Towards an High intensity Muon Beam (HiMB) at PSI

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HiMB motivations

- Aim: O(**10^{10}** muon/s); Surface (positive) muon beam (**p = 28 MeV/c**); **DC** beam
- Time schedule: **O(2025)**

- PSI delivers the highest intensity DC μ^+ beam:
  5×10^8 μ^+/s

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

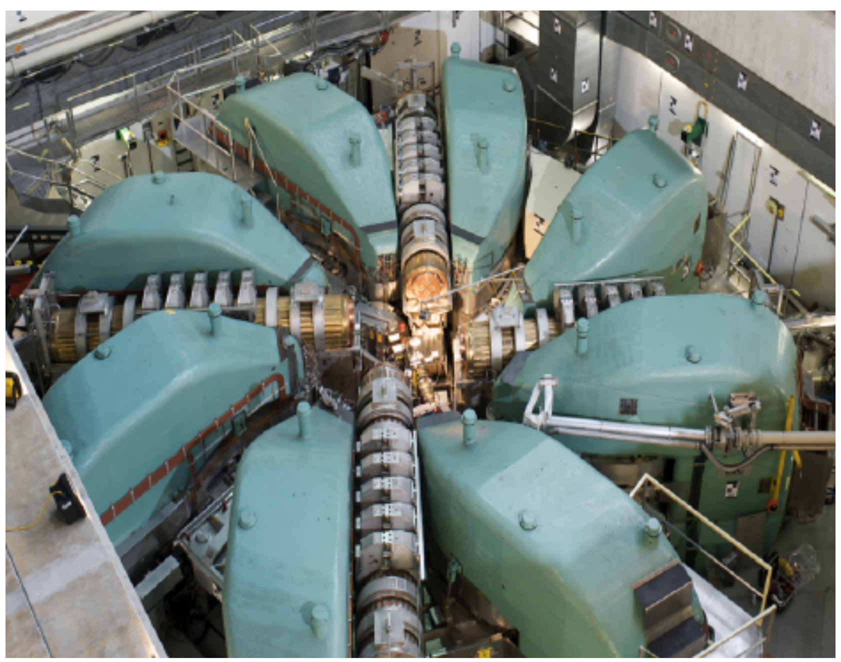
- Different experiments demand for a variety of beam characteristics:
  - DC vs pulsed
  - Momentum depends on applications: stopped beams require low momenta

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

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

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

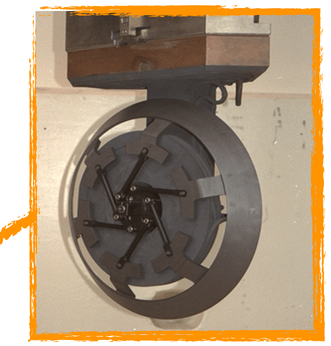


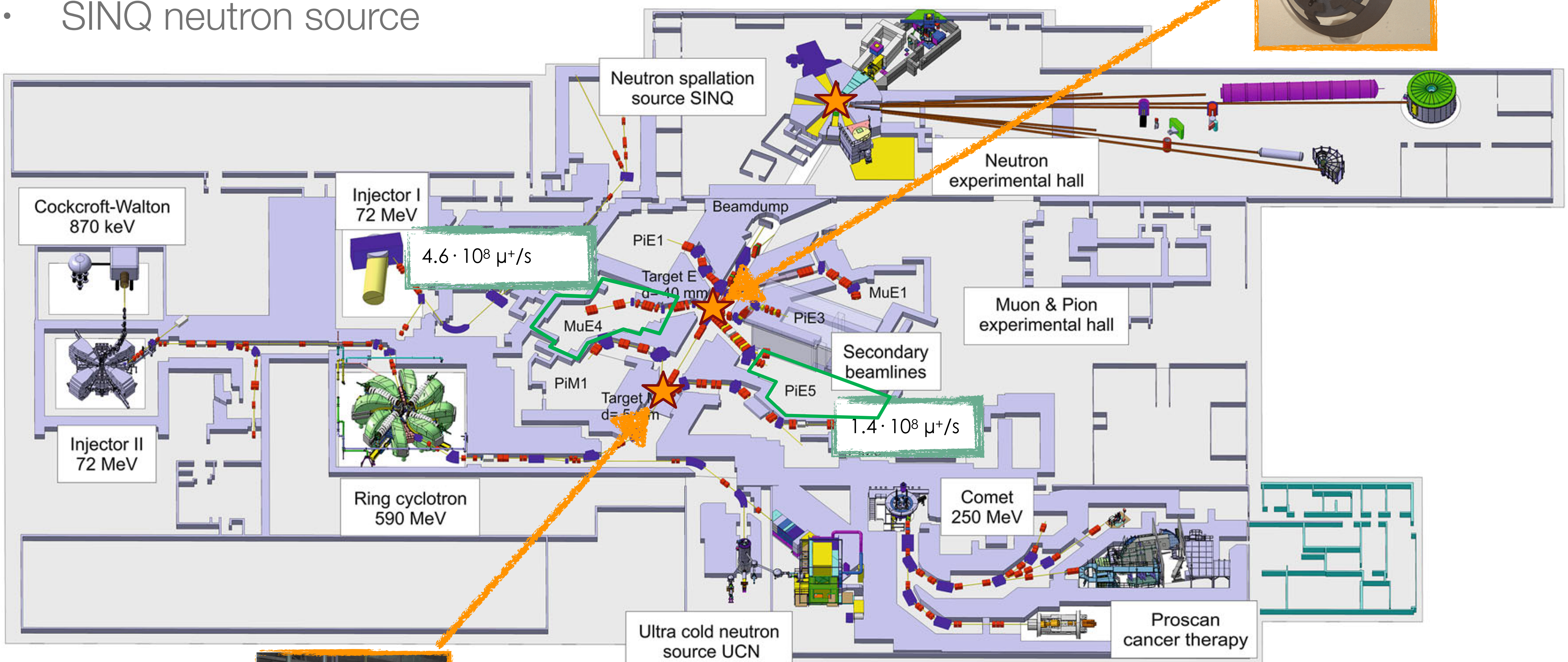
590 MeV proton ring cyclotron
Time structure: 50 MHz/20 ns
Power: 1.4 MW

PSI landscape

The world's most intense continuous muon beam

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

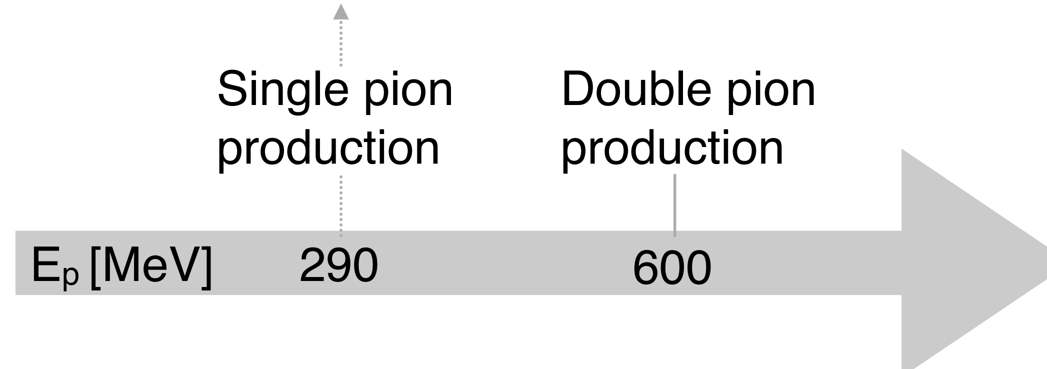


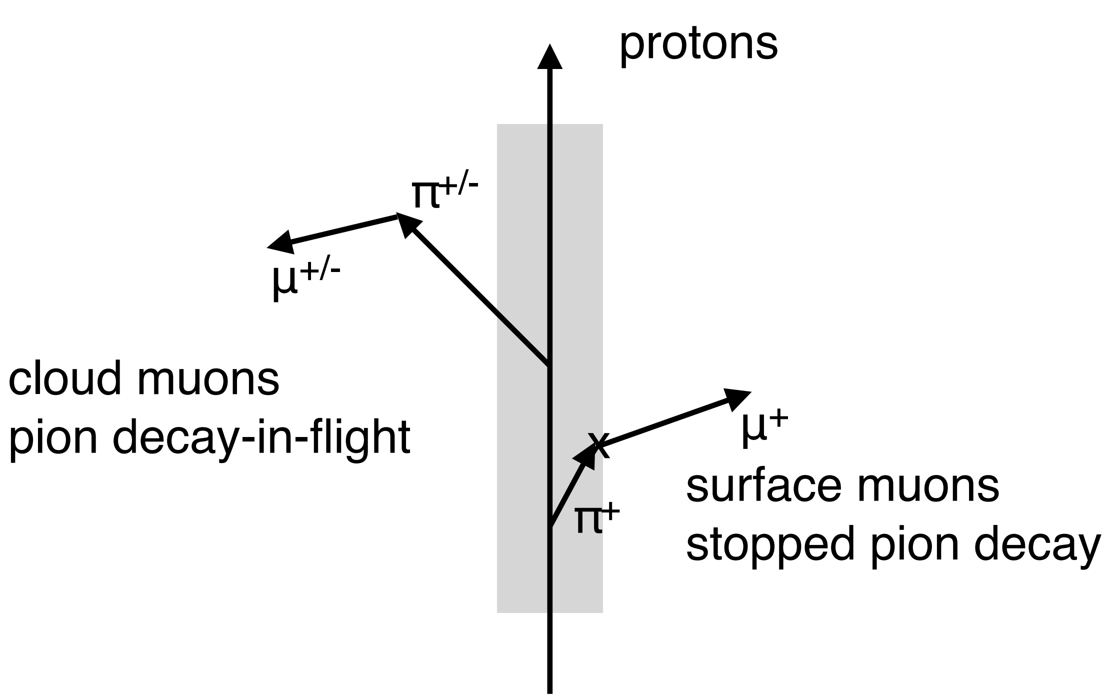


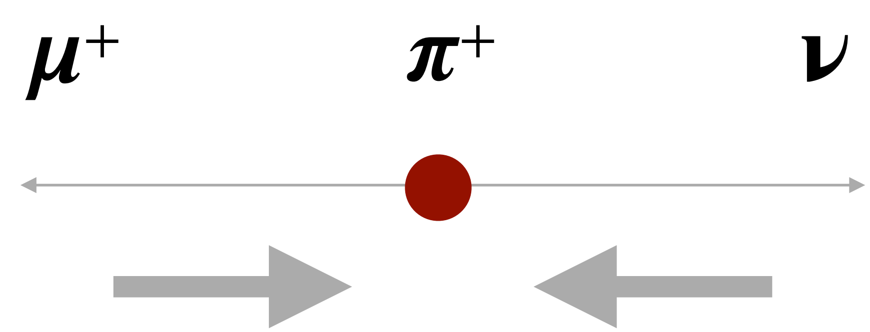
Muon production via pion decay

- Single pion production at 290 MeV proton energy (LAB)
- Low-energy muon beam lines typically tuned to surface-μ^+ at
~ 28 MeV/c
- Note: surface -μ —> polarized 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

$$
\begin{array}{ll}
p + p \rightarrow p + n + \pi^+ & p + n \rightarrow p + n + \pi^0 \\
p + p \rightarrow p + p + \pi^0 & p + n \rightarrow p + p + \pi^- \\
p + p \rightarrow d + \pi^+ & p + n \rightarrow n + n + \pi^+
\end{array}
$$







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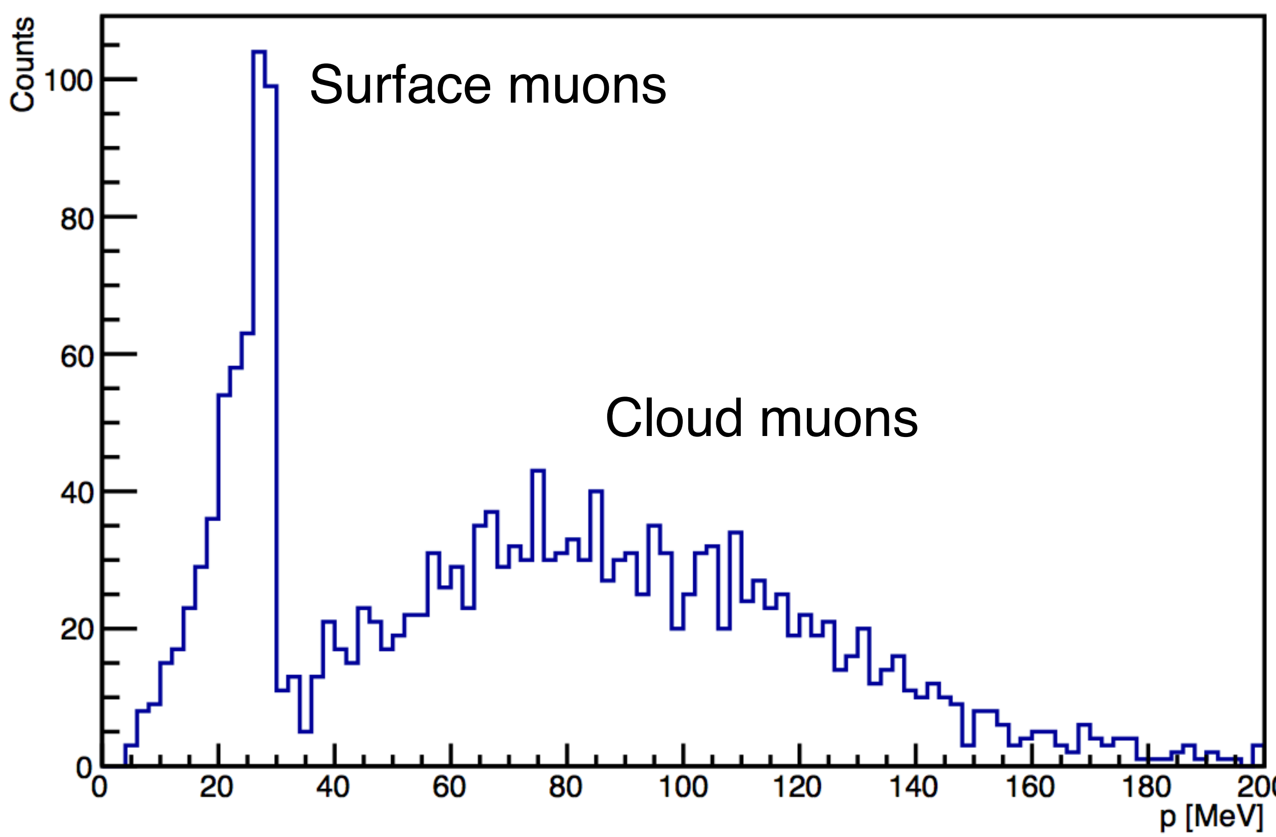
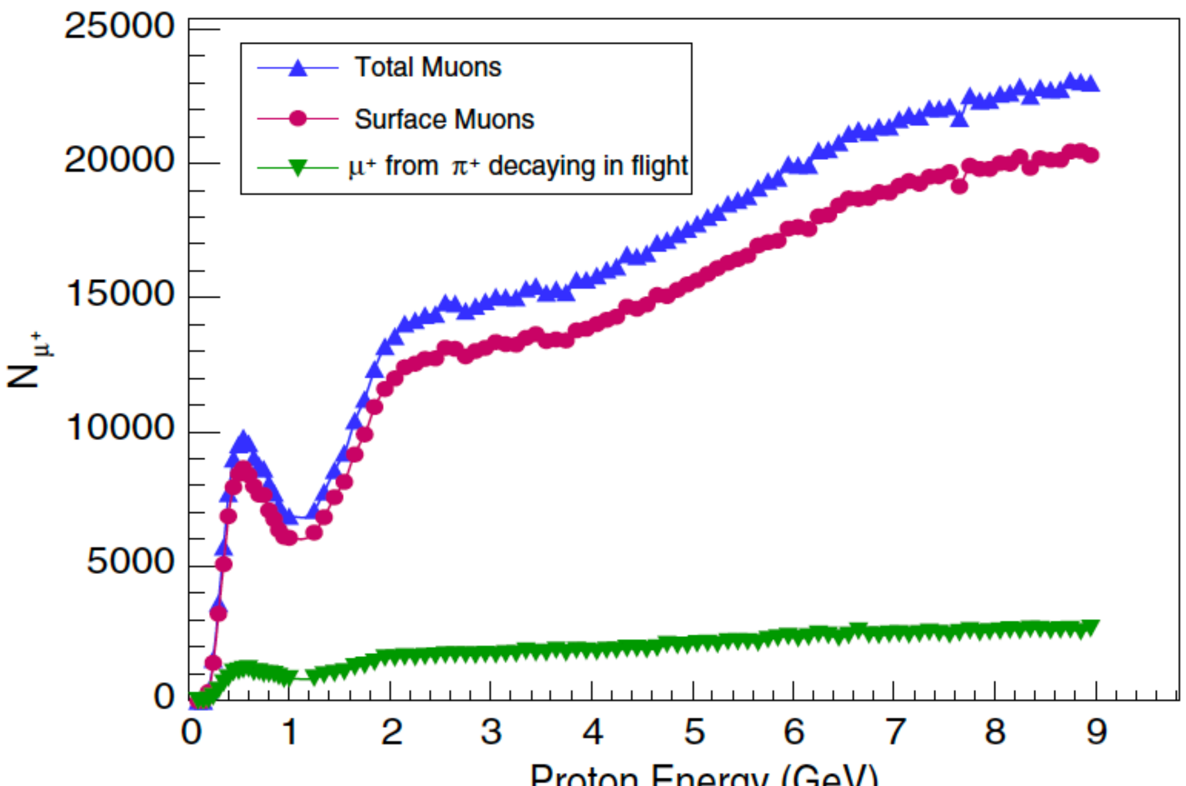


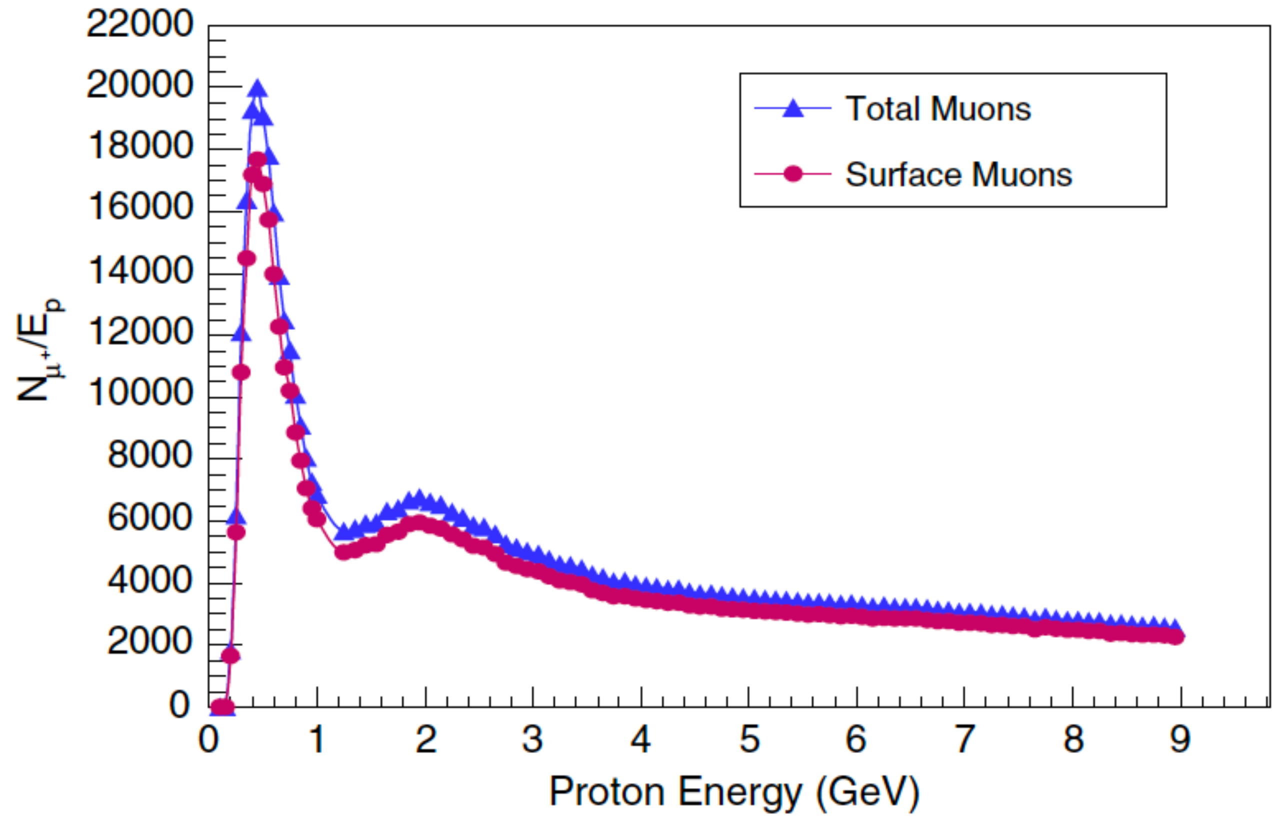
Optimal surface muon production

- **BUNGAU** et al., Phys. Rev. ST Accel. BEAMS **16**, 014701 (2013)
- Target: graphite
- Simulation validation: ISIS data
- For stand alone muon facility: 500 MeV proton energy is the optimal energy

Variation of muon yield with proton energy at higher energies

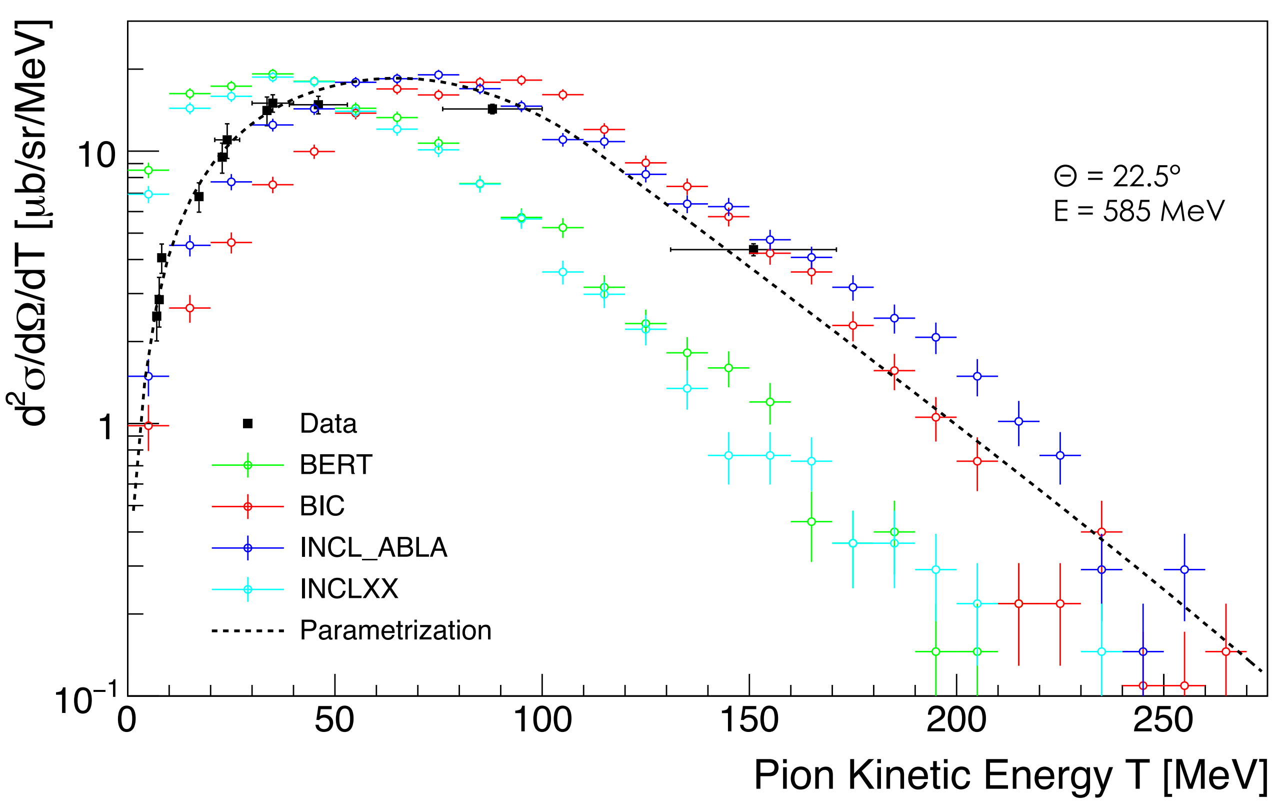


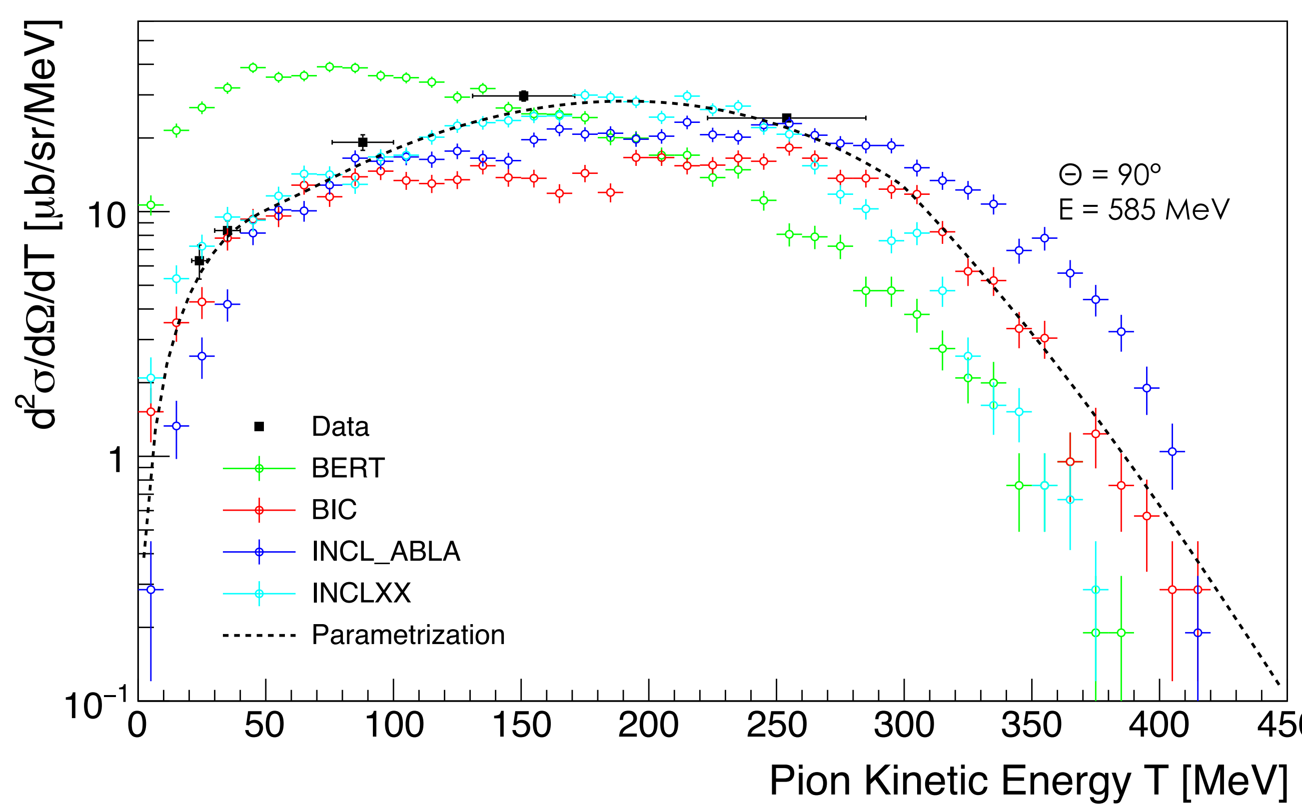
Normalization of the muon yield to the proton energy



HiMB Simulation

- Geant4 pion production cross sections not optimised for low energies
- Implemented our own pion production cross section into Geant4/G4beamline based on measured data and two available parametrizations (**HiMB model**)
- Valid for all pion energies, proton energies < 1000 MeV, all angles and all materials
- Reliable results at 10% level

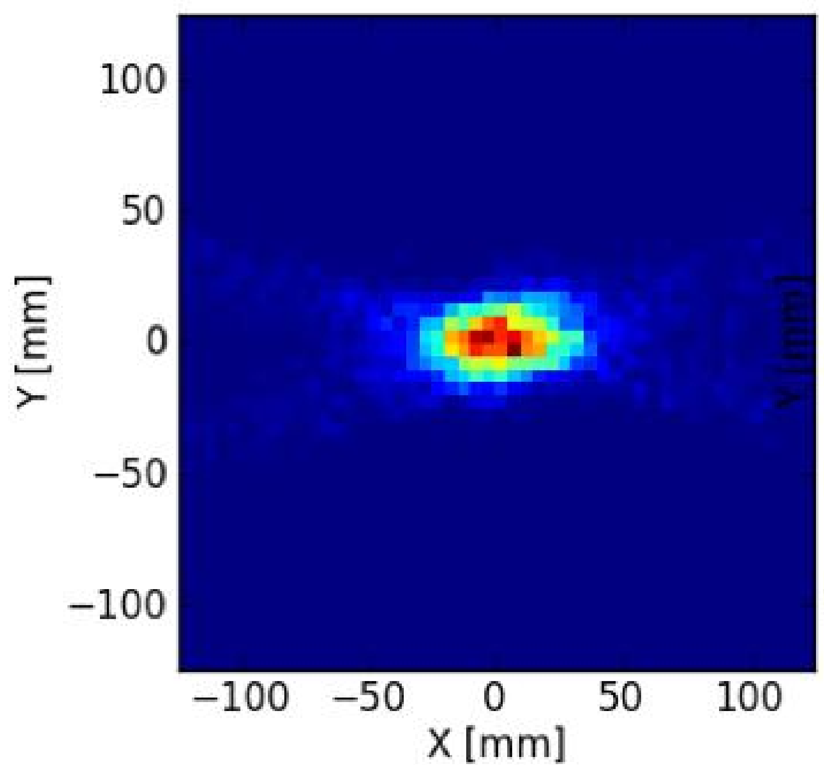


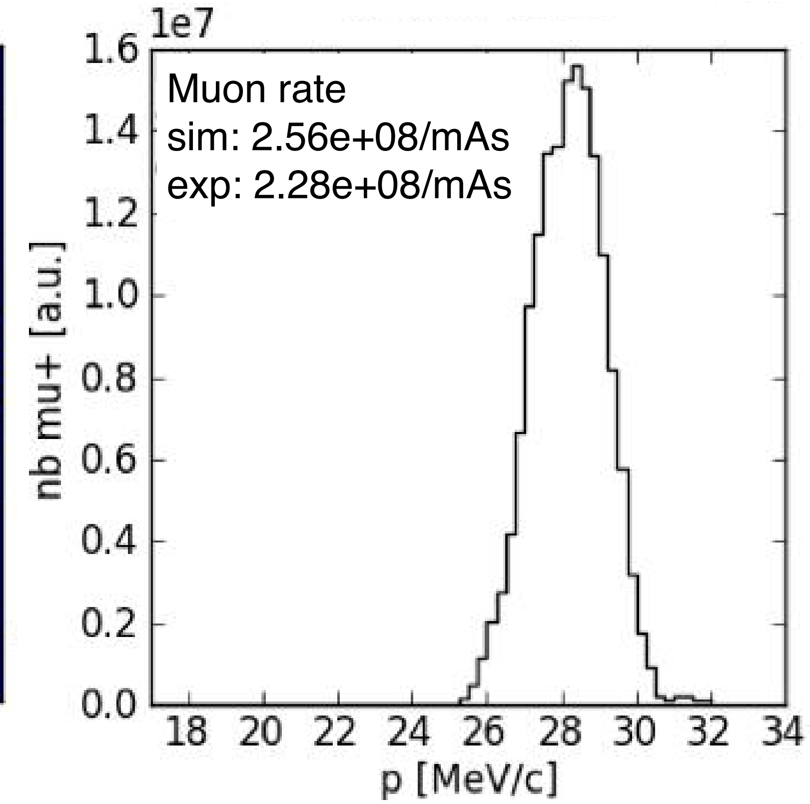


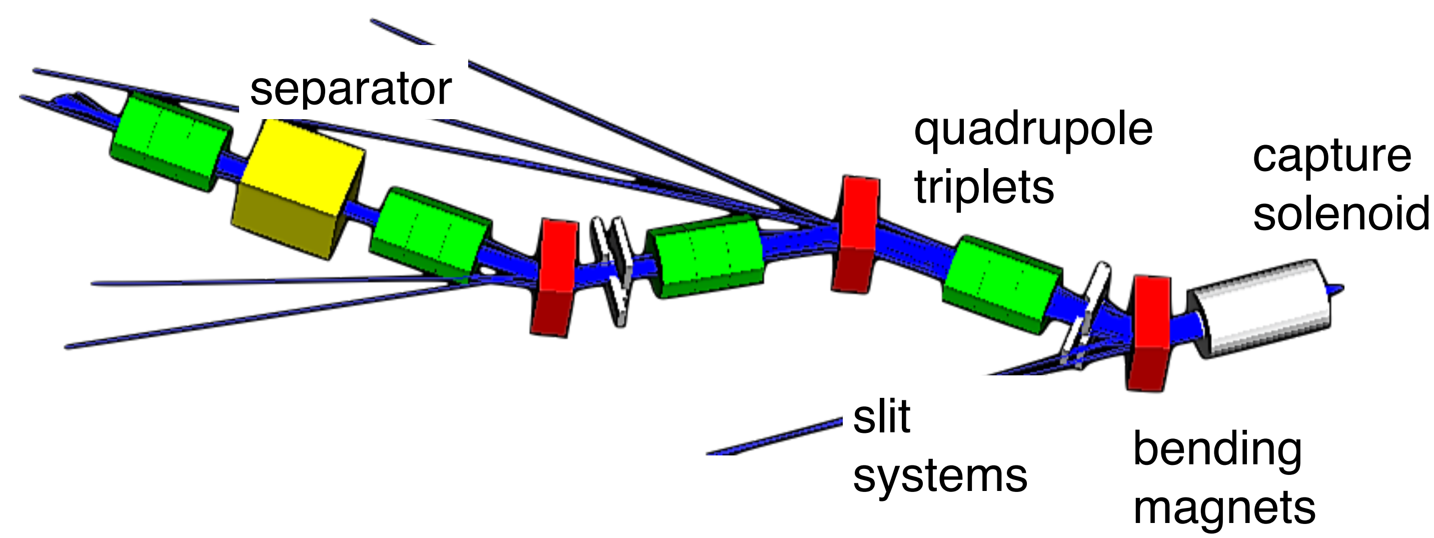
R. L. Burman and E. S. Smith, Los Alamos Tech. Report LA-11502-MS (1989)
R. Frosch, J. Löffler, and C. WIgger, PSI Tech. Report TM-11-92-01 (1992)
F. Berg et al., Phys. Rev. Accel. Beams **19**, 024701 (2016)

HiMB model validation

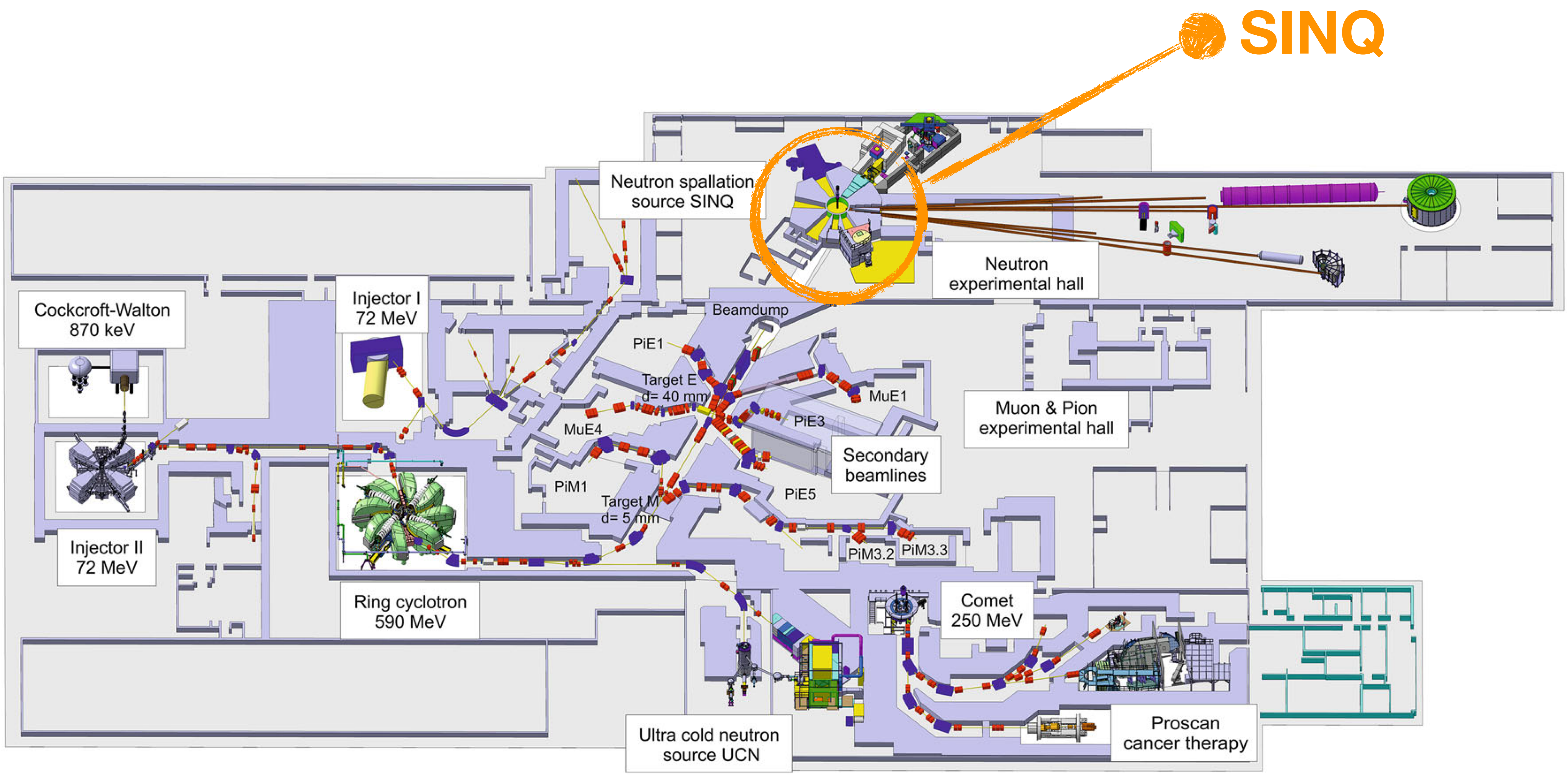
- Full simulation of μE4 and piE5 beam lines starting from proton beam
- Detailed field maps available for all elements
- Very good agreement between simulation and measurements







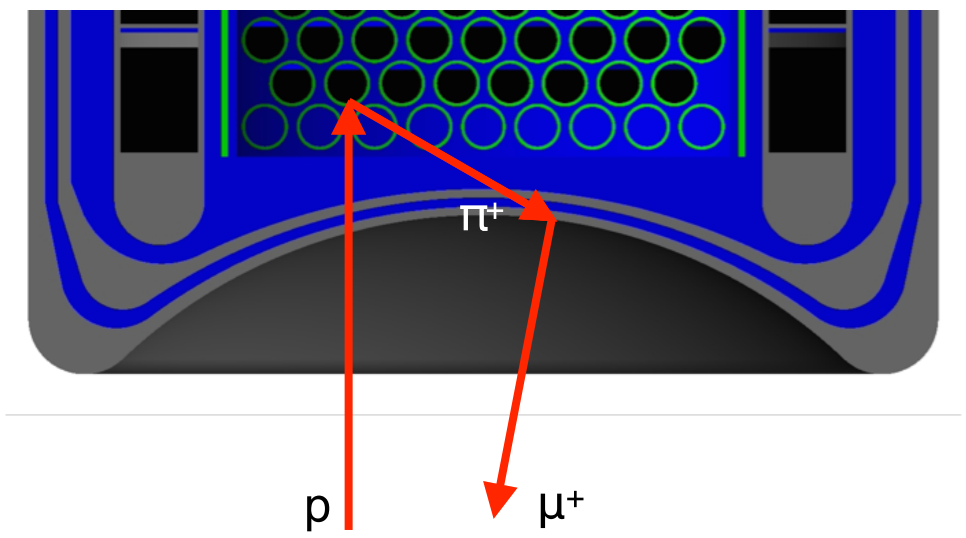
Initial HiMB concept: @SINQ



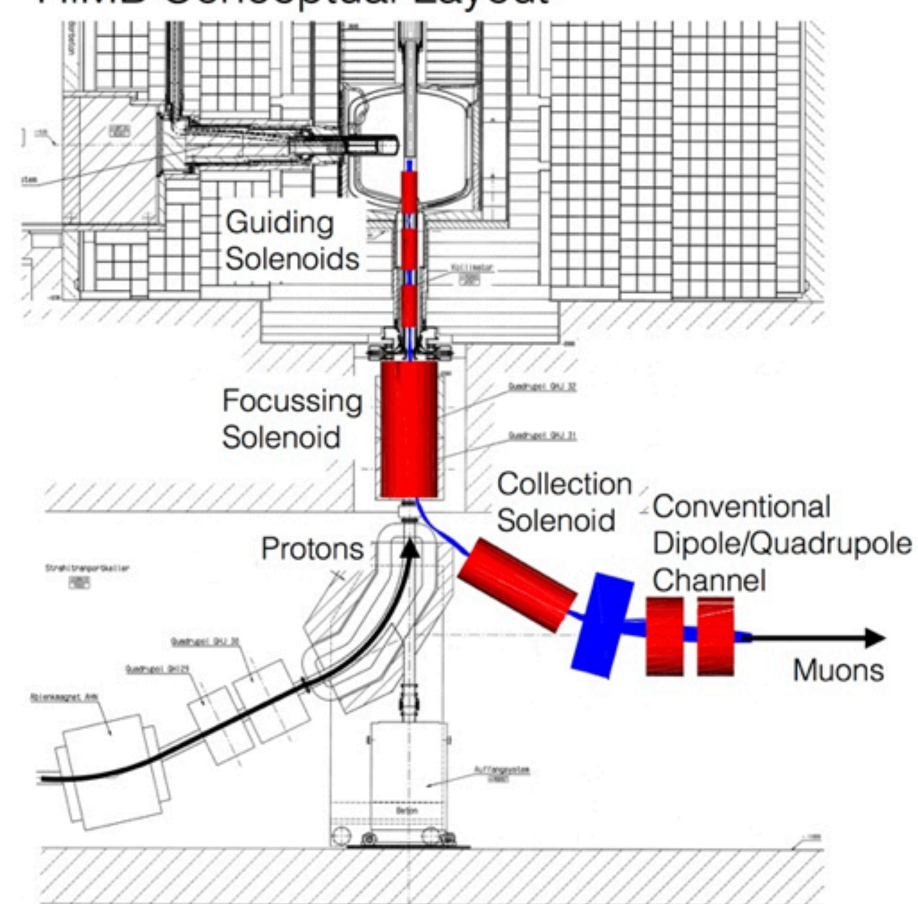
Initial HiMB concept: @SINQ

- Source simulation (below safety window):
  9 x 10^{10} surface-μ^+/s @ 1.7 mA I_p
- 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**

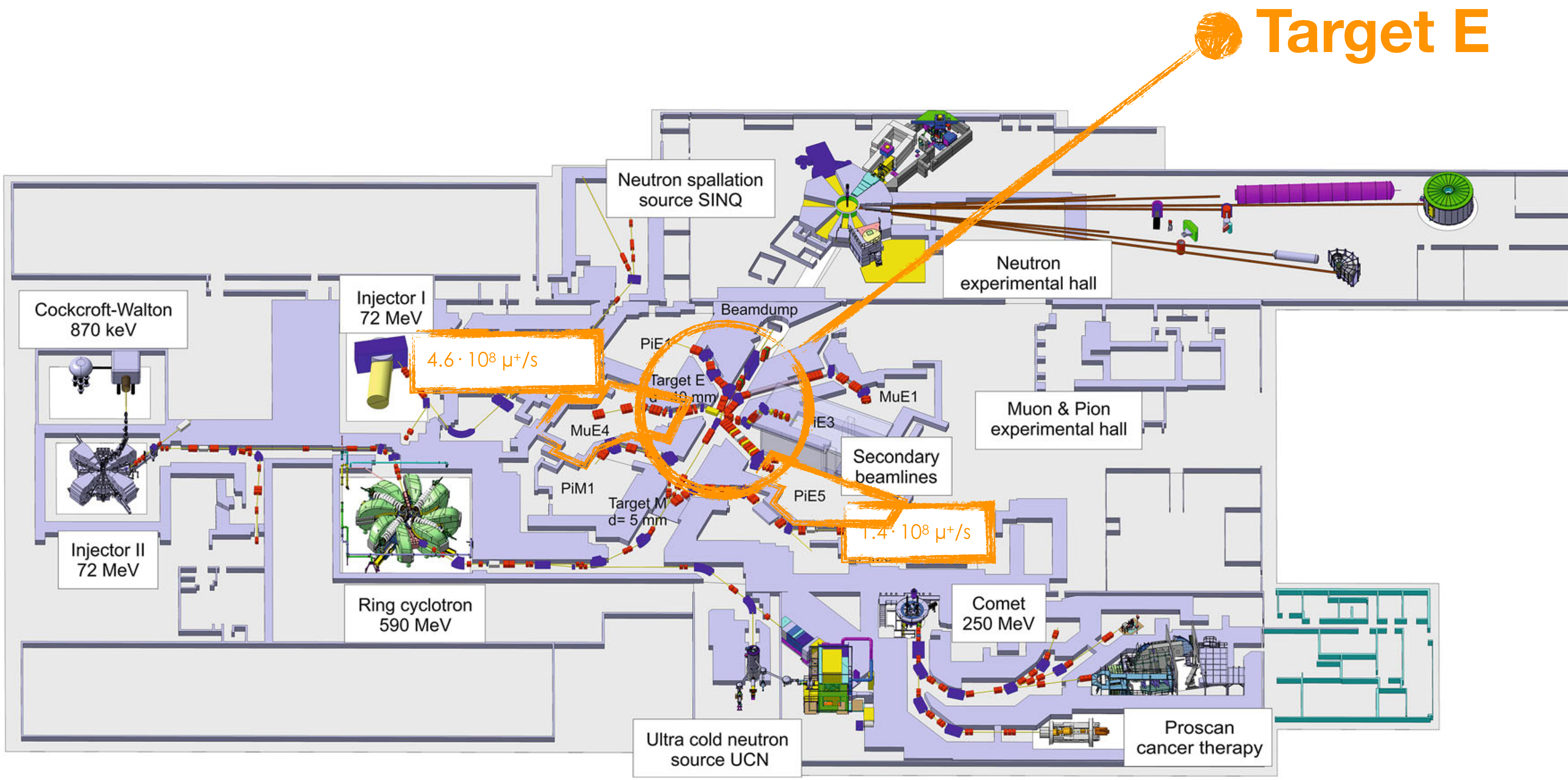
SINQ spallation target



HiMB Conceptual Layout

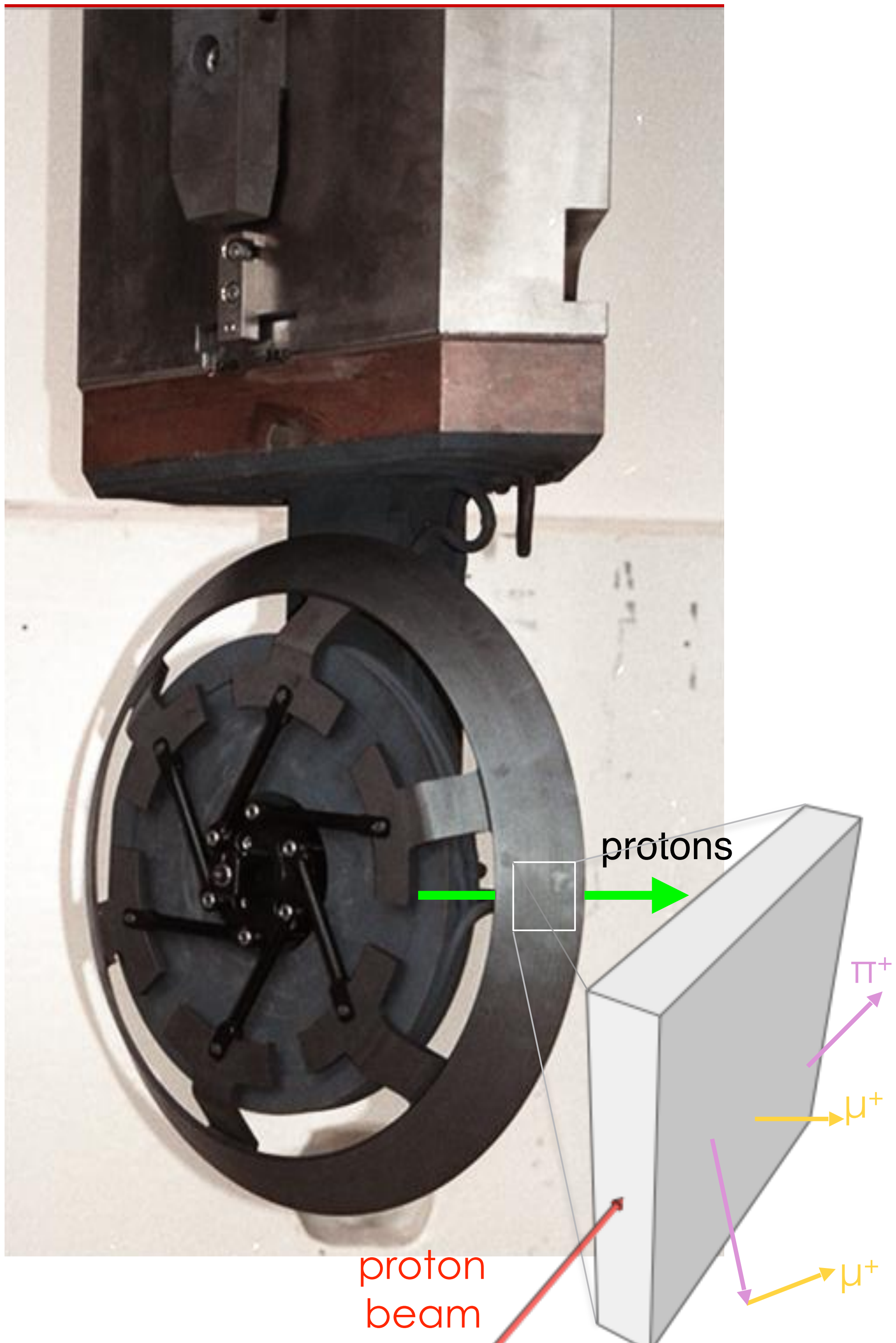


Current high beam intensity: @Target E



Target E

- Rotating target (1 Hz)
- Polycrystalline graphite
- 40 mm length in beam direction
- 50 kW proton beam energy deposit
- 1700 K radiation cooled
- 30 % loss of protons
- Delivers world most intense surface muon beams



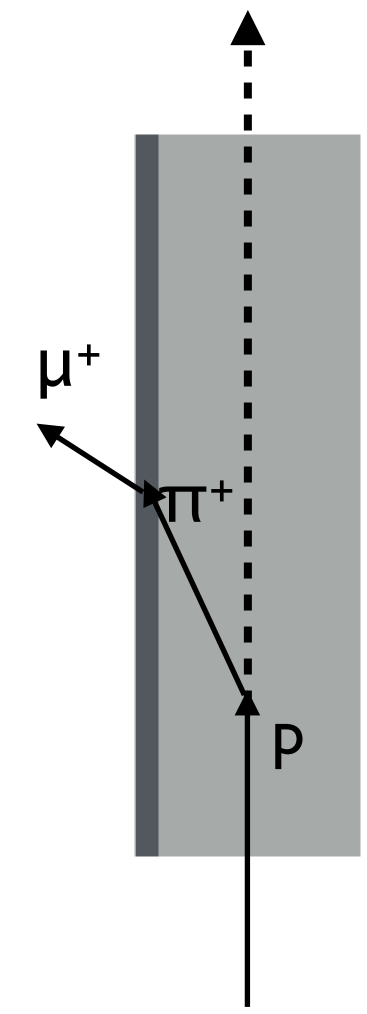
HiMB @ HE

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

Optimization of standard production targets

- Back to standard target to exploit possible improvements towards high intensity beams:
    - **Target alternate materials**
        - Search for high pion yield materials -> higher muon yield

$$
\begin{aligned}
\textit{relative } \mu^{+} \textit{yield} \;&\propto\; \pi^{+}\textit{stop density} \cdot \mu^{+}\textit{Range} \cdot \textit{length} \\
&\propto n \cdot \sigma_{\pi^{+}} \cdot SP_{\pi^{+}} \cdot \frac{1}{SP_{\mu^{+}}} \cdot \frac{\rho_C (6/12)_C}{\rho_x (Z/A)_x} \\
&\propto Z^{1/3} \cdot Z \cdot \frac{1}{Z} \cdot \frac{1}{Z} \\
&\propto \frac{1}{Z^{2/3}}
\end{aligned}
$$



Optimization of standard production targets

- Strategy: either increasing the surface volume (surface area times acceptance depth) or the pion stop density near the surface

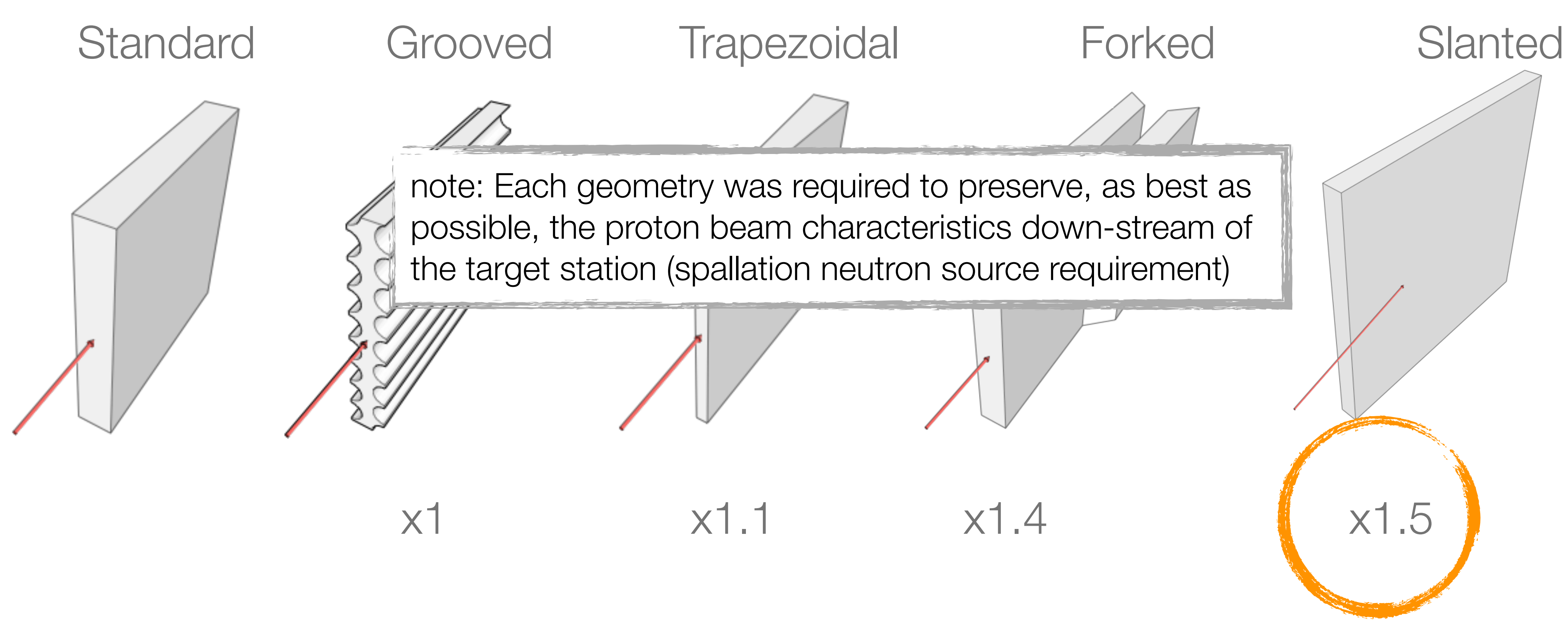
  - **Target geometry**
    - Comparison studies of different target geometries: **TgE for different lengths**

Surface muon rate

Length [mm]	Upstream	Downstream	Side
10	1.4×10^{10}	9.0×10^{9}	1.8×10^{10}
20	1.6×10^{10}	1.2×10^{10}	5.1×10^{10}
30	1.9×10^{10}	1.1×10^{10}	8.5×10^{10}
40	1.8×10^{10}	1.1×10^{10}	1.2×10^{11}
60	1.8×10^{10}	1.2×10^{10}	2.1×10^{11}

Optimization of standard production targets

- Strategy: either increasing the surface volume (surface area times acceptance depth) or the pion stop density near the surface
  - **Target geometry**
    - Comparison studies of different target geometries: **Different shapes and rotation angles**
    - Enhancements normalised to standard target



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)

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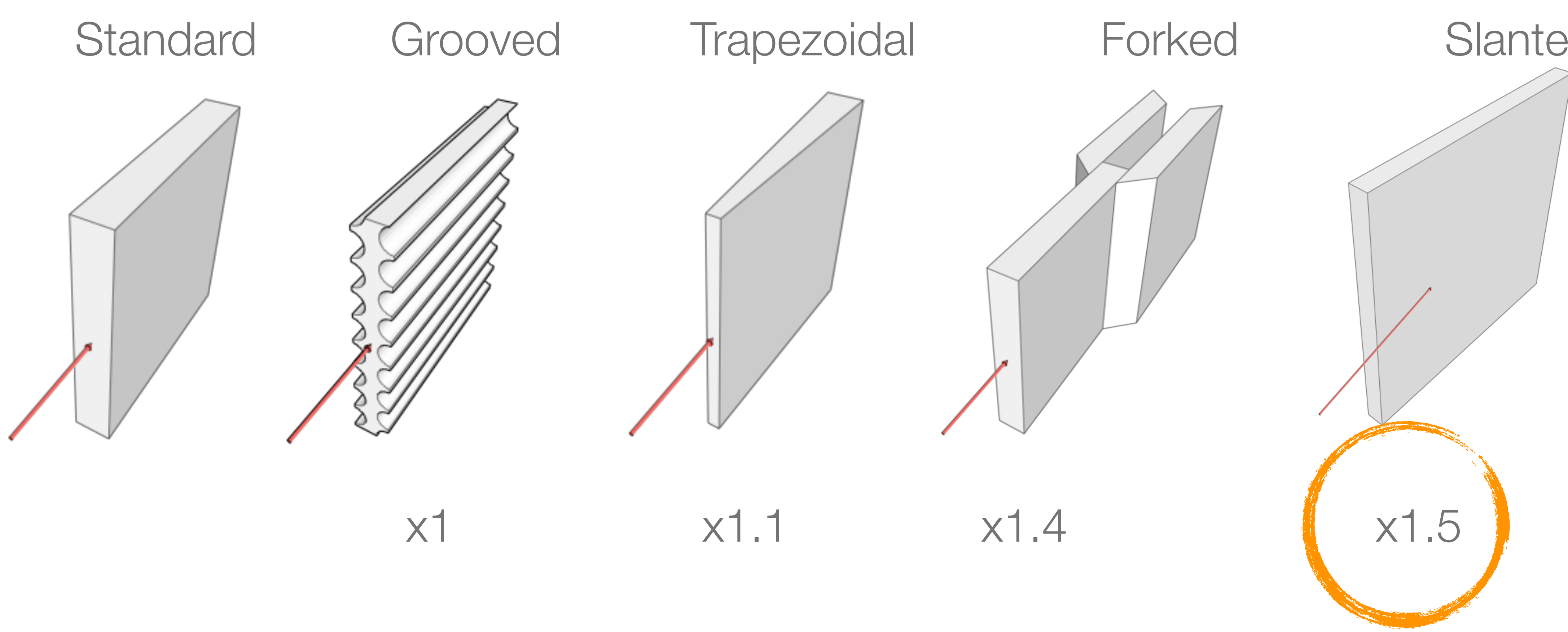

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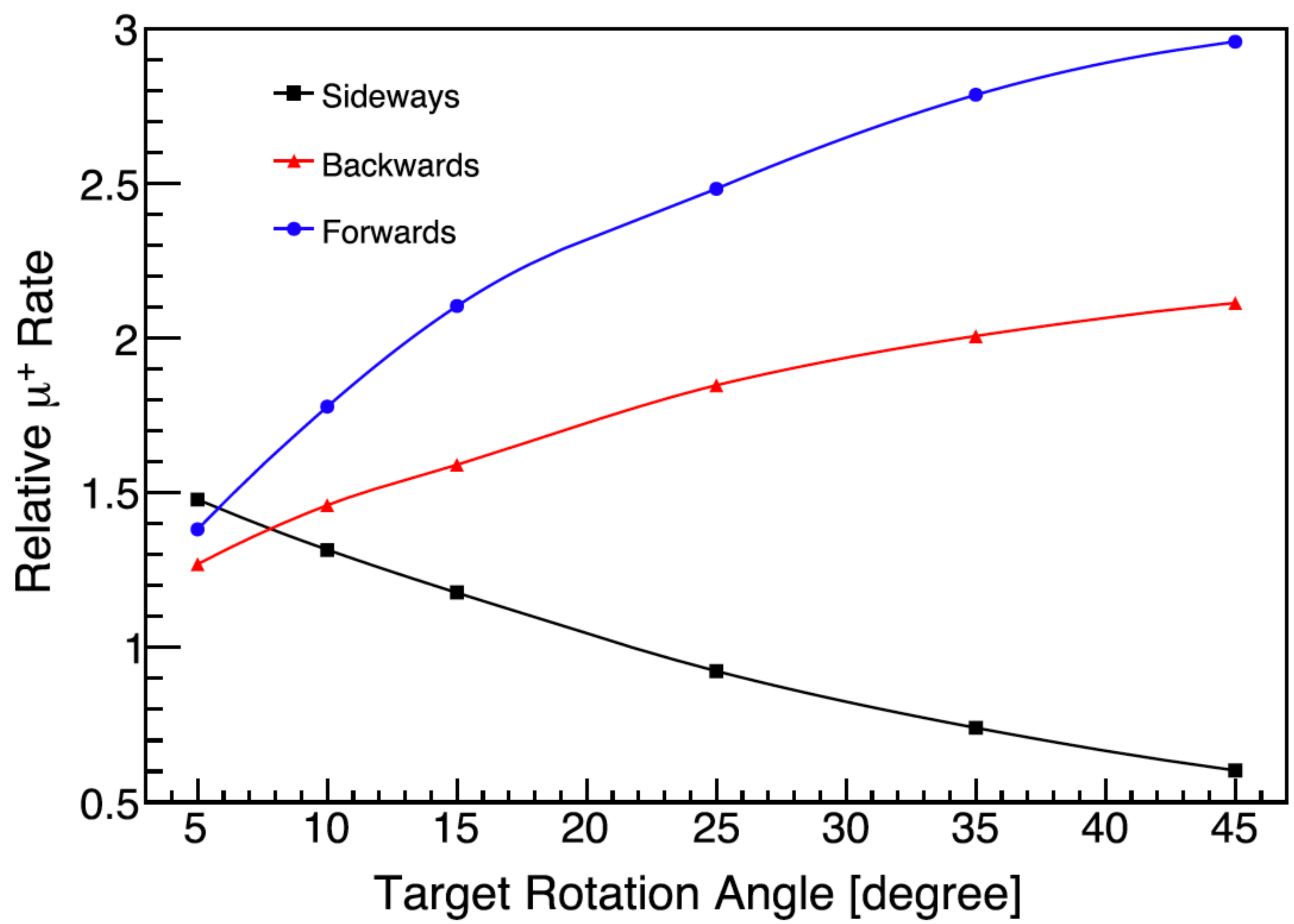
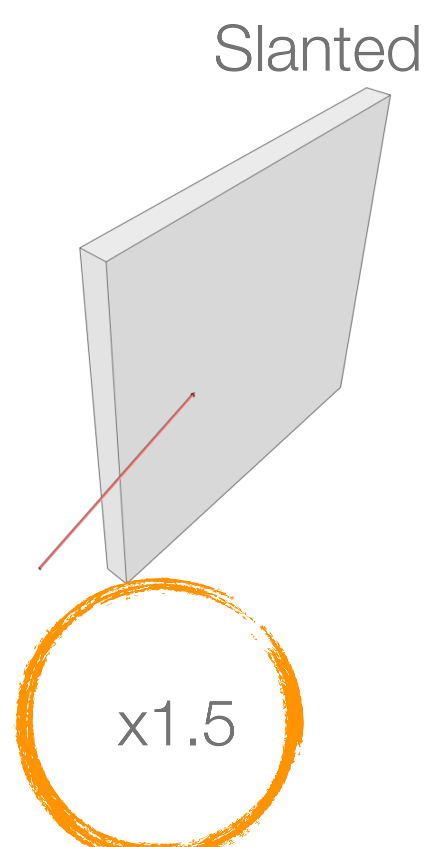
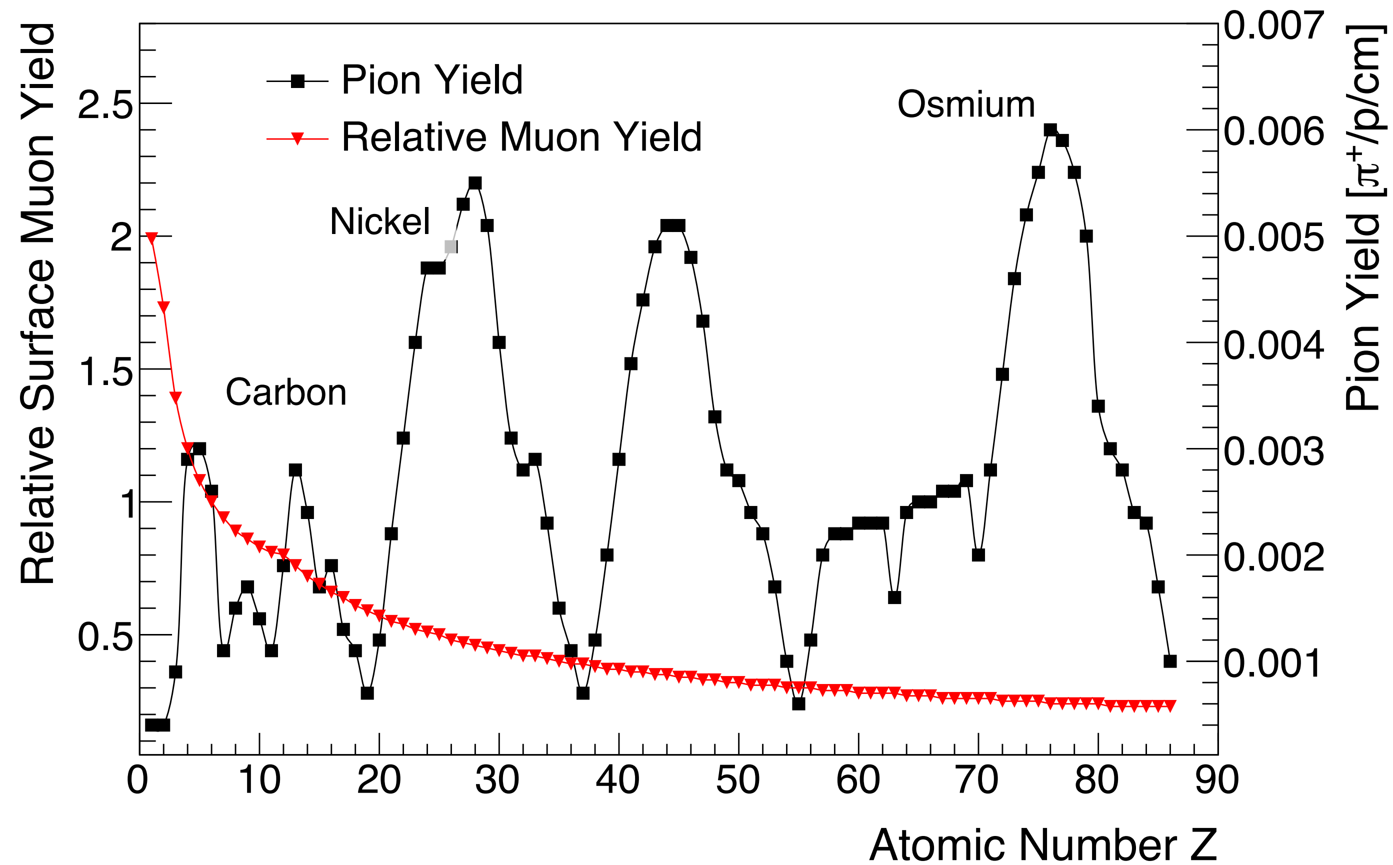




Optimization of standard production targets

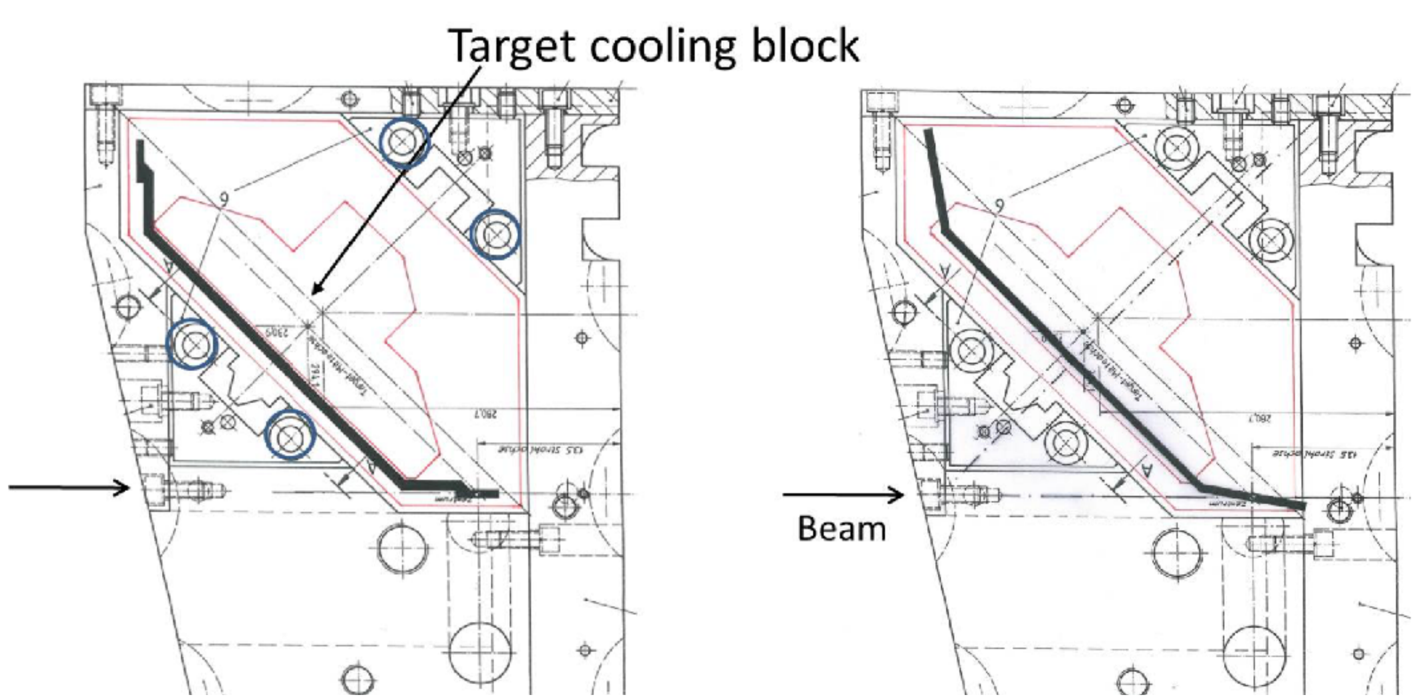
- Back to standard target to exploit possible improvements towards high intensity beams:
  - **Target alternate materials**
    - Search for high pion yield materials -> higher muon yield

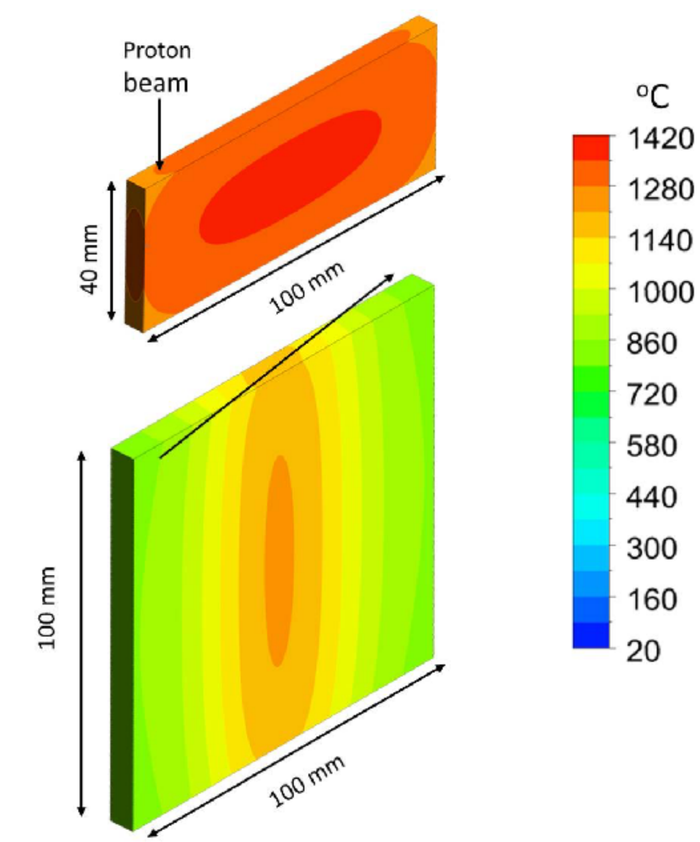
- Several materials have pion yields > 2x Carbon
- Relative muon yield favours low-Z materials, but difficult to construct as a target
- B_4C and Be_2C show 10-15% gain



Slanted target: Prototype test

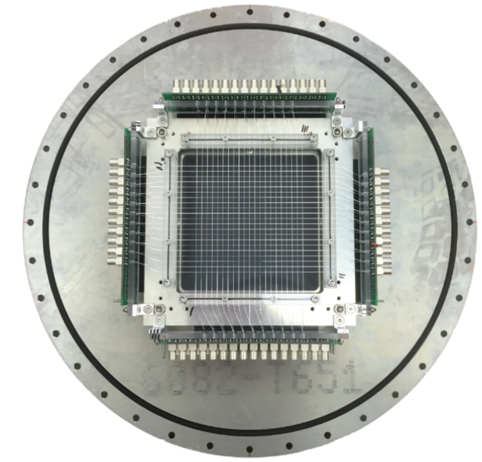
- Upgrade existing graphite production target E 40 mm
  - 8° slanting angle: Measurement in forward / backward / sideways direction
  - Production and implementation feasible
  - Thermal simulation ongoing

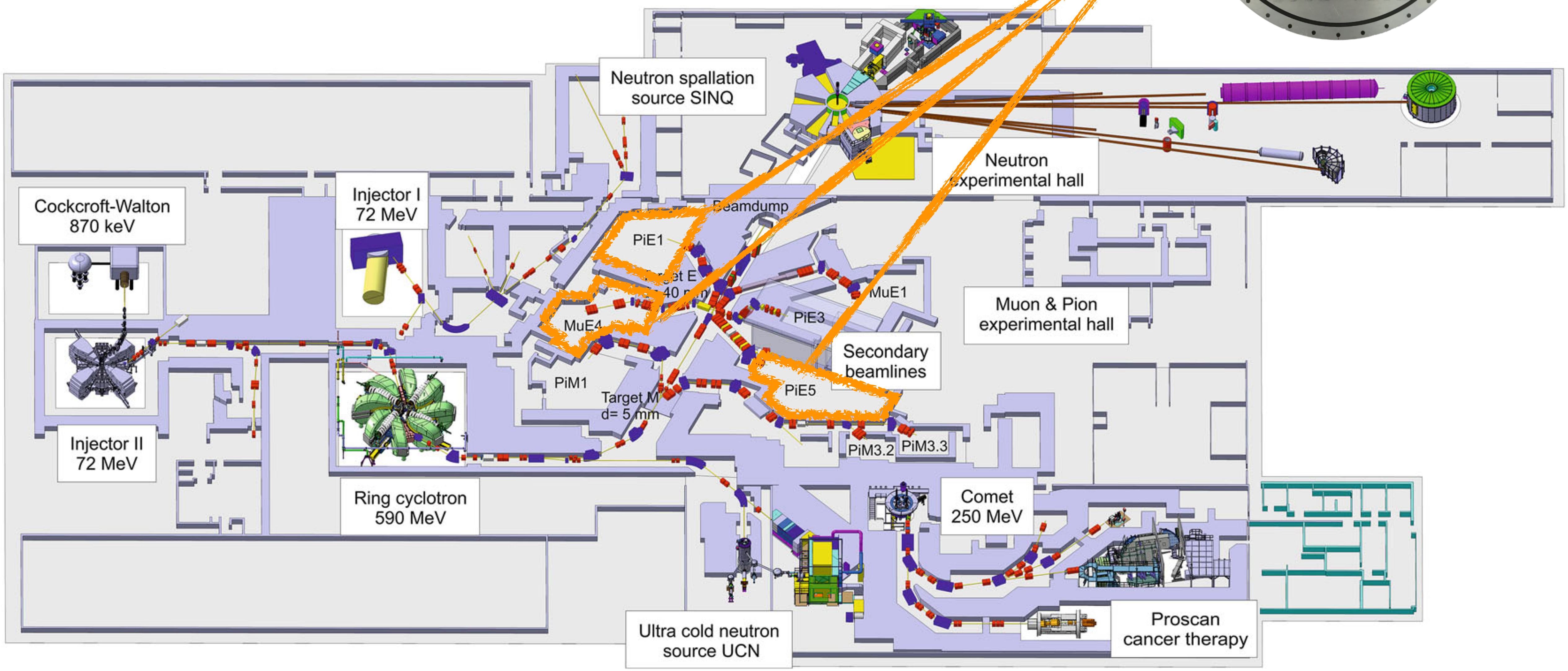




Slanted target: Prototype test

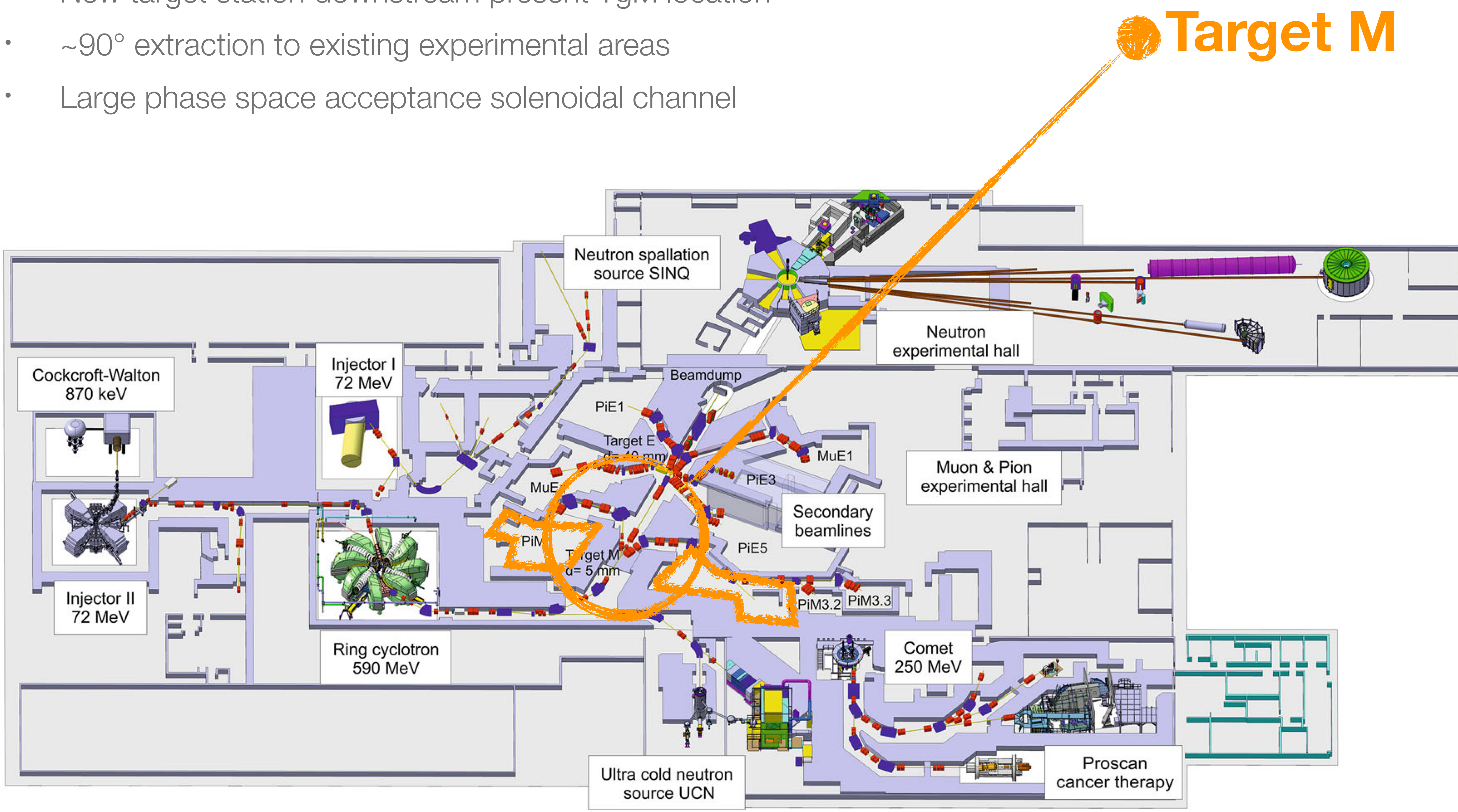
- Expect 30-50 % enhancement
- Measurement foreseen in three directions in 2019





HiMB project @ PSI

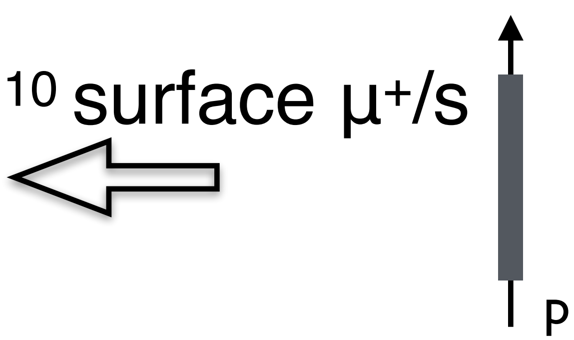
- New target station downstream present TgM location
- ~90° extraction to existing experimental areas
- Large phase space acceptance solenoidal channel



Target geometry for new target M*

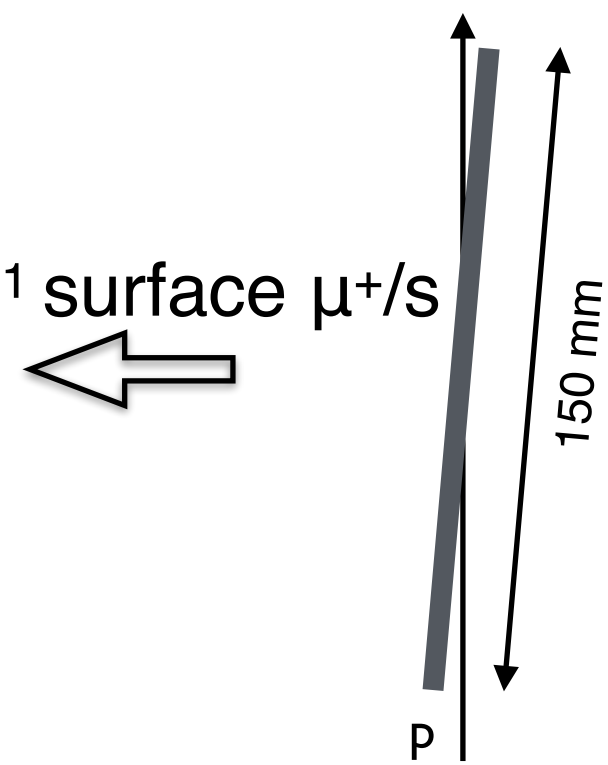
- Change current 5 mm TgM for 20 mm TgM*
- 20 mm rotated slab target as efficient as Target E

4.9×10^{10} surface μ^+/s



20 mm target

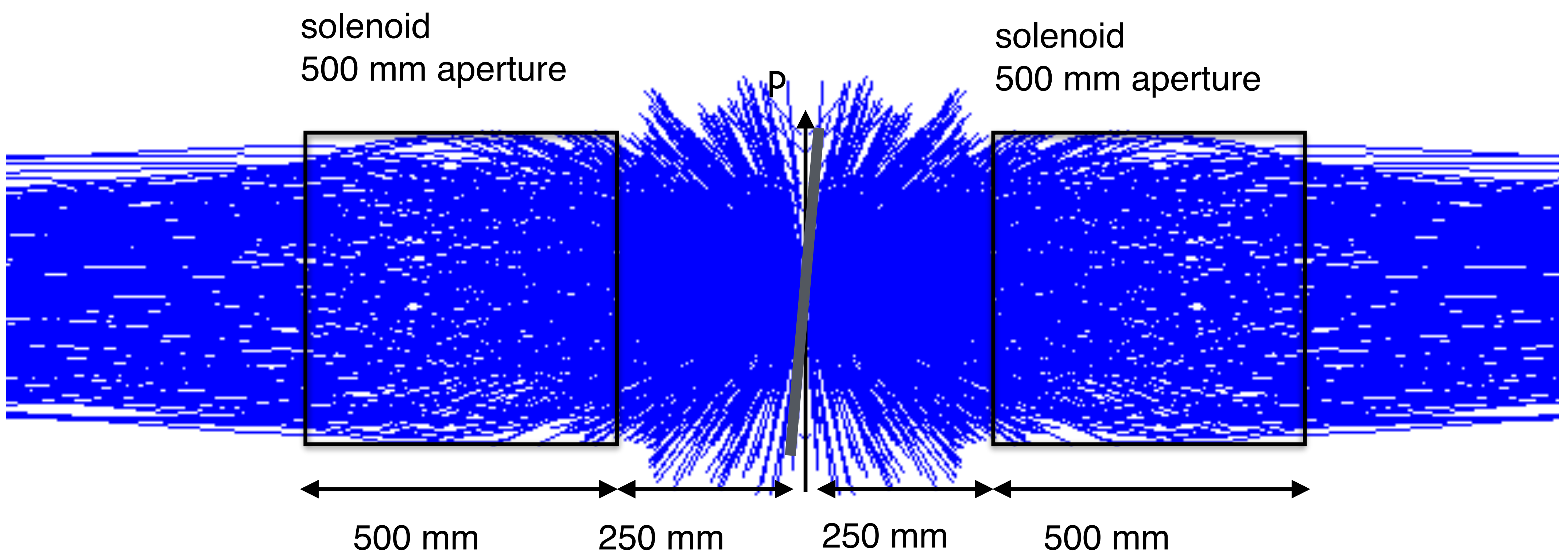
1.3×10^{11} surface μ^+/s



20 mm effective length
5° rotated slab

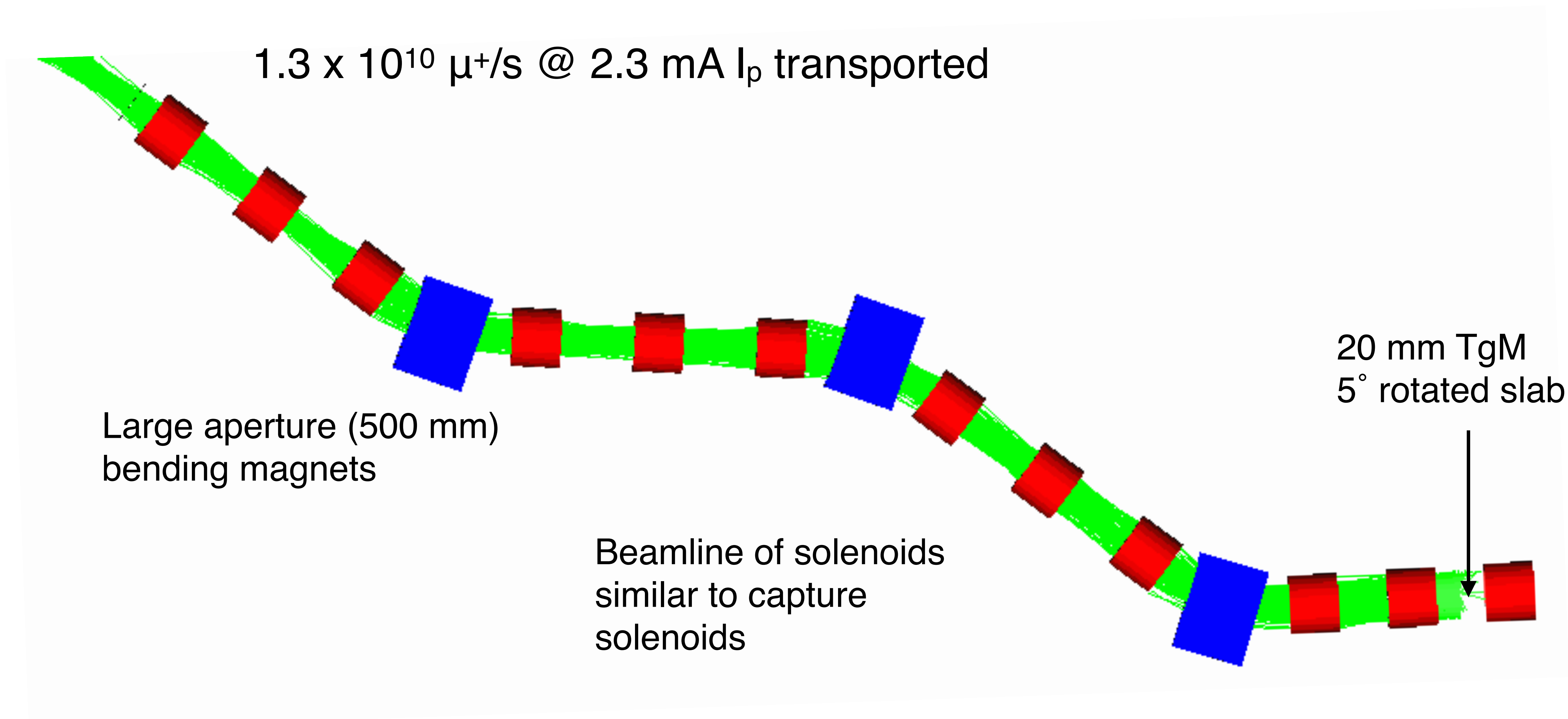
Split capture solenoids

- 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



Solenoid beam line

- First version of beam optics showing that large number of muons can be transported.
- Almost parallel beam, no focus, no separator, …
- Final beam optics under development



Prospects

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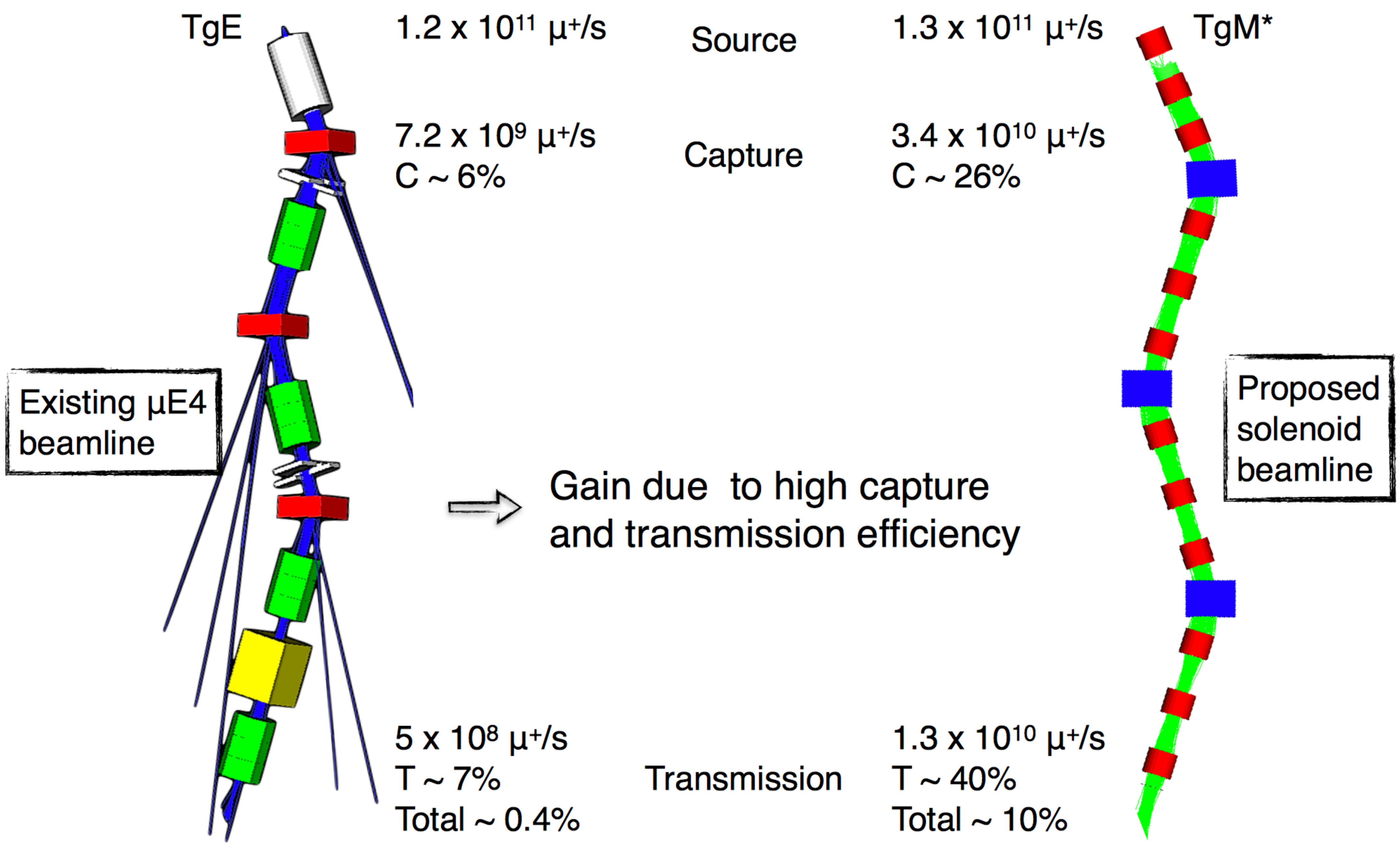
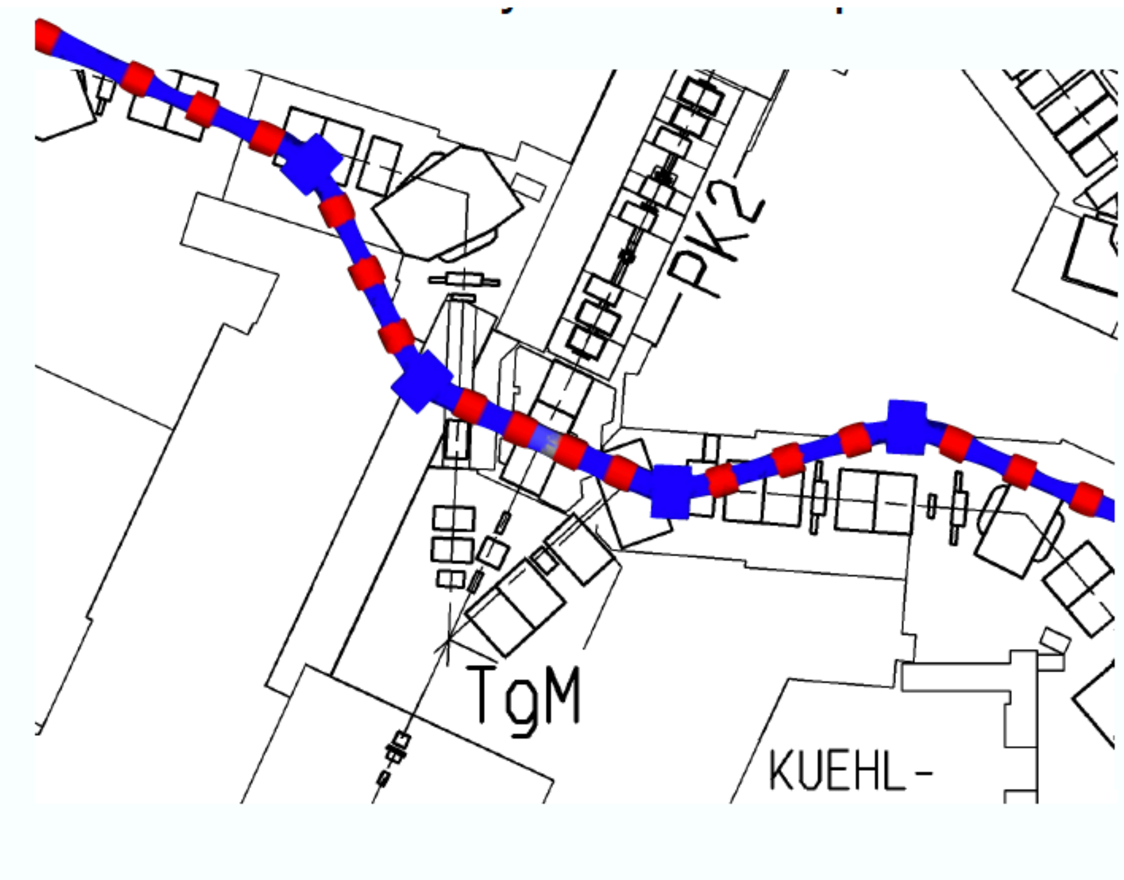
- Time schedule: **O(2025)**



ToDo

- Optimization of capturing
- Optimize final focussing
- Iterative Beam line optimization and implementation of beam monitoring and particle separator locations with max. transmission
- Minimize shielding modifications
- Particle separation
- Investigate impact on proton beam properties
- Study extraction angle
- Determine new target location
- Disposal of highly radioactive waste
- Study Mu3e setup phase space acceptance and optimize final focus properties
- Find solution with current users of Target M

Schematic of the layout in the experimental hall



Outlook

- 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**

IPA ETH zürich PAUL SCHERRER INSTITUT PSI