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HiMB – A Possible "Next Generation" High-intensity Muon Beam Facility for Particle Physics & Materials Science

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Abstract

Muons are a prime tool for both, particle and condensed matter physics. High intensity muon beams enable unique research and play an increasingly prominent role at the "High Intensity Frontier". However, in order to undertake these "Next Generation" experiments in both fields, new concepts are needed to deliver muon intensities far in excess of the current world frontier limits produced at PSI. The HiMB feasibility study will explore such a possibility for PSI.

Introduction

Muons are an excellent tool for probing both the fundamental and applied aspects of the structure and properties of matter.

The search for "New Physics" beyond the Standard Model (SM) is of fundamental importance as it ultimately leads to a more unified understanding of the nature of our "universe". Particularly suited to this search are precision-type experiments at the high-intensity frontier, an important complementary approach to similar strivings in the high-energy sector at the world's leading collider facilities.

Materials science with its novel techniques such as muon spin resonance (MuSR), is also able to address fundamental questions concerning the magnetic nature of complex novel materials by utilizing the properties of the muon such as its magnetic moment and 100% spin polarization.

Currently, PSI leads the world at the intensity frontier, with its high-intensity proton accelerator complex HIPA, producing a nominal DC beam power of more than 1.3 MW (cf. Fig. 1), in-turn leading to the most intense low-energy muon beams in the world, with fluxes in excess of 10^8 muons/sec. However, large efforts are underway worldwide to improve intensities beyond the present state of the art in order to open up new research options.

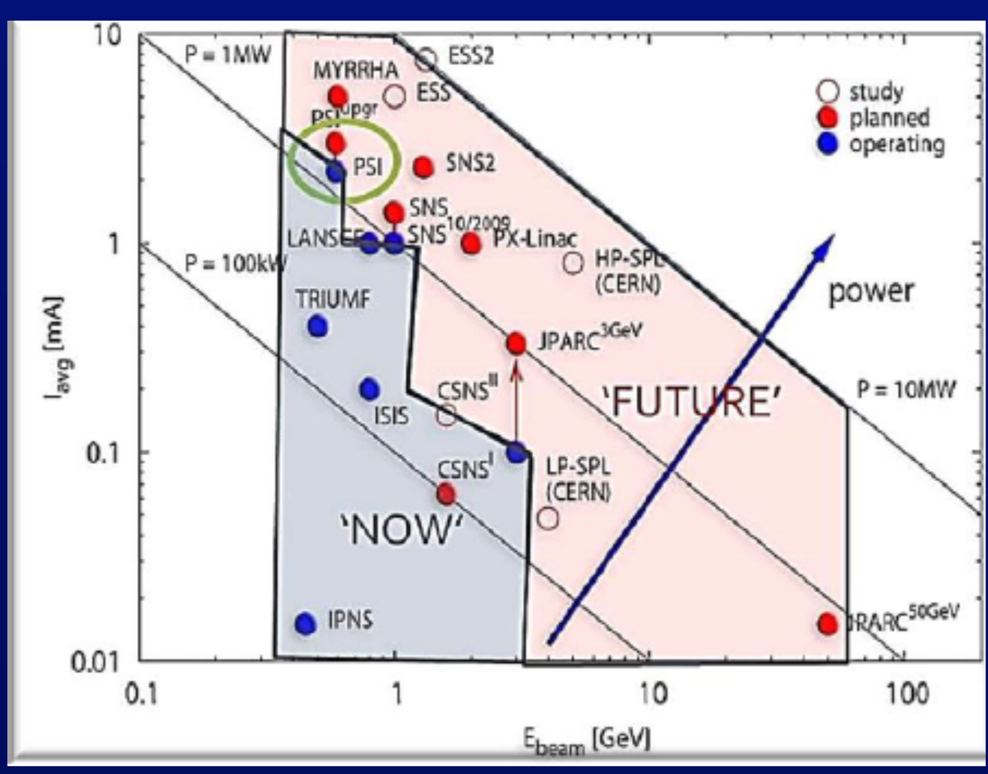
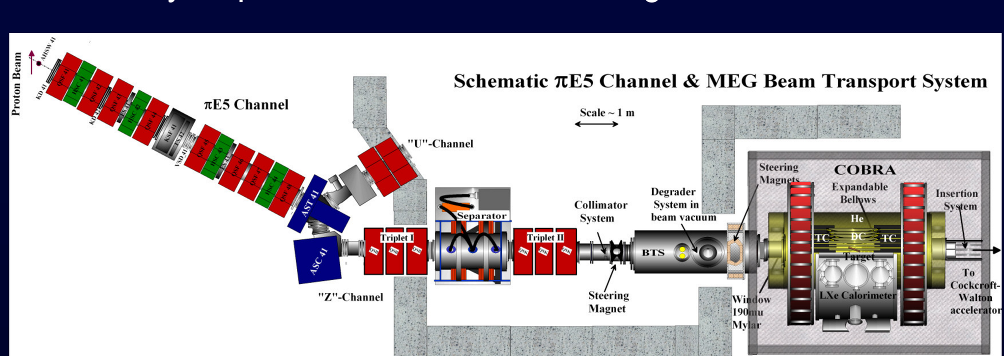


Fig.1: The Intensity Frontier- current & future accelerator facilities around the world. The diagonal lines represent beam power contours of 0.1, 1 & 10 MW.

Motivation

On the particle physics side a new generation of charged lepton-flavour violating experiments (cLFV) is in planning worldwide: MEG2 [1] and Mu3e [2] at PSI (cf. Fig. 2), COMET & PRISM/PRIME at J-PARC [3] in Japan and Mu2e and Project X Mu2e at Fermilab [4] in the US. Furthermore, LFV has been endorsed as a key area of investigation by the national road-maps on particle physics of the major nations involved [4-8], that of the USA, Europe (including Switzerland) and Japan. However, the sensitivities aimed for by these experiments requires new concepts to achieve stopped muon beams with orders of magnitude more intensity than currently available at PSI. Mu3e and other muon experiments will ultimately require muon rates exceeding 10^9 s^{-1}.



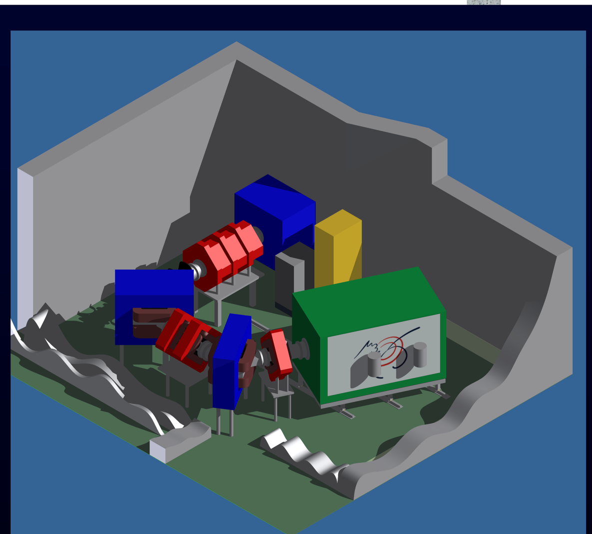


Fig.2: Top – Schematic of the MEG Experiment in the PiE5 Area of PSI. Bottom – Proposed Mu3e Phase I compact beam line in the front-part of the PiE5 area.

The HiMB project will explore the possibility of providing such intensities of polarized surface muons, serving both particle physics and materials science. The landscape of present and "in planning" muon facilities is shown in Table 1.

Table 1:Current and "in-planning" muon beam facilities/experiments.

Laboratory/ Beam Line	Energy/ Power	Present Surface μ^+ Rate Hz	Future estimated μ^+/μ^- Rate Hz
PSI (CH)	(590 MeV,1.3MW, DC)		
- LEMS	"	$4 \cdot 10^8$	
- πE5	"	$1.6 \cdot 10^8$	
- HiMB	(590 MeV, 1 MW DC)		~10^{10} (μ+) (for cf. only)
J-PARC (JP)	(3 GeV, 1MW Pulsed) currently 300kW		
- MUSE D-line	"	$4.5 \cdot 10^6$	$1.5 \cdot 10^7$ (μ+) 2013
- MUSE U-Line	"	$1.5 \cdot 10^8$	2 - $5 \cdot 10^8$ (μ+) 2013
- COMET	(8 GeV, 56kW Pulsed)		10^{11} (μ-) 2019/2020
- PRIME/PRISM	(8 GeV, 300 kW Pulsed)		10^{11-12} (μ-) >2020
FNAL (FermiLab) (USA)			
- Mu2e	(8GeV, 25kW Pulsed)		$5 \cdot 10^{10}$ (μ-) 2019/2020
- Project X Mu2e	(3GeV, 750kW Pulsed)		$2 \cdot 10^{12}$ (μ-) >2022
TRIUMF (CA)	(500 MeV, 75kW, DC)		
-M20		$2 \cdot 10^6$	
KEK (JP)	(500 MeV, 2.5 kW Pulsed)		
- Dai Omega	"	$4 \cdot 10^5$	
RAL -ISIS (UK)	(800 MeV, 160kW, Pulsed)		
- RIKEN-RAL		$1.5 \cdot 10^6$	
RCNP Osaka Univ. (JP)	(400 MeV, 400W DC)		
- MUSIC	currently max 4W		10^8 (μ+)* 2012 *(≡ > 10^{11} per MW!!!)
DUBNA (RU)	(660 MeV, 1.65kW Pulsed)		
- Phasotron Ch:I-III		$3 \cdot 10^4$	

Concept

Although still in its infancy and subject to a 2-year feasibility study, just started, one such new concept [9] which holds the potential to maintain PSI's muon beams at the intensity frontier, as well as the possibility to provide a multi-port high-intensity muon facility, should the concept prove feasible, is the use of the SINQ spallation neutron source (cf. Fig. 3) target window as a source of low-energy surface muons (P < 29.79 MeV/c, T< 4.12 MeV, kinematic limit).

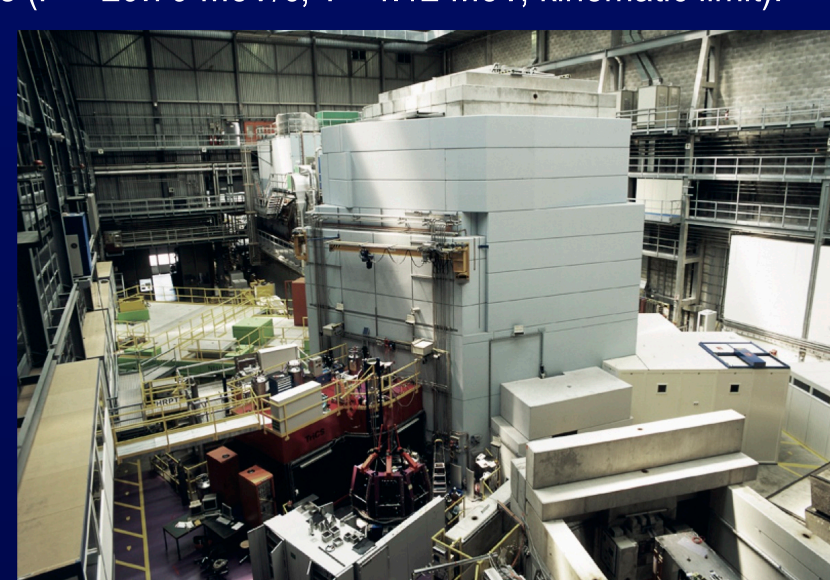


Fig.3: PSI SINQ Spallation Neutron Source.

Like-signed charge muons, from stopped pion decay in the target window, would be guided in a downward direction, opposite to the incoming protons by a solenoidal guiding field. A focussing solenoid would allow the upward protons to be defocussed on the target window, as is currently the case, while still allowing the muons of much lower momentum to be transmitted in the opposite direction. Muon extraction is currently foreseen in the fringing field at the top of the large dipole magnet AHO shown in Fig.4.

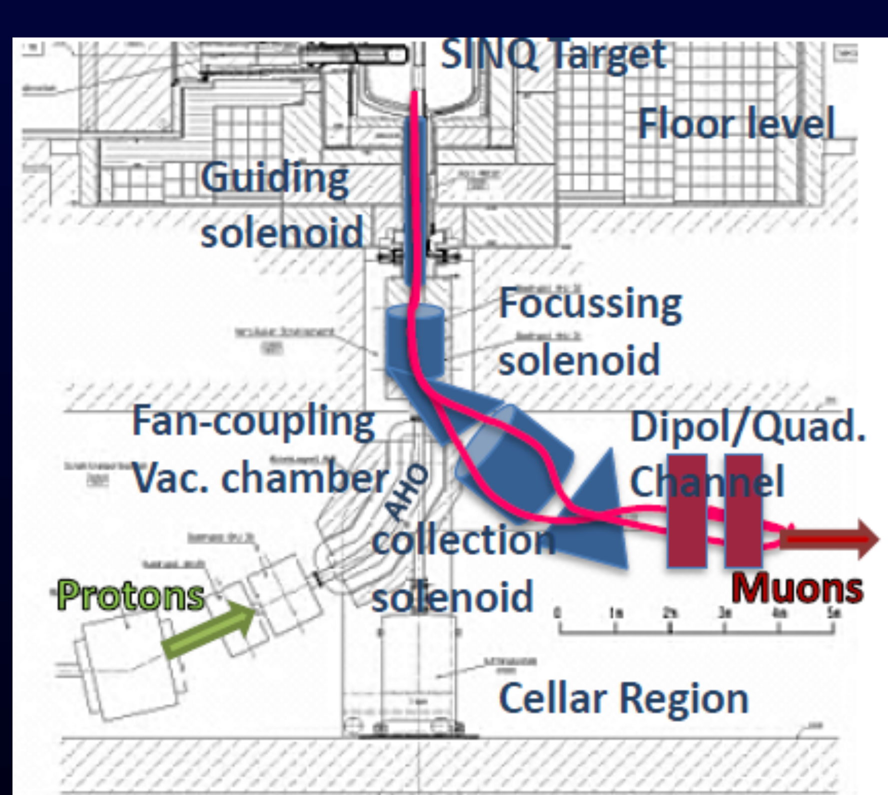


Fig. 4: HiMB concept showing extraction from the SINQ target (top) to the cellar region.

A collection solenoid would focus the muon beam for injection into a conventional large aperture dipole/quadrupole channel placed in the current empty cellar region under the SINQ target. The beam would be bent and extracted at the end of the cellar to an experimental hall external to the SINQ hall, on the east-side of the complex.

Advantages compared to a conventional target such as the PSI thick Target station E are:

- 70% of protons are stopped compared to 12% at Target E
- Can exploit a larger energy-range of the π-production cross-sections (up to 150 MeV, compared to ~45 MeV at Target E)
- Larger π-production volume (up to 50% of proton range)
- Pion range is limiting, not the width of the Δ-resonance
- Higher average Z cross-sections (Pb,Zr, Al compared to C)
- Can exploit a larger surface muon acceptance volume

Target Simulations

Initial muon source intensity calculations have since been confirmed by realistic 3D Monte-Carlo simulations of the SINQ target region using the code MCNPX (also used for the design of the SINQ target). The simulation involved $4 \cdot 10^8$ protons generated from a realistic 2-D Gaussian profile interacting in a complete model description of the SINQ target (cf. Fig 5). Three different physics models were used to generate pion production and stopping, followed by surface muon production. The statistical uncertainty of the number of muons produced with the correct energies, heading downwards within the beam pipe and passing a plane 25 cm below the window, is better than 2%, while the model estimates agree to within 35% for μ^+.

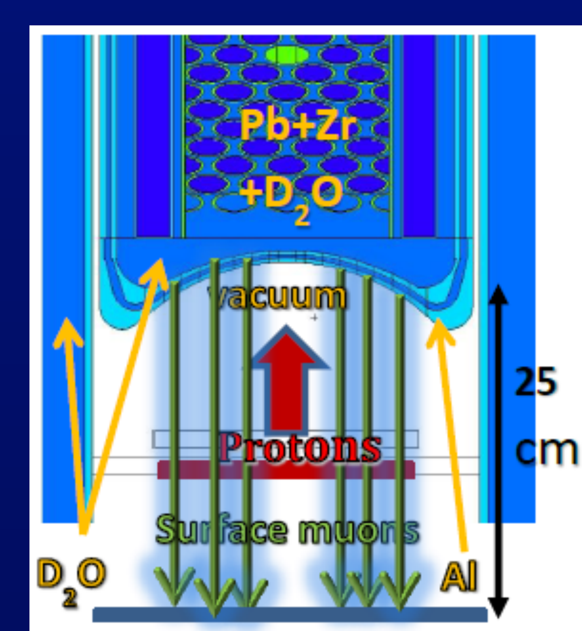


Fig.5: PSI. MCNPX Monte-Carlo model of SINQ Target region

Normalizing the number of muons with energies < 4.12 MeV to a proton beam intensity at the SINQ target of 2.1 mA (3mA at Target E) and allowing for the 35% variation, a maximum muon rate of:

R_μ(<4.12 MeV) = $1 \cdot 10^{11}$ μ^+ s^{-1} at 2.1 mA I_p on SINQ
passing surface 25 cm below target heading downwards

can be expected.

Limiting the source results to a realistic momentum-byte of 10% FWHM, surface muon rates below the SINQ target of order 10^{10} s^{-1} at a modest proton current of I_P =2.4 mA on TgE (1.7 mA SINQ), which has already been achieved, could be expected, as shown in Table 2. As an example, an 80% muon survival probability can be expected for a beam line length of 40 m.

Table 2: expected muon rates below SINQ

Central Momentum [MeV/c]	Momentum-byte [%] FWHM	Estimated Muon Rate (Below SINQ Target) [Hz] I_P = 2.4 mA Tg E
28 (Surface muons)	Full	$(7\pm1)\cdot10^{10}$
28 (Surface muons)	10	$(3\pm1)\cdot10^{10}$
26 (sub-surface muons)	10	$(3\pm1)\cdot10^{10}$

Challenges

There remain many challenging aspects of the project to be studied, notably: muon extraction & transmission optics; maintaining machine & SINQ safety requirements & diagnostic elements; radiation hardened magnets in a limited space; and finally maintaining the current proton "footprint" on the SINQ target.

References

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