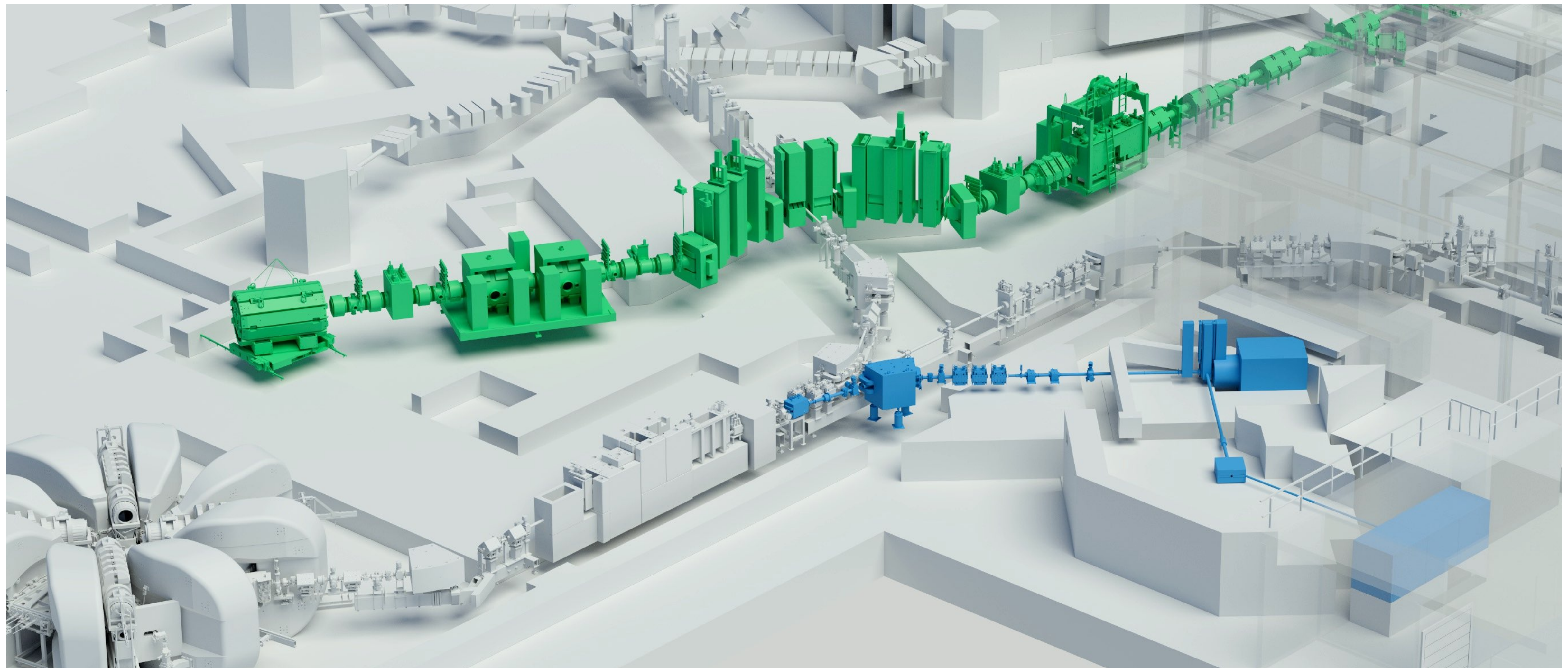
PSI Center for Neutron and Muon Sciences

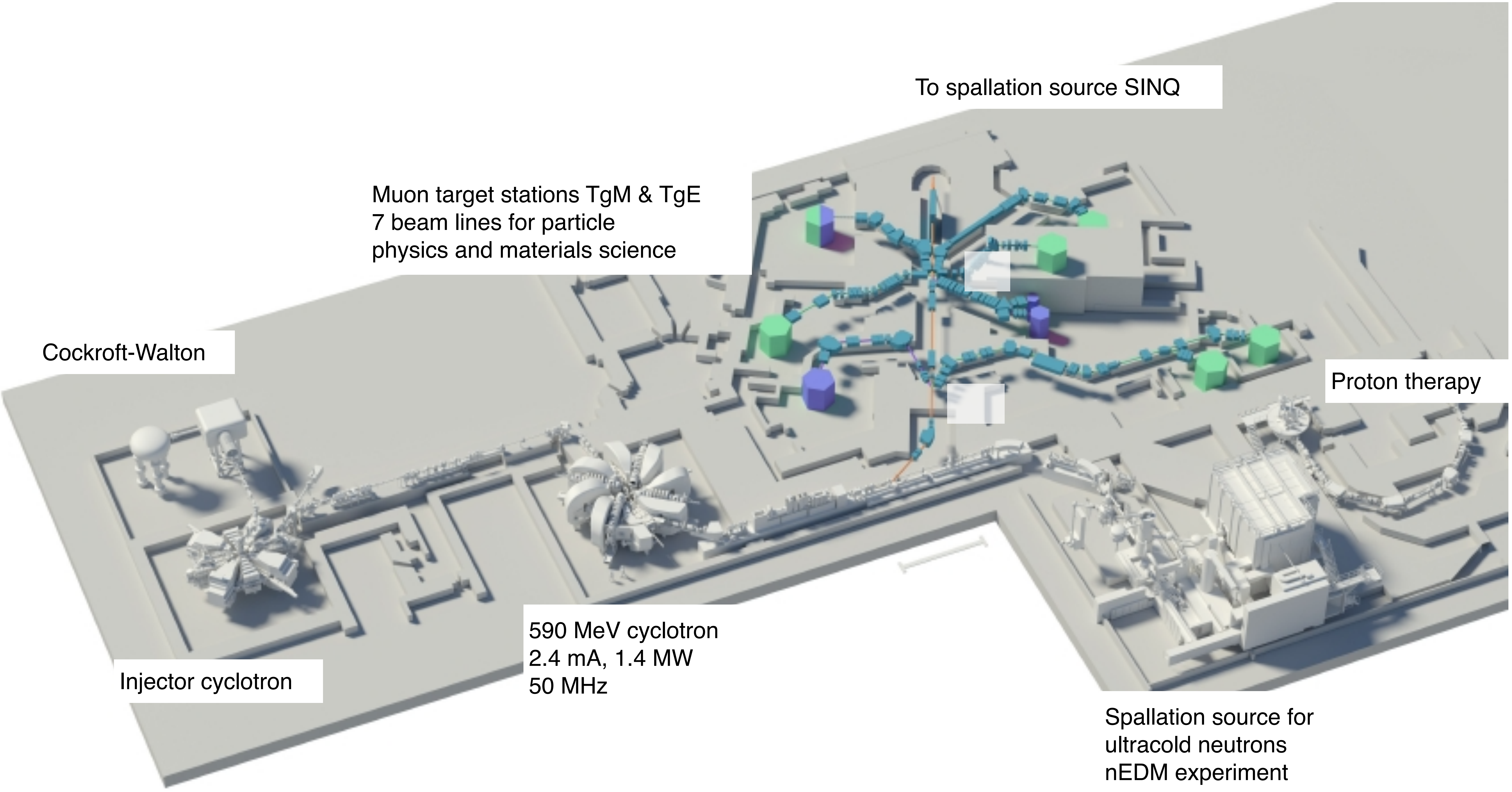
The high-intensity muon beams (HIMB) project at PSI



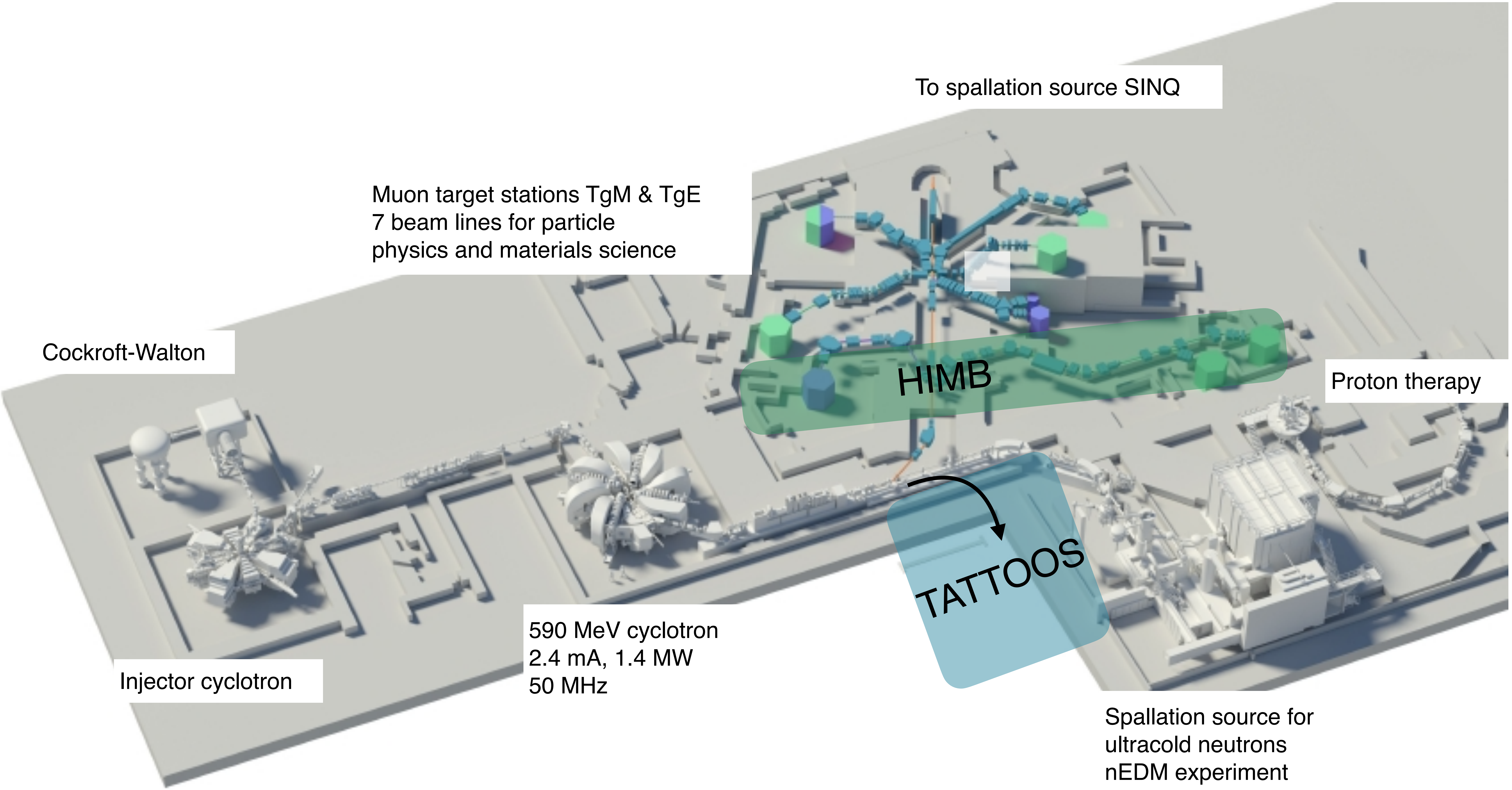
Andreas Knecht for the IMPACT project
MIP2025, Changsha, China & online
18. May 2025

The Paul Scherrer Institute PSI

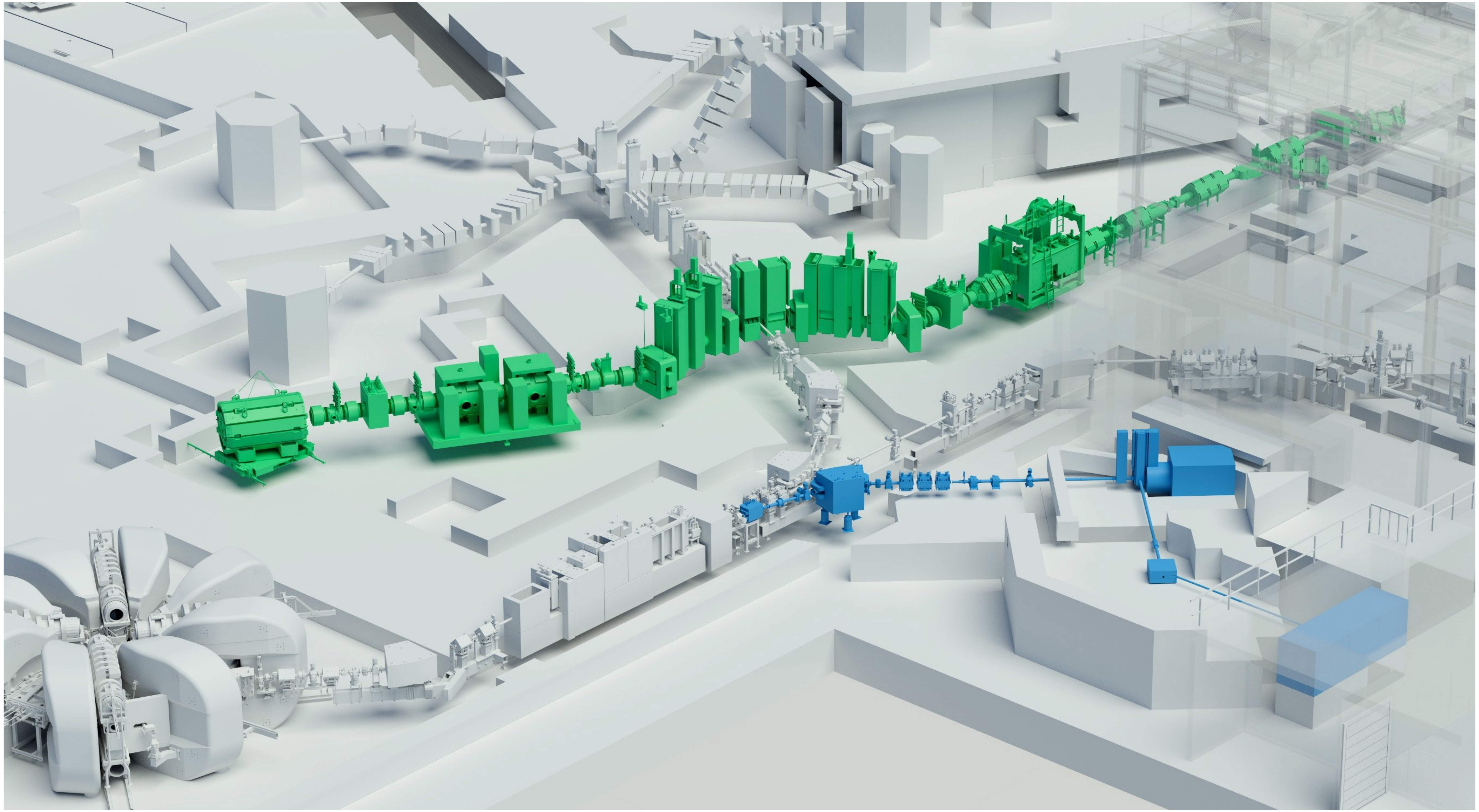
PSI Proton Accelerator HIPA



PSI Proton Accelerator HIPA



IMPACT: HIMB & TATTOOS



HIMB Science Case Workshop & Document

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

In short some highlights:

- Higher-intensity muon rates for particle physics and µSR
- Better quality muon beams with muCool
- Pixel detector based µSR
- µSR with sub-surface muons

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

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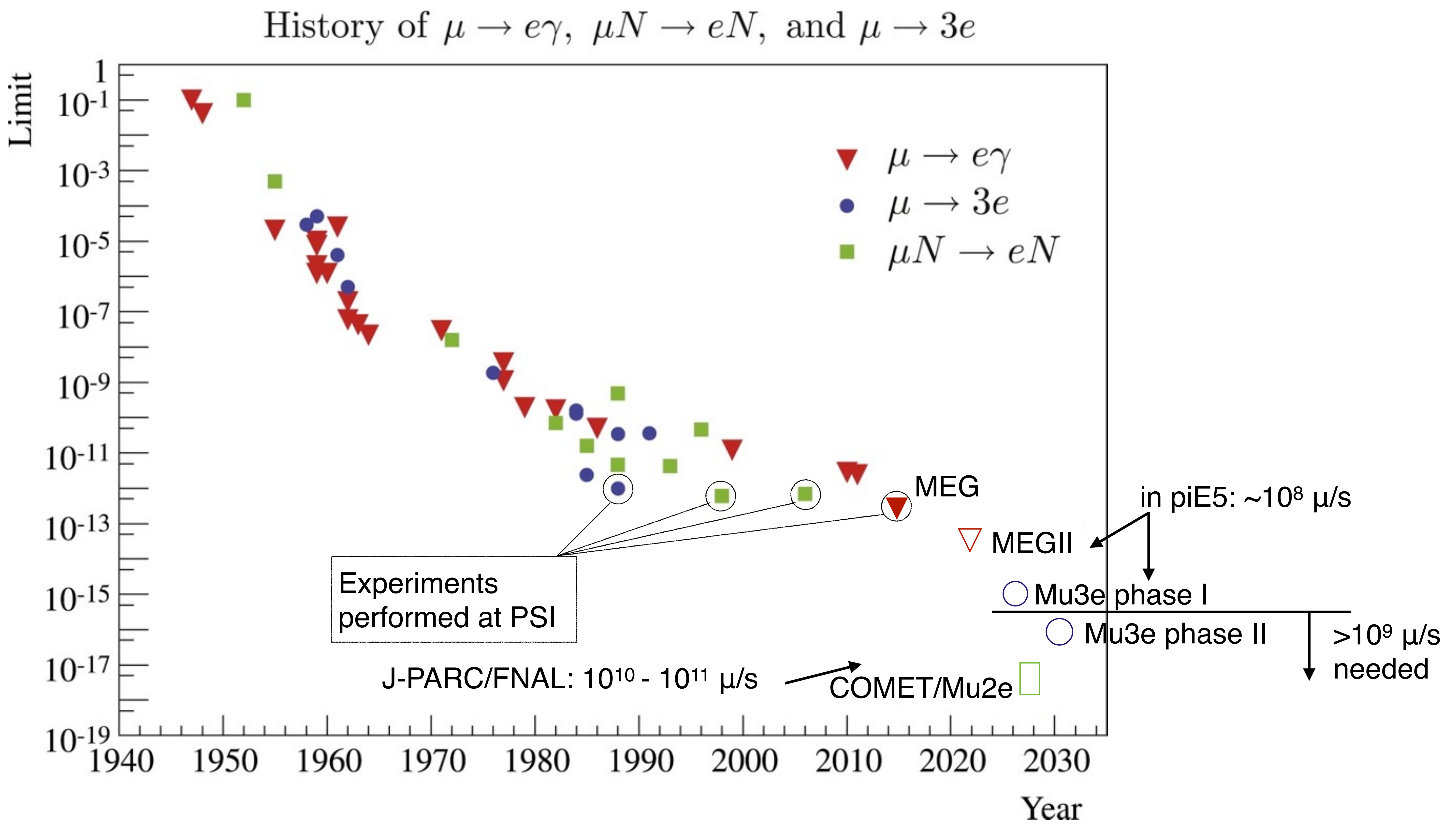
Rare muon decay searches

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

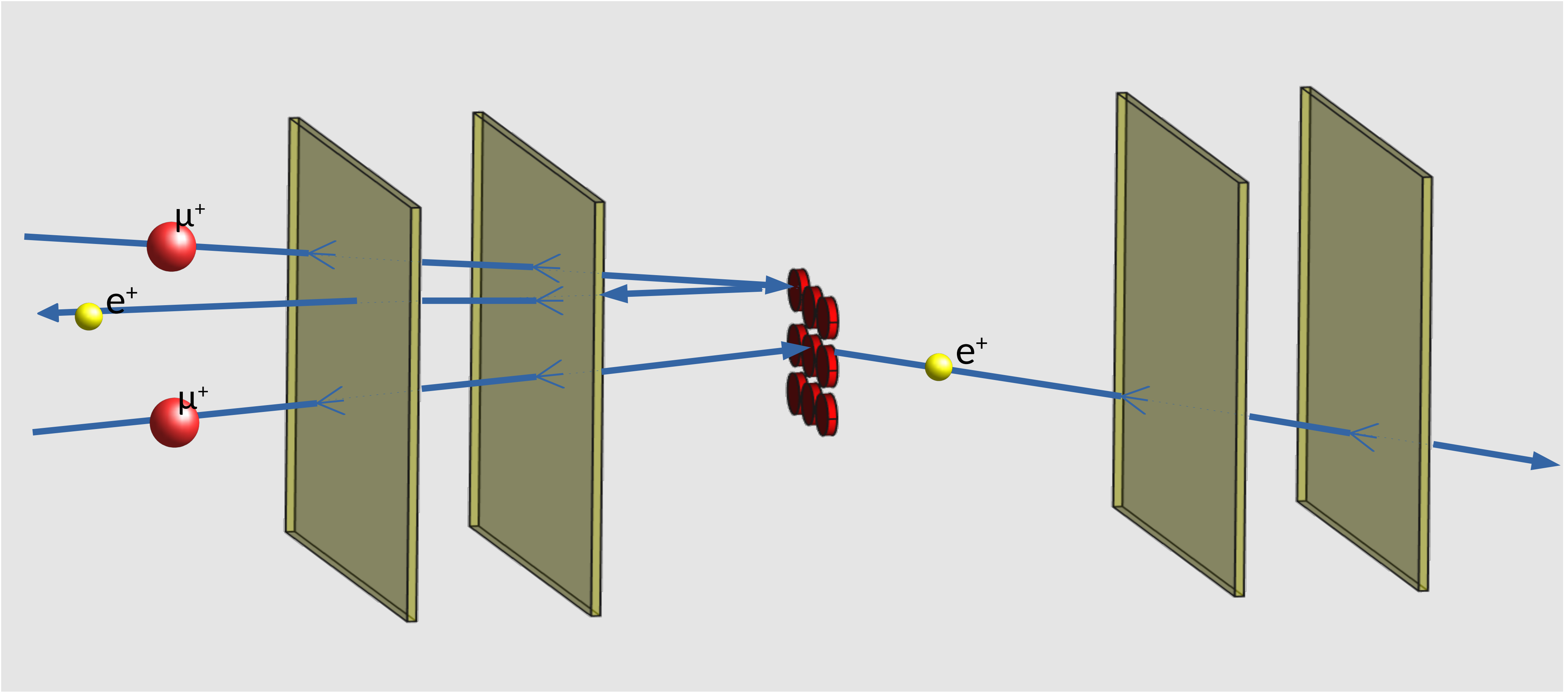


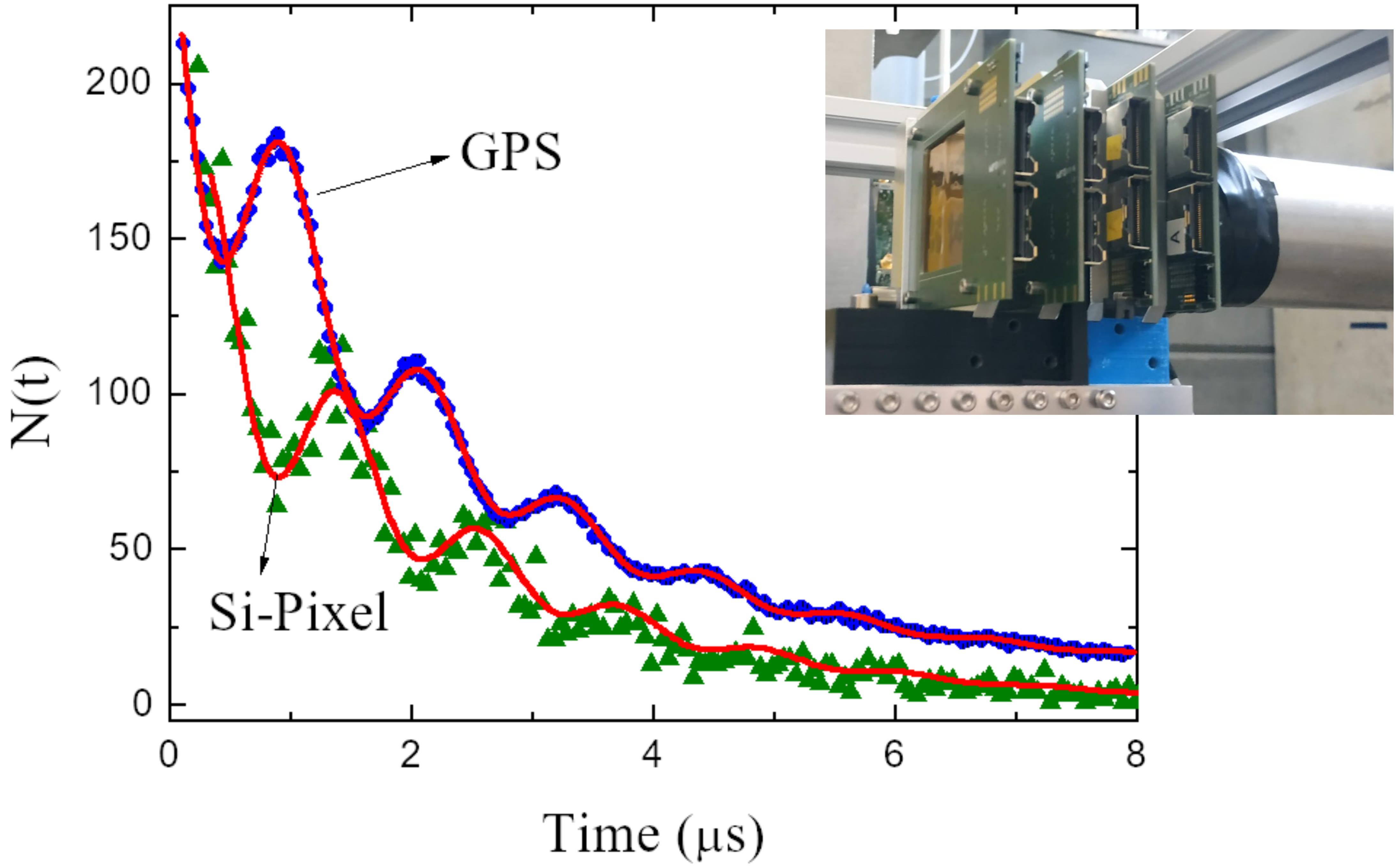
Muon spin rotation

Vertexing for µSR 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

First successful tests with prototype detector





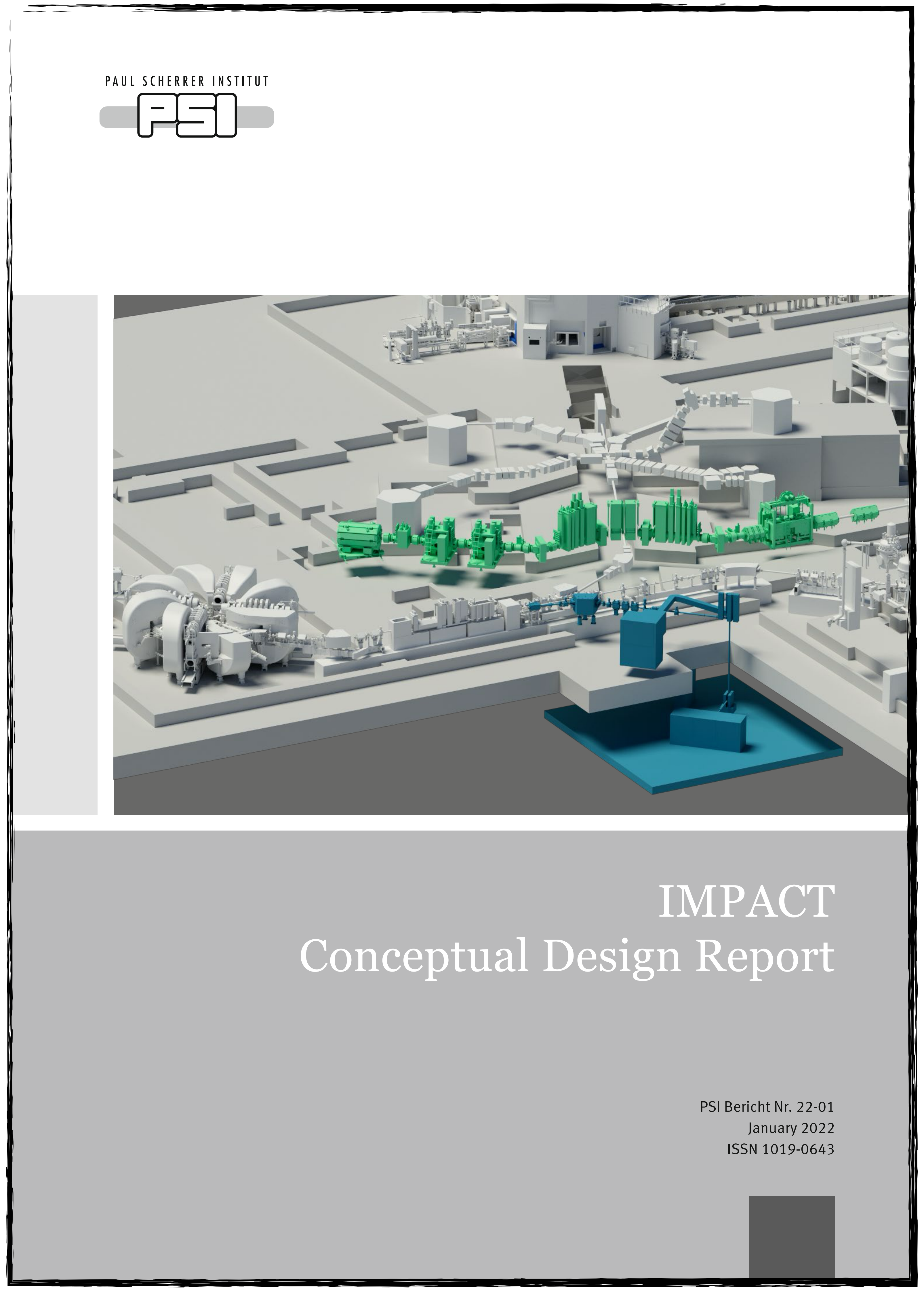
IMPACT Conceptual Design Report

304 page document detailing all the concepts

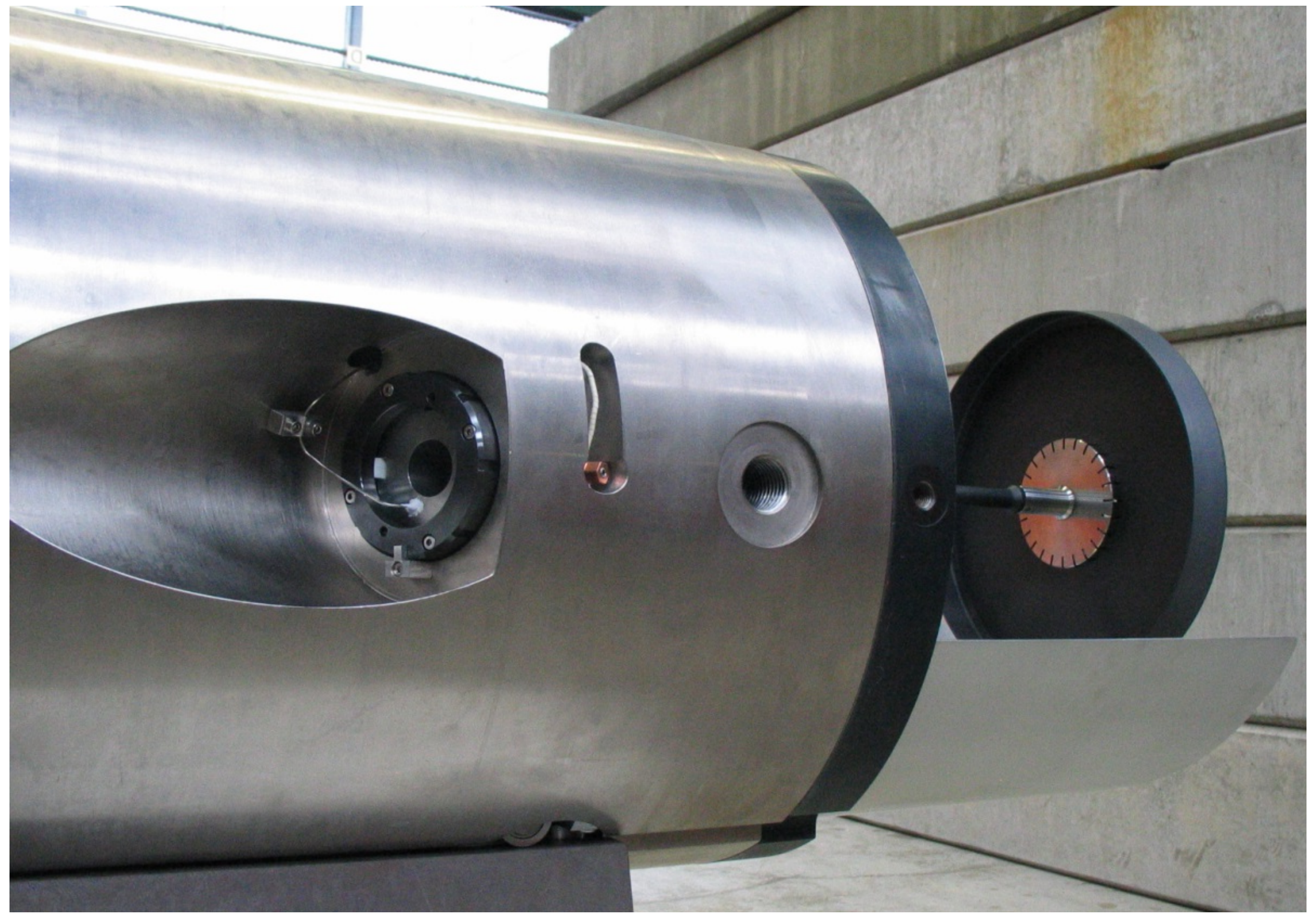
Forming the basis for the full approval and funding process

Since January 2022 available at:
https://www.dora.lib4ri.ch/psi/islandora/object/psi%3A41209

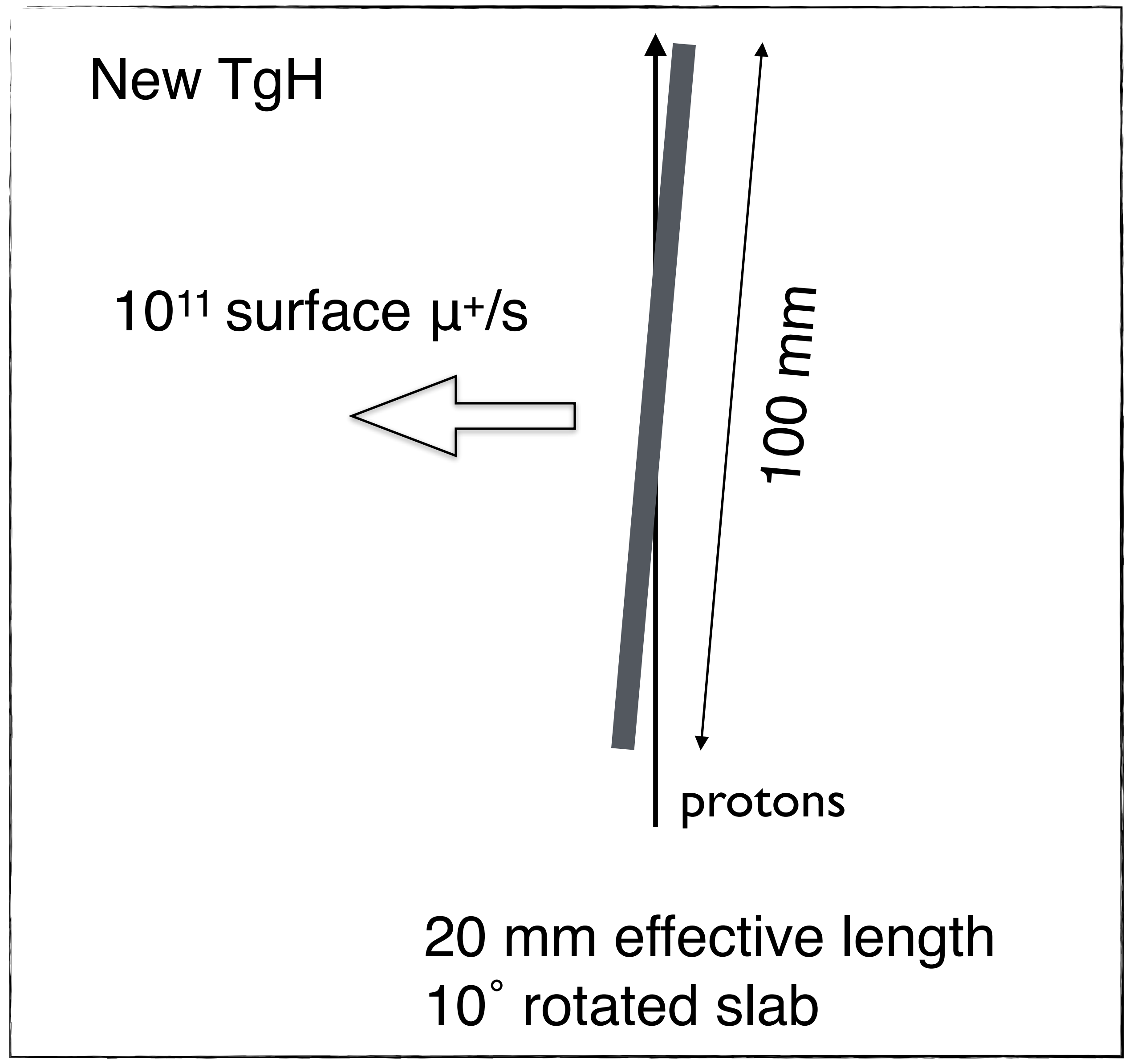
TDR currently being finalized



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

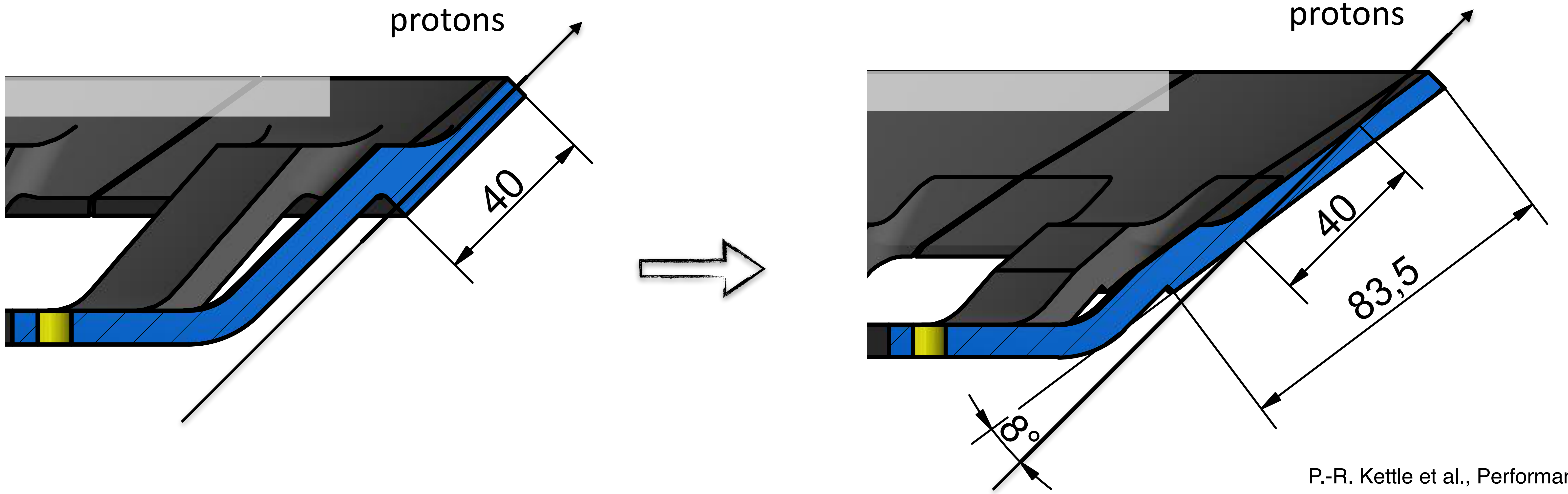
First HIMB development at HIPA: Slanted TgE

Goals:

- Change geometry of TgE to increase surface muon rates
- Increase safety margin for “missing” TgE with proton beam

First test at the end of 2019; new standard geometry since then

40-50% gain in surface muon rate in all connected beamlines



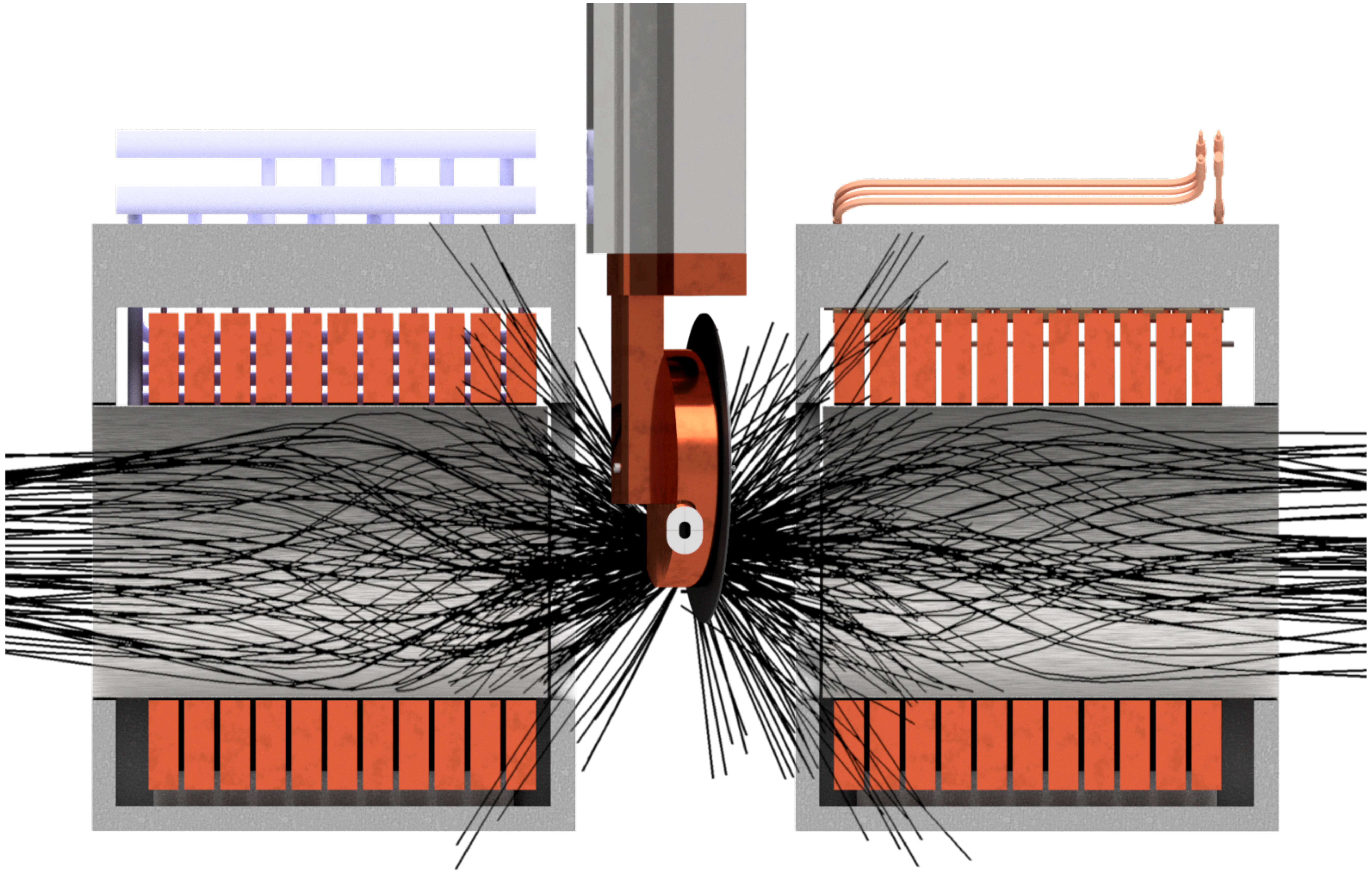
P.-R. Kettle et al., Performance Summary of the HiMB Slanted Target versus the Standard 60 mm Target E, HIMB Technical Note (2020)

Split Capture Solenoids for Muon Collection

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

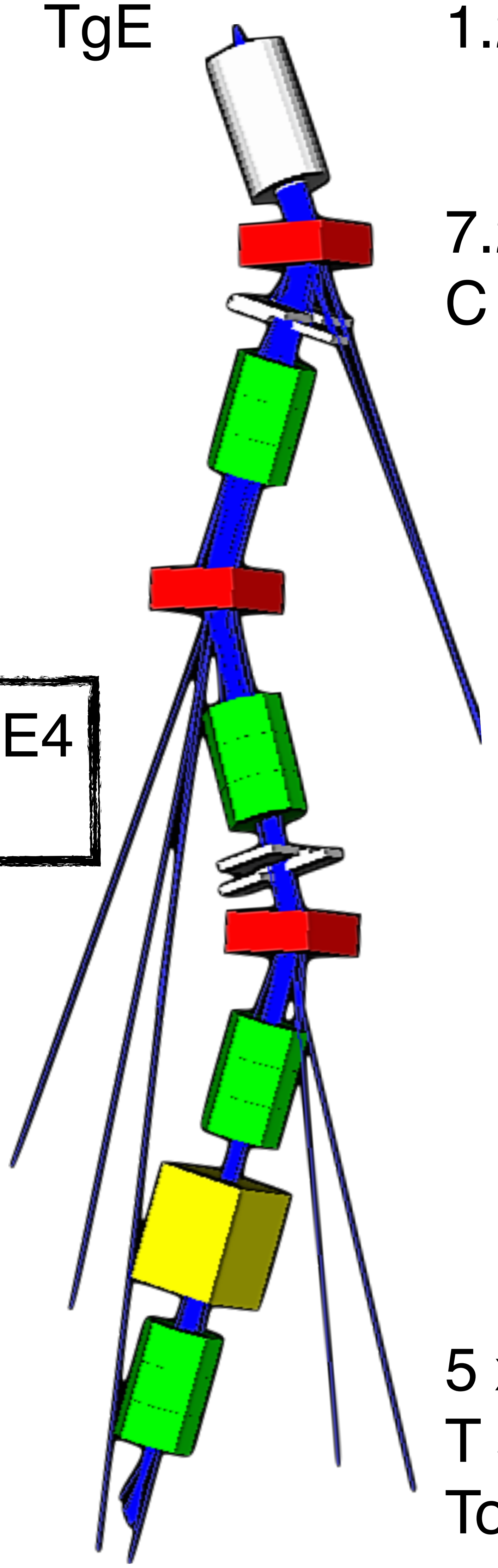
Central field of solenoids up to 0.45 T

Graded-field capture solenoid: stronger field at capture side, weaker at exit



Solenoid beamline

TgE

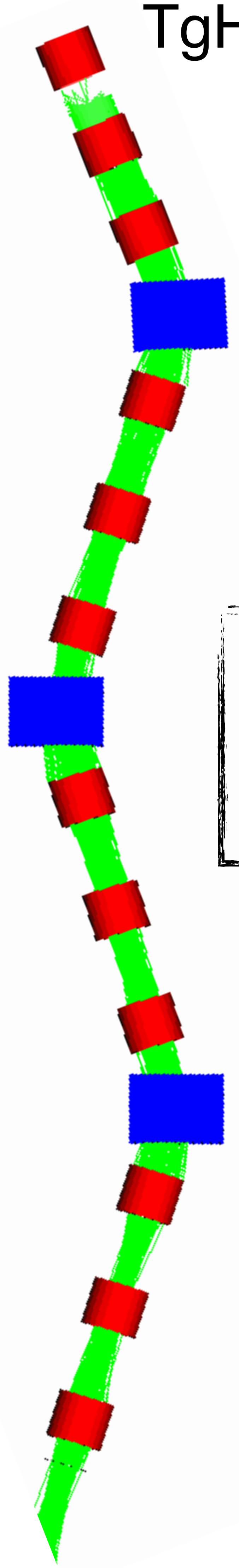


Existing μE4 beamline

	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%

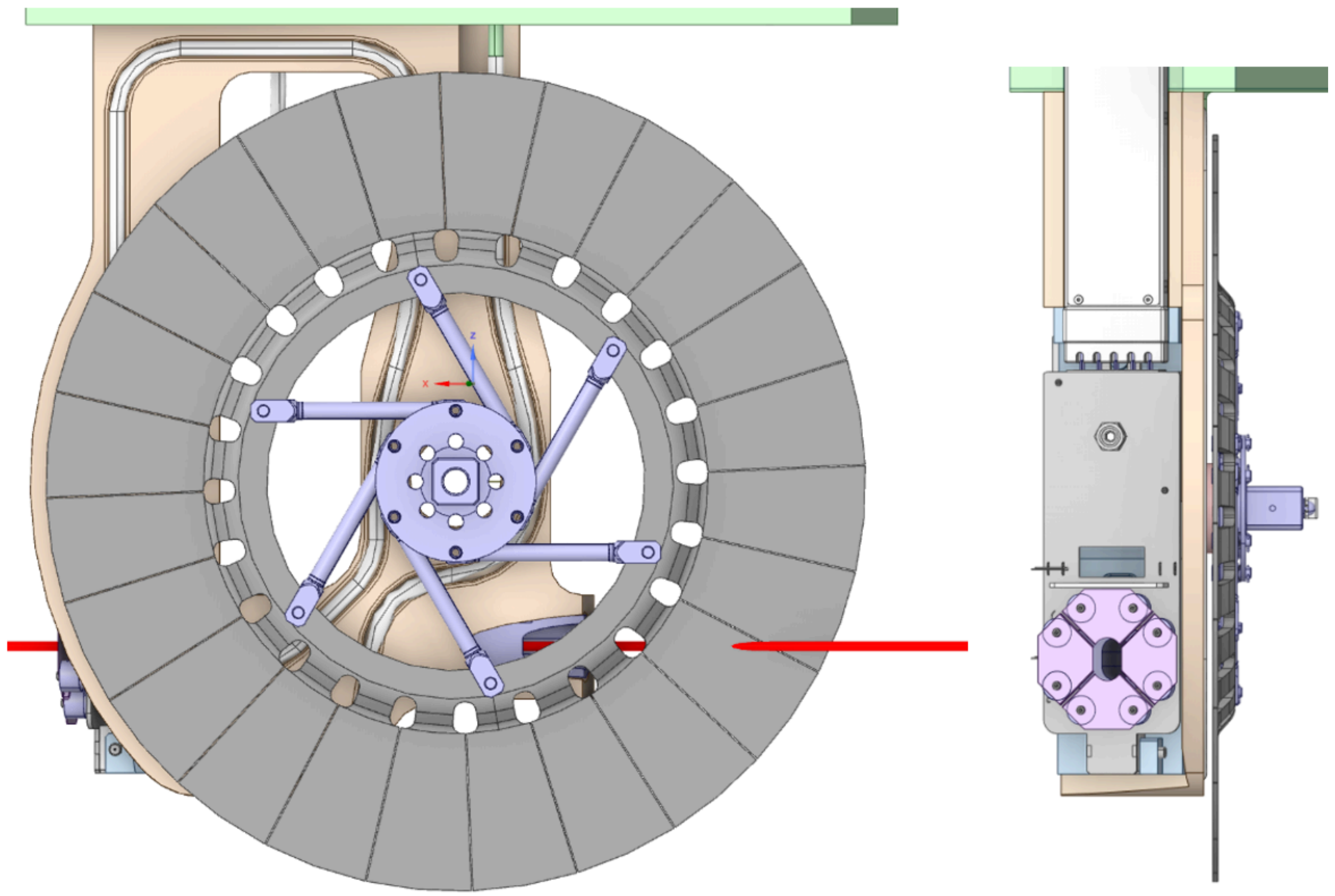
⇨ Gain due to high capture and transmission efficiency

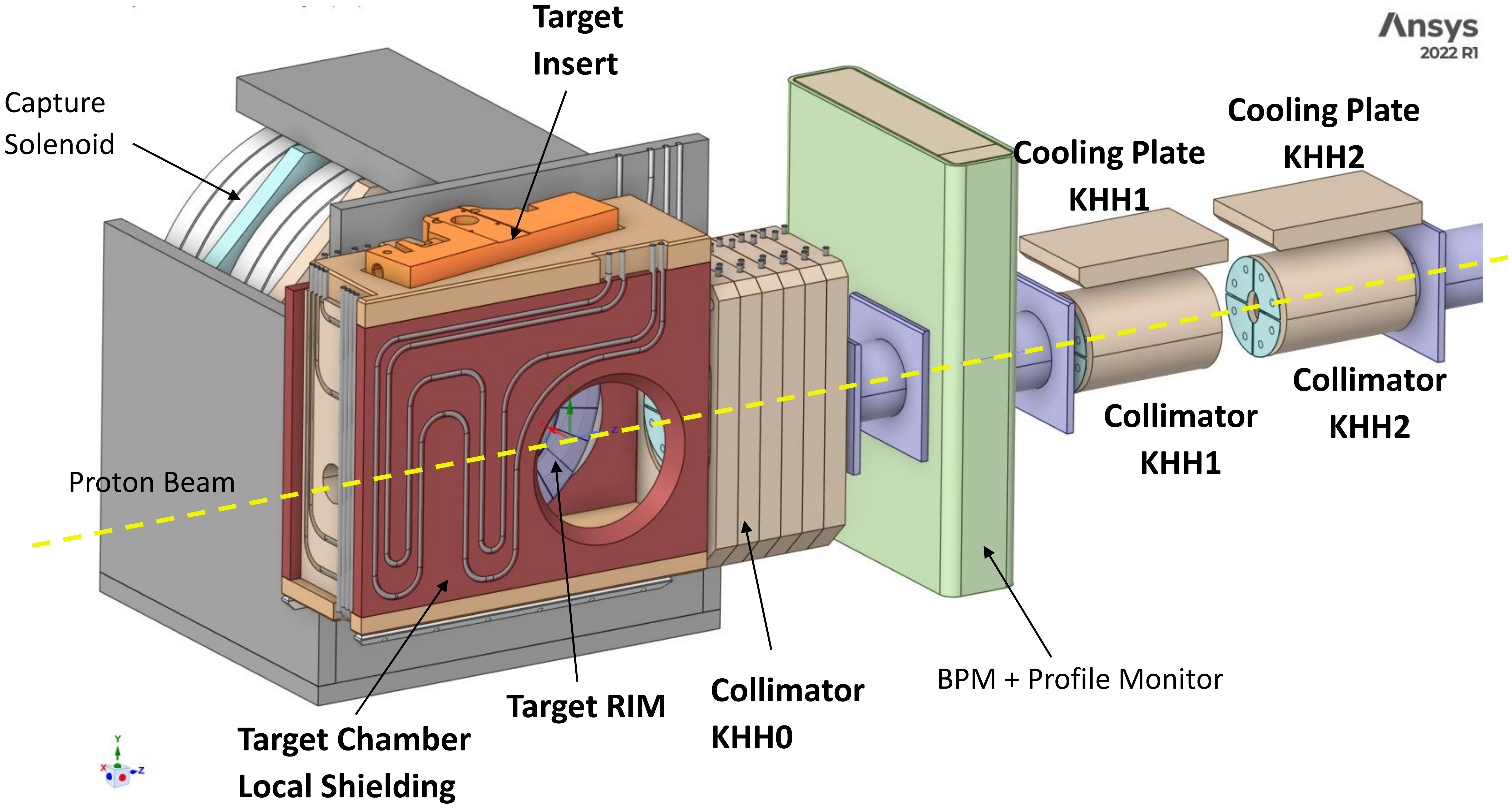
TgH



Solenoid-based beamline

New Target H

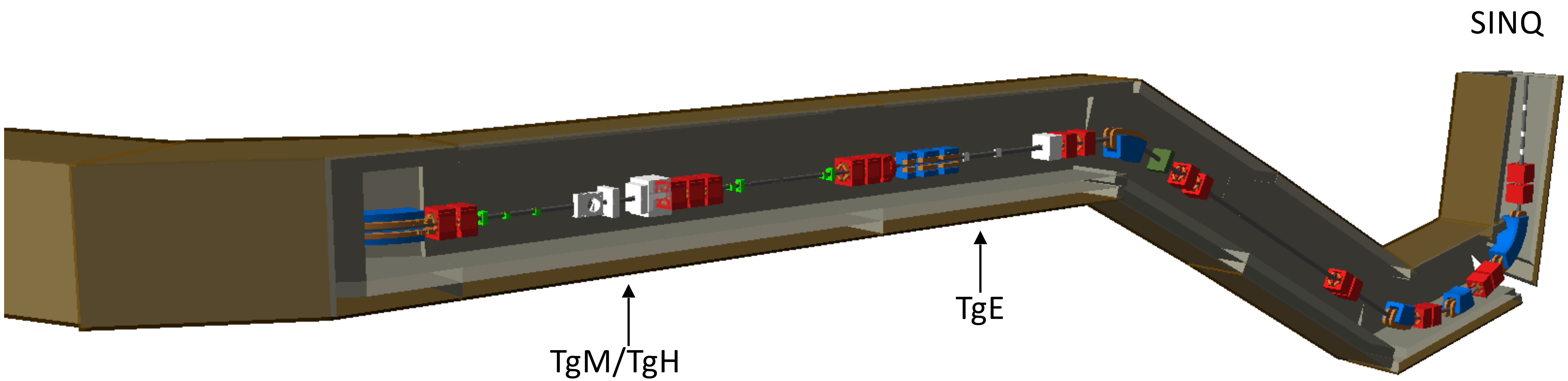




Based on experience from TgM & TgE

Same exchange concept as for TgE

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 67% compared to 69% with TgM

Can increase transmission back up to 69% when collimators after TgE are optimised

Beam shape at TgE and SINQ preserved

MUH2/MUH3 Beamlines

General 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

  MUH2 for particle physics using high-transmission solenoid based beamline

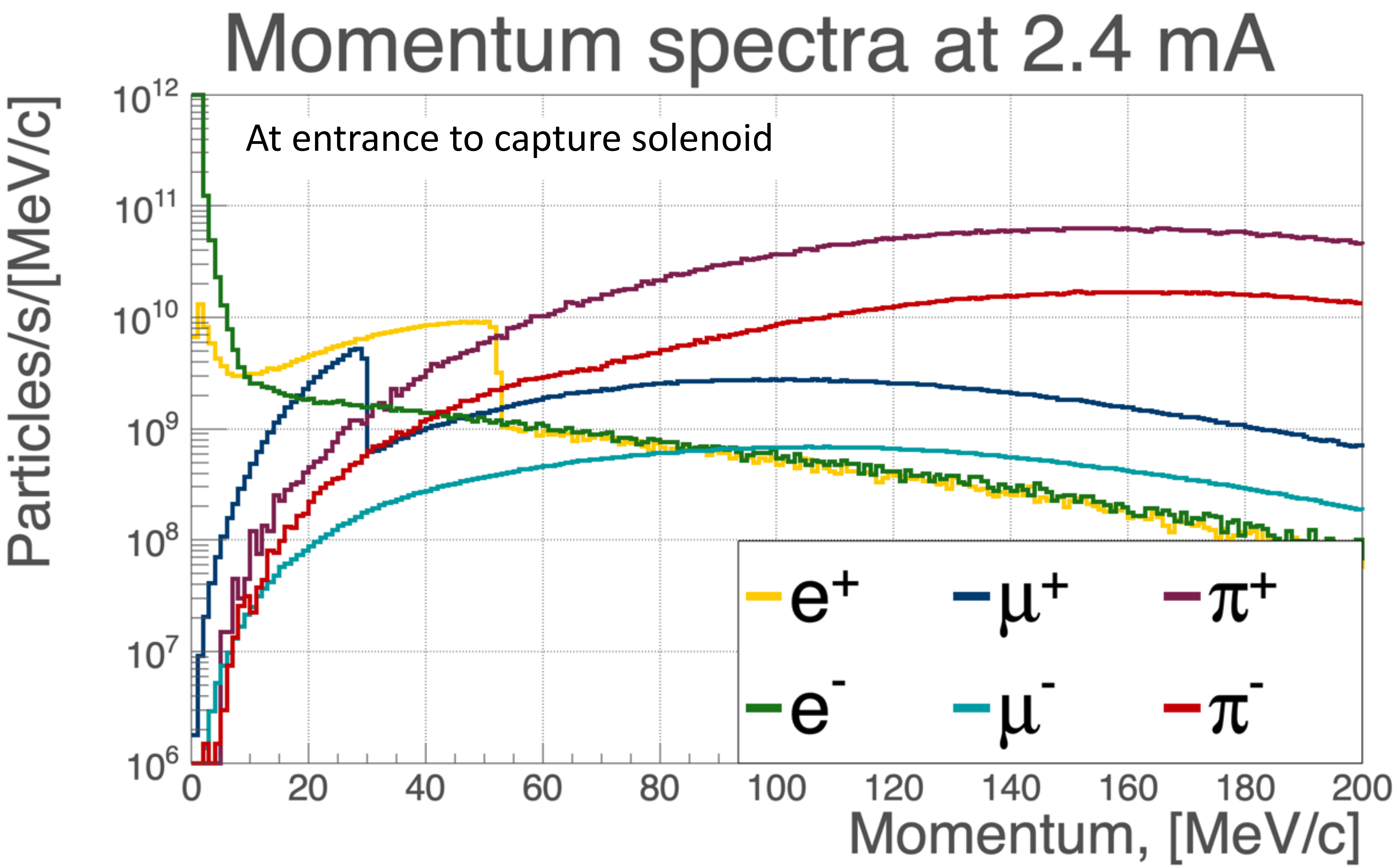
  MUH3 for μSR solenoid based beamline until experimental area; couples into existing beamline

Particle production at TgH

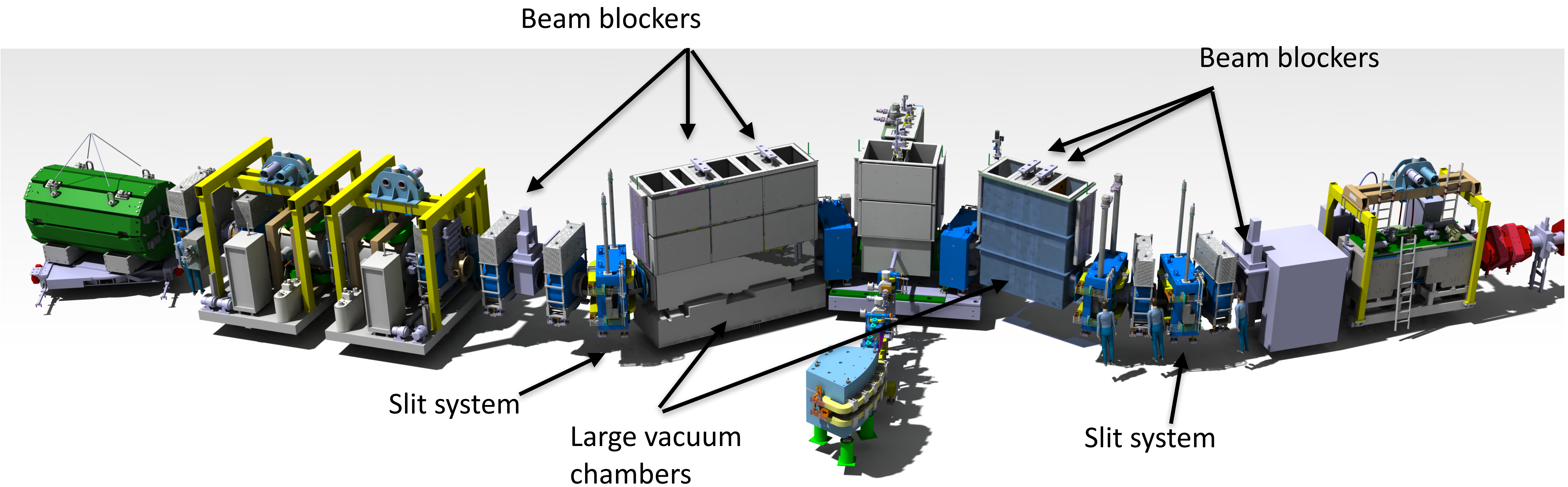
We are not only producing surface muons

Will have good capture and transport efficiency up to 40 MeV/c (given by capture solenoid)

Dipoles designed to go up to 80 MeV/c



MUH2/MUH3 Beamlines



Mechanical designs for all components available

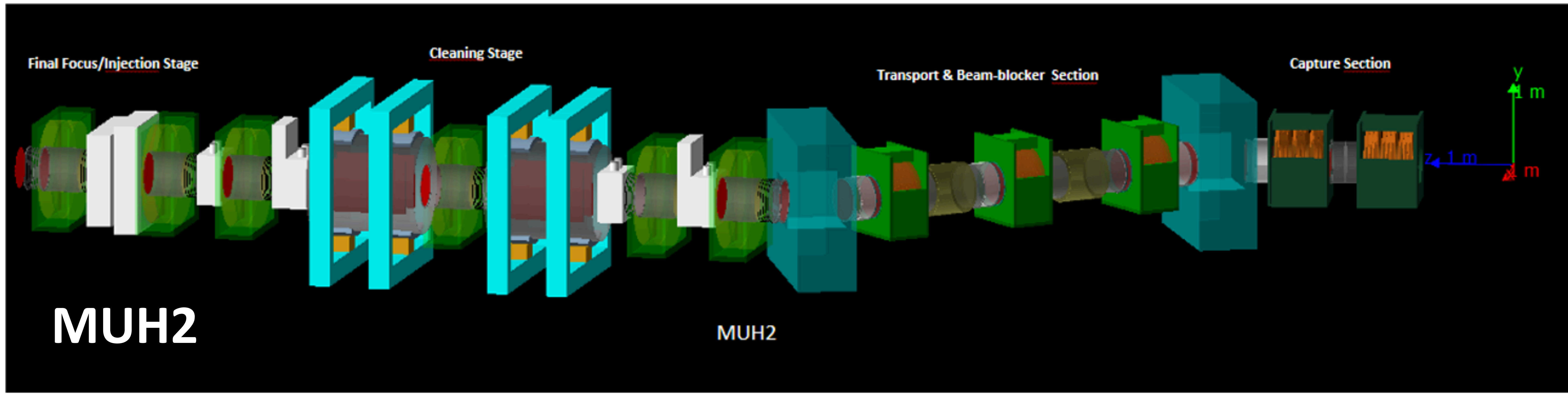
Large vacuum chambers for MUH2 and MUH3 with inserts

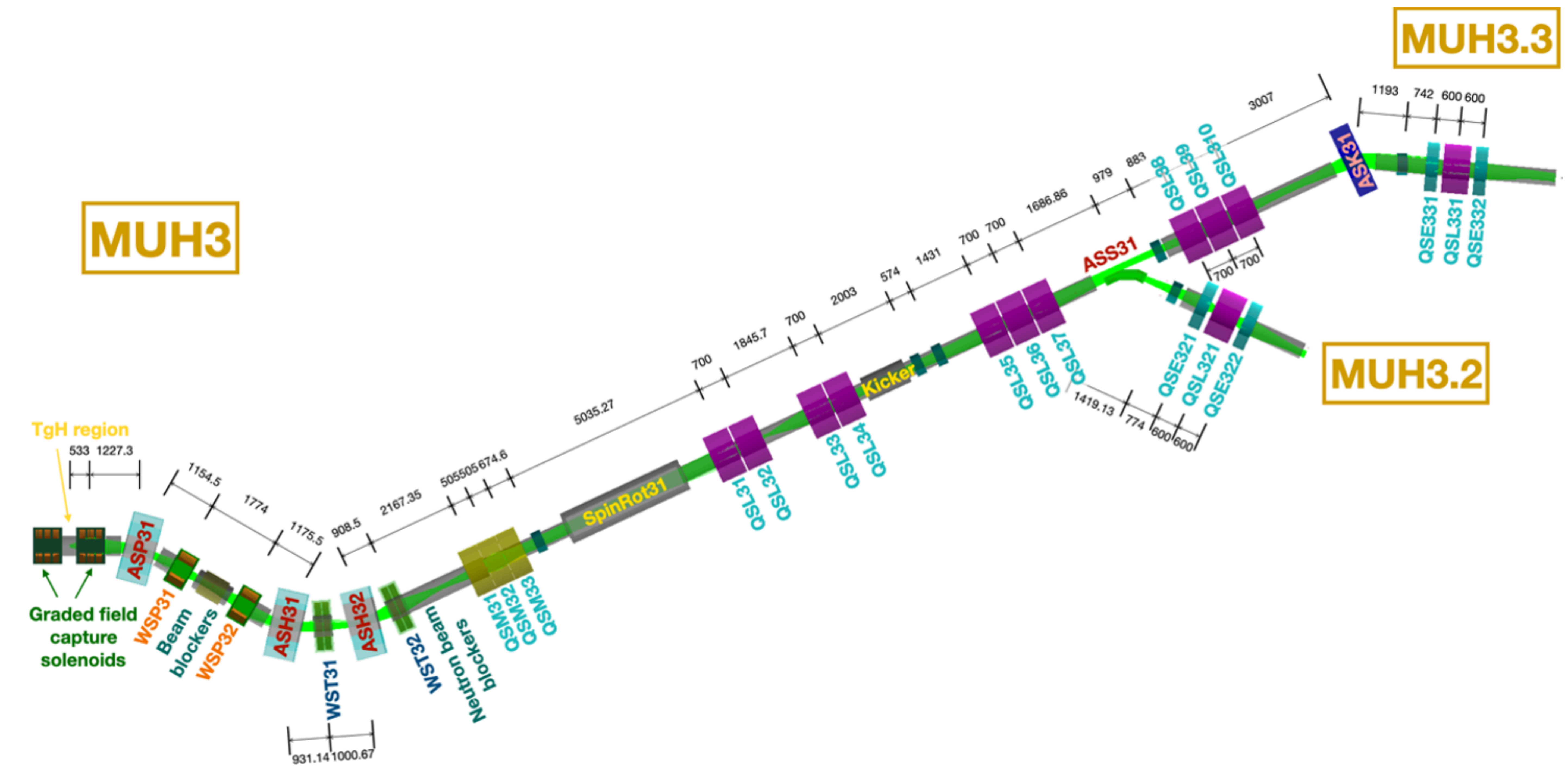
Pumping ports identified and vacuum simulation gave satisfactory results

Two charged particle beam blockers and two neutron beam blockers on either side

MUH2/MUH3 Beamlines

Both beamlines fully simulated in G4beamline using realistic field maps, mechanical models of the magnets an all mechanical constraints on layout





Summary performance of MUH2/MUH3

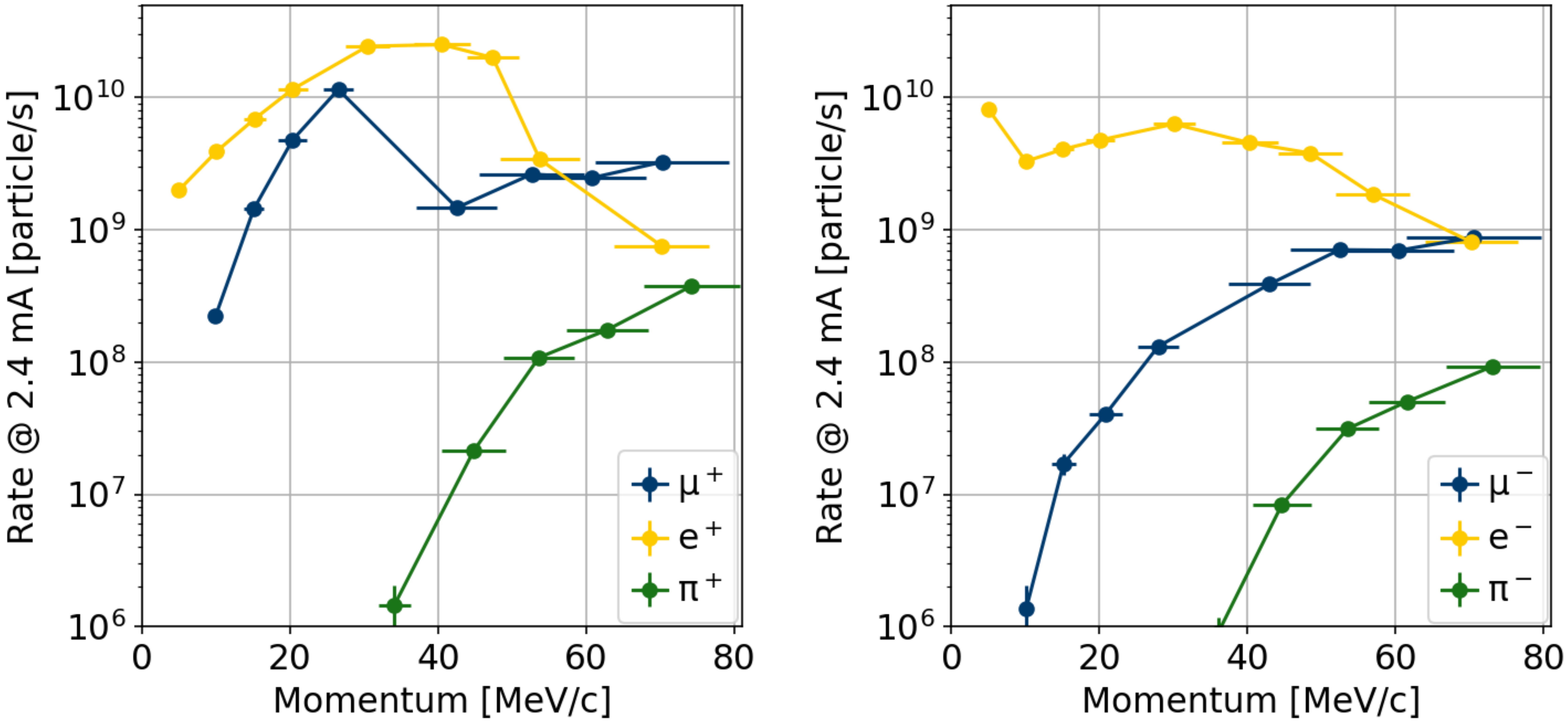
Transmitted rate to the end of the MUH2 beamline at 2.4 mA proton current (maximum rate):

- ~1.06×10^{10} μ^+/s at 28 MeV/c
- Beam spot at final focus: $\sigma_x \sim \sigma_y \sim$ 36 mm
- Positron contamination ~4%

Transmitted rates to the end of the MUH3 beamline at 2.4 mA proton current:

- More than 10^{10} μ^+/s at 28 MeV/c at the end of the solenoidal part
- More than a factor 10 higher muon rate on 8-mm µSR entrance detector than currently available: ~ 4×10^6 μ^+/s
- Pixel detector technology crucial to go beyond the current maximum rate of ~4×10^4 μ^+/s

Full large-scale optimisation of MUH2



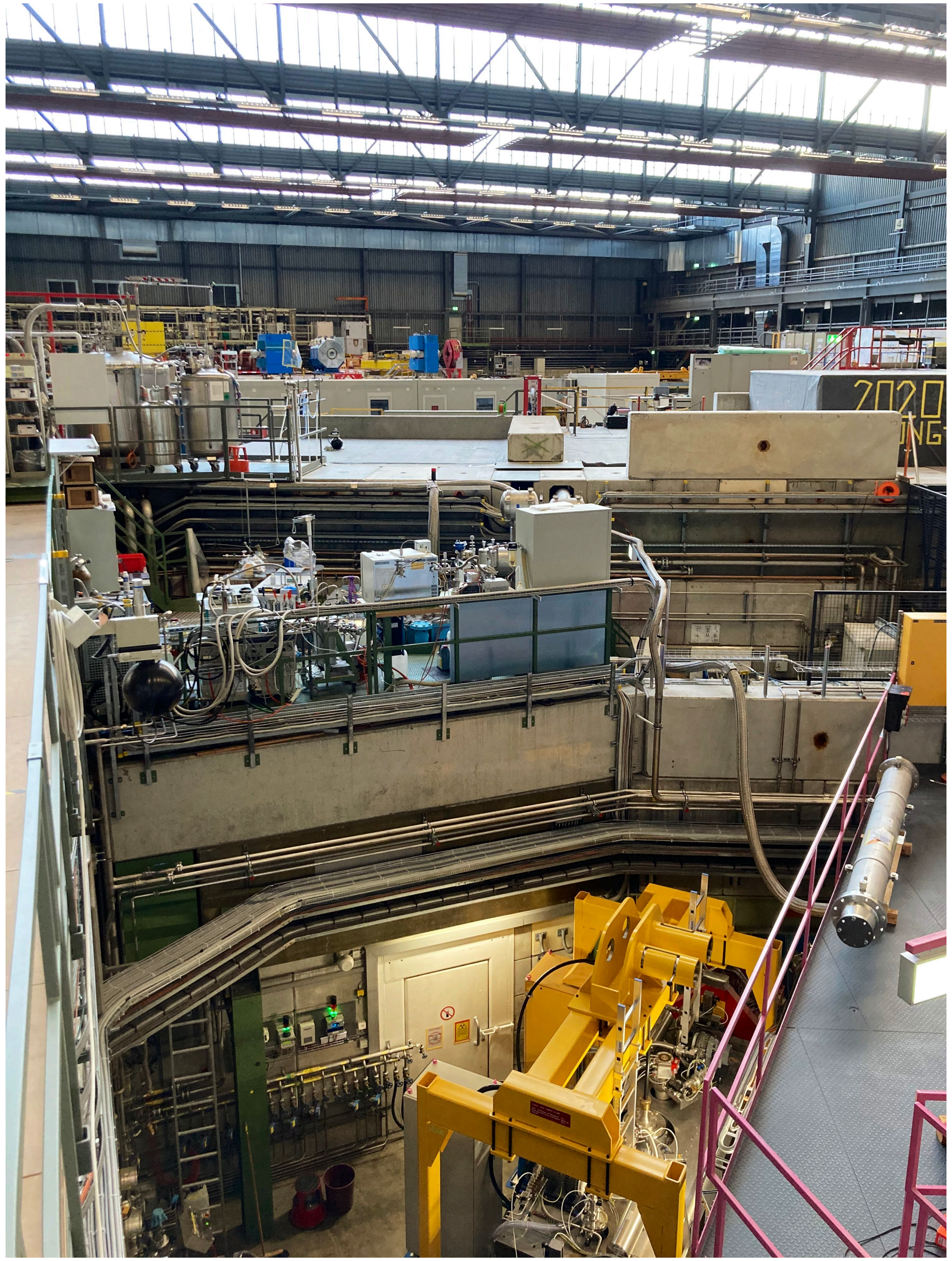
Optimising always on maximum rate for each species

Building a new target station

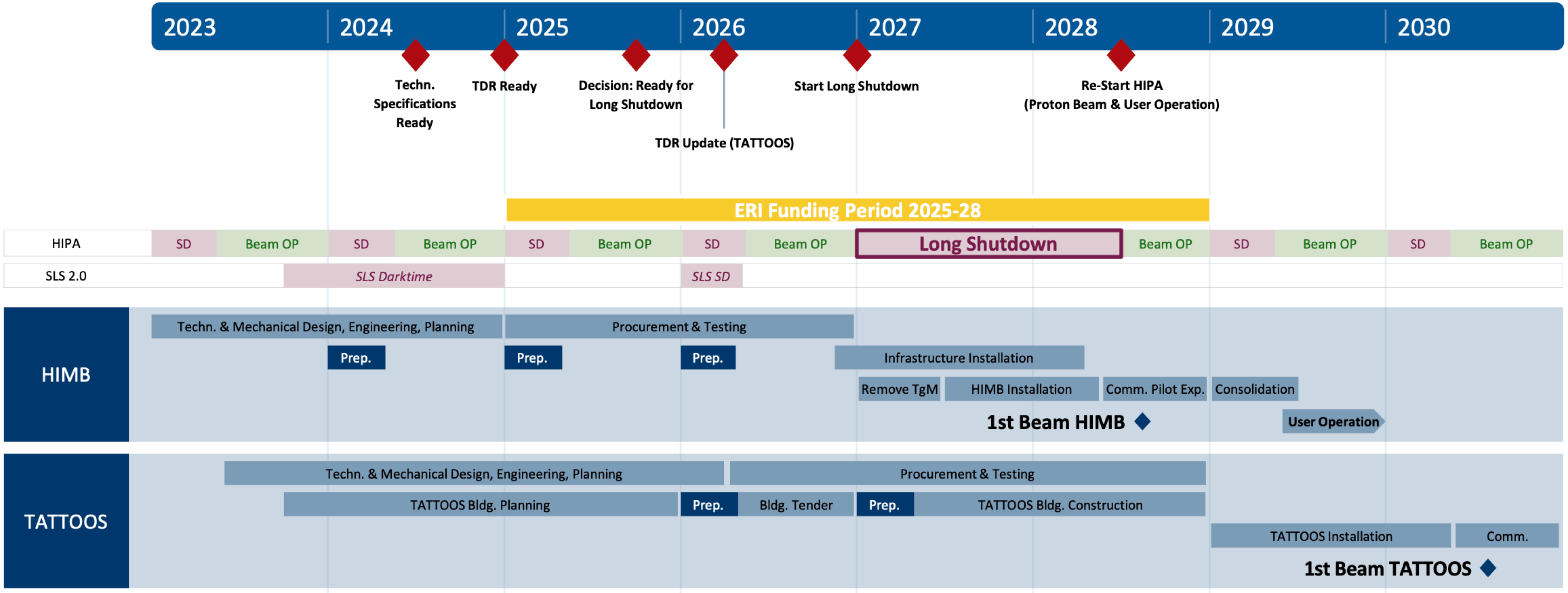
Challenging environment around TgM to change layout

Helium liquefier, tertiary cooling loop 7, lots of pipes, cables and conduits, power supply platforms, …

And of course in an environment with doses up to several Sv/h



Timeline & next steps



Scientific review passed with highest ranking in summer 2022

Final funding decision by Swiss parliament received end of 2024

Long shutdown of ~1.5 years beginning of 2027

Commissioning and pilot experiments at HIMB starting mid 2028, at TATTOOS mid 2030

Conclusions

On track for realising IMPACT at PSI

HIMB will enable forefront muon research at PSI for the next 20+ years

TATTOOS will bring novel radioisotopes into clinical studies and open a whole new research field at PSI

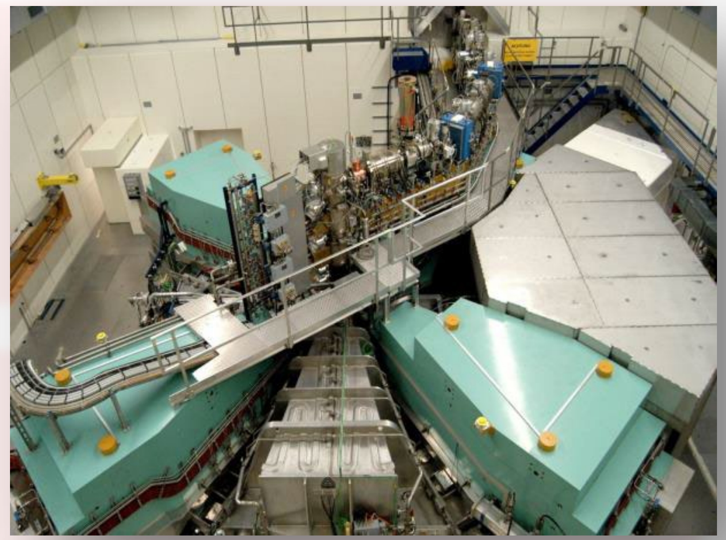
Many thanks to everyone from the IMPACT project for providing slides and input to this presentation!

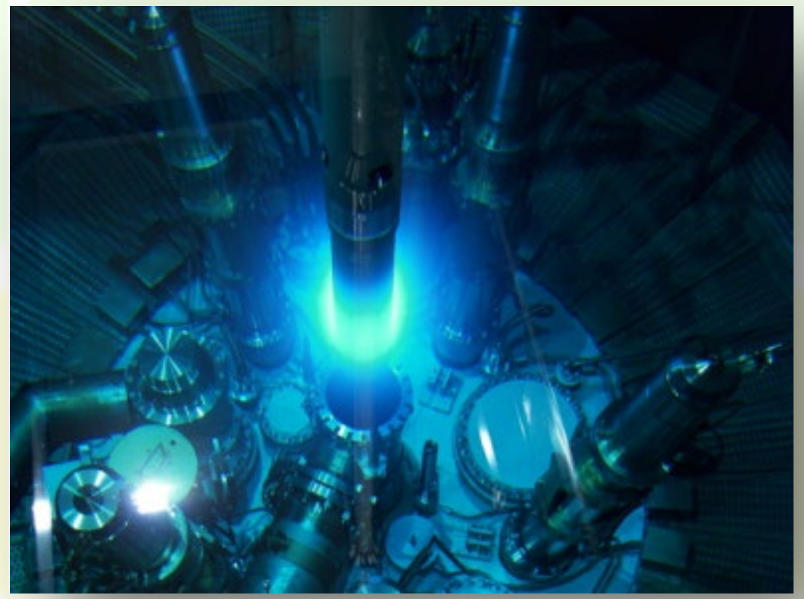
Backup

“Matched Pairs” Towards Theragnostics: The Next Generation

PSI

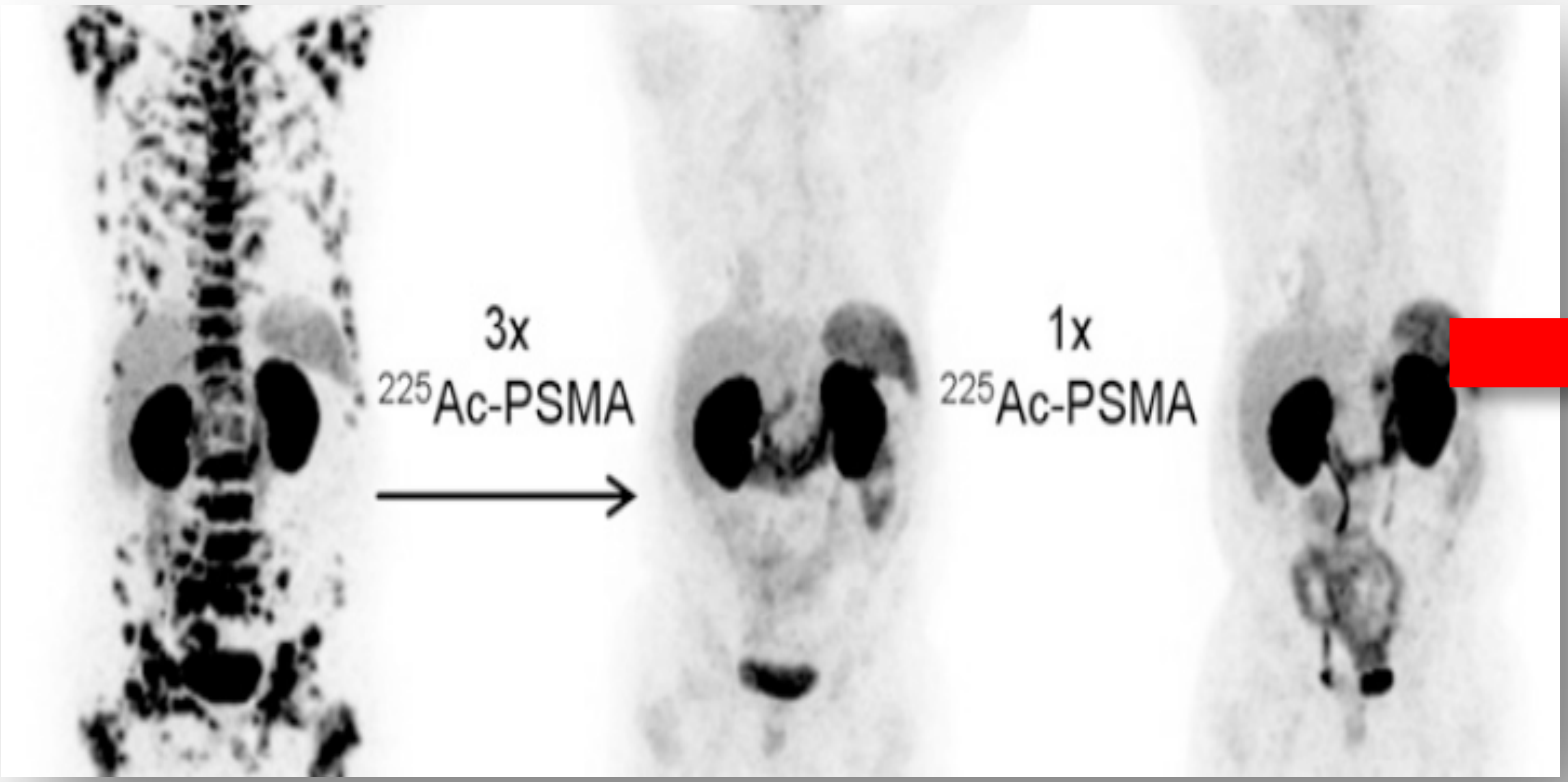
	Clinically Applied	Next-Generation Radionuclides
SPECT (γ)	In 111 2.80 d; Tc 99m 6.01 h	Tb 155 5.32 d
PET (β^+)	Ga 68 68 min	Tb 152 17.5 h
β^--Therapy	Y 90 2.67; Lu 177 6.65 d	Tb 161 6.89 d
Auger-e^- Therapy		
α-Therapy	Ac 225 10.0 d; Bi 213 46 min	Tb 149 4.1 h

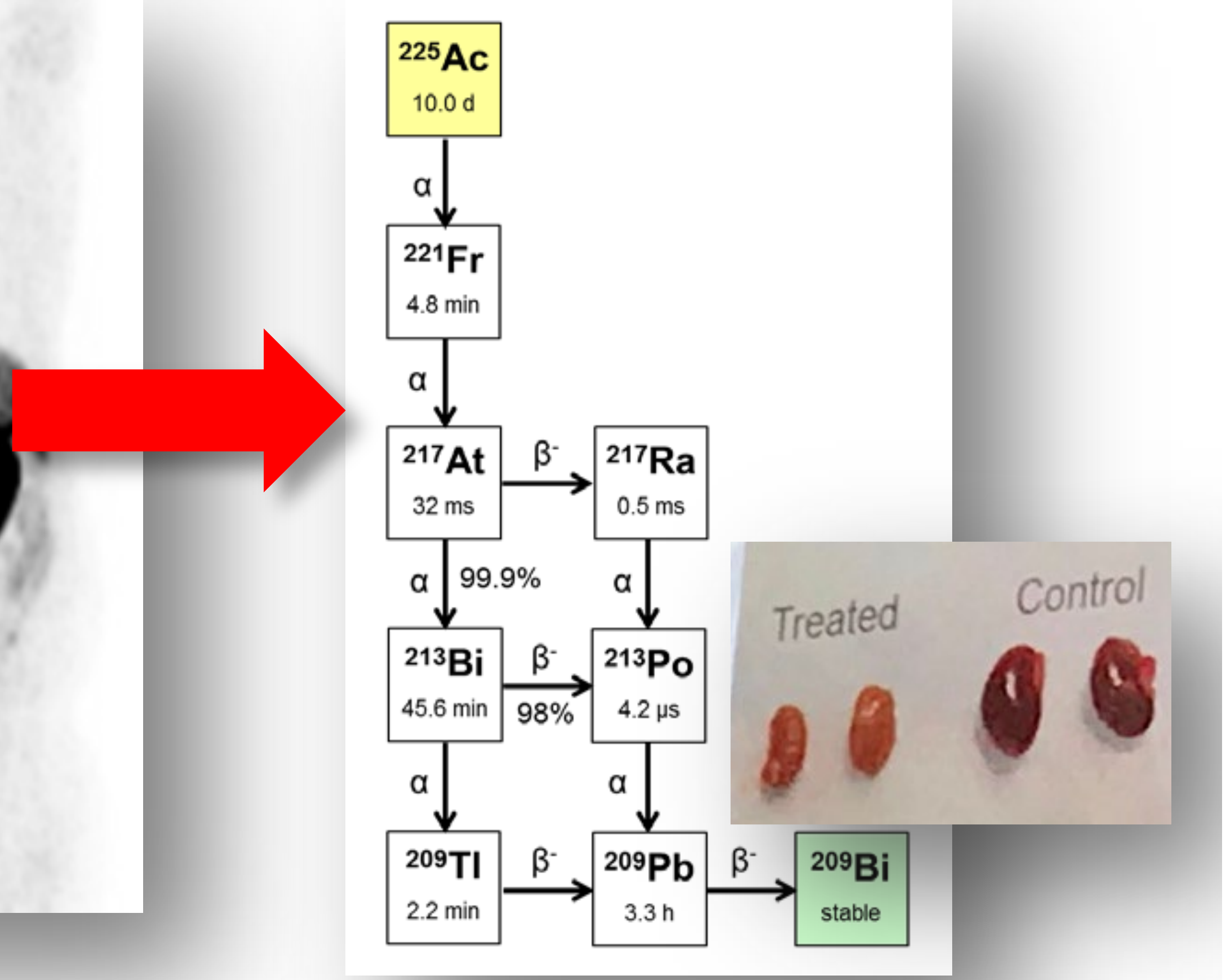




Targeted alpha therapy

^{149}Tb is the IDEAL α-emitter for Targeted Alpha Therapy!





Mulitple α-decay chain can cause much damage,
Resulting in side effects!

Kratochwil et al. **2016**, J Nucl Med Mol Imaging 57:1941

^{149}Tb has NO α-daughters!