The High Intensity Muon Beam project at PSI and its future developments

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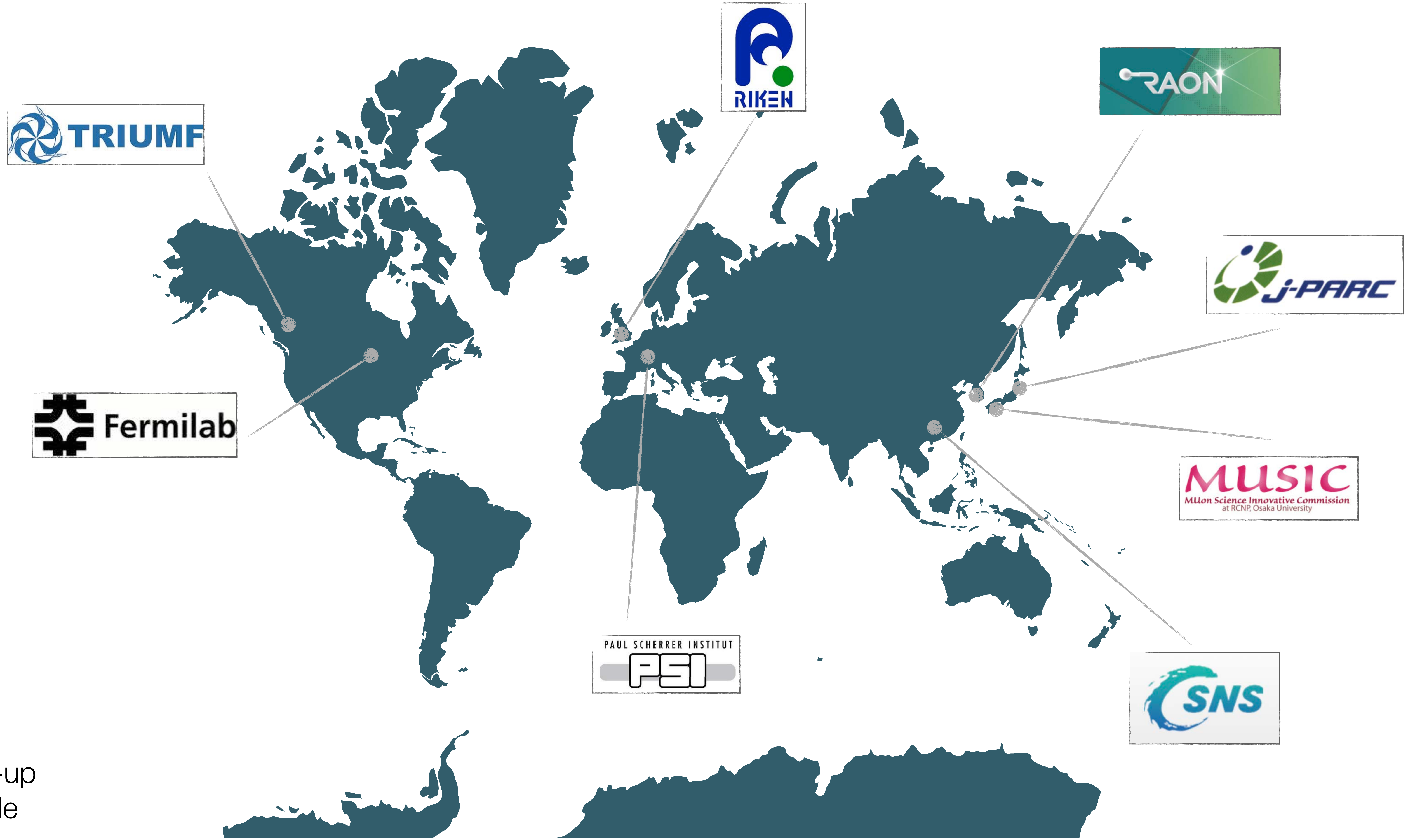
June 20th-322nd 2023, Heidelberg - Germany
cLFV workshop

Contents

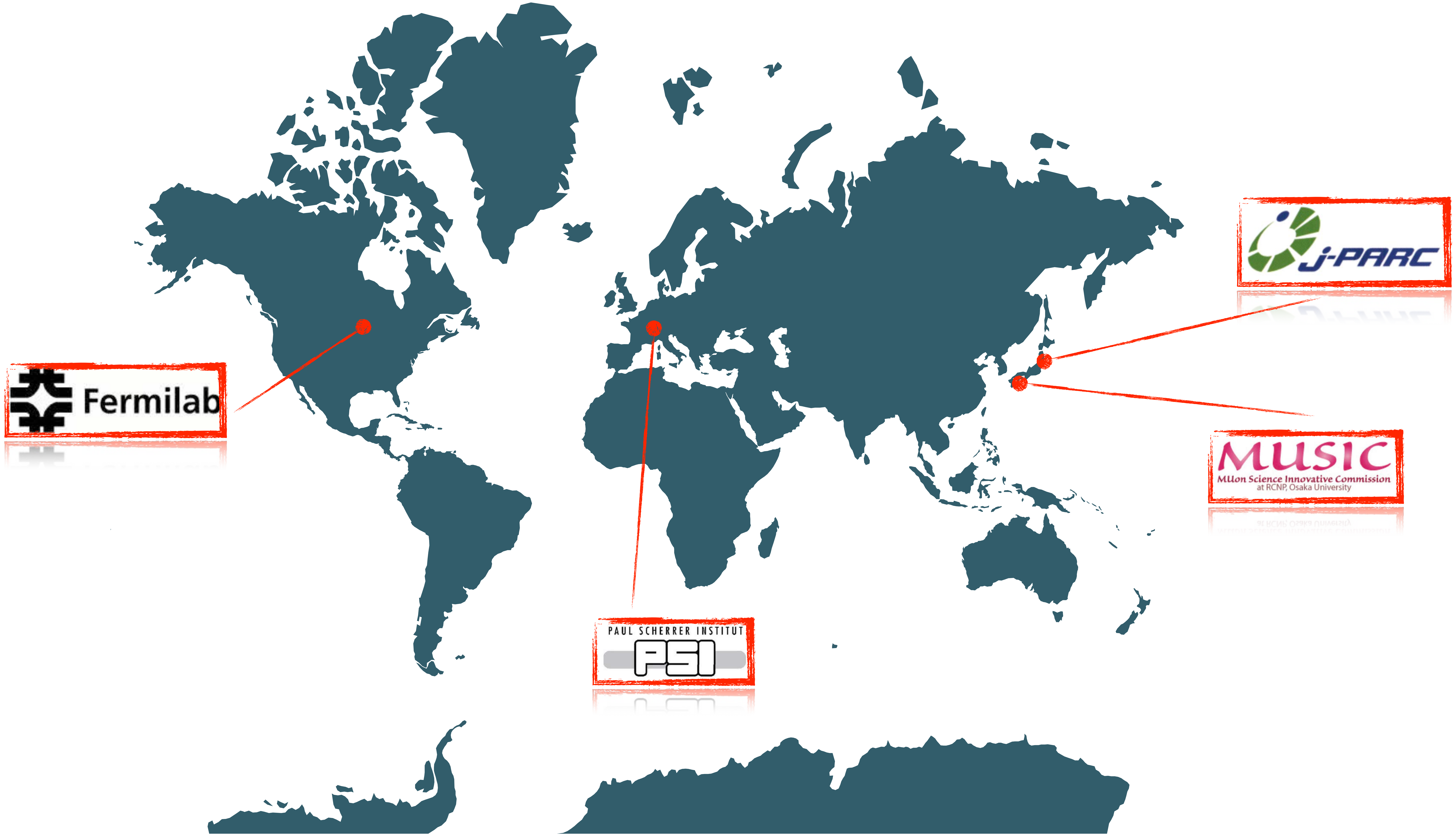
- PSI current beam lines
- PSI future beam line developments
  - **HiMB**
  - muCool
- Physics cases already associated to this NEW beams
  - Mu3e phase II
  - muEDM

Muon beams worldwide



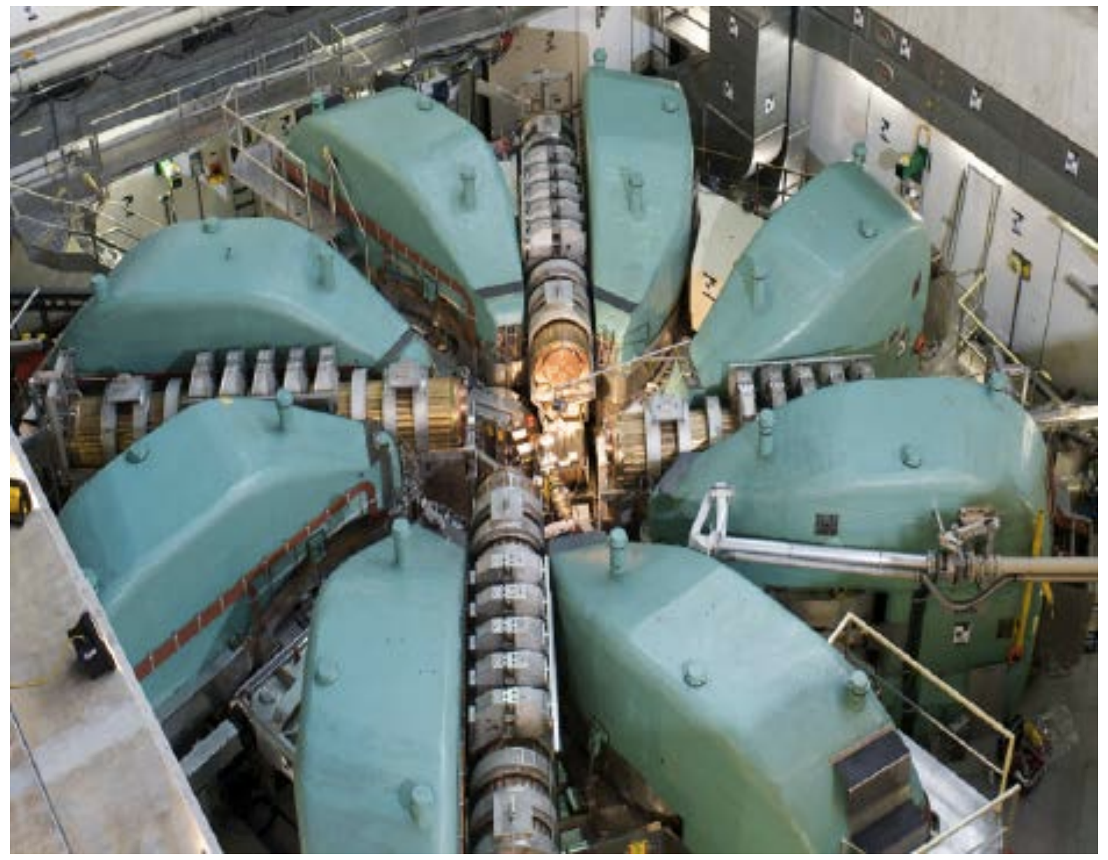
Note: See the back-up for a summary table

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

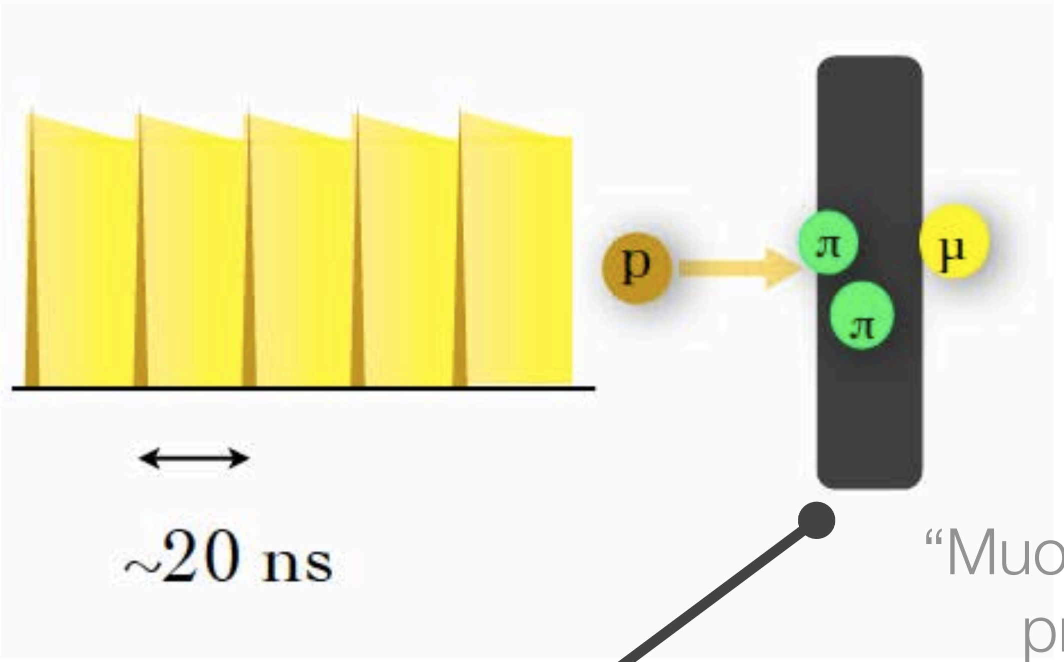


PSI's muon beams

- 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**)

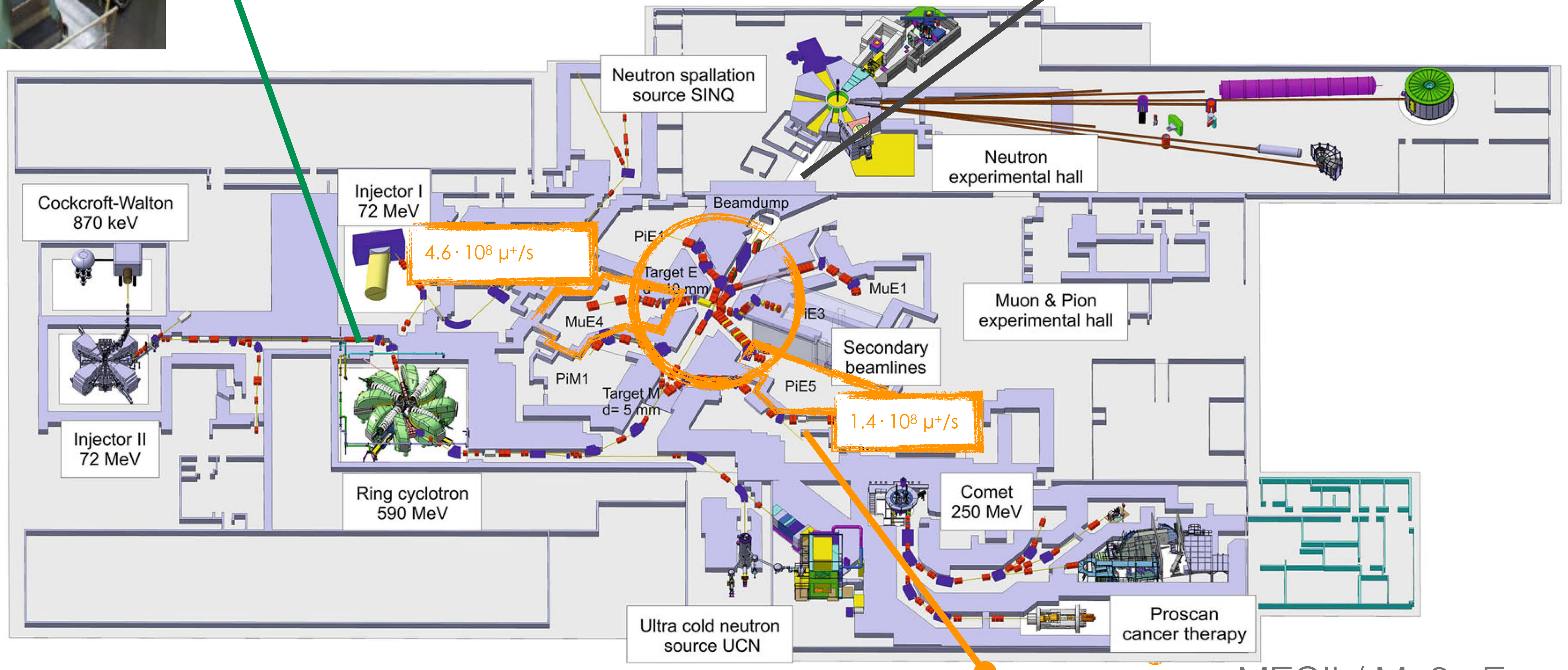


590 MeV proton ring cyclotron **1.4 MW**



Proton RF ~ 50 MHz
"DC" muon beam

"Muon" Target "E" production

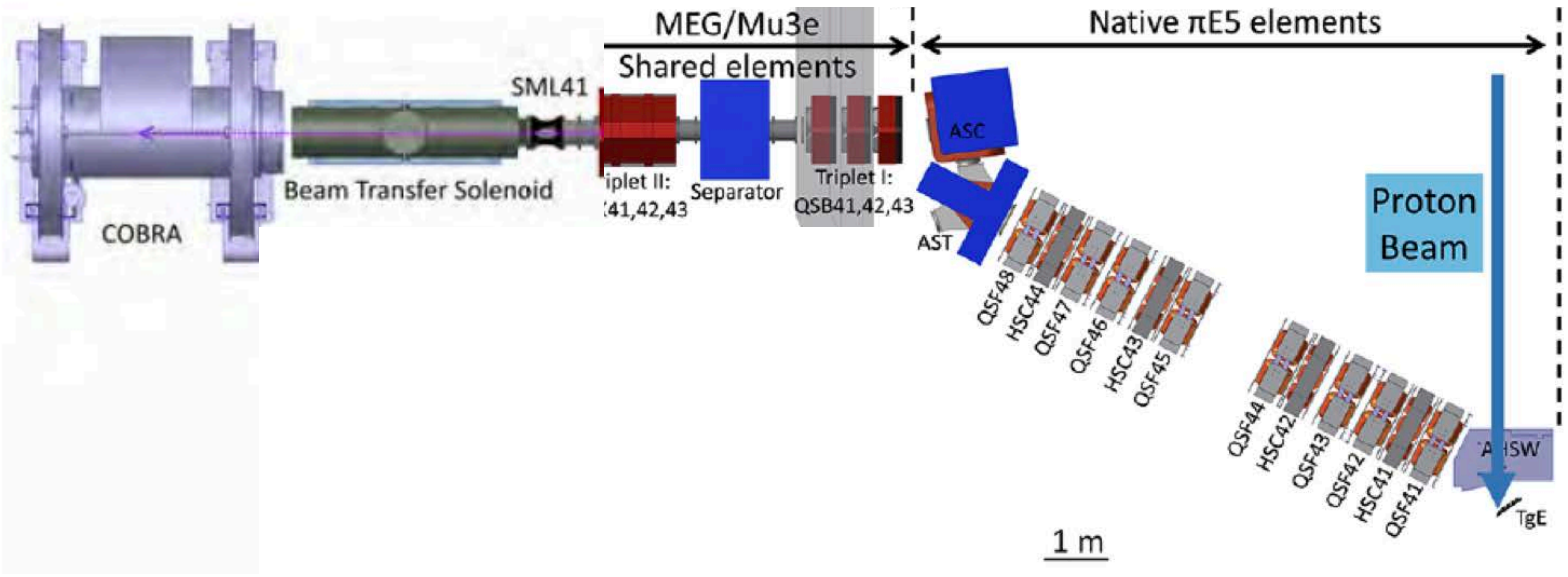


MEGII / Mu3e Experimental area

The MEGII and Mu3e beam lines

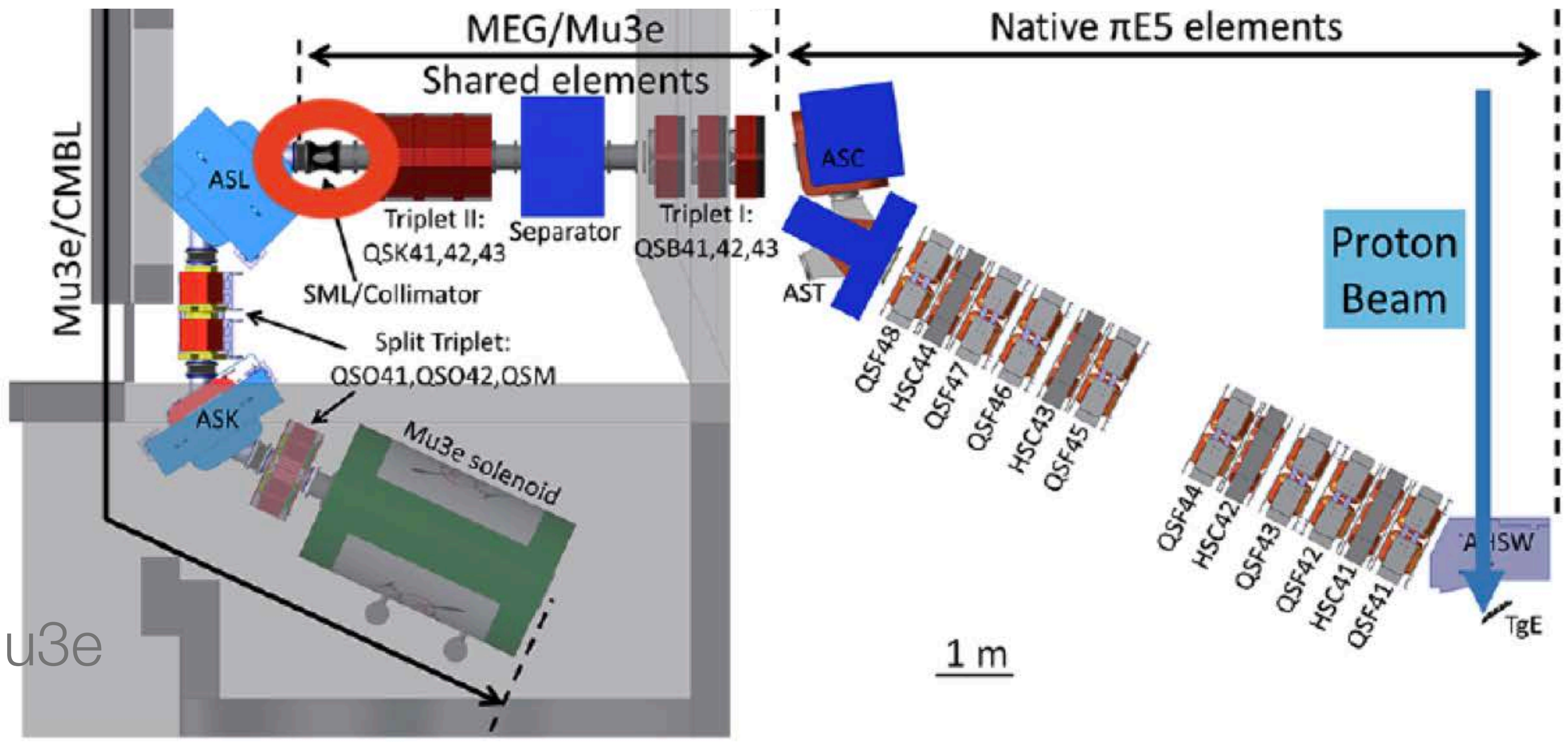
- MEGII and Mu3e (phase I) similar beam requirements:
  - **Intensity O(10^8 muon/s), low momentum p = 28 MeV/c**
  - **Small straggling and good identification of the decay region**
- MEG II beam settings released since 2019. More then 10^8 μ^+/s can be transport into Cobra (up to 1.6e8@2.2 mA during the 2022 beam time)

The MEGII



The MEGII and Mu3e beam lines

- MEGII and Mu3e (phase I) similar beam requirements:
  - **Intensity O(10^8 muon/s), low momentum p = 28 MeV/c**
  - **Small straggling and good identification of the decay region**
- A dedicated compact muon beam line (CMBL) sharing a large fraction of the native piE5&MEG elements will serve Mu3e
  - Proof-of-Principle: Delivered 8 x 10^7 μ^+/s during 2016 test beam (up to 1e8@2.4 mA during the 2022 beam time with the full assembled Mu3e beam line [at the center of the Mu3e magnet])



The Mu3e

HiMB motivations

- Current beam intensity: Up to 5×10^{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

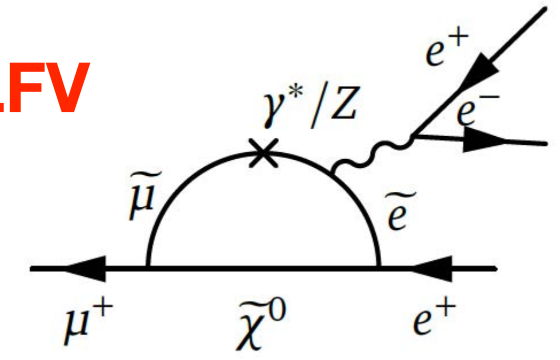
Fermilab $\rightarrow 5\times10^{10}$ μ^{-}/s

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

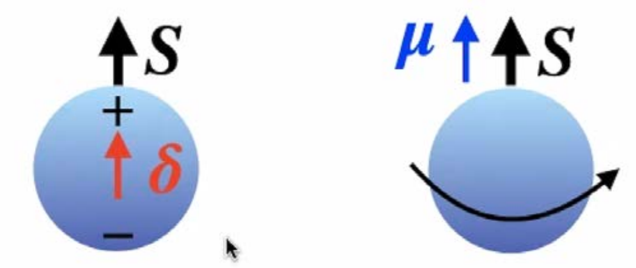
J-PARC $\rightarrow 10^{10}$ μ^{-}/s

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

cLFV



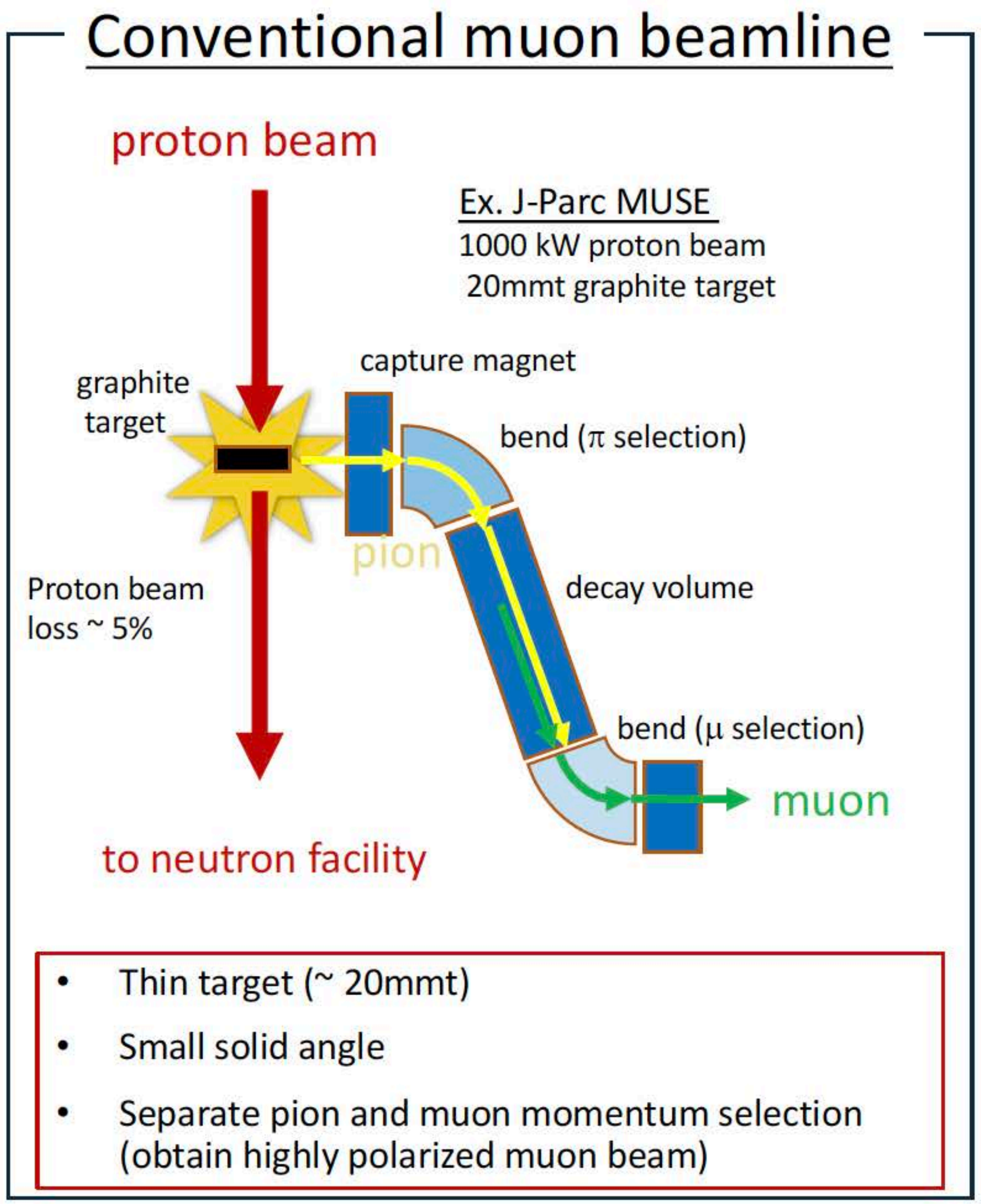
muEDM

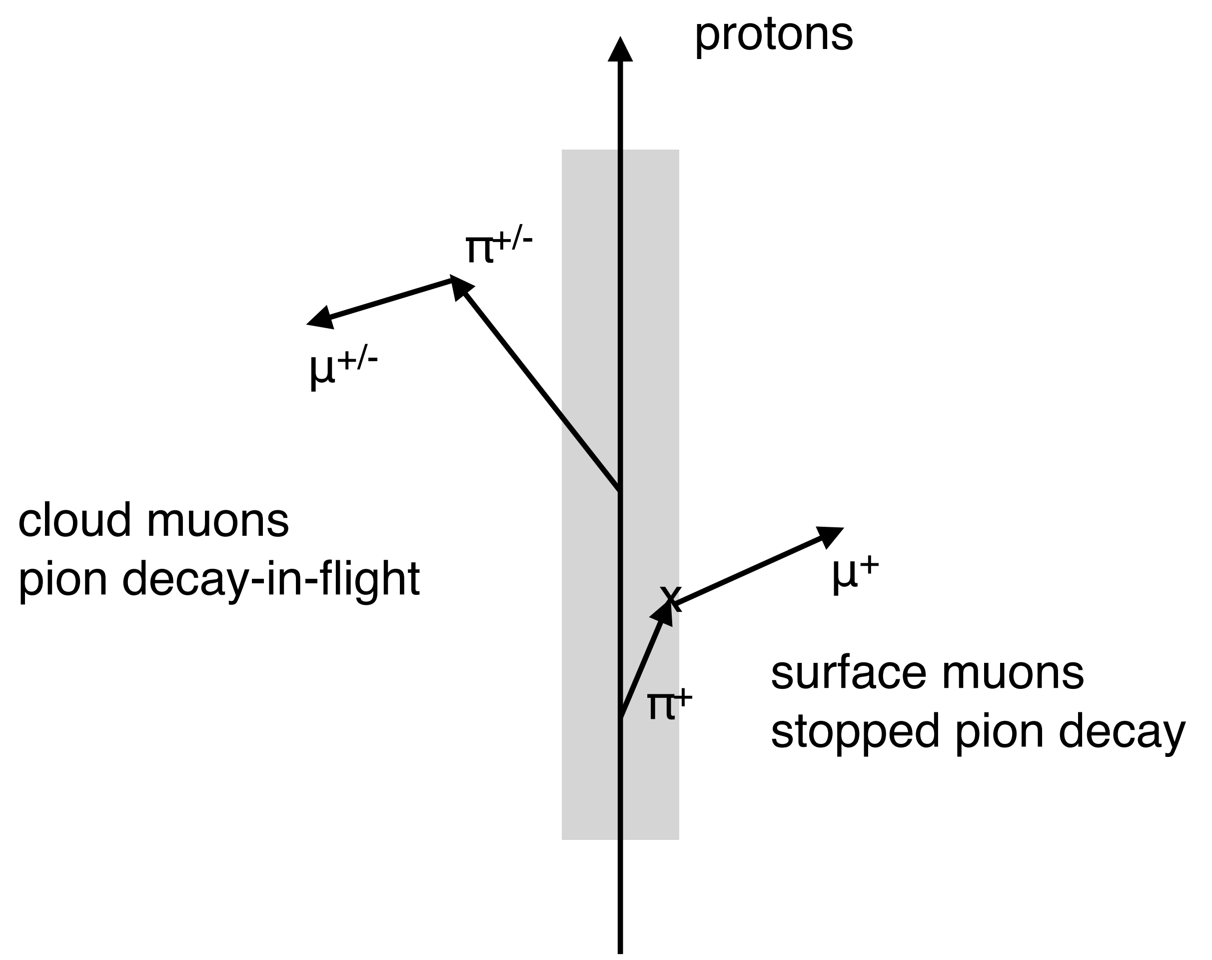


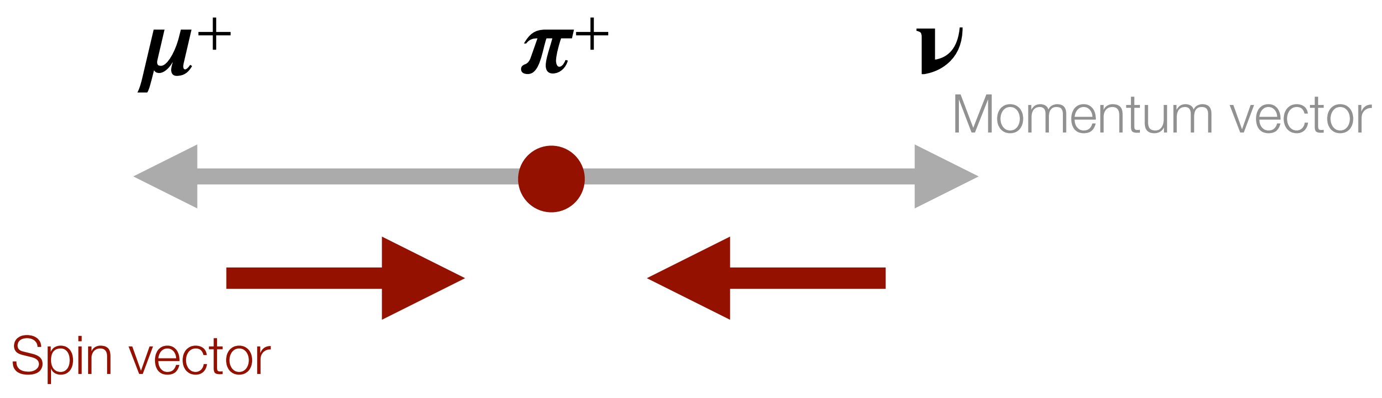
δ= electric dipole moment (EDM)

μ= magnetic dipole moment (MDM)

PSI’s muon beams



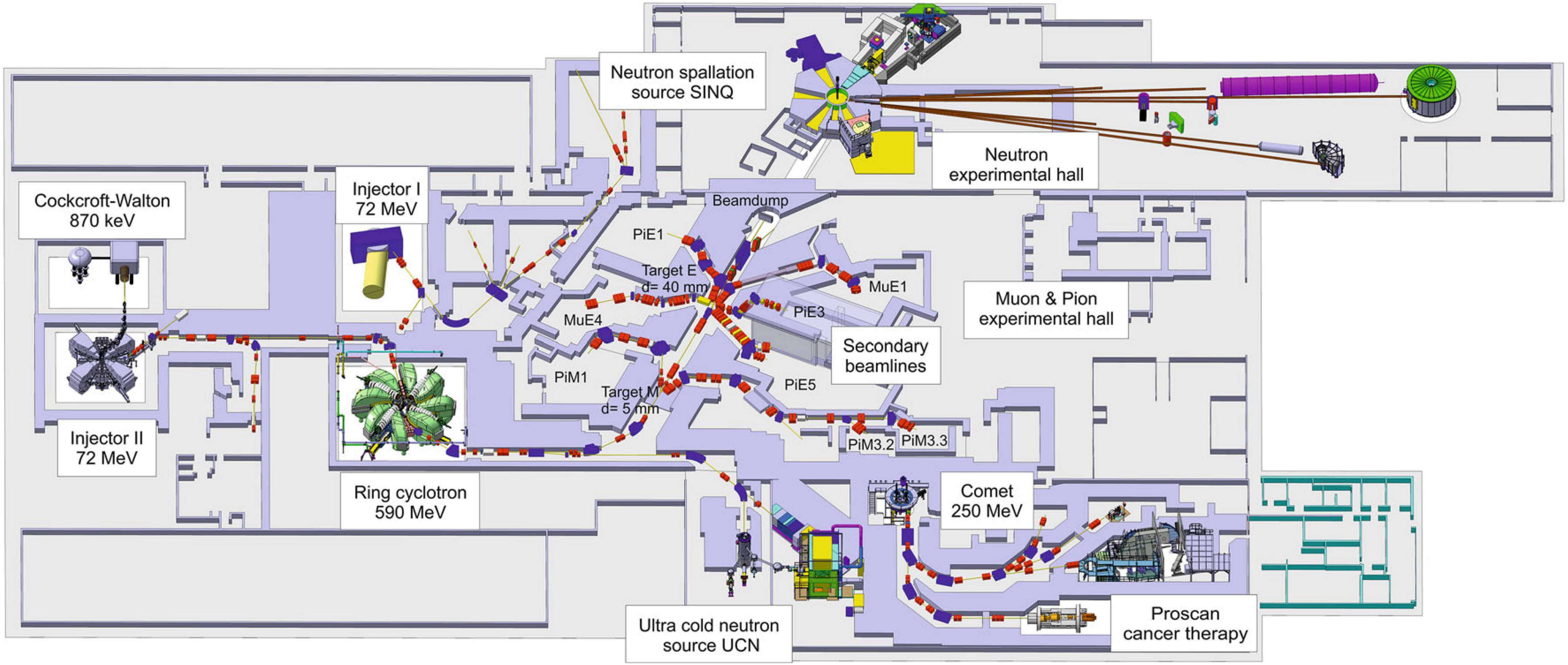




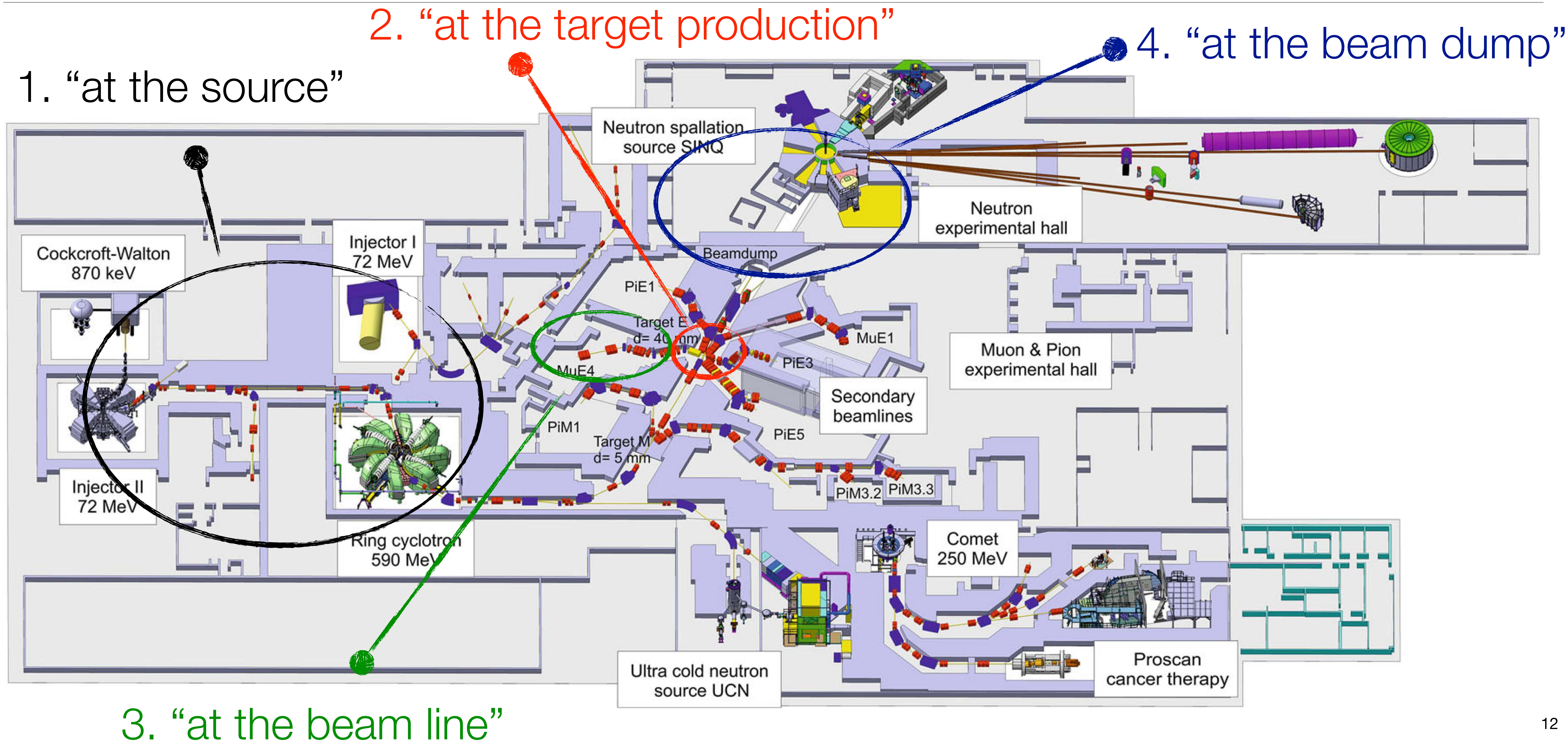
- Muon beams: **secondary** beam lines
- Low-energy muon beam lines typically tuned to surface-μ^+ at ~ 28 MeV/c
- **Note:** surface-μ —> polarised positively charged muons (spin antiparallel to the momentum)
- Contribution from cloud muons at similar momentum about 100x smaller
- Negative muons only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

How the beam intensity can be increased…

How the beam intensity can be increased…



How the beam intensity can be increased…

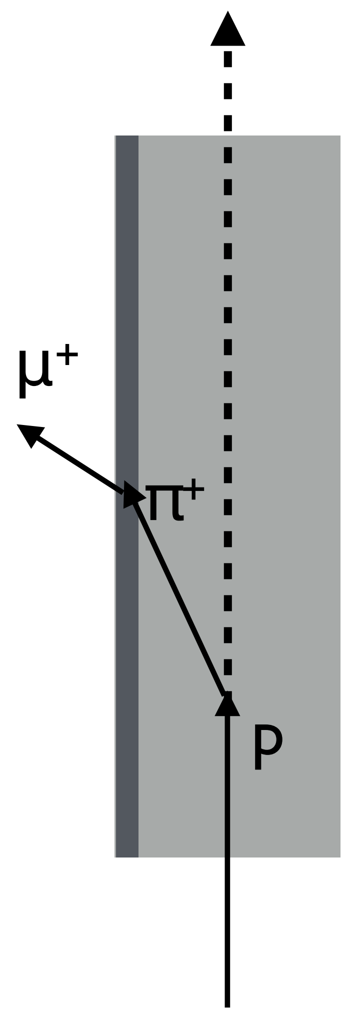


How the beam intensity can be increased…

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

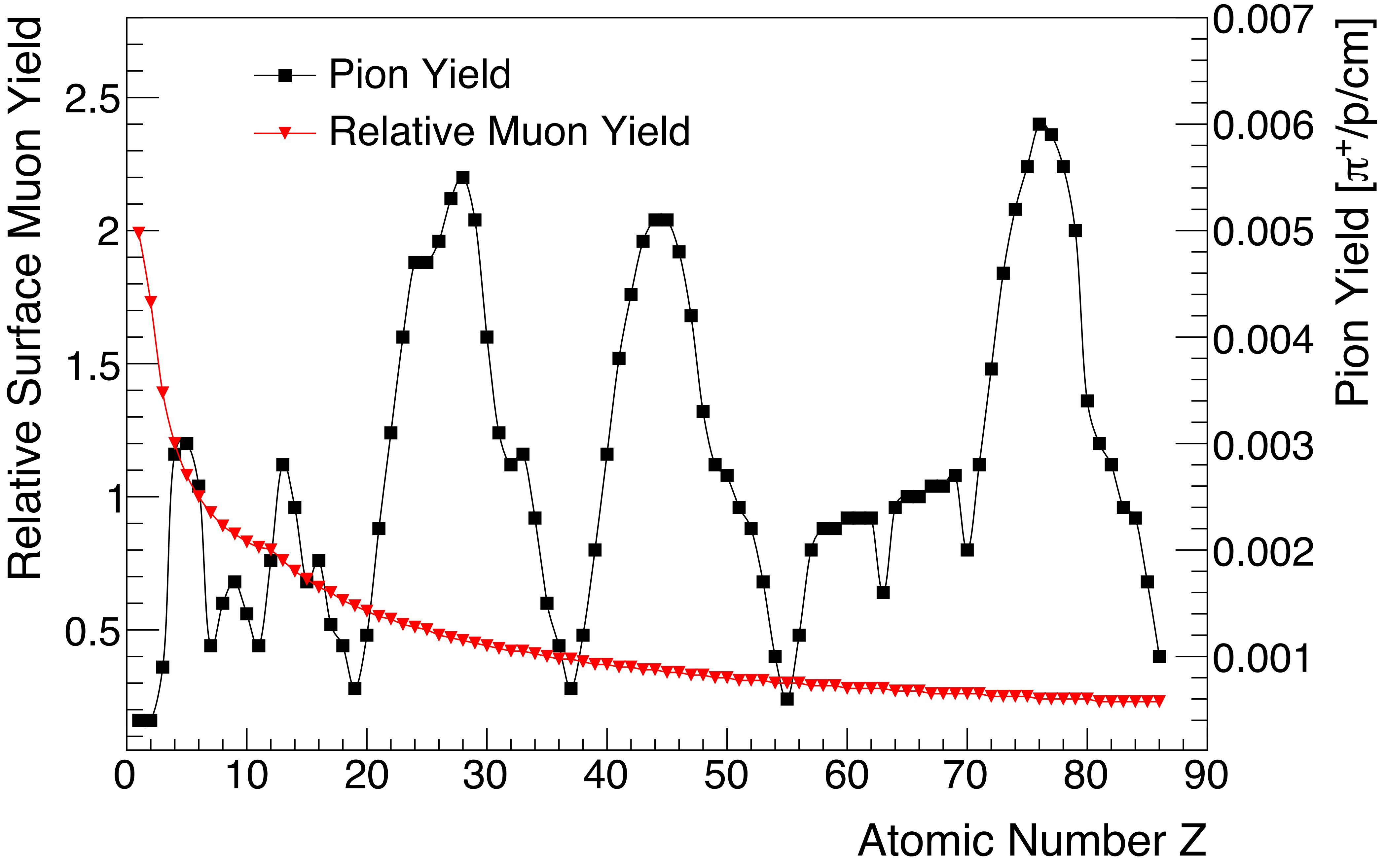


$$relative\ \mu^{+} yield \ \propto\ \pi^{+} stop\ density \cdot \mu^{+} Range \cdot length$$

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

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

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

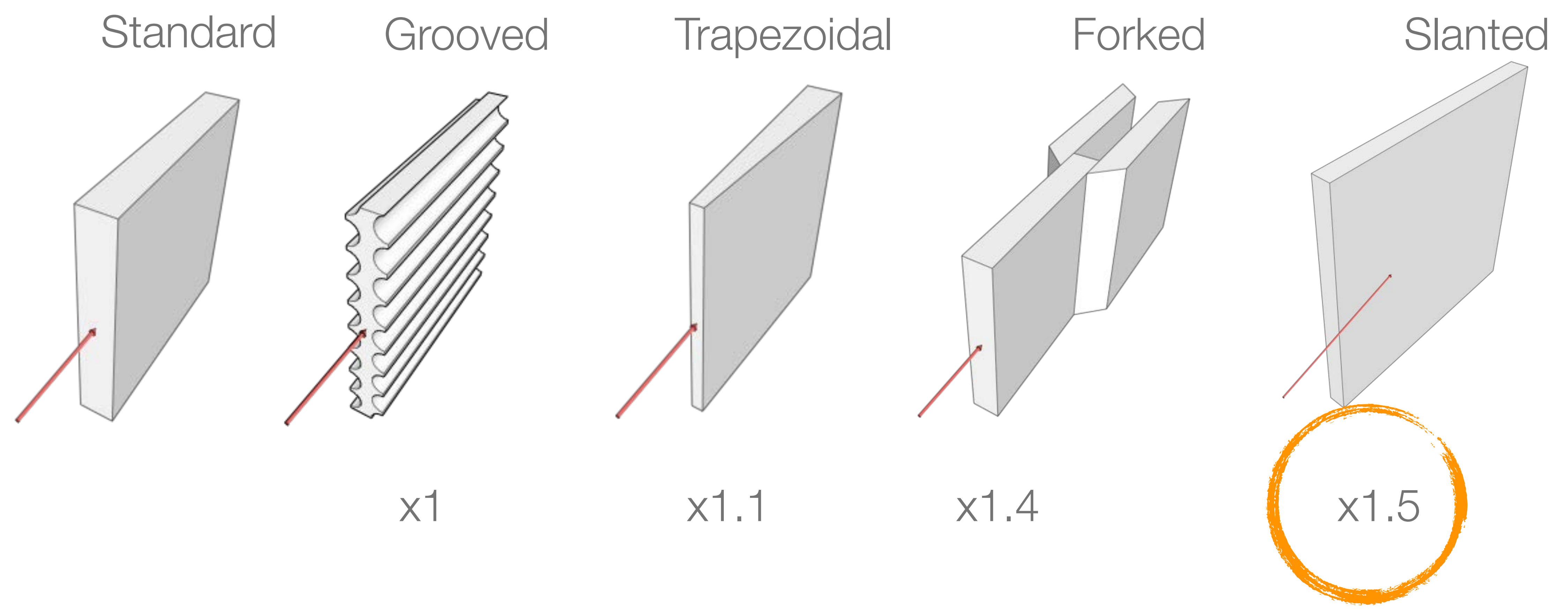


At the target:

- Optimised Target: Alternative materials and/or **different geometry**
  - 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

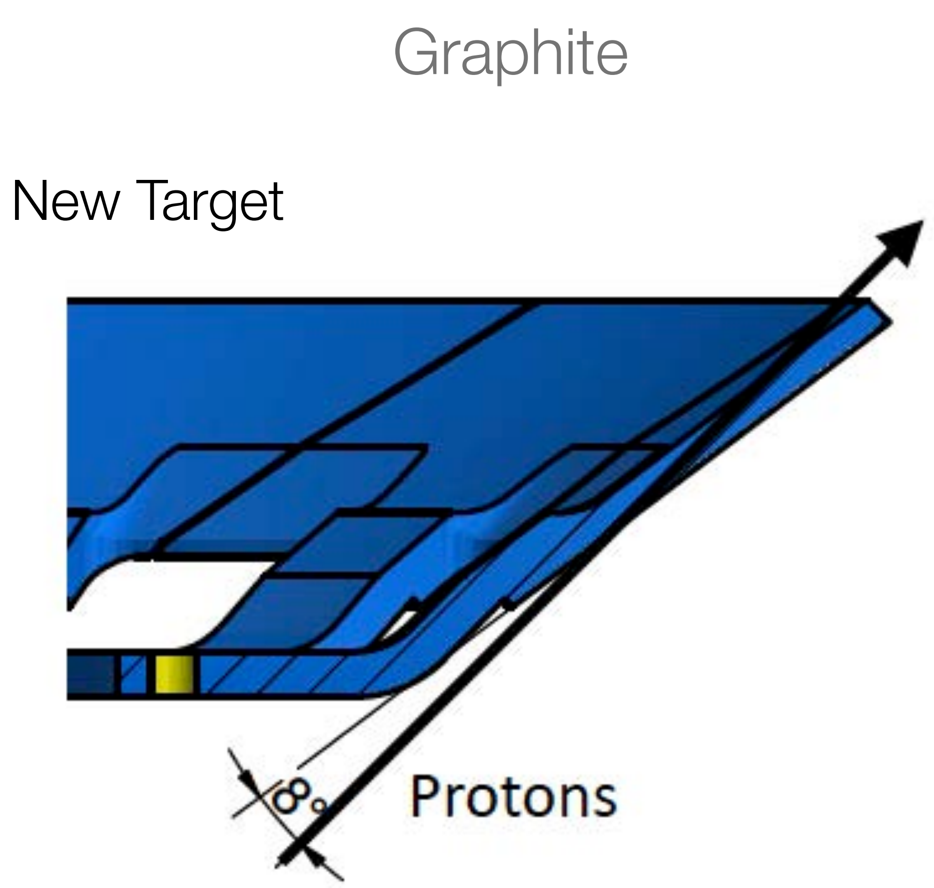
- Several materials have pion yields > 2x Carbon
- Relative muon yield favours low-Z materials, but difficult to construct as a target
- B_4C and Be_2C show 10-15% gain

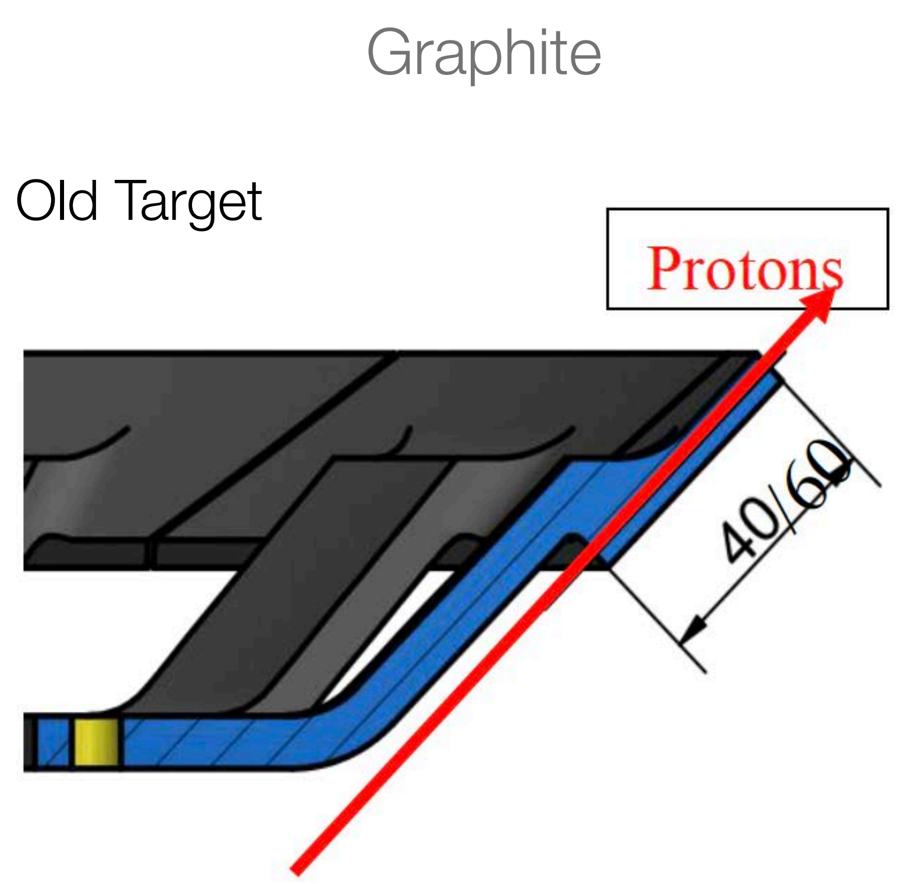
Note: Each geometry was required to preserve, as best as possible, the proton beam characteristics down-stream of the target station (spallation neutron source requirement)

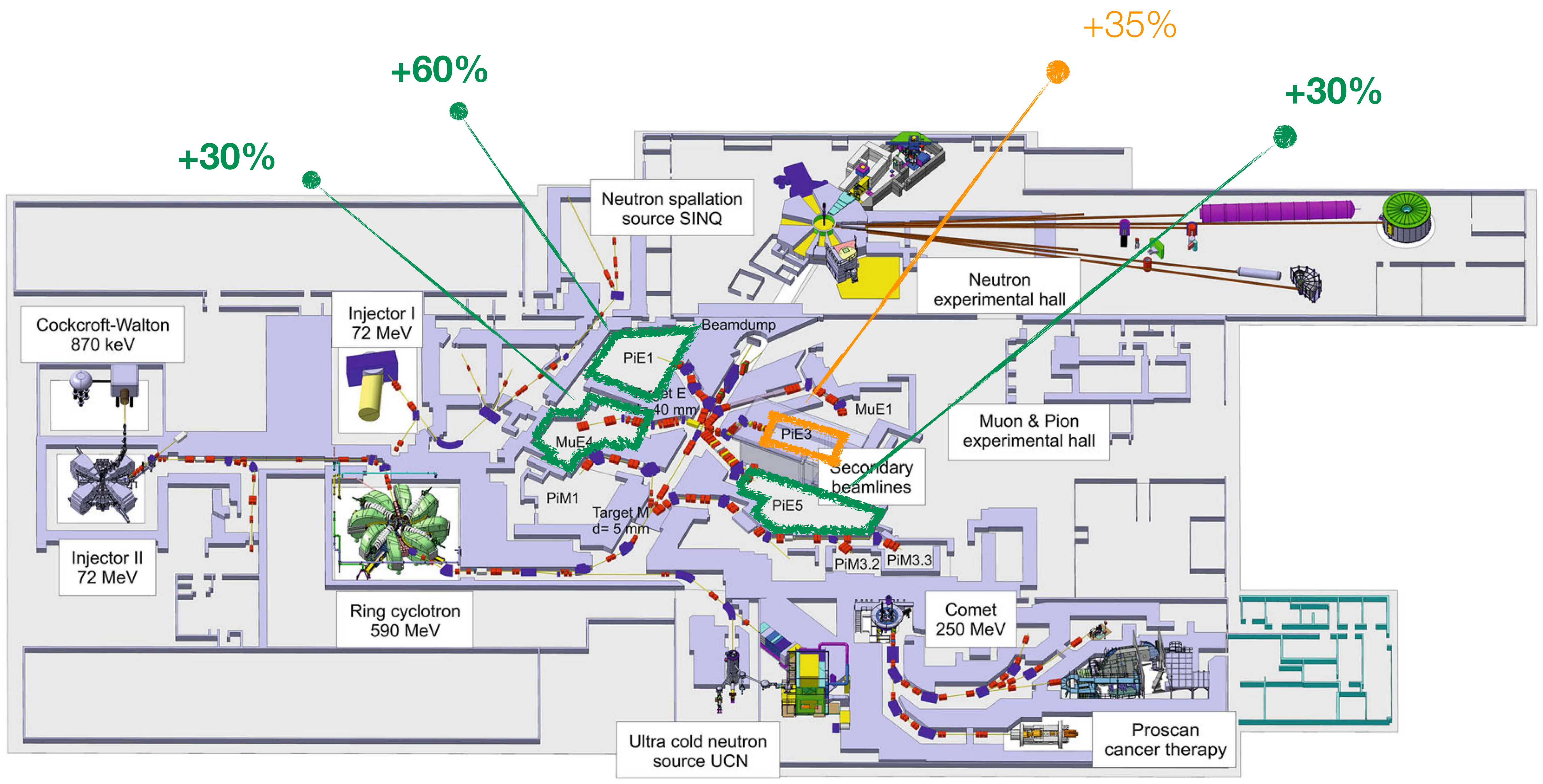


Slanted target: First test at the end of 2019

- 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**

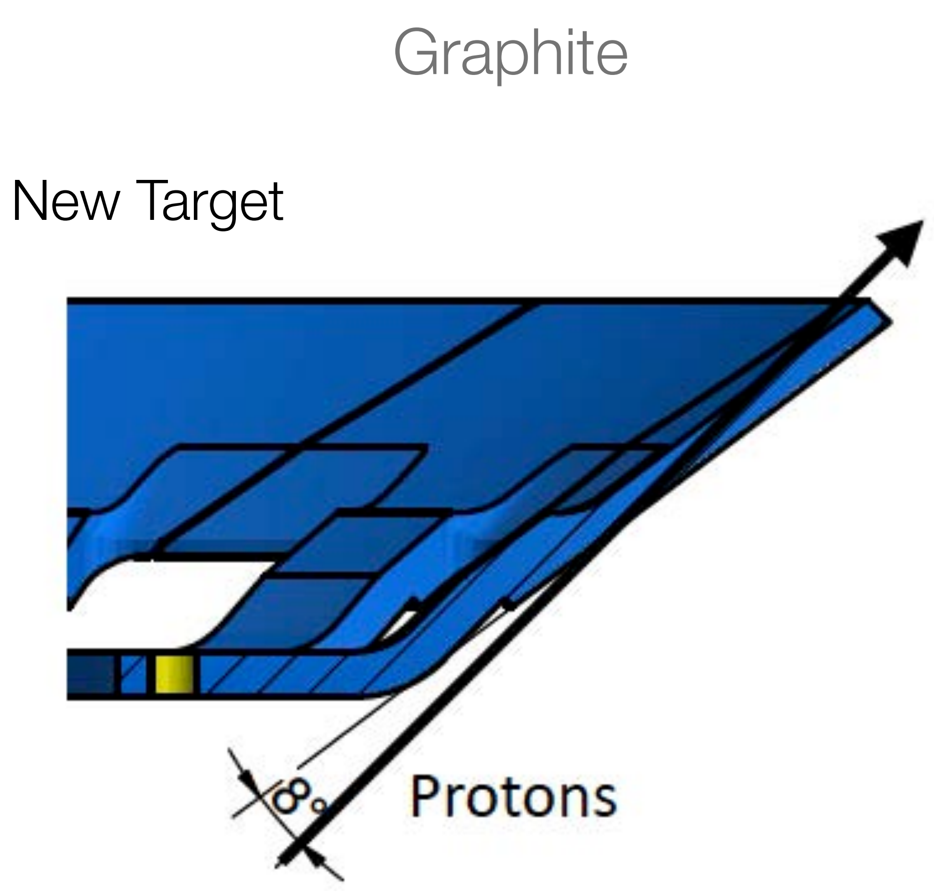


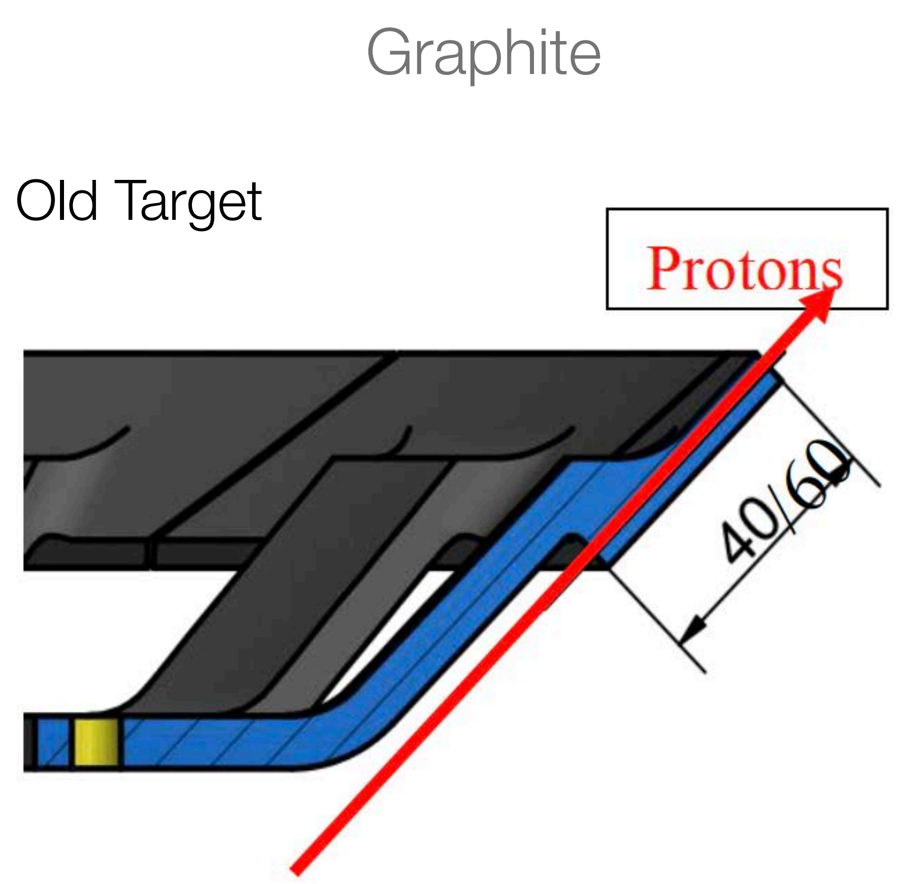


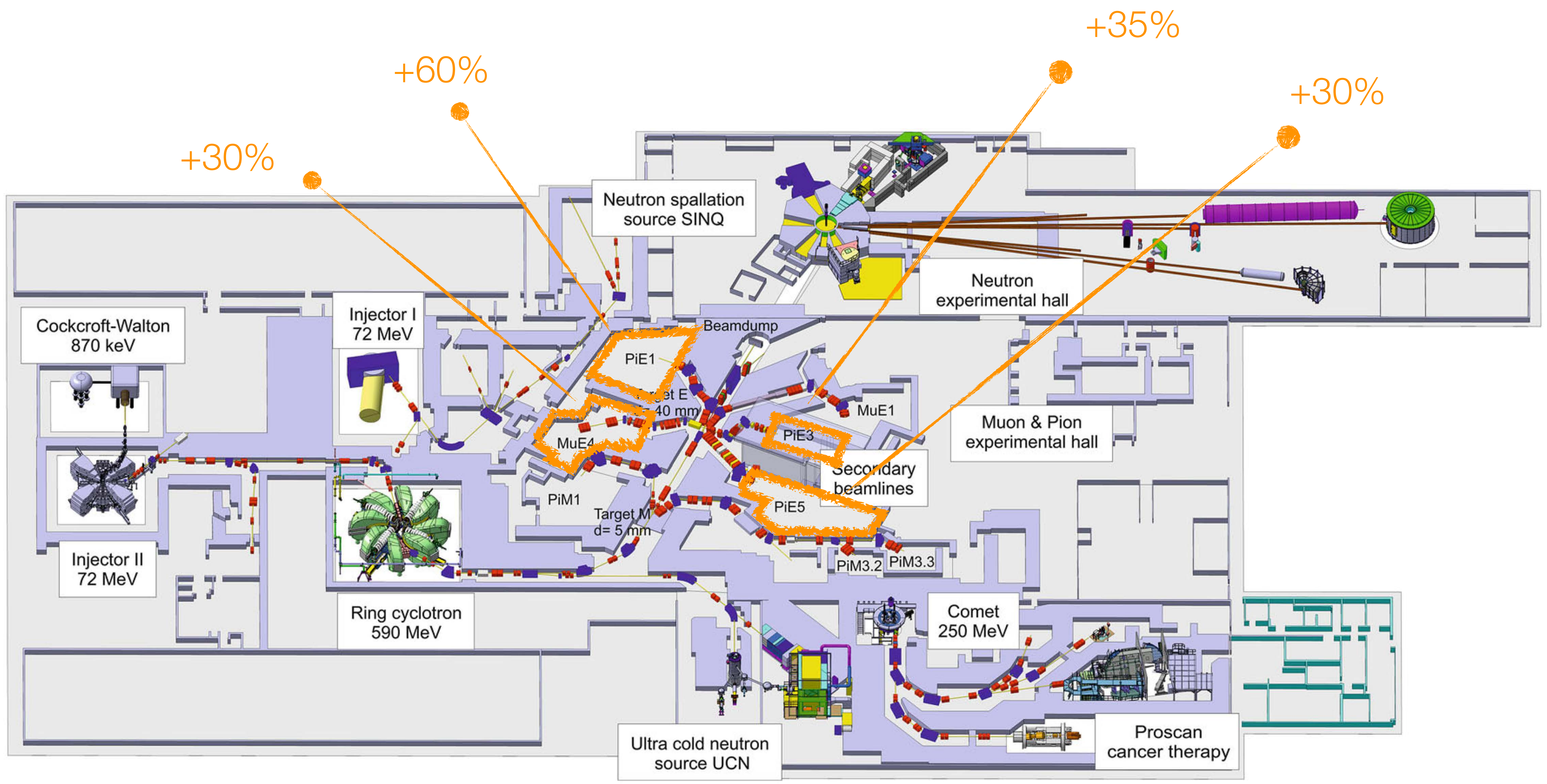


Slanted target: Impact

- 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

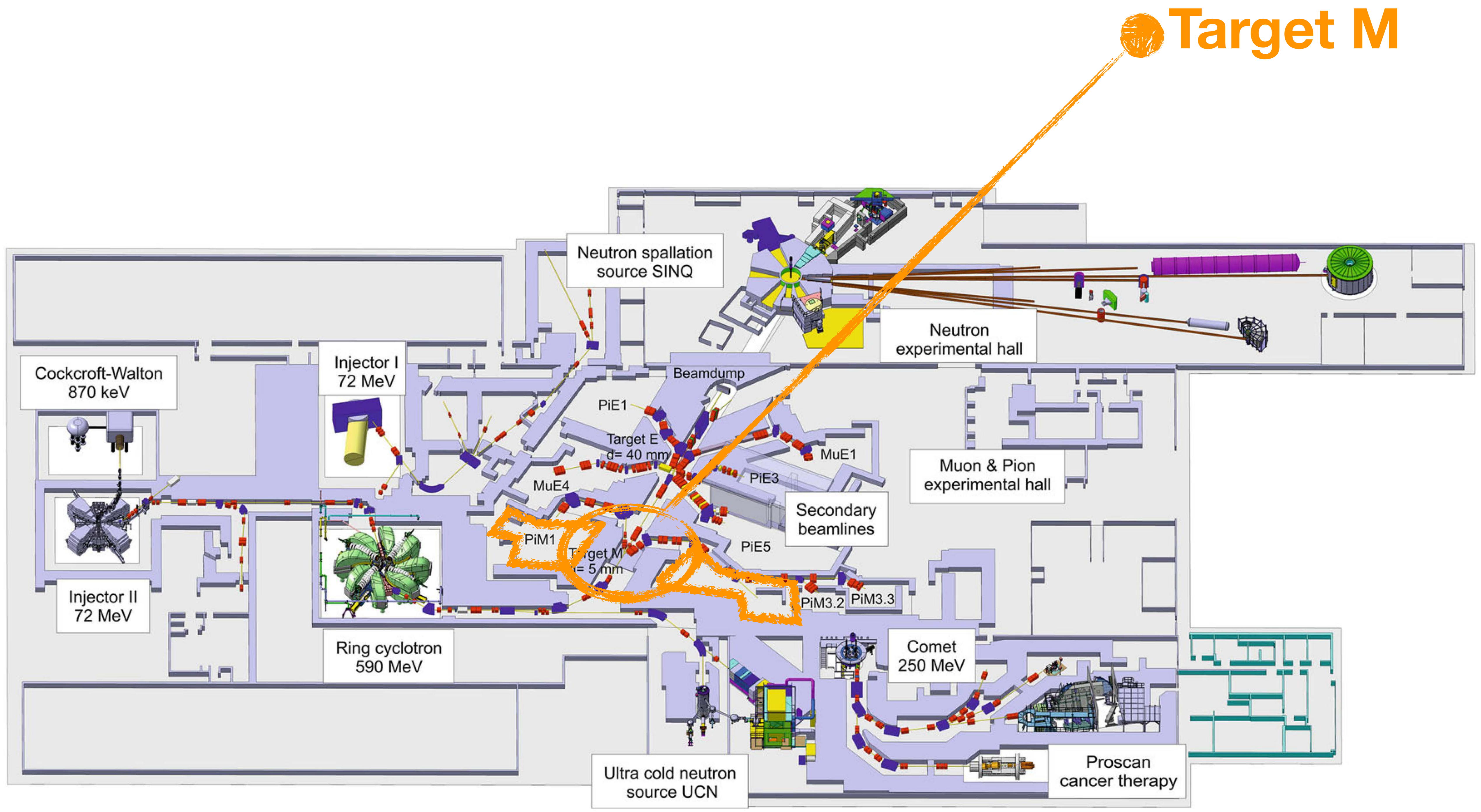


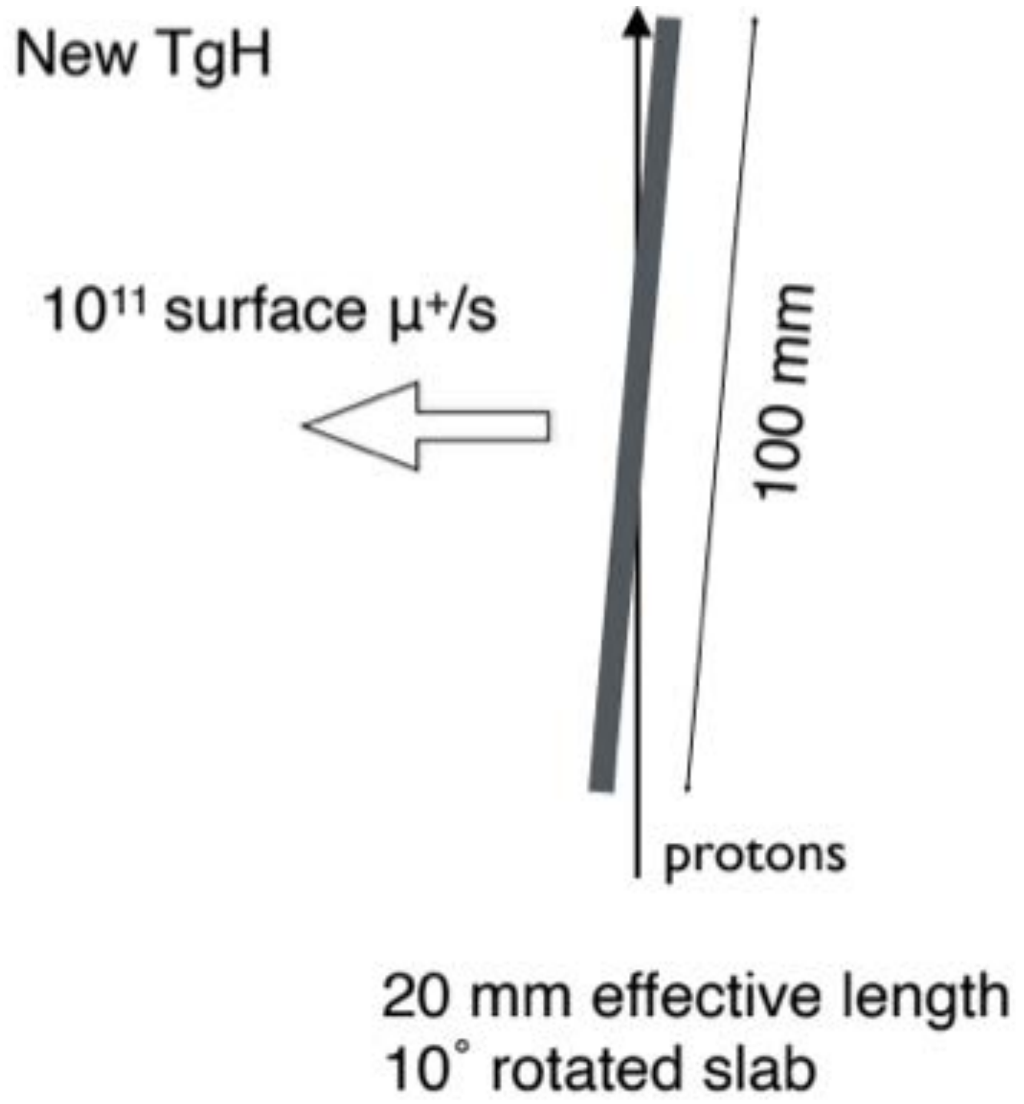




The HiMB target: TgH

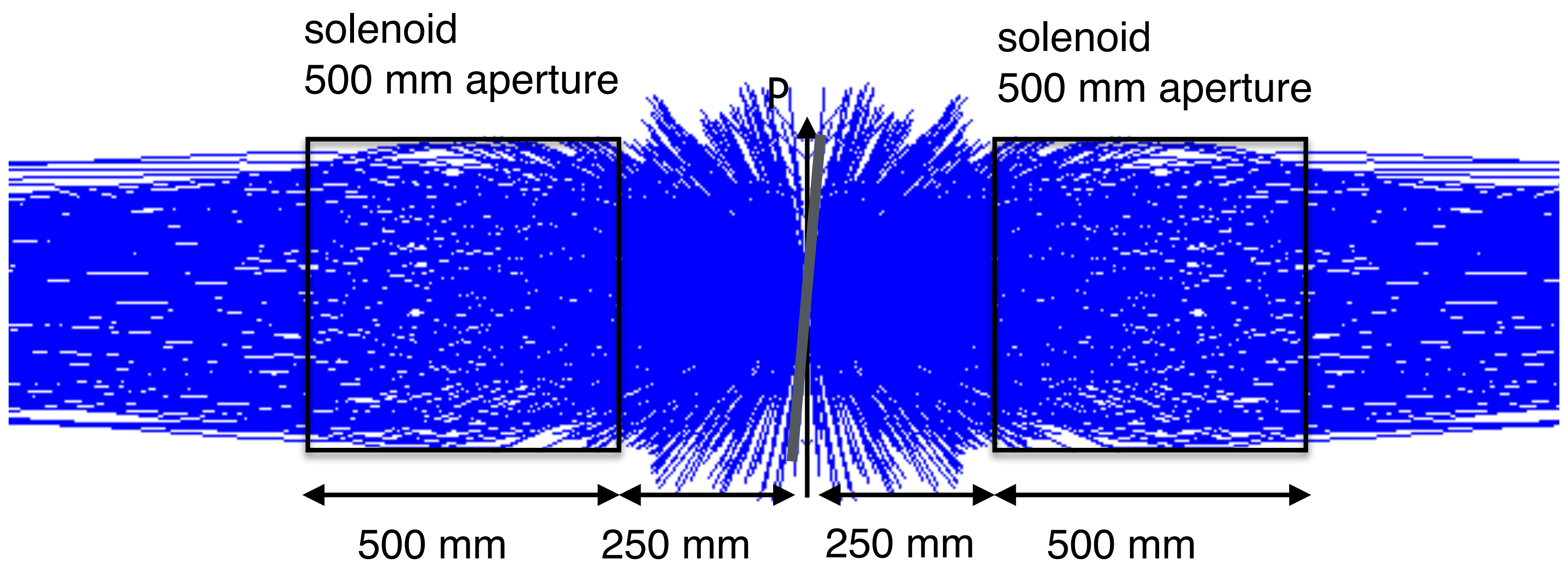
- **Final position for the HiMB target: “Present" Target M location**
- ~90° extraction to existing experimental areas
- Large phase space acceptance solenoidal channel





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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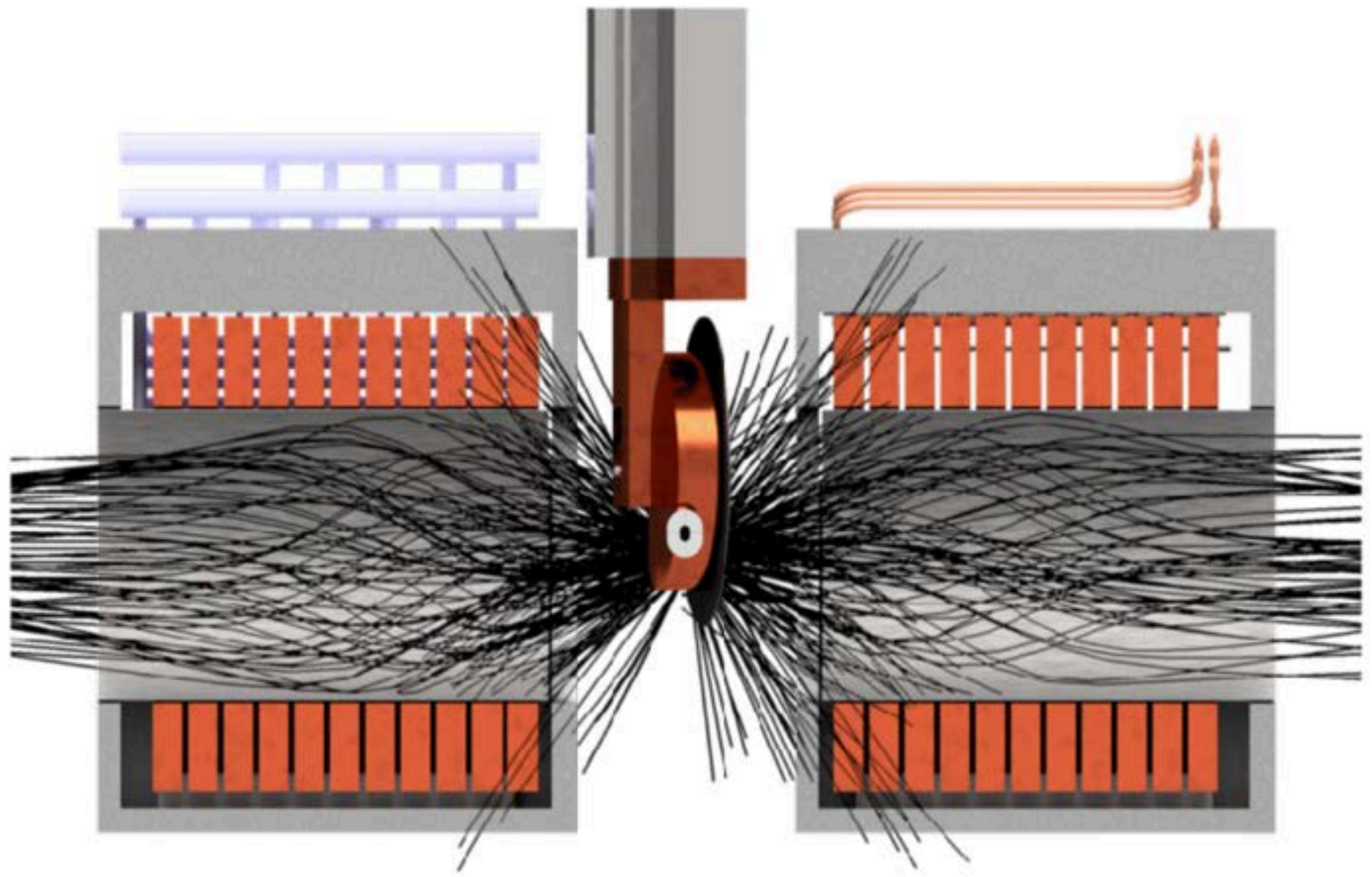
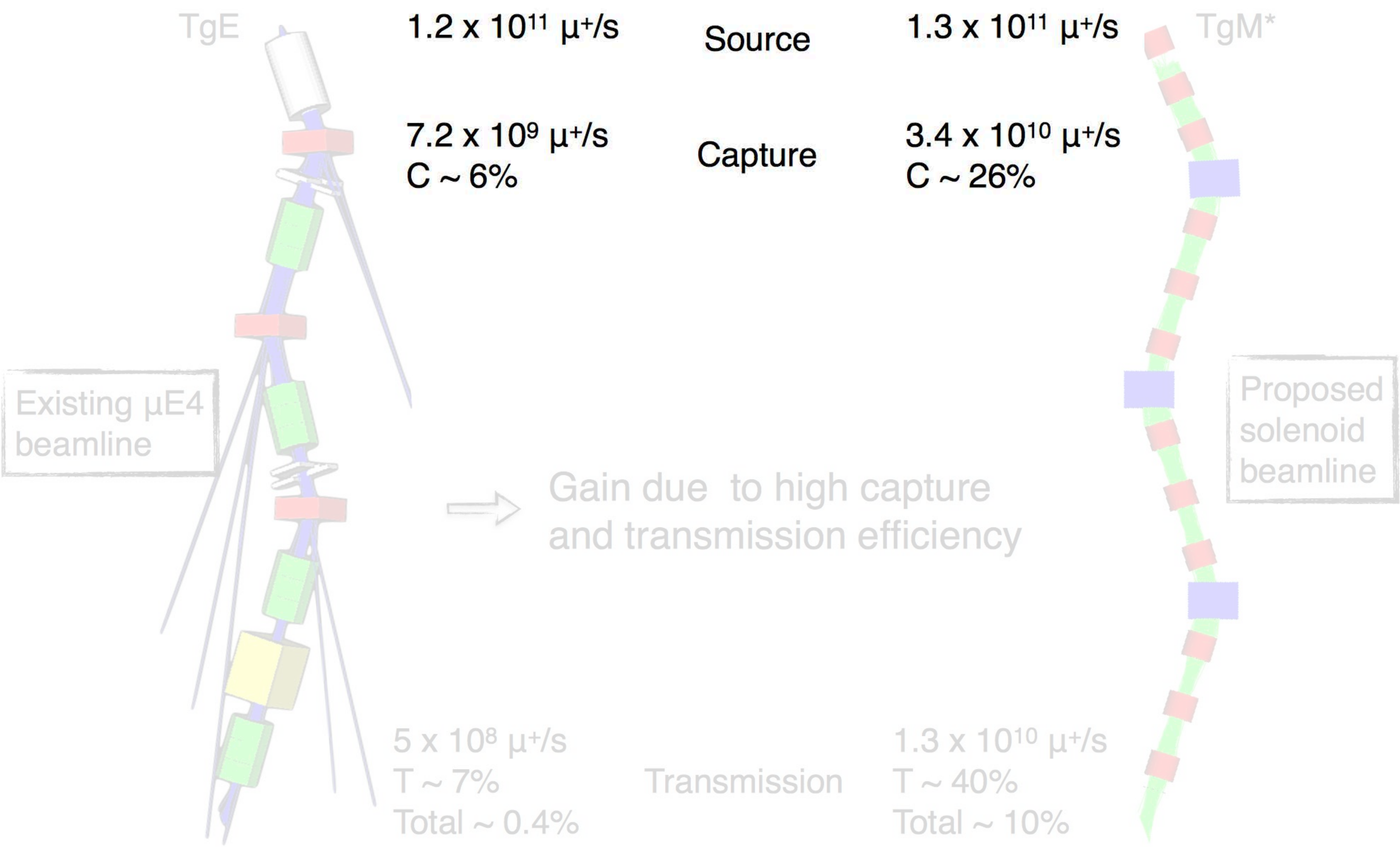
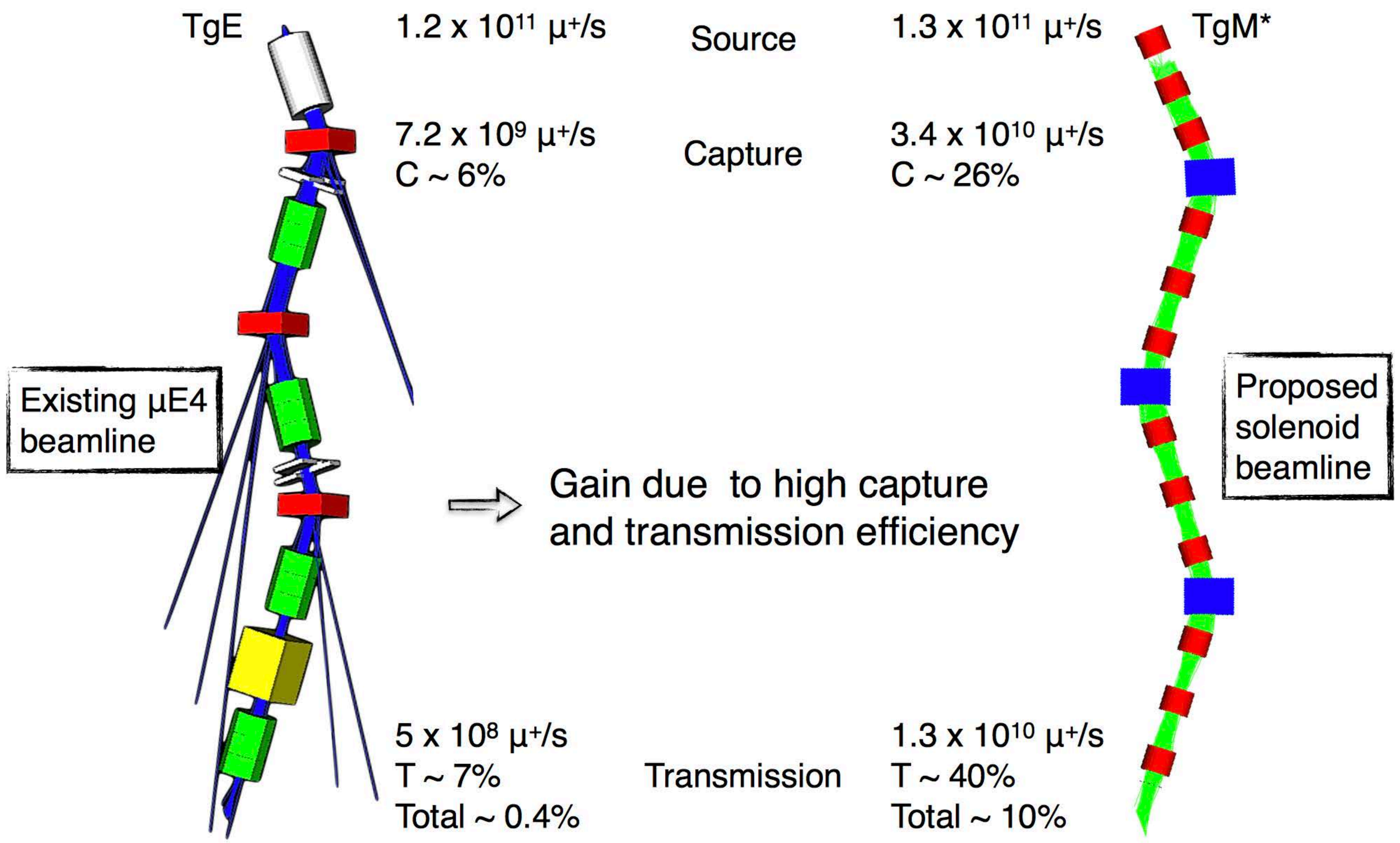


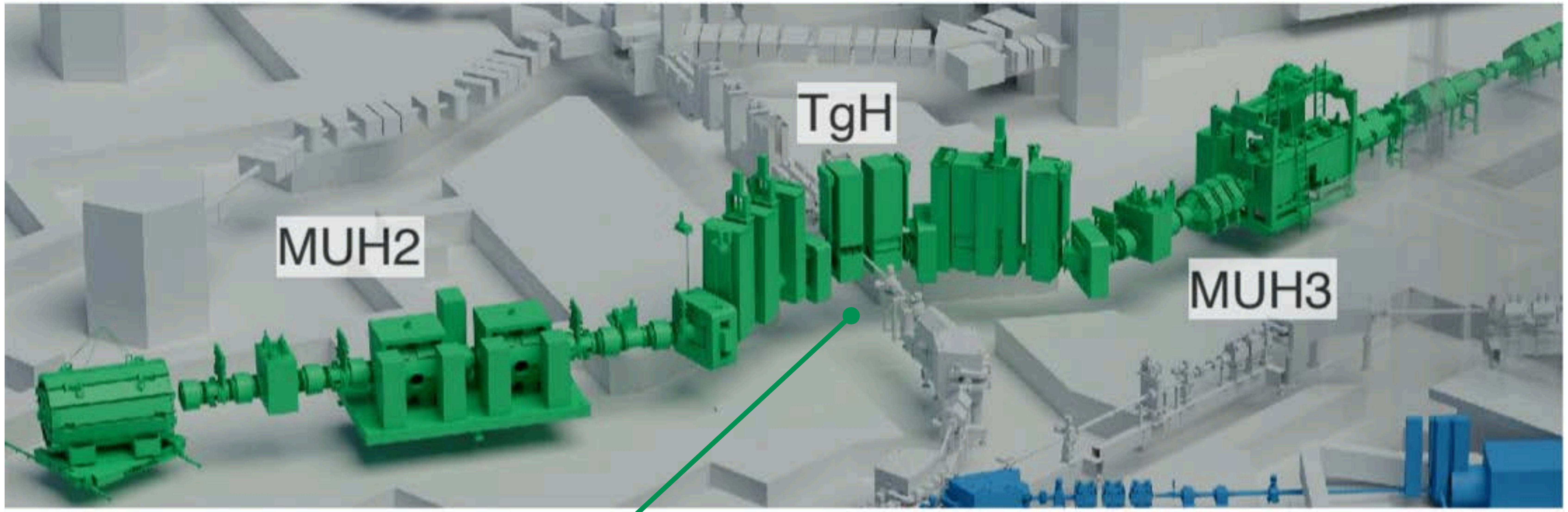


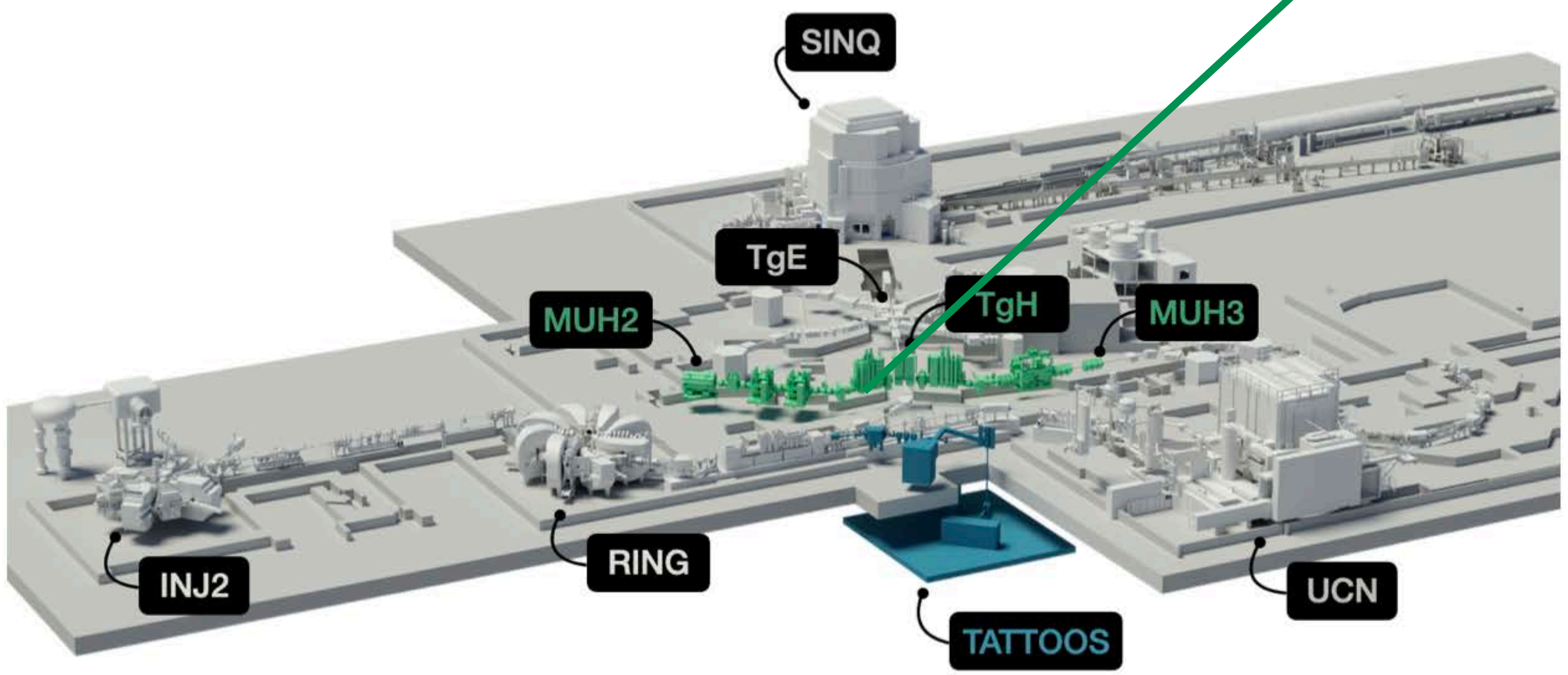
Along the beam line

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



MUH2 and MUH3 beamlines

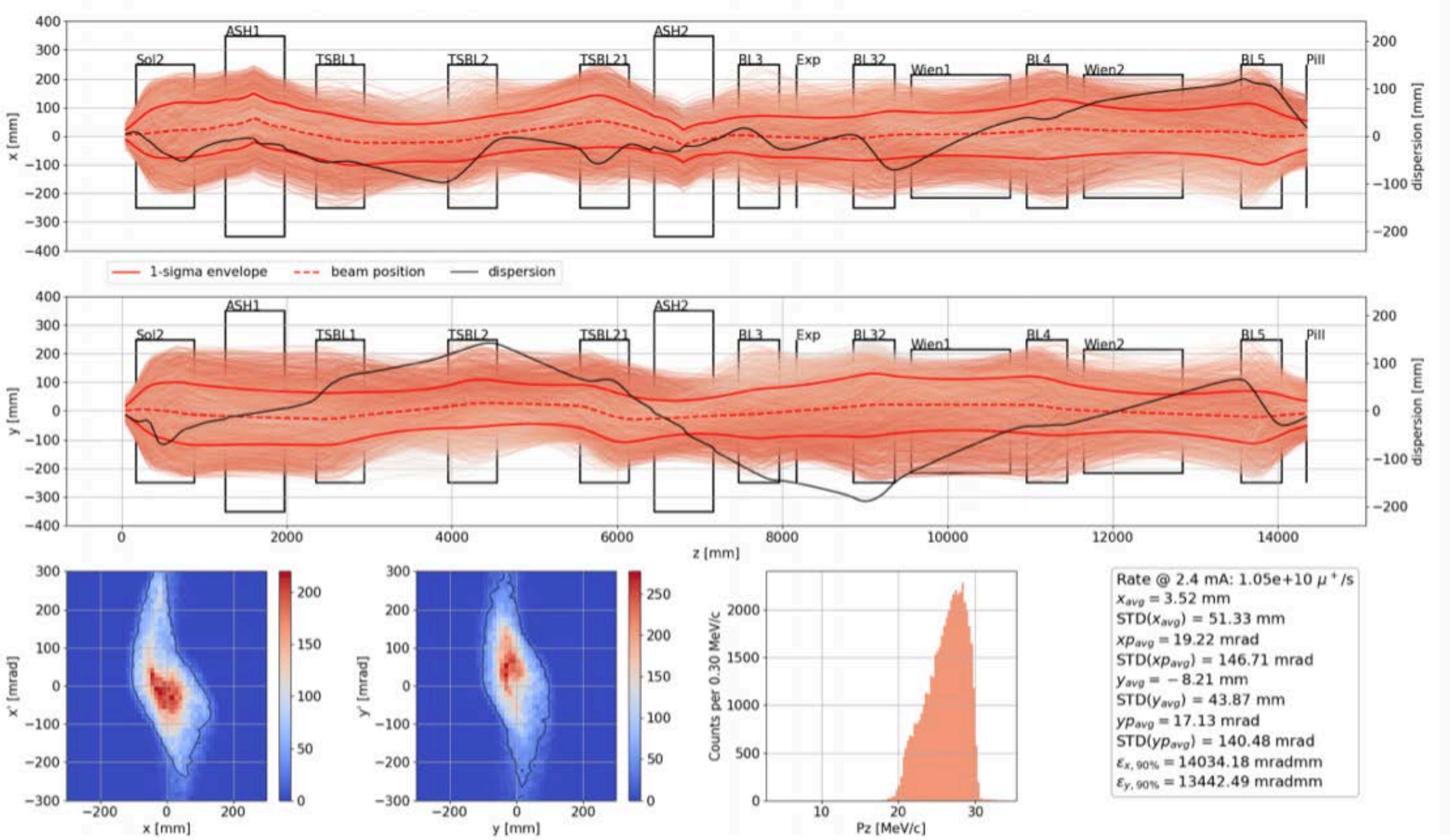


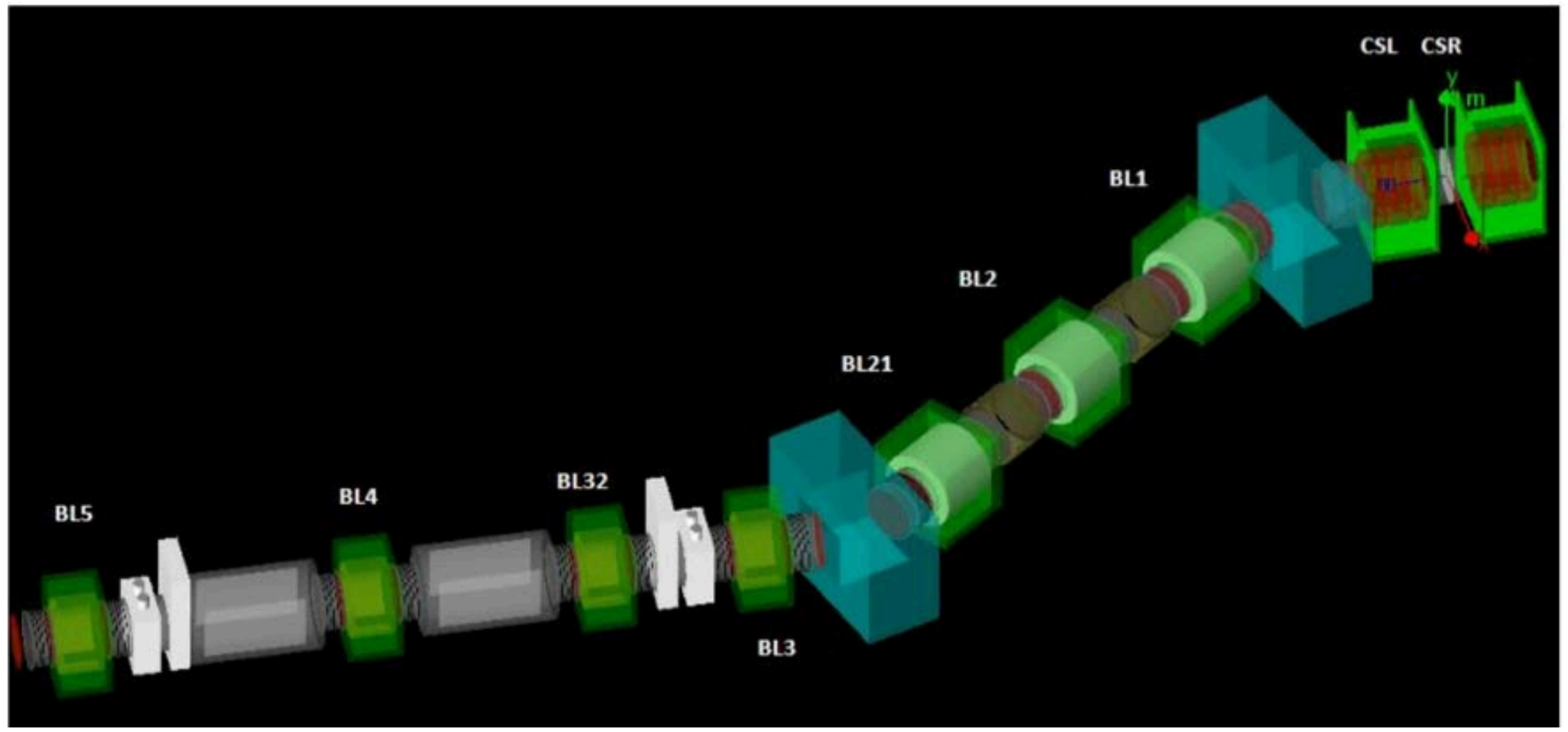


- ~90° extraction with first bend in upstream direction
- MUH2 for particle physics
- MUH3 for muSR research [H. Luetkens's talk]

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





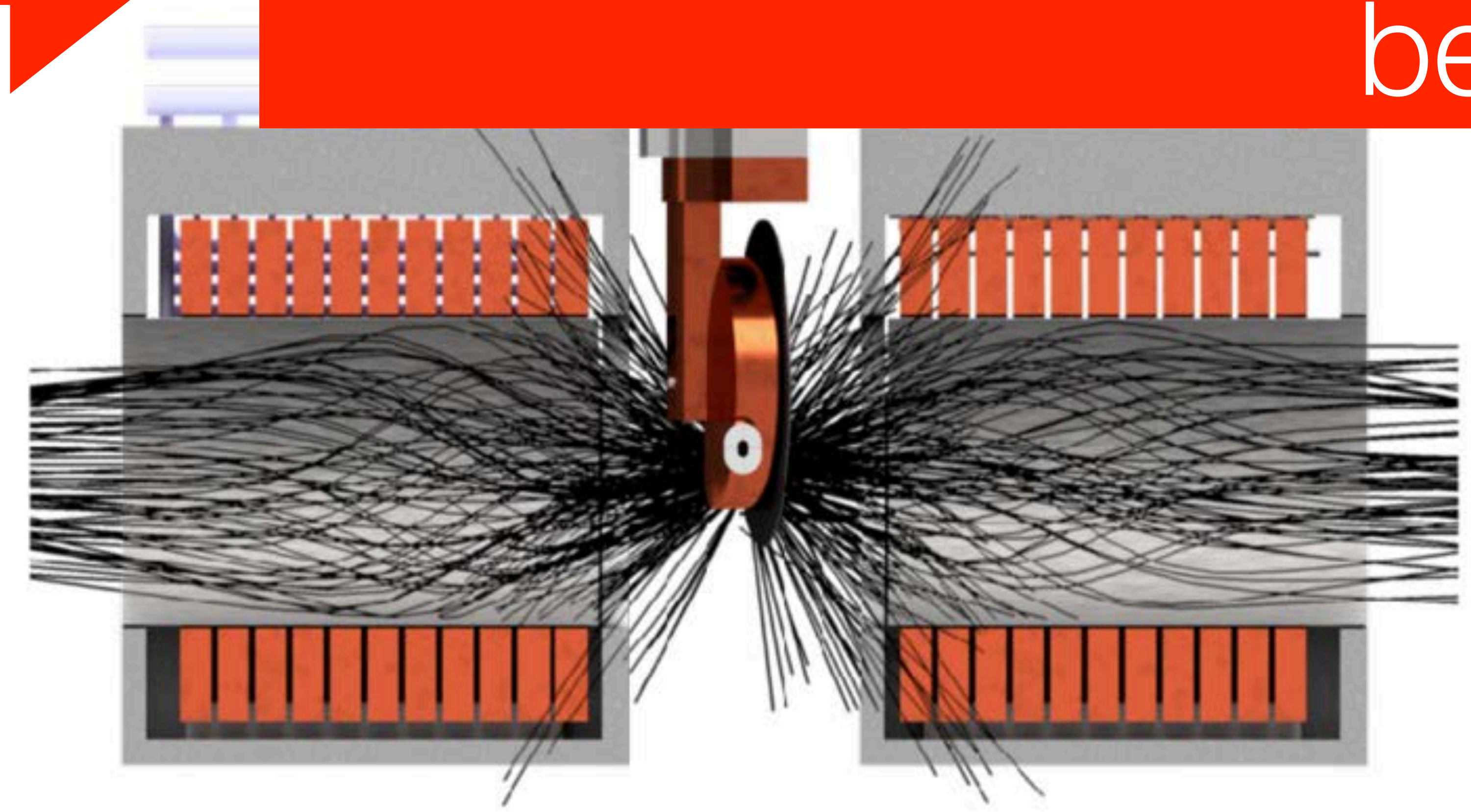
At the target + along the beam line

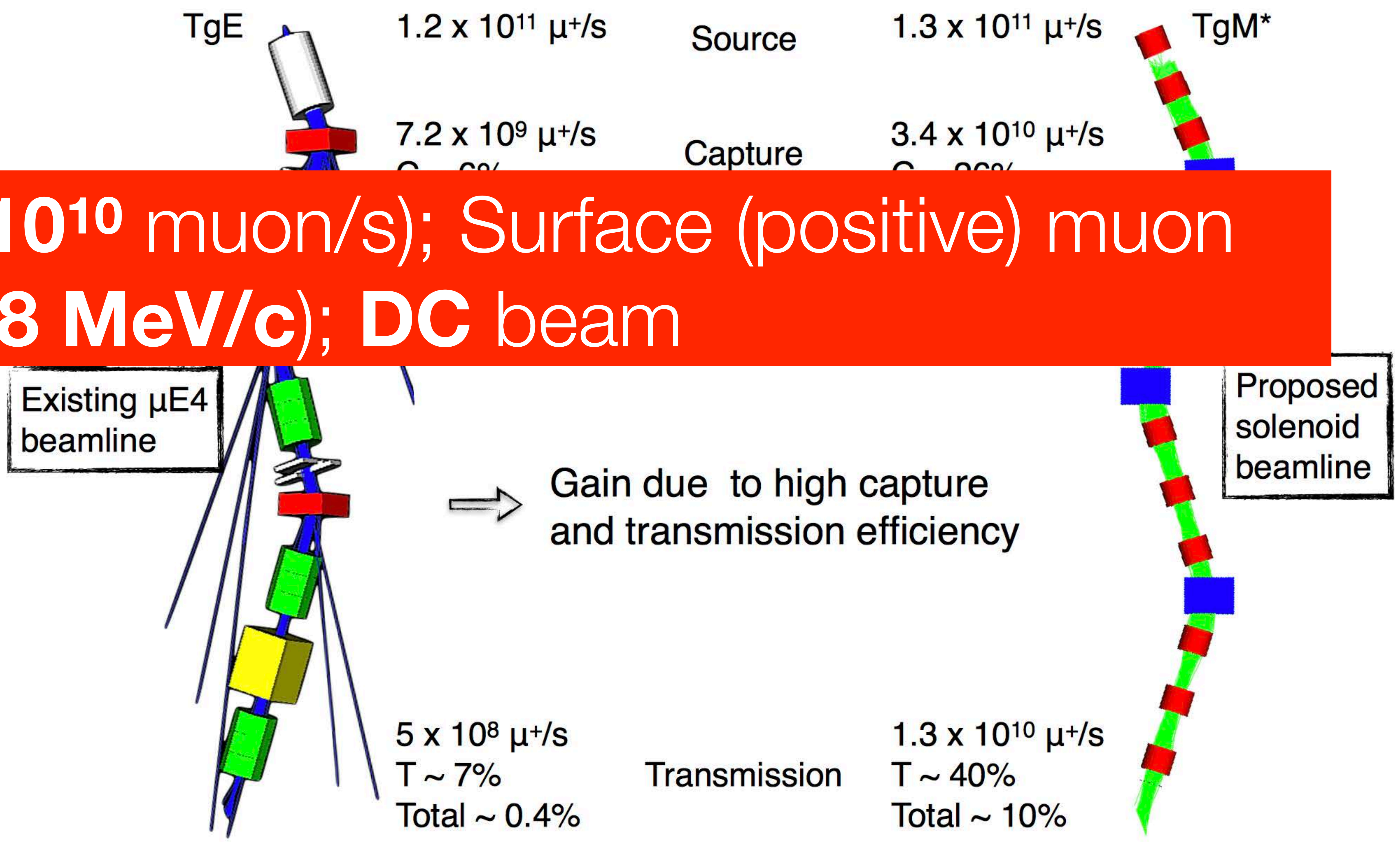
- Optimised beam line: increased capture and transmission

  - 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





A quick departure: The HiMB project at the beam dump

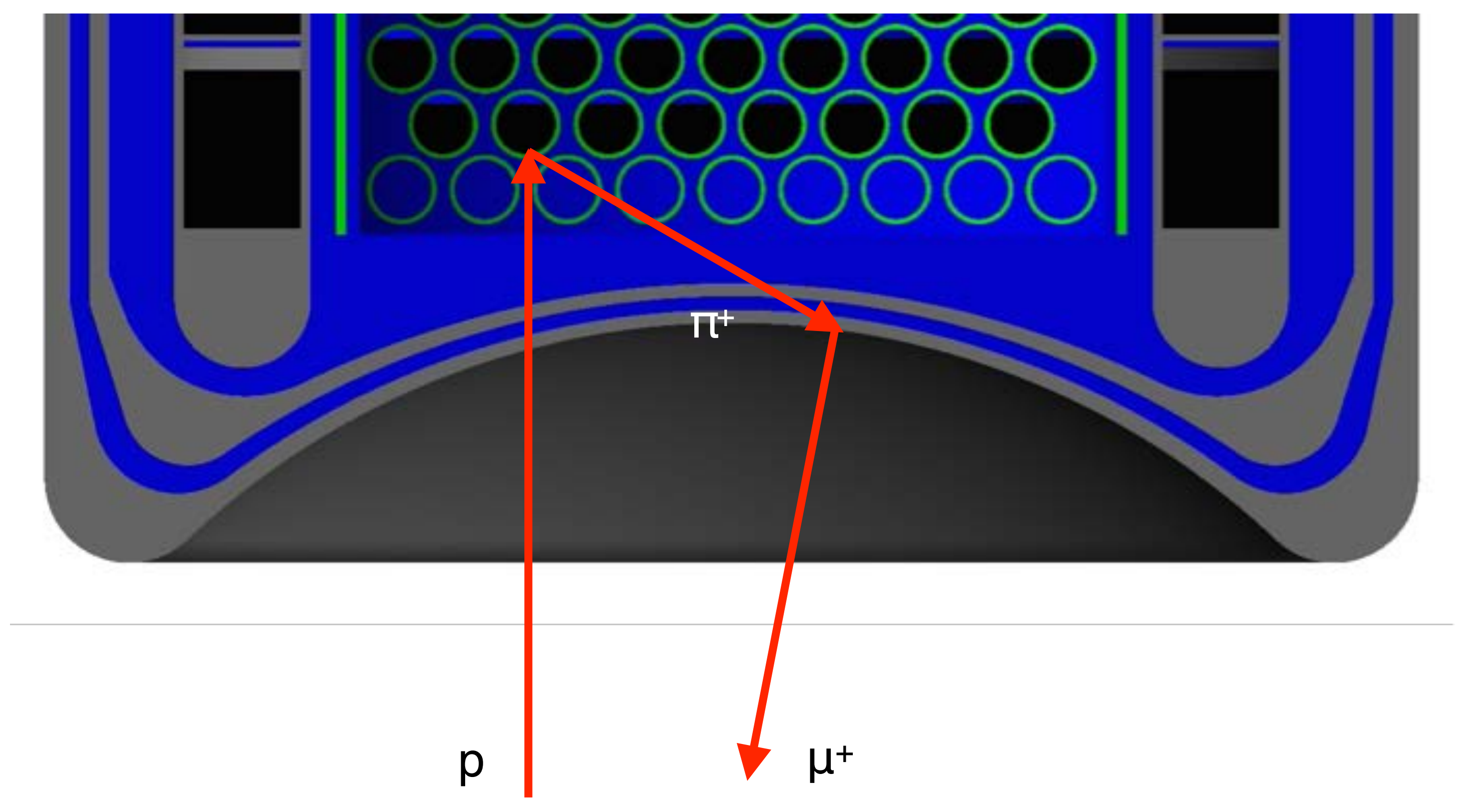
- Source simulation (below safety window):
  9 x 10^{10} surface-μ^+/s @ 1.7 mA I_p
- Profit from stopping of full beam
- Residual proton beam (~1 MW) dumped on SINQ

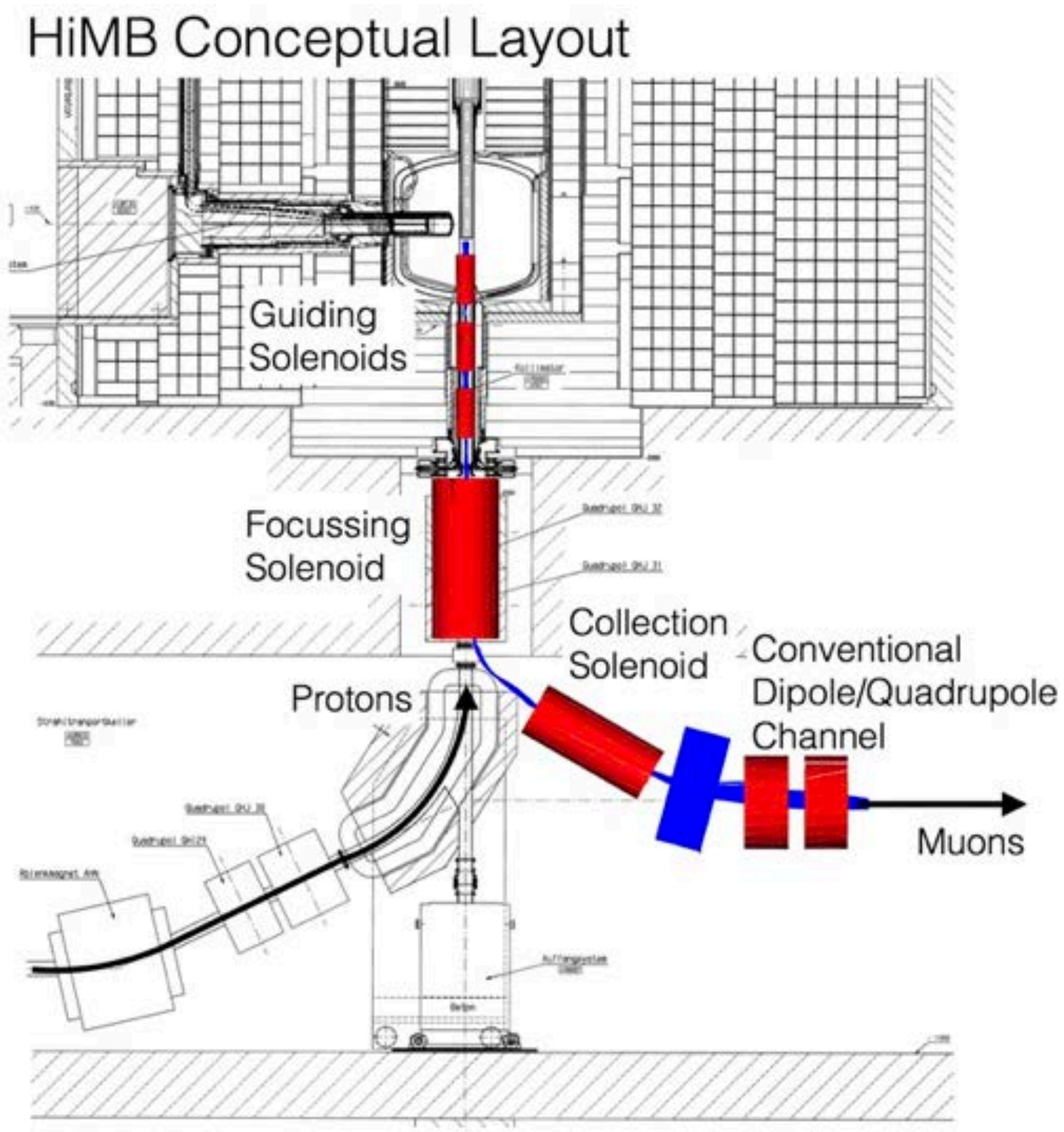
- Replace existing quadrupoles with solenoids:
  - Preserve proton beam footprint
  - Capture backward travelling surface muons
- Extract muons in Dipole fringe field
- Backward travelling pions stopped in beam window

- 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

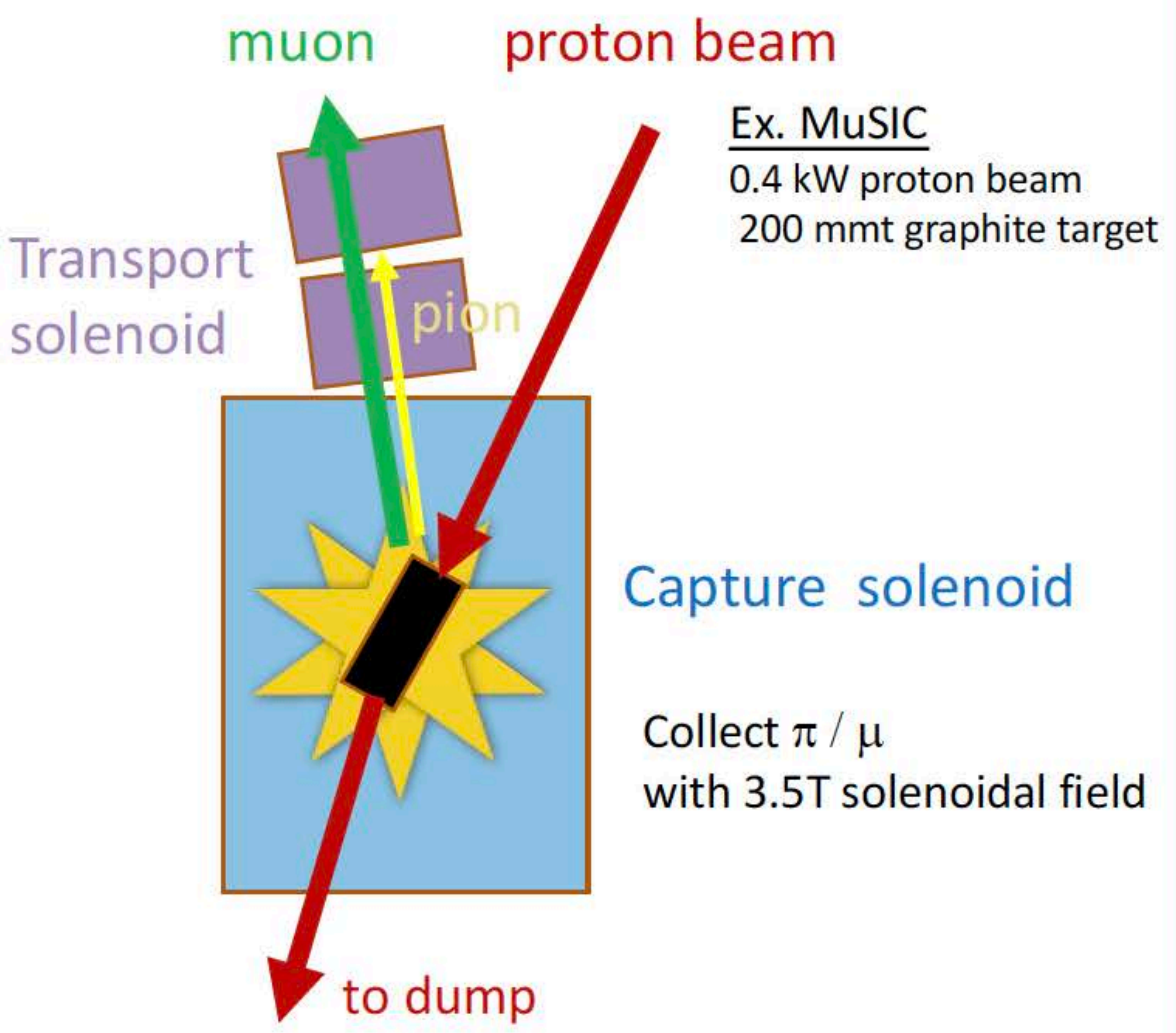
- **Due these constraints** and after several iterations with different capturing elements:
  - **Not enough captures muons to make an high intensity beam**
  - **Alternative solution: HiMB @ EH**

SINQ spallation target



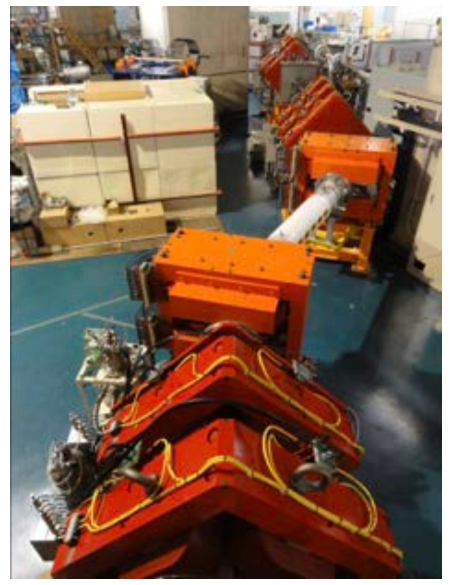


MuSIC's muon beams



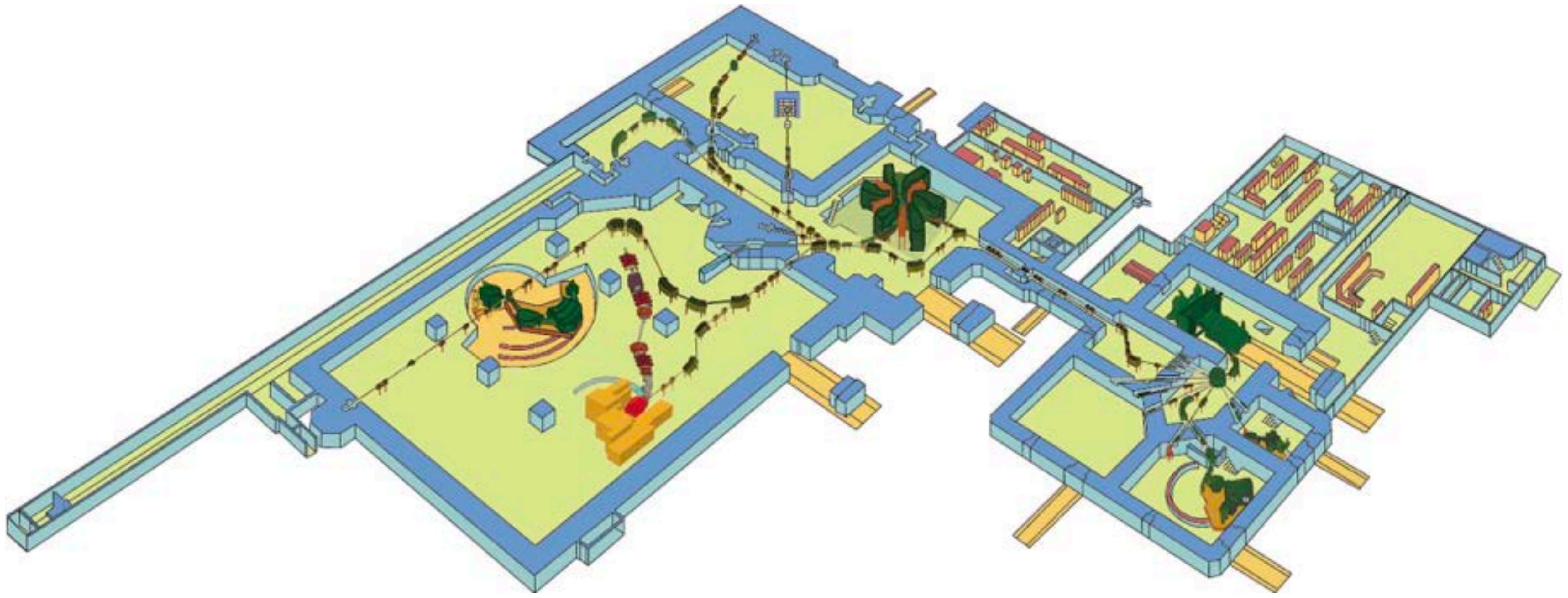
- Thick target (200mmt)
- Large solid angle, good collection efficiency
- No muon spin selection (no selection of pion / muon momentum)

- 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)

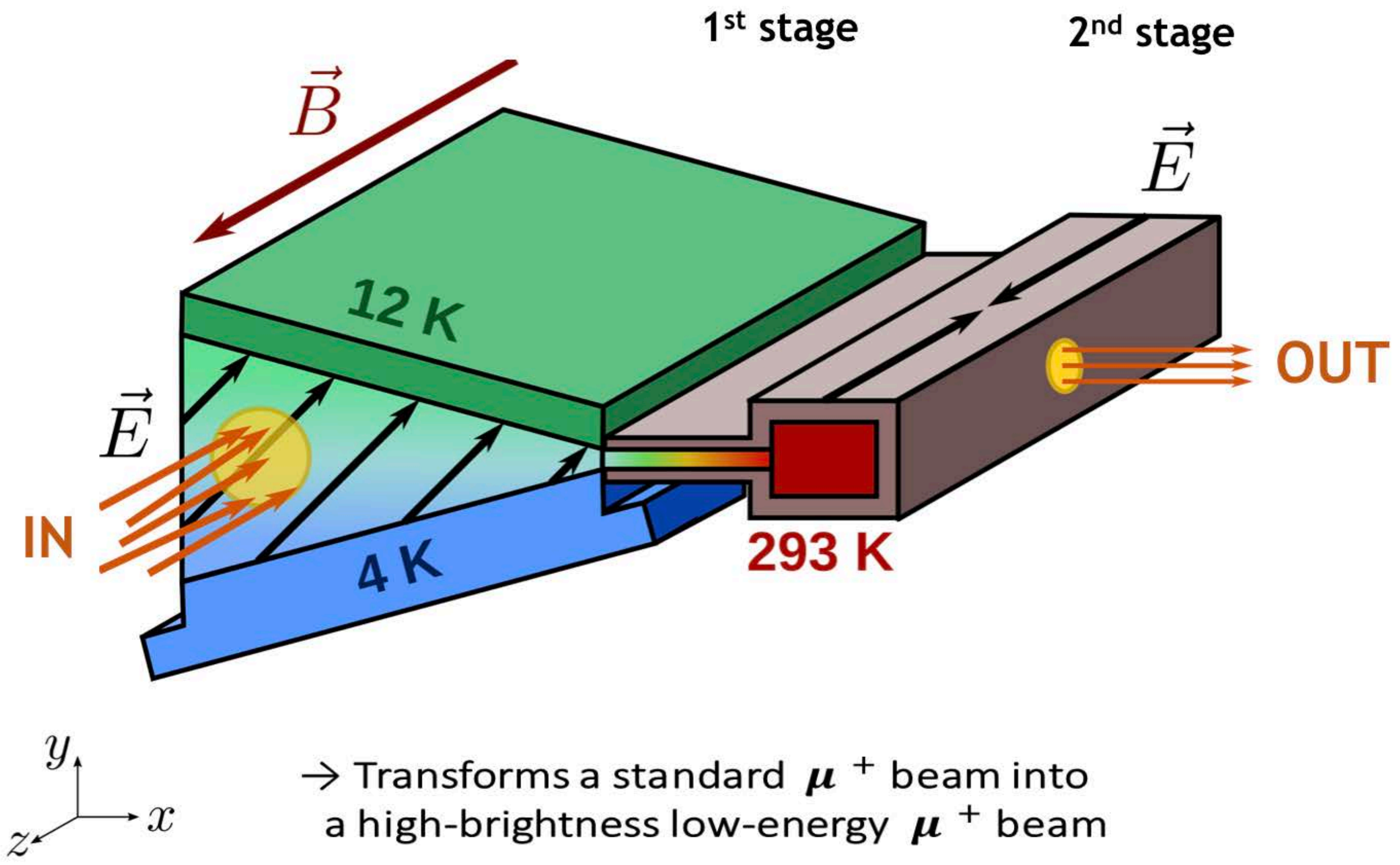


- proton beam energy is only 100 MeV above pion production threshold (～$2m_{\pi}$)
- muon source with low proton power (1.1 uA ~0.4kW, 5 uA in future)

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
- **σ** = 10 mm
- E = 4 MeV
- Continuous

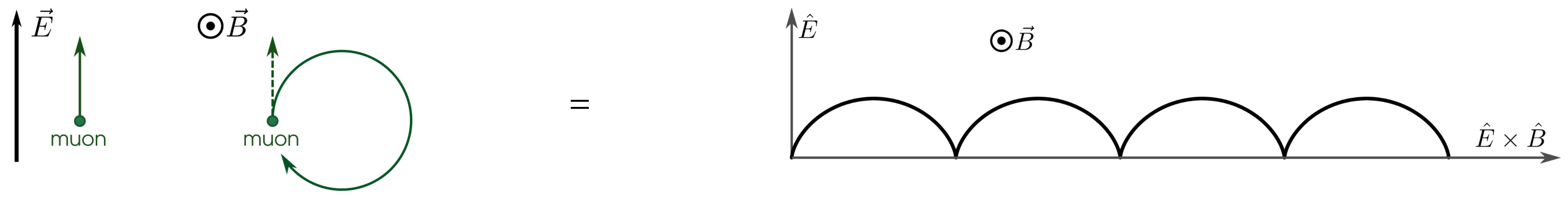


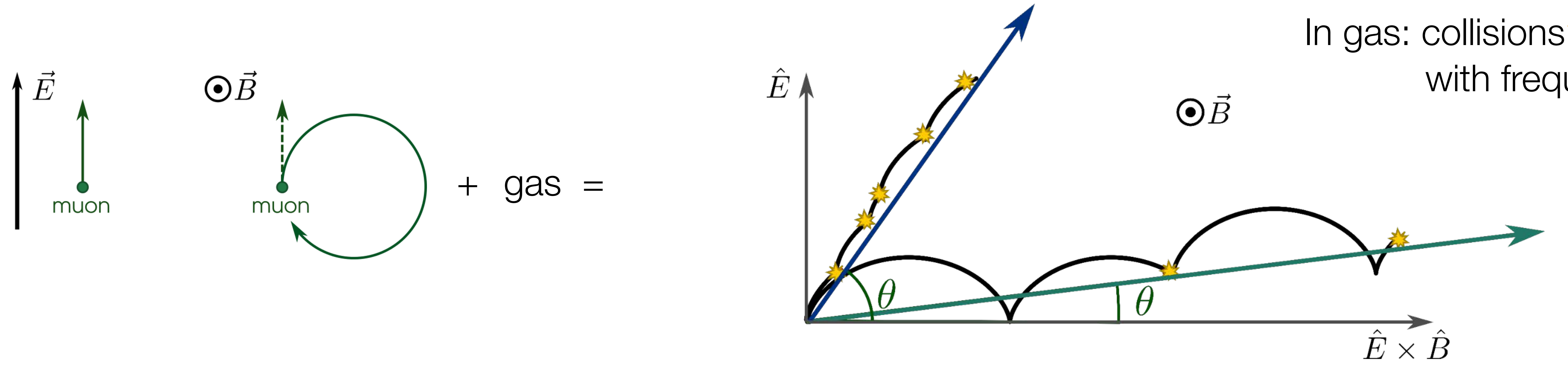
muCool/tertiary μ^+ beam
- **σ** < 1mm
- E < eV
- Tagged

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

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

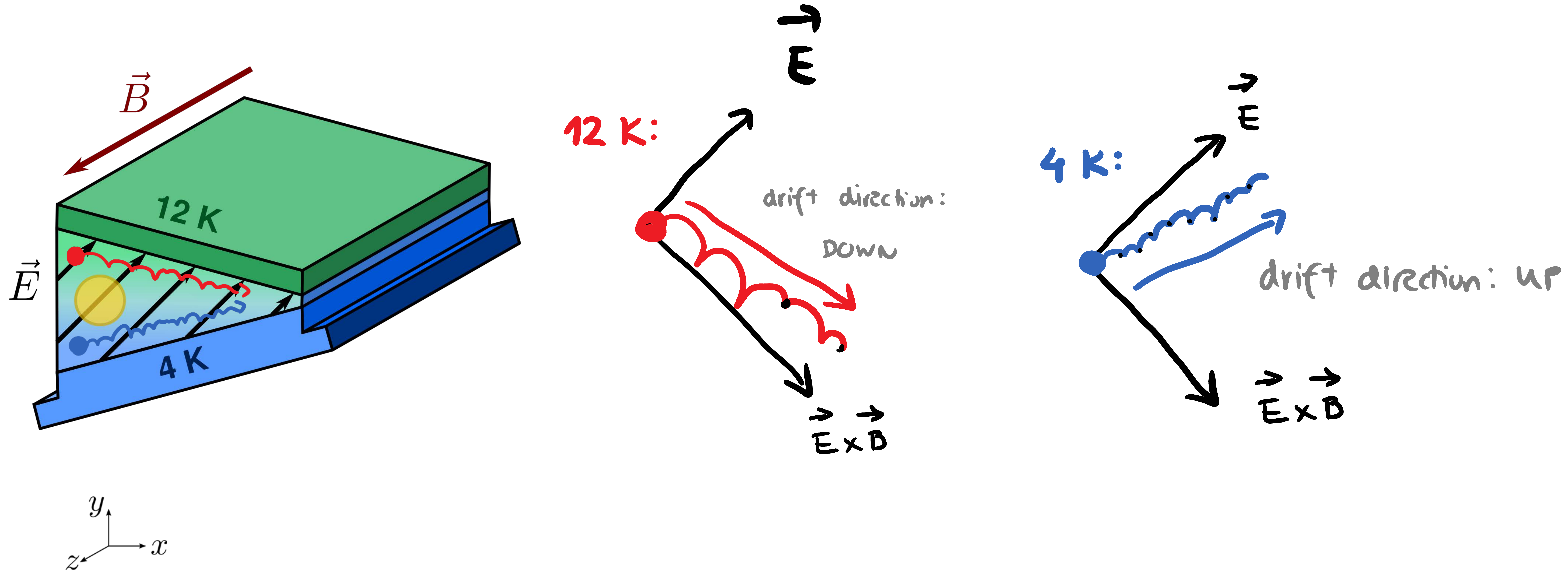
Trajectories in E and B field





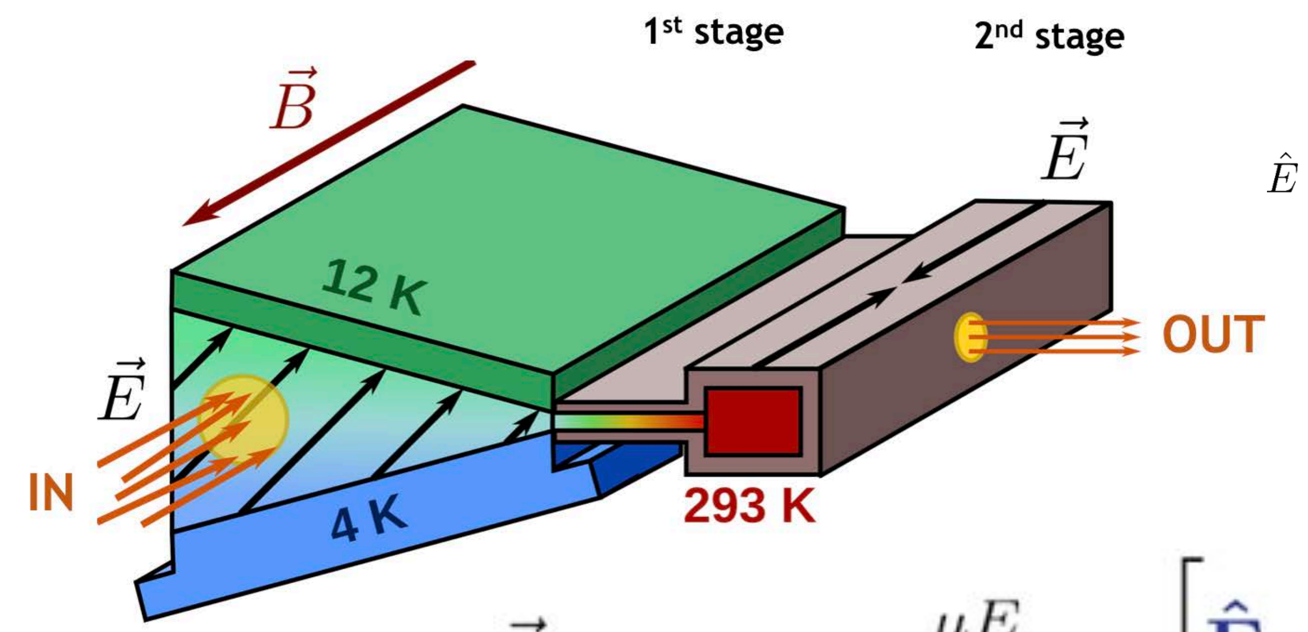
In gas: collisions
with frequency f_{col}

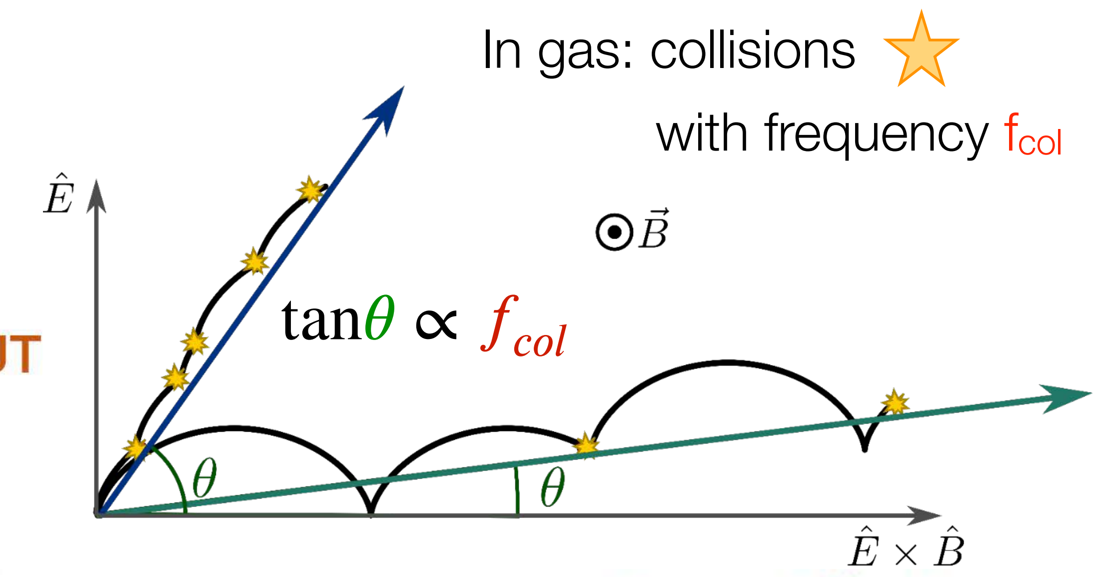
Working principle: 1st Stage



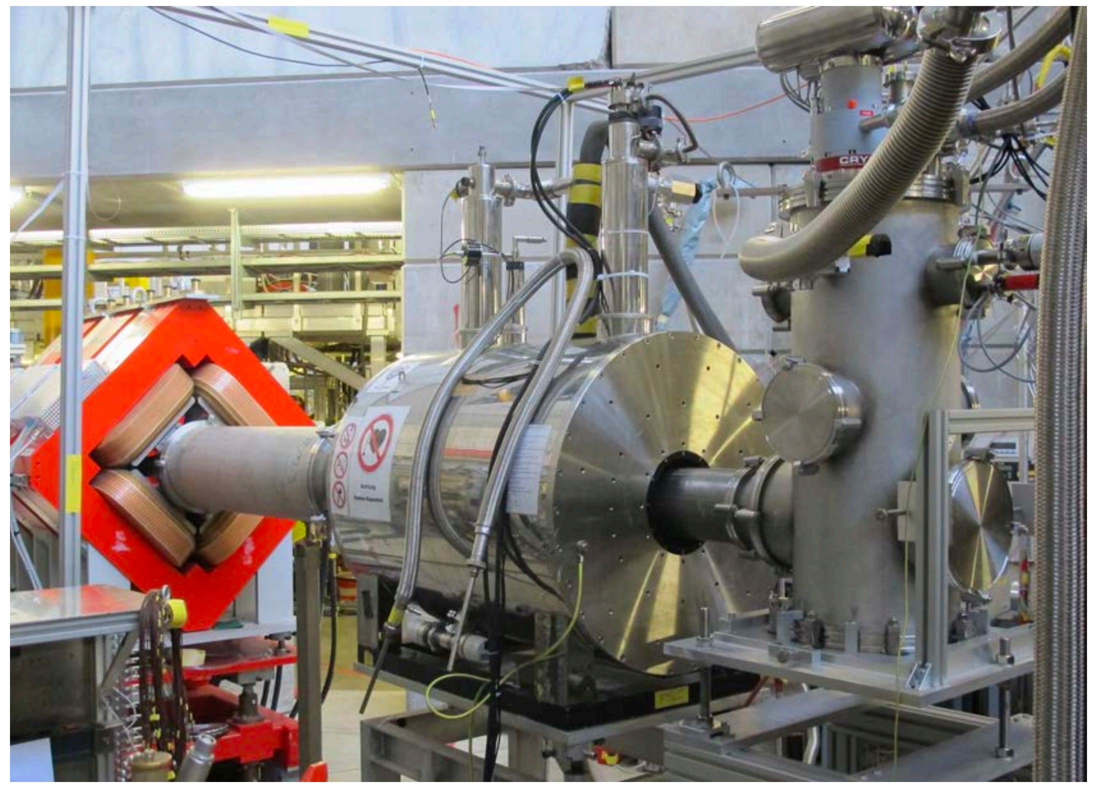
Summary: The muCool project at PSI

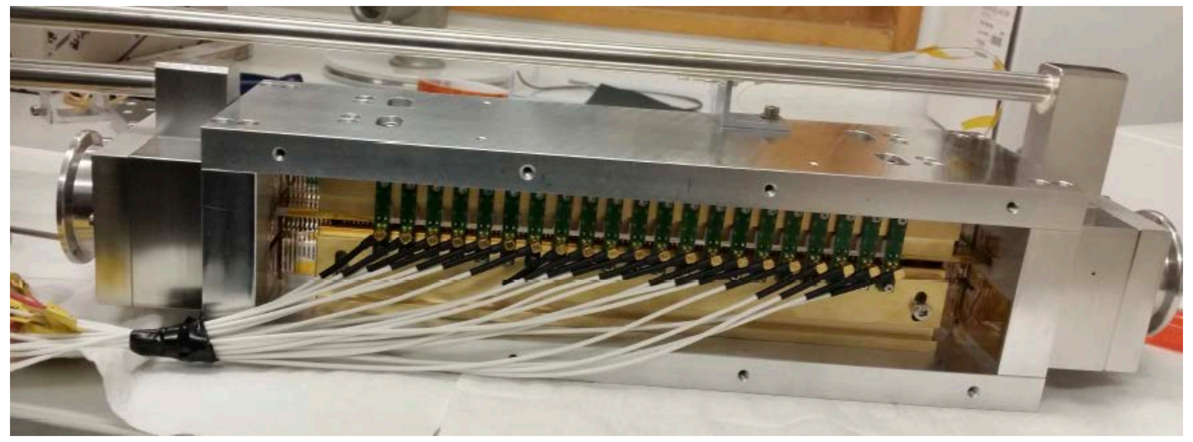
- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor **10^{10}** with an efficiency of O(**10^{-4}**)
- Longitudinal and transverse compression (1st stage + 2nd stage): experimentally proved
- **Next Step**: Extraction into vacuum
- Current activity: abundant MC simulations in order to define the detailed experimental setup for the beam extraction in vacuum and eventually the beam re-acceleration

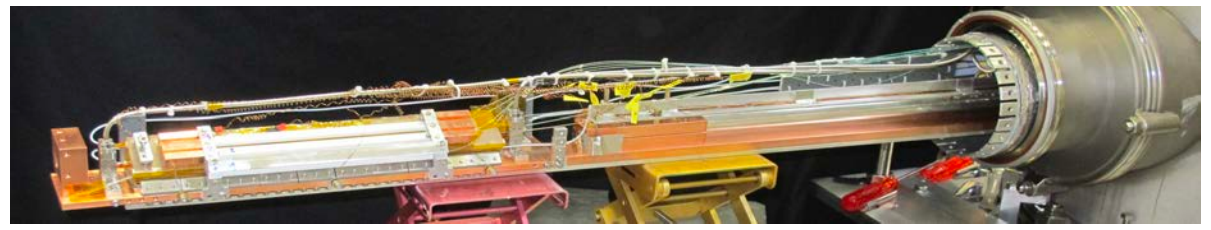




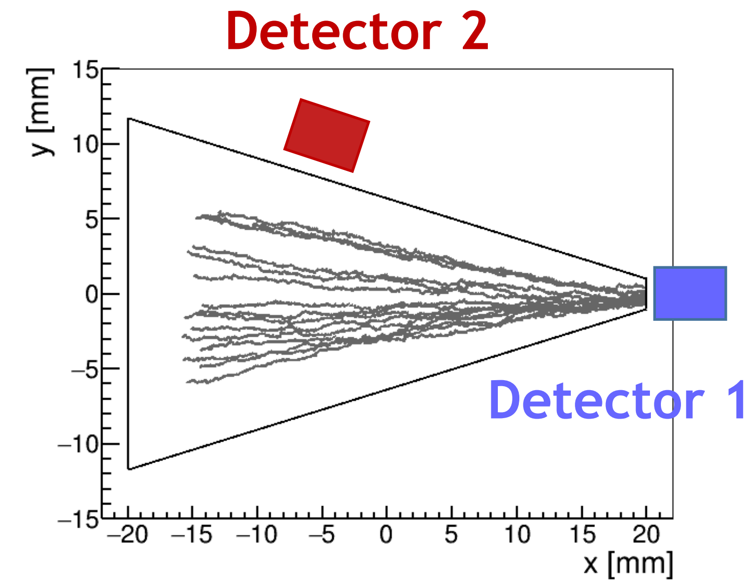
$$\vec{v}_{drift} = \frac{\mu E}{1+\left(\frac{\omega}{\nu_{col}}\right)^2}\left[\hat{\mathbf{E}} + \frac{\omega}{\nu_{col}}\hat{\mathbf{E}}\times\hat{\mathbf{B}} + \left(\frac{\omega}{\nu_{col}}\right)^2\left(\hat{\mathbf{E}}\cdot\hat{\mathbf{B}}\right)\hat{\mathbf{B}}\right]$$

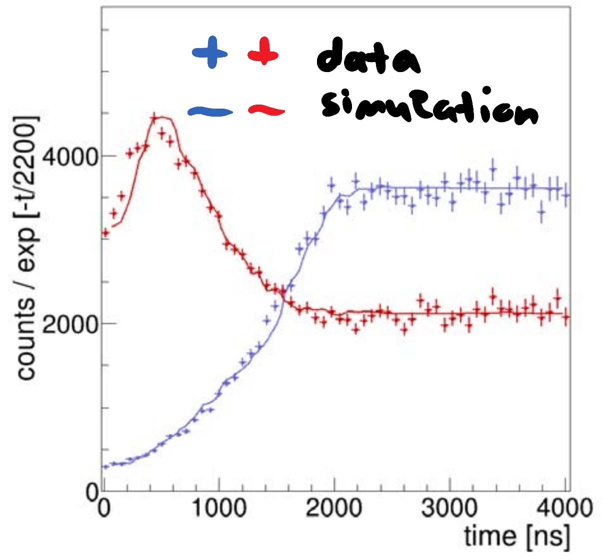




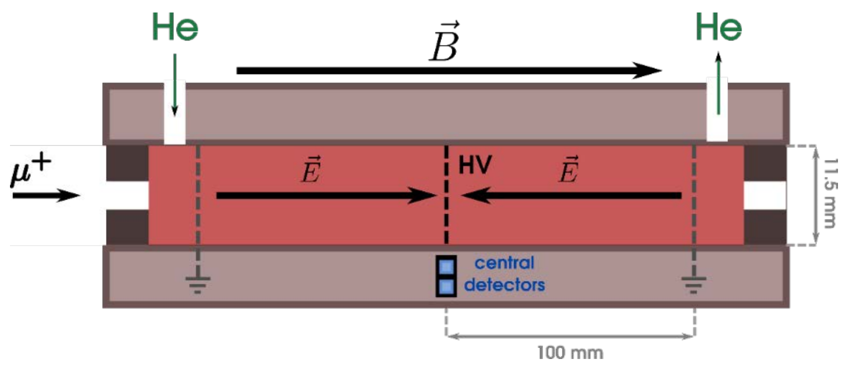


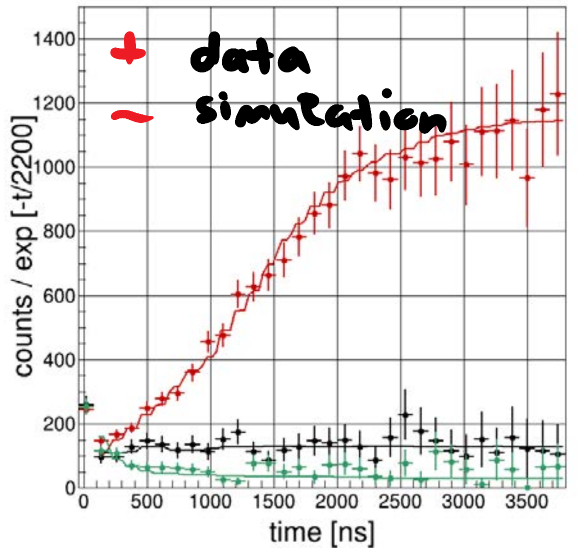
Transverse Compression



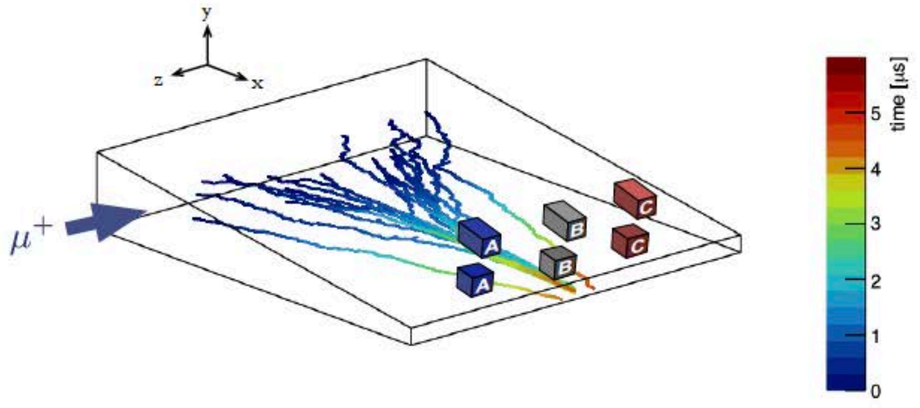


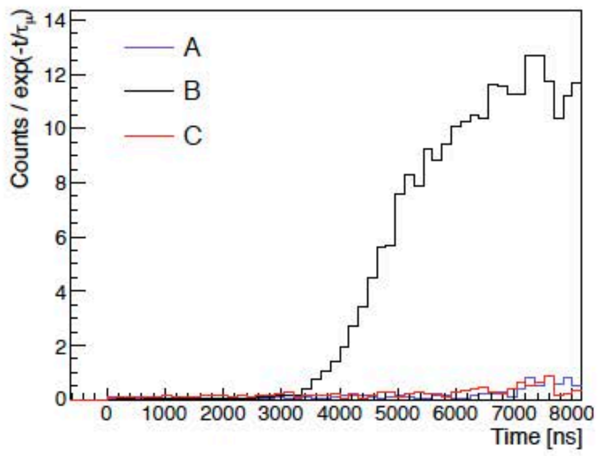
Longitudinal Compression





Longitudinal+ Transverse Compression



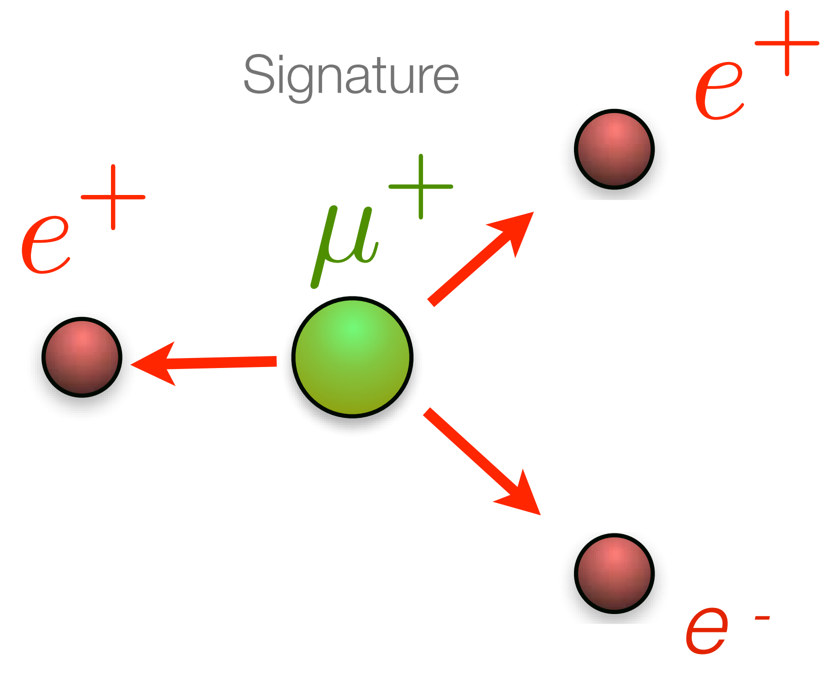


Beneficiaries in the incoming future…

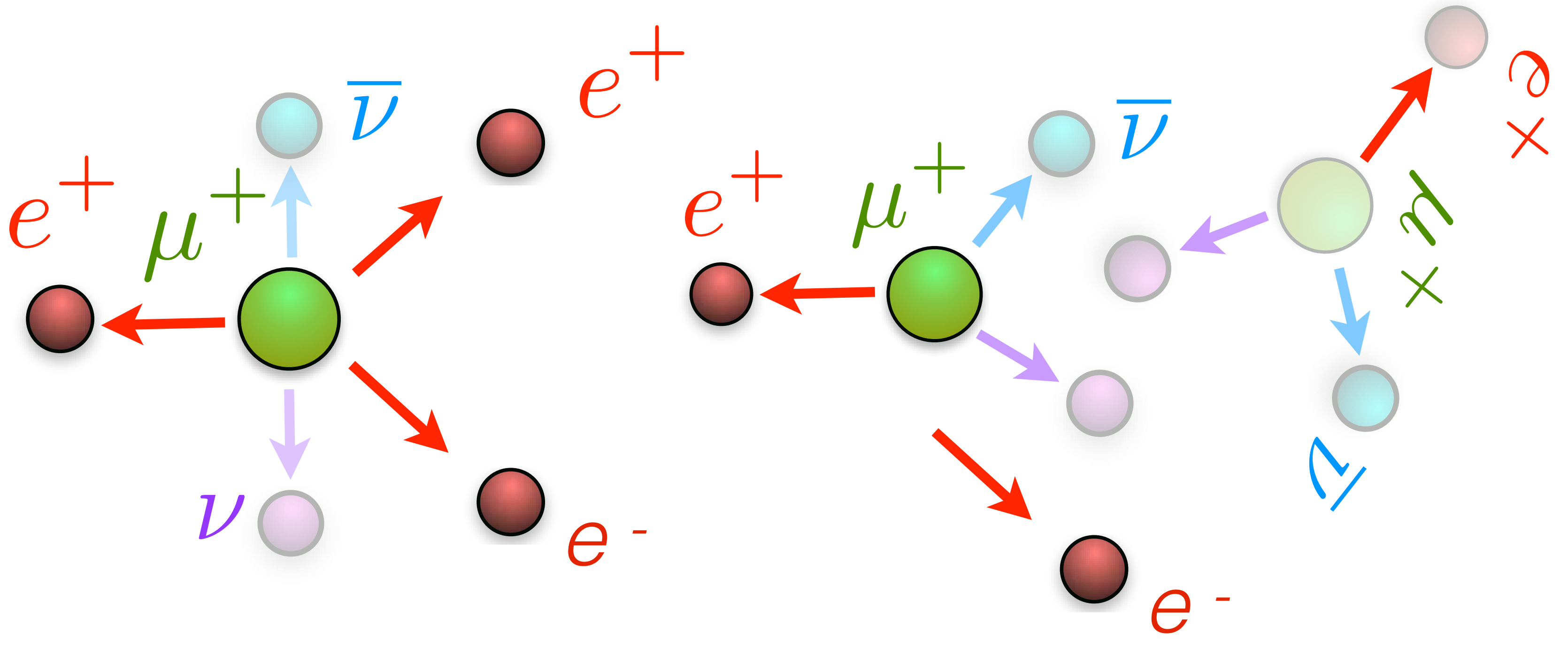
Summary: The Mu3e experiment at PSI

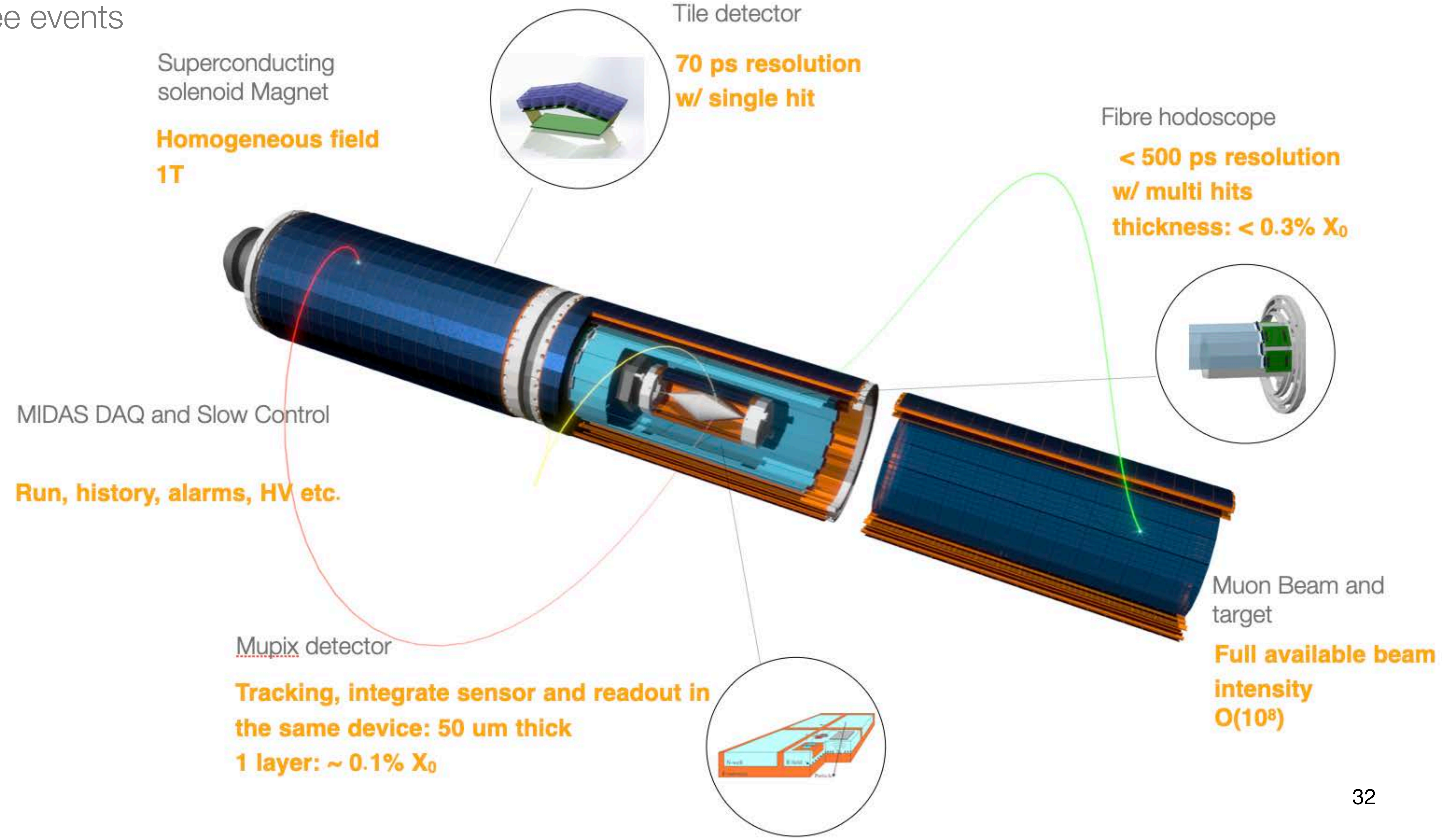
- The Mu3e experiment aims to search for $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of **~10^{-15}** (Phase I) up to down **~10^{-16}** (Phase II)
  - **Phase II at 10^9 μ^+/s**
- Previous upper limit BR(μ+ → e+ e+ e-) ≤ 1 x 10^{-12} @90 C.L. by SINDRUM experiment)
- Observables (Ee, te, vertex) to characterize μ→ eee events

Signature

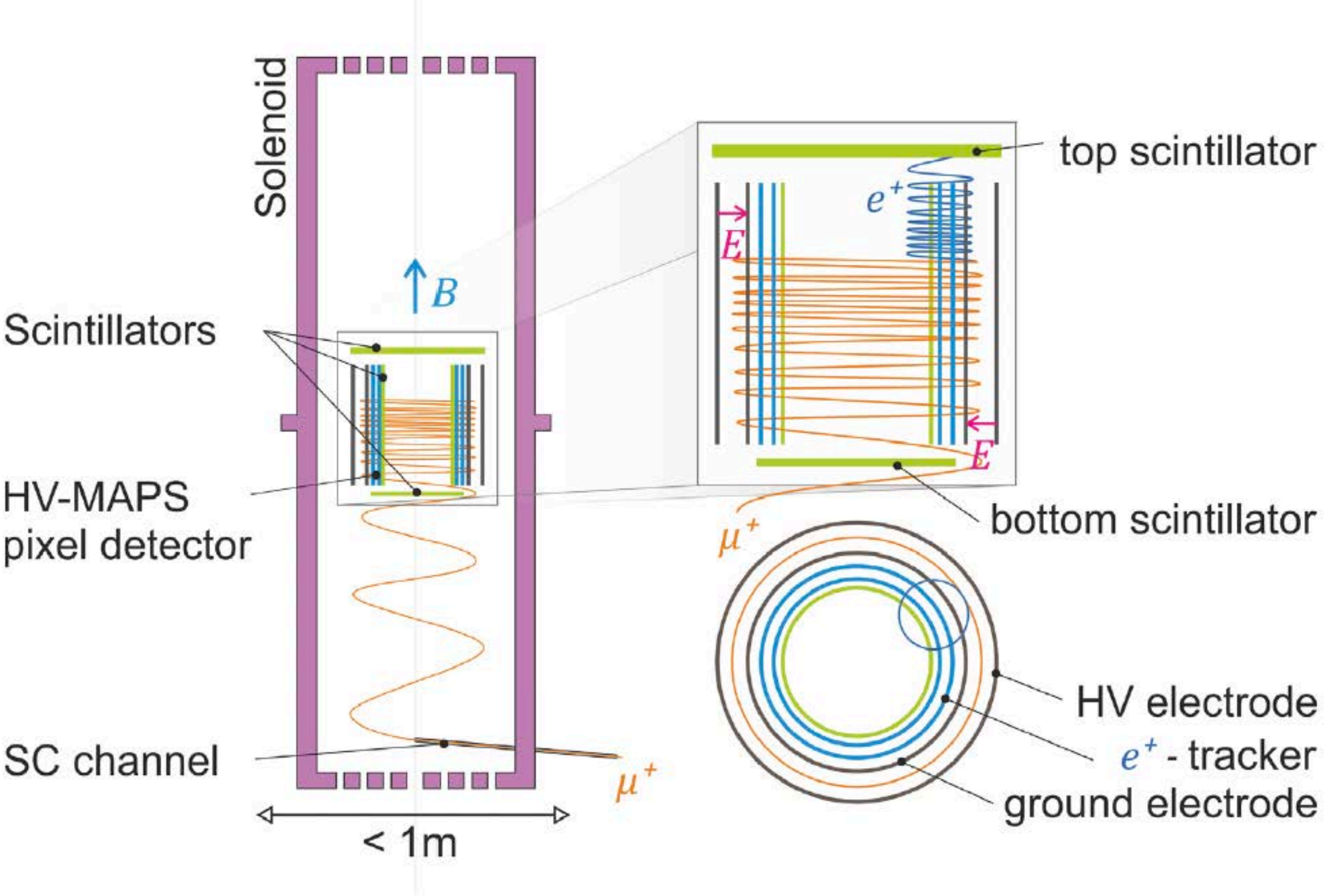


Backgrounds





Summary: muEDM with the Frozen spin and longitudinal injection



- μ^+ from Pion–decay → high polarization $p \approx 95\%$
- Injection through superconducting channel
- Fast scintillator triggers pulse
- Magnetic pulse stops longitudinal motion of μ^+
- Weakly focusing field for storage
- Thin electrodes provide electric field for frozen spin
- Pixelated detectors for e^+– tracking

Beneficiaries in the incoming future…

- …inputs from this workshop

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

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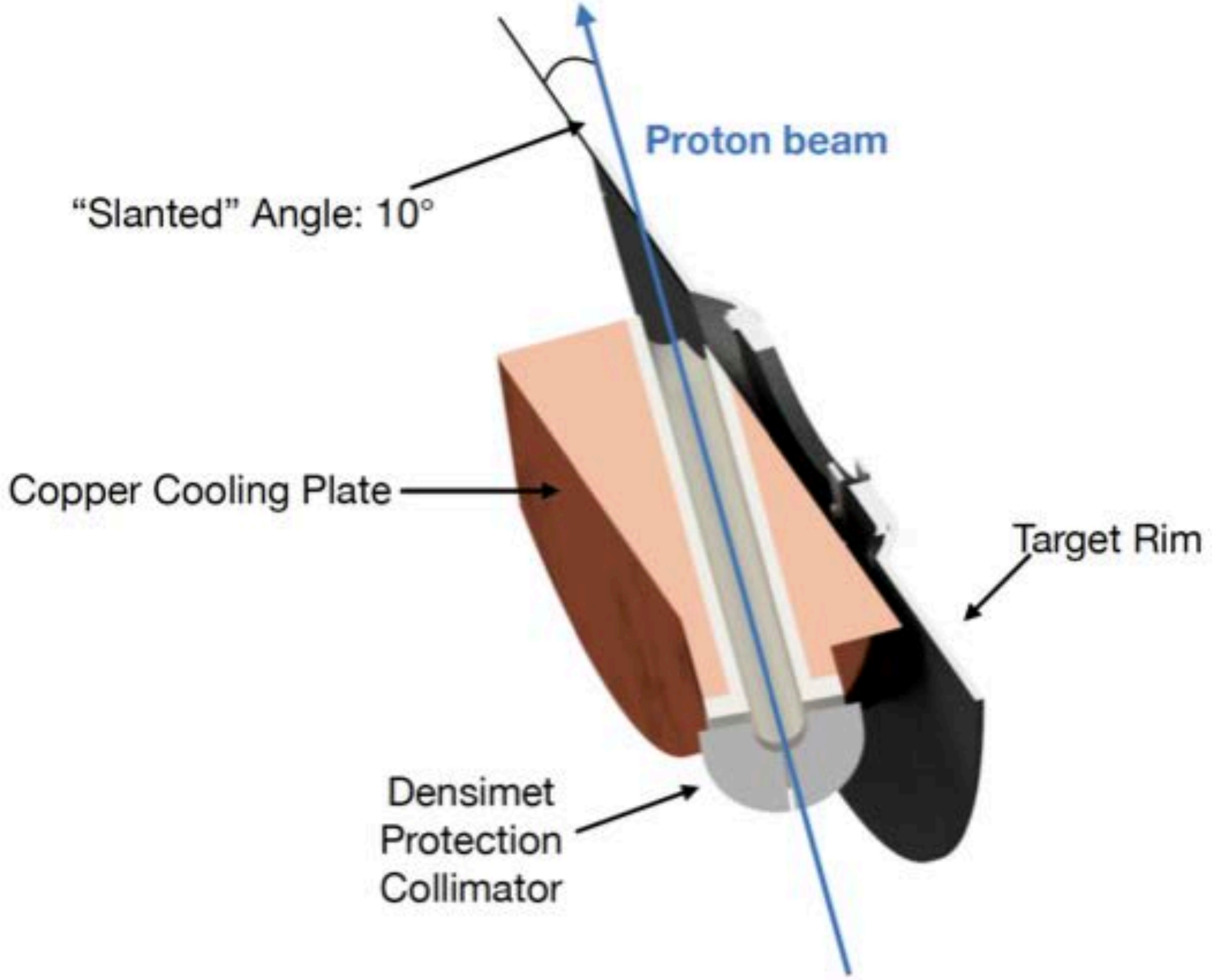
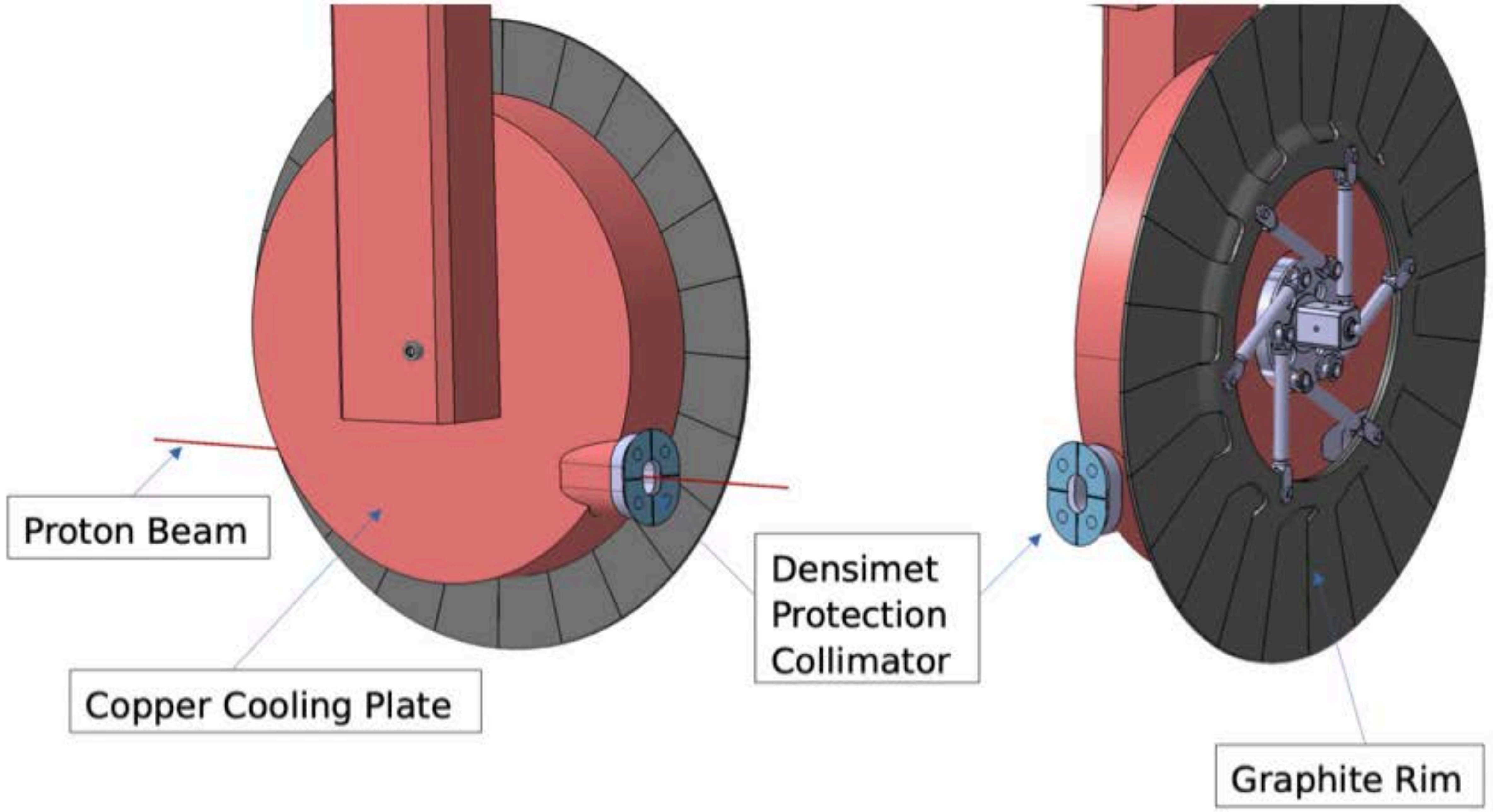
(EPJ Web of Conferences **282**, 01012 (2023) *SSP 2022*
https://doi.org/10.1051/epjconf/202328201012)

Credits and acknowledgments

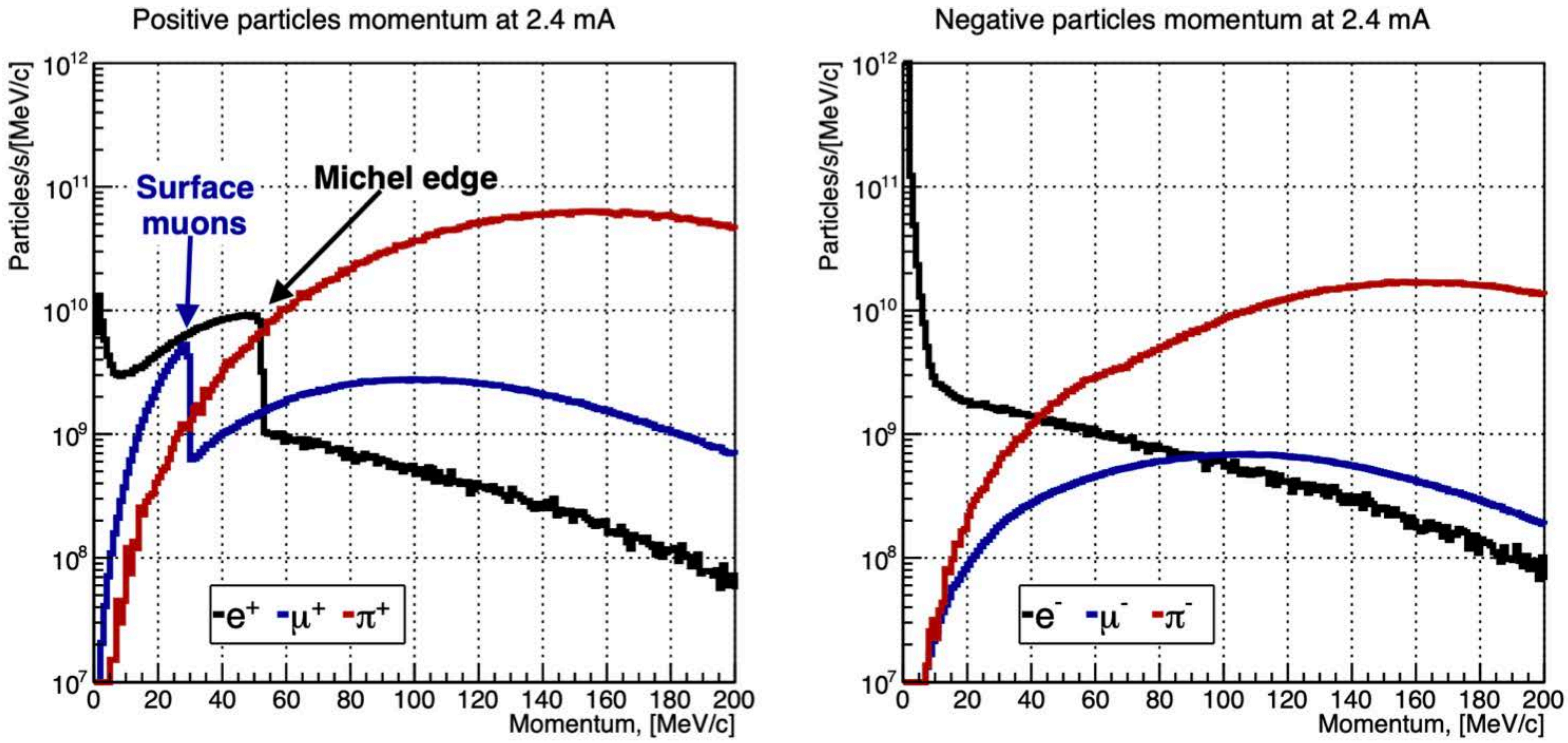
- **The IMPACT project at PSI**
- The muCool project at PSI
- The MEGII collaboration
- The Mu3e collaboration
- The muEDM collaboration
- …

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)	