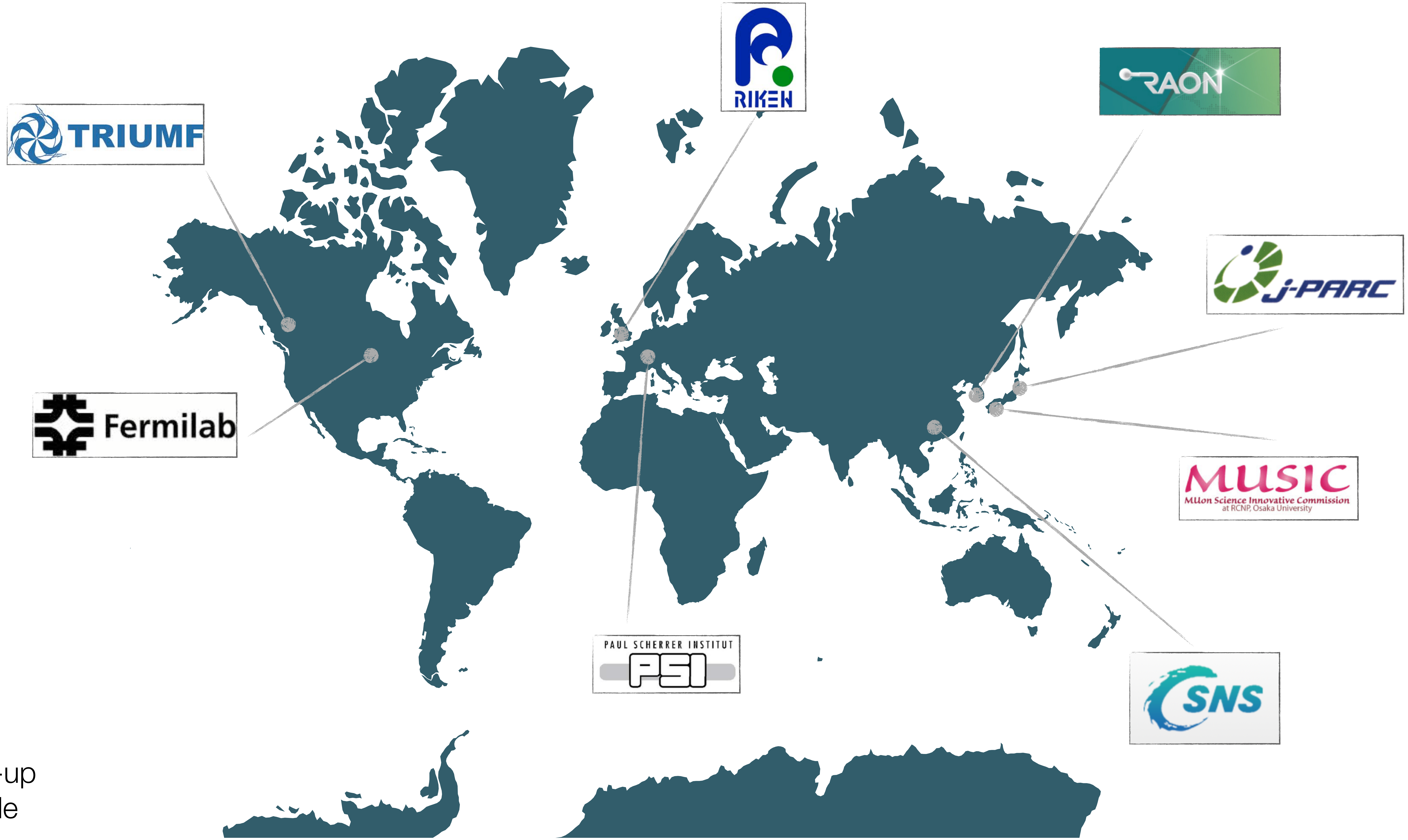
The High Intensity Muon Beam & muCool project at PSI

Angela Papa, PSI & UniPi-INFN on behalf of the HiMB & muCool collaborations
ICHEP 2024
July 17th-24th 2024, Prague - Czech Republic

Contents

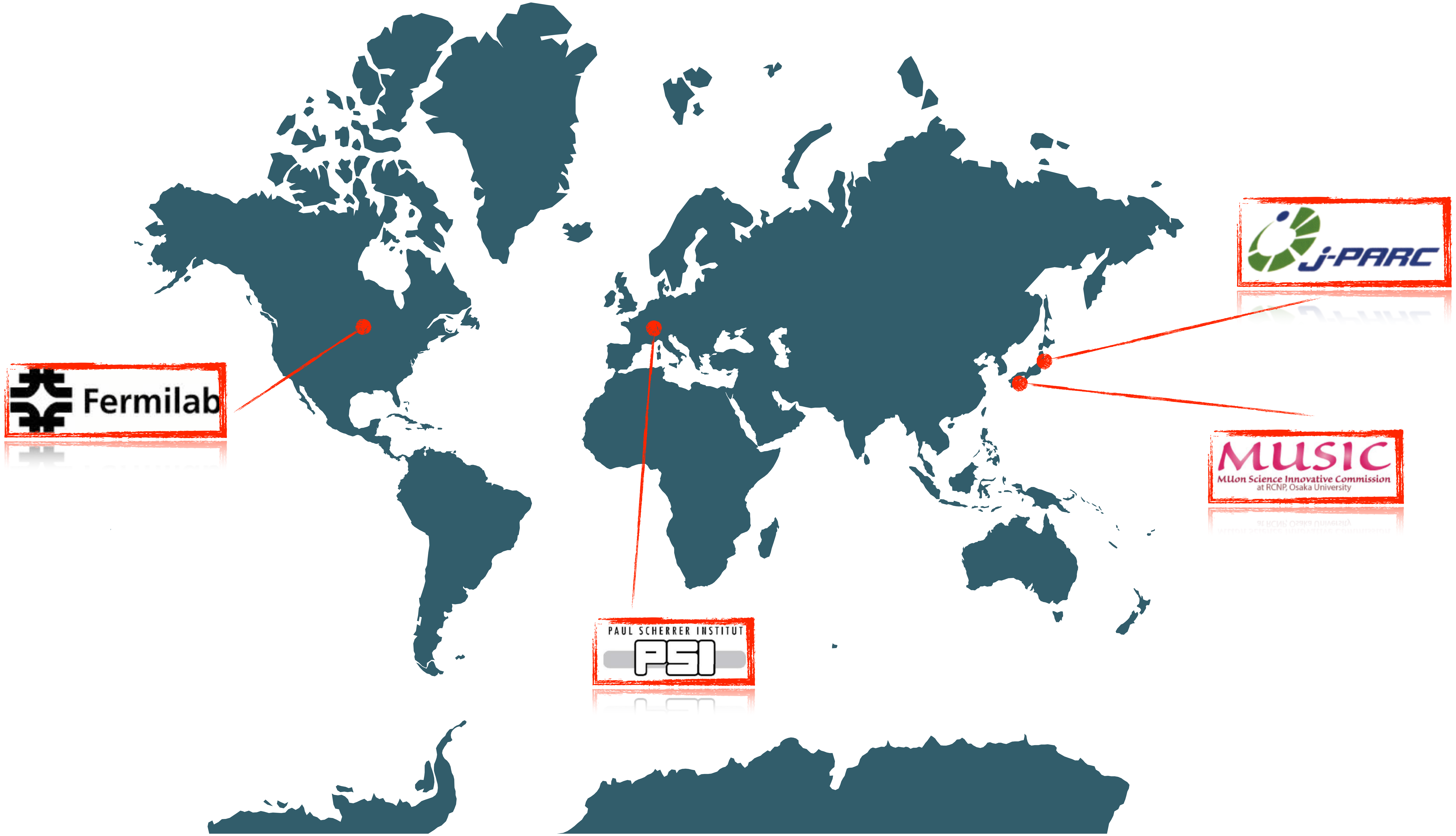
- PSI current beam lines
- PSI future beam line developments
  - **HiMB**
  - muCool

Muon beams worldwide



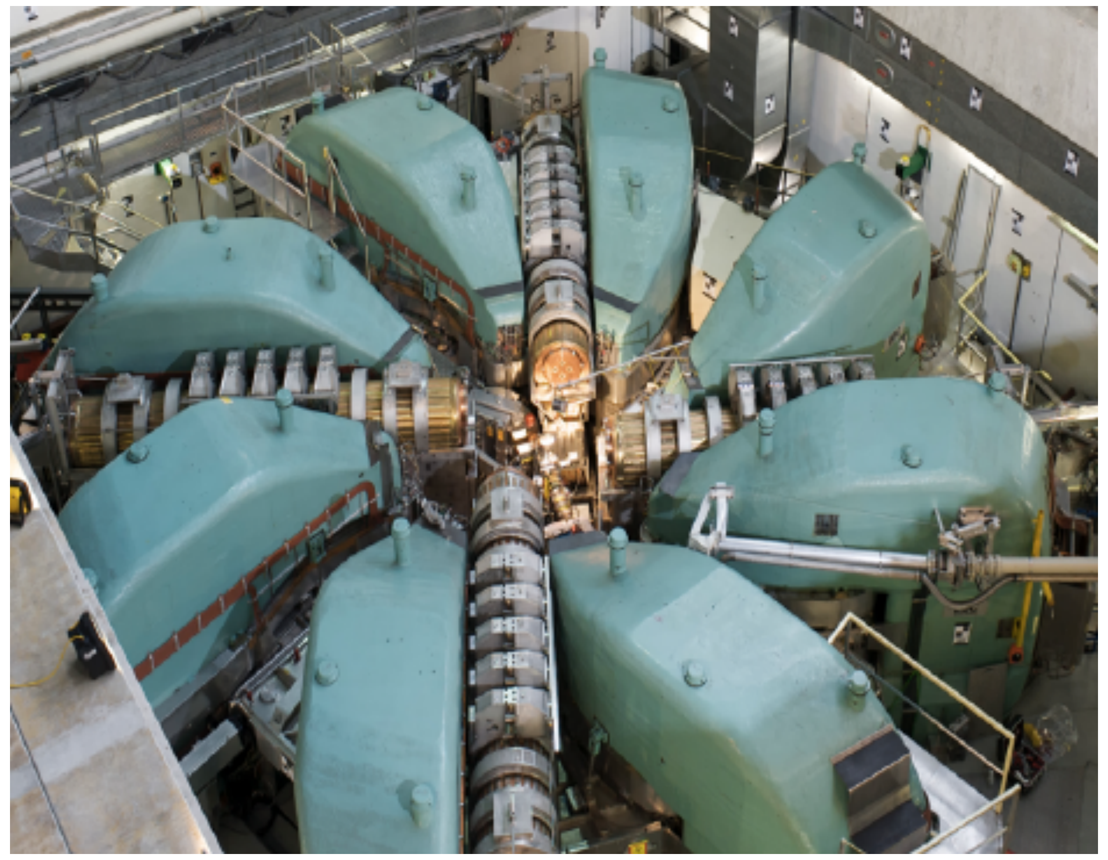
Note: See the back-up
for a summary table

Muon beams worldwide associated to “present” particle phyiscs-experiments

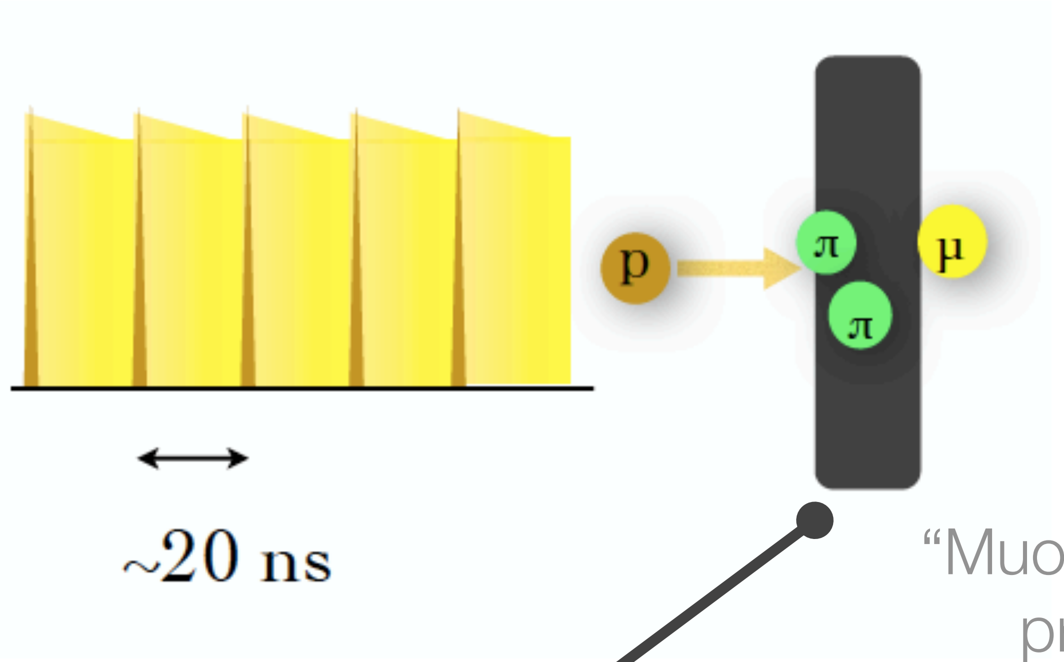


PSI's muon beams

- PSI delivers the most intense continuous (DC) low momentum (surface) muon beam in the world up to few x 10^8 mu/s (28 MeV/c, polarised beam (**Intensity Frontiers**)

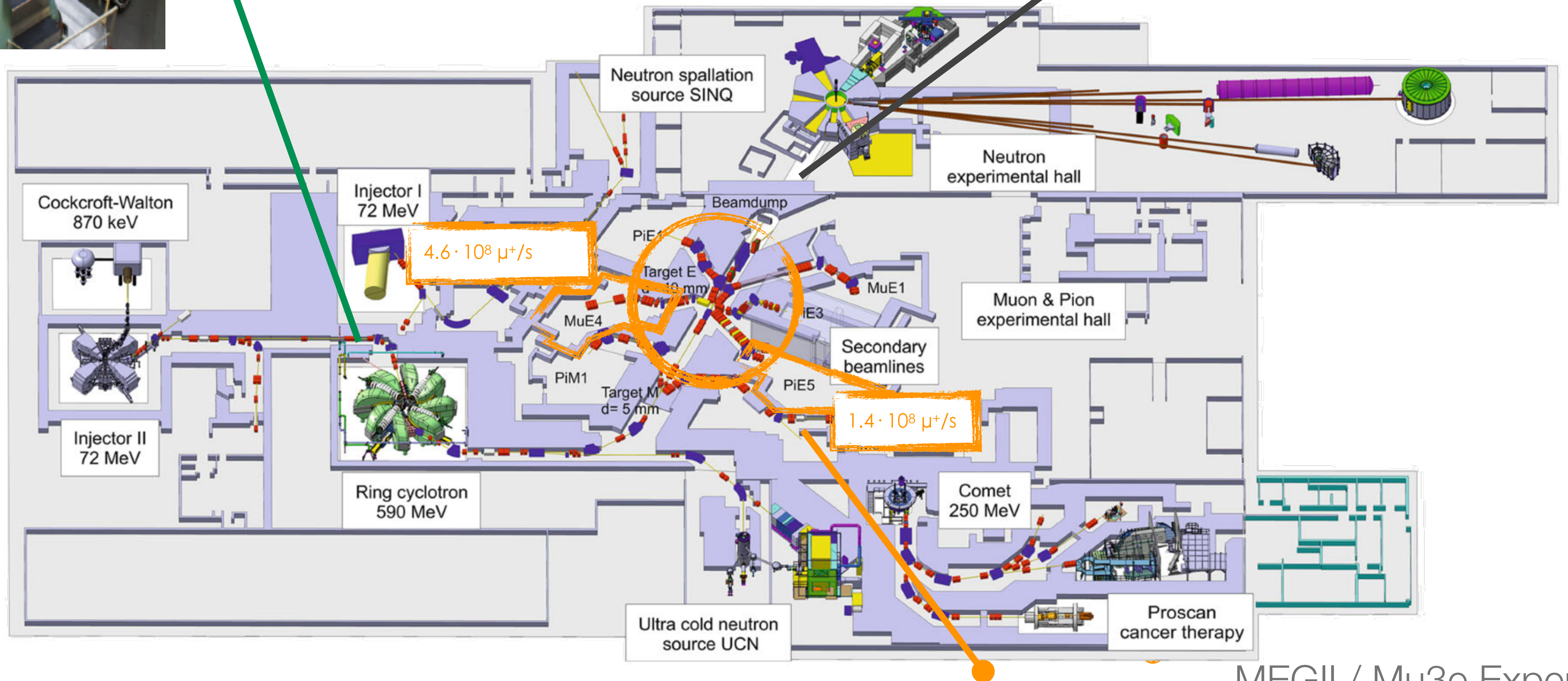


590 MeV proton ring cyclotron
1.4 MW



Proton RF ~ 50 MHz
"DC" muon beam

"Muon" Target "E" production



MEGII / Mu3e Experimental area

HiMB motivations

- Current beam intensity: Up to 5 x 10^8 μ^+/s (the highest intensity DC μ^+ beam)

- HiMB's Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Time schedule: Long Shut-Down **2027-2028**

- Next generation cLFV experiments require higher muon rates
- New opportunities for future muon (particle physics) based experiments (i.e. the new muEDM project@PSI)
- 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

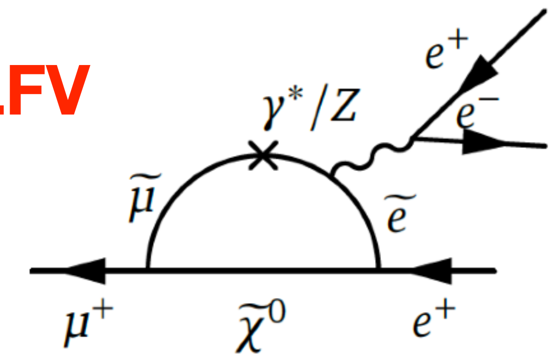
Fermilab →5x10^{10} μ^-/s

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

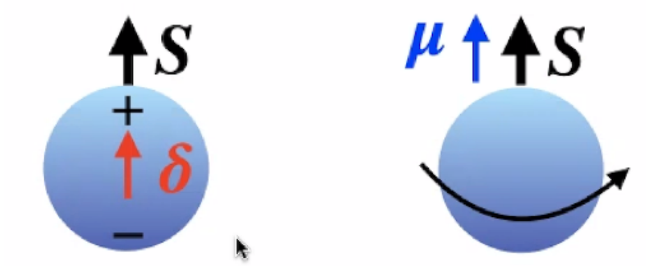
J-PARC →10^{10} μ^-/s

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

cLFV

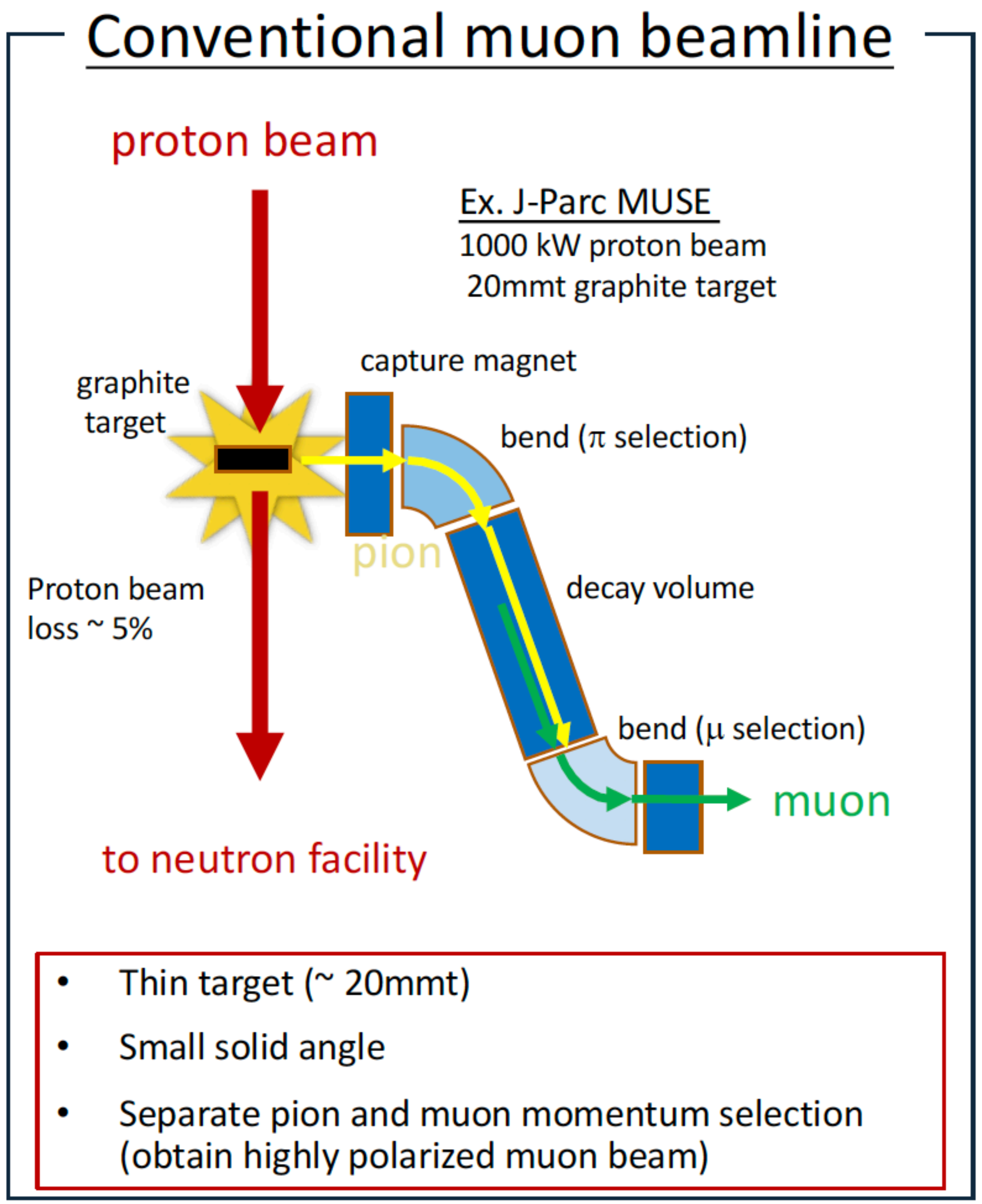


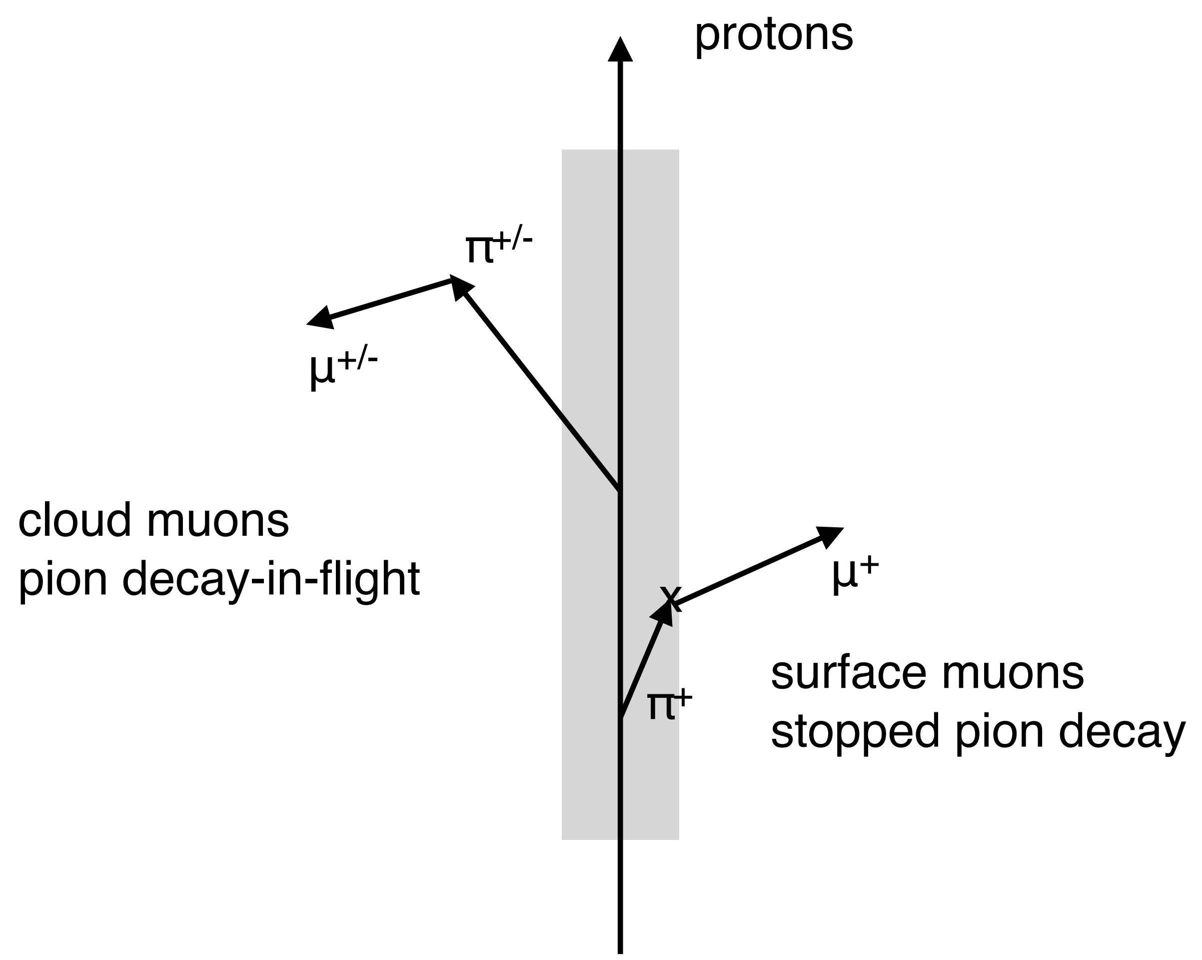
muEDM

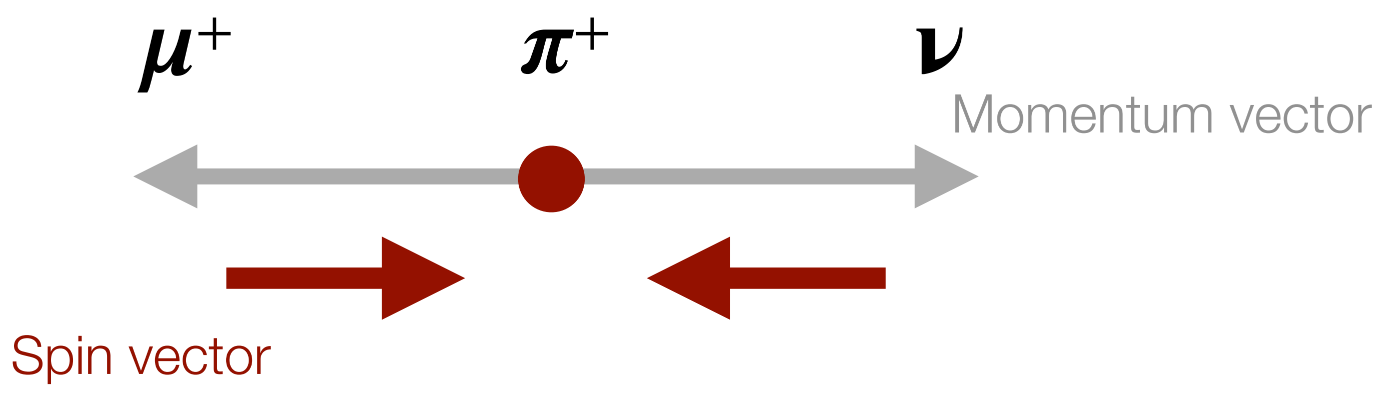


δ= electric dipole moment (EDM)
μ= magnetic dipole moment (MDM)

PSI's muon beams







- Muon beams: **secondary** beam lines
- Low-energy muon beam lines typically tuned to surface-μ^+ at ~ 28 MeV/c
- **Note:** surface-μ —> polarised positively charged muons (spin antiparallel to the momentum)
- Contribution from cloud muons at similar momentum about 100x smaller
- Negative muons only available as cloud muons

How the beam intensity can be increased…

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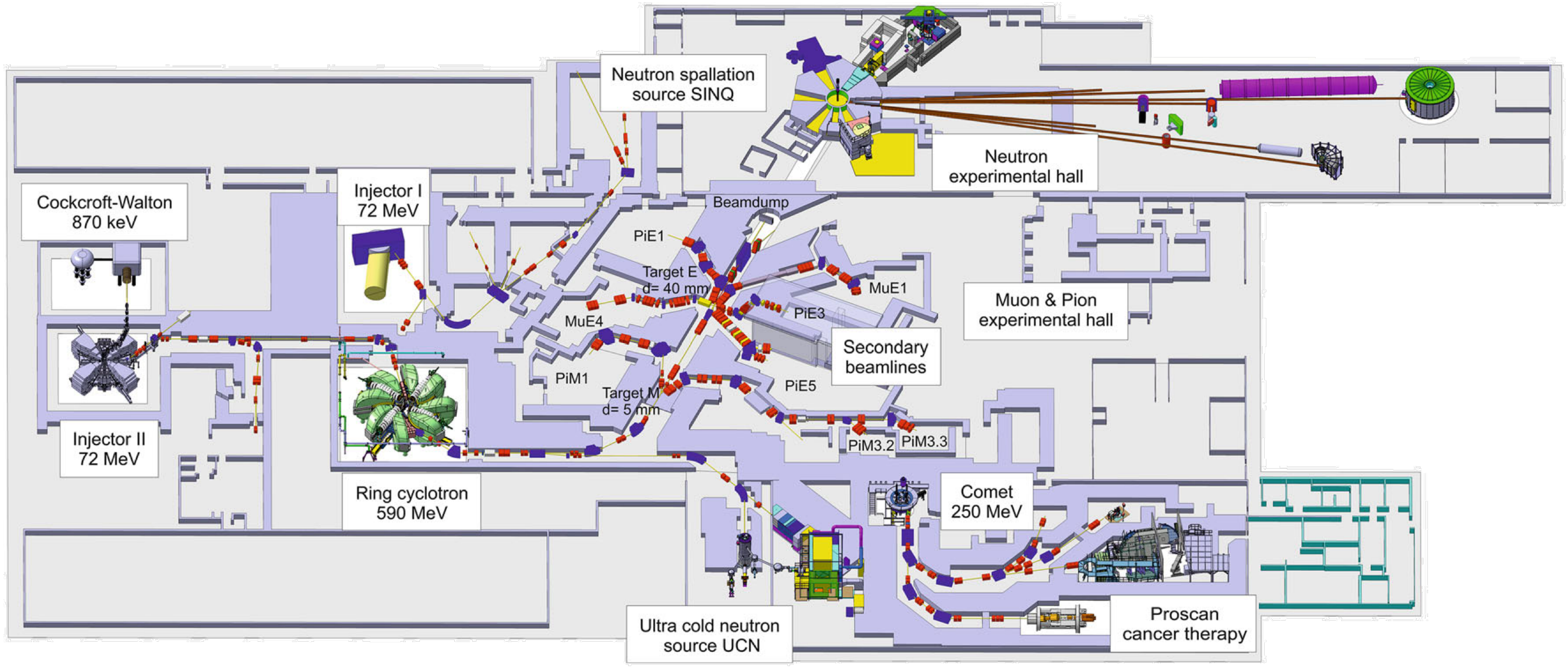
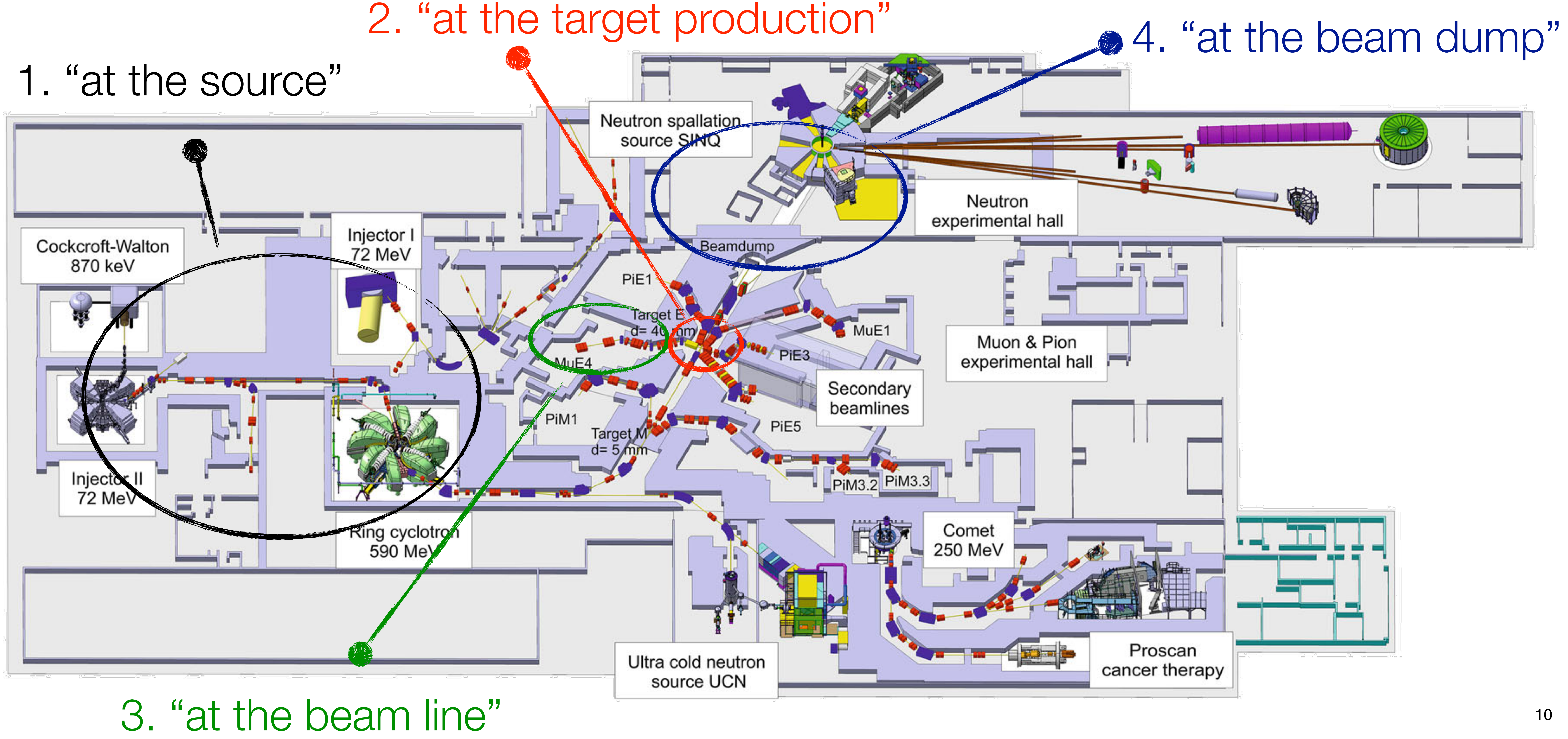


How the beam intensity can be increased…

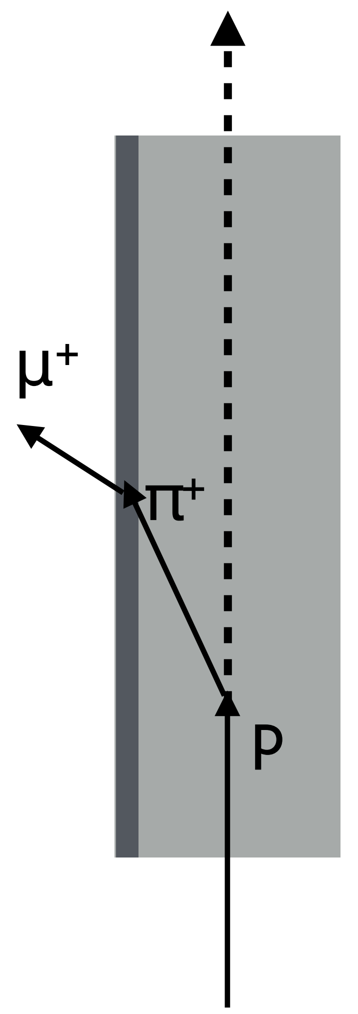


How the beam intensity can be increased…

Always looking for —> Relative “simple”, “easy”, “fast” and “cheap” solutions

At the target:

- Optimised Target: **Alternative materials** and/or different geometry
  - Search for high pion yield materials -> higher muon yield
  - Either increasing the surface volume (surface area times acceptance depth) or the pion stop density near the surface

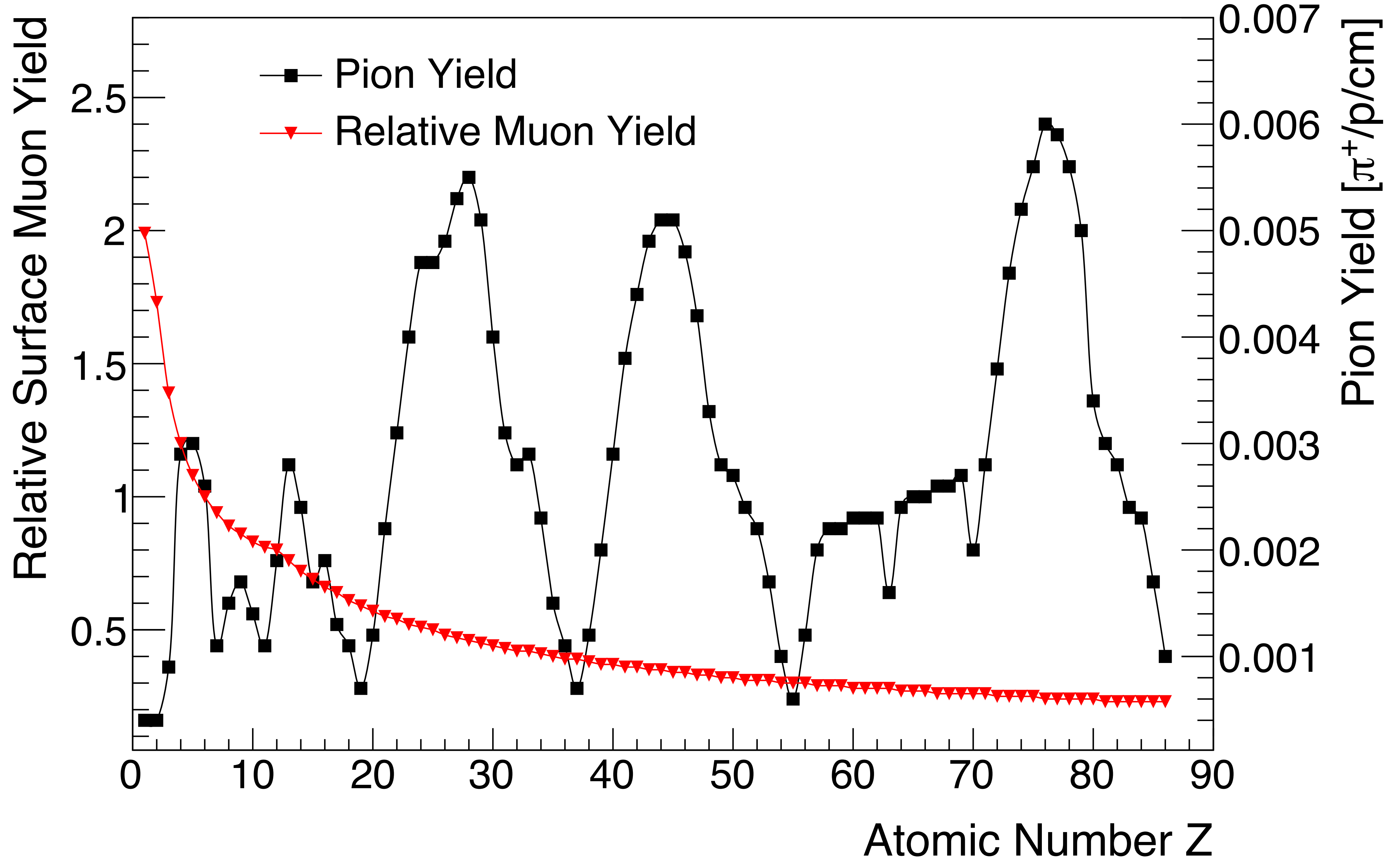


$$\text{relative } \mu^+ \text{yield} \propto \pi^+ \text{stop density} \cdot \mu^+ \text{Range} \cdot \text{length}$$

$$\propto n \cdot \sigma_{\pi^+} \cdot SP_{\pi^+} \cdot \frac{1}{SP_{\mu^+}} \cdot \frac{\rho_C (6/12)_C}{\rho_x (Z/A)_x}$$

$$\propto Z^{1/3} \cdot Z \cdot \frac{1}{Z} \cdot \frac{1}{Z}$$

$$\propto \frac{1}{Z^{2/3}}$$



At the target:

- Optimised Target: Alternative materials and/or **different geometry**
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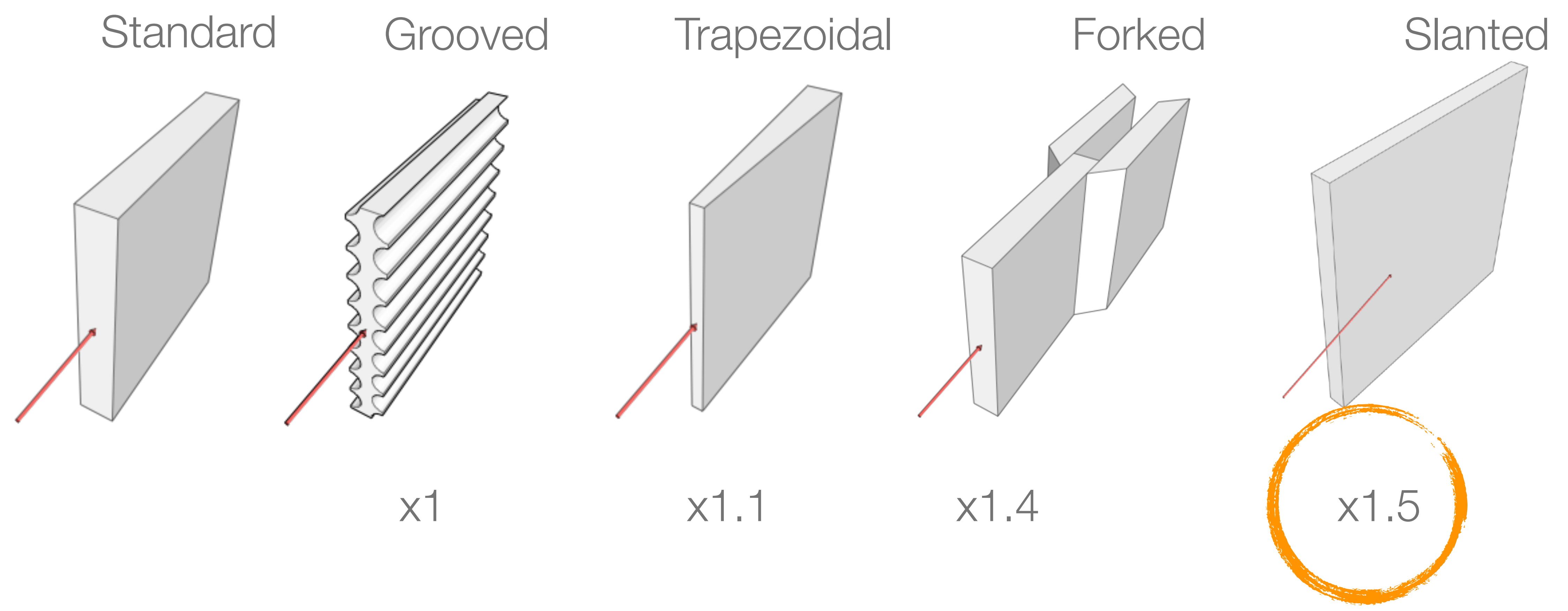
  - Either increasing the surface volume (surface area times acceptance depth) or the pion stop density near the surface

Note: Each geometry was required to preserve, as best as possible, the proton beam characteristics down-stream of the target station (spallation neutron source requirement)

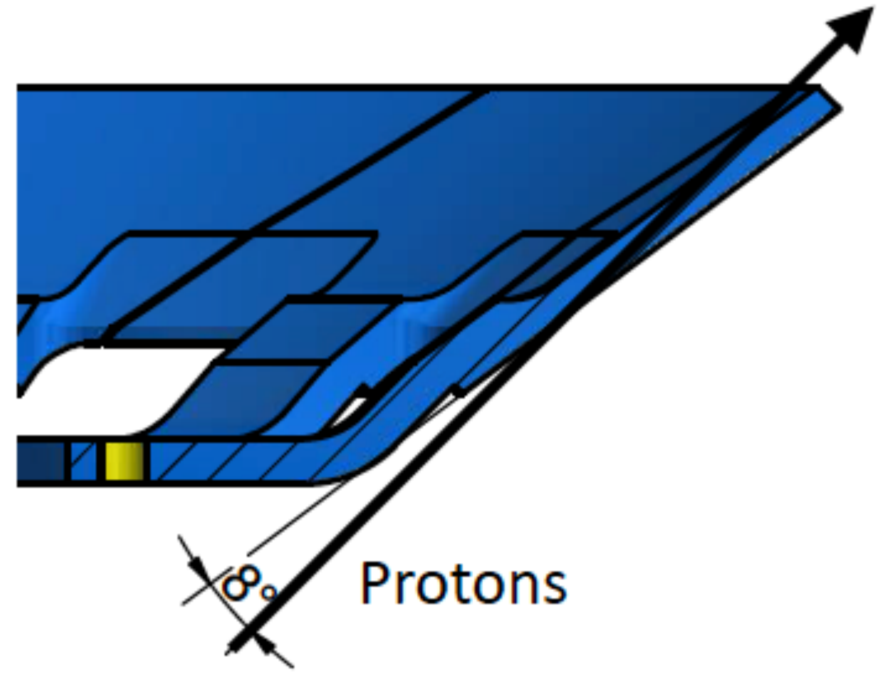
- Several materials have pion yields > 2x Carbon
- Relative muon yield favours low-Z materials, but difficult to construct as a target
- B_4C and Be_2C show 10-15% gain



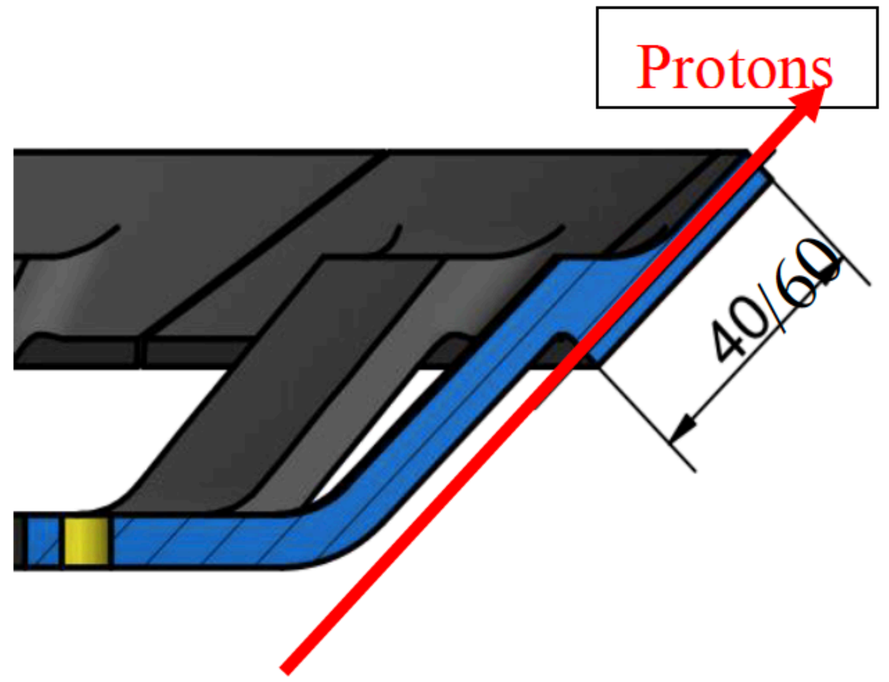
Slanted target: First test at the end of 2019

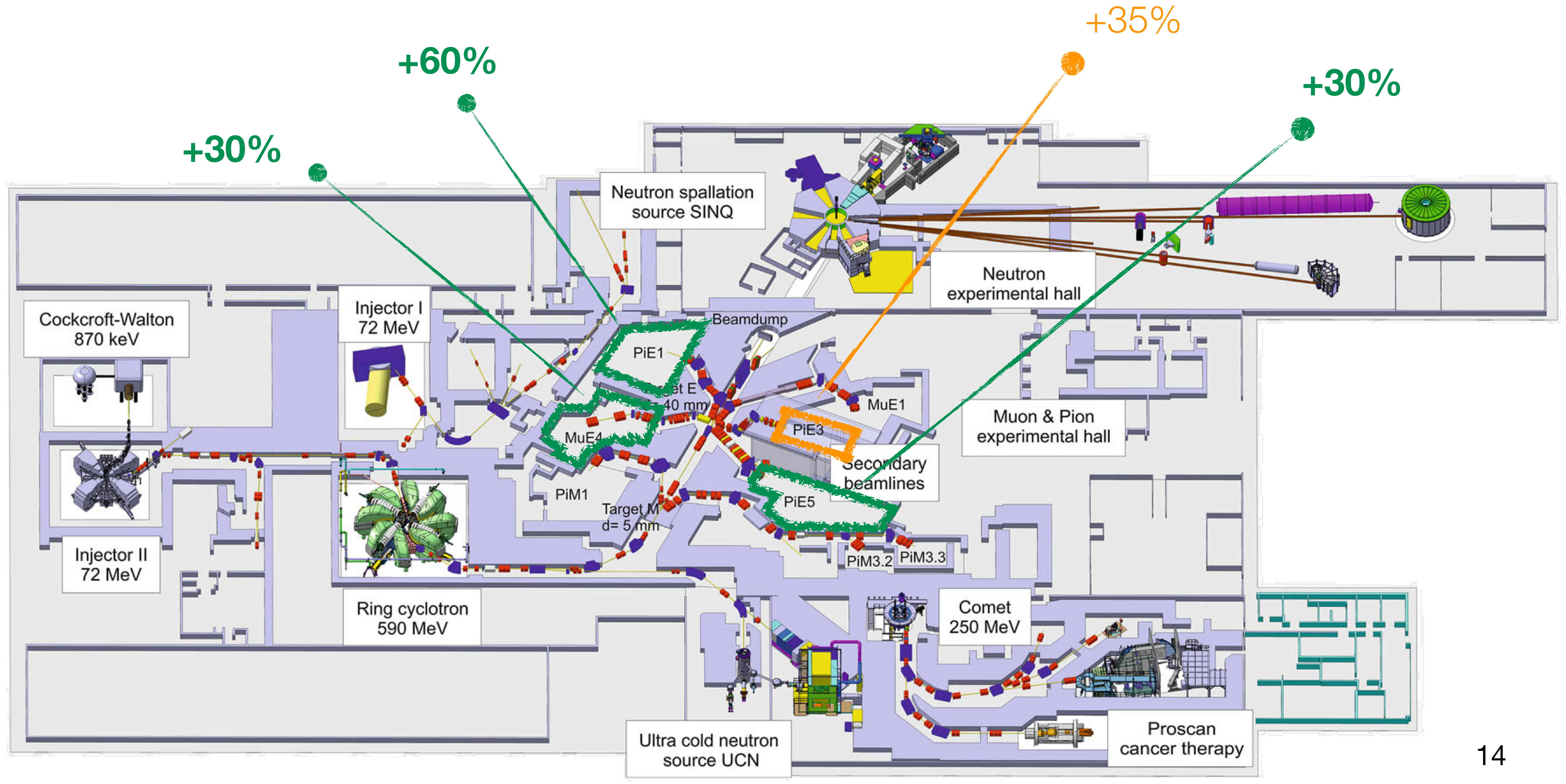
- Expect 30-60 % enhancement
- Measurements performed in three directions (forward / backward / sideways direction)
- **Increased muon yield CONFIRMED**
- **Target E as slanted target configuration since second part of 2020**
- **T**arget optimisation only, corresponding to **50%,** would corresponds to effectively raising the proton beam power at PSI by **650 kW**, equivalent to a beam power of almost **2 MW**

New Target Graphite



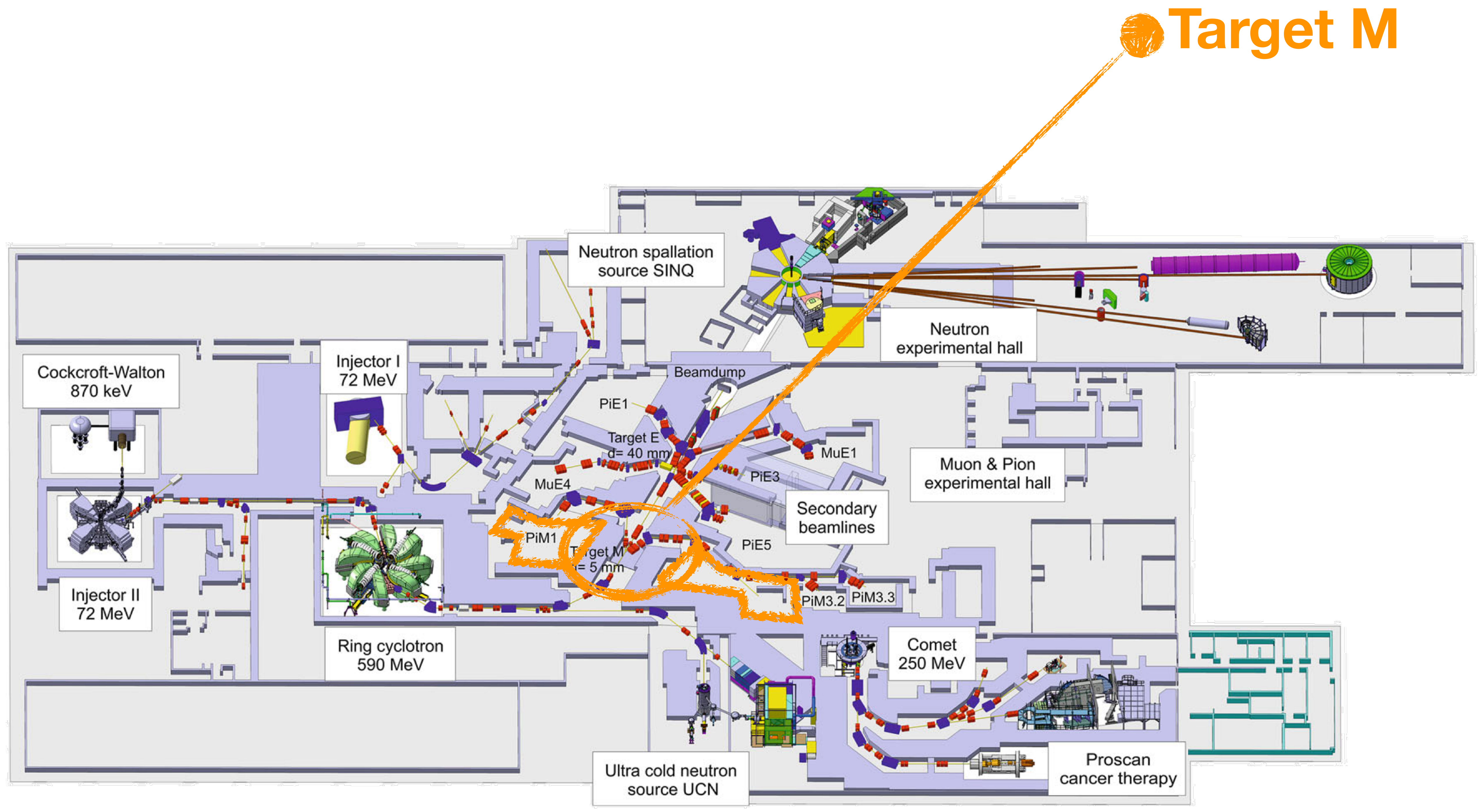
Old Target Graphite

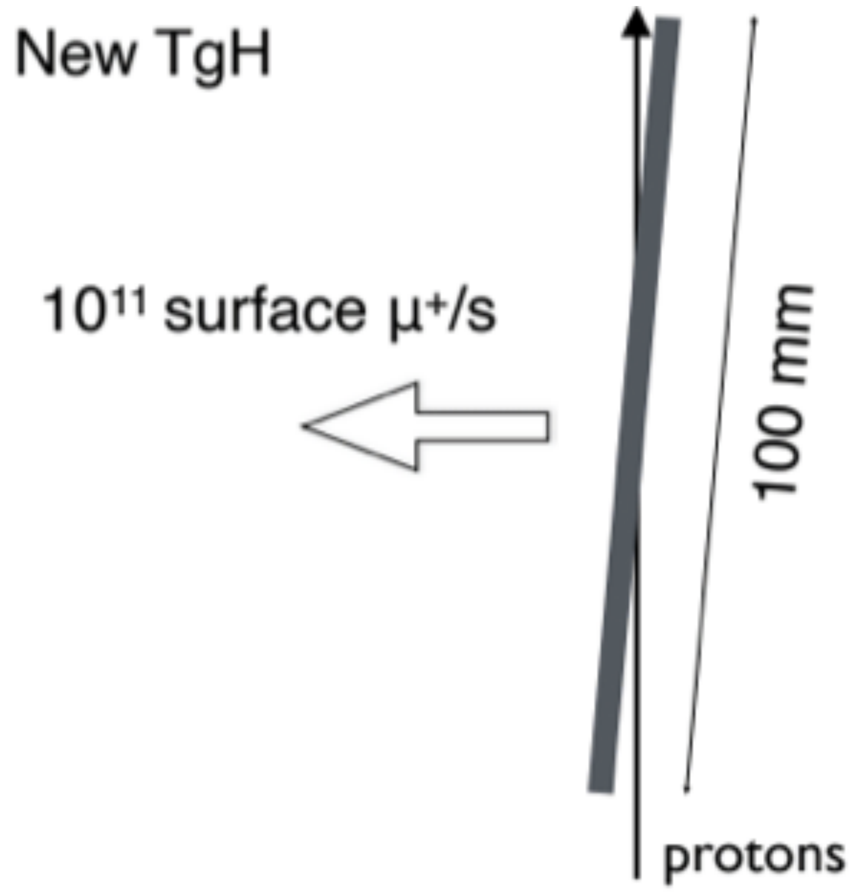




The HiMB target: TgH

- **Final position for the HiMB target: “Present" Target M location**
- ~90° extraction to existing experimental areas
- Large phase space acceptance solenoidal channel

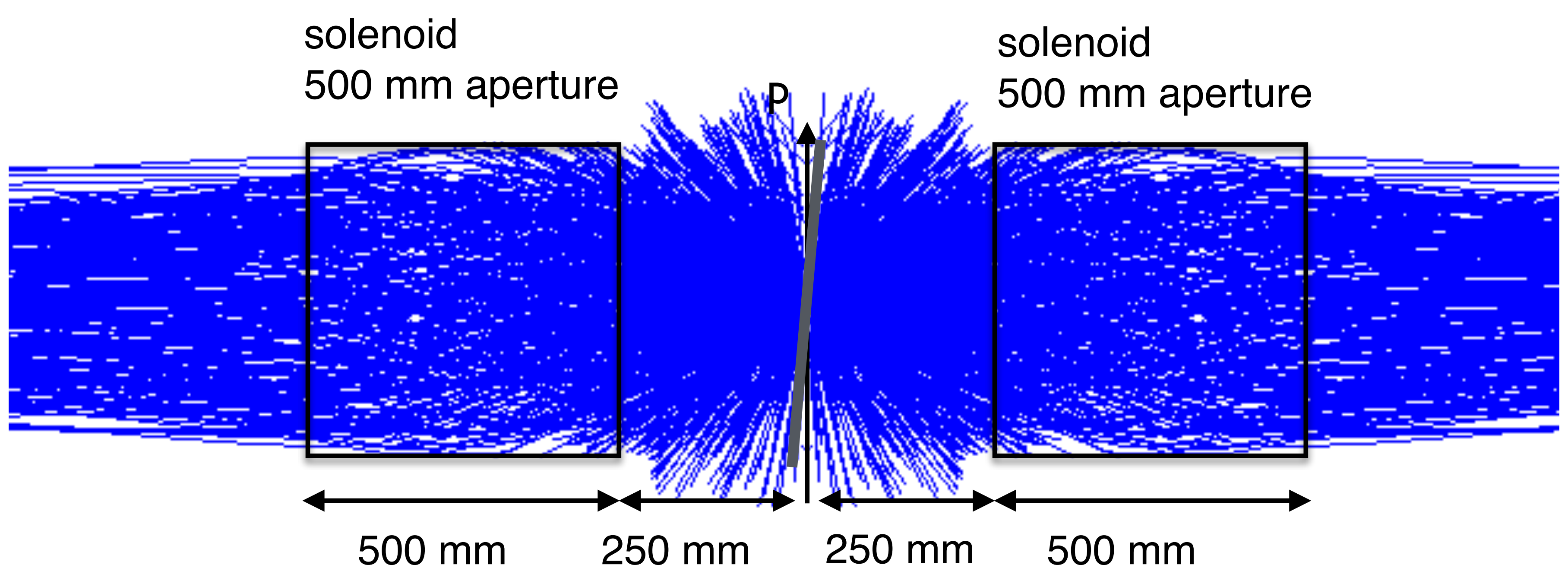




20 mm effective length
10˚ rotated slab

Along the beam line

- Optimised beam line: **increased capture** and transmission
  - Two normal-conducting, radiation-hard solenoids close to target to capture surface muons
    - Field at target ~0.1 T
    - Magnetic field up to 0.45 T
    - Graded field solenoid to improve the muon collection: Stronger at capture side



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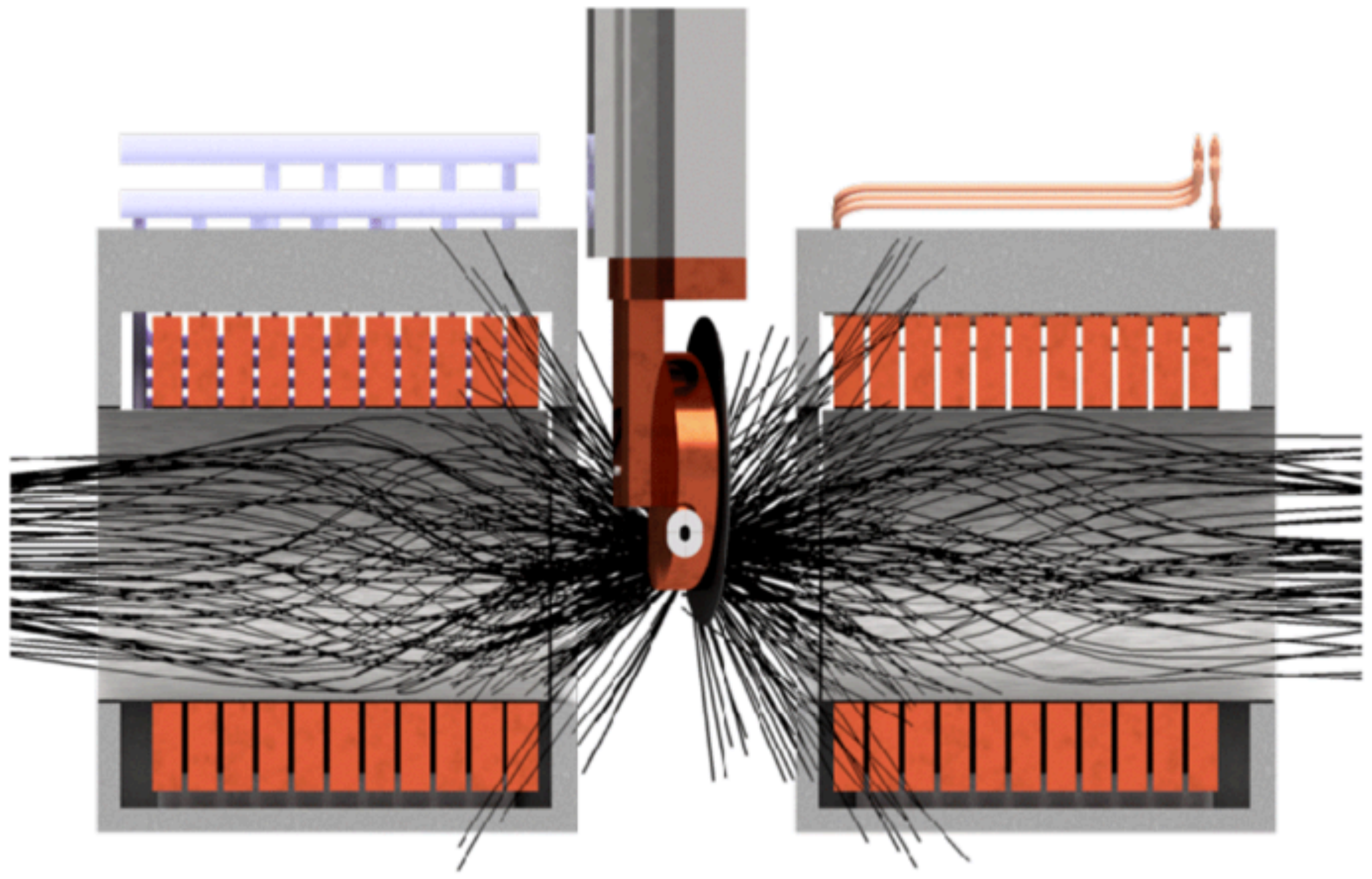
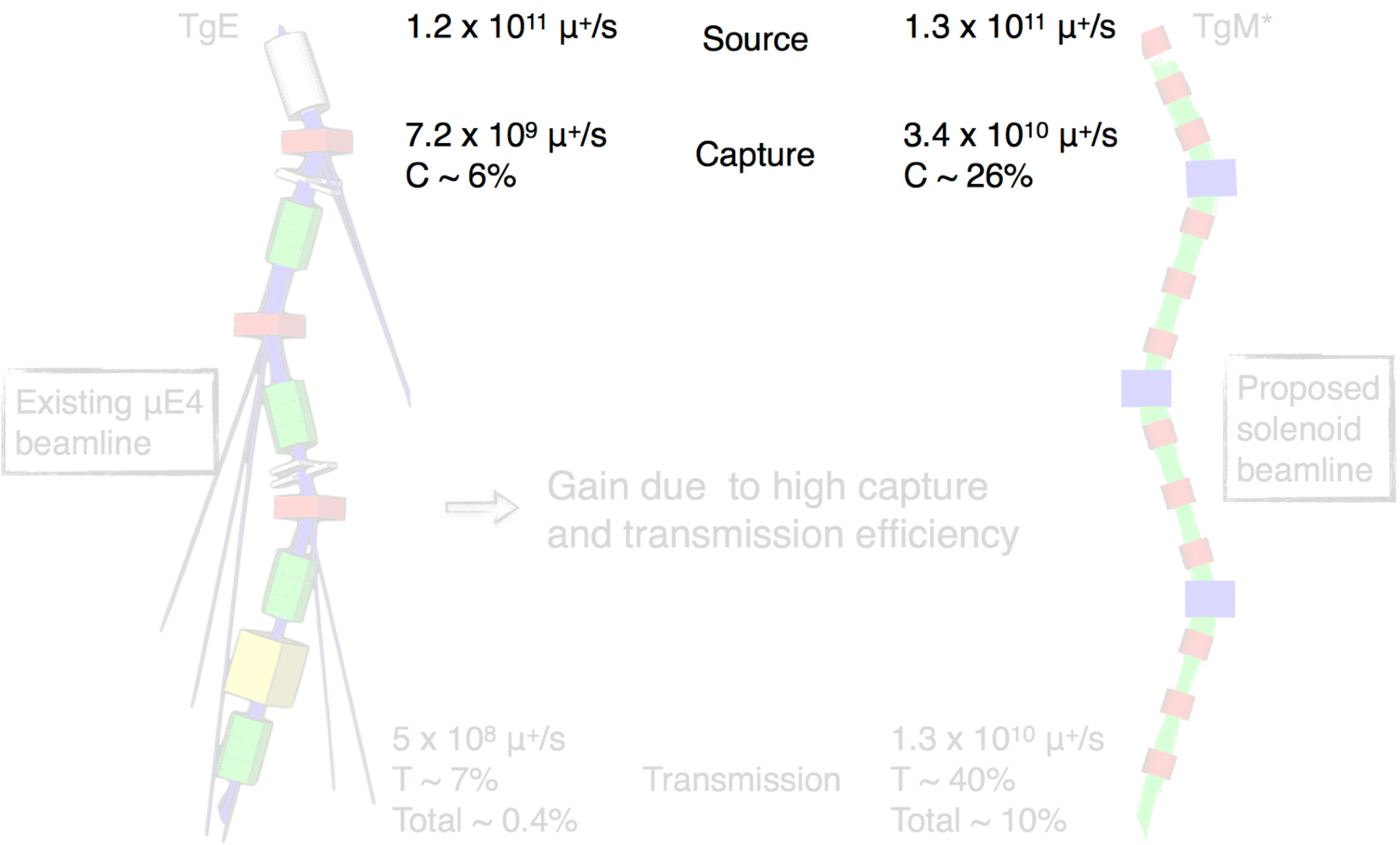
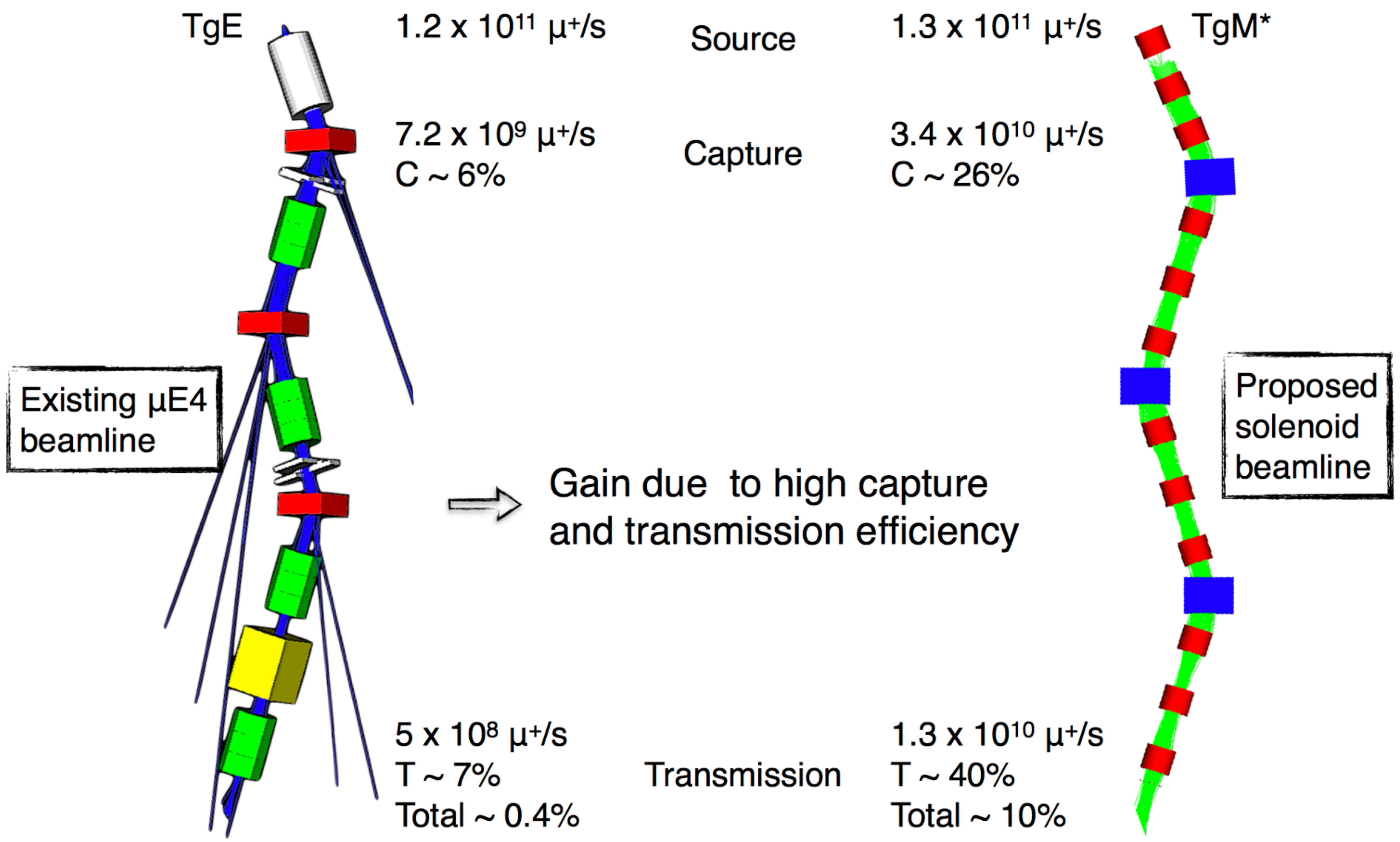


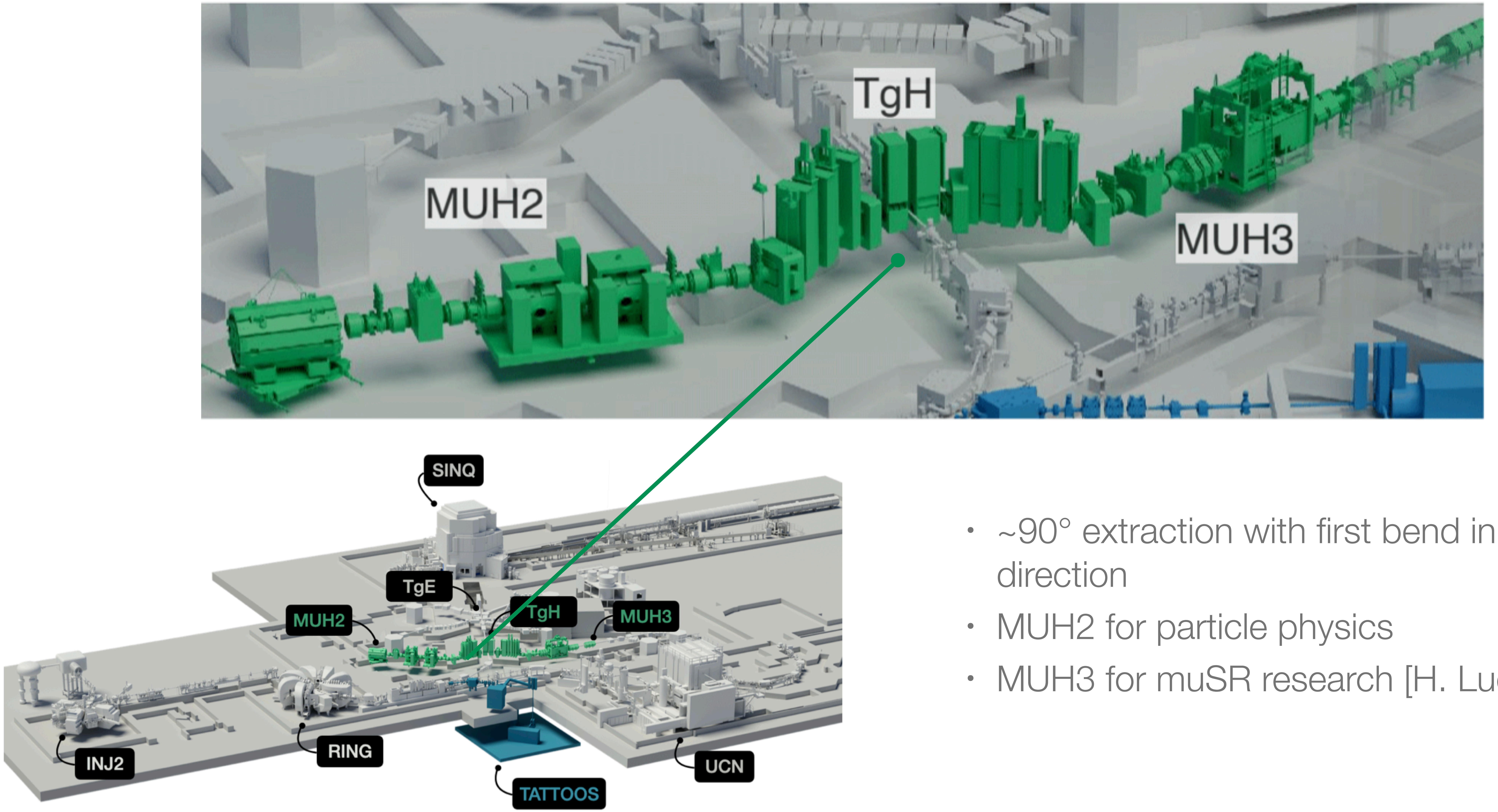


Along the beam line

- Optimised beam line: increased capture and **transmission**
  - A quasi “pure” solenoidal beam line to increase the transmission



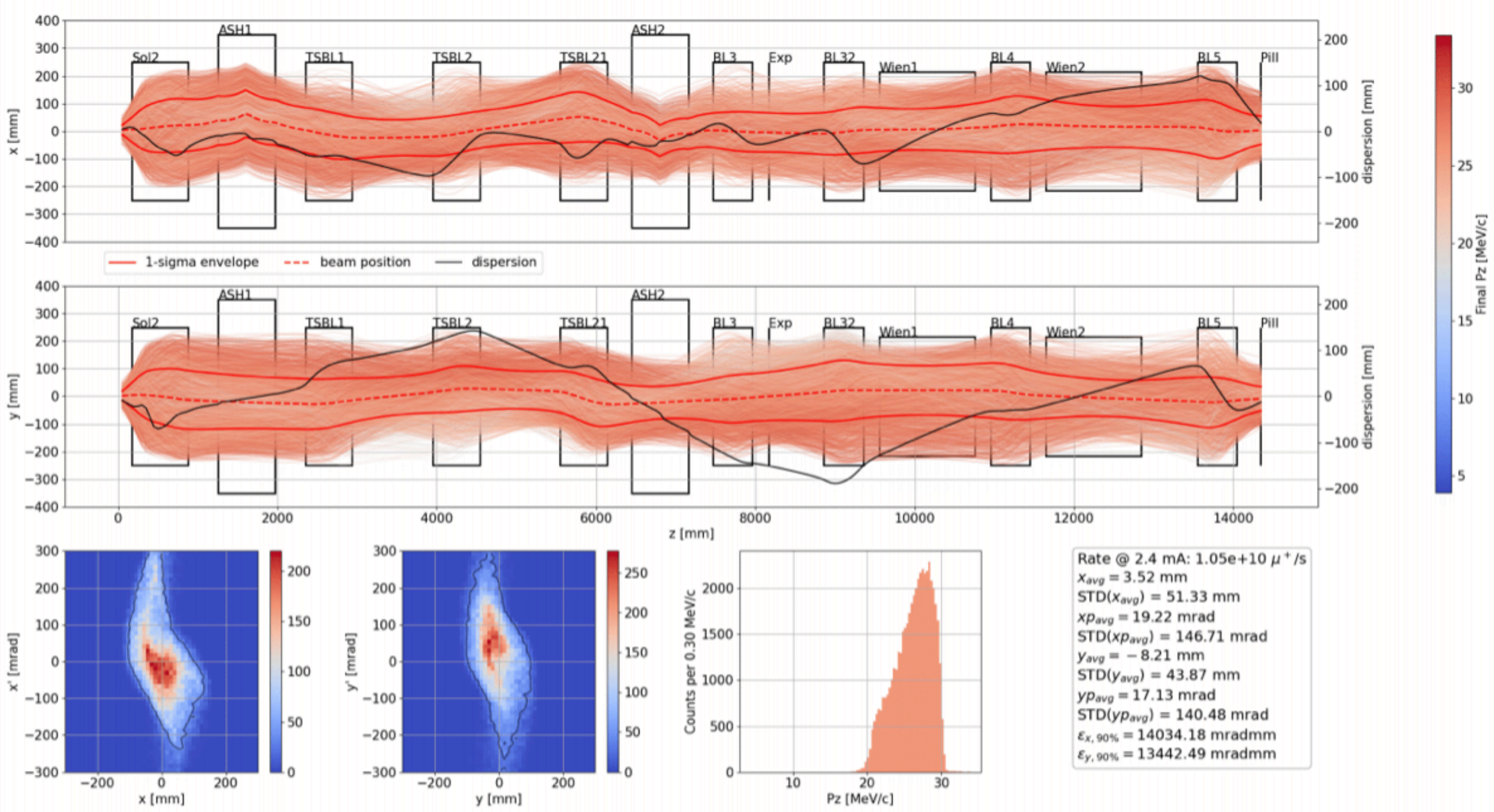
MUH2 and MUH3 beamlines

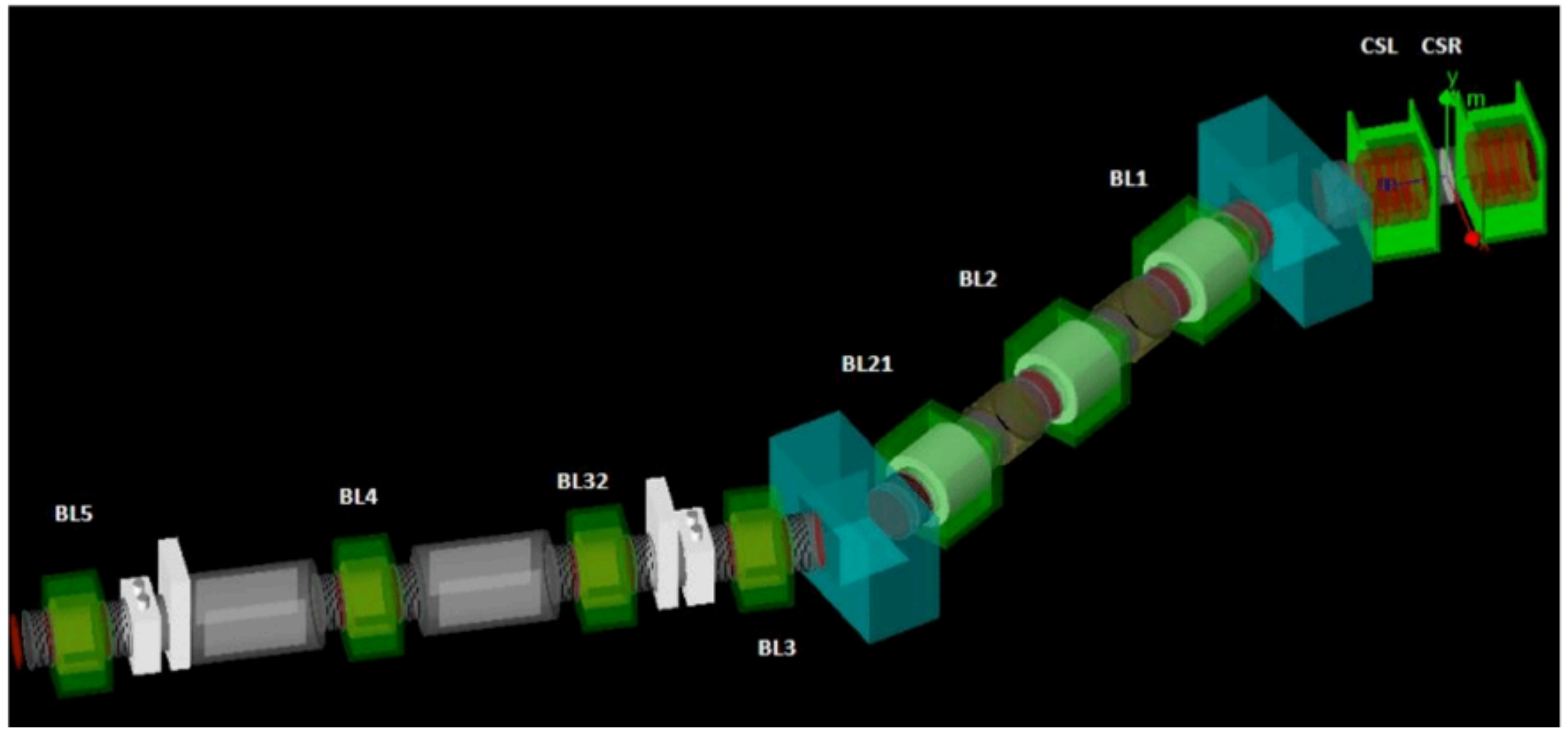


- ~90° extraction with first bend in upstream direction
- MUH2 for particle physics
- MUH3 for muSR research [H. Luetkens's talk]

Example: Expected performance of MUH2

- Transmitted rates to the end of the beamline at 2.4 mA proton current
  - ~1.0 x10^{10} μ^+/s at 28 MeV/c
  - Beam spot final focus: $\sigma_x = \sigma_y \sim 40$ mm
  - Positron contamination at highest muon rate 20-30% (can be further reduced at a cost of a small loss in muon rate)
- Robust results using different optimisation strategies





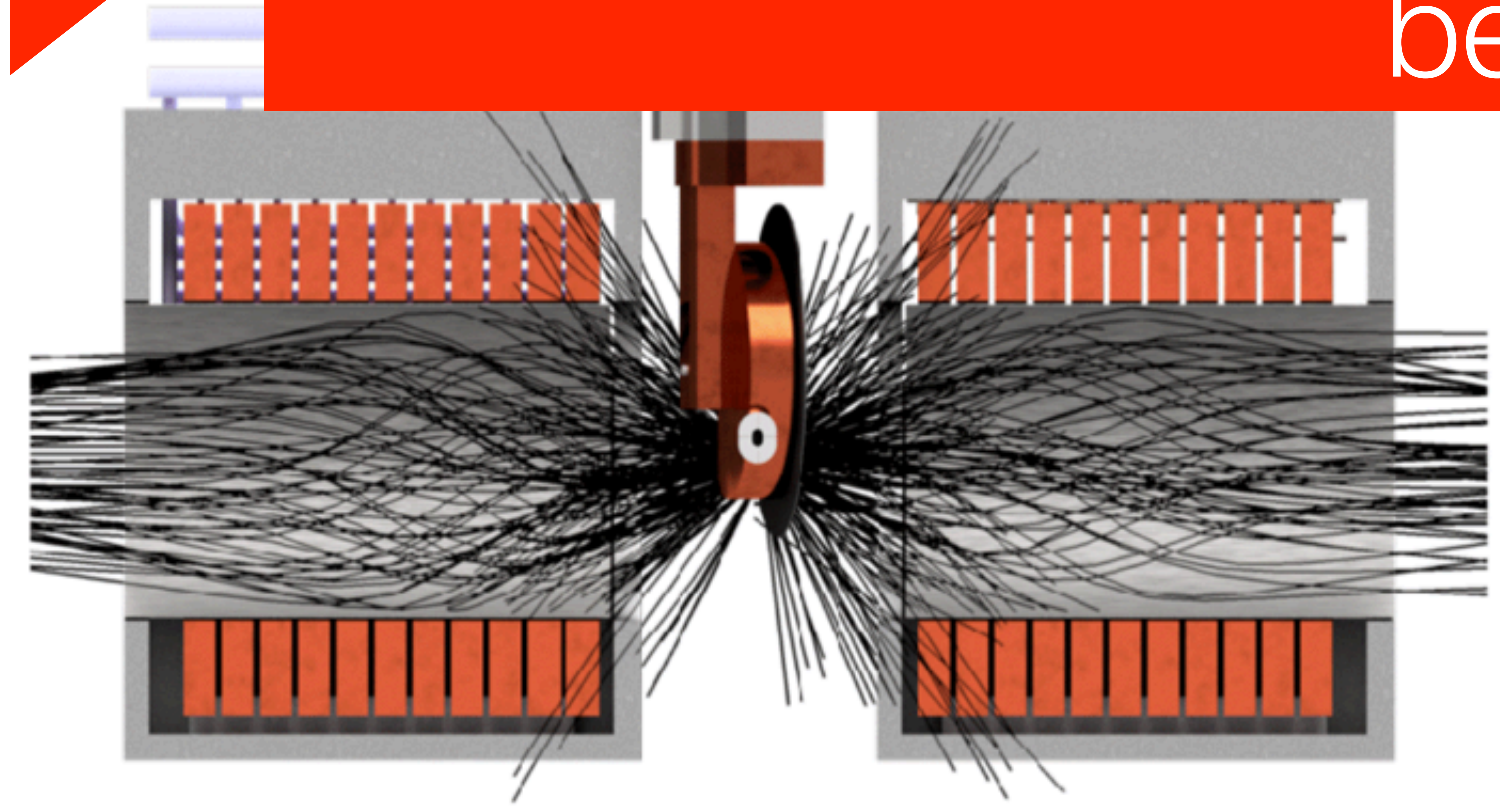
At the target + along the beam line

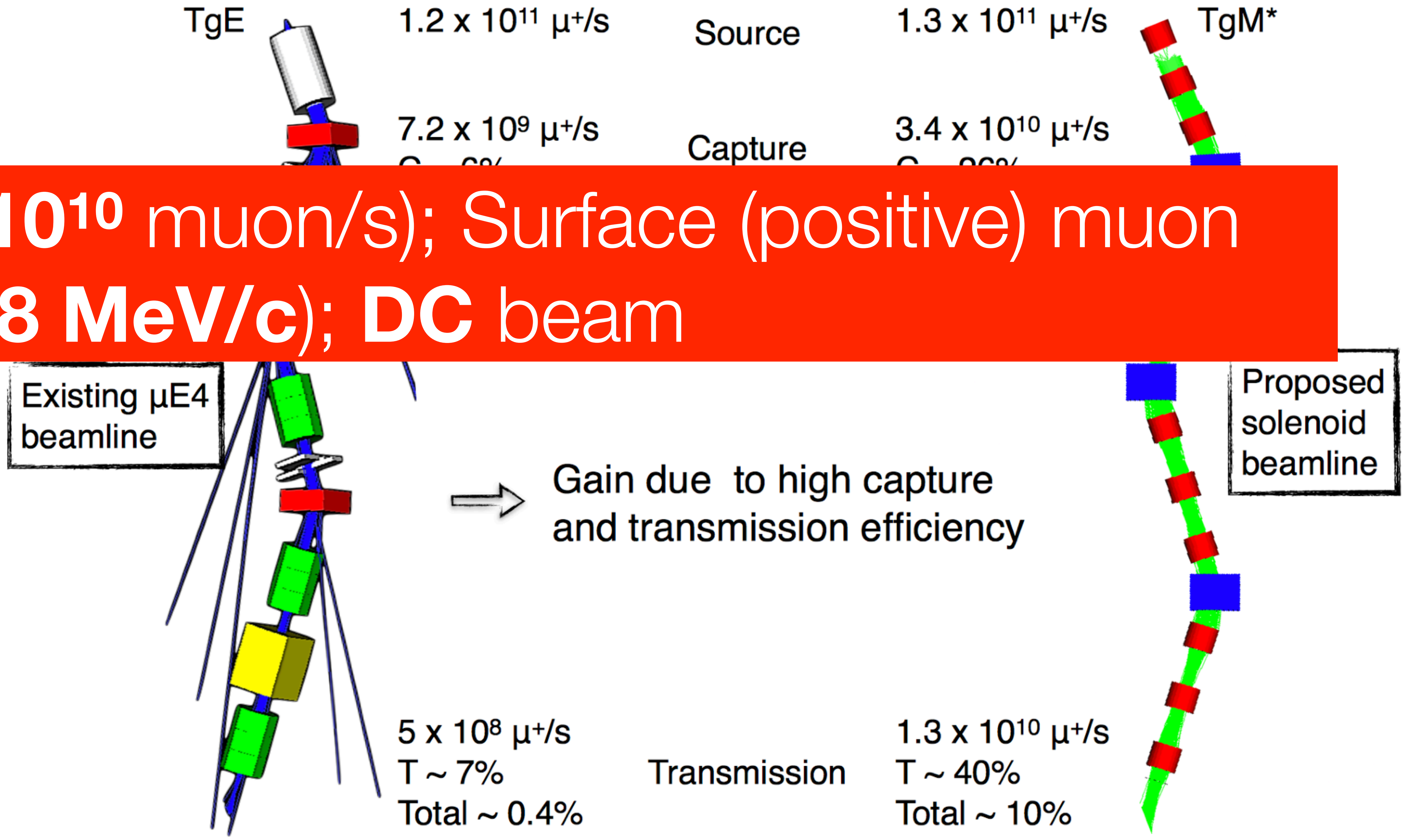
- Optimised beam line: increased capture and transmission

- Two normal-conducting, radiation-hard solenoids close to target to capture surface muons
  - Central field of solenoids ~0.35 T
  - Field at target ~0.1 T

- A quasi “pure” solenoidal beam line to increase the transmission

HIMB project at PSI. Aim: O($\mathbf{10^{10}}$ muon/s); Surface (positive) muon beam (p = 28 MeV/c); DC beam

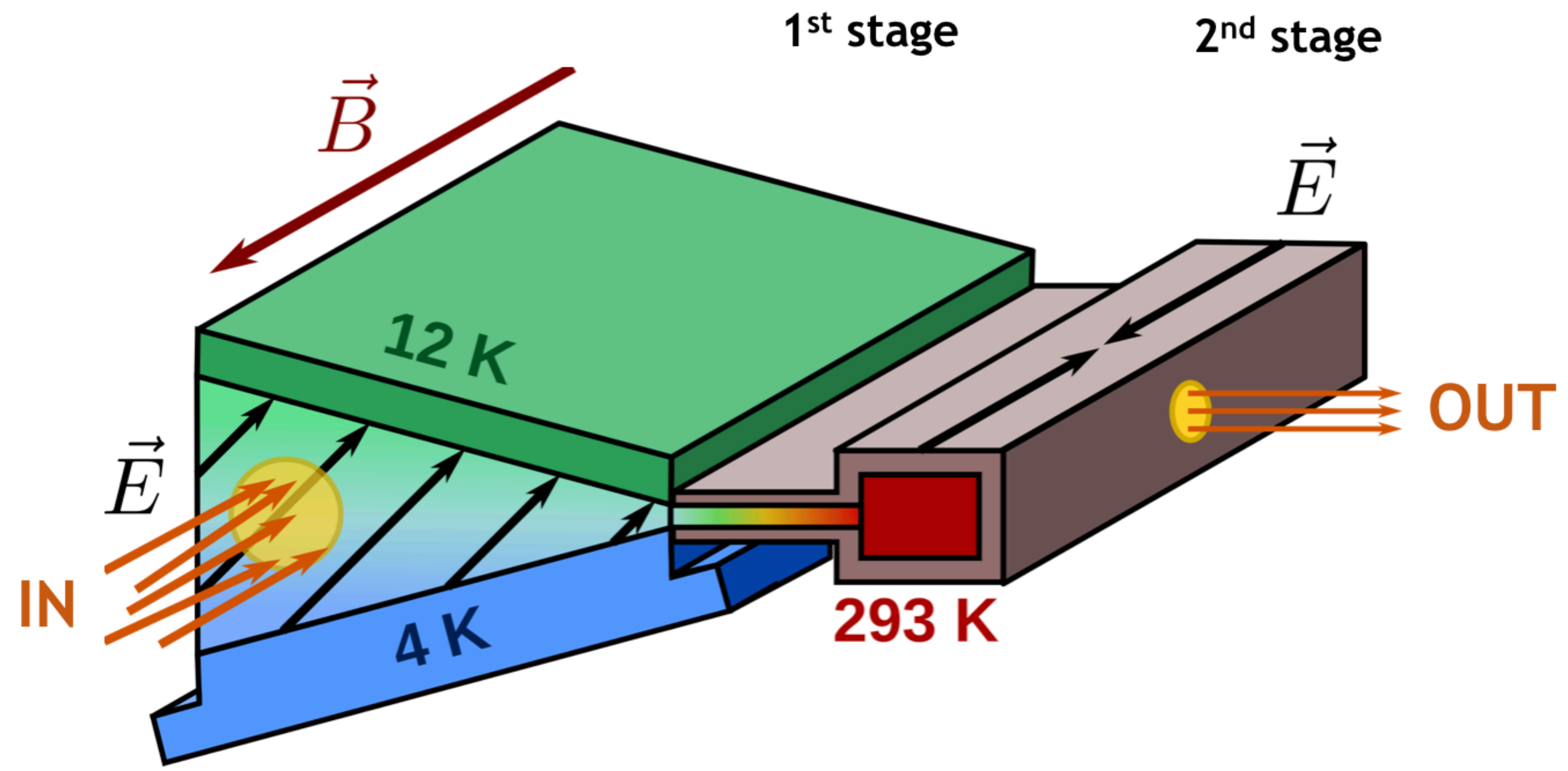




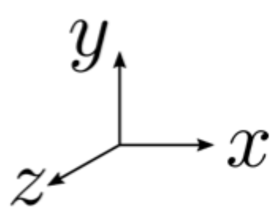
The muCool project at PSI

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

Standard/secondary μ^+ beam
- $\boldsymbol{\sigma}$ = 10 mm
- E = 4 MeV
- Continuous



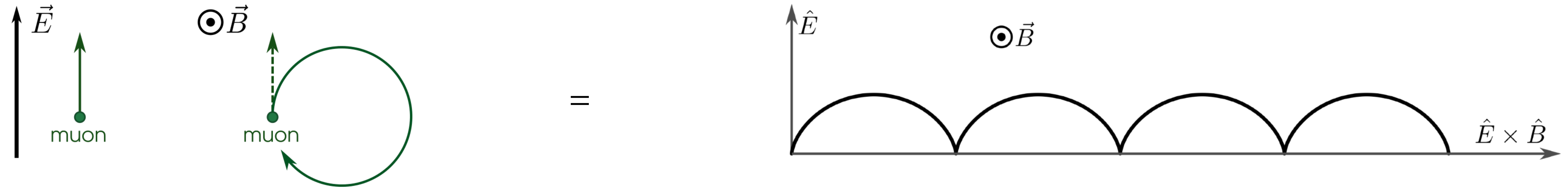
muCool/tertiary μ^+ beam
- $\boldsymbol{\sigma}$ < 1mm
- E < eV
- Tagged

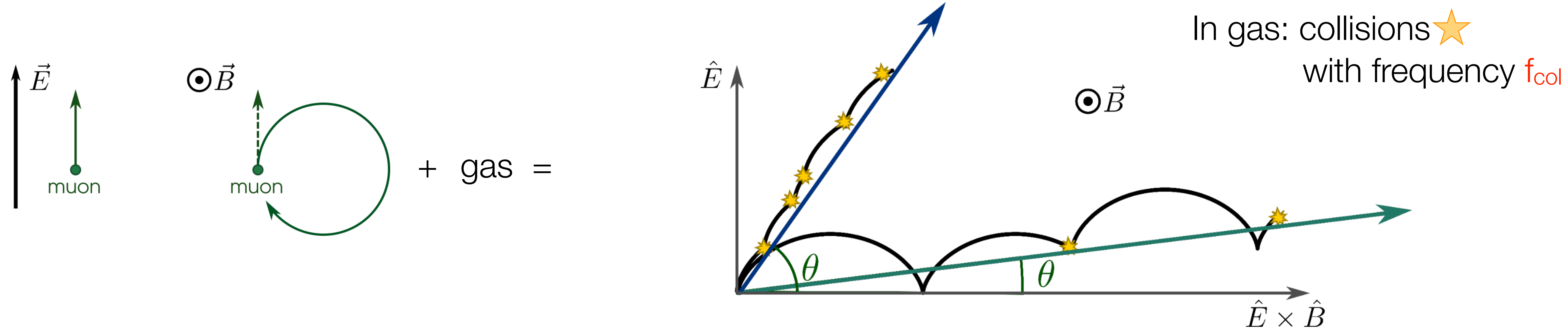


→ Transforms a standard $\boldsymbol{\mu}^+$ beam into a high-brightness low-energy $\boldsymbol{\mu}^+$ beam

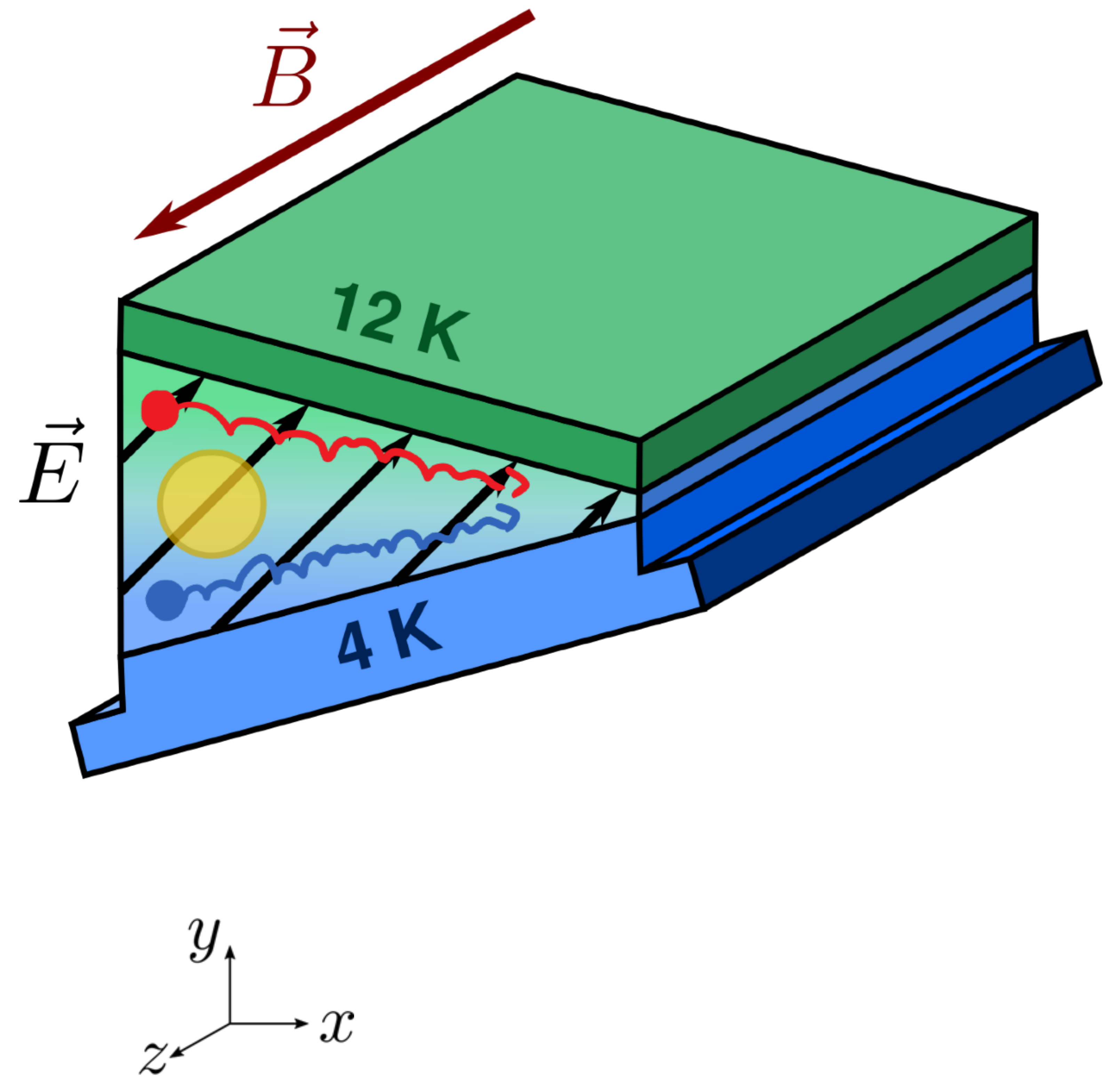
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

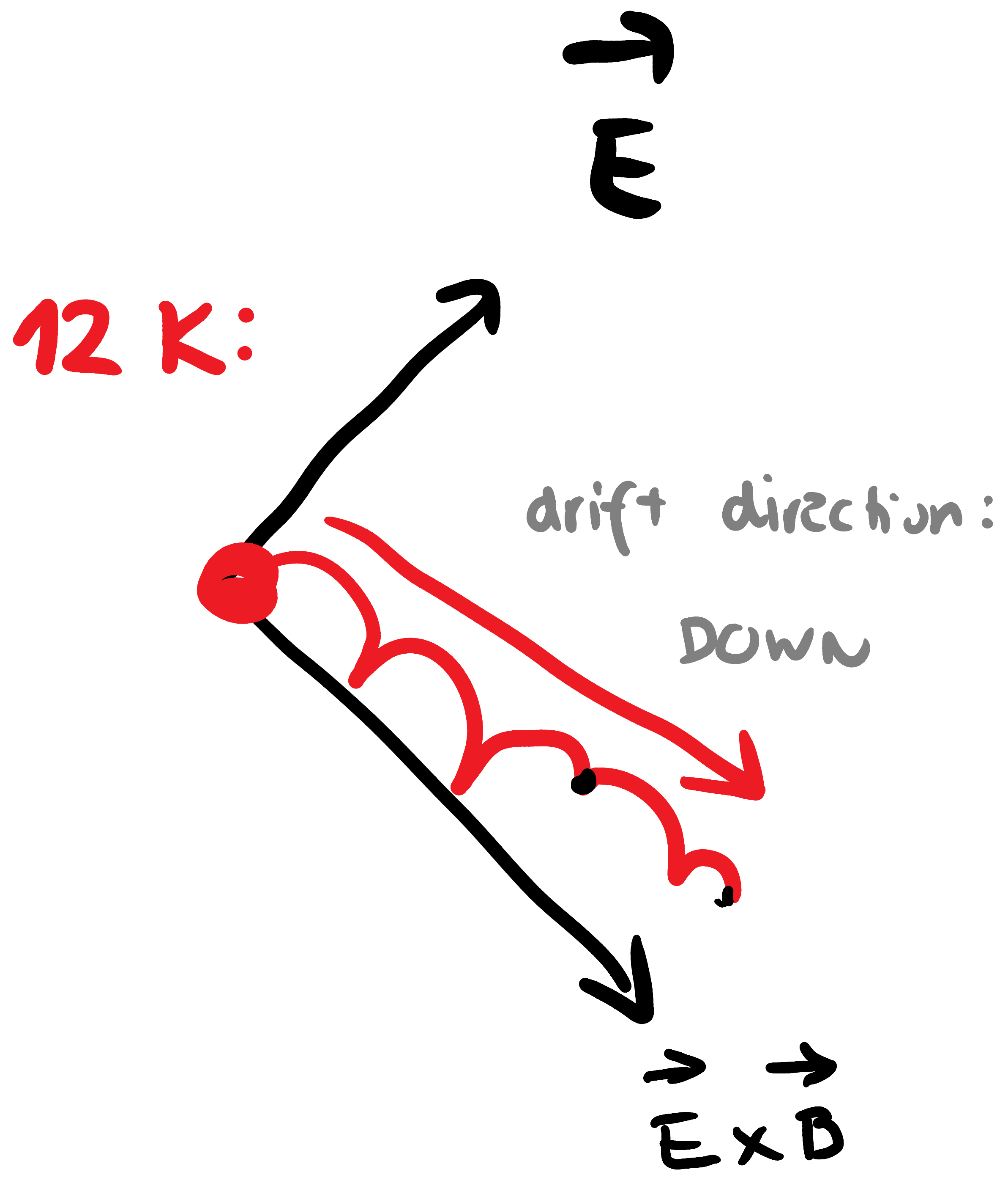
Trajectories in E and B field

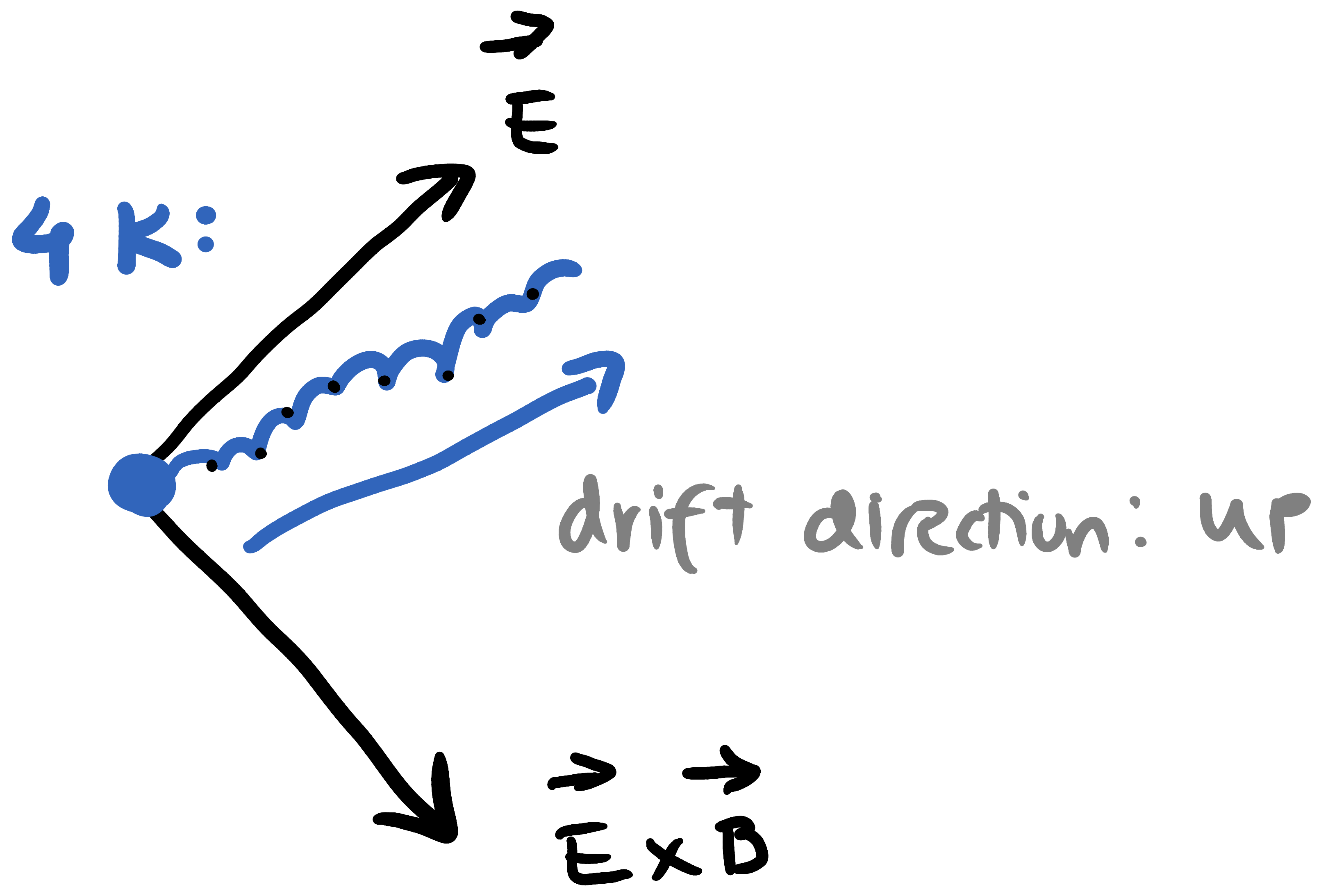




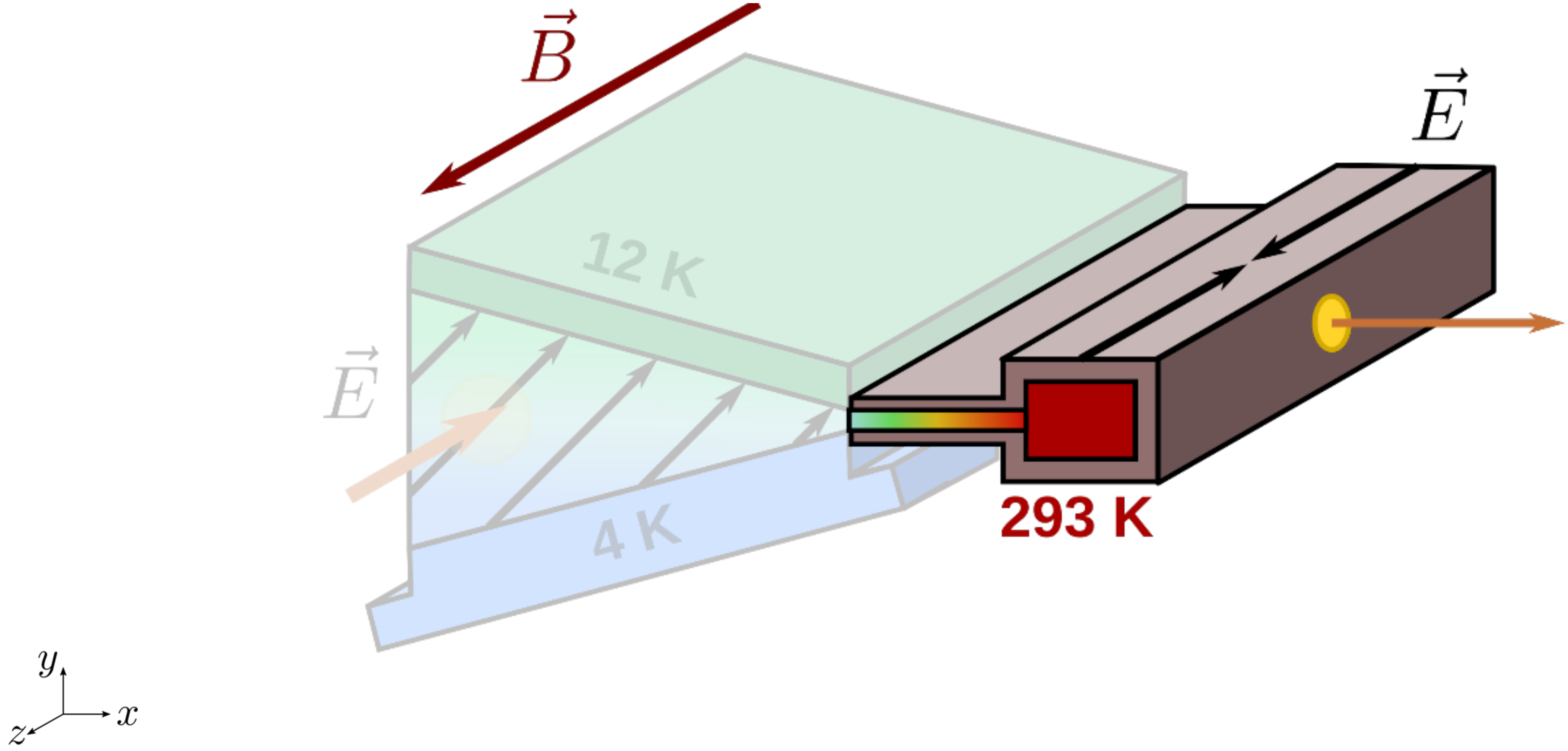
Working principle: 1st Stage





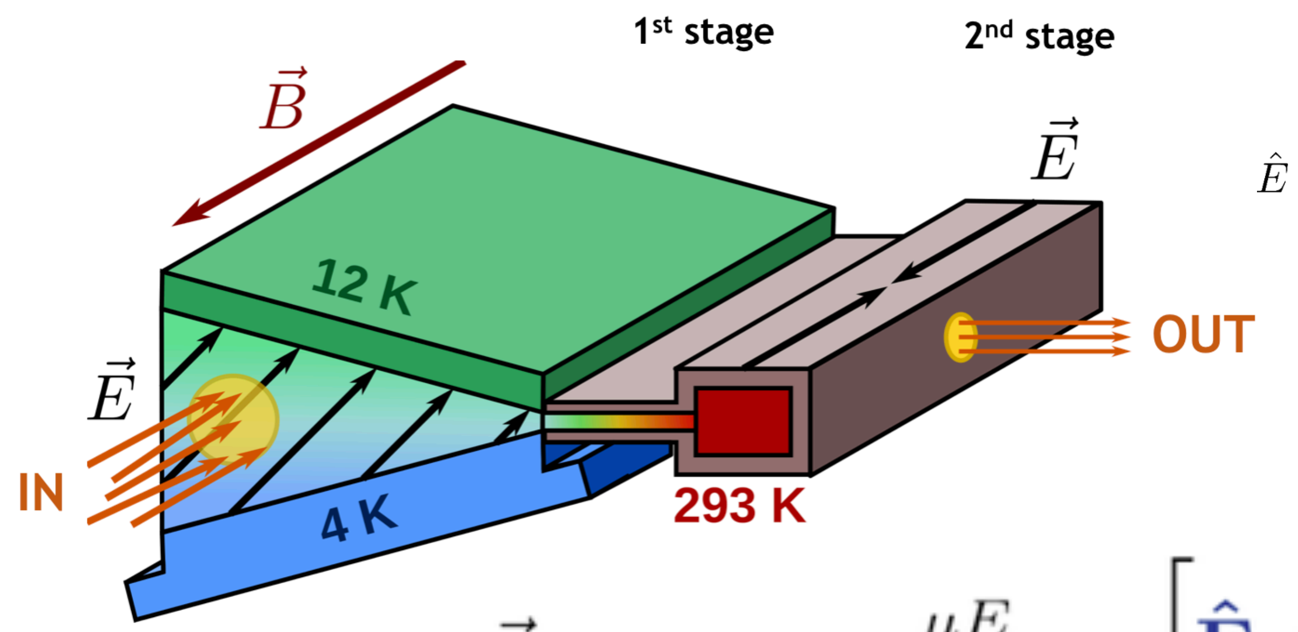


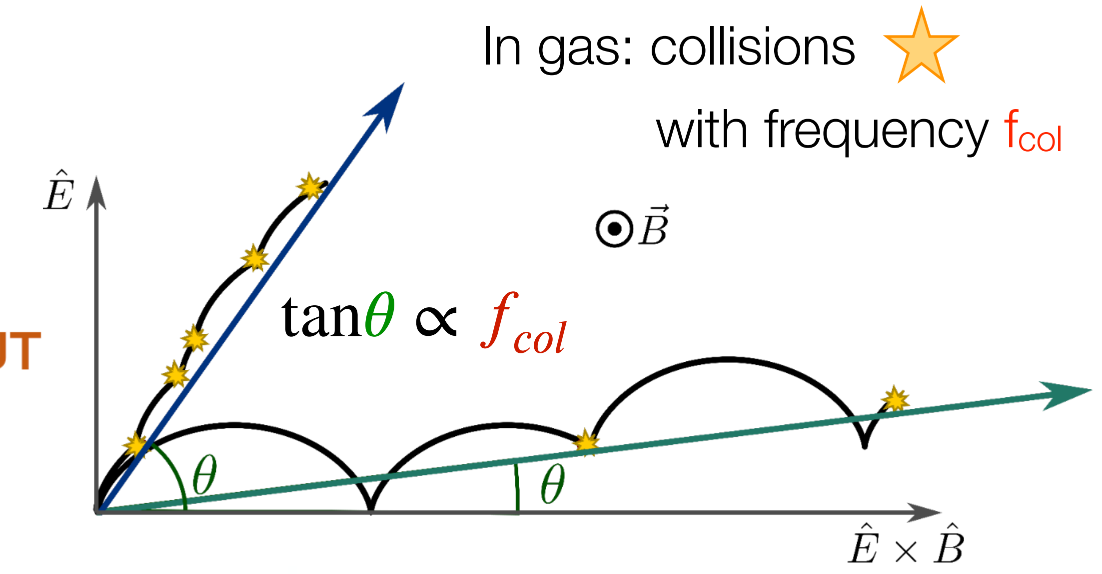
Working principle: 2nd Stage



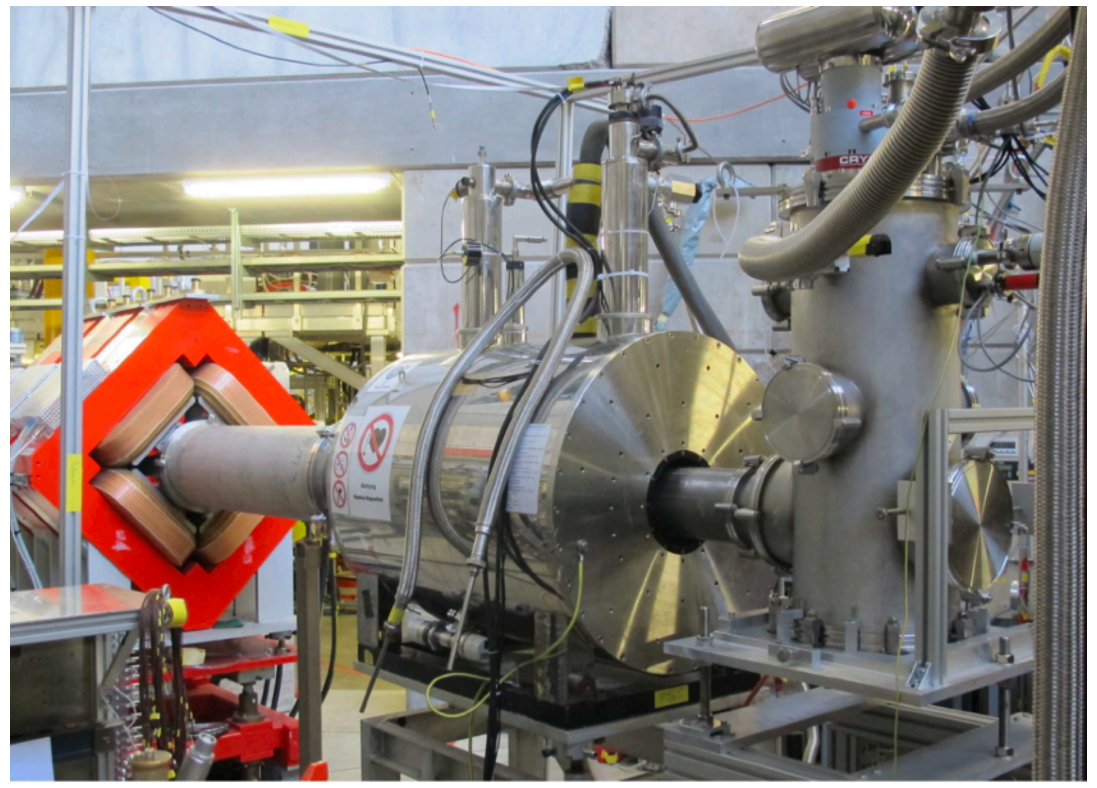
Summary: The muCool project at PSI

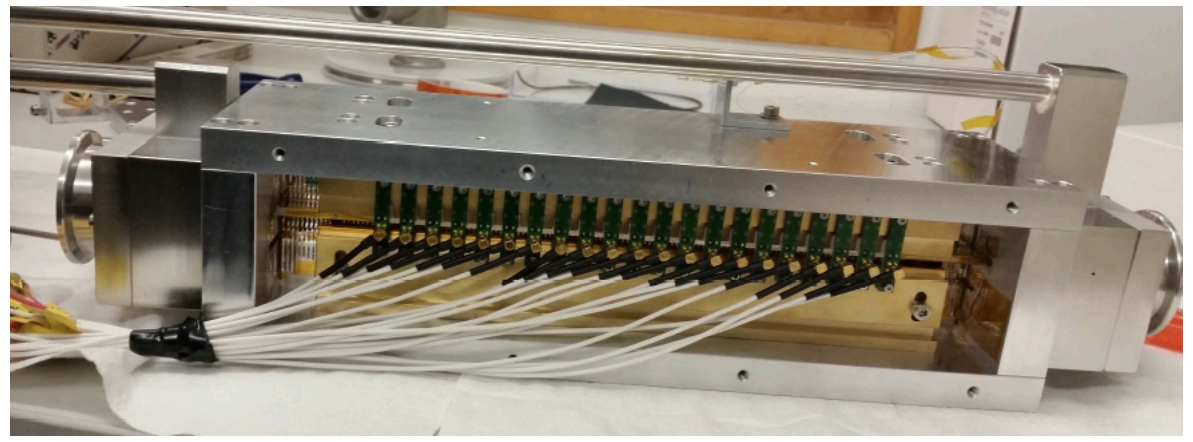
- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor $\mathbf{10^{10}}$ with an efficiency of O($\mathbf{10^{-4}}$)
- Longitudinal and transverse compression (1st stage + 2nd stage): experimentally proved
- **Next Step**: Extraction into vacuum

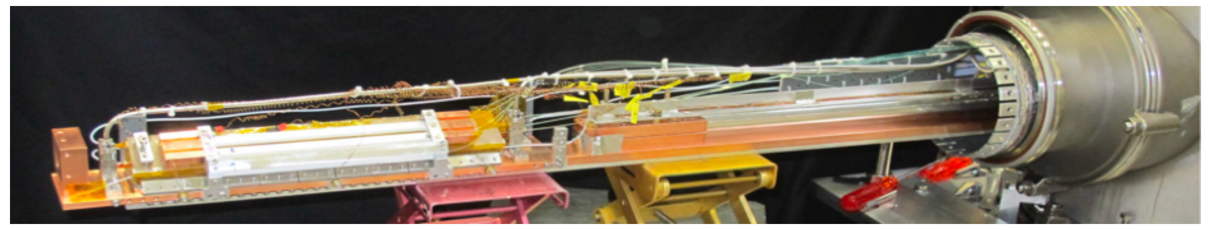




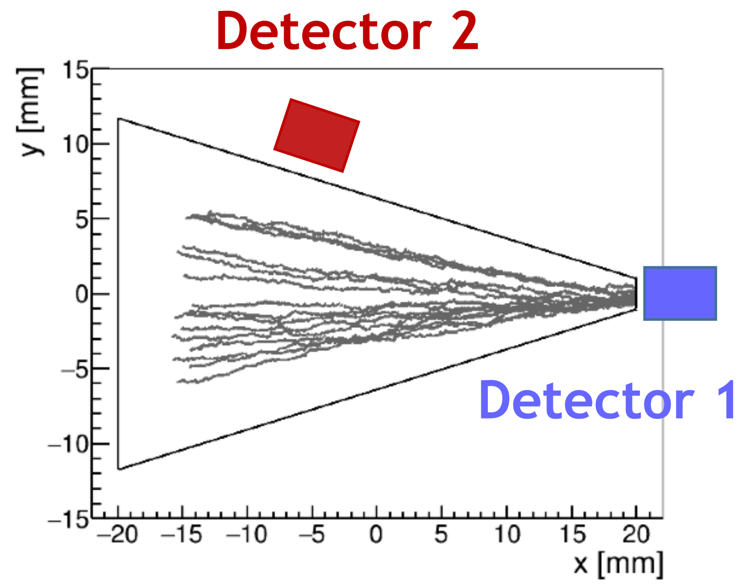
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}} \times \hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2 \left(\hat{\mathbf{E}} \cdot \hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

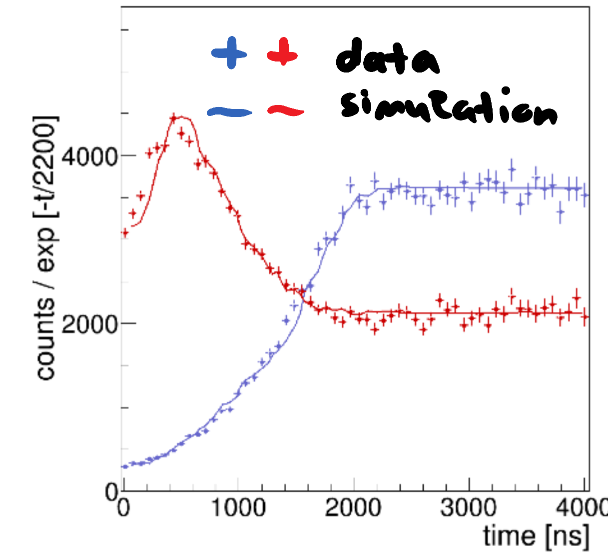




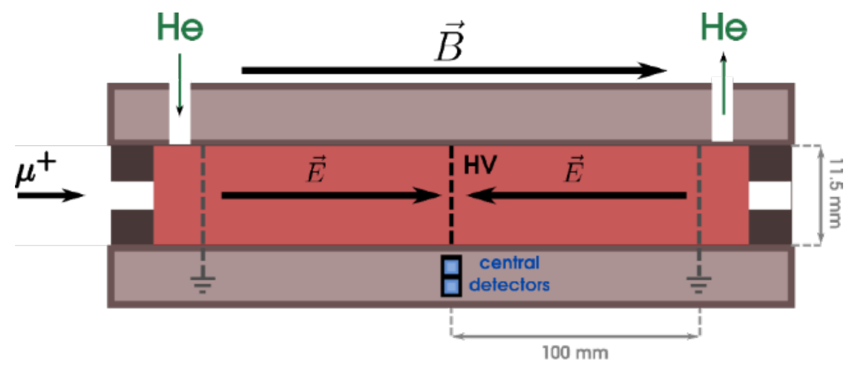


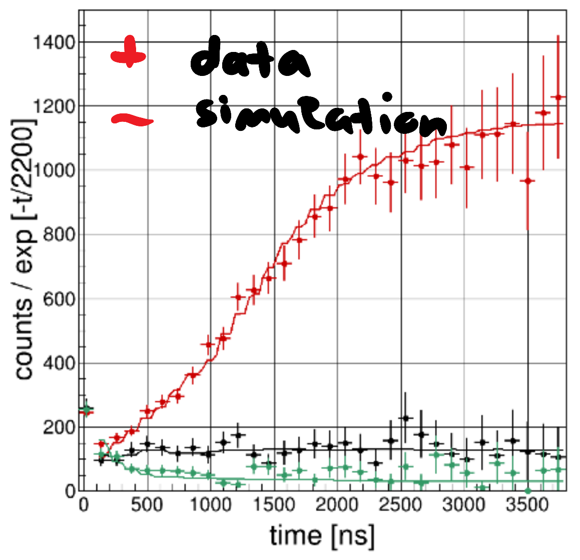
Transverse Compression



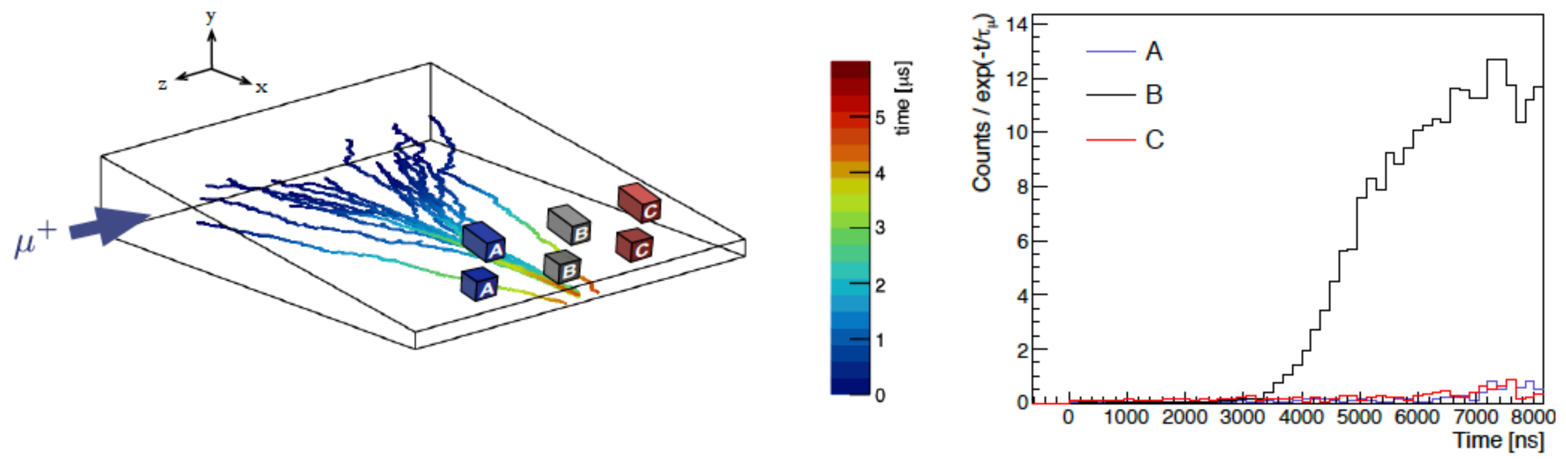


Longitudinal Compression

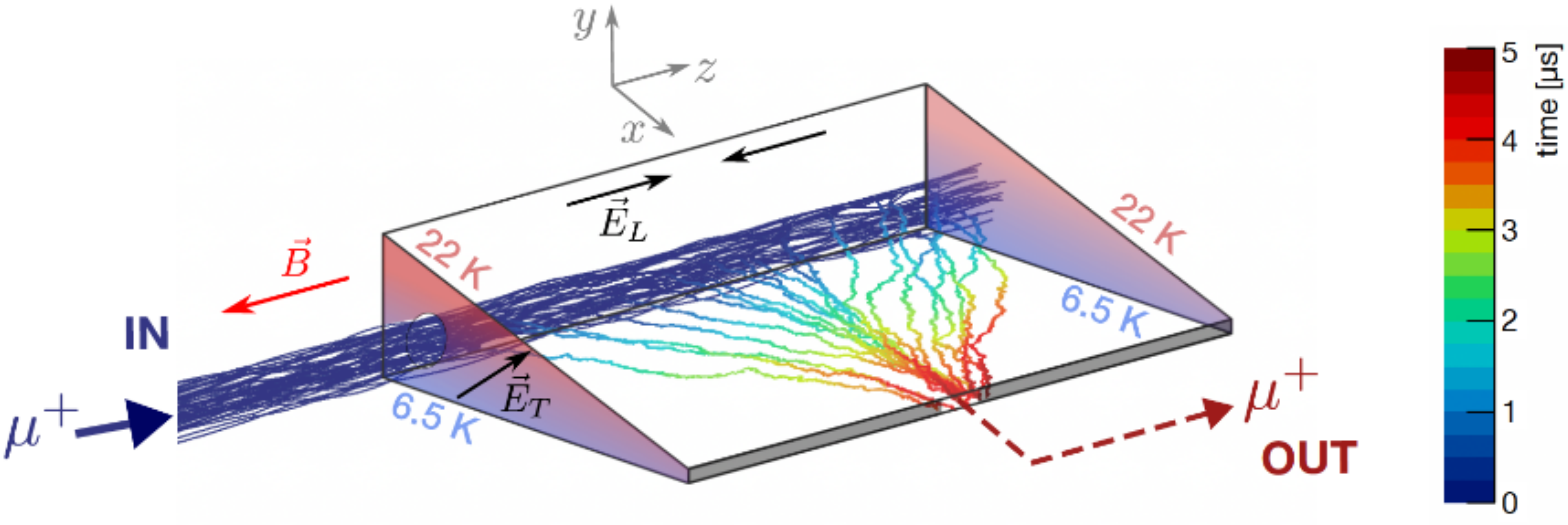




Longitudinal+ Transverse Compression

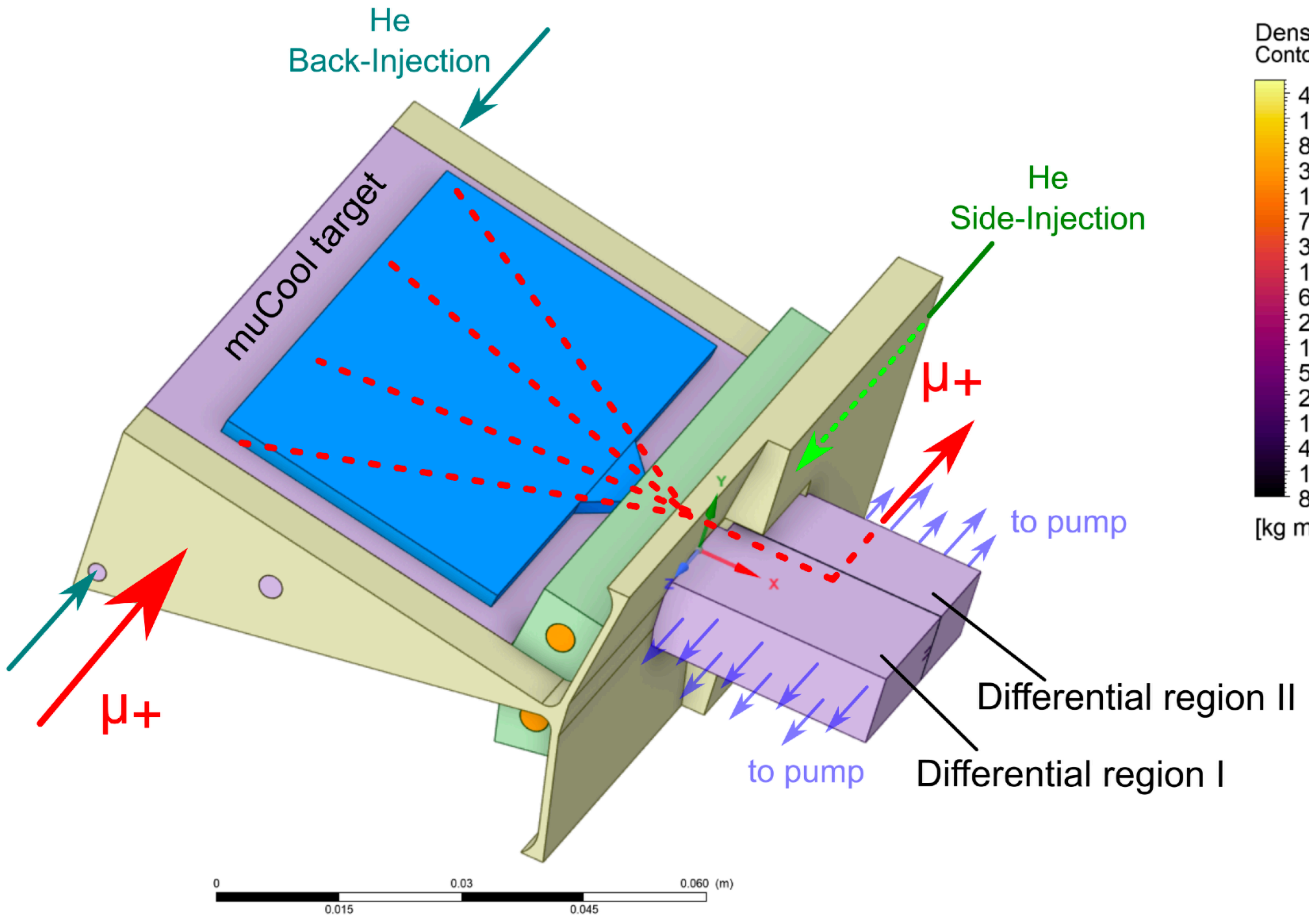


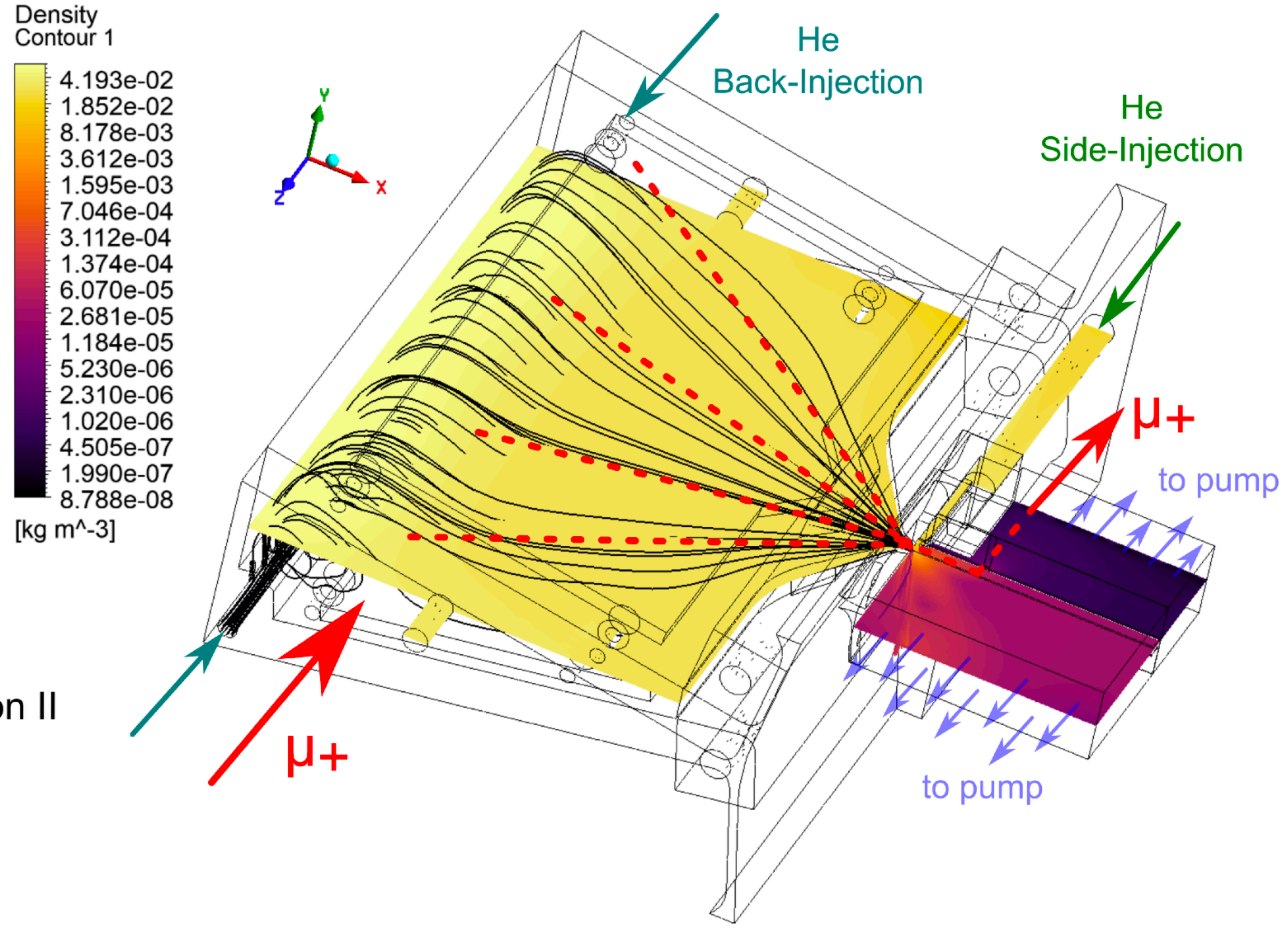
Where we are now:



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

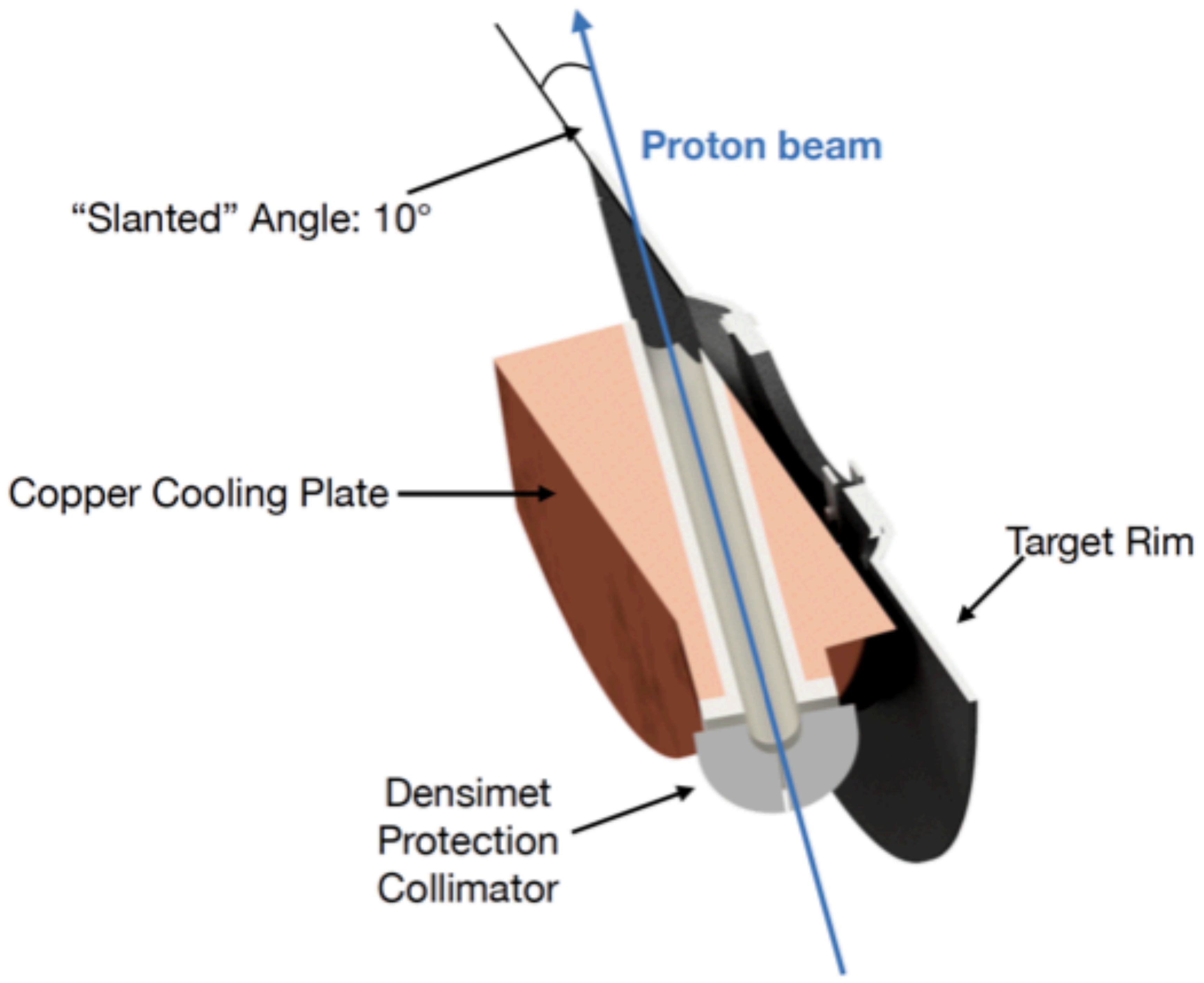
- Next generation on muon based experiments require higher muon rates
  - New opportunities for future muon (particle physics) based experiments
  - New opportunities for μSR experiments
- Different experiments demand for a variety of beam characteristics:
  - DC vs pulsed
  - Momentum depends on applications: stopped beams require low momenta
  - Phase space
- Beam with different characteristics are/will be available worldwide

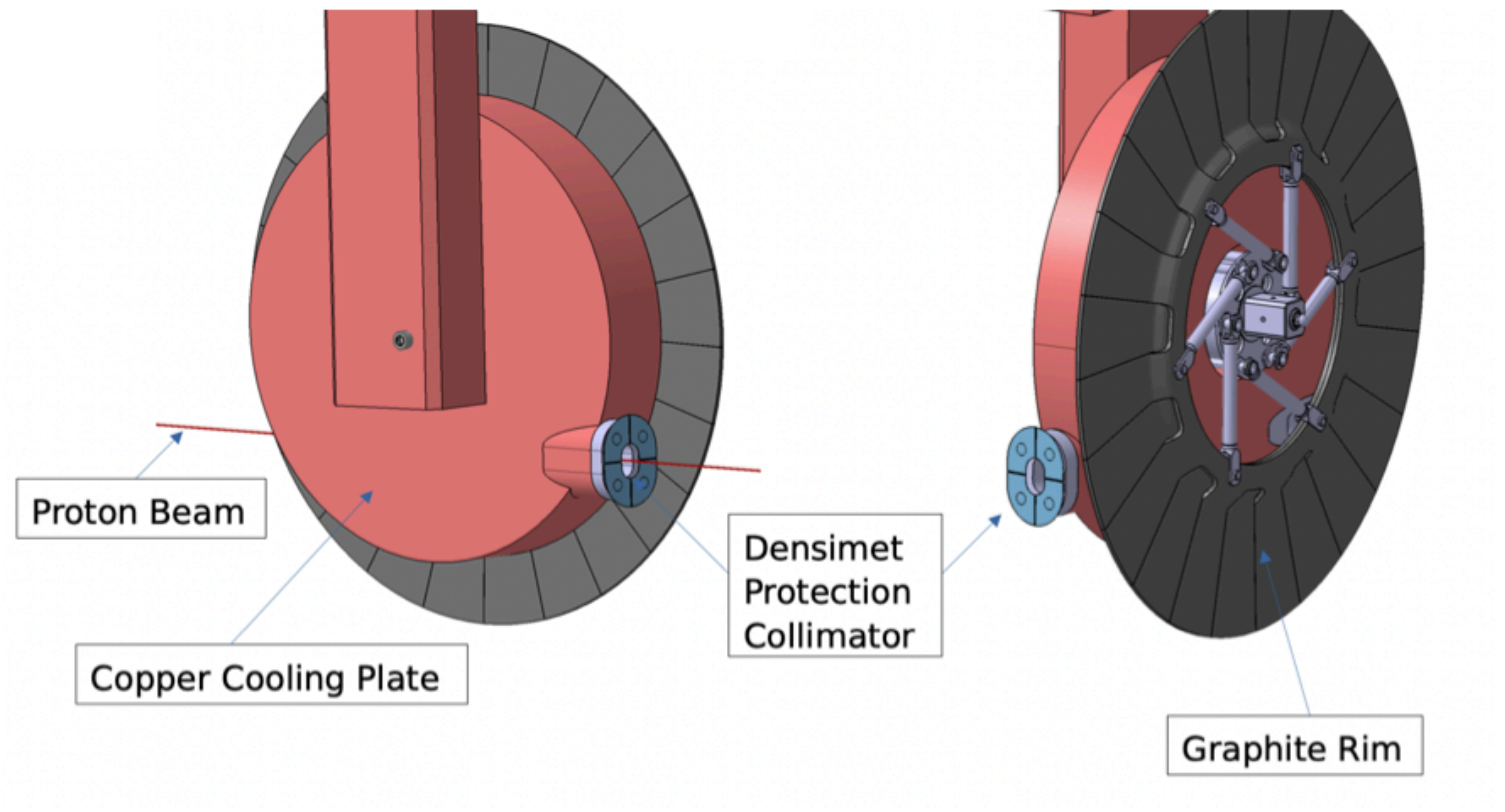
Credits and acknowledgments

- **The IMPACT project at PSI**
- **The muCool project at PSI**
- The MEGII collaboration
- The Mu3e collaboration
- The muEDM collaboration
- …

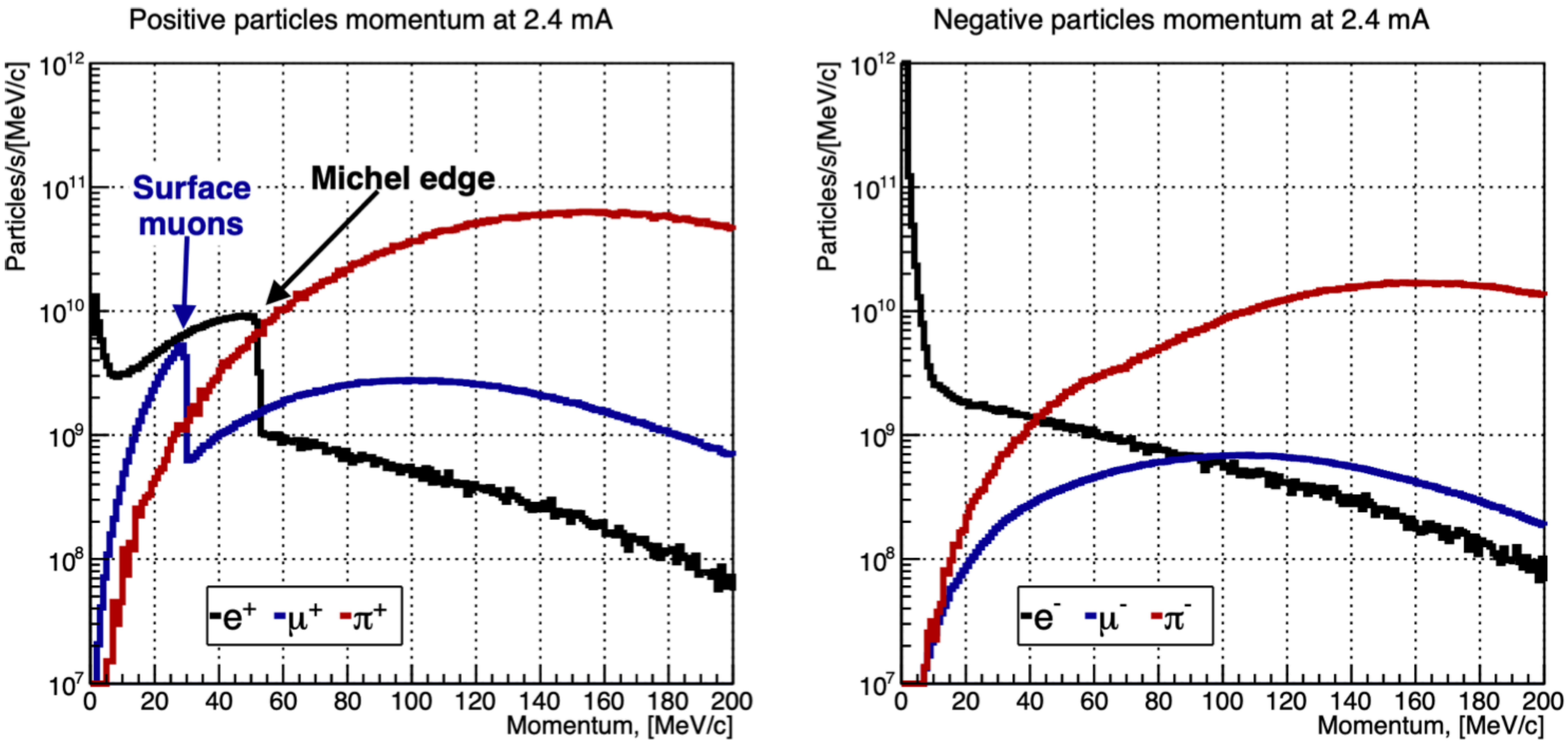
Thanks for your attention !

TgE: A few details





Momentum spectrum of the relevant particles produced at TgH



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)	

A quick departure: The HiMB project at the beam dump

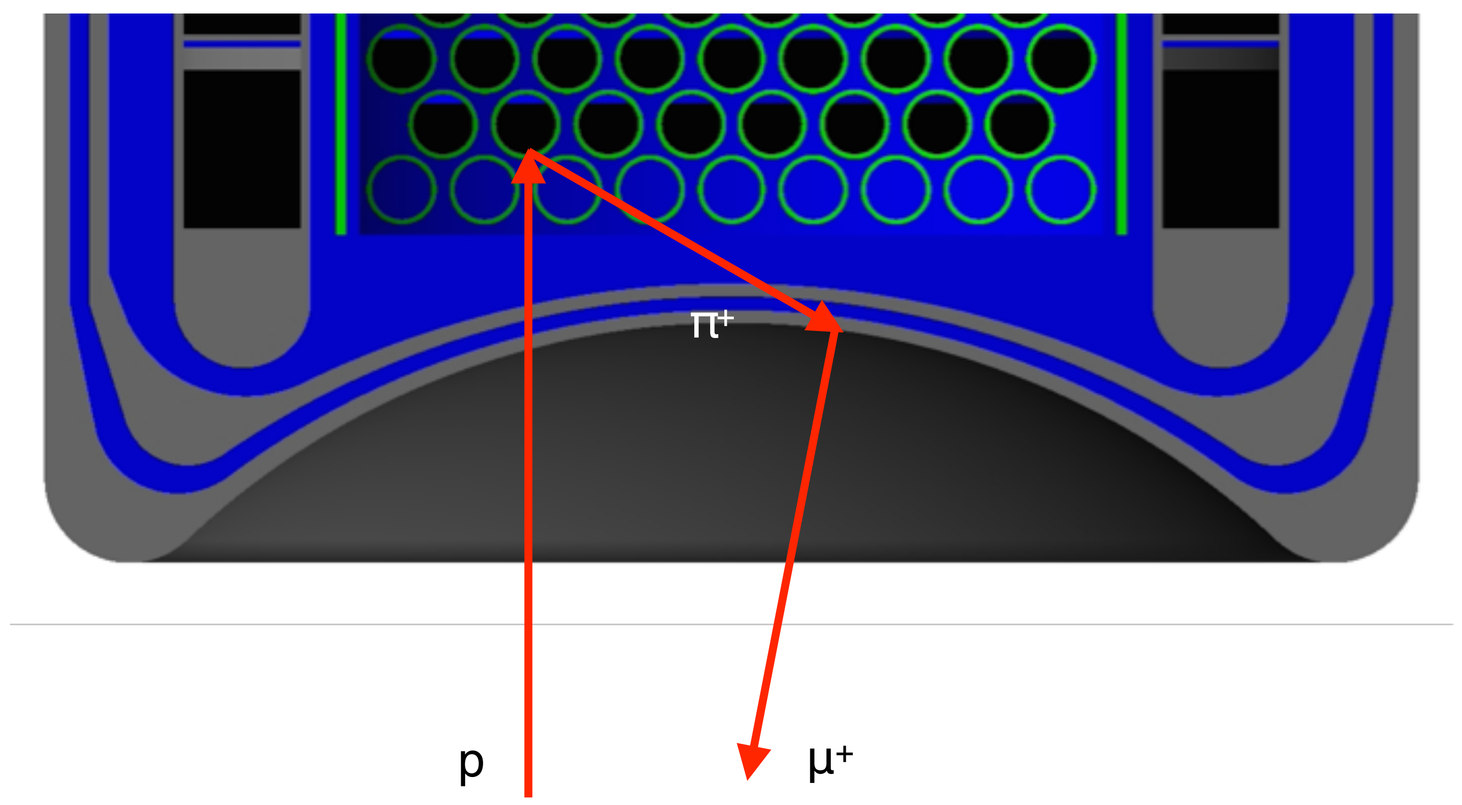
- Source simulation (below safety window):
  9 x 10^{10} surface-μ^+/s @ 1.7 mA I_p
- Profit from stopping of full beam
- Residual proton beam (~1 MW) dumped on SINQ

- Replace existing quadrupoles with solenoids:
  - Preserve proton beam footprint
  - Capture backward travelling surface muons
- Extract muons in Dipole fringe field
- Backward travelling pions stopped in beam window

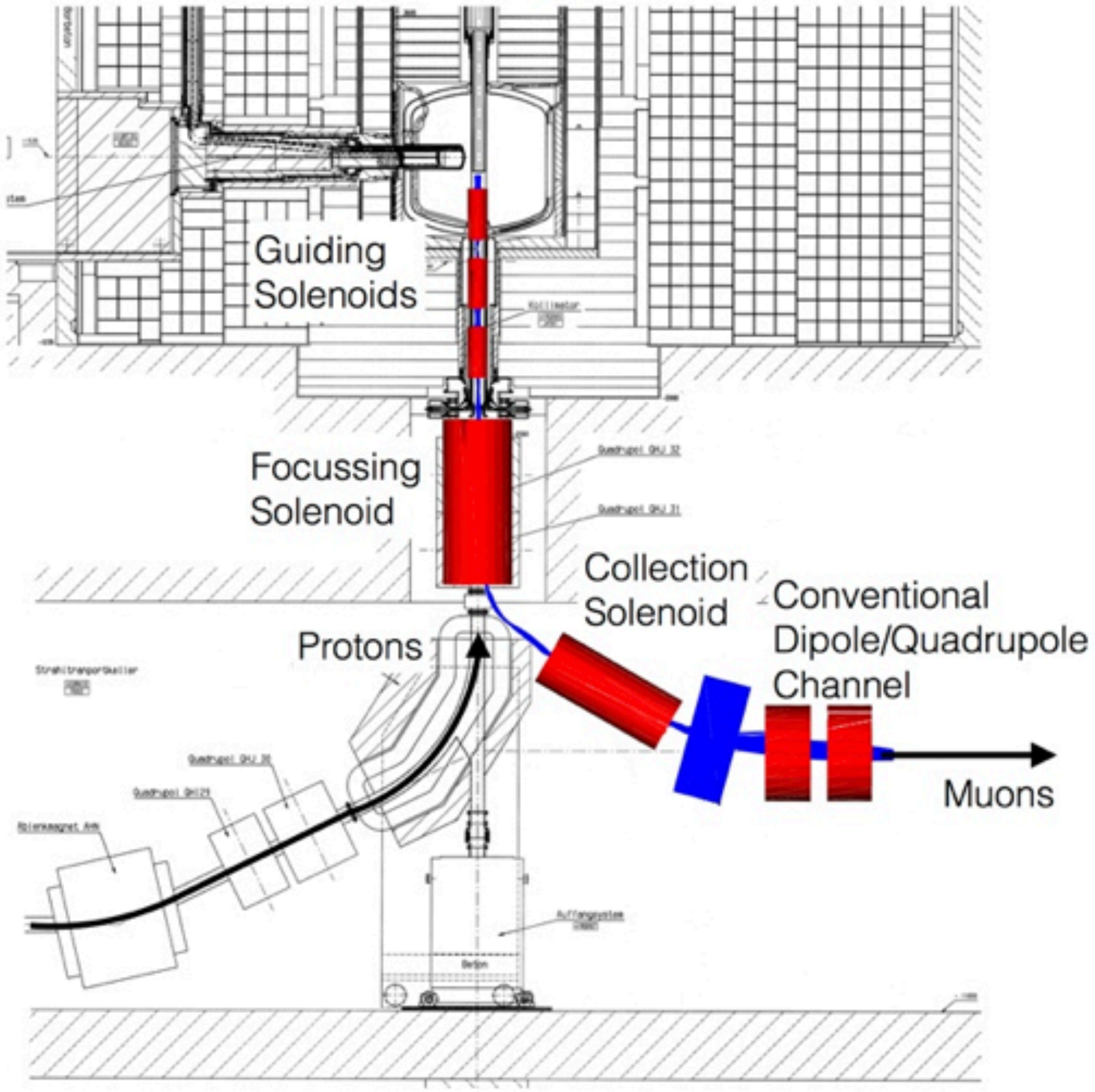
- Capturing turned out to be difficult :
  - Large phase space (divergence & ‘source‘ extent)
  - Capture solenoid aperture needed to be increased, but constrained by moderator tank
- High radiation level close to target

- **Due these constraints** and after several iterations with different capturing elements:
  - **Not enough captures muons to make an high intensity beam**
  - **Alternative solution: HiMB @ EH**

SINQ spallation target

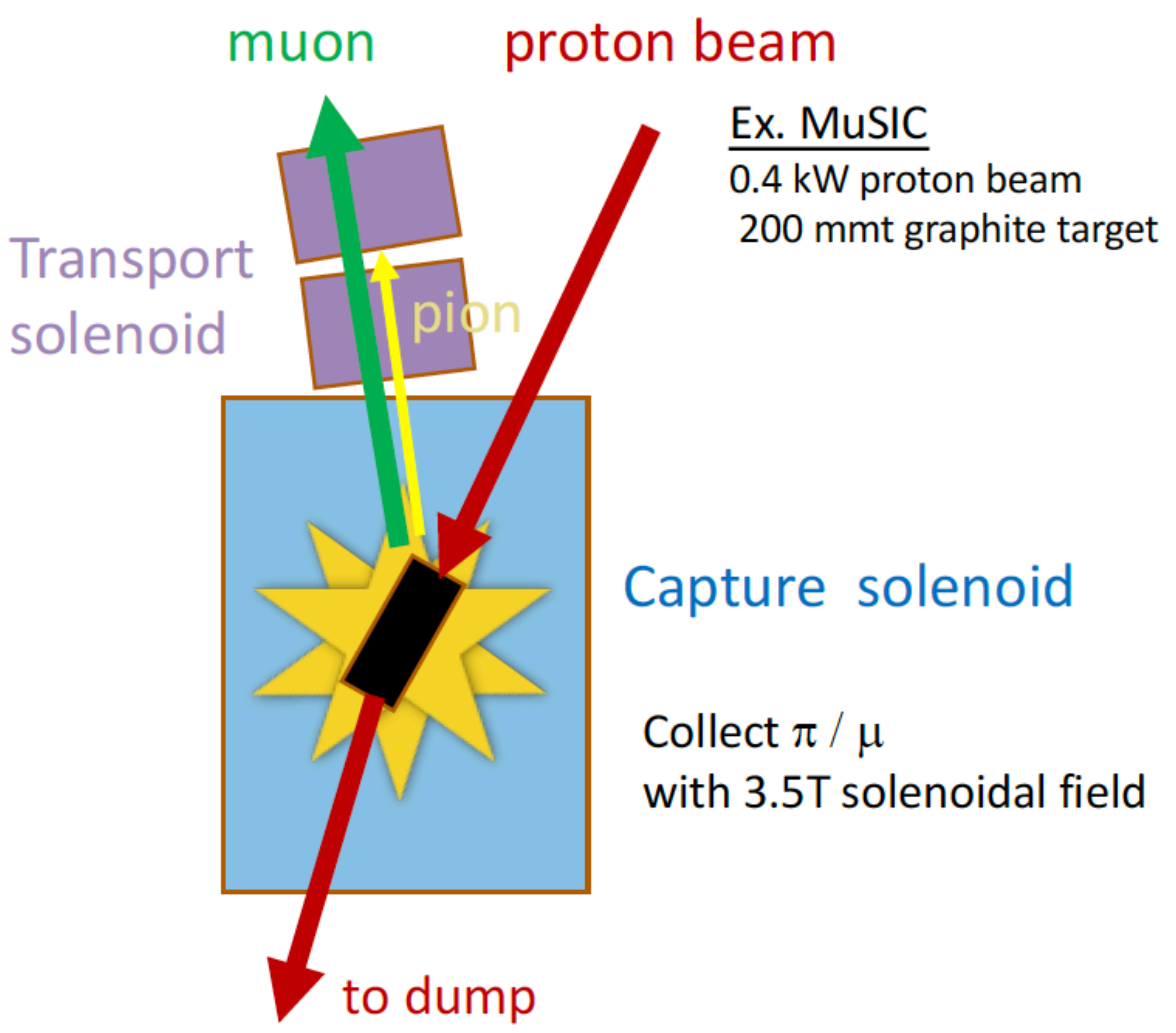


HiMB Conceptual Layout



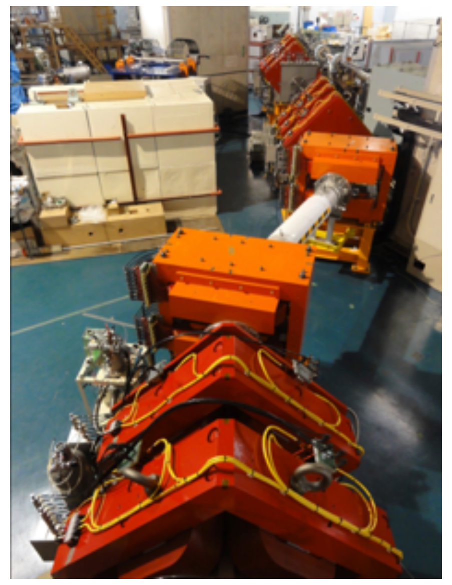
MuSIC's muon beams

MuSIC beamline



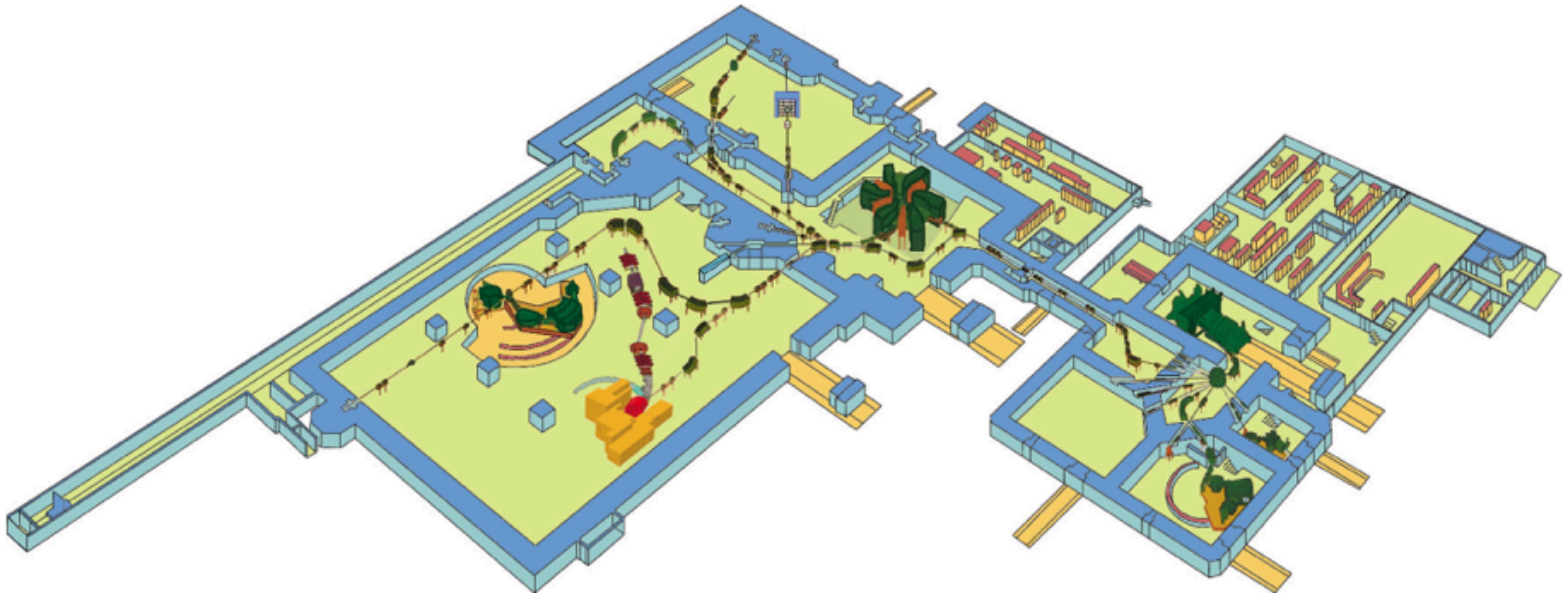
- Thick target (200mmt)
- Large solid angle, good collection efficiency
- No muon spin selection (no selection of pion / muon momentum)

- Aim: O(10^8 muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam



MuSIC
M1 Beam line

Ring
Cyclotron
~392MeV
(variable)
1.1uA
proton,
(0.4kW)

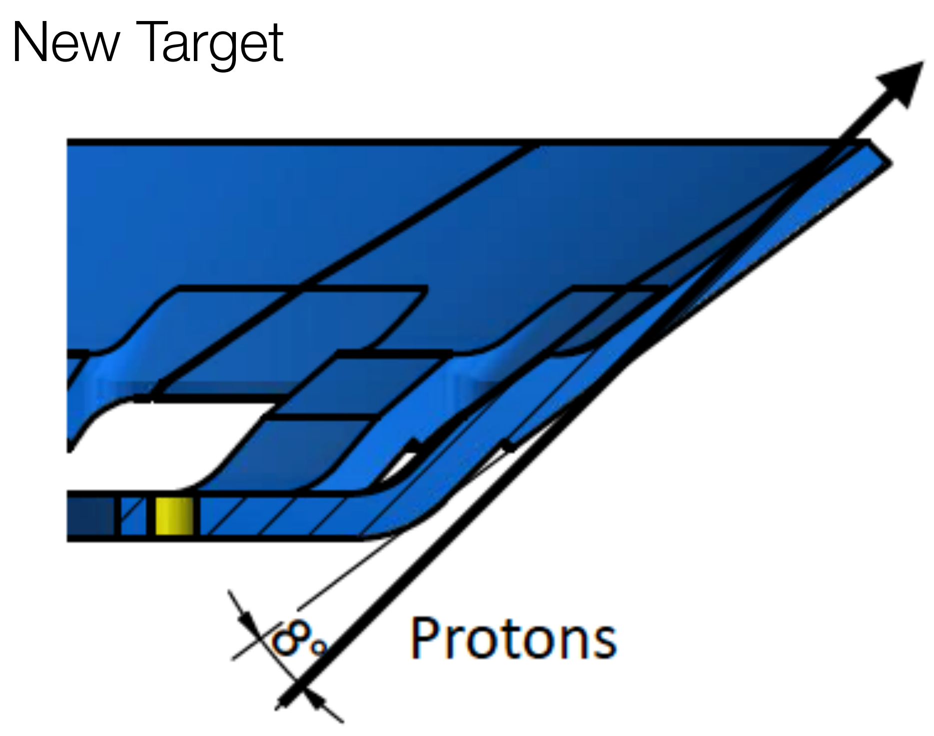


- proton beam energy is only 100 MeV above pion production threshold ($\sim 2m_\pi$)
- muon source with low proton power (1.1 uA ~0.4kW, 5 uA in future)

Slanted target: Impact

- Impact of the optimised target:
  - 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

Graphite



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