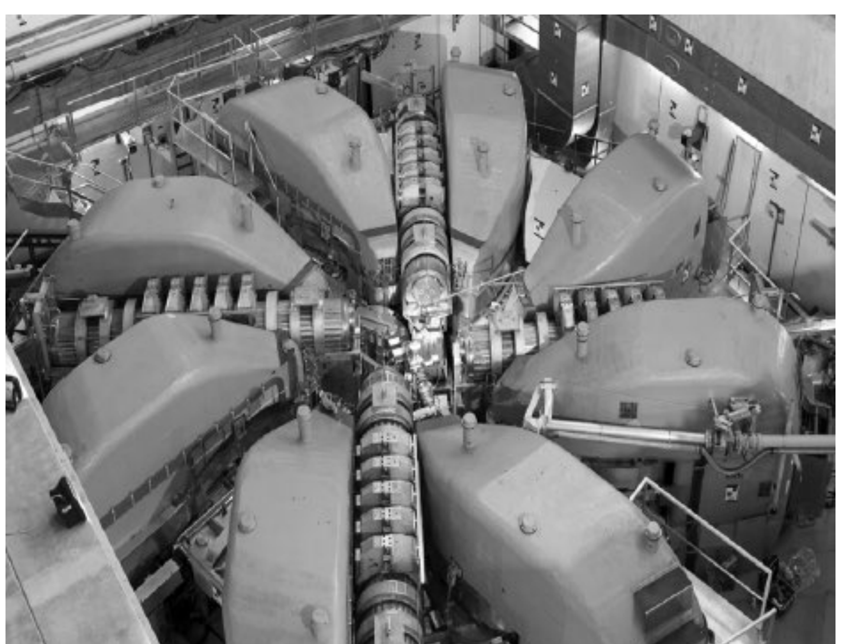
The muCool project at PSI: A novel high-brightness muon beam

Angela Papa, Paul Scherrer Institut and University of Pisa/INFN on behalf of muCool collaboration
CERN, Switzerland (remote)
Muon Cooling Working group, 10th December 2020

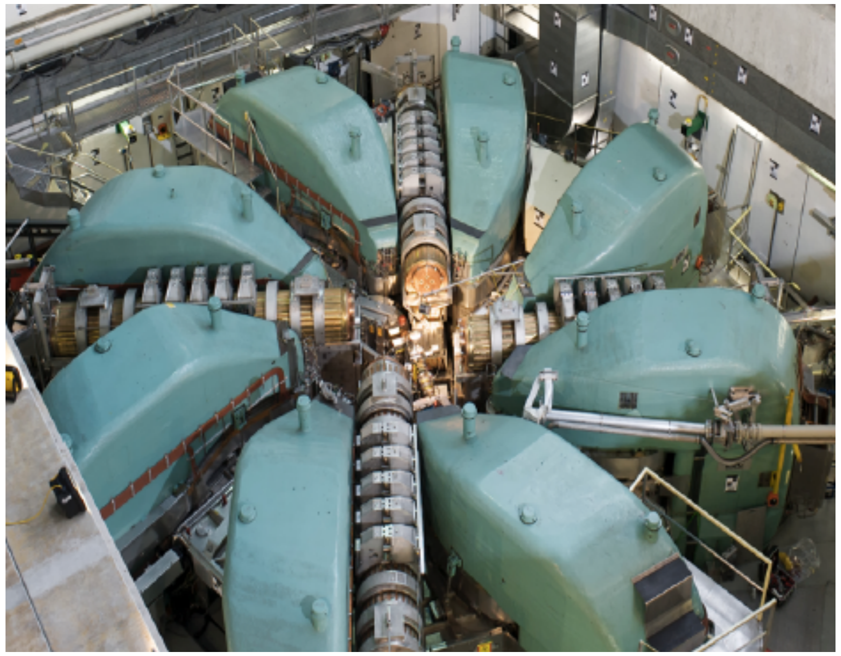



Outline

- Current and incoming status of PSI facility
- Developments for high brightness muon beams

The world's most intense continuous muon beam

- PSI delivers the most intense continuous low momentum muon beam in the world (**Intensity Frontiers**)
  - Intensity = 5x 10^8 muon/s, low momentum p = 28 MeV/c

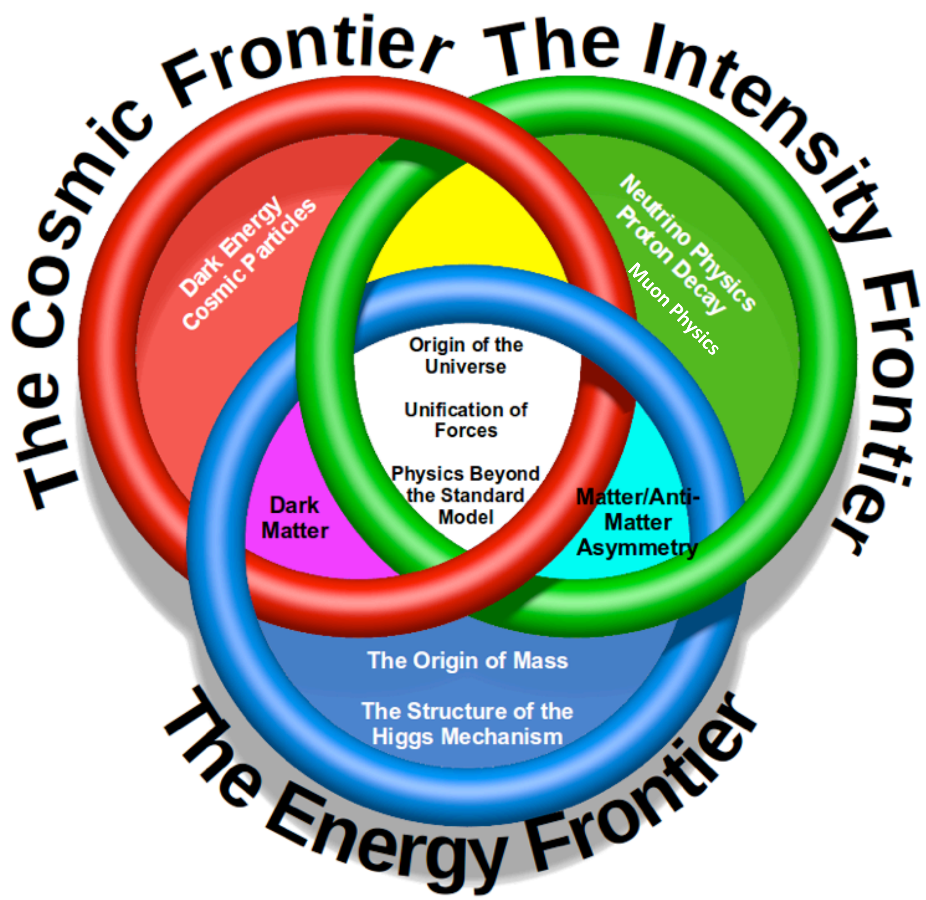


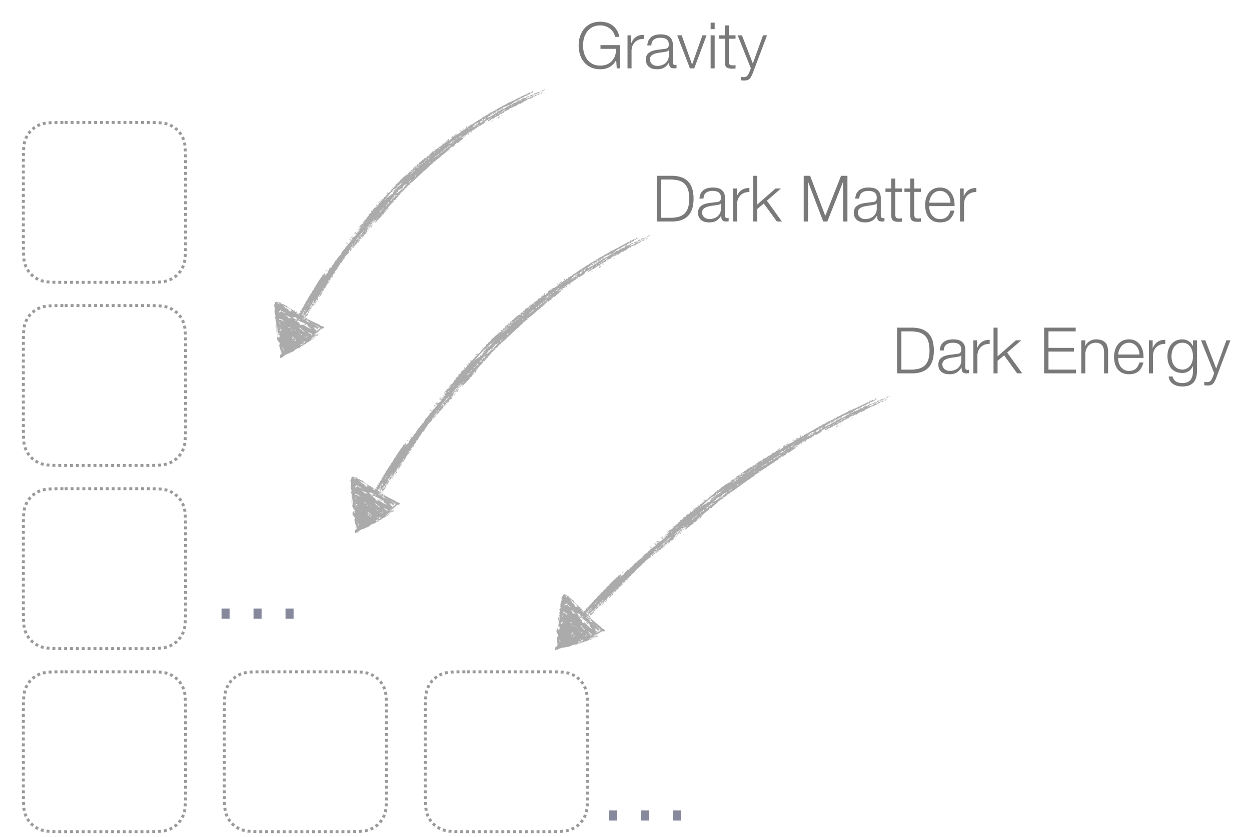
590 MeV proton ring cyclotron
Time structure: 50 MHz/20 ns
Power: 1.4 MW

PSI landscape

The role of the low energy precision physics

- The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory

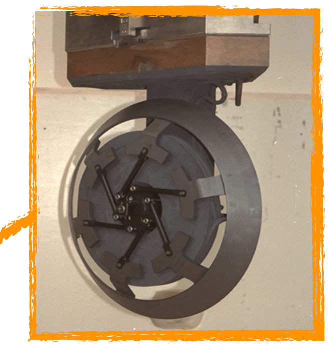


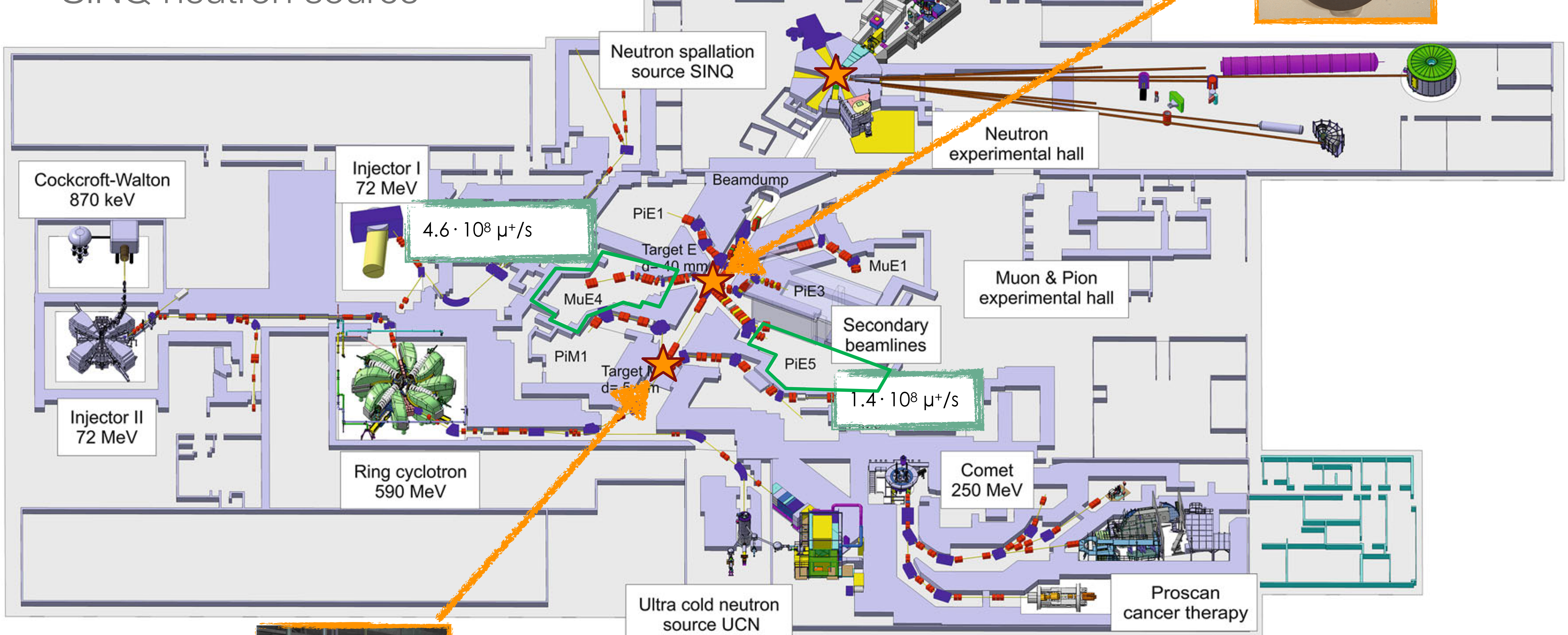


- Low energy precision physics: Rare/forbidden decay searches, symmetry tests, precision measurements very sensitive tool for unveiling new physics and probing very high energy scale

The world’s most intense continuous muon beam

- PSI High Intensity Proton Accelerator experimental areas
- Two production targets
- SINQ neutron source





HiMB motivations

- PSI delivers the highest intensity DC μ^+ beam: 5×10^8 μ^+/s
- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Time schedule: **O(2025)**

- Next generation cLFV experiments require higher muon rates
- New opportunities for future muon (particle physics) based experiments
- New opportunities for µSR experiments

- Different experiments demand for a variety of beam characteristics:
  - DC vs pulsed
  - Momentum depends on applications: stopped beams require low momenta

- Here focus on **DC low momenta muon beams**

- Maintain PSI leadership in DC low momentum high intensity muon beams

Fermilab $\rightarrow 5\times10^{10}$ μ^-/s

Mu2e: $R_{\mu e} = \mathcal{O}(10^{-17})$

J-PARC $\rightarrow 10^{10}$ μ^-/s

COMET: $R_{\mu e} = \mathcal{O}(10^{-17})$

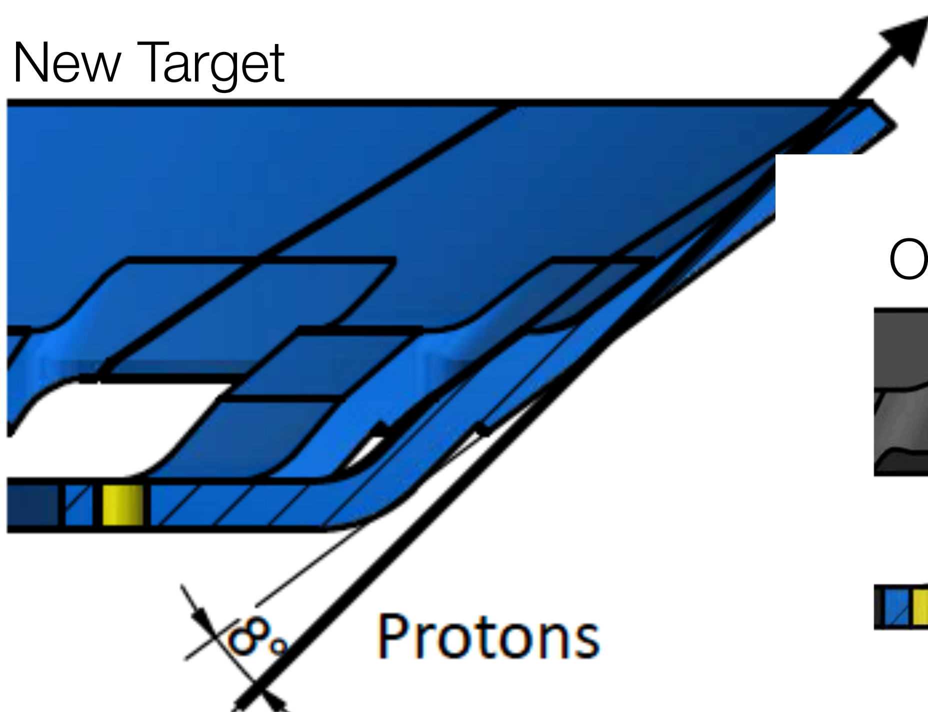
HiMB @ HE

- Back to standard target to exploit possible improvements towards high intensity beams:
  - Target
    - alternate materials
    - geometry
  - Beam line
    - high capture efficiency
    - large phase space acceptance transport channel

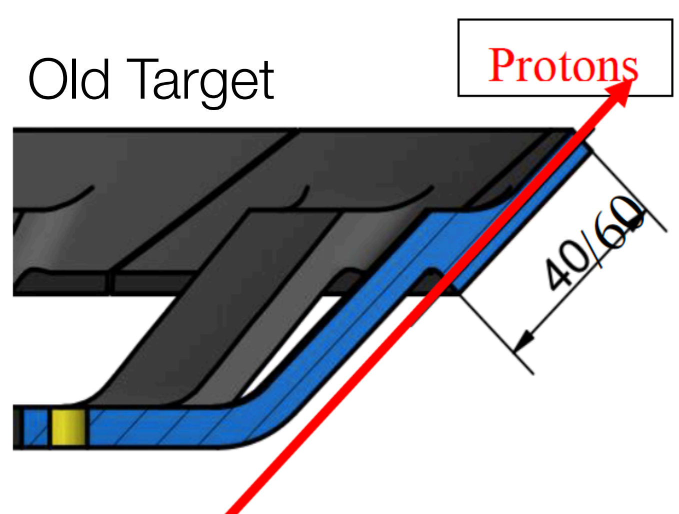
Slanted target: towards the test

- Upgrade existing graphite production target E 40 mm
  - 8° slanting angle: Measurement in forward / backward / sideways direction
  - Production and implementation feasible
  - Mechanical and thermal simulations completed and no show-stopper found
  - **Installed in week 48 (Nov. 25th, 2019)**
  - **Goals**
    - **Increase surface muon rates for all connected beam lines**
    - **Increase safety margin for “missing” target with the proton beam**

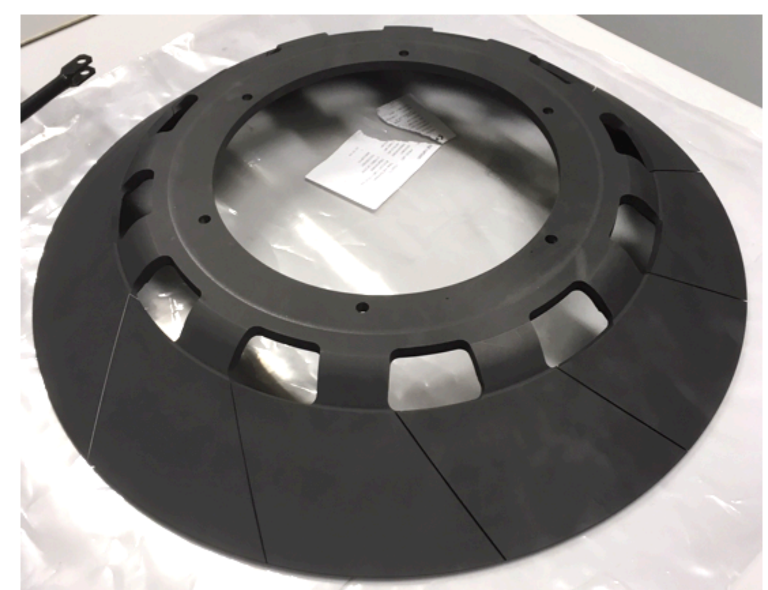
New Target



Old Target



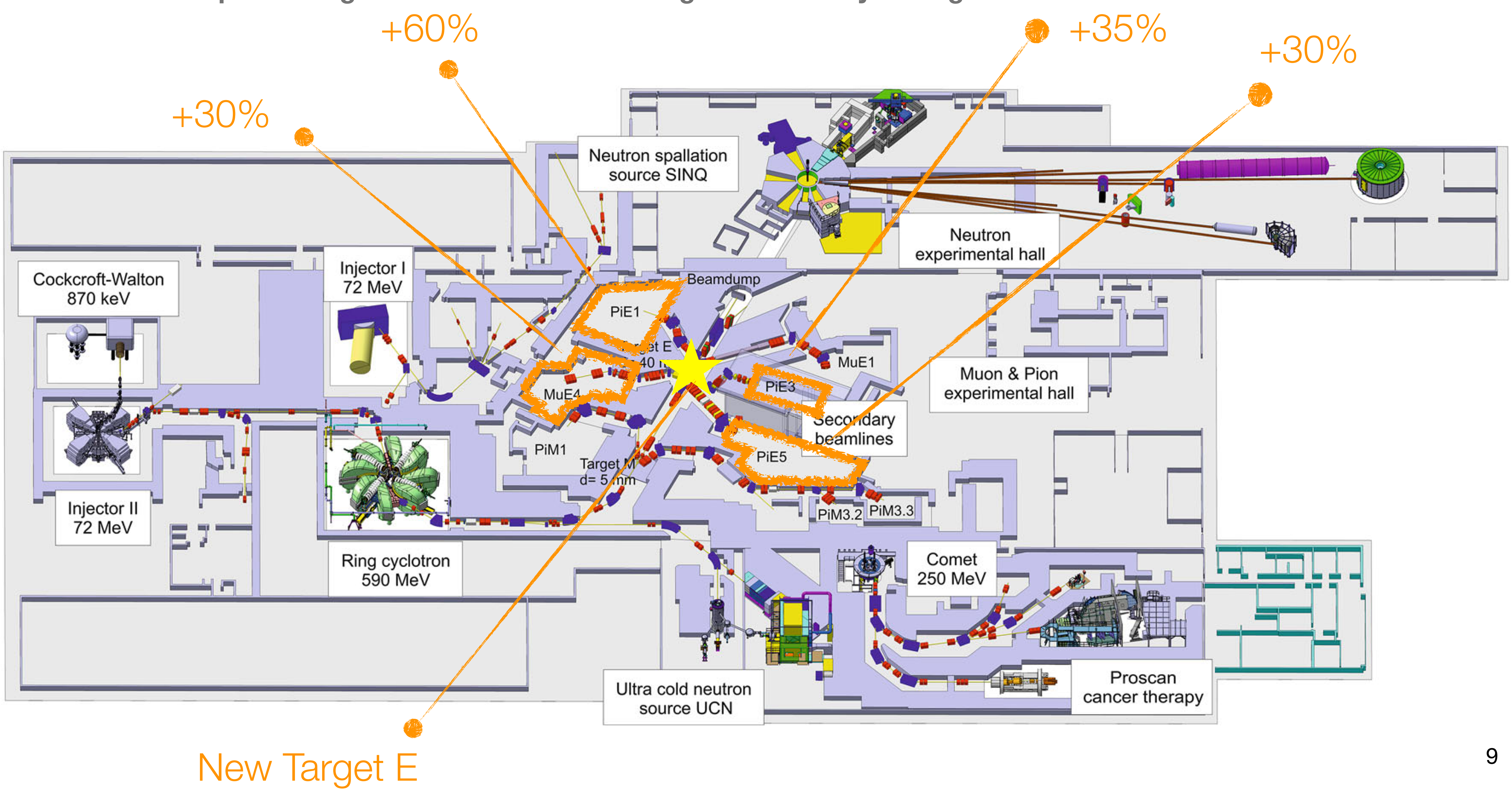
Prototype for the New Target E



New Target E

Slanted target: 2019 test Results

- Expect ~30-60 % enhancement
- Measurements successfully done in different experimental areas in fall 2019
- Analysis still undergoing: **increased muon yield CONFIRMED!**
- To be seen: **impact of higher thermal stress on long term stability of target wheel**



D. Taqqu, PRL 97 (2006) 194801
Y. Bao, A.P. et al., PRL 112 (2014) 224801

The muCool project at PSI

- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor $\mathbf{10^{10}}$ with an efficiency of $\mathbf{10^{-3}}$

for:
μSR (solid state physics)
muonium (spectroscopy, gravitational interaction...)
muon experiments (μEDM, g-2…)

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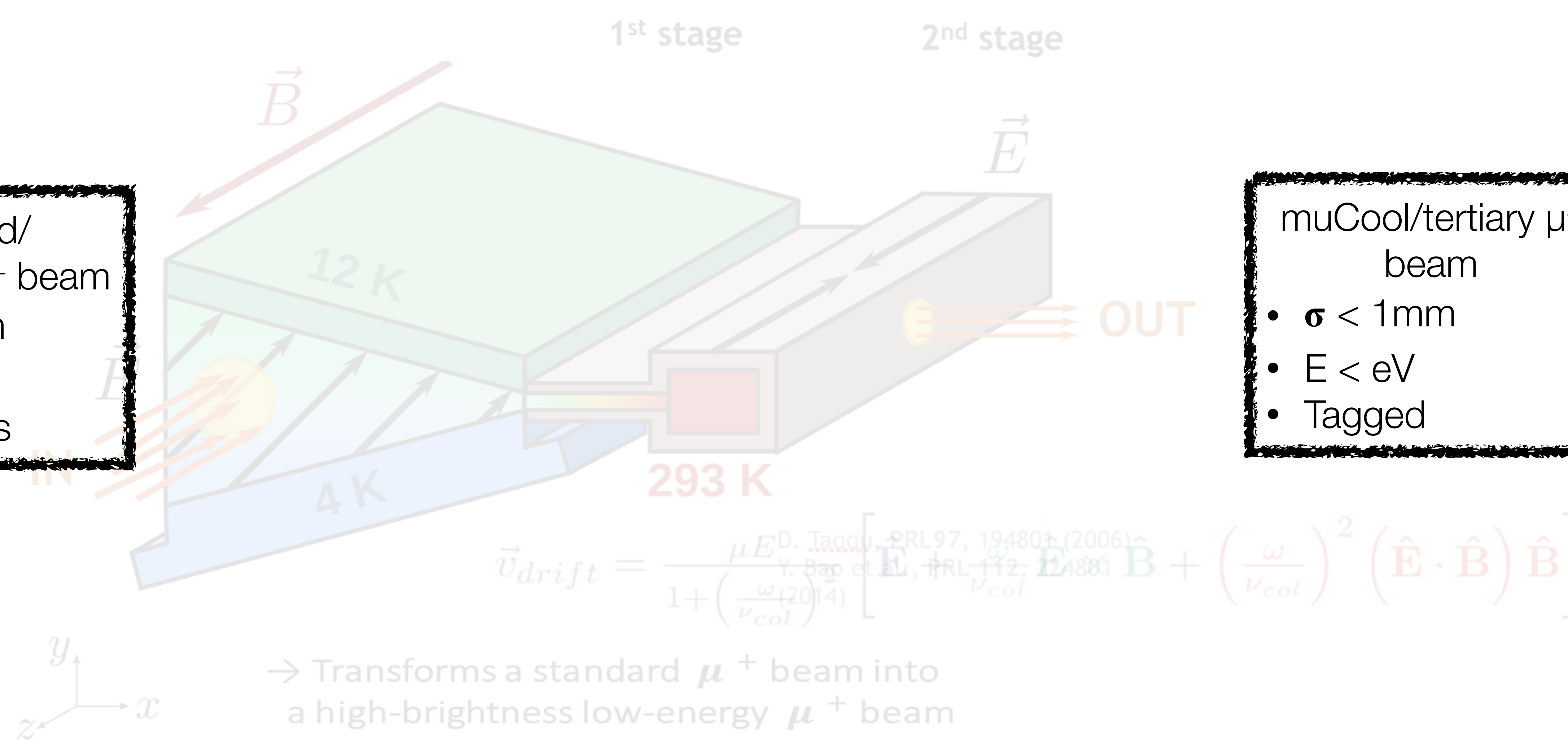
Standard/ secondary μ^+ beam

- $\boldsymbol{\sigma}$ = 10 mm
- E = 4 MeV
- Continuous



muCool/tertiary μ^+ beam

- $\boldsymbol{\sigma}$ < 1mm
- E < eV
- Tagged

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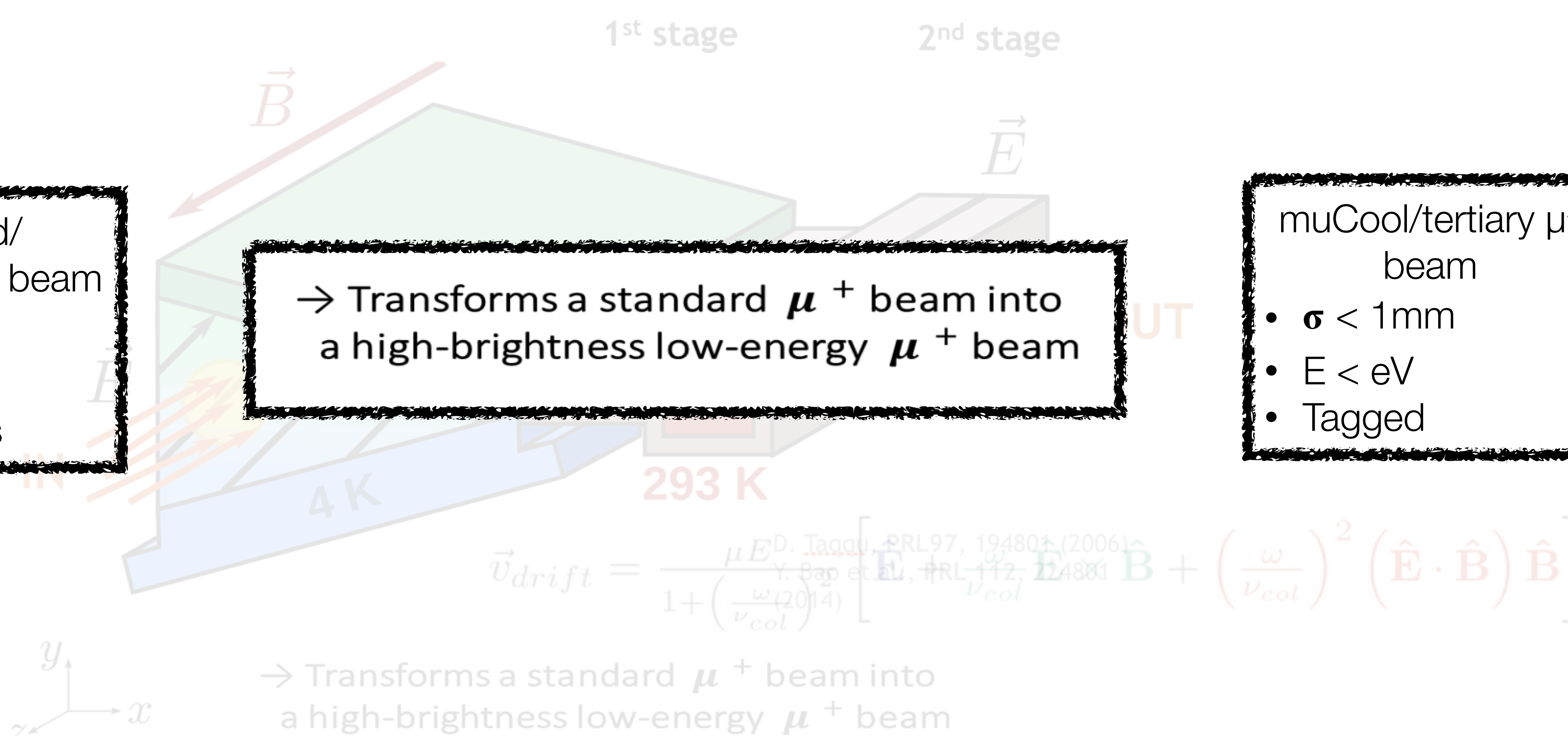

Standard/ secondary μ+ beam
- σ = 10 mm
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- Continuous

→ Transforms a standard μ^+ beam into a high-brightness low-energy μ^+ beam

muCool/tertiary μ+ beam
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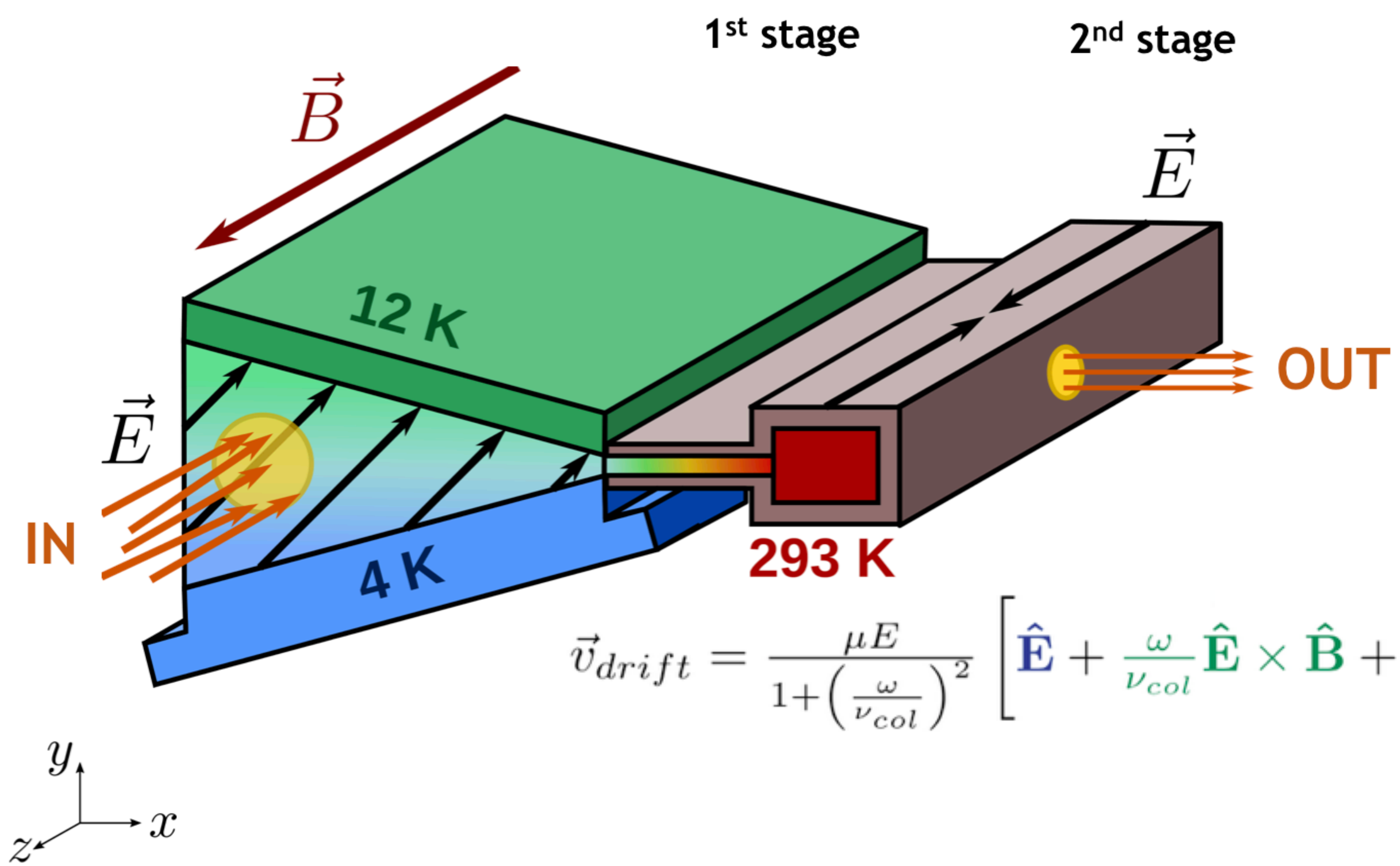
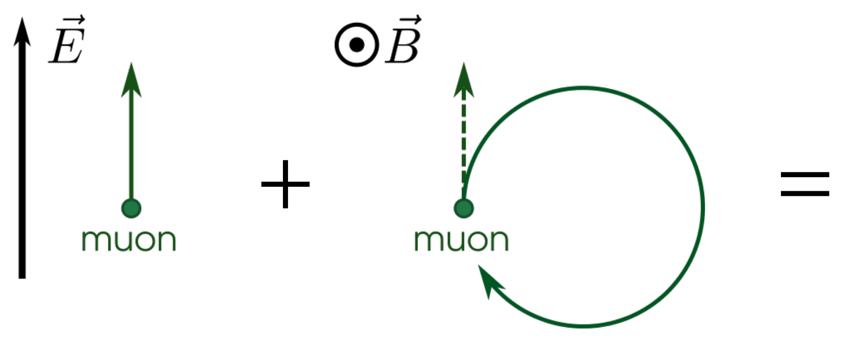


$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

Trajectories in E and B field



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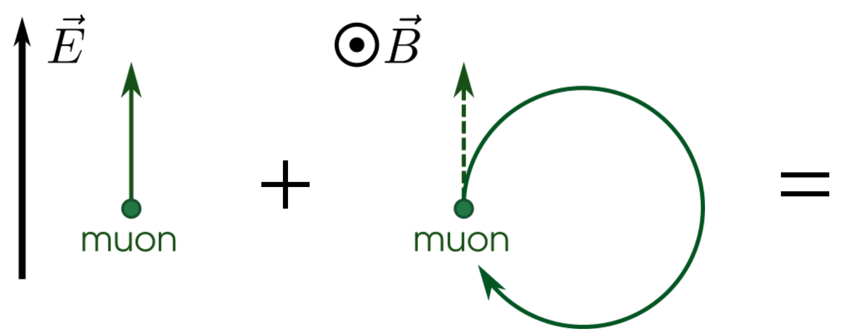
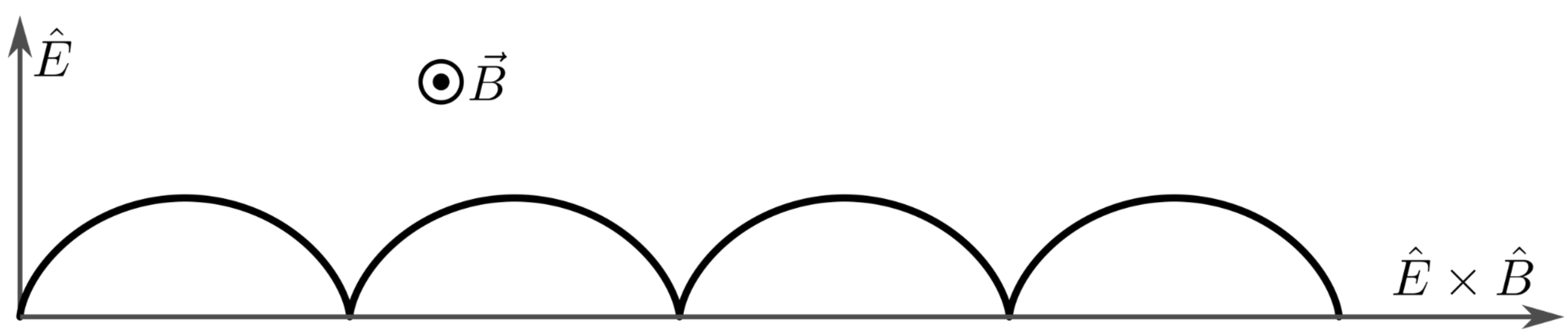
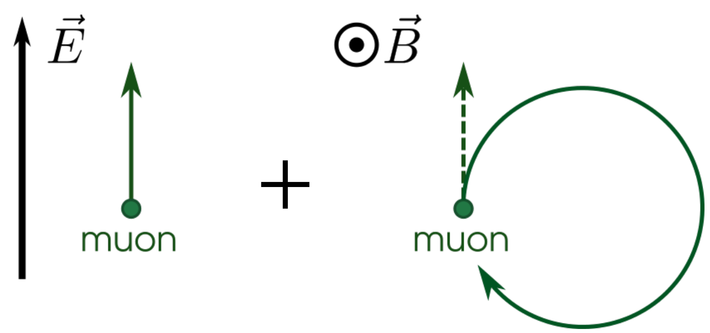


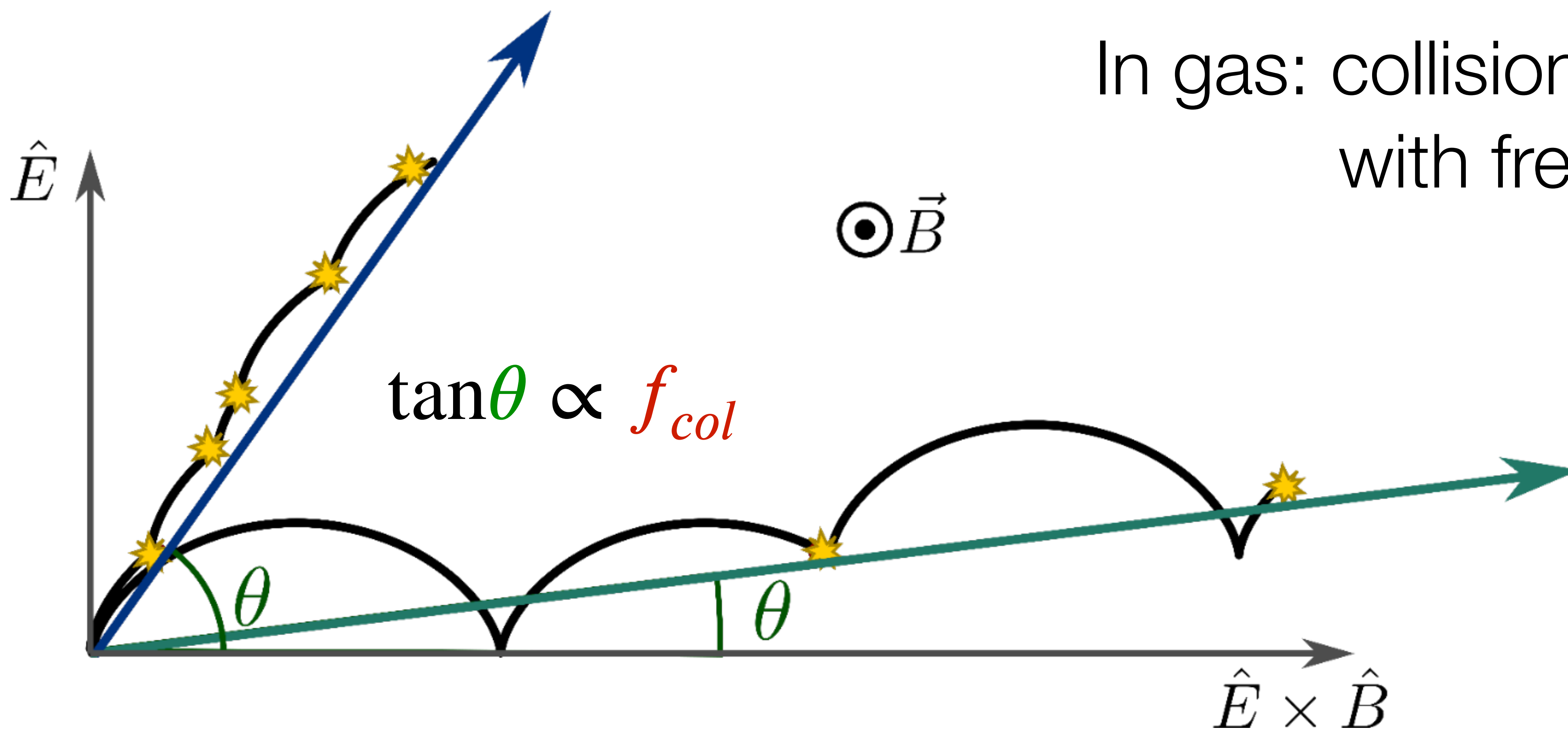


Trajectories in E and B field + gas

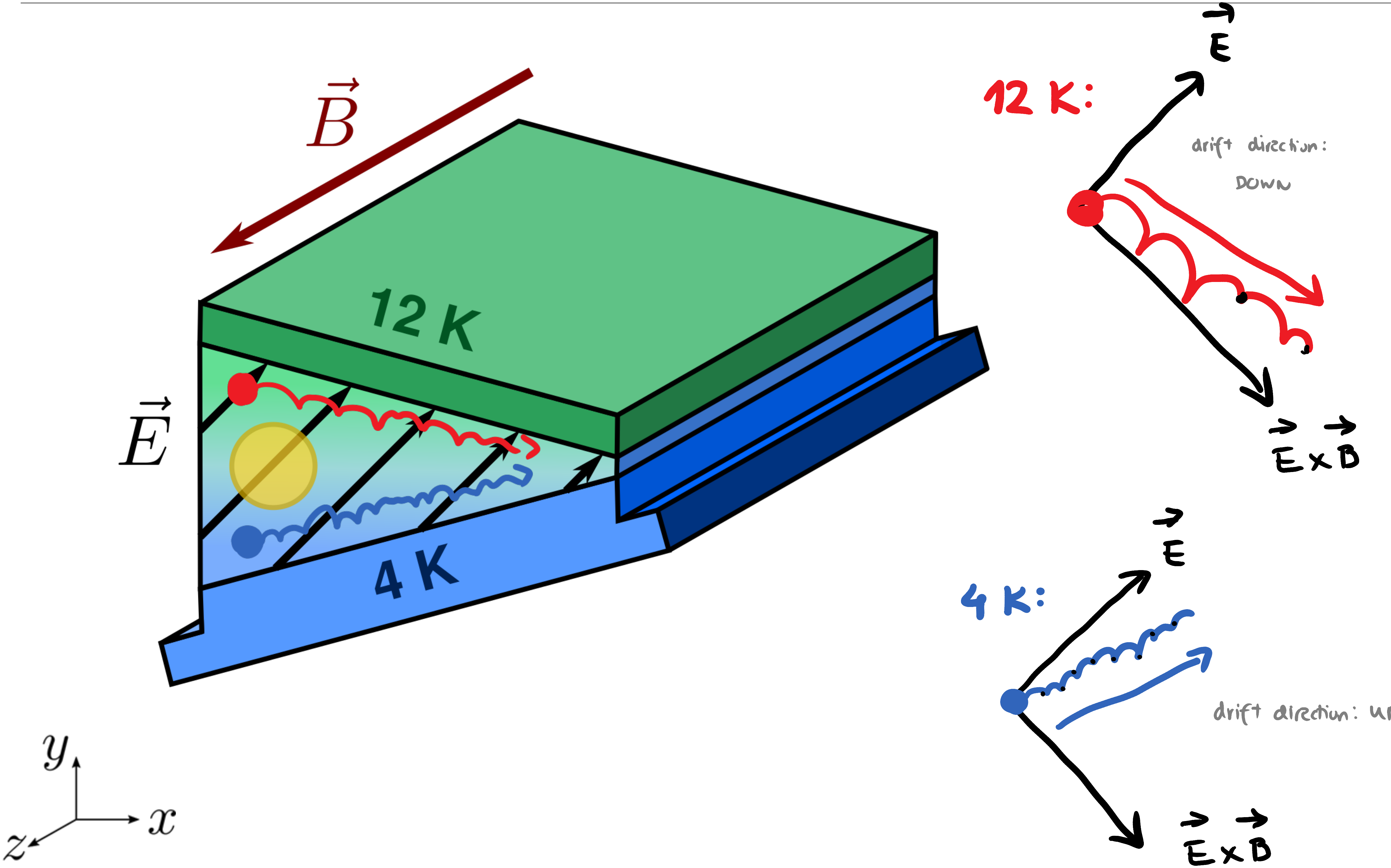


+ gas =

In gas: collisions ☆
with frequency f_{col}

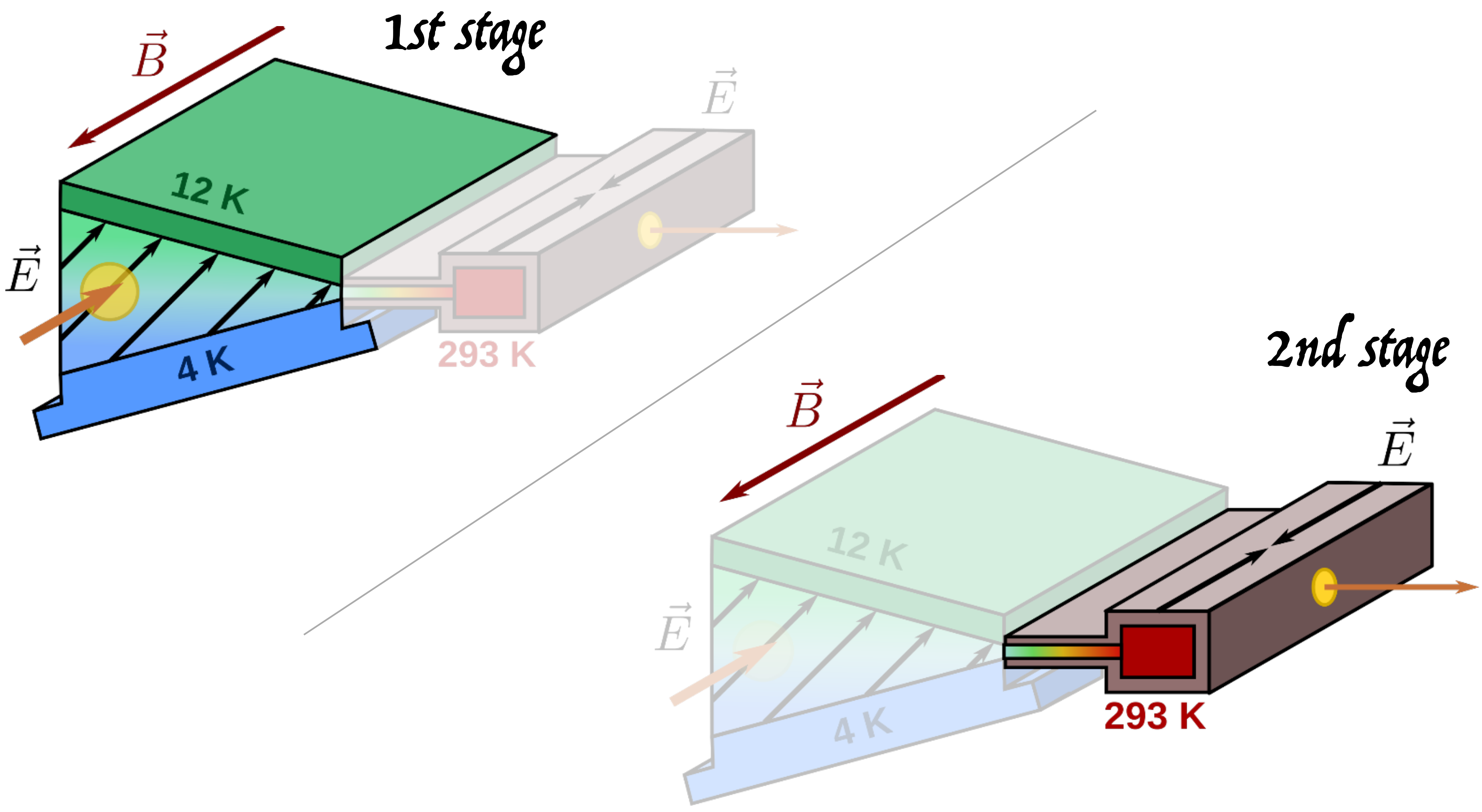


Working principle: 1st Stage



Experimental setup and results: 1st stage and 2 stage

- Separately longitudinal and transverse compression: **PROVED**
- **Very good agreement between data and simulations**



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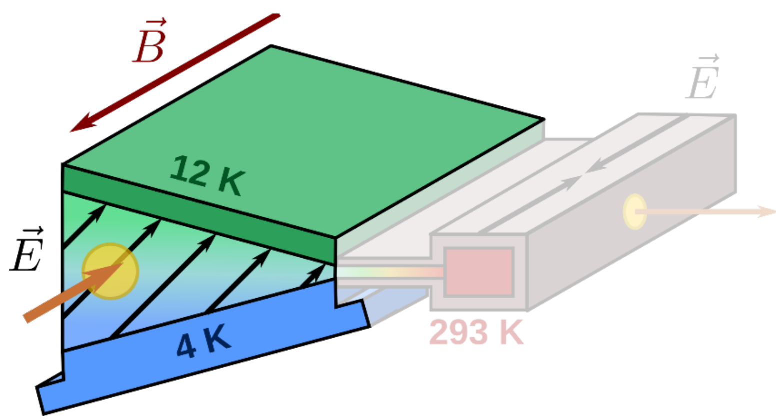

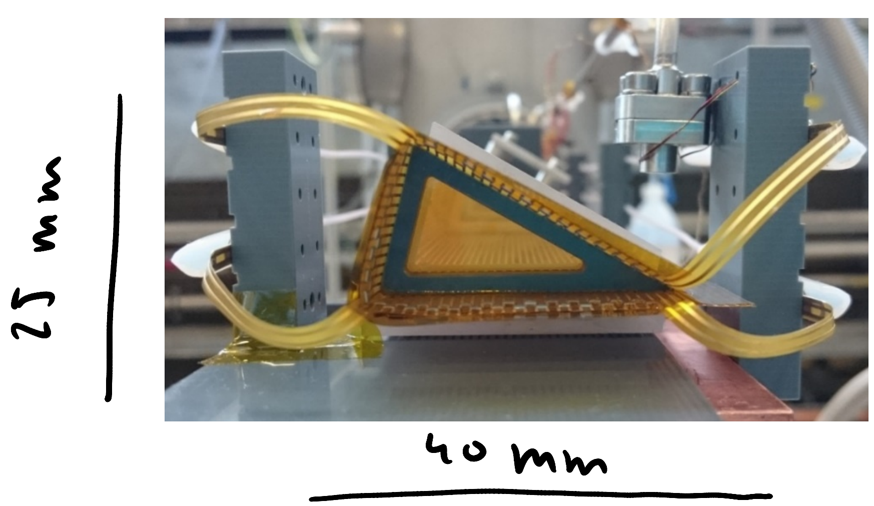

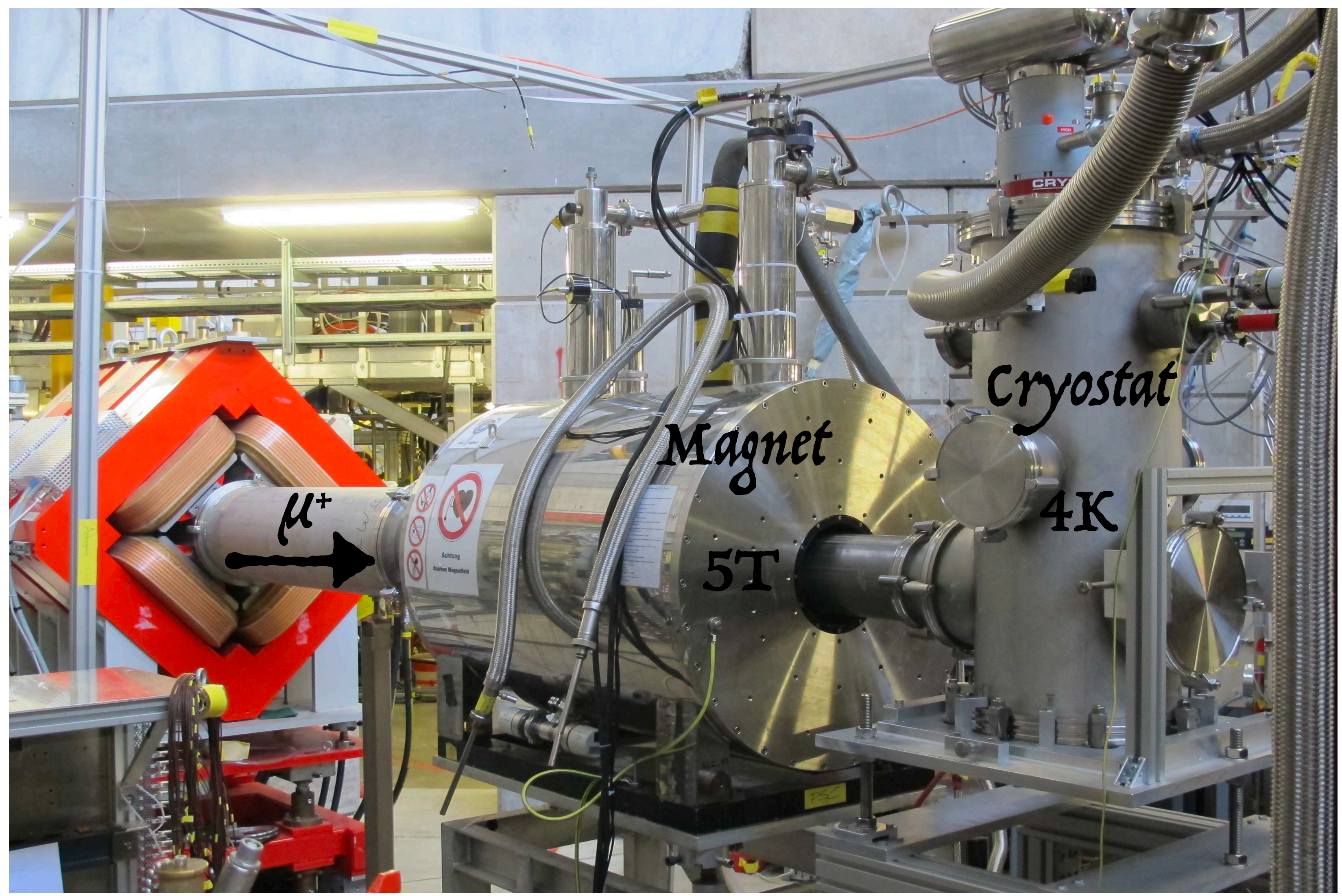

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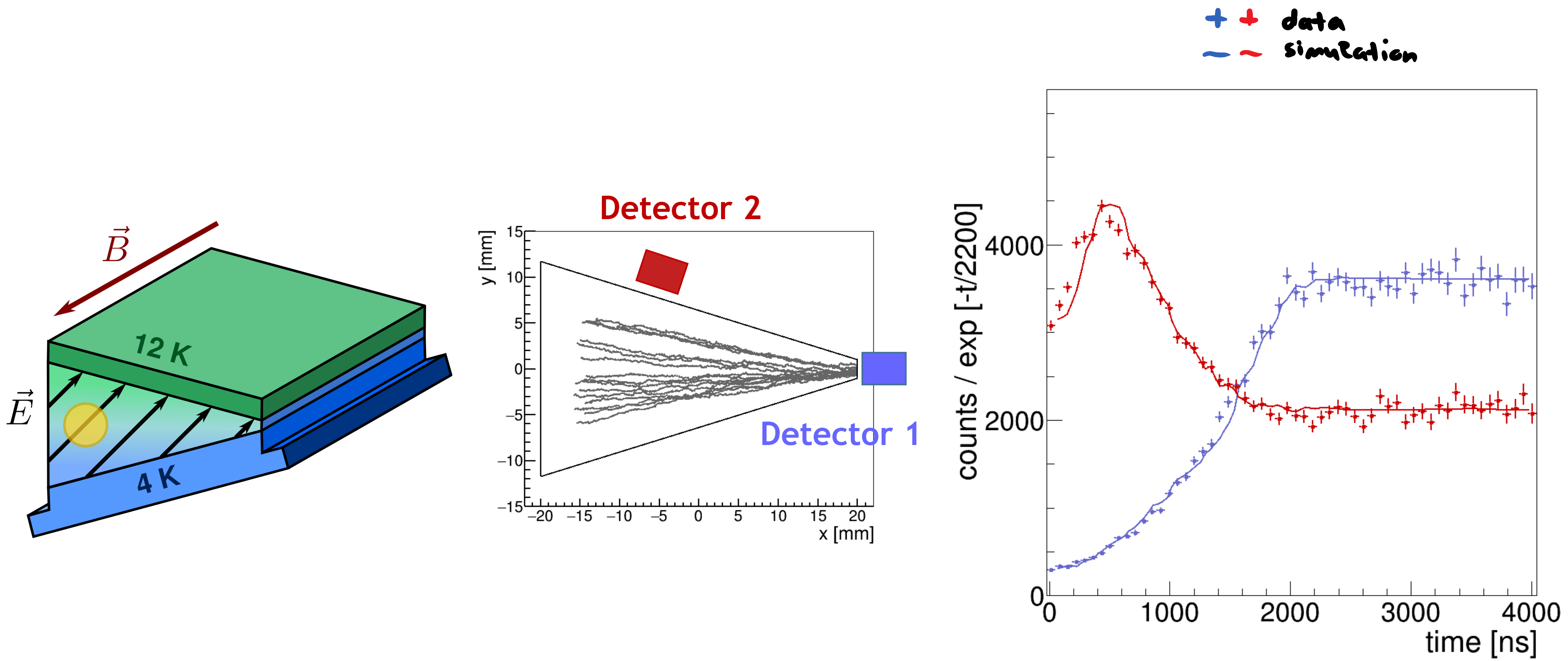
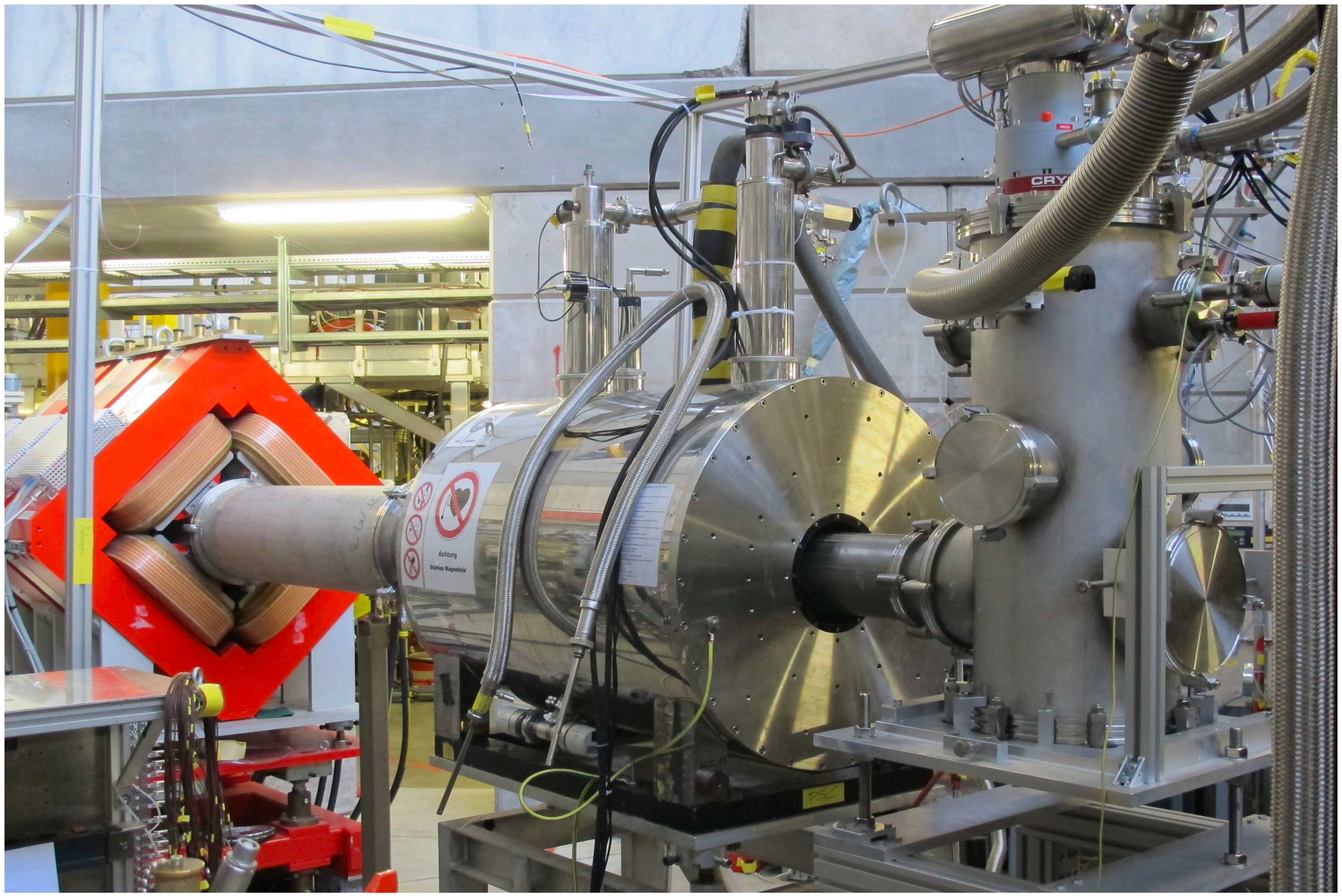
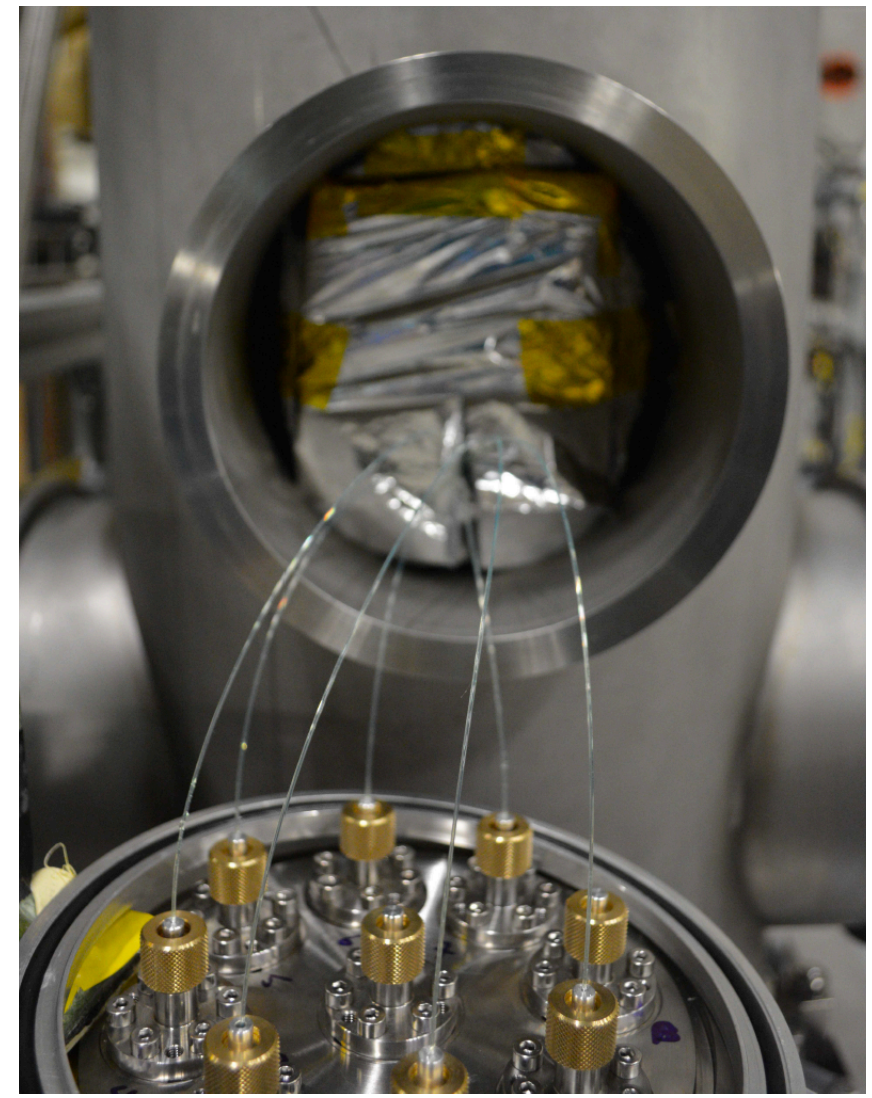
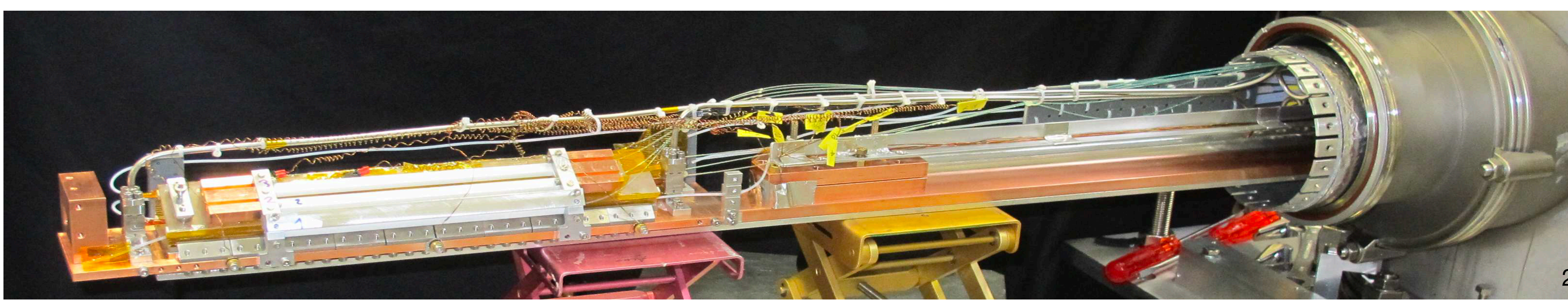


Experimental setup and results: 1st stage

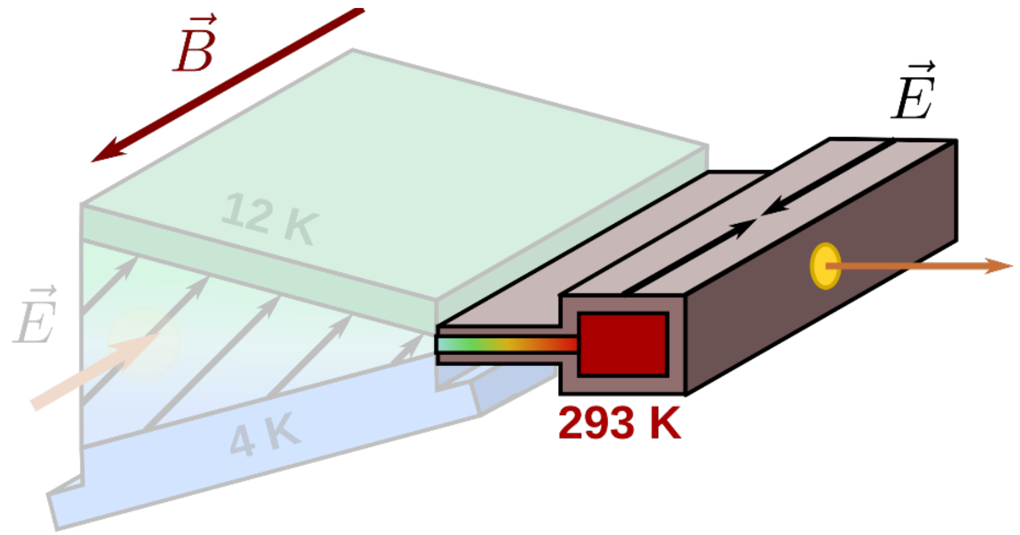


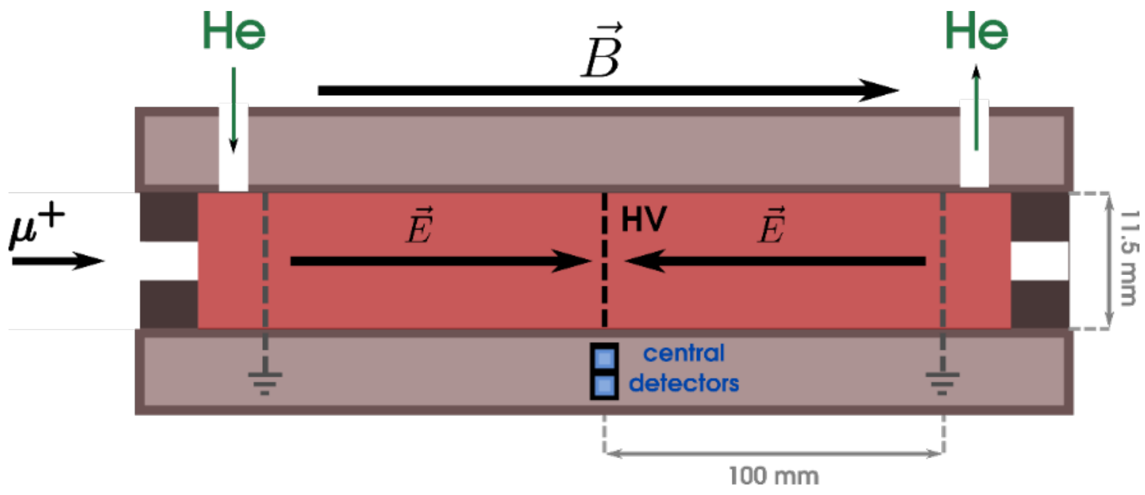


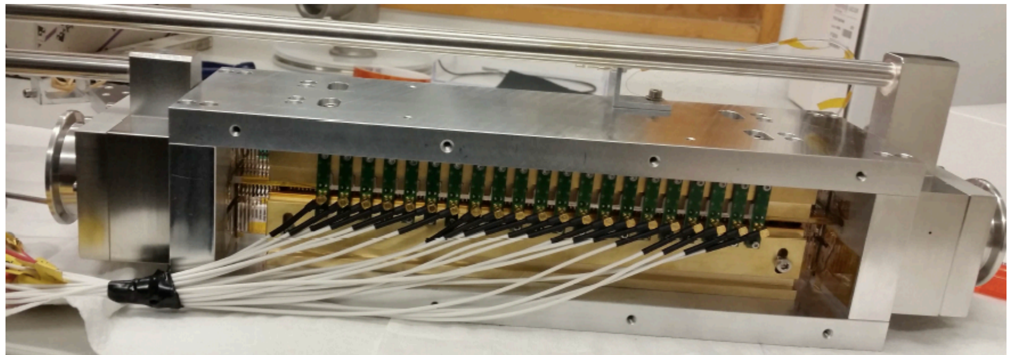


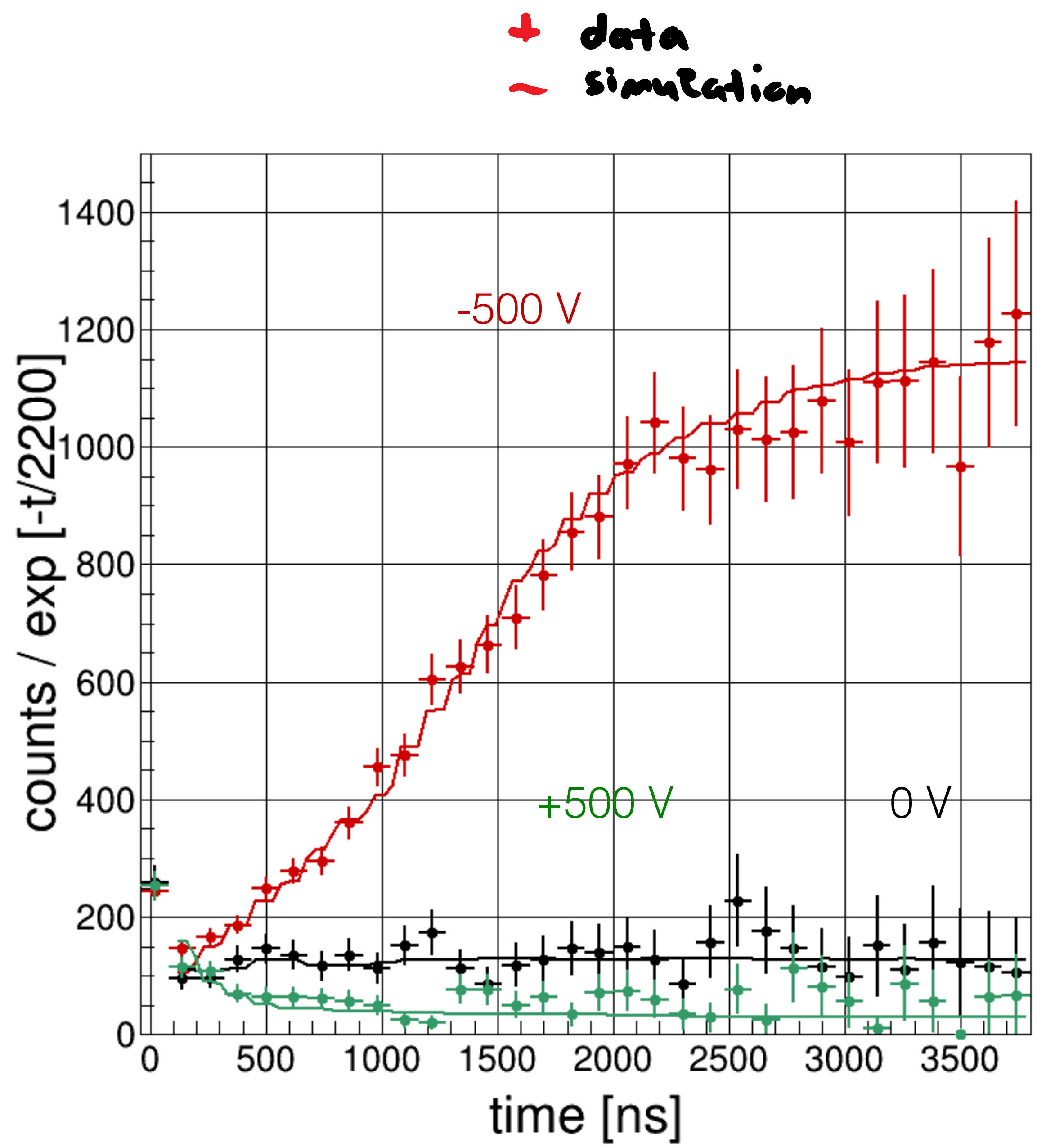
Experimental setup and results: 2nd stage

- Separately longitudinal and transverse compression: **PROVED**
- **Very good agreement between data and simulations**



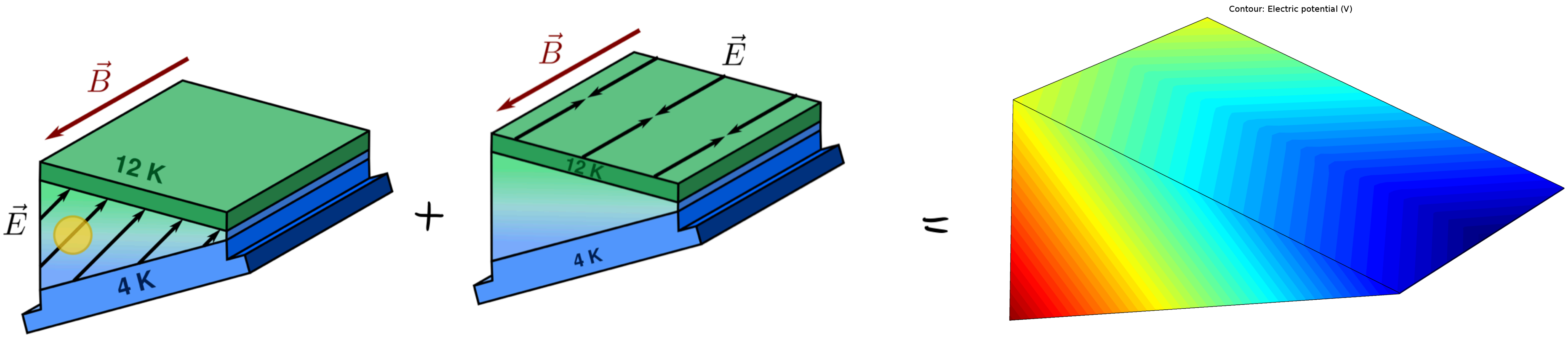


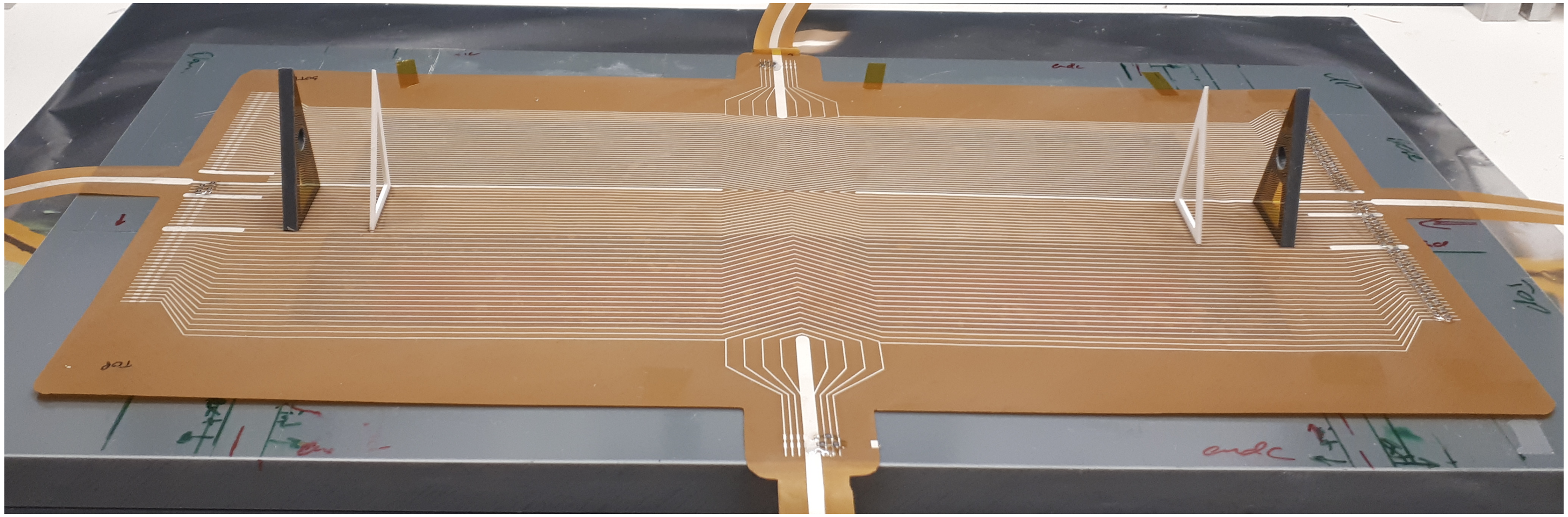




The muCool project at PSI: Status

- 1st stage + 2nd stage
- **Next Step**: Extraction into vacuum





Outlook - HiMB

- HiMB aims at surface high intensity muon beam **O(10^{10} muon/s)**
- Initial simulations show that such rates are feasible
- Beam optics and investigations on proton beam modifications underway
- HiMB opens the door to interesting physics opportunities for particle physics and materials science using high-intensity and high-brightness muon beams (Mu3e Phase II, Low energy MuSR, Muonium spectroscopy, …)
- Put into perspective the target optimisation only, corresponding to **50%** of muon beam intensity gain, would corresponds to effectively raising the proton beam power at PSI by **650 kW**, equivalent to a beam power of almost **2 MW** without the additional complications such ad increased energy and radiation deposition into the target and its surroundings
- If the same exercise is repeated put into perspective the beam line optimisation the equivalent beam power would be of the order of **several tens of MW**

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Outlook - muCool

- Aim: low energy high-brightness muon beam
- Increase in brightness by a factor **10^{10}** with an efficiency of **10^{-3}**
- First two stages demonstrated independently
- Measurements and simulations agree
- Current development: vacuum extraction

Thank you for your attention!

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