Status of muCool at PSI

Angela Papa, Paul Scherrer Institute and University of Pisa&INFN
on behalf of the muCool project at PSI

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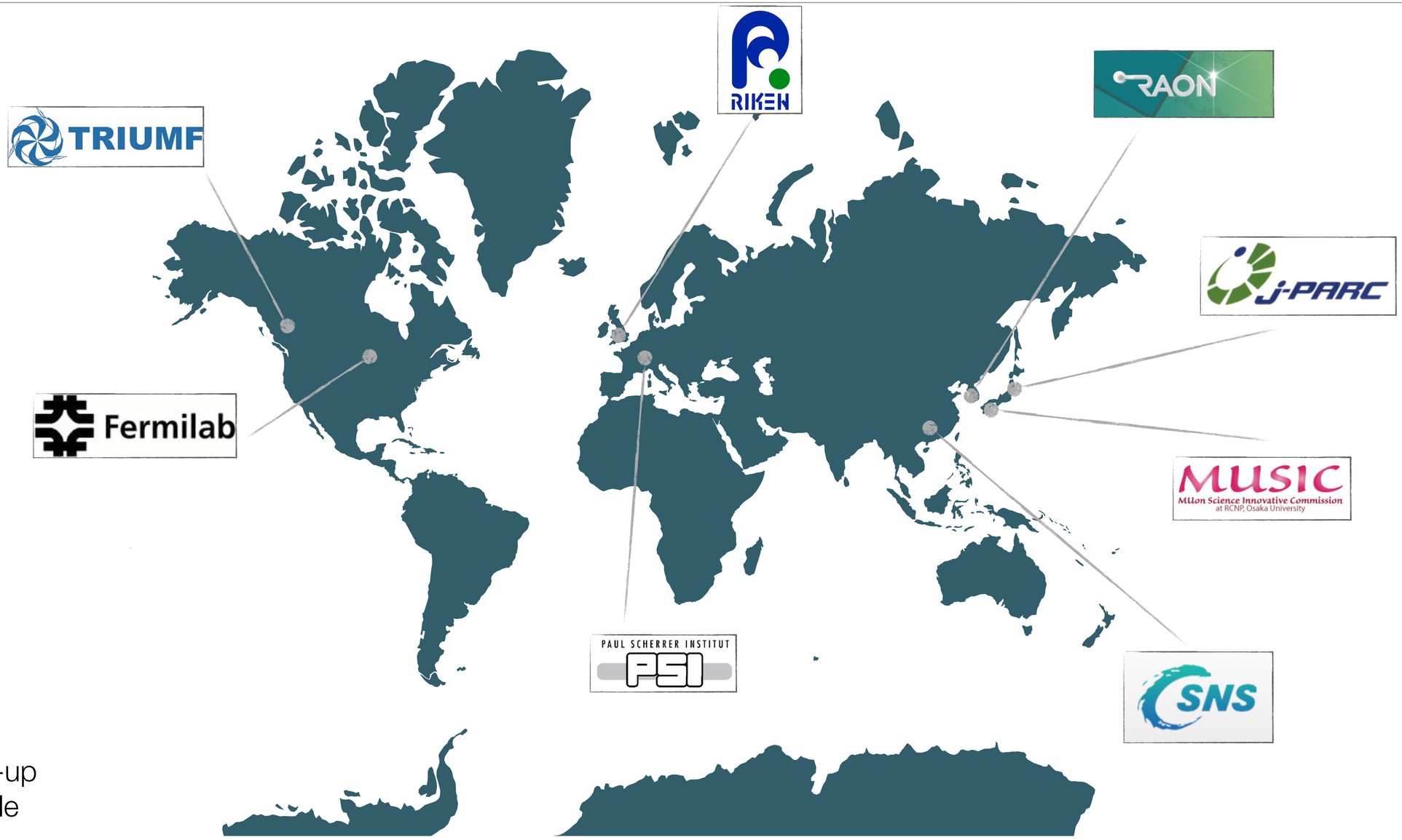
Contents

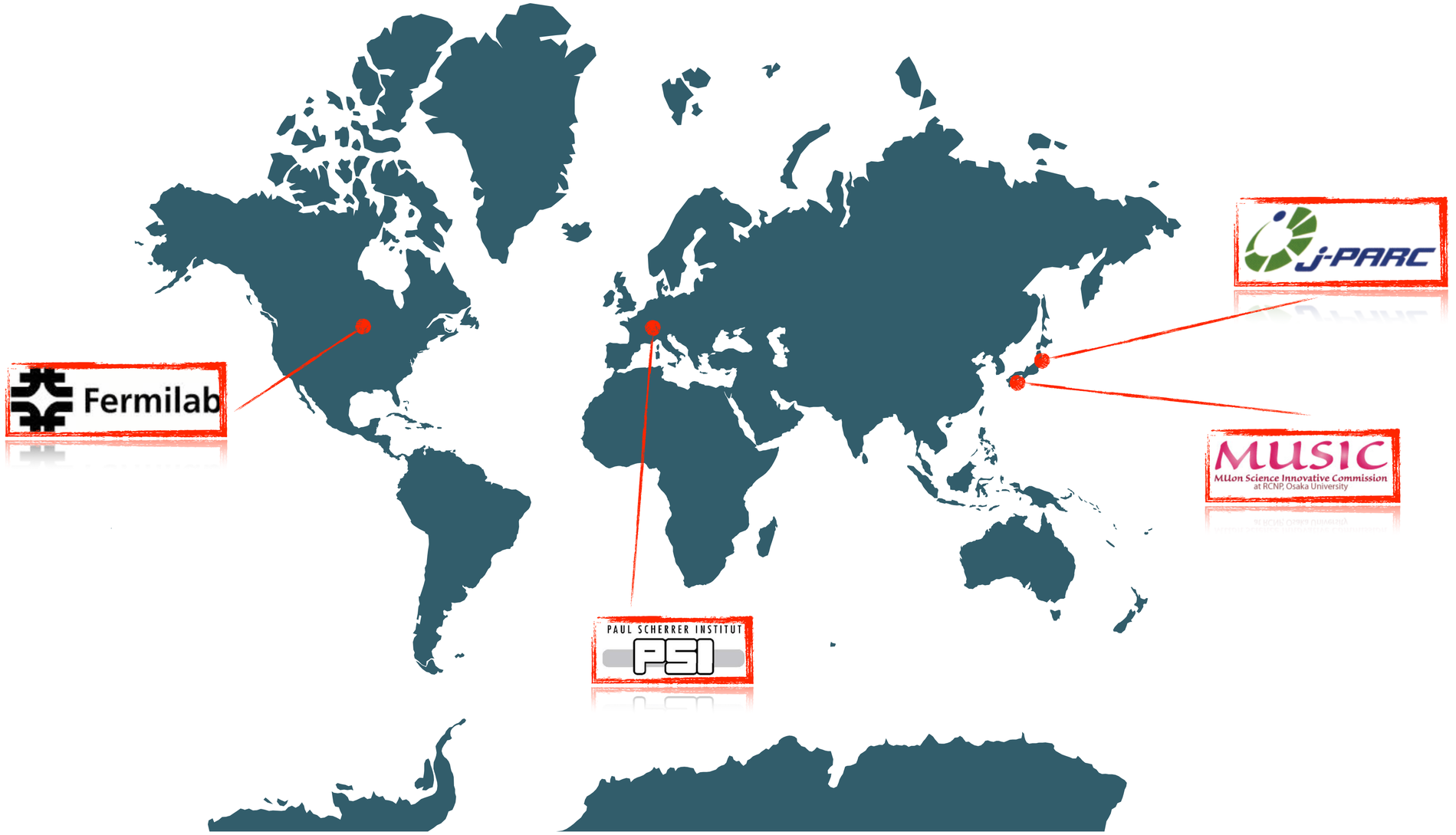
- Current muon beam lines worldwide
- PSI future beam line developments
  - The muCool project

Muon beams worldwide



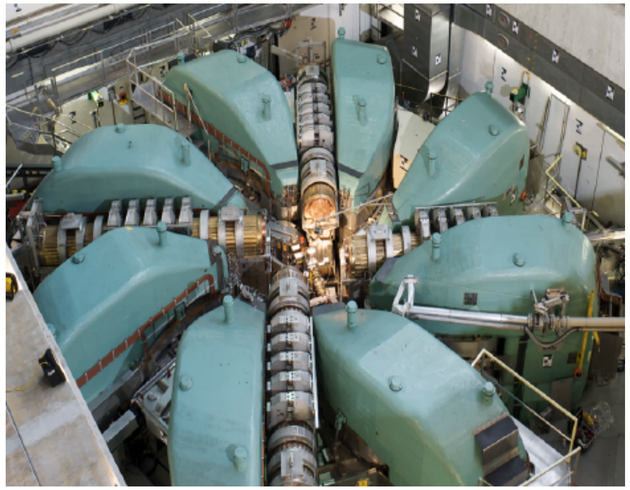
Note: See the back-up for a summary table

Muon beams worldwide associated to “present” experiments



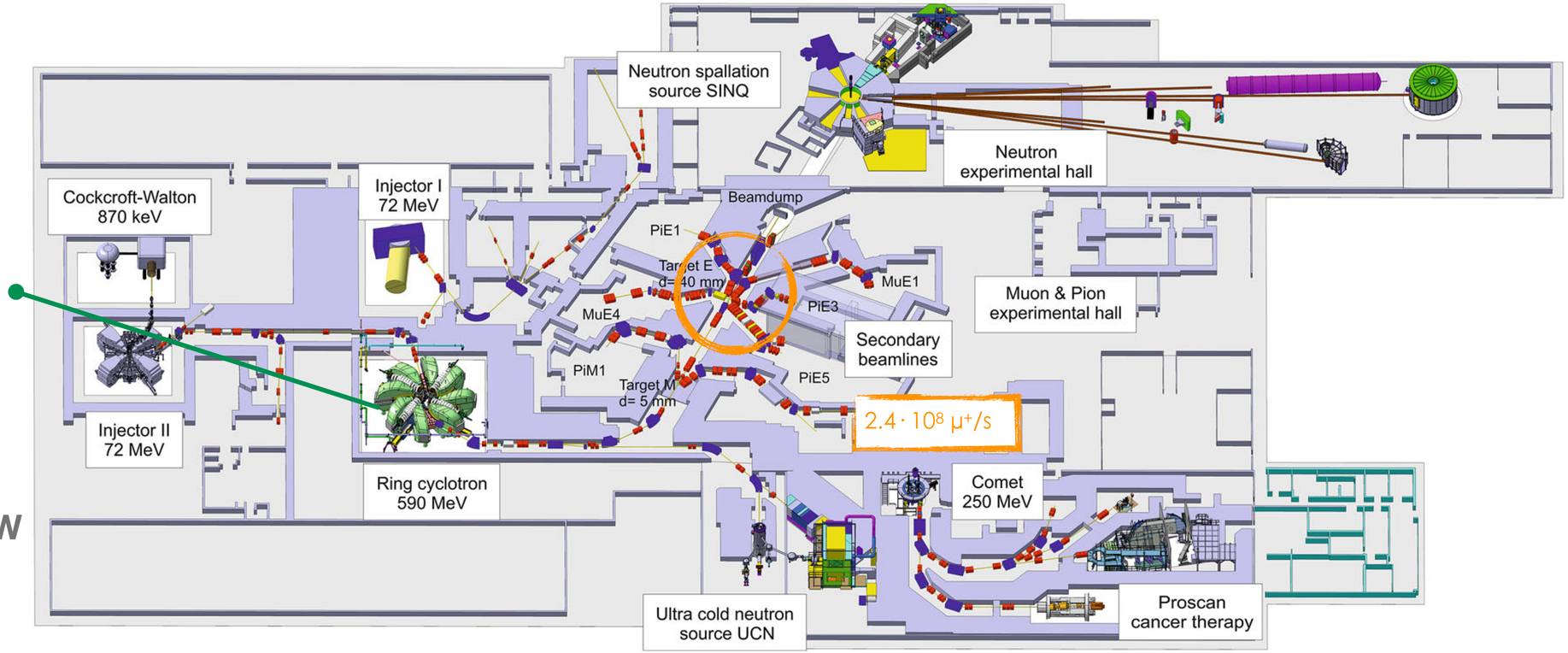
Muon beam major characteristics

- **Intensity**: Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world's highest beam intensities



590 MeV proton ring cyclotron**: 1.4 MW**

Up to a **few x10⁸ mu/s** (28 MeV/c)



Muon beam major characteristics

- **Intensity**: Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world's highest beam intensities
- **Time structure**: "Continuous" or pulsed

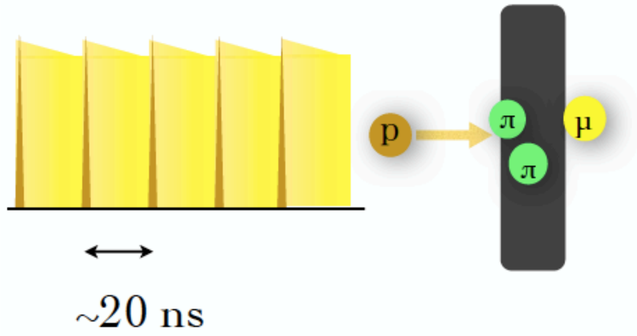
I_{beam} ~ 10^{8} - 10^{10} μ/s

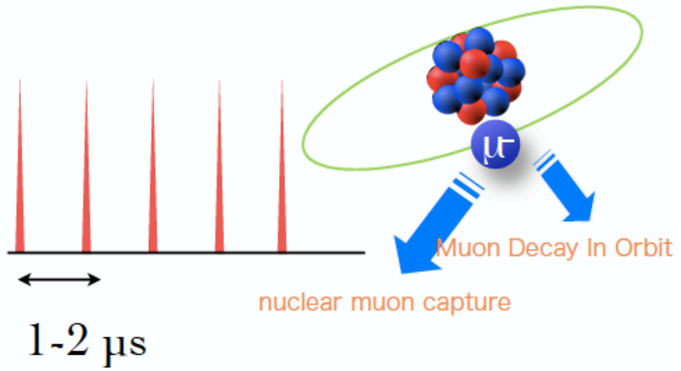
DC or Pulsed?

I_{beam} ~ 10^{11} μ/s

- DC beam for coincidence experiments
  - $\mu \rightarrow e\gamma$, $\mu \rightarrow e\ e\ e$
- Pulse beam for non-coincidence experiments
  - μ-e conversion

@ PSI

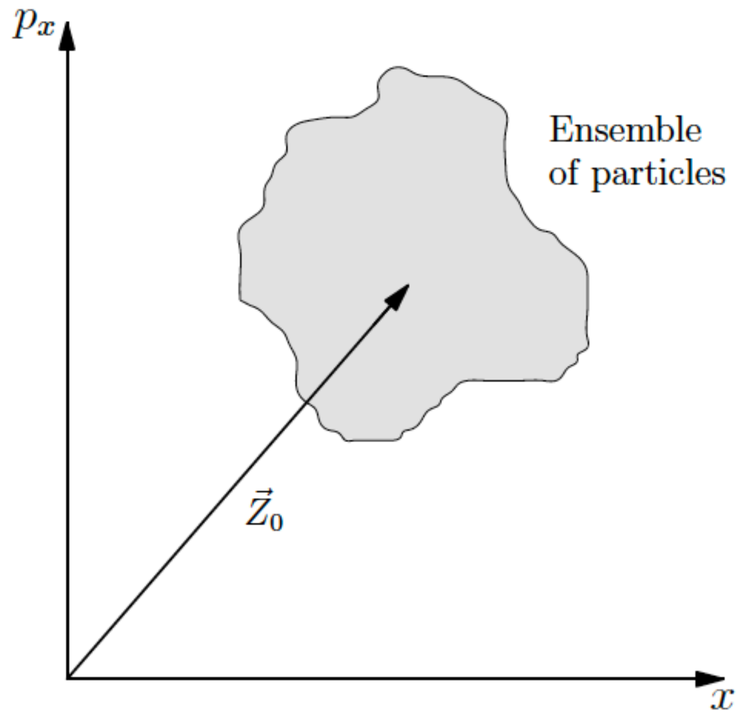




@ JPARC, FERMILAB

Muon beam major characteristics

- **Intensity**: Dedicated beam lines for high precision and high sensitive SM test/BSM probe at the world's highest beam intensities
- **Time structure**: "Continuous" or pulsed
- **Phase space**: High-brightness



$$\vec{Z} = (x, p_x, y, p_y, z, p_z)$$

The muCool project at PSI

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

The muCool project at PSI

INPUT

Standard/secondary μ^+ beam

- σ = 10 mm
- E = 4 MeV
- Continuous

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

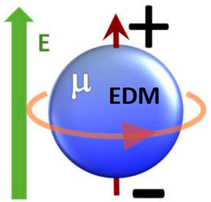
OUTPUT

muCool/tertiary μ^+ beam

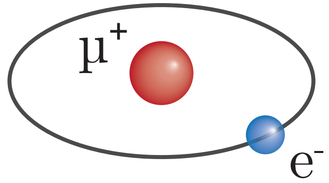
- σ < 1mm
- E < eV
- [Tagged]

The muCool project at PSI

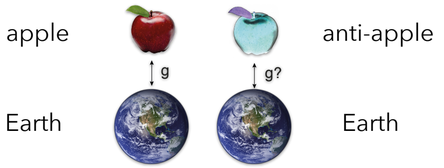
New generation of EDM/g-2



Muonium precision spectroscopy



Muonium gravity experiment



Standard/secondary μ⁺ beam

- σ = 10 mm
- E = 4 MeV
- Continuous

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

muCool/tertiary μ⁺ beam

- σ < 1mm
- E < eV
- Tagged

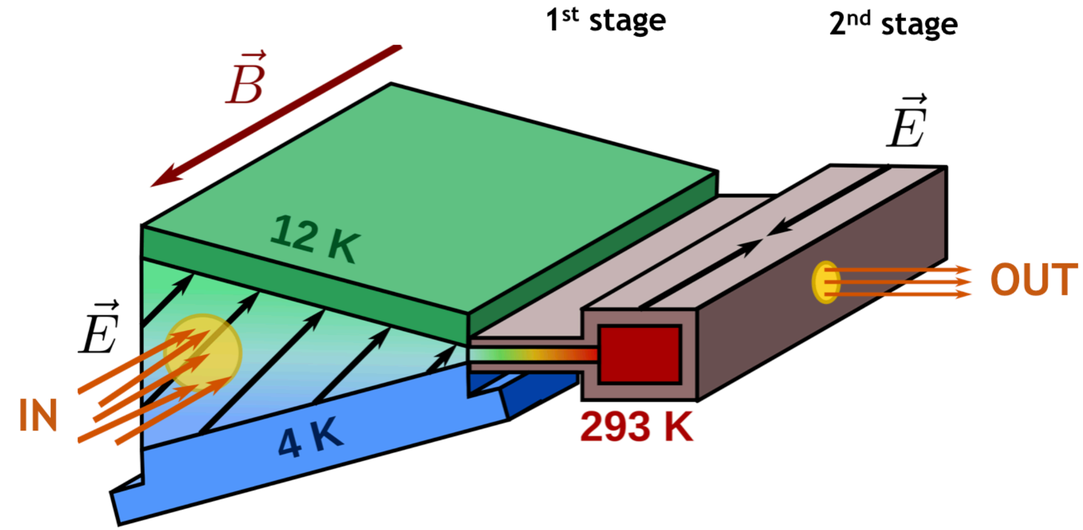
BENEFICIARIES

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

D. Taqqu PRL 97, 194801 (2006)

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
  - by a factor **10^{10}** with an efficiency of O(**10^{-4}**)



Standard/secondary μ⁺ beam
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muCool/tertiary μ⁺ beam
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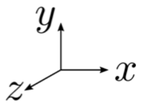
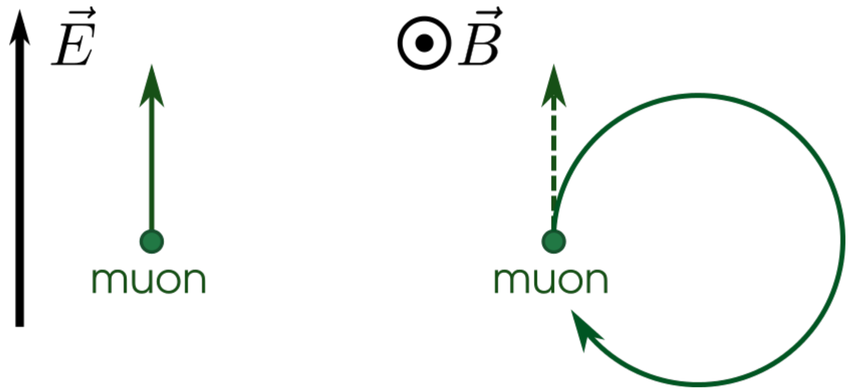


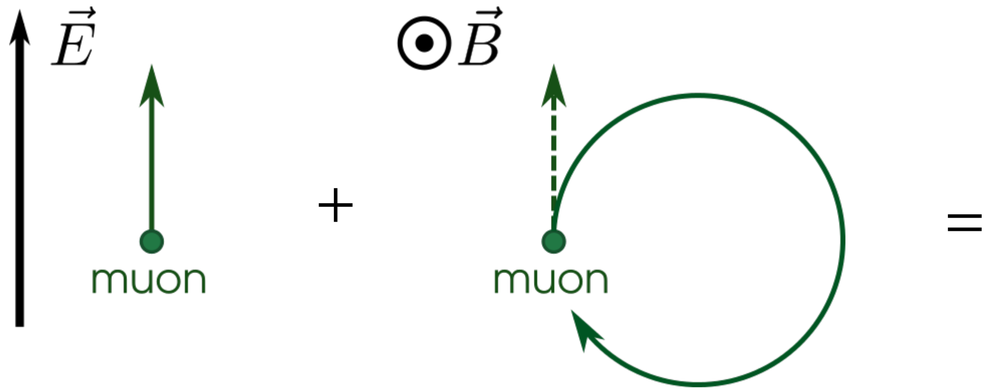
→ Transforms a standard μ^+ beam into a high-brightness low-energy μ^+ beam

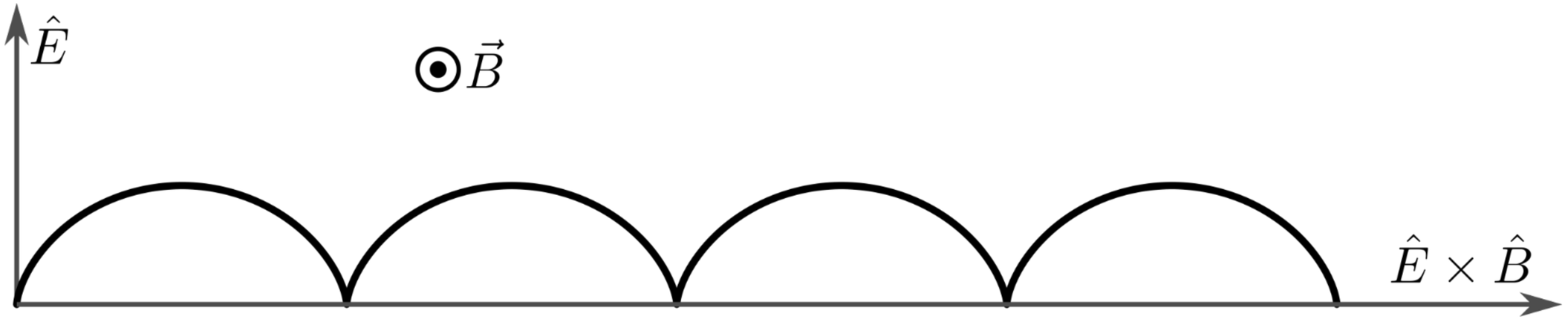
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

Trajectories in E and B field

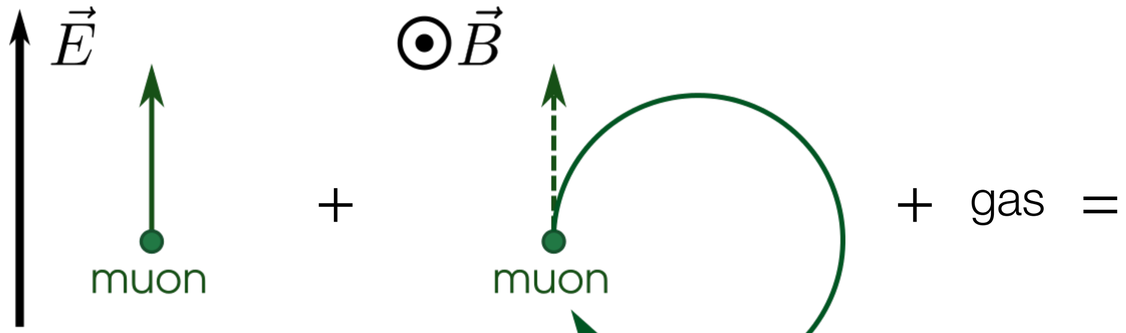


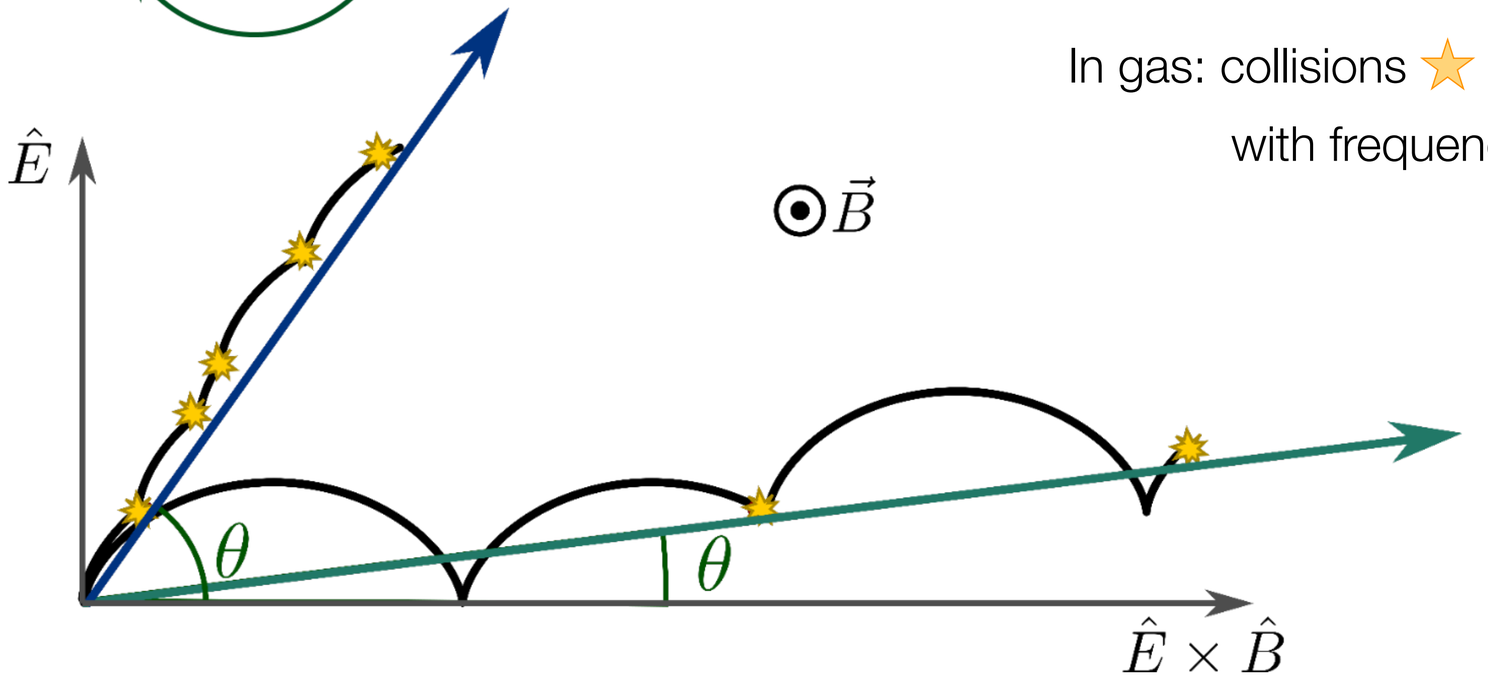
Trajectories in E and B field





Trajectories in E and B field

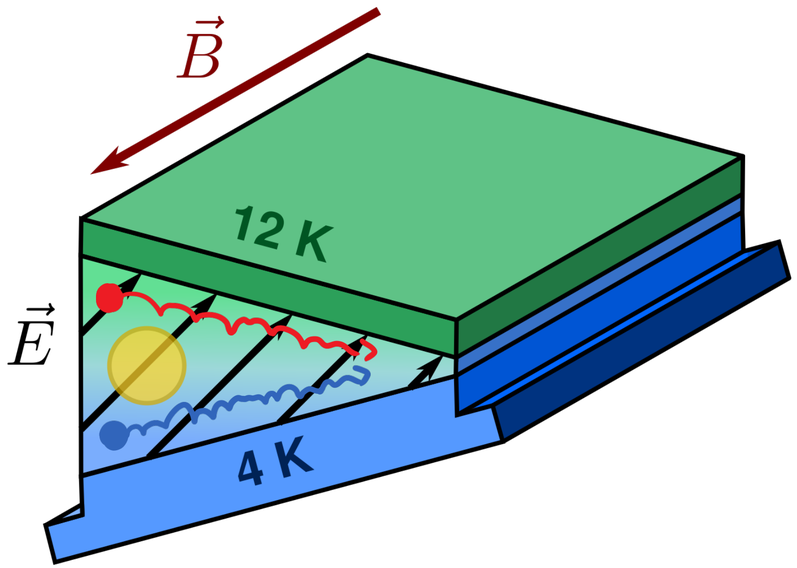


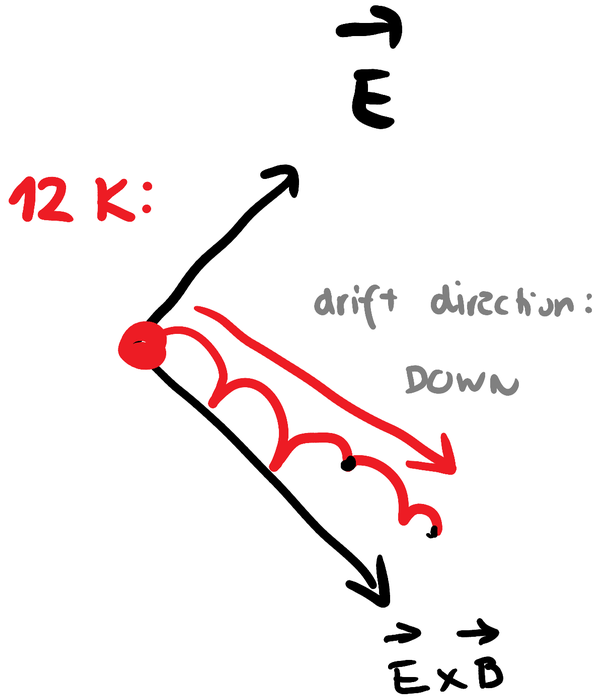


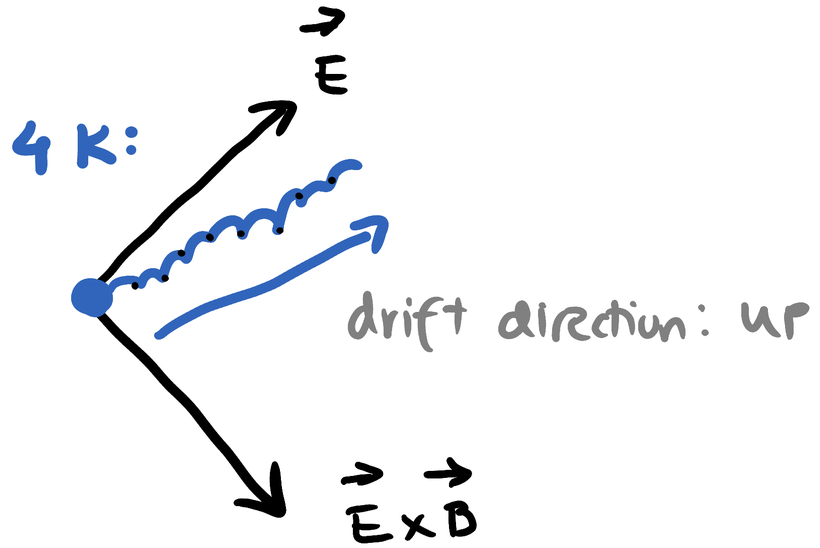
In gas: collisions ★

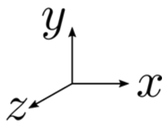
with frequency f_{col}

Working principle: Transverse compression [1st Stage]

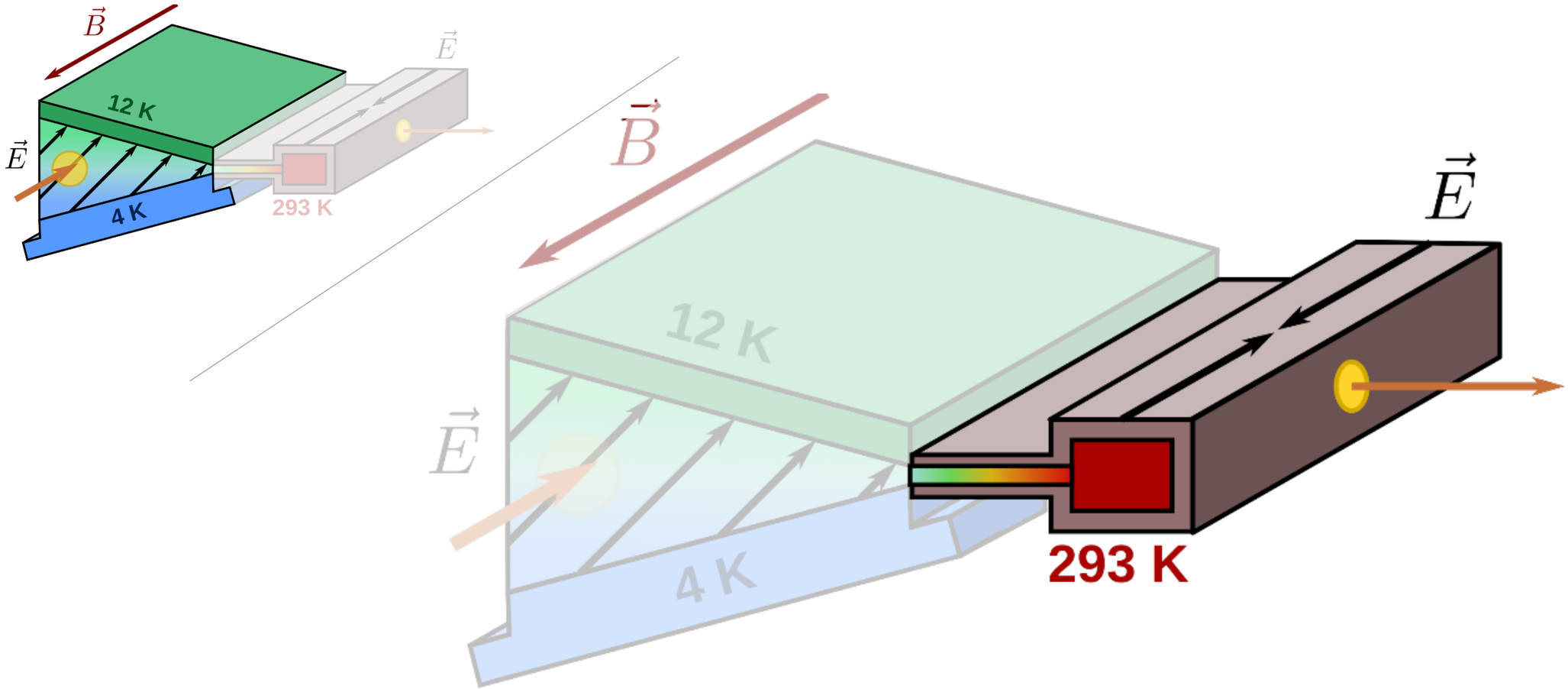




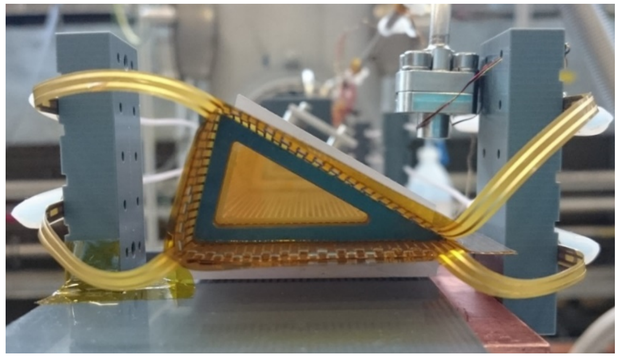


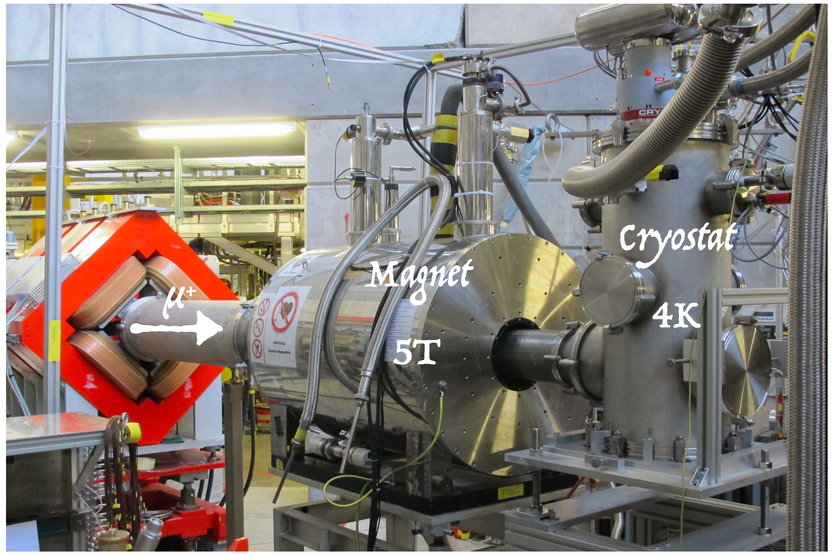


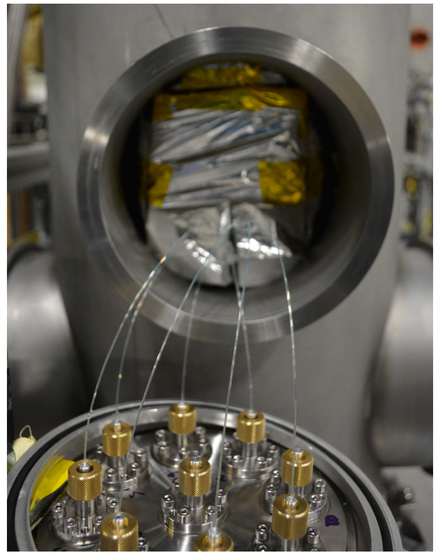
Working principle: Longitudinal compression [2nd Stage]

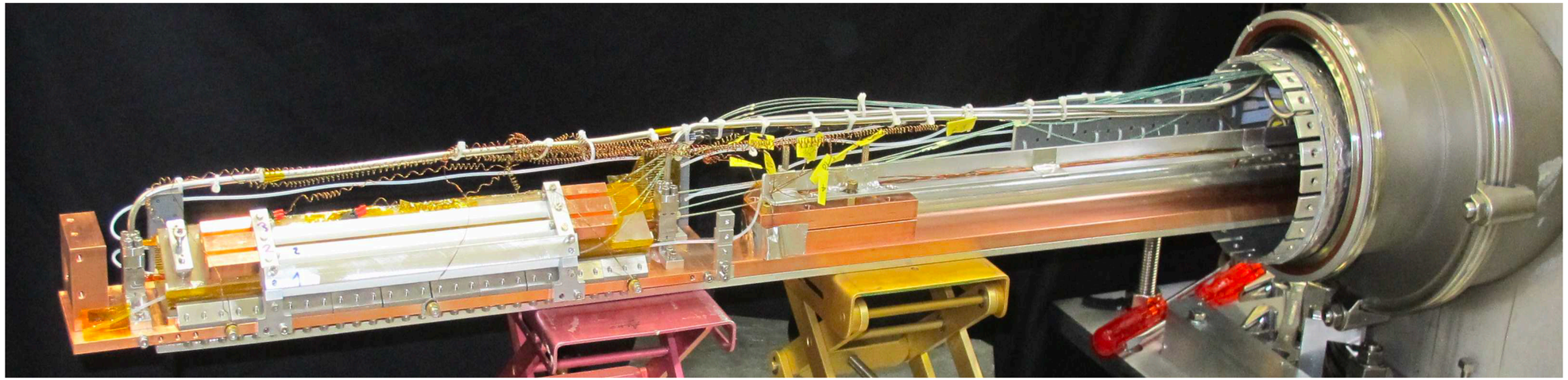


Experimental setup and results: Transverse compression [1st Stage]





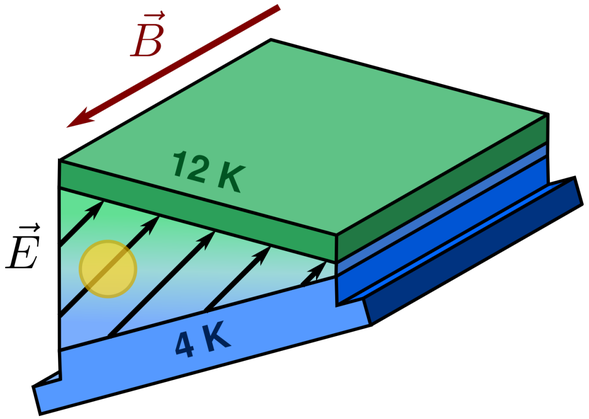


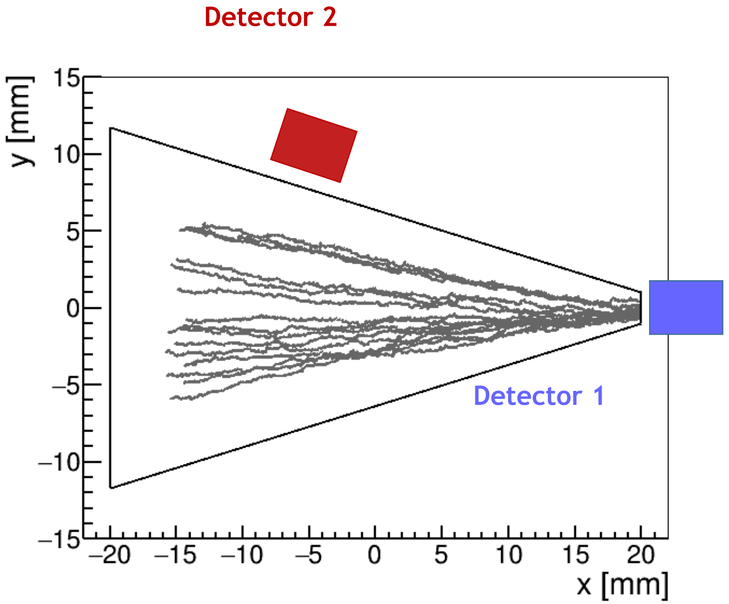


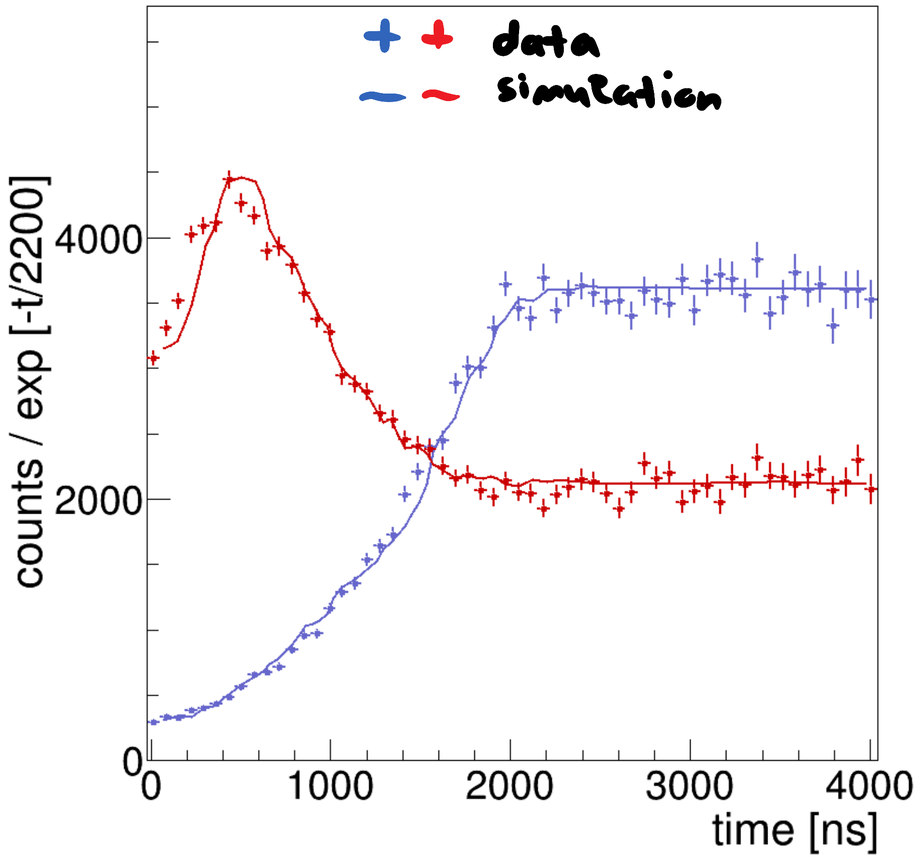
A. Antognini, AP, et al. PRL 125, 164802 (2020)

Experimental setup and results: Transverse compression [1st Stage]

- Transverse compression: **PROVED**
- **Very good agreement between data and simulations**



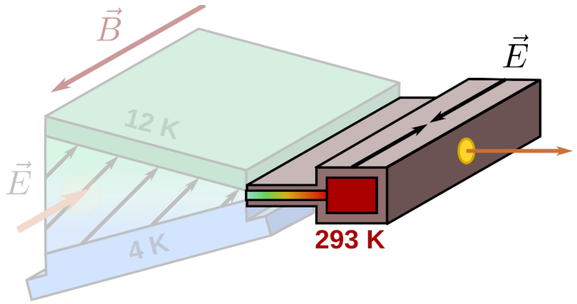


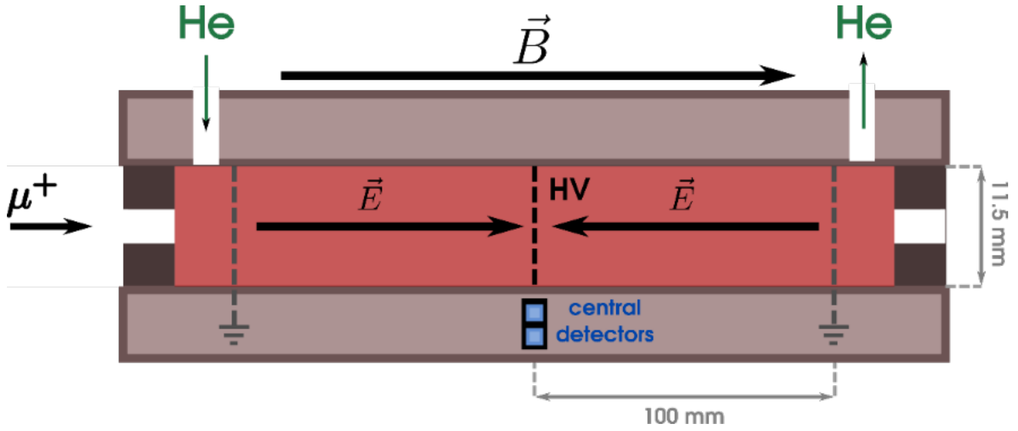


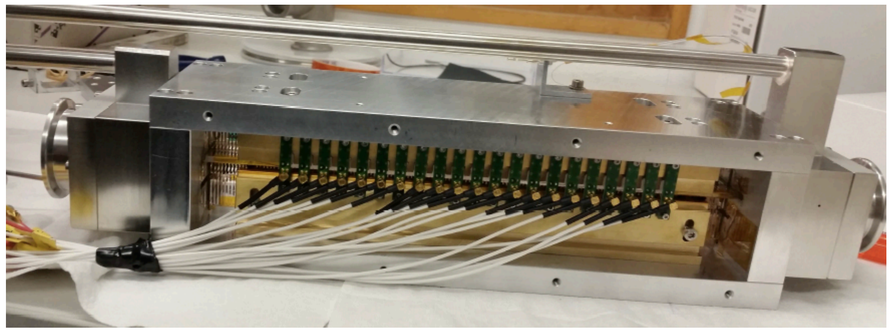
Y. Bao, AP, et al. PRL 112, 224801 (2014)

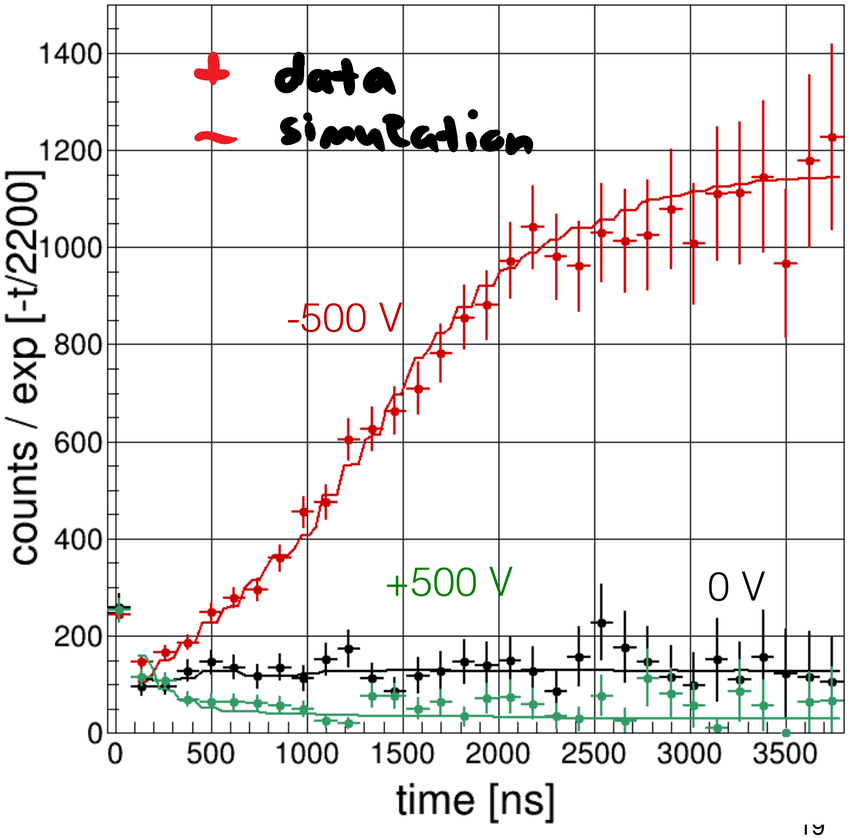
Experimental setup and results: Longitudinal compression [2nd Stage]

- Longitudinal compression: **PROVED**
- **Very good agreement between data and simulations**





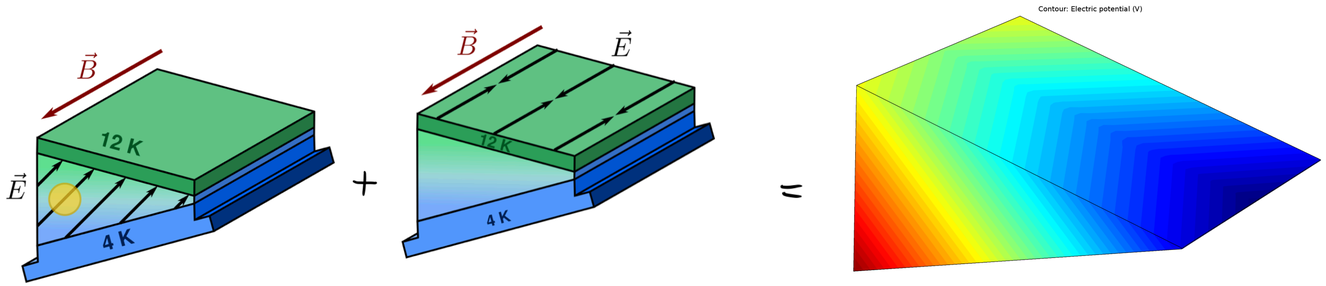


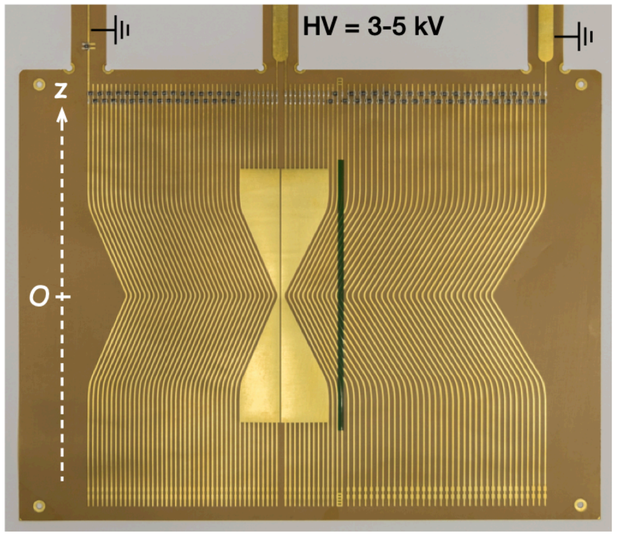


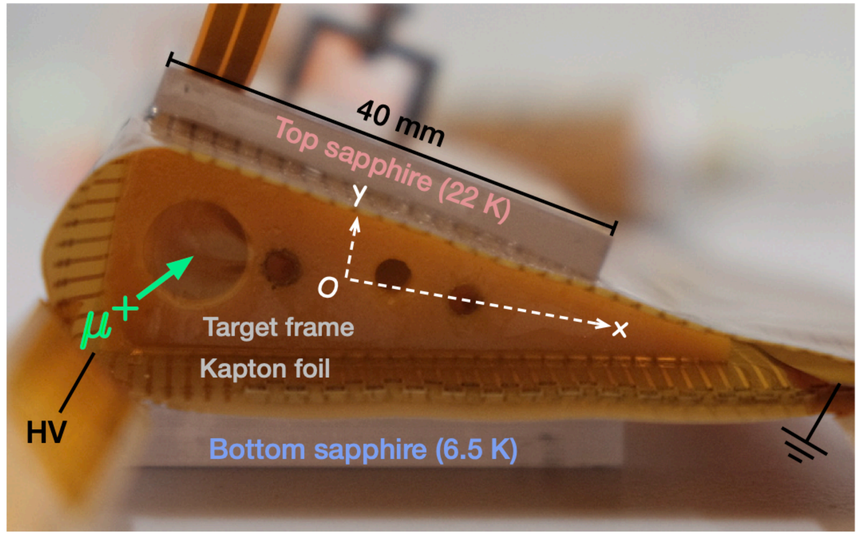
A. Antognini, R. Iwai, AP et al.:https://arxiv.org/pdf/2410.21162

Experimental setup and results: Transverse + Longitudinal compression

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







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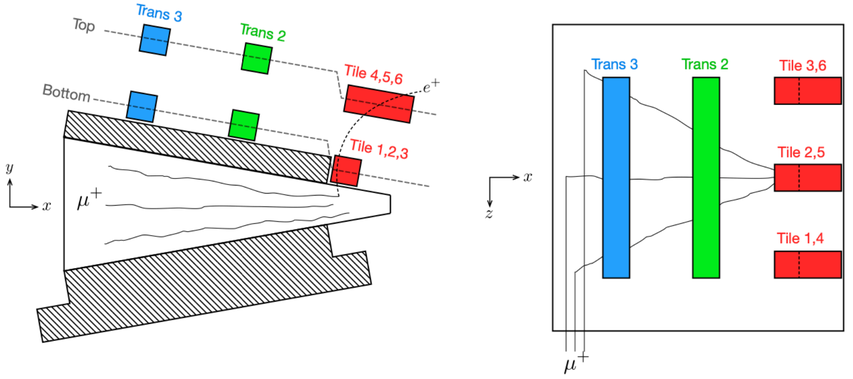
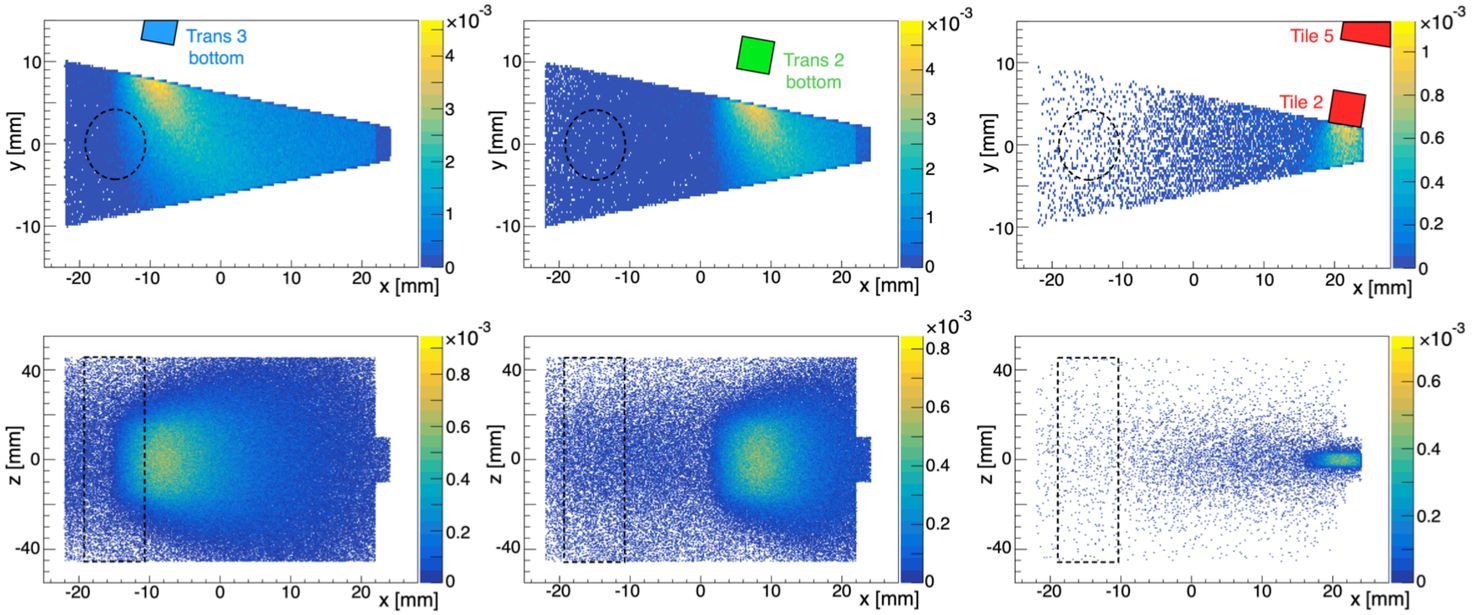


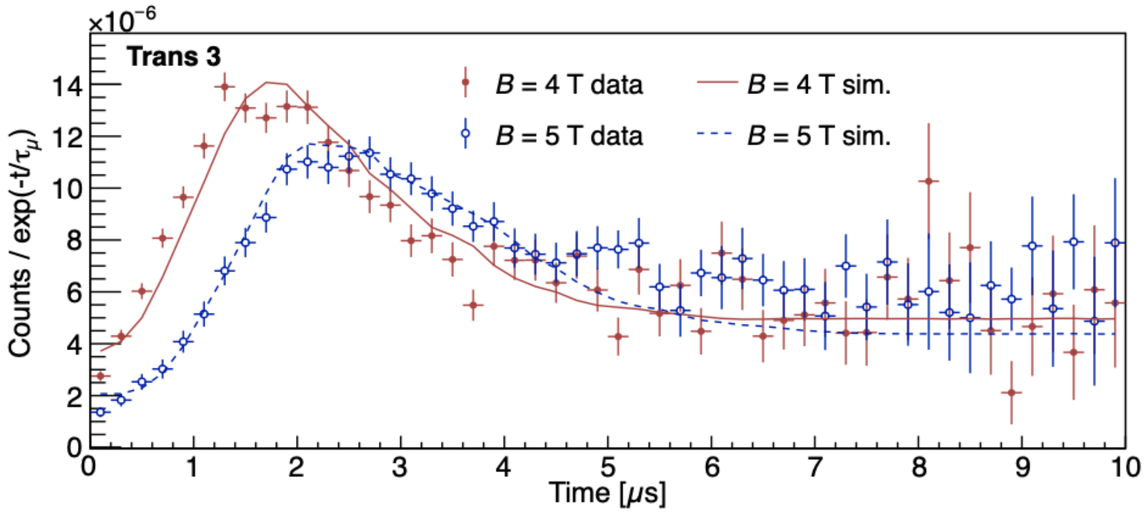
MC simulation

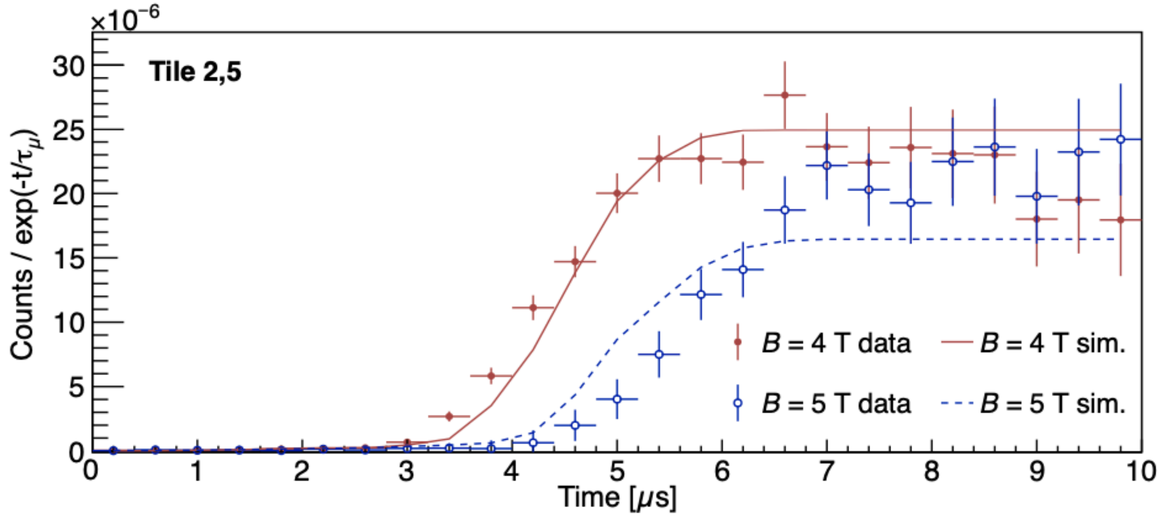


Experimental setup and results: Transverse + Longitudinal compression

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

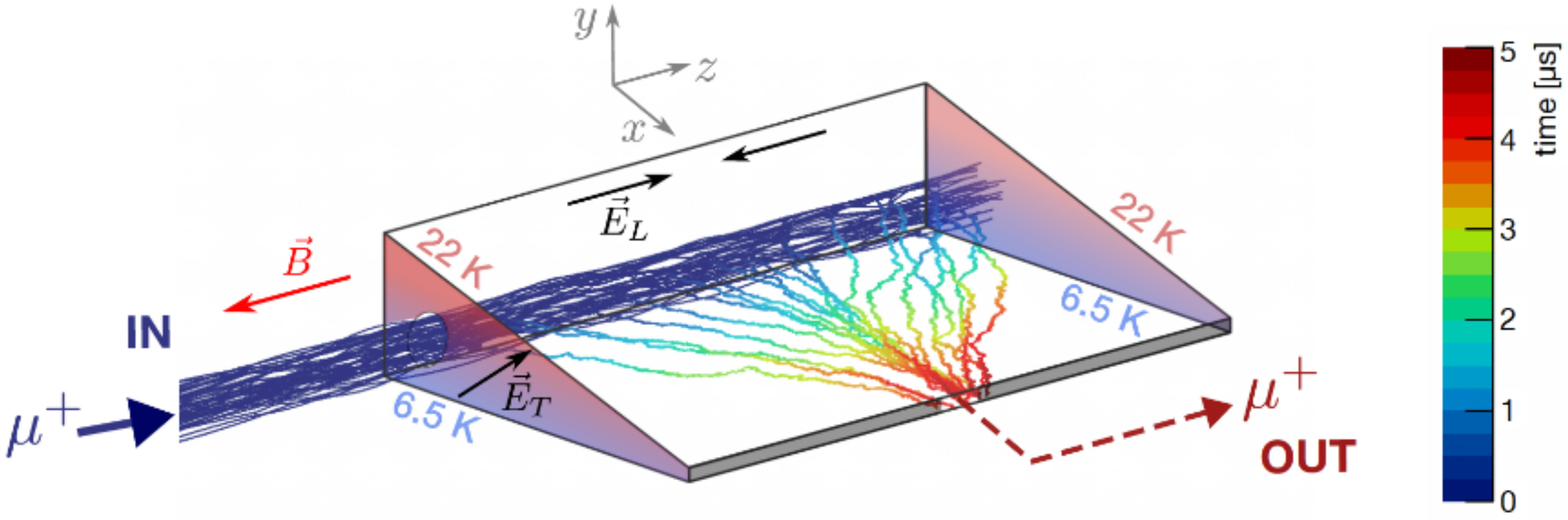
Data [points] and MC [lines] at 8 mbar and HV = 4.16 kV for two magnetic filed values





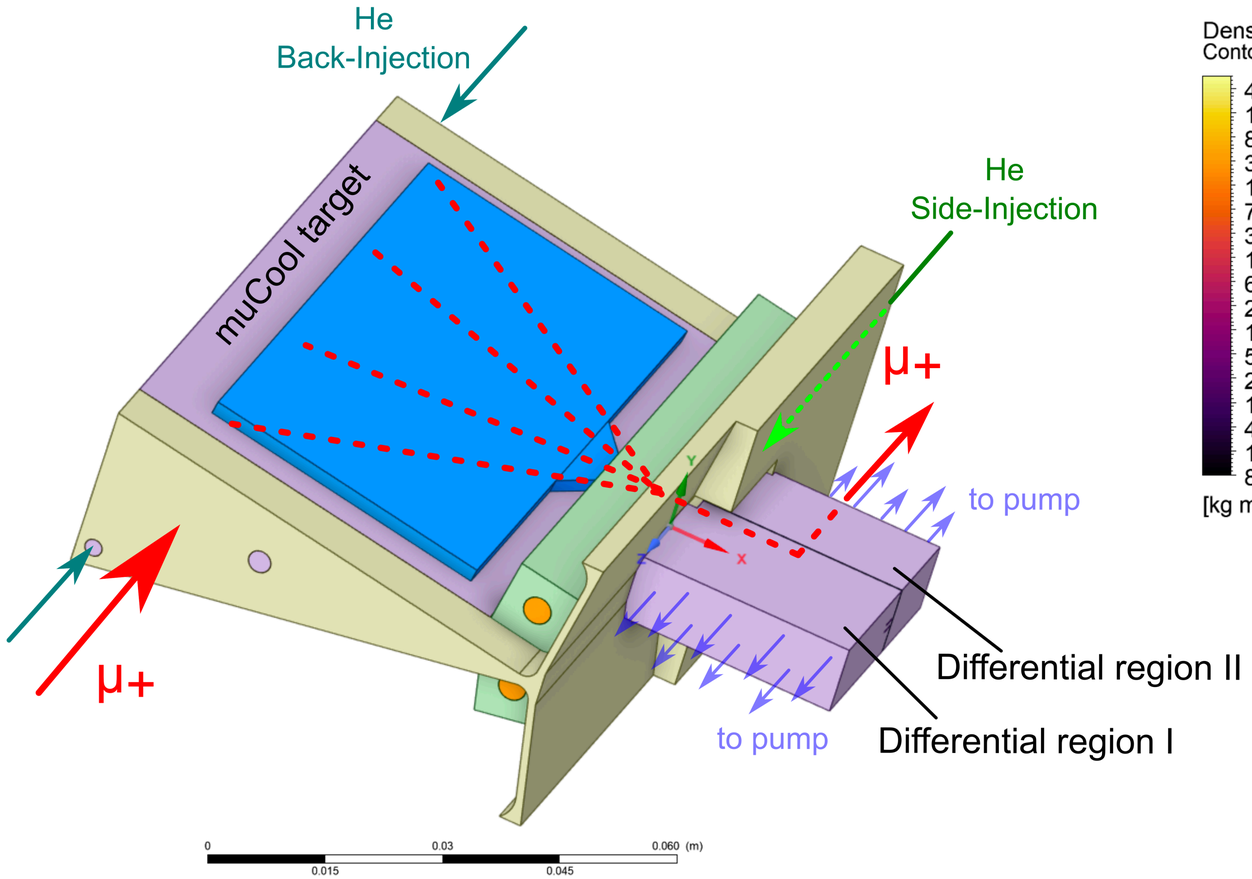
Where we are now:

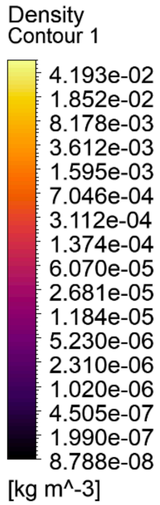
- Next step: Extraction of particles in vacuum

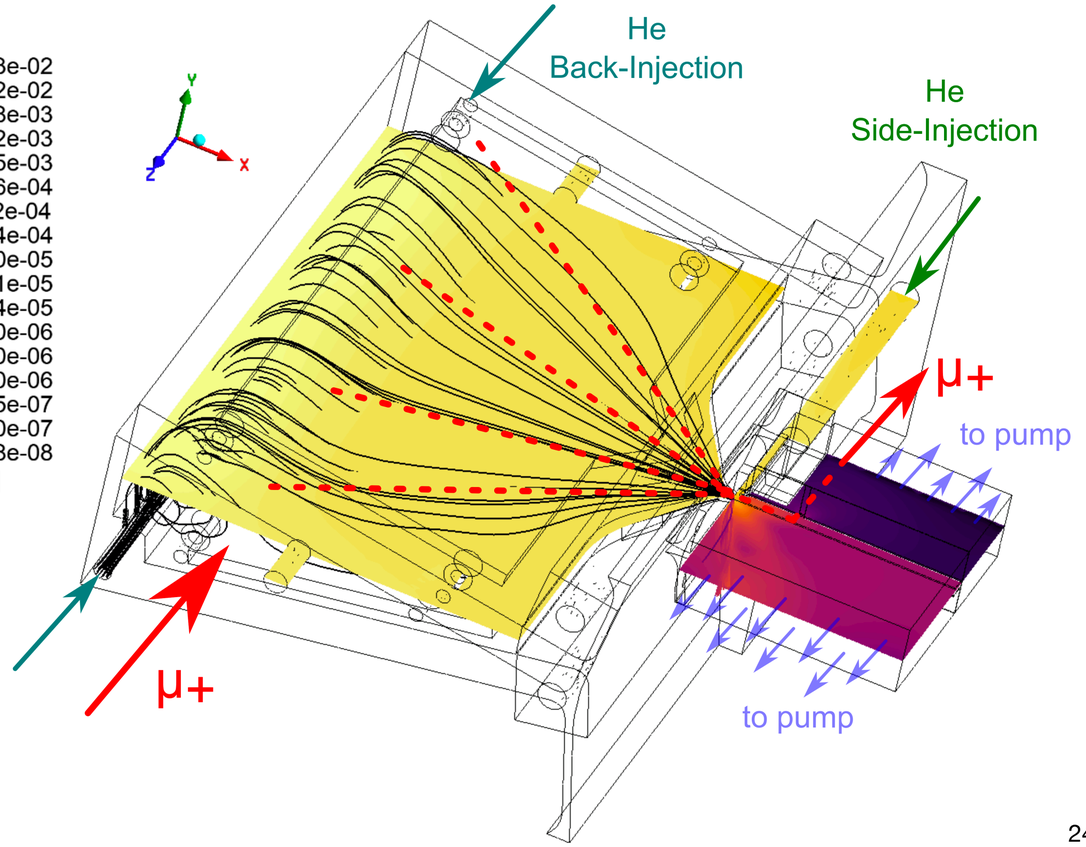


Where we want to be:

- Extraction in vacuum: Control of the gas density and flow crucial
- Final settings: Found and to be tested by the end of the year







Outlook

- A completely new concept of high-brightness muon beam is under development at PSI
  - It is based on a dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
  - It is expected to increase the input beam phase space by a factor $\mathbf{10^{10}}$ with an efficiency of O($\mathbf{10^{-4}}$)

- It could pave the way for a new generation of muon based experiments and material characterisation
  - New opportunities for future muon (particle physics) based experiments
  - New opportunities for μSR experiments
  - Synergie with Muon Collider

Thank you for your attention !!!

Muon beams worldwide summary

Laboratory	Beam Line	DC rate (μ/sec)	Pulsed rate (μ/sec)
PSI (CH) (590 MeV, 1.3 MW)	$\mu E4, \pi E5$ HiMB at EH	$2 \div 4 \times 10^8$ (μ^+) $\mathcal{O}(10^{10})$ (μ^+) (>2018)	
J-PARC (Japan) (3 GeV, 210 kW) (8 GeV, 56 kW)	MUSE D-Line MUSE U-Line COMET		$3 \times 10^7(\mu^+)$ $6.4 \times 10^7(\mu^+)$ $1 \times 10^{11}(\mu^-)$(2020)
FNAL (USA) (8 GeV, 25 kW)	Mu2e		$5 \times 10^{10}(\mu^-)$(2020)
TRIUMF (Canada) (500 MeV, 75 kW)	M13, M15, M20	$1.8 \div 2 \times 10^6(\mu^+)$	
RAL-ISIS (UK) (800 MeV, 160 kW)	EC/RIKEN-RAL		$7 \times 10^4(\mu^-)$ $6 \times 10^5(\mu^+)$
KEK (Tsukuba, Japan) (500 MeV, 25 kW)	Dai Omega		$4 \times 10^5(\mu^+)$(2020)
RCNP (Osaka, Japan) (400 MeV, 400 W)	MuSIC	$10^4(\mu^-) \div 10^5(\mu^+)$ $10^7(\mu^-) \div 10^8(\mu^+)$(>2018)	
JINR (Dubna, Russia) (660 MeV, 1.6 kW)	Phasotron	$10^5(\mu^+)$	
RISP (Korea) (600 MeV, 0.6 MW)	RAON	$2 \times 10^8(\mu^+)$(>2020)	
CSNS (China) (1.6 6eV, 4 kW)	HEPEA	$1 \times 10^8(\mu^+)$(>2020)	