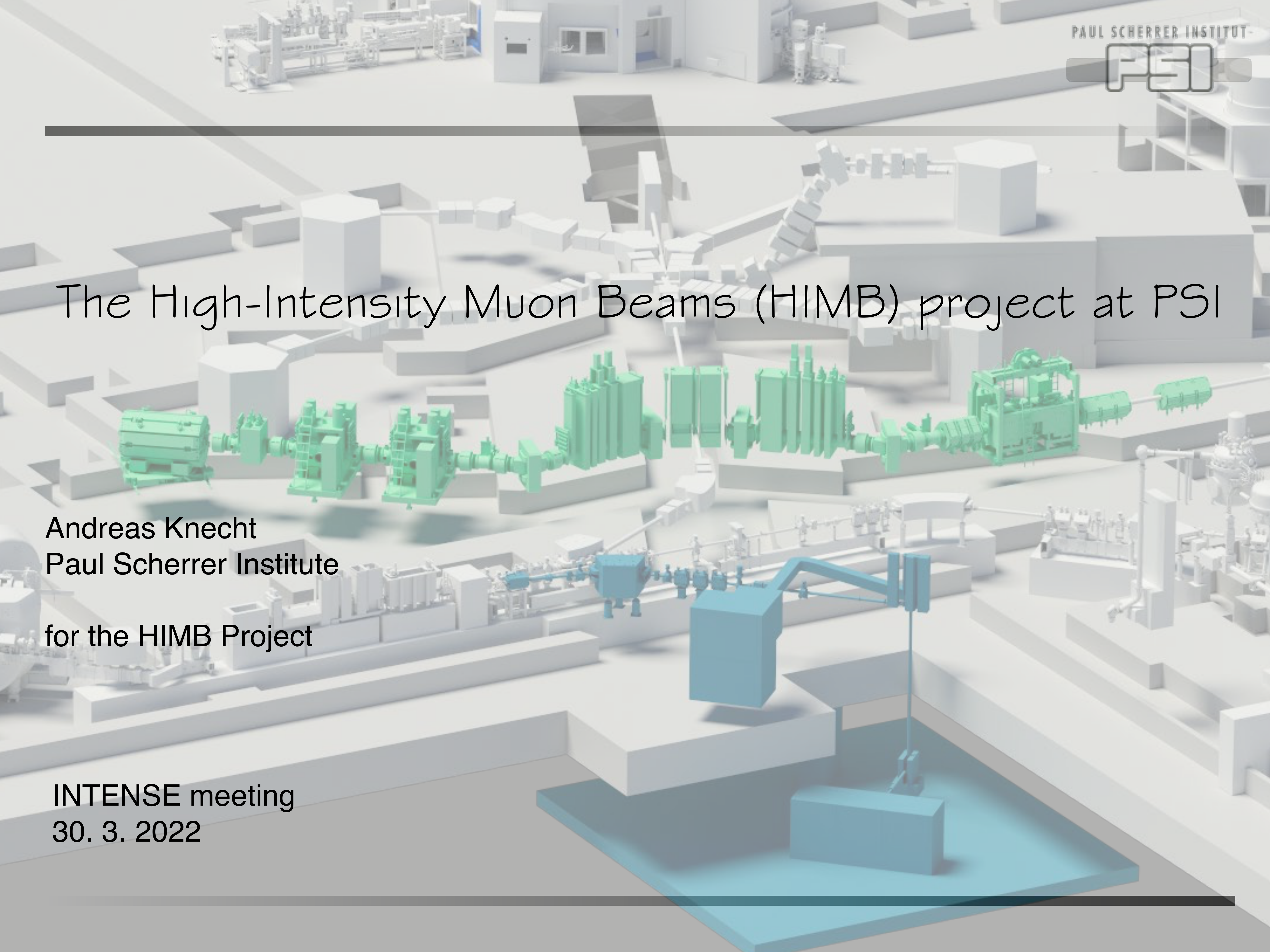


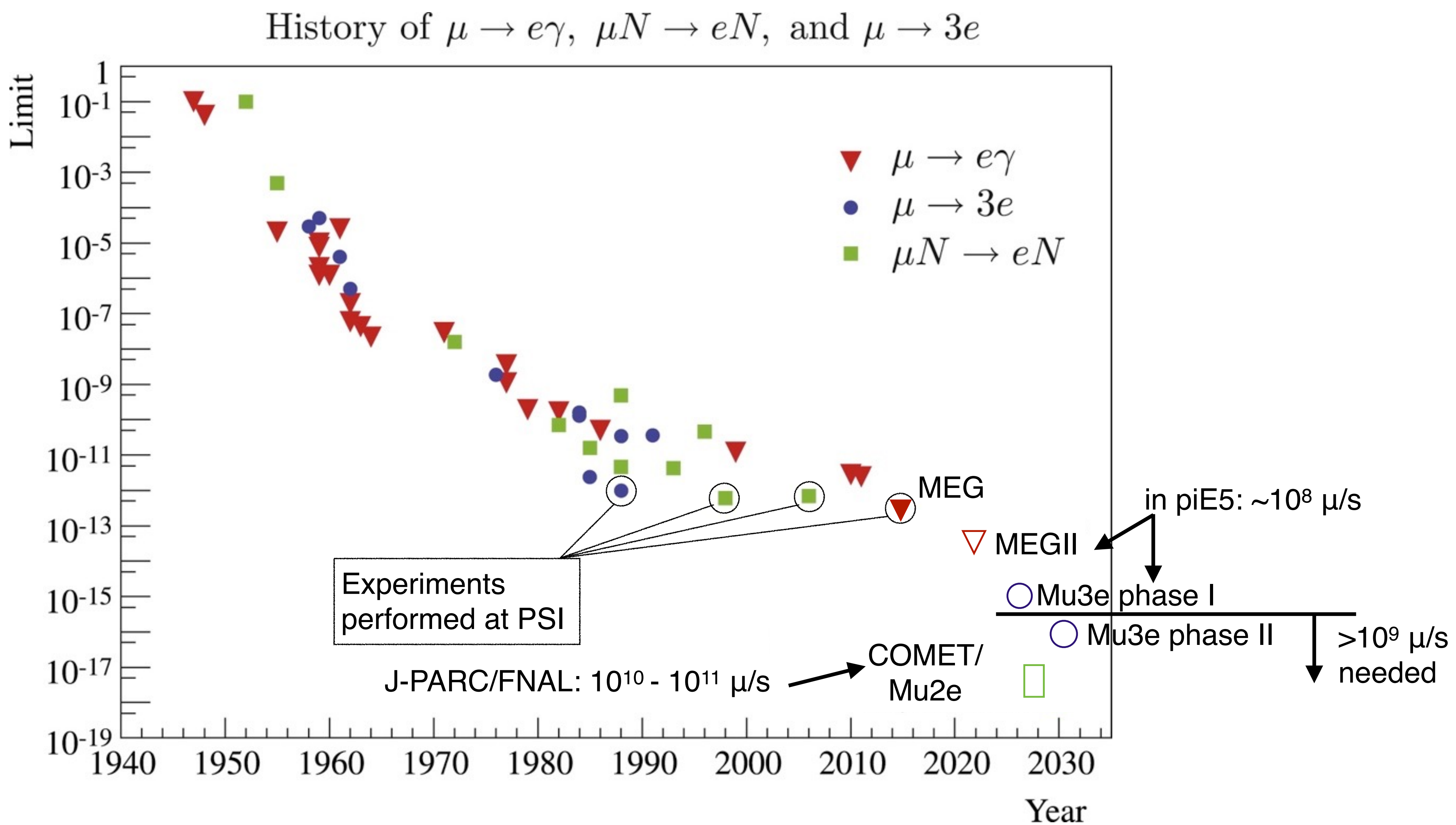
The High-Intensity Muon Beams (HIMB) project at PSI

Andreas Knecht
Paul Scherrer Institute

for the HIMB Project

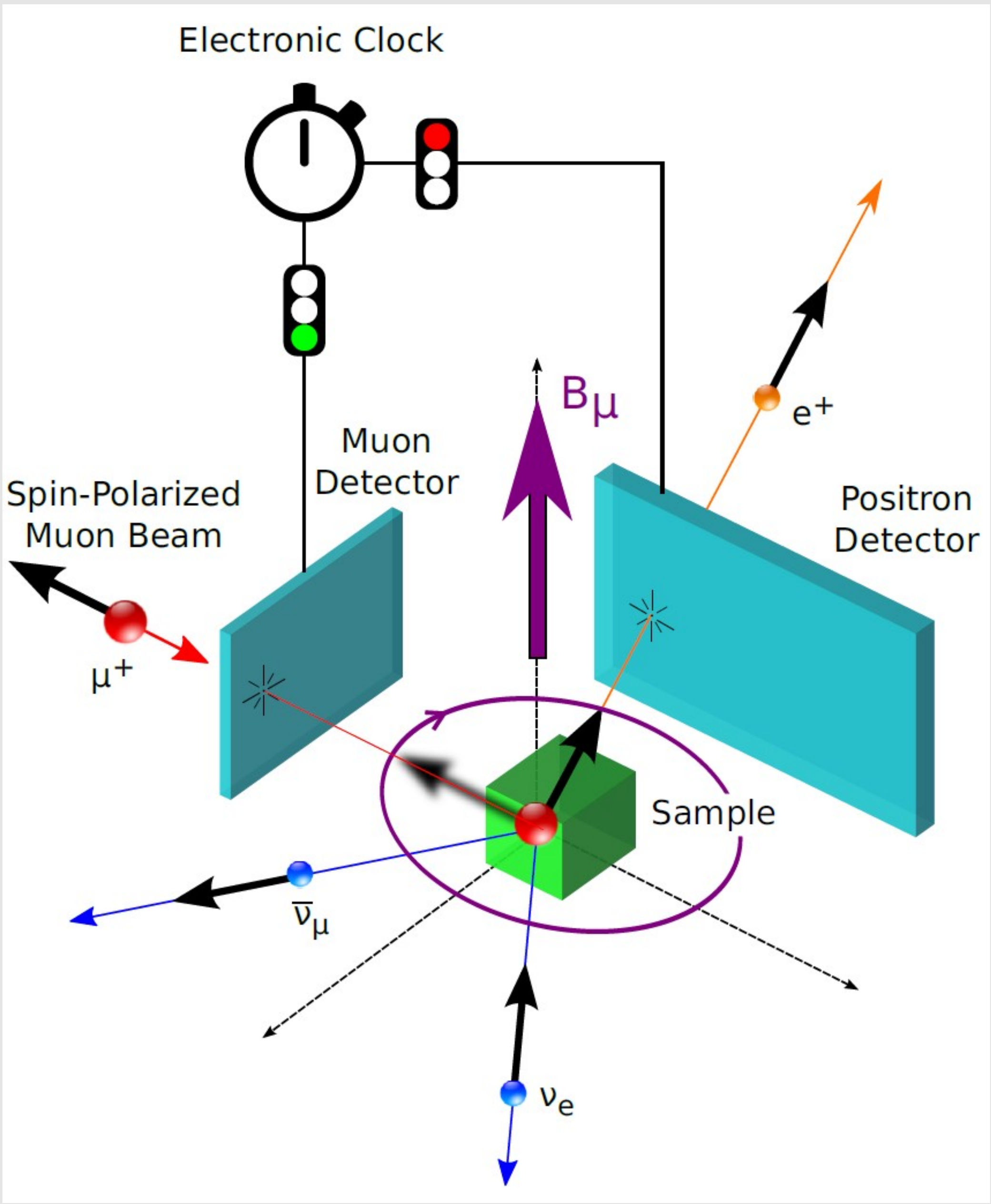
INTENSE meeting
30. 3. 2022

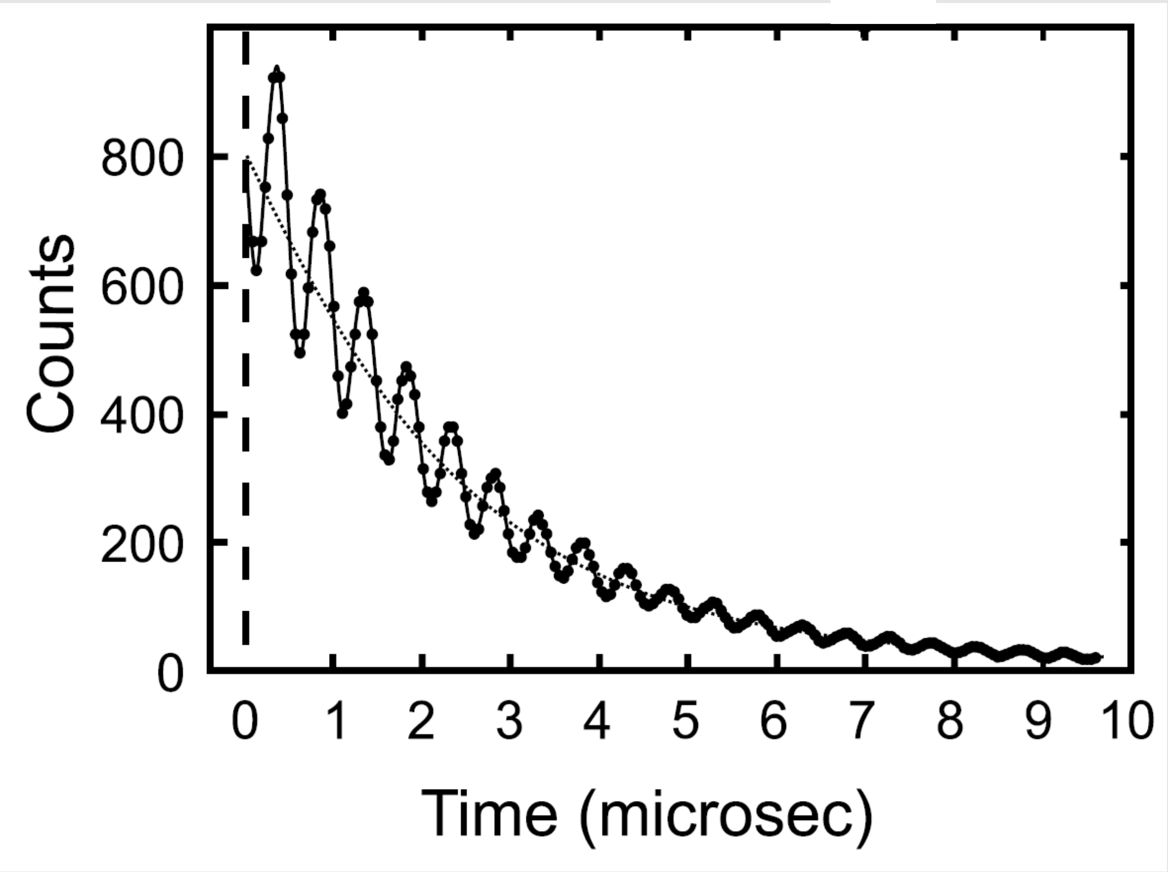
Motivation: cLFV



- Neutrinoless muon decays one of the most sensitive probes for new physics
- $\mu^+ \to e^+\gamma$ & $\mu^+ \to e^+e^-e^+$ only possible at DC & intensity-frontier machine such as PSI's HIPA accelerator
- Any future cLFV search at PSI will need higher beam intensities

Muon spin spectroscopy





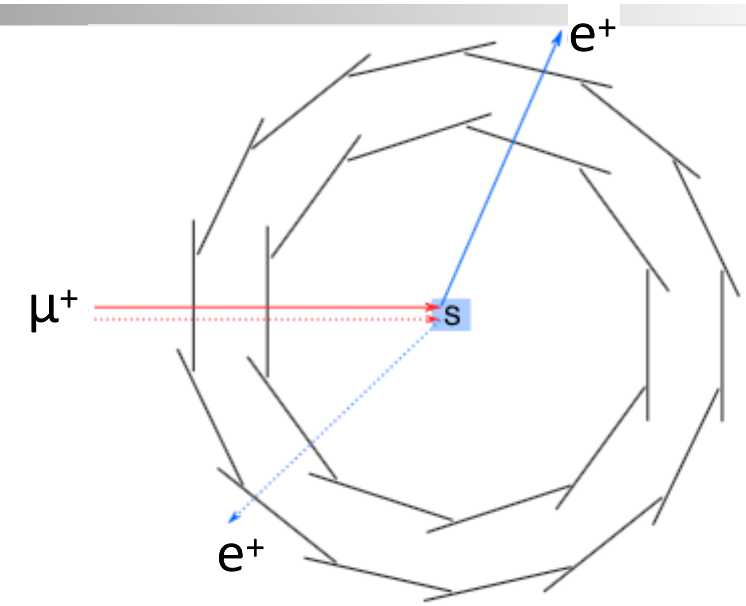
$$N(t) = Bkg + N_0 \exp(-t/\tau_\mu)[1 + a\,\hat{\boldsymbol{n}} \cdot P(t)]$$

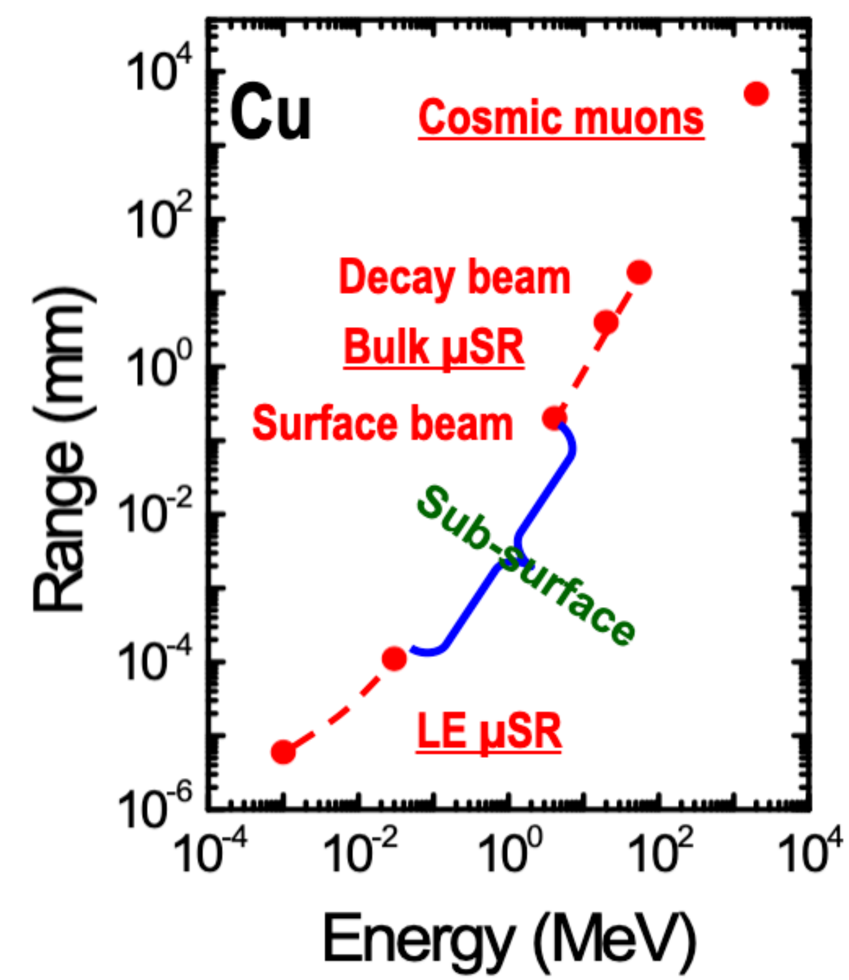
$\hat{\boldsymbol{n}}$ - direction of detector

- Muons probe local, internal magnetic field revealing the magnetic properties of the sample

Motivation: muSR

- Vertexing for muSR applications:
  - Pixel detector development together with particle physics
  - Enables 10-100x faster measurements.
  - Unprecedented small samples, 10-100x smaller ("μ-microscope").
  - Allows putting samples in extreme conditions at unprecedented levels, e.g. 10x pressure
- Sub-surface muons at high rate:
  - They stop in thinner layers and cover a yet inaccessible depth range of 200 nm - 200 μm.
  - Perfectly suited for studies of energy materials and devices.





HIMB Science Case Workshop & Document

PAUL SCHERRER INSTITUT PSI

- Workshop held in April 2021 with 122 participants to gather and identify HIMB Science Case
- 116 page long HIMB science case document published on arXiv:2111.05788v1
- Comprehensive overview of all the identified experiments and measurements that benefit from HIMB both in particle physics and materials science

Science Case for the new High-Intensity Muon Beams HIMB at PSI

Edited by A. Knecht, F. Meier Aeschbacher, T. Prokscha, S. Ritt, A. Signer

M. Aiba[1], A. Amato[1], A. Antognini[1,2], S. Ban[3], N. Berger[4], L. Caminada[1,5], R. Chislett[6], P. Crivelli[2], A. Crivellin[1,5], G. Dal Maso[1,2], S. Davidson[7], M. Hoferichter[8], R. Iwai[2], T. Iwamoto[3], K. Kirch[1,2], A. Knecht[1], U. Langenegger[1], A. M. Lombardi[9], H. Luetkens[1], F. Meier Aeschbacher[1], T. Mori[3], J. Nuber[1,2], W. Ootani[3], A. Papa[1,10], T. Prokscha[1], F. Renga[11], S. Ritt[1], M. Sakurai[2], Z. Salman[1], P. Schmidt-Wellenburg[1], A. Schöning[12], A. Signer[1,5,*], A. Soter[2], L. Stingelin[1], Y. Uchiyama[3], and F. Wauters[4]

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[6]Department of Physics and Astronomy, University College London, WC1E 6BT, United Kingdom
[7]LUPM, Université de Montpellier, Place Eugène Bataillon, 34095 Montpellier, France
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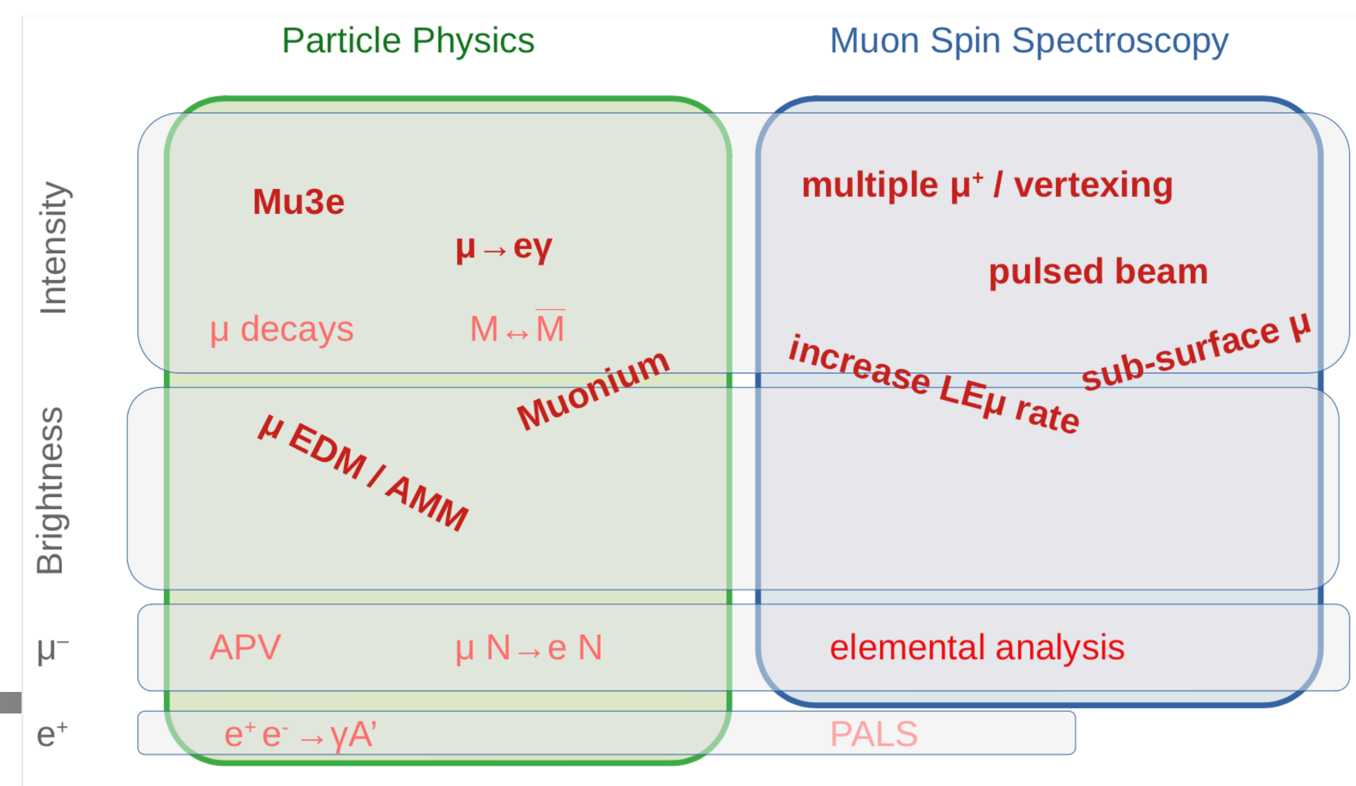
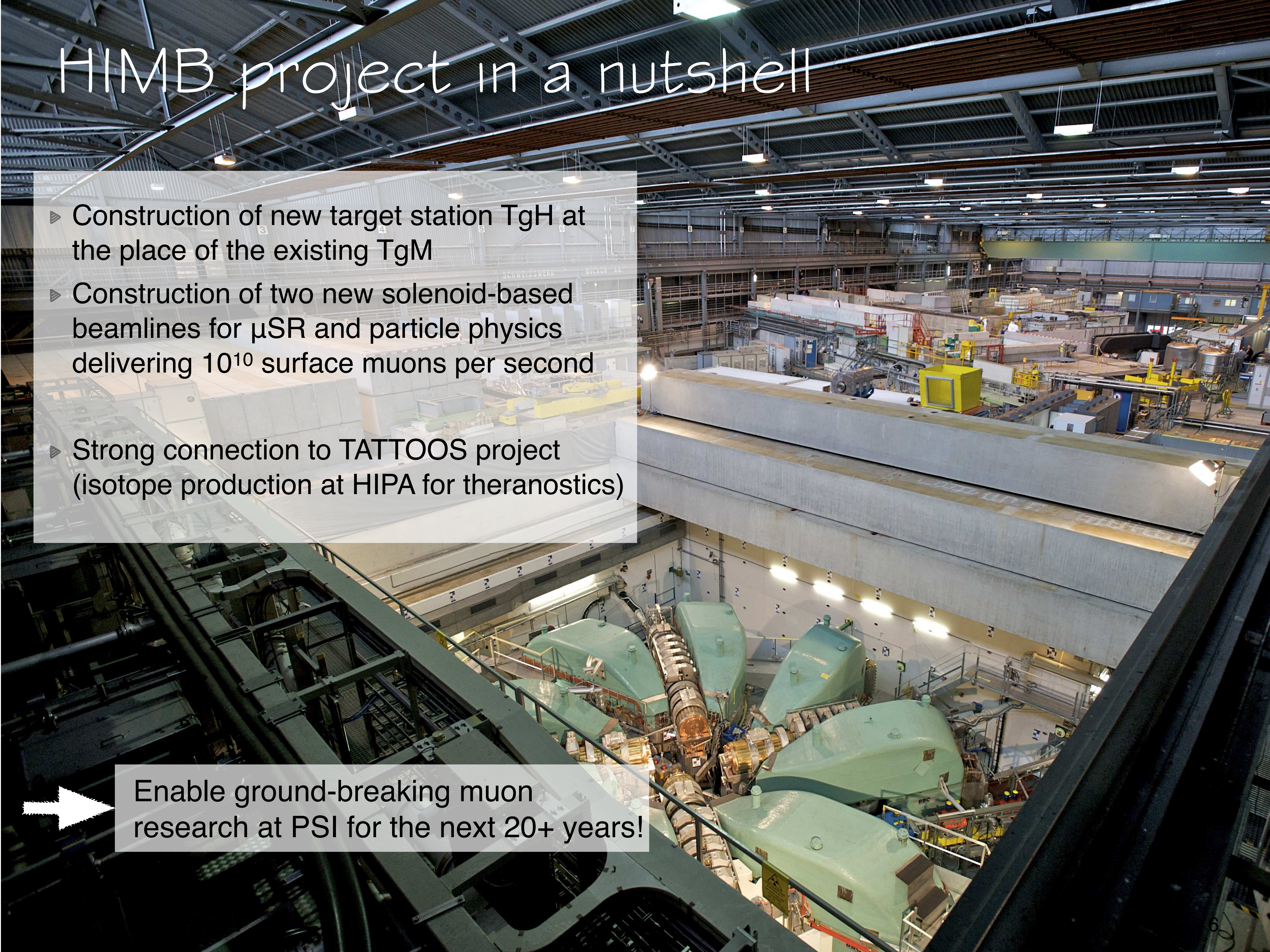
[11]INFN Sezione di Roma, Piazzale A. Moro 2, 00185 Roma, Italy
[12]Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany
*Corresponding author: adrian.signer@psi.ch



HIMB project in a nutshell

- Construction of new target station TgH at the place of the existing TgM
- Construction of two new solenoid-based beamlines for µSR and particle physics delivering 10^{10} surface muons per second
- Strong connection to TATTOOS project (isotope production at HIPA for theranostics)

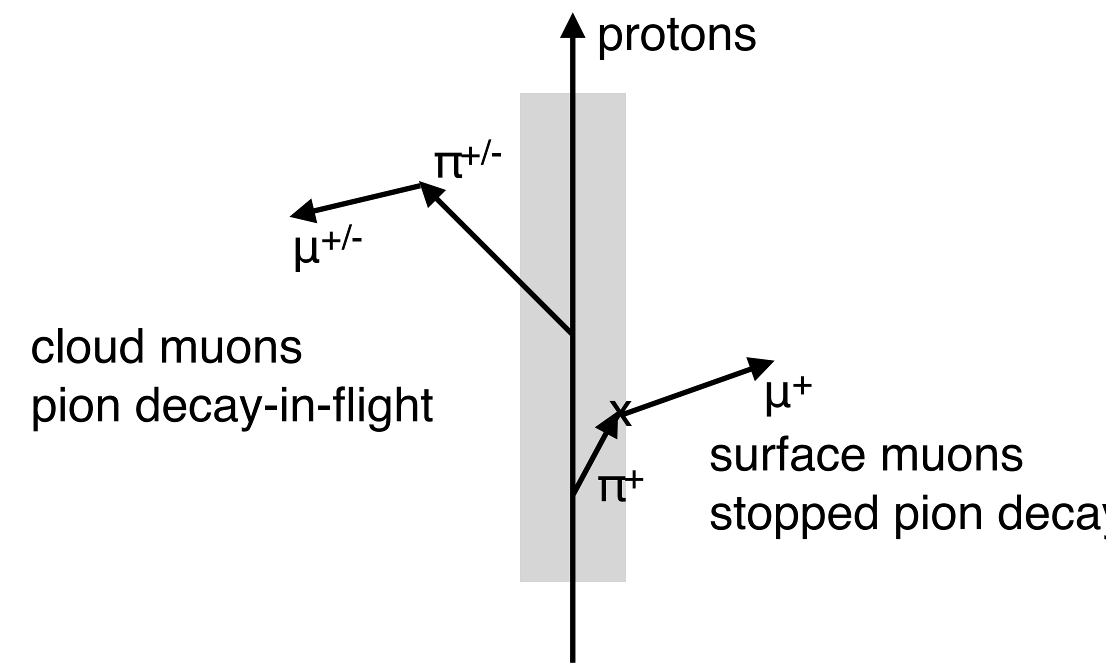
→ Enable ground-breaking muon research at PSI for the next 20+ years!

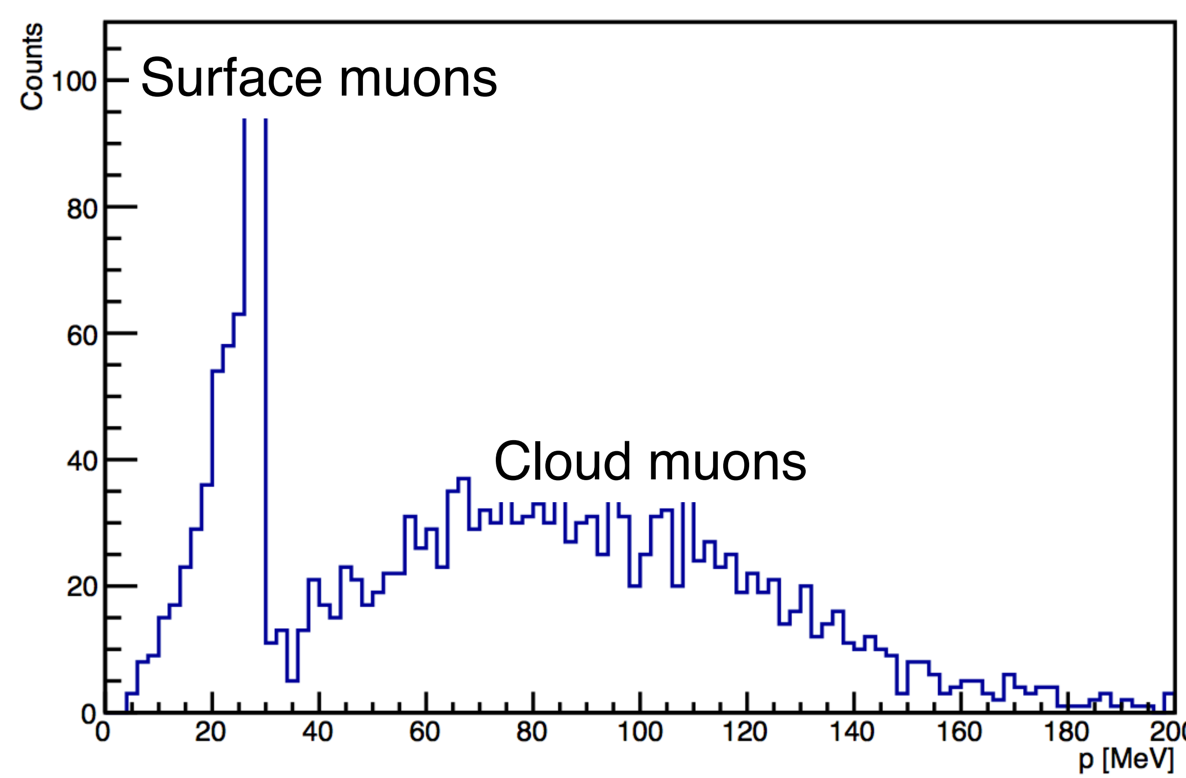


Pions, surface and cloud muons

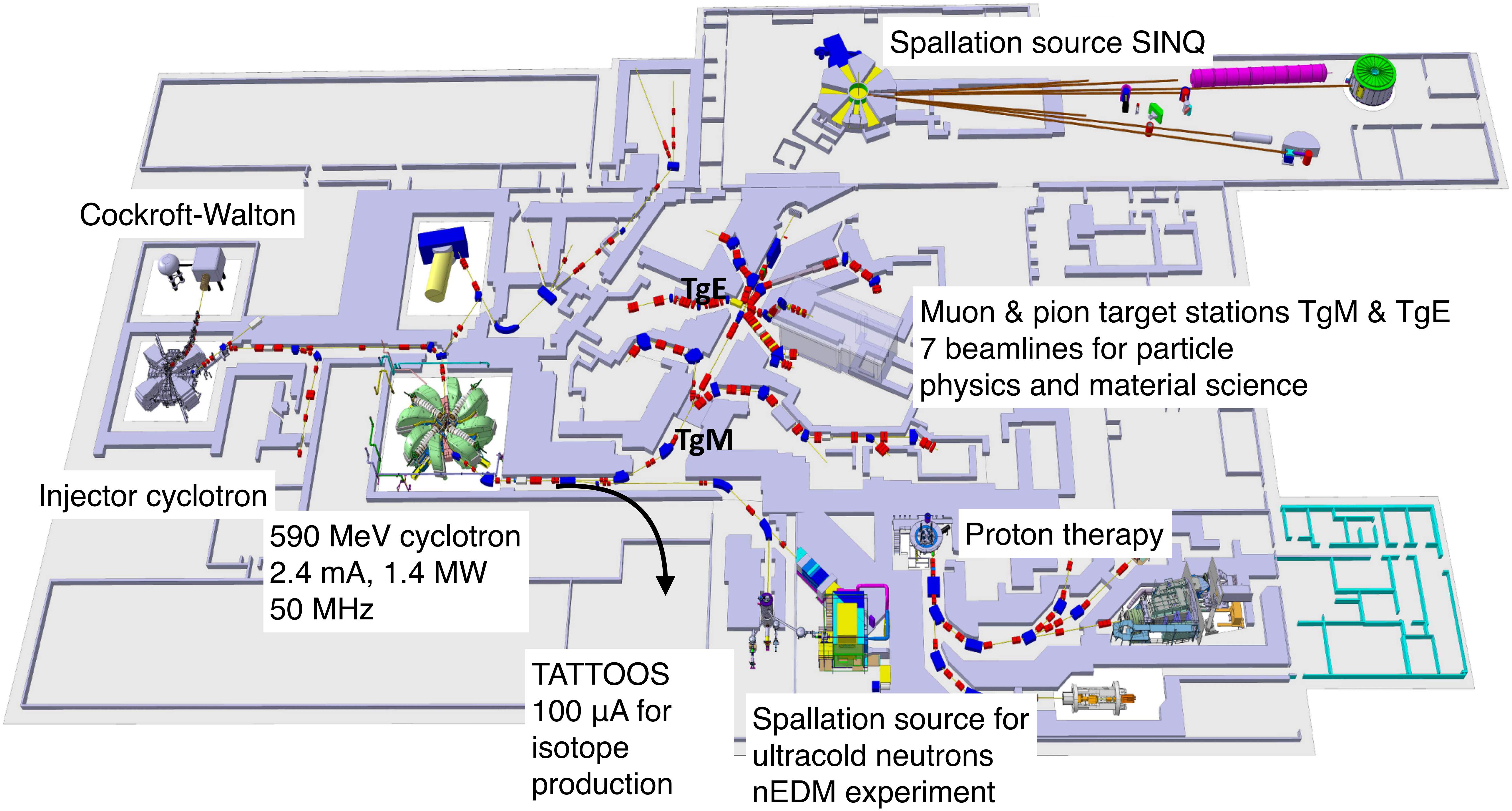
- Pions produced through the interaction of the protons with the target
- Low-energy muon beam lines typically tuned to surface-μ+ at ~ 28 MeV/c
- Contribution from cloud muons at similar momentum about 100x smaller
- Negative muons only available as cloud muons
- 50 MHz beam structure for pions and cloud muons
- For surface muons: time structure of cyclotron smeared out by pion lifetime → DC muon beams

$$p + p \to p + n + \pi^+ \qquad p + n \to p + n + \pi^0$$
$$p + p \to p + p + \pi^0 \qquad p + n \to p + p + \pi^-$$
$$p + p \to d + \pi^+ \qquad p + n \to n + n + \pi^+$$
$$p + n \to d + \pi^0.$$



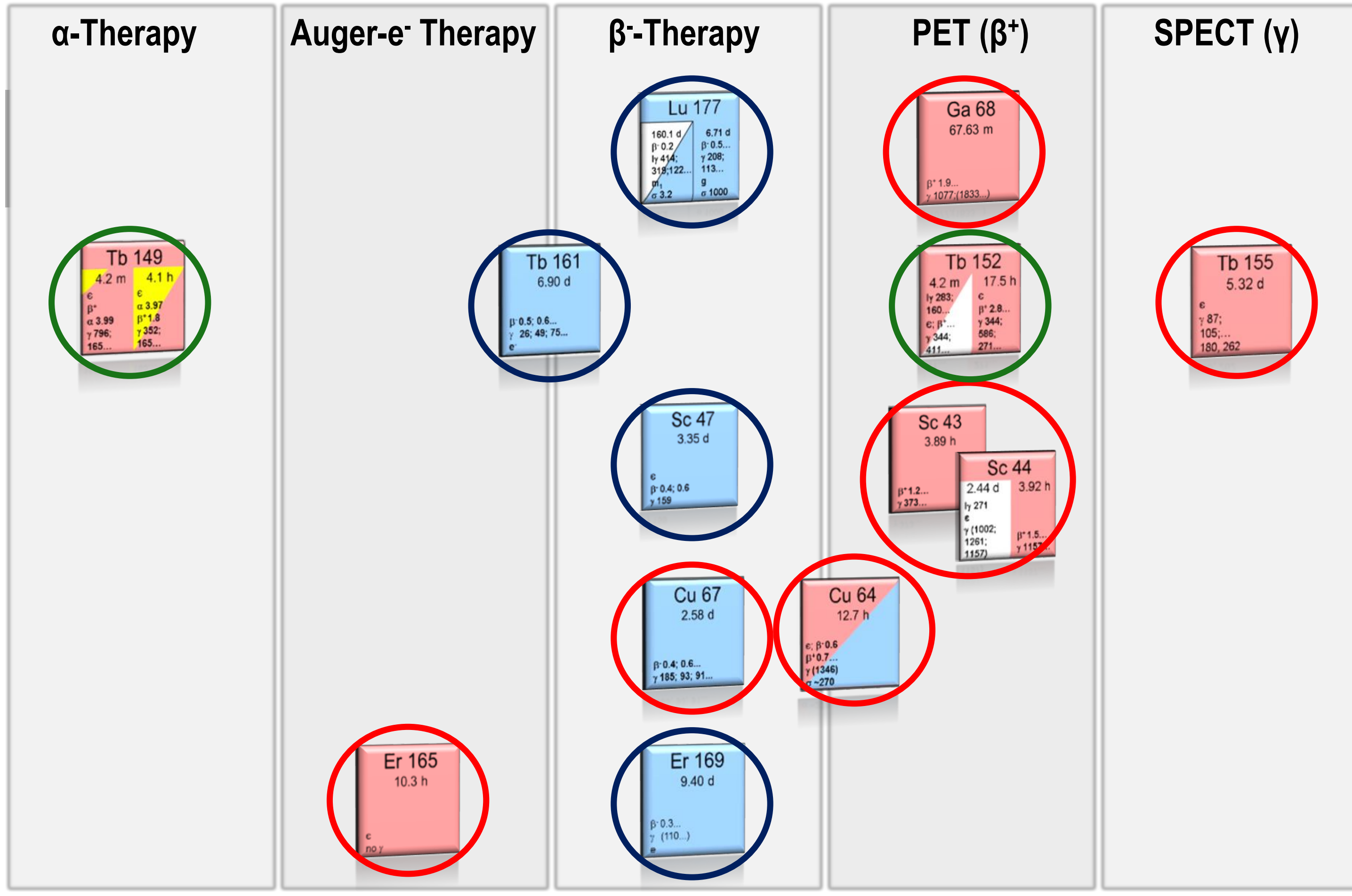


PSI Proton Accelerator HIPA

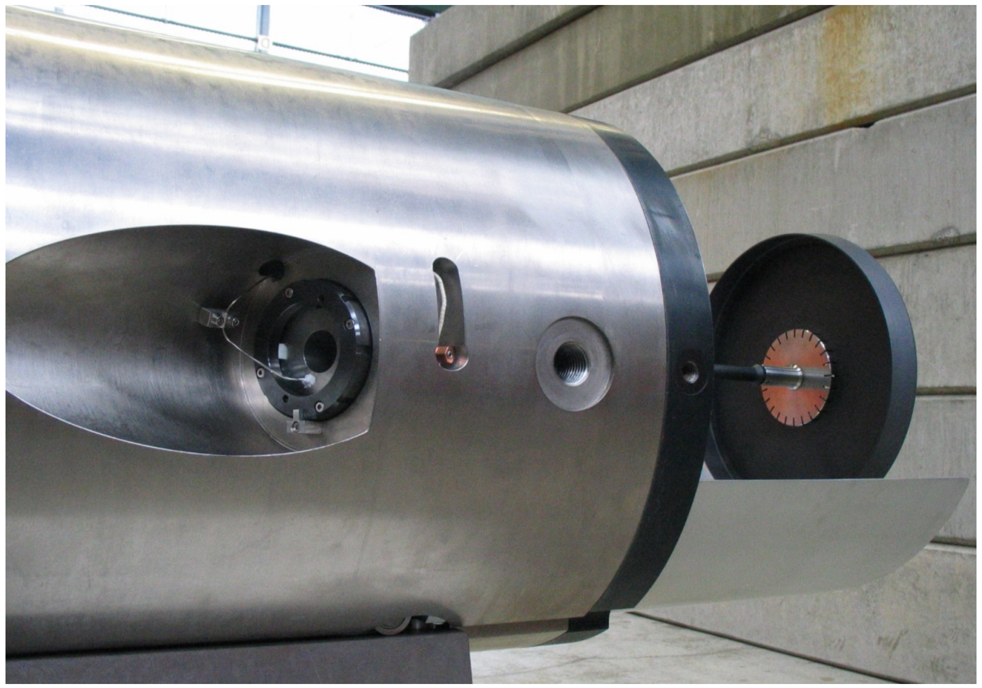


TATTOOS

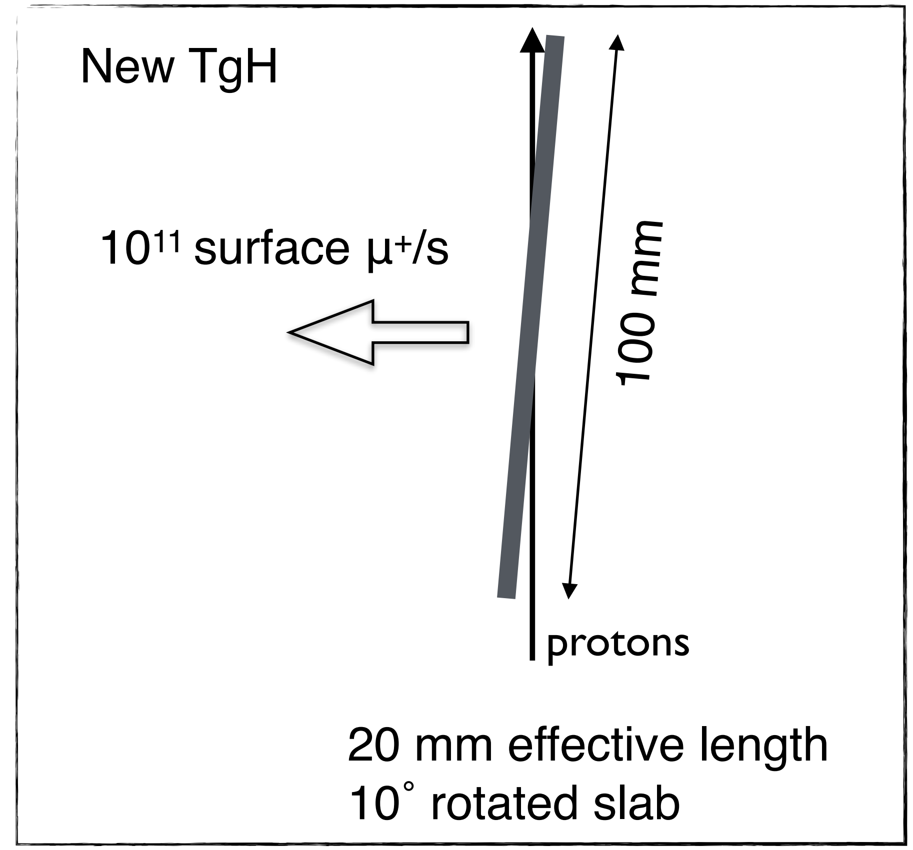
- Targeted Alpha Tumour Therapy and Other Oncological Solutions
- Spallation on tantalum target; online isotope separation; hot cells for processing of radioisotopes
- Produce suitable alpha-emitting radioisotopes for clinical studies of theranostics
- Terbium of particular interest, but other interesting isotopes also available
- By the way:
  HIMB + TATTOOS -> IMPACT



Target Geometry for new TgH



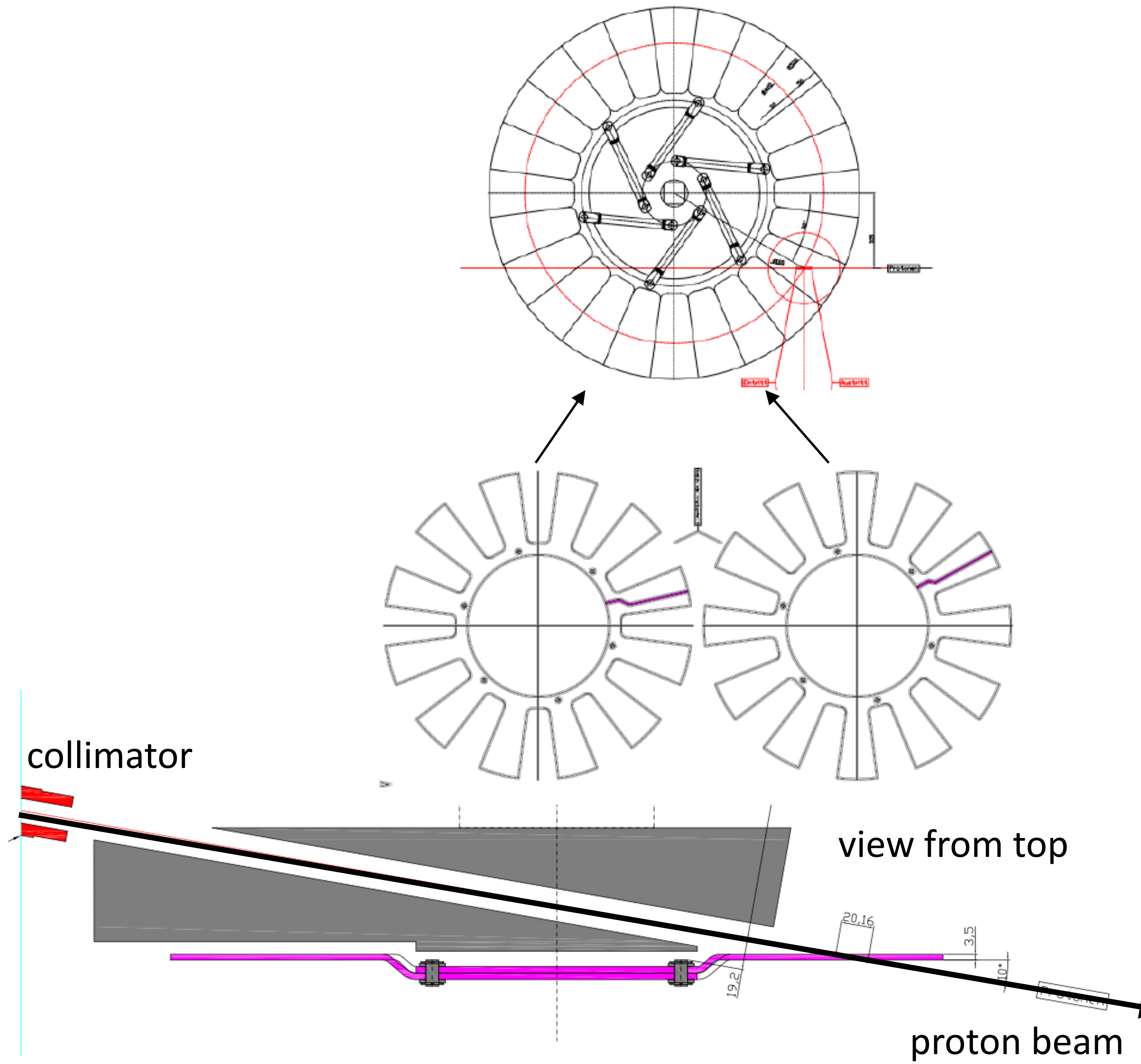
Existing TgM



- Change current 5 mm TgM for 20 mm TgH (known situation from 60 mm TgE)
- 20 mm rotated slab target as efficient as 40 mm standard Target E
- Slanted target geometry also implemented and tested for TgE → 40-50% gain in surface muon rate

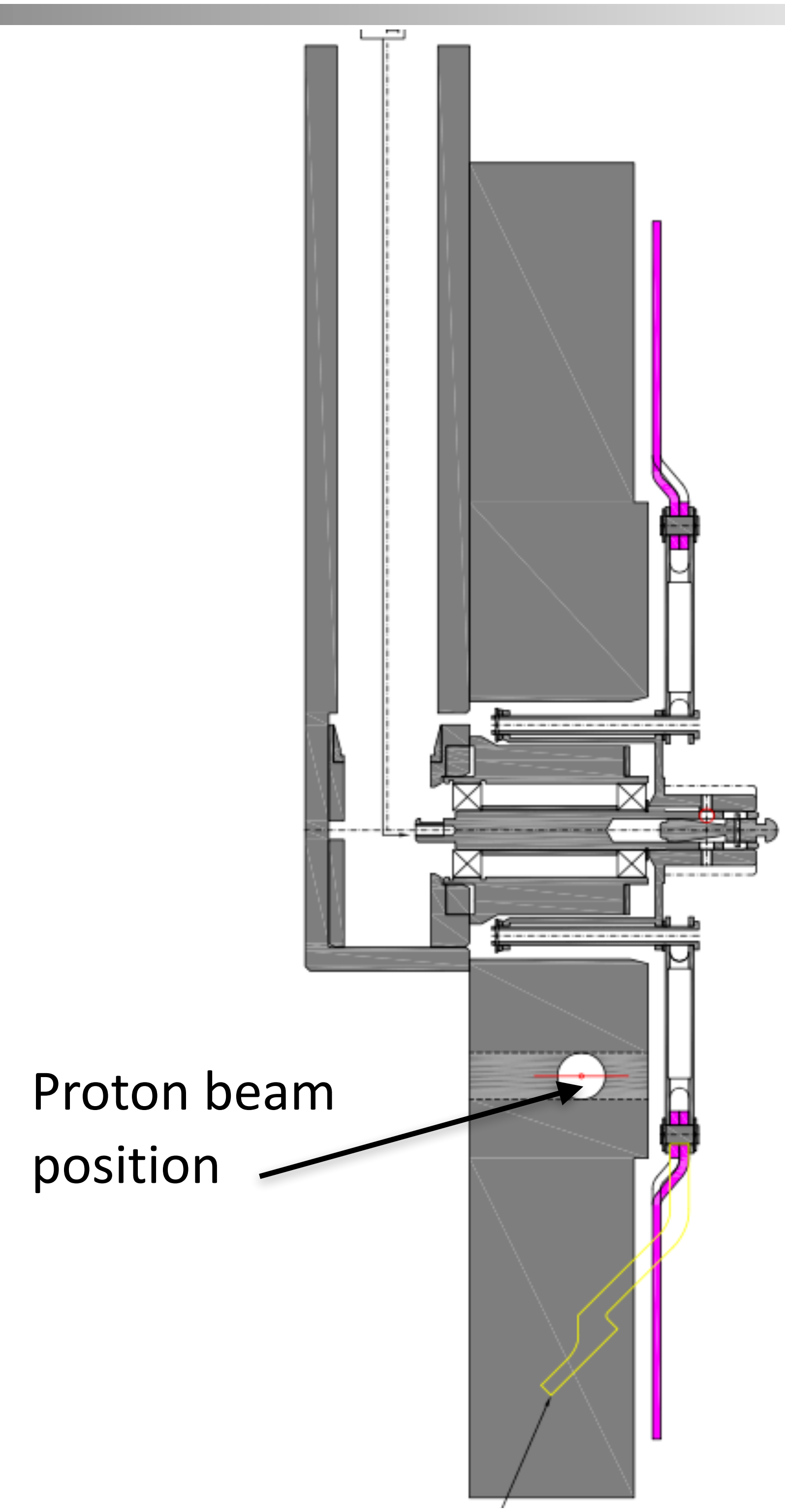
Target design

- Two discs with individual "leaves" that sit on top of each other -> well controllable slits
- Proton beam impinges target from the back
- Protection collimator upstream
- Fits into existing TgE exchange flask

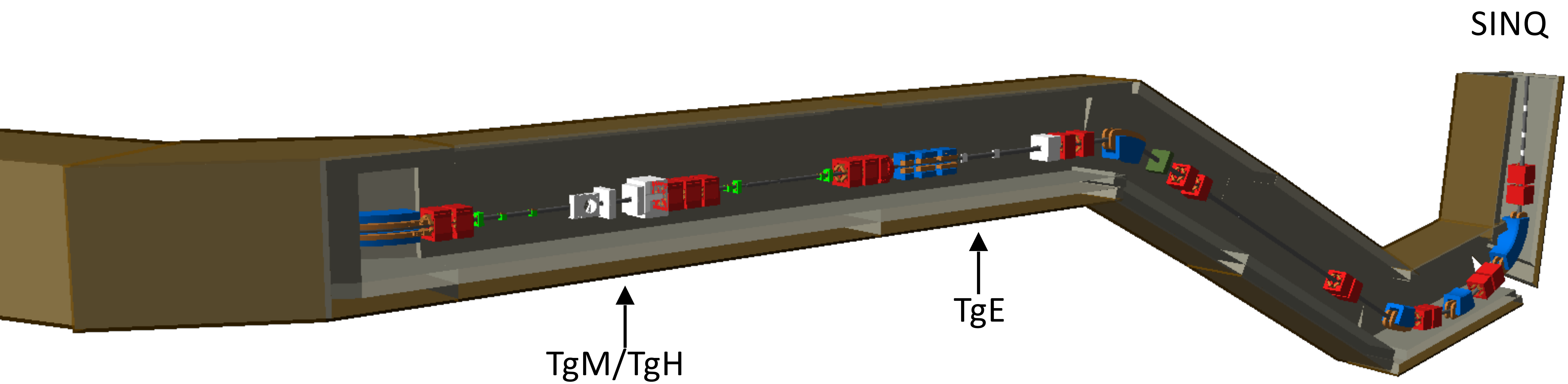


Target design

- Proton beam impinges on target wheel below the rotation axis
  -> allows “flat” target, gives a bit more usable space and moves the proton beam away from the shaft of the target wheel

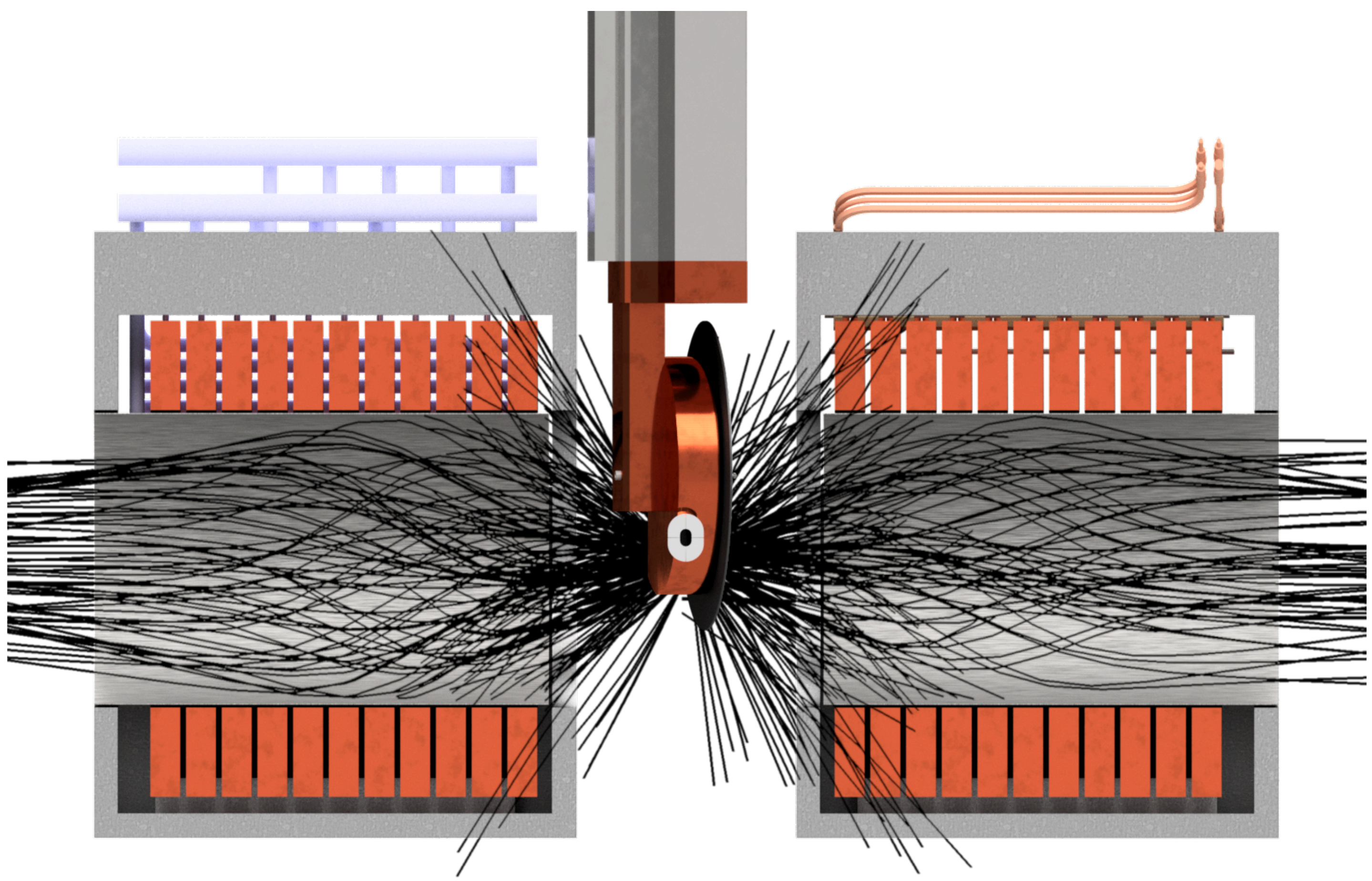


Impact on other facilities of HIPA



- Full simulation of high-energy proton beam line in BDSIM using either TgM or TgH to assess impact on the other HIPA target stations
- Transmission to SINQ with TgH 61% compared to 65% with TgM
- Beam shape at TgE and SINQ preserved

Split Capture Solenoids for Muon Collection

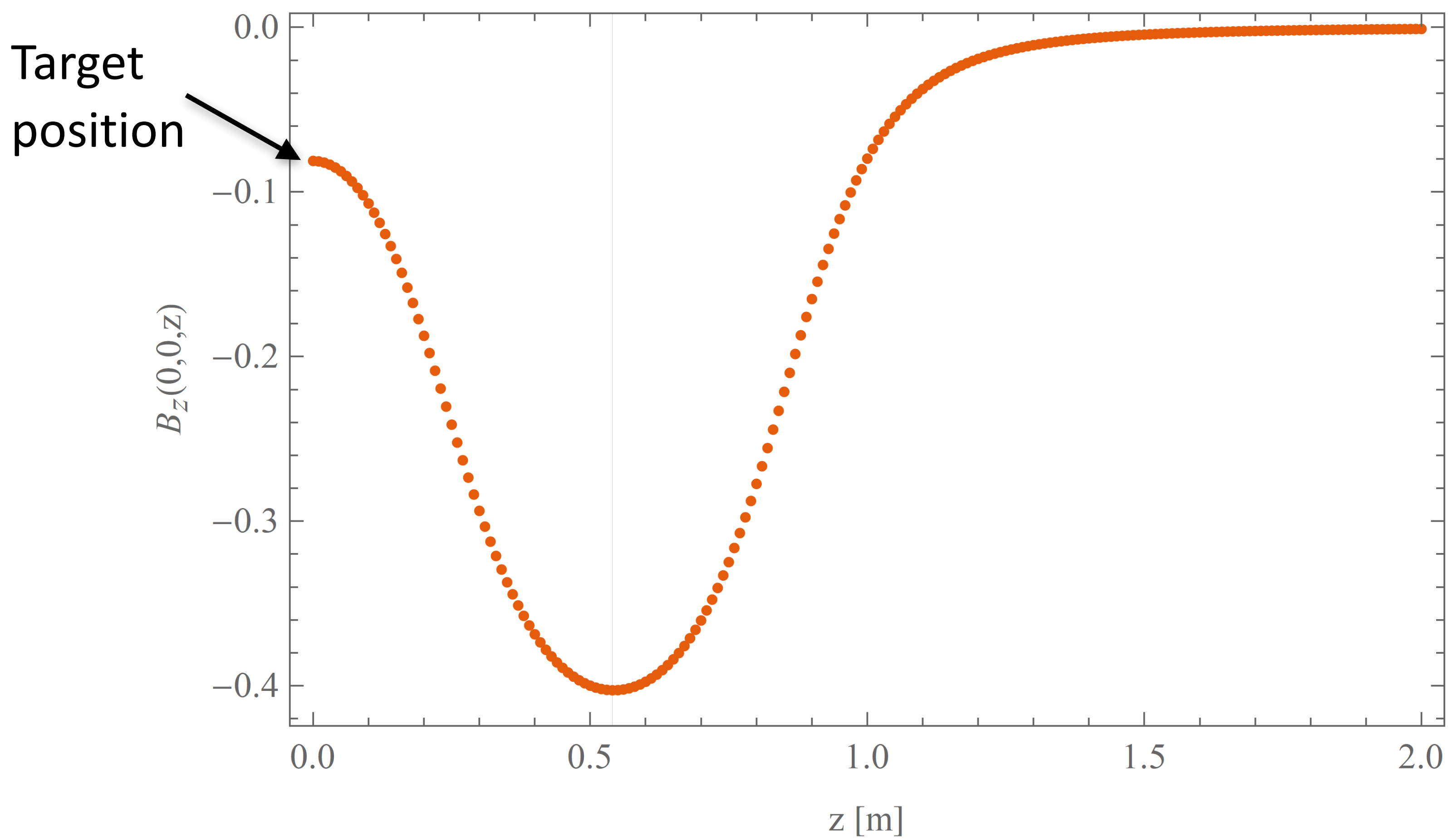


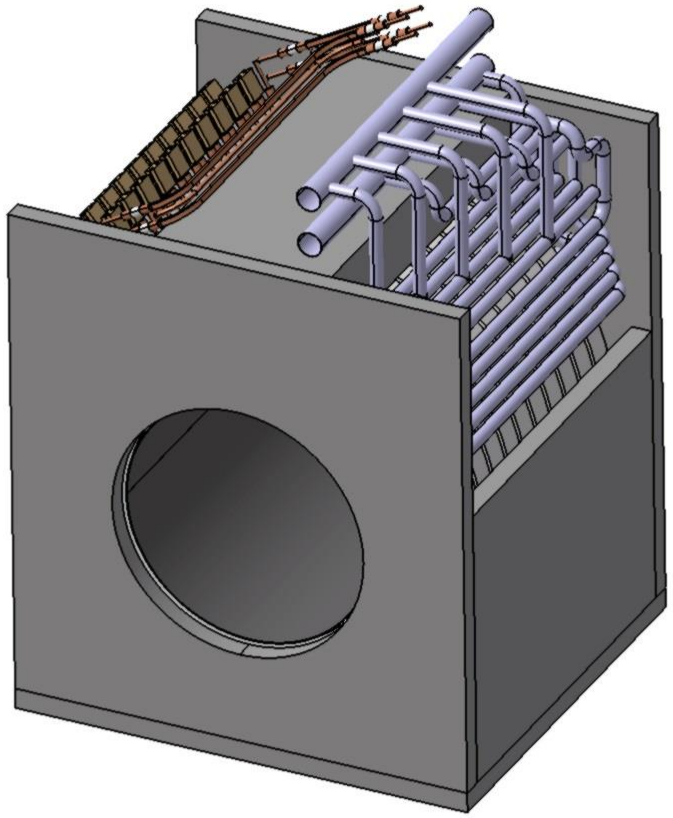
- Two normal-conducting, radiation-hard solenoids 250 mm away from target to capture surface muons

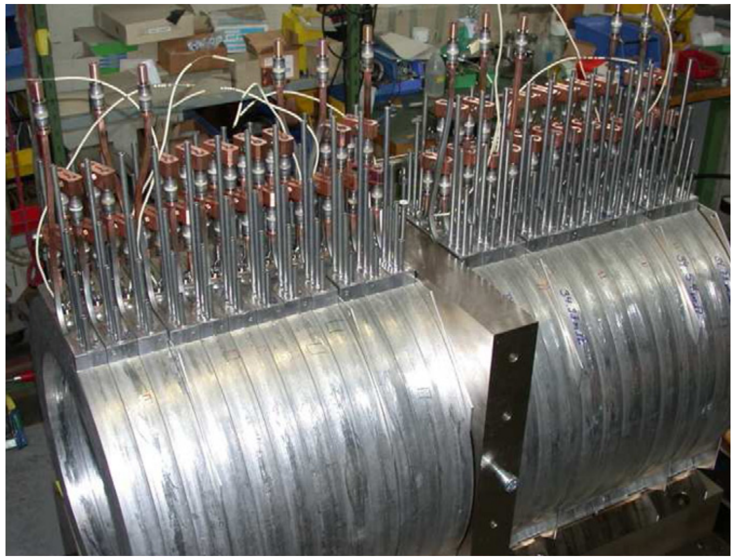
- Central field of solenoids up to 0.45 T

Capture solenoids

- Current design of capture solenoid with iron return yoke
- Modelled after existing radiation-hard μE4 solenoids
- The two capture solenoids will create a non-negligible field at the target







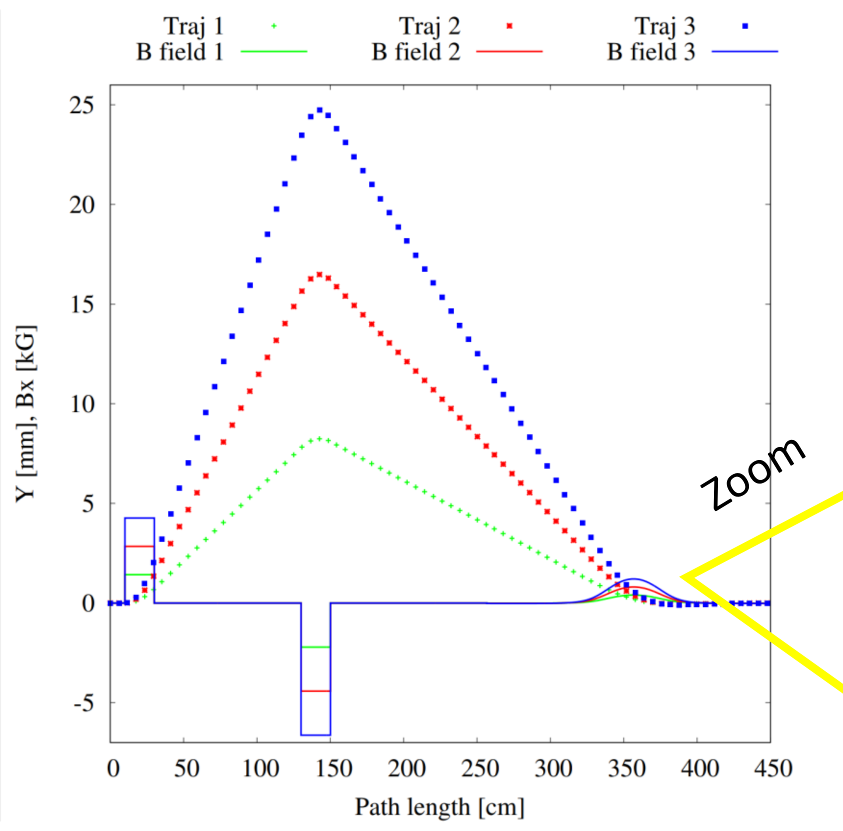
μE4 solenoids

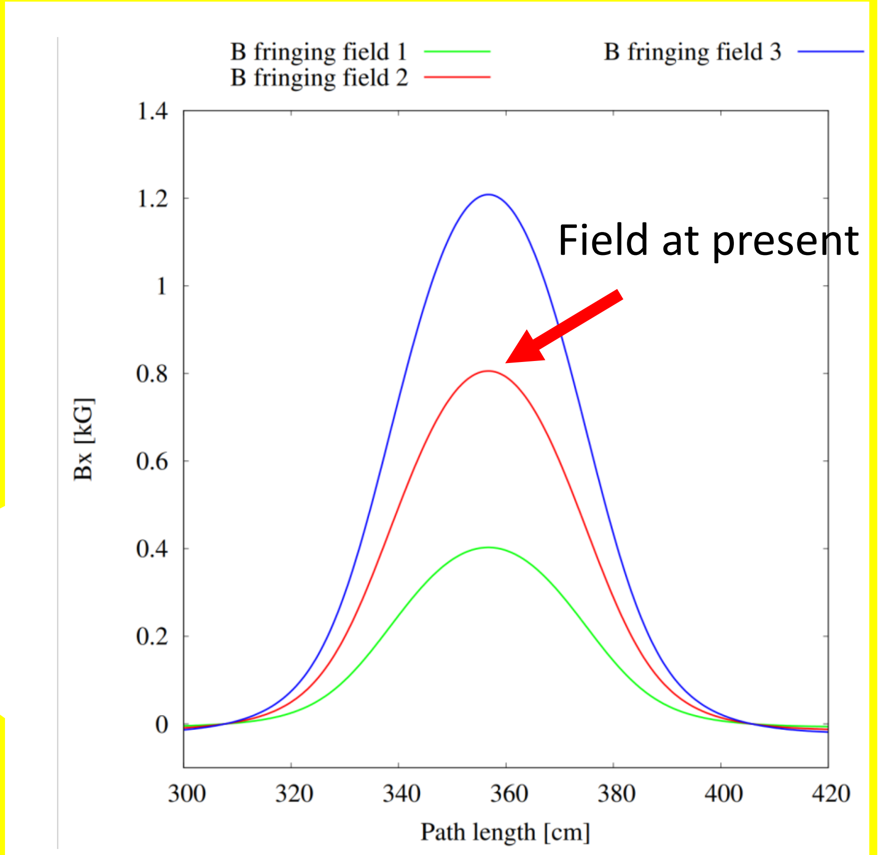
Different fringing fields

- Next, we fix the position of the new steerer and modify the fringing field strength. The objective is to demonstrate that we can always achieve the beam matching condition and take a safety margin.

	B kicker 1	B kicker 2
Case 1	1.42 kG	-2.21 kG
Case 2	2.84 kG	-4.42 kG
Case 3	4.27 kG	-6.63 kG

Kicker strength requirements

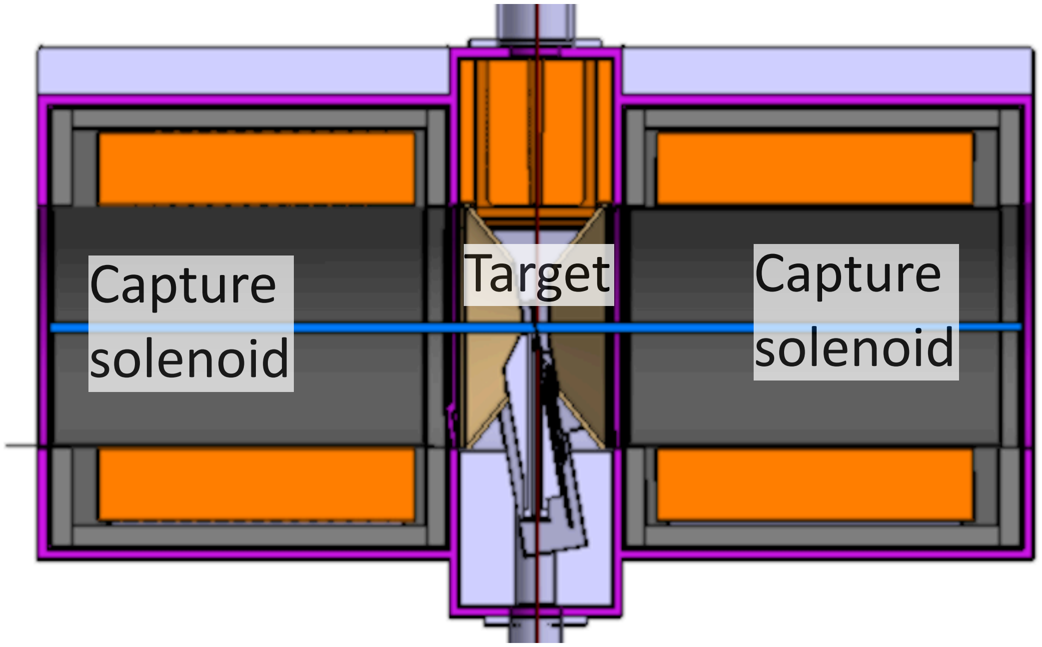


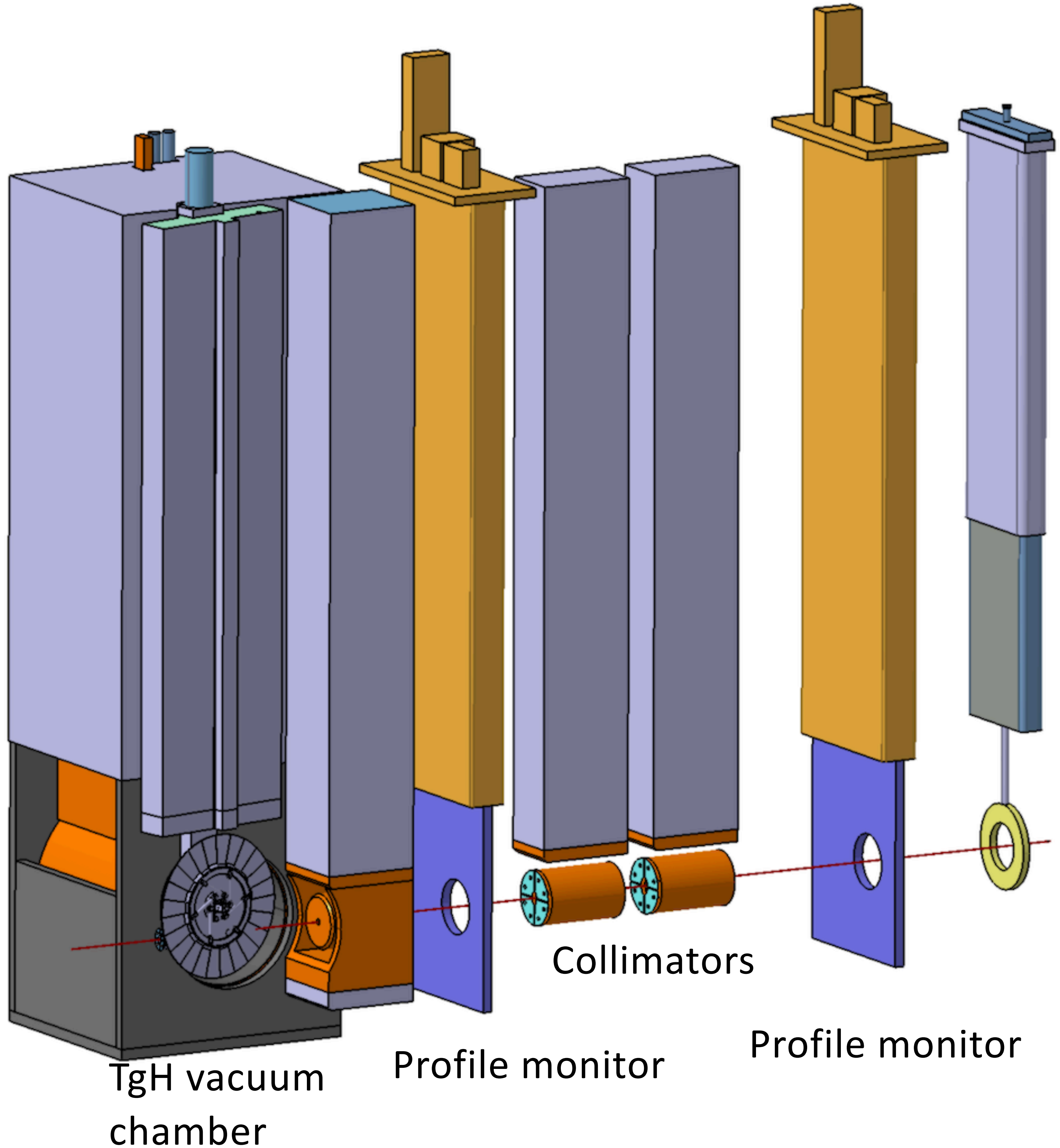


Changing the field strength of the solenoid shall not be allowed without changing the kicker field strength. 9

Concept for new target station TgH

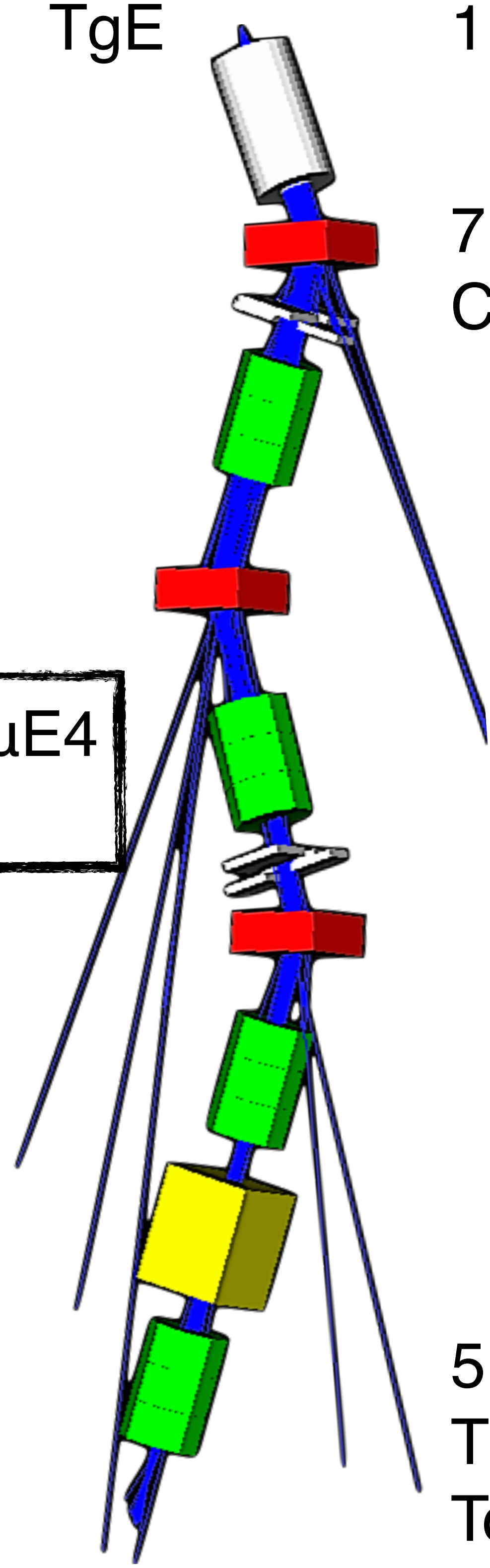
- Concept similar to existing TgE
  → allows to profit from existing tools and experience
- Separate exchange flask for capture solenoids
- In order to have capture elements for muons as close as possible, they are integrated into the target vacuum chamber





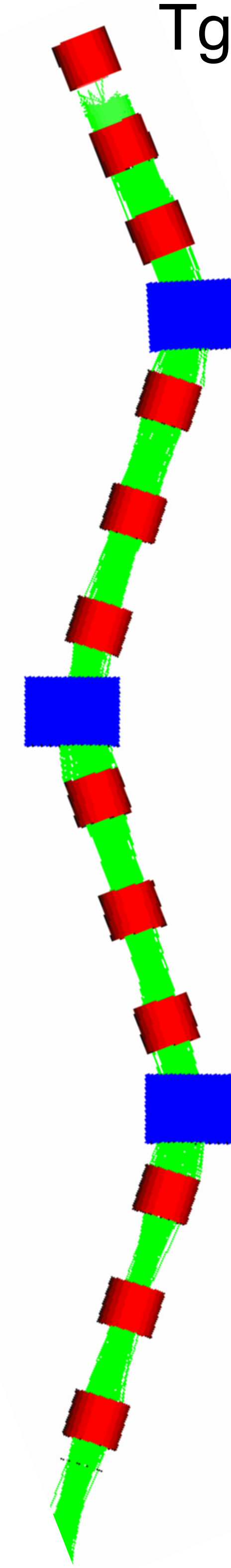
Solenoid Beamline

	TgE		TgH
Source	1.2×10^{11} μ+/s		1.3×10^{11} μ+/s
Capture	7.2×10^{9} μ+/s C ~ 6%		3.4×10^{10} μ+/s C ~ 26%
Transmission	5×10^{8} μ+/s T ~ 7% Total ~ 0.4%		1.3×10^{10} μ+/s T ~ 40% Total ~ 10%



Existing μE4 beamline

⇨ Gain due to high capture and transmission efficiency



Solenoid-based beamline

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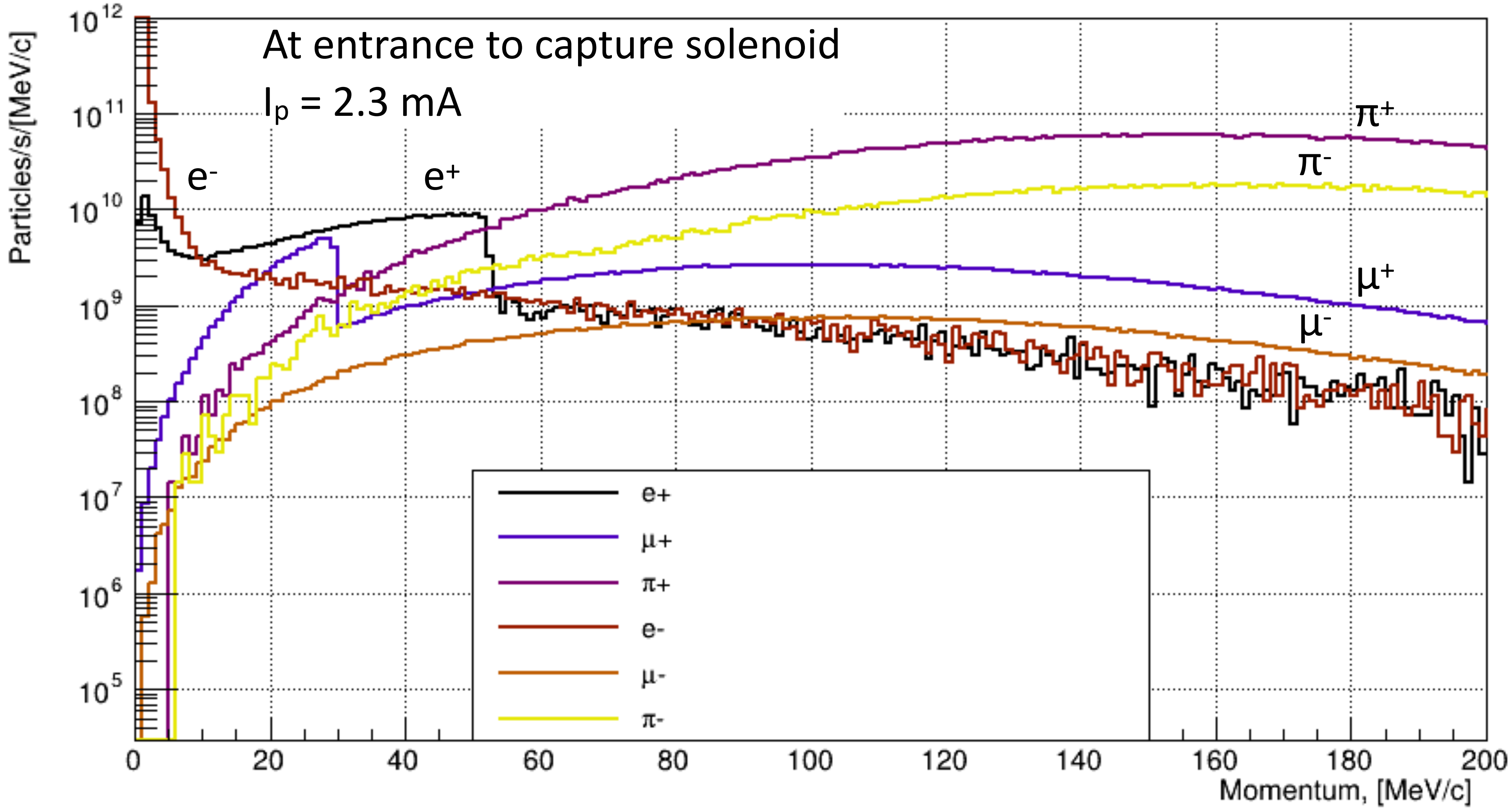
Beamline layouts

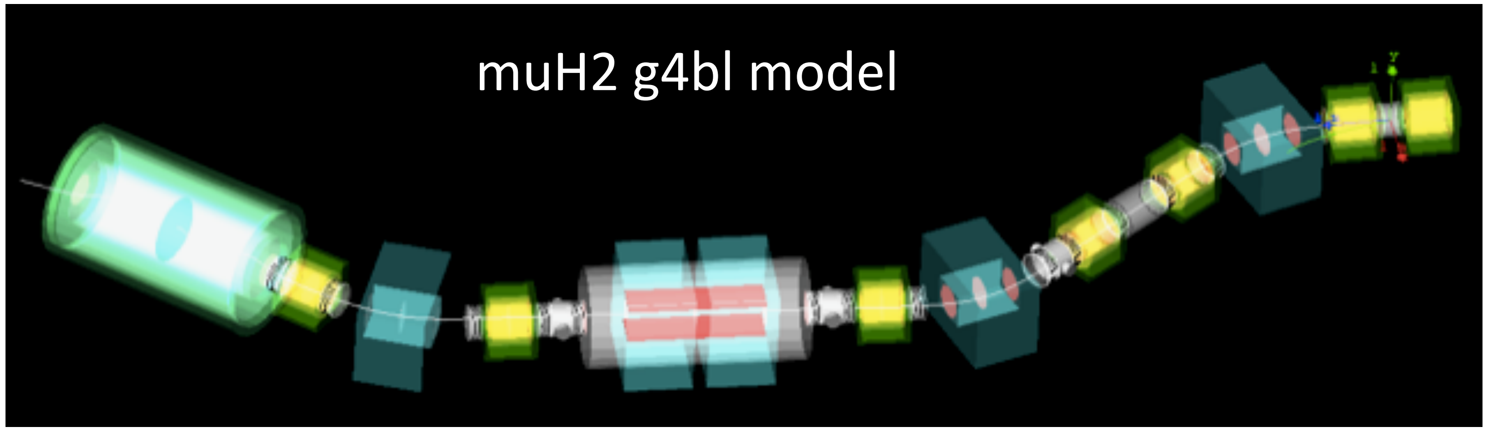
- Baseline scenario for target and beamline layouts:
  - New TgH at the same location as current TgM
  - 90 degree angle of muon beamlines with first bend in the upstream direction
- Technical layout, currently optimising positions of individual magnetic elements

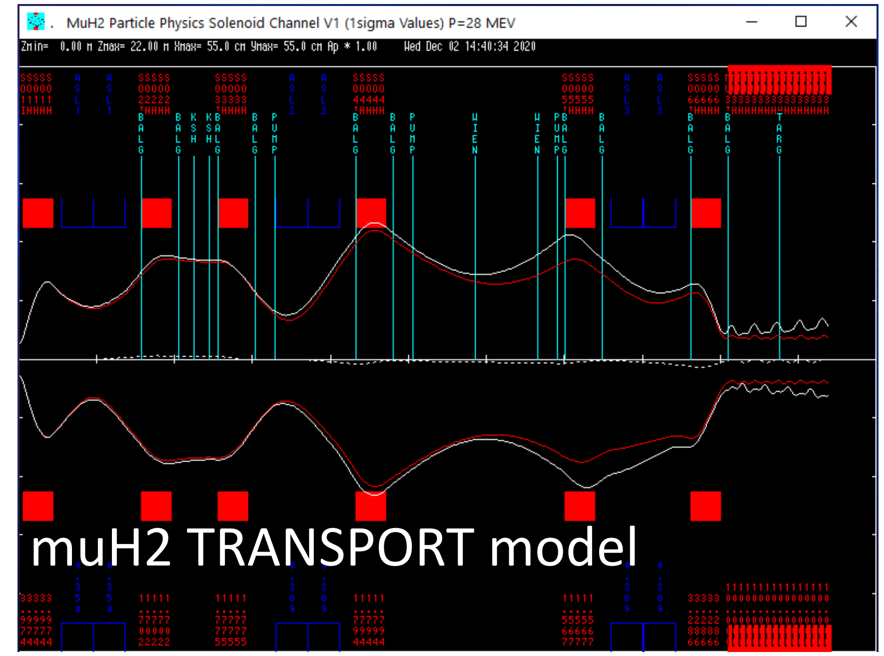
Particle production at TgH

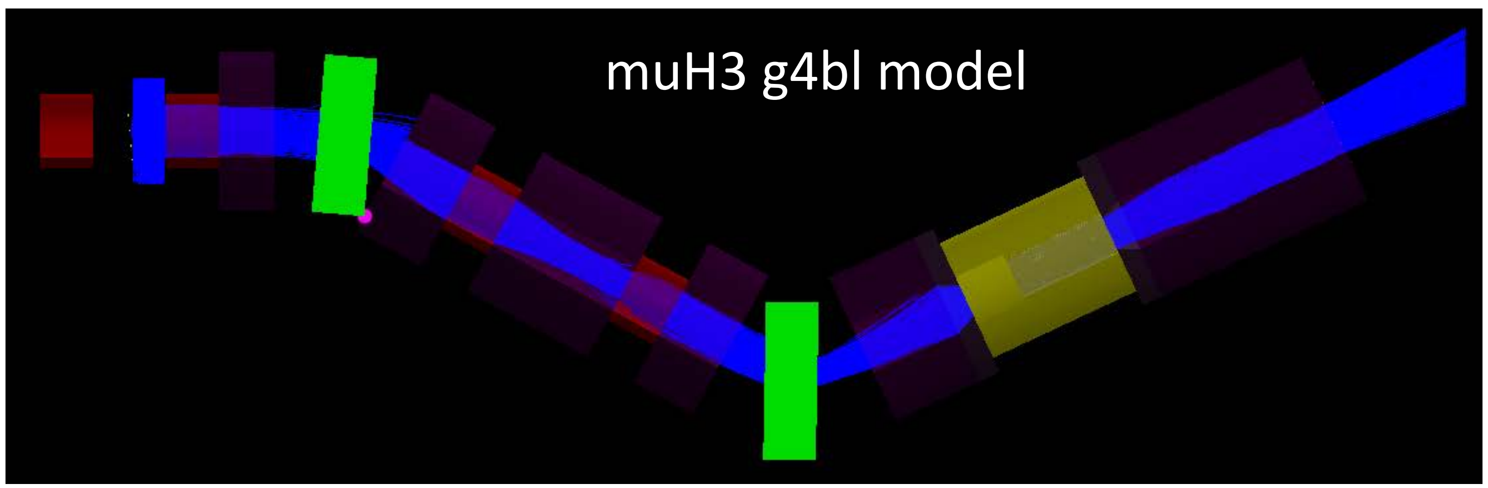


- Of course we are not only producing surface muons
- We will have good transport efficiency up to 40 MeV/c (given by capture solenoid)
- Plan is to design dipoles up to 80 MeV/c

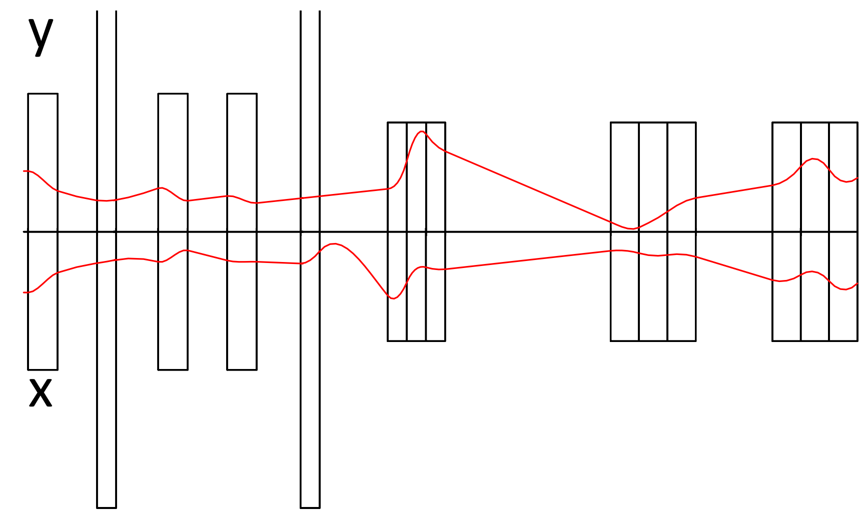
Simulation of beamlines







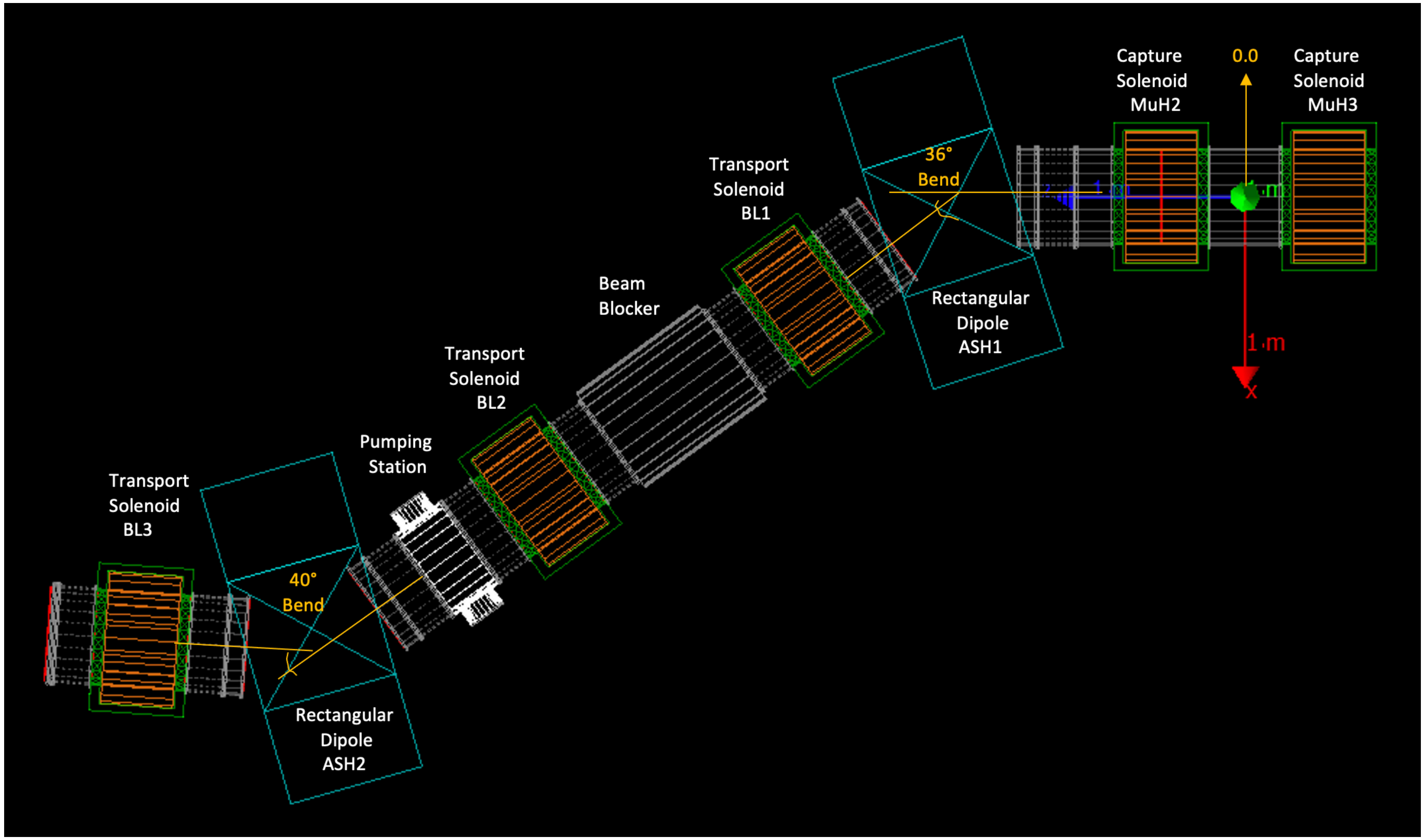
muH3 COSY INFINITY model



- Simulation tools: g4bl, TRANSPORT, TURTLE, COSY INFINITY
- Optimization tools: grid searches, hyperparameter searches

Status muH2

- We have in excess of 10^{10} mu+/s at the final focus without the separator
- Working on getting the beam nicely through the separator, probably need two short separators in series for good transmission and sufficient separation power



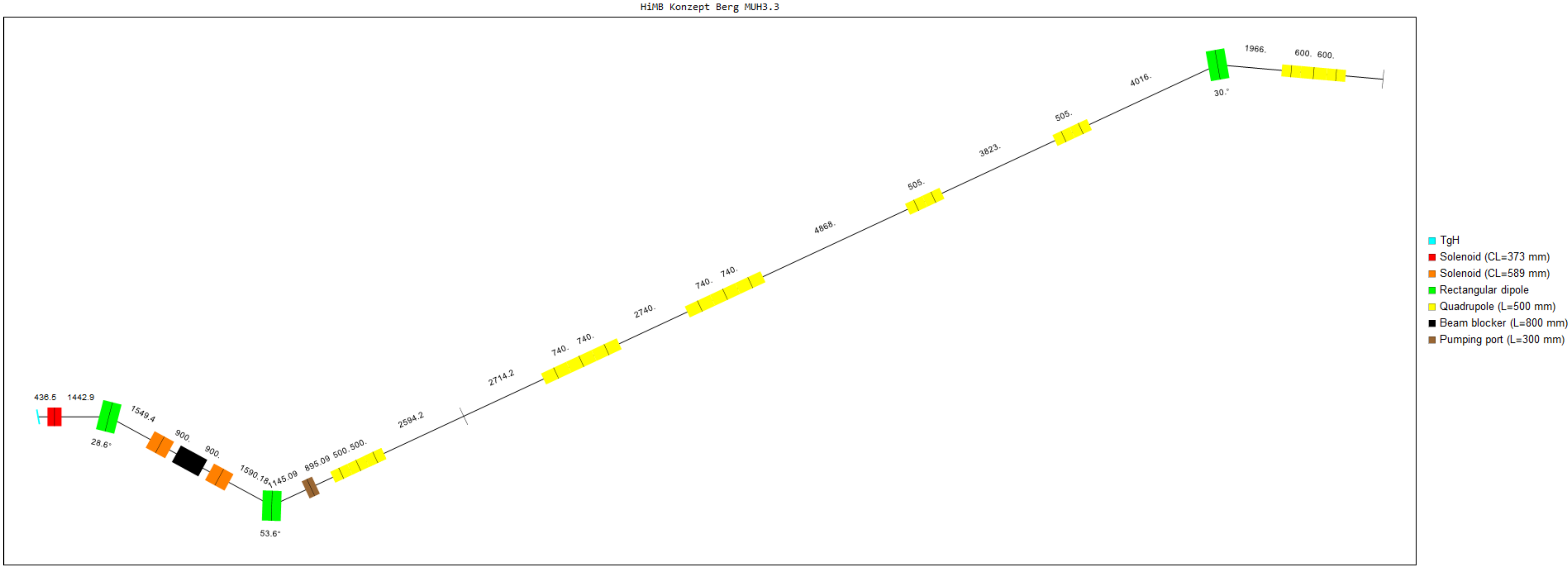
Separator

- Beamline transports any charged particle of the same momentum
- Typically have muons, pions and electrons in the beam
- At low energy pions decay along the path
- Electrons and muons are separated in a separator with crossed electric and magnetic fields by balancing $q\mathbf{E} = q(\mathbf{v} \times \mathbf{B})$ for the muons

Status muH3

- We have ~10^{10} mu+/s at the end of the solenoidal channel, a few 10^9 mu+/s after the first triplet and ~10^8 mu+/s at the end of the 38-m long beamline
- Losses when coupling into the triplet and along the long quadrupole based beamline unavoidable

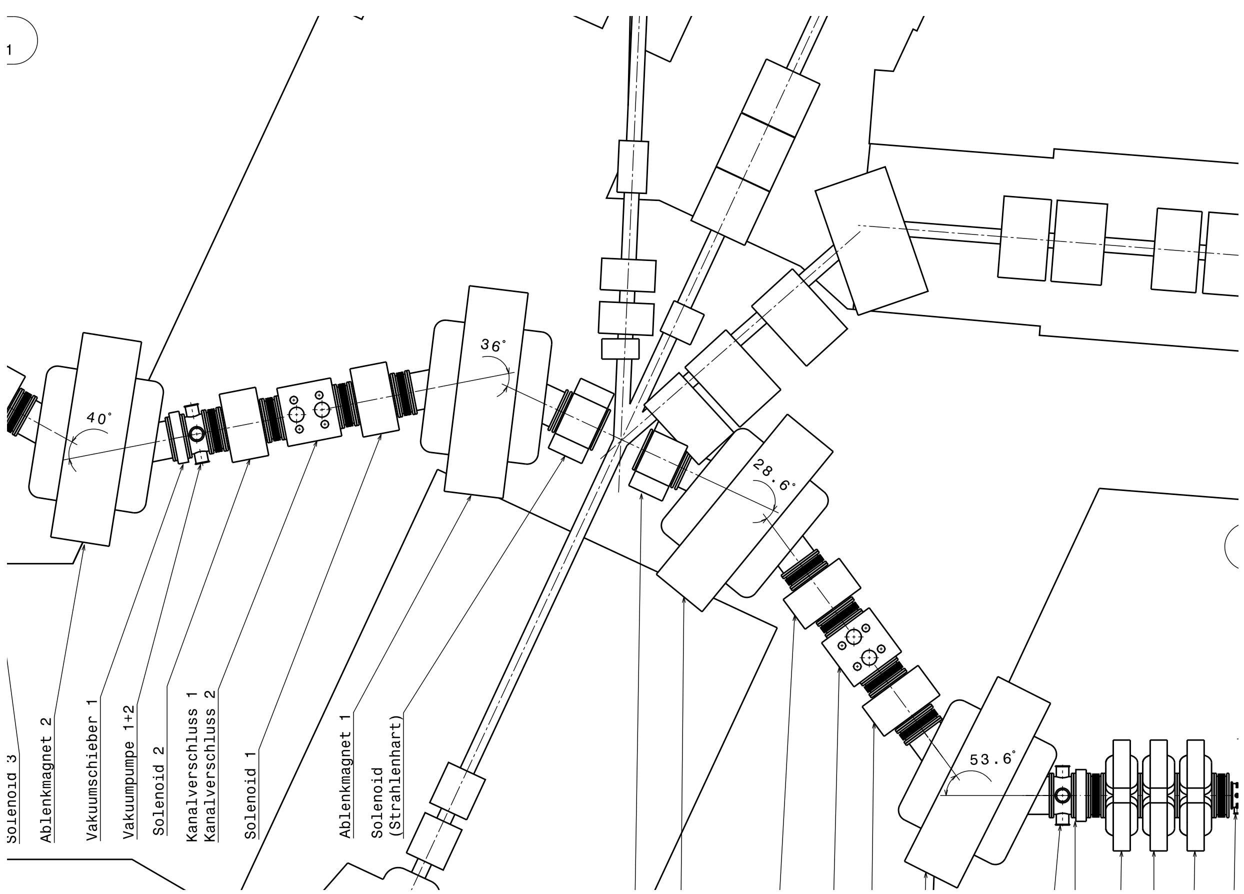
HiMB Konzept Berg MUH3.3

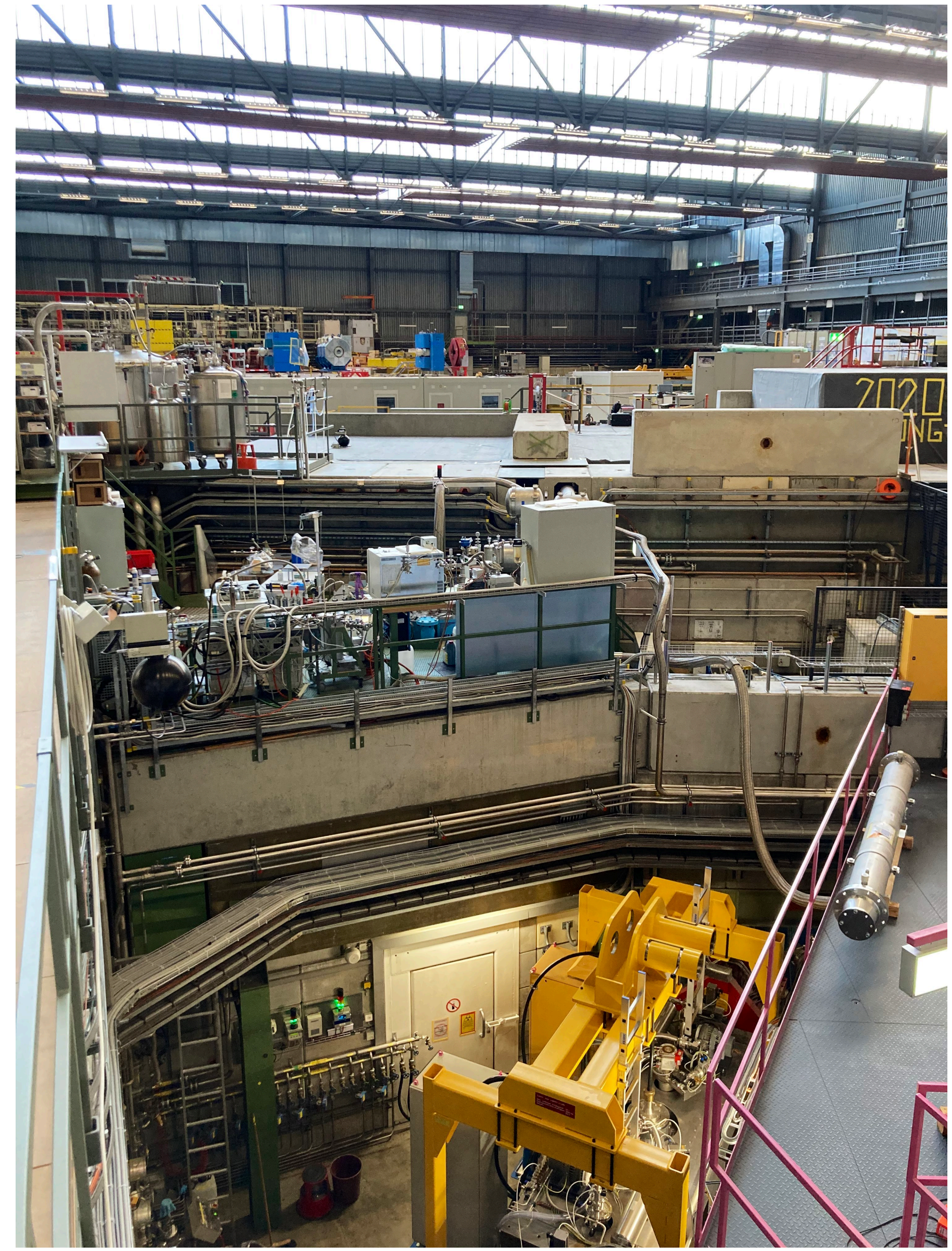


Distances between elements are measured in mm from element center to element center.

Building a new target station

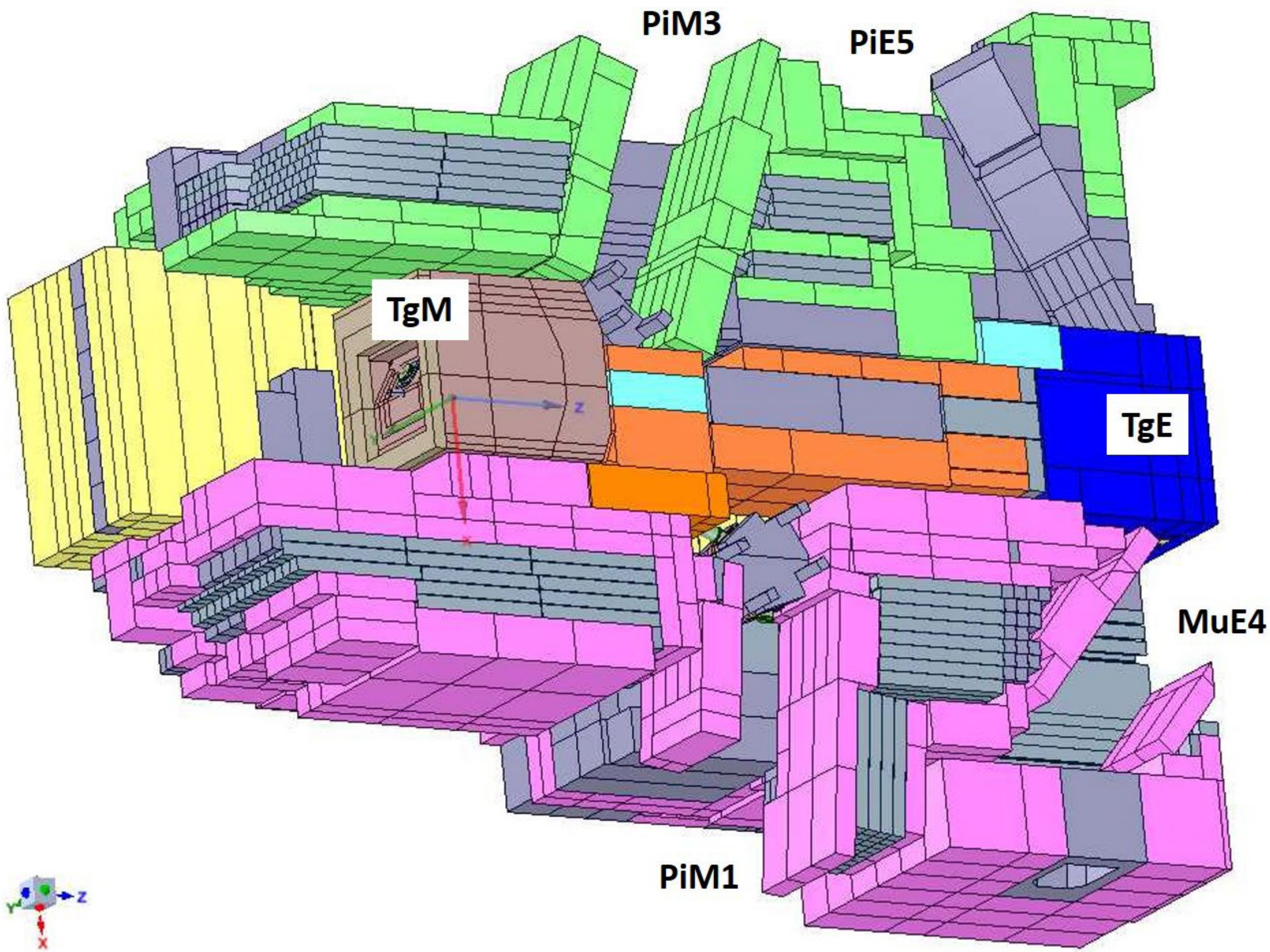
- Challenging environment around TgM to change layout
- Helium liquefier, tertiary cooling loop 7, lots of pipes, cables and conduits, power supply platforms, …
- And of course in an environment with doses measured in Sv/h



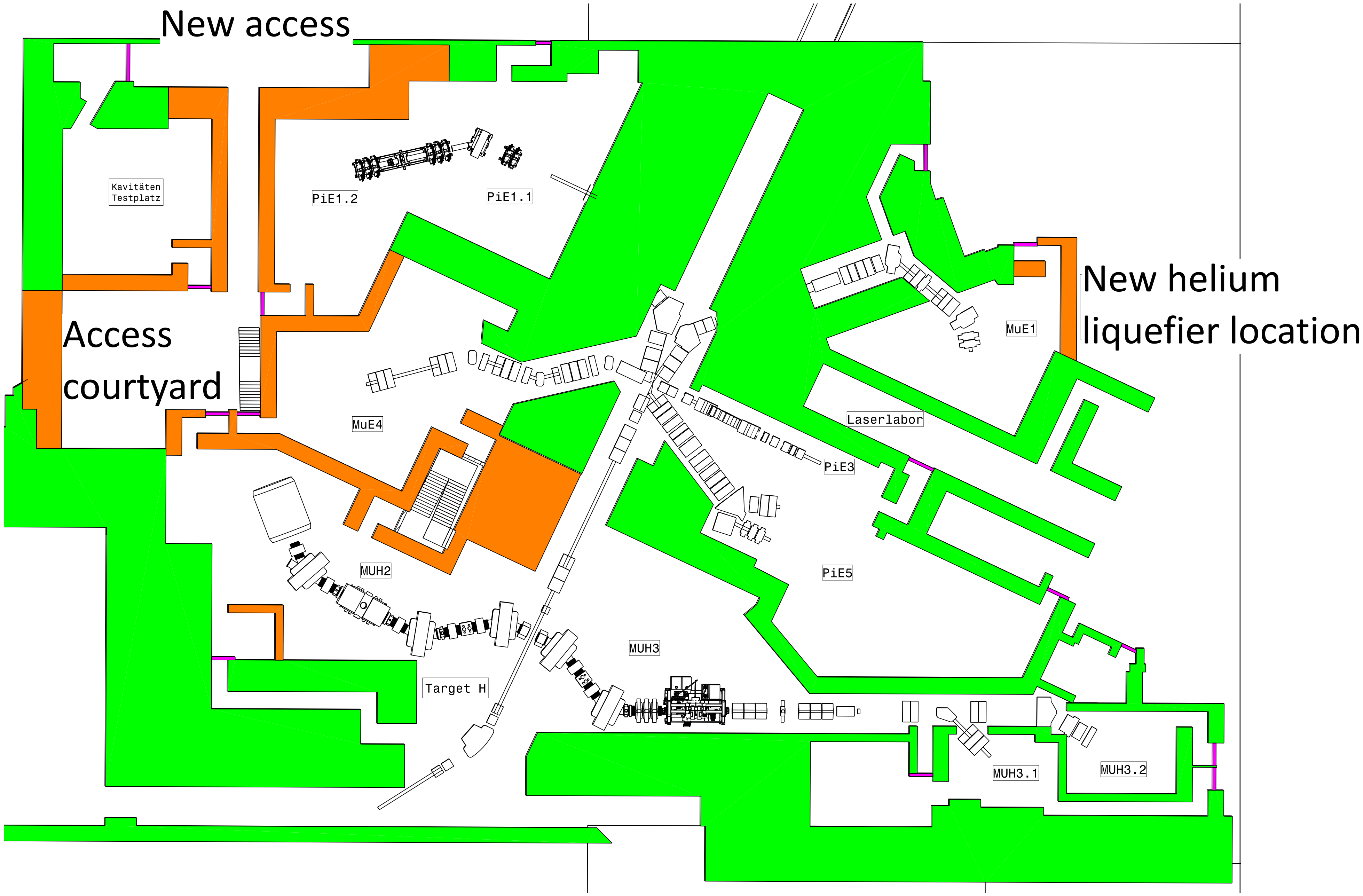


Shielding

- Shielding built up from individual iron and concrete blocks
- Very flexible, but of course very time consuming to dismantle and re-assemble

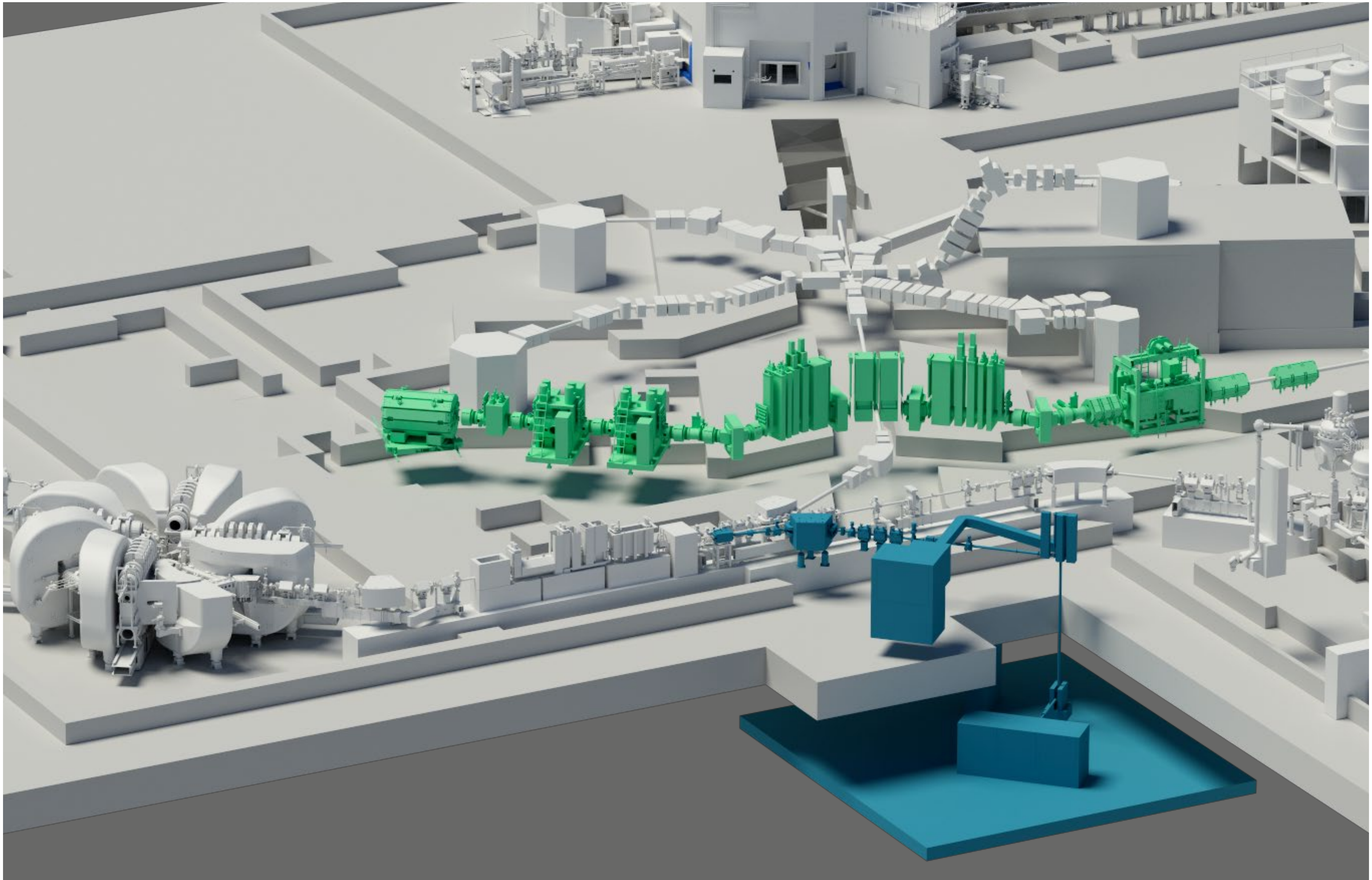


New beamlines and area layouts

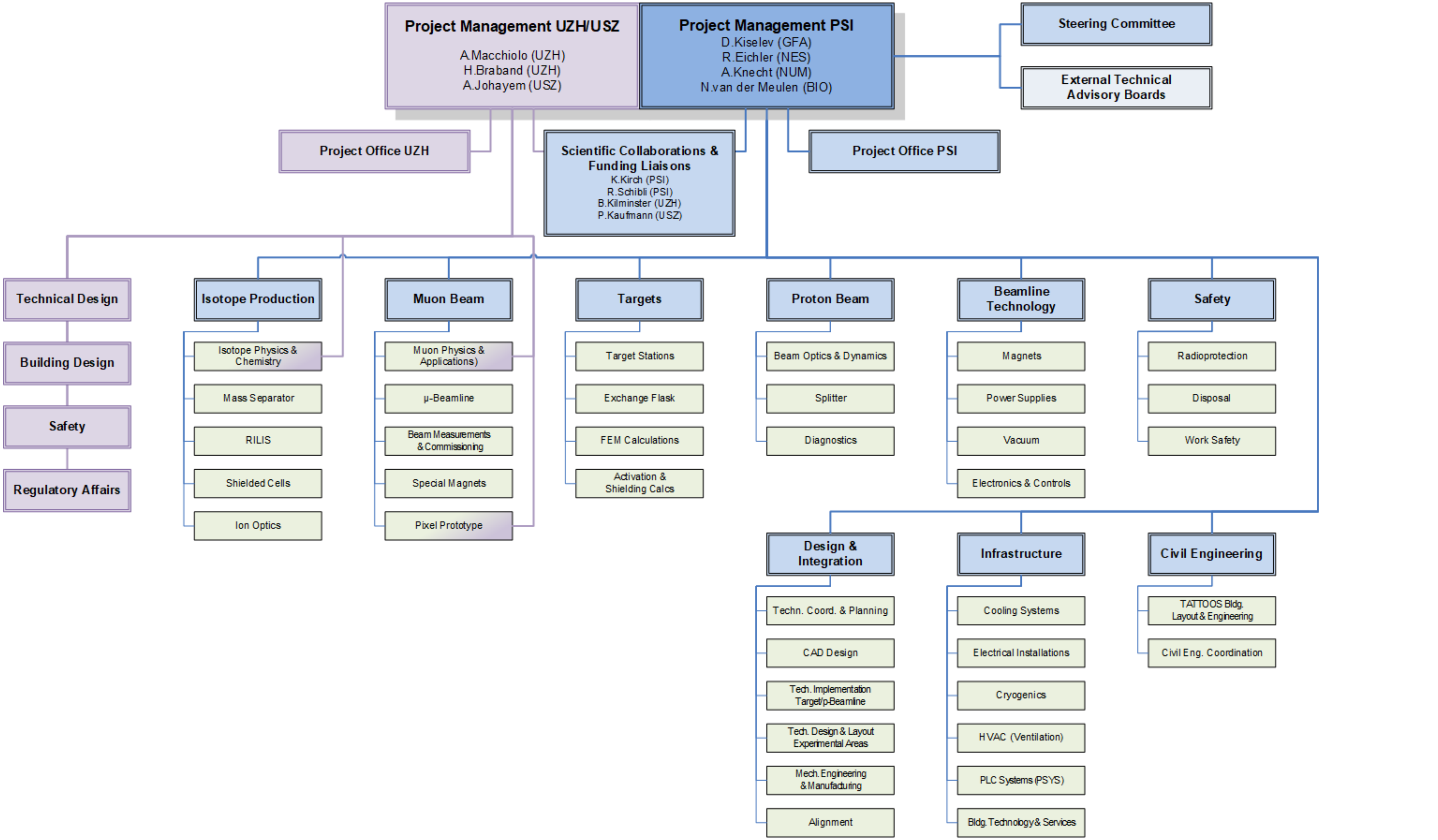


- Together with the implementation of the beamlines will also need to adjust the experimental areas, access ways, infrastructure etc.
- At the same time will try to clean up legacy walls and structures as much as possible & allow for a more user-friendly and safer environment

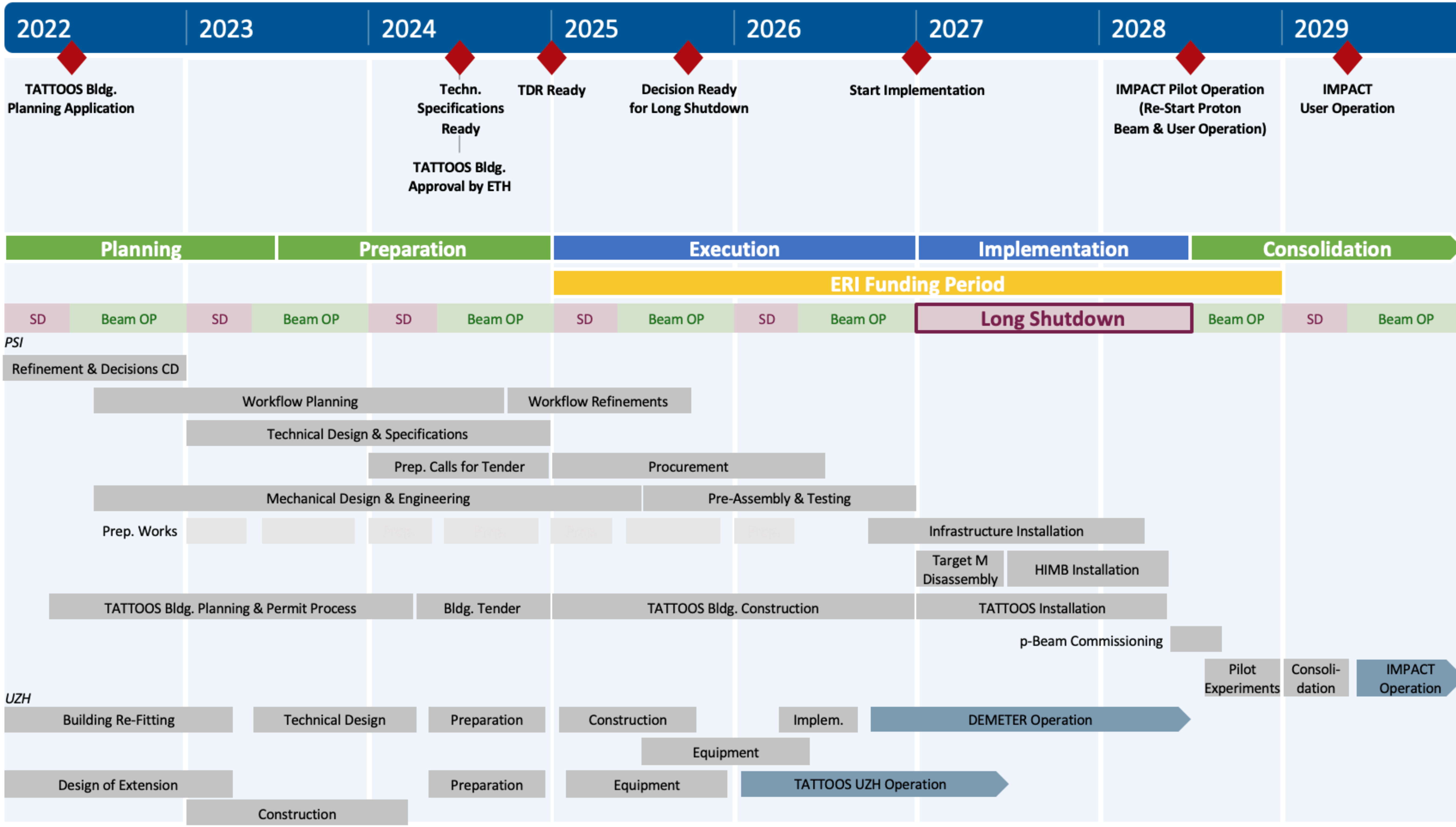
The Future!



Organization

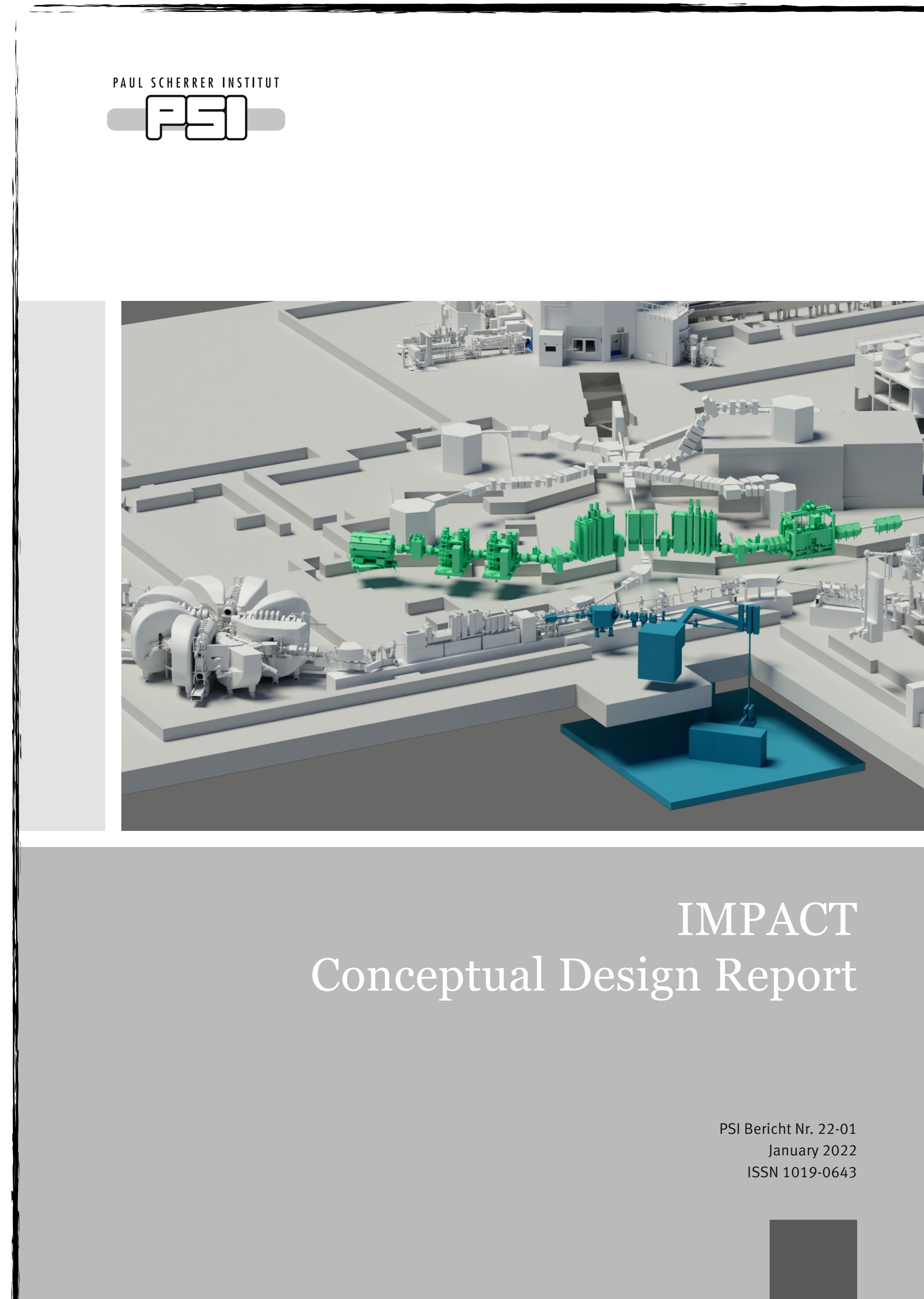


Timeline & next steps



IMPACT Conceptual Design Report

- 304 page document detailing all the concepts
- Forming the basis for the full approval and funding process
- Available at: https://www.dora.lib4ri.ch/psi/islandora/object/psi%3A41209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PSI

IMPACT

Conceptual Design Report

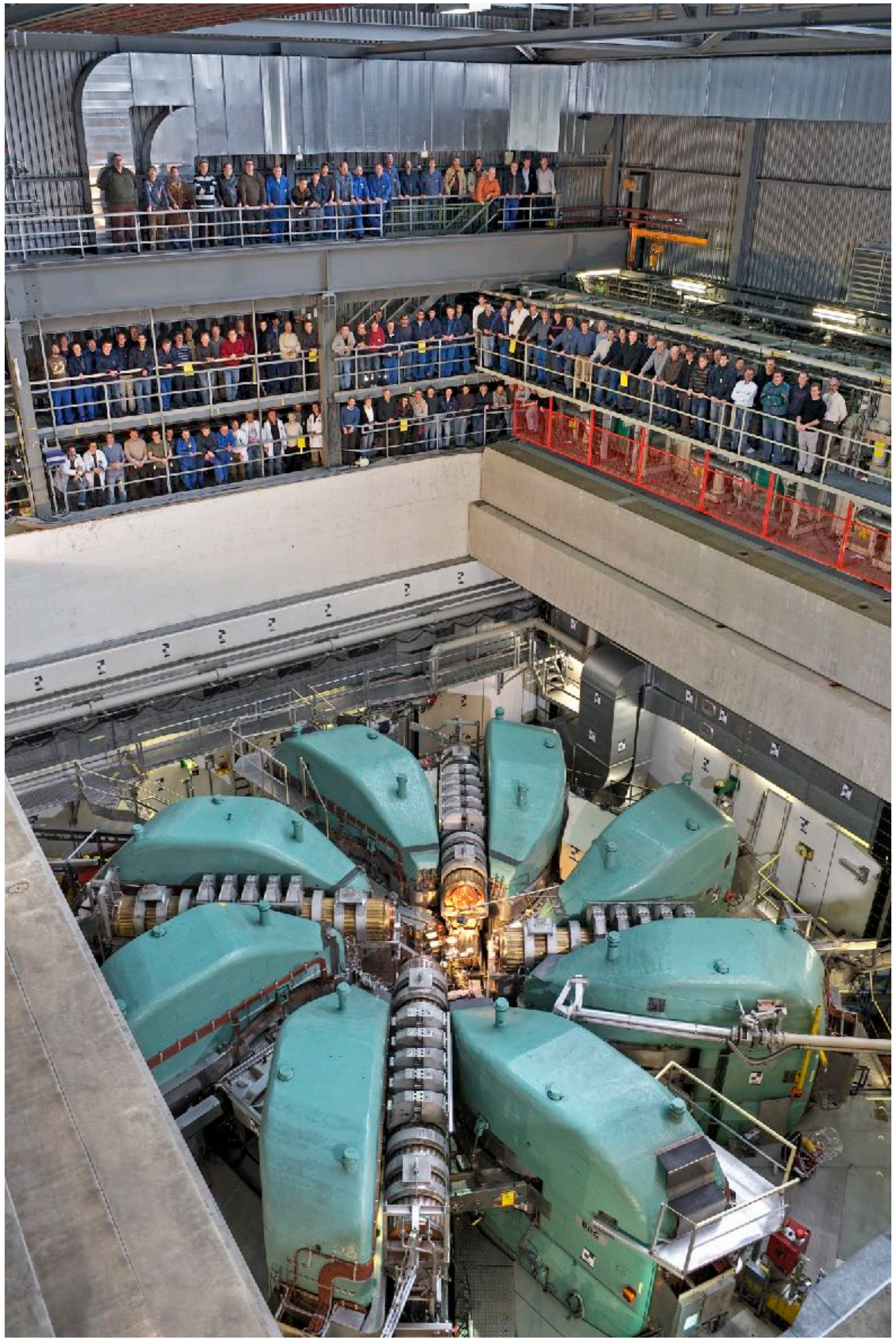
PSI Bericht Nr. 22-01

January 2022

ISSN 1019-0643

Conclusions

- On track for achieving muon rates of 10^{10} mu^{+}/s at PSI, but many challenges ahead
- HIMB will enable forefront muon research at PSI for the next 20+ years



Many thanks to everyone from the HIMB project for providing slides and input for this presentation!