Overview

- Muon storage ring ($\mu^-$ or $\mu^+$)
- Long straight sections for decays
- Produce $\nu_e$, $\nu_\mu$, $\bar{\nu}_e$ and $\bar{\nu}_\mu$ beams
- Well known spectrum and flux
- Candidate site at CERN

\[
\begin{align*}
\mu^- & \longrightarrow e^- + \bar{\nu}_e + \nu_\mu \\
\mu^+ & \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu \\
\pi^- & \longrightarrow \mu^- + \bar{\nu}_\mu \\
\pi^+ & \longrightarrow \mu^+ + \nu_\mu
\end{align*}
\]
Physics case

- < 1% flux error give unique precision
- measure neutrino-nucleon cross sections
  - $\nu_e$, $\nu_\mu$, $\bar{\nu}_e$ and $\bar{\nu}_\mu$
  - First precision $\nu_e$ and $\bar{\nu}_e$ cross sections in 1-4 GeV range
- Sterile neutrinos search
- R&D synergy with Neutrino Factory, Muon accelerators and colliders
• Proton target with magnetic horn produces pion beam
• Chicane for charge selection
• Stochastic injection into main ring
• Long decay straights - ~150m
• Return arcs – total ring ~500m

• No kickers
• no acceleration
• no ramping
Fermilab

- Project definition report stage
- 120 GeV from the Main Injector
- $10^{21}$ POT
- $5\pm1$ GeV/c pions injected
- $3.8\pm10\%$ GeV/c muon stored
- 50m, 2000m detectors
CERN

- Investigated as part of Physics Beyond Colliders
- 100 GeV protons from SPS
- Muons up to 6.5 GeV/c
- Far detector at LHC point 2 (1.75 km) + near detector
- Feasibility studies done for integration, civil eng and radiation protection
Stochastic injection

- Novel stochastic injection – purely optical
- Injection channel for Pion momentum
- Pions decay to muon in 1\textsuperscript{st} straight
- Muons within momentum acceptance captured
Stochastic injection

- No kicker required
- Remaining pions extracted by mirror and end of straight
Lattice options

• Requirements
  - Large dynamic aperture
  - Small angles in straights

• 3 lattice options
  - FODO – traditional FODO lattice
  - Fixed-Field Alternating-Gradient (FFA)
  - Hybrid (FODO on injection straight)
FODO lattice

- Race-track synchrotron
- Zero dispersion straights
- Tune crosses integers
- Significant resonant losses
Fixed-field Alternating-Gradient

- Magnets fixed in time
  - Like a cyclotron
- Alternating Gradient
  - Like a Synchrotron
- Field increases with radius
- Higher momentum particles move outwards
- In scaling FFA optics same for all momentum

\[ B(x, y) = B_0 (x - x_0)^k F(y) \]
FFA lattice

- Straight FFA section
- Magnets have field
  \[ B(x, y) = B_0 e^{m(x-x_0)} F(y) \]
- Zero chromaticity
- Large acceptance
- Triplet and quadruplet options
FFA issues

• FFA inherently has dispersion
  - Closed orbit for incoming pions is offset from captured muons
  - Reduces capture efficiency

• Scallop angle
  - Closed orbits not straight
  - Greater spread in ν beam
Hybrid lattice

- FODO straight for capture/decay
  - Zero dispersion to maximised capture
  - No scallop angle
- FFA return straight to control tune
  - Low chromaticity
  - Higher acceptance
Hybrid optimisation

Matching quad cell

Regular quad cell only
Prospects at ESS

- **Protons at 2 GeV**
  - Smaller arcs
  - New horn design
  - Lower pion momentum
  - Reduced pion lifetime
  - Compact pion transport

- Early study on muon storage rings by Neuffer considered 8, 4.5 and 1.5 GeV muons (based on 80, 30 and 8 GeV protons)
Conclusion

- NuStorm low flux error gives unique access to $\nu$ cross sections which are a large source of systematic in long baseline experiments
- Contributes to searches for sterile $\nu$
- Proof or principle for Neutrino Factory, step to Muon Collider
- Several lattice options being optimised and compared
- Feasibility study for CERN
- ESS source would be lower momentum than previously investigated
- Detailed studies needed