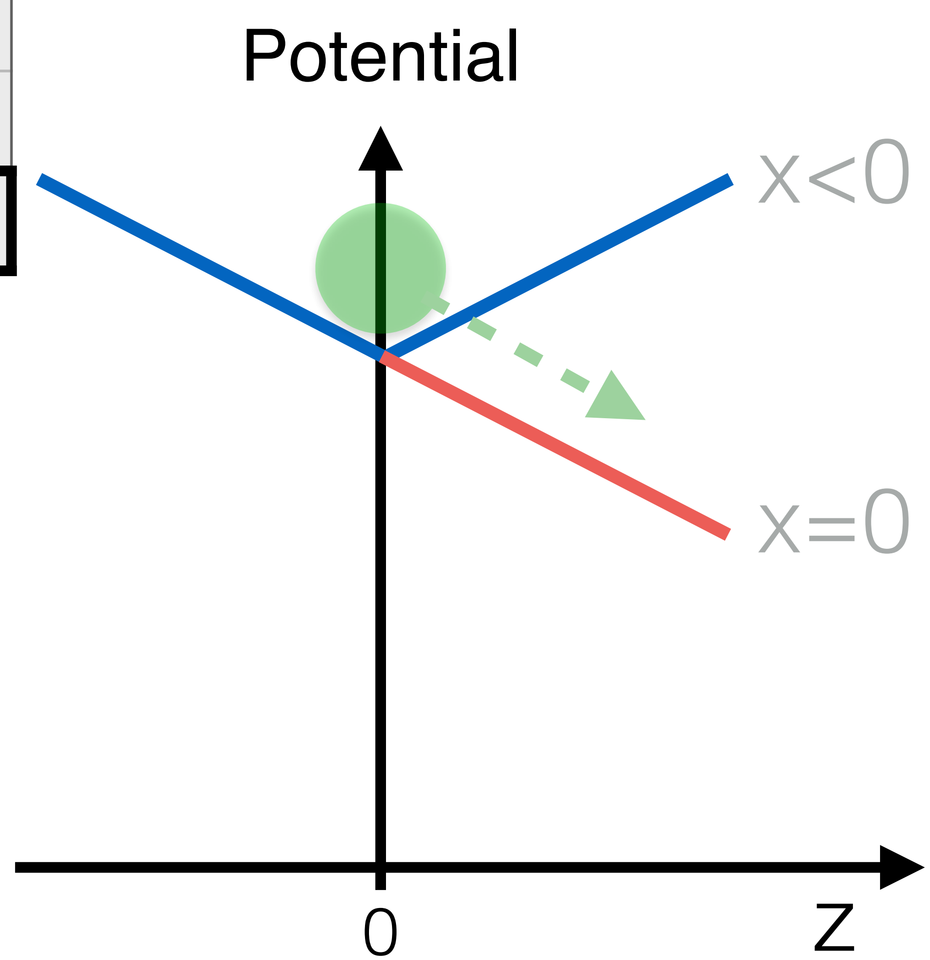
Efficiency for cw acceleration using mixed target

5×10^{-1}	3×10^{-1}	Injection into solenoid and coupling into gas target
1×10^{-2}	6×10^{-3}	Stopping in active region of gas target (10 mbar, 14 K)
1.5×10^{-1}	1.0×10^{-1}	Compression towards orifice (in about 5 μs)
6×10^{-1}	6×10^{-1}	Extraction from orifice
4×10^{-1}	4×10^{-1}	Drift from orifice to re-acceleration region
		~~Accumulation and pulsing~~
8×10^{-1}	8×10^{-1}	Muon decay till end of solenoid
7×10^{-1}	7×10^{-1}	Transmission through grid
1.0×10^{-4}	**2.5×10^{-5}**	**Total efficiency**

Using demonstrated mixed target

Upper limit with this mixed layout





“Adjabatic” efficiency improvements

- E-field design, colder T, larger active region, smaller B, elongated orifice, material that allows larger field strengths…..

Applications

Assume an efficiency of **5 x 10^{-5}** (cw extraction)

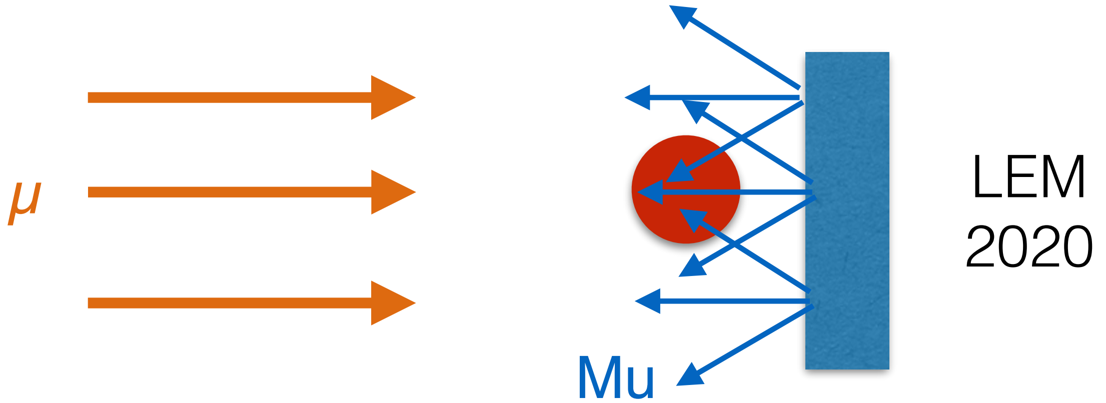
⇨ Muon rate of **5 x 10^5 μ/s**

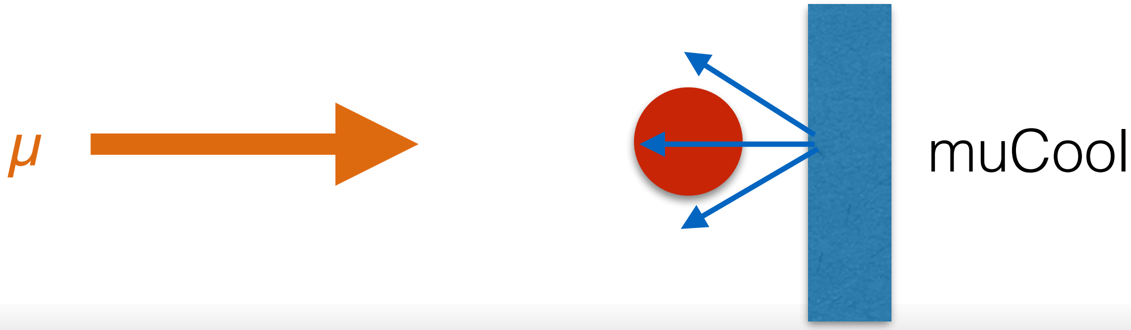
μSR

- Focus the beam to have > 100 mrad
  ⇨ beam diameter of < 1 mm (@ 10 keV)
- Beam could be switched between multiple spectrometers operating in parallel to avoid pile-up losses.
  - Including 60% losses to transport the muons to the various spectrometer 3 beamlines (left, center, right) with 5×10^4 μ/s each and sub-mm size could be operated
- Well suited also for post-acceleration to hundreds of keV
  A. Masamitsu

Muonium spectroscopy — P. Crivelli

- Focus the beam to 1 mm diameter (@ 5 keV), better overlap with lasers
- Improve laser excitation rates by > 200 compared to present experiment at LEM



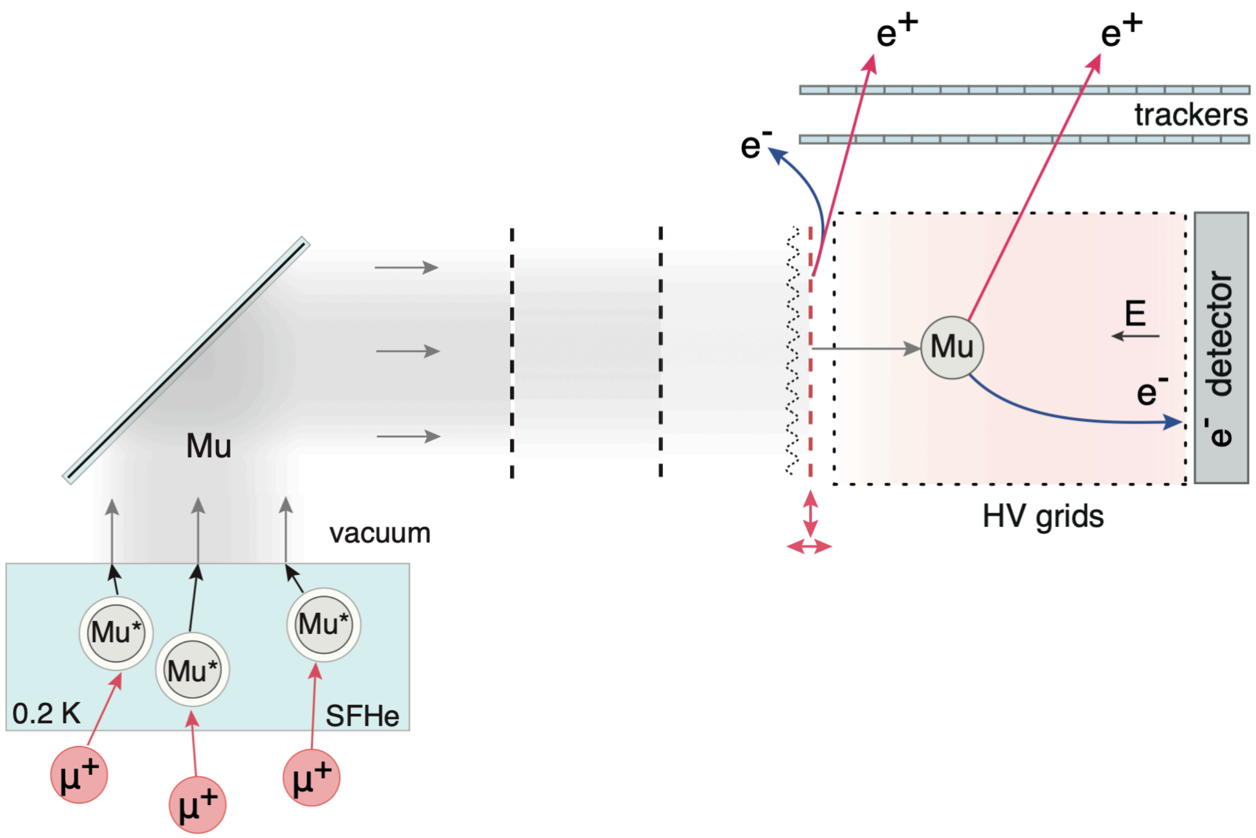


Applications

Muonium gravity — A. Soter

Assume an efficiency of **5 x 10^{-5}** (cw extraction)

⇨ Muon rate of **5 x 10^{5} *μ*/s @ 10 keV,** **sub-mm size**



Measure g with an accuracy of
1 m/s^2 in 2 weeks
100 nm grating pitch

- The low energy
  improves muon to vacuum muonium conversion
- The small size
  simplifies grating production (pitch, size, precision)

- Alternative with Whispering Gallery setup is explored where the size of the muCool beam is even more important (A. Soter & V. Nesvizhevsky)

Applications (push muCool performance)

μEDM P. Schmidt-Wellenburg

- To have $d_\mu < 10^{-23}$ e cm
  - 5×10^5 μ/s @ 125 MeV/c,
  - 100 kHz rep. rate pulsing
  - Phase-space V: 2 mm mrad
  - Phase-space H: 20 mm mrad
  - 4 ns timing
- Presently using μE1
  - 5x 10^4 μ/s @ 125 MeV/c
- **Requires post-acceleration from 1.5 MeV/c to 125 (200) MeV/c**

A. Masamitsu

- Alternative: cw extraction + entrance detector
  - Assume cw extraction efficiency of **5×10^{-5}**
  - 20% losses in post-acceleration stage

  ⇨ Muon rate: **4×10^5 μ/s**

  - Improve d_μ limit (relative to μE1) by $\lesssim 2$ (pileup !)
  - Less background?
- Next improvement 2 muons per bunch at 200 kHz pulsing
  - leads to a muon rate of **4×10^5 μ/s**
  - with a factor of 3 losses during accumulation an extraction efficiency of about **1.5×10^{-4}** is needed
  - beam size increase during accumulation?

Summary

Long way to go

- Injection into solenoid and target
- 👍 Compression in target
- Extraction from gas target
- Drift from orifice to re-acceleration region
- Acceleration
- Extraction from B-field

Total estimated efficiency for CW-extraction HIMB output → muCool outside solenoid:

2×10^{-5} — 1×10^{-4}

For pulsed extraction there are additional losses

E:	10 keV
ΔE:	100 eV
Diameter:	20 mm
Divergence:	2 mrad

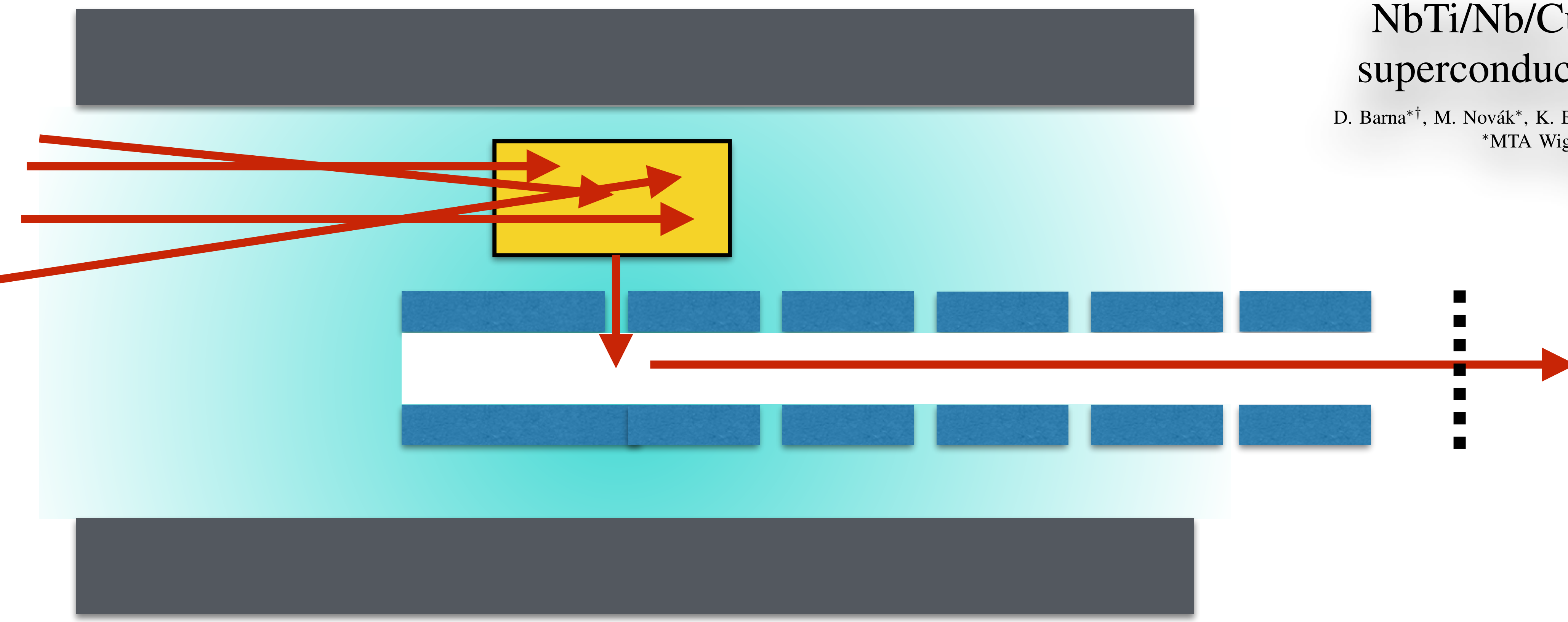
Many challenges & risks

- Mechanical stability
- Discharge issues
  (could increase at the HIMB rates, target tested only at 10 kHz)
- Gas, vacuum and thermal management
- Beam degradation in drift-region, accumulations and re-acceleration

Larger improvements ?

- If dispersion could be obtained at target position the stopping probability could be increased by a factor of 2 (inhomogeneous degrader)
- Other target layout & material?
- Concatenation of two mixed compression regions could be used to double stopping efficiency.
  Issues: evacuation / μ-He-collisions

Is possible to decrease phase space?



NbTi/Nb/Cu multilayer shield for the superconducting shield (SuShi) septum

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- Superconductor that cancel or decrease B-field
- Freeze desired amount of B-field to keep polarisation, e.g. 0.1 T
- 6 mm thickness needed to shield 5 T, 5 K operation
- Super-conducting shield could be used also to accelerate muons
- Injection through a tiny slit or hole
- Use strips as before to drift atoms into shield with ExB
- grad B effect on muon motion ?
- Collisions in injection region
- Alternative: Longitudinal extraction from target and longitudinal injection in shield

$$\boldsymbol{v}_D = \frac{mc}{2q}(v_\perp^2 + 2v_\parallel^2)\frac{\boldsymbol{B}\times\nabla|\boldsymbol{B}|}{|\boldsymbol{B}|^3}.$$

Probably wrong thinking and stupid idea