nuSTORM Facility Update

P. B. Jurj[1,2]

[1]Particle Physics Department
STFC (RAL)

[2]Blackett Laboratory
Imperial College London

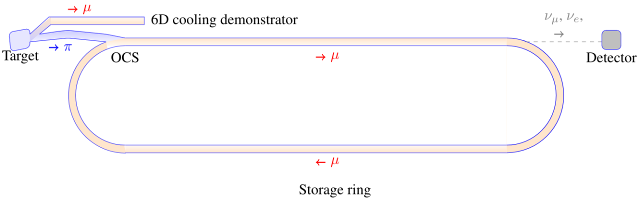
nuSTORM Workshop, 23 Nov 2023

Outline

- Introduction
- Update on target and horn simulations
    - Magnetic horn focusing
    - Baseline design
    - Horn current scaling & optimisation
    - Low-energy challenges & prospects
- Muon transmission in the production straight
- Conclusion and future work

Introduction

- Facility designed to produce and store $\mu^{\pm}$ beams with 1 - 6 GeV/c central momentum and $\sim \pm$ 16% momentum spread
- Proton-driven pion production, horn-based capture
- Magnetic channel ($\pm$ 10% momentum acceptance) transports and injects pion beam into the decay ring
- Pion production system may be shared with a 6D cooling demonstrator facility



Magnetic Horn Focusing

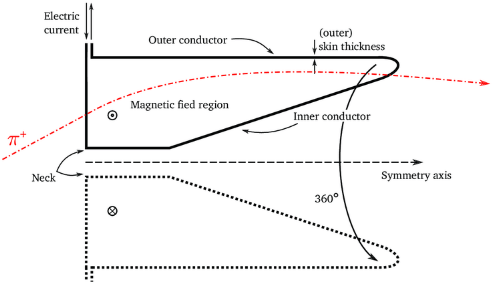
Toroidal magnetic field generated between the inner and outer conductors

$$B_\phi = \frac{\mu_0 I}{2\pi r};\ B_z = B_r = 0$$

Induces a radial kick to charged particles passing through the field region

$$\Delta\theta \approx \frac{B_\phi z}{p} = \frac{\mu_0 I}{2\pi r}\frac{z}{p}$$

Horn geometries generally seek to ensure a larger radial kick for particles entering the field region at larger radii.

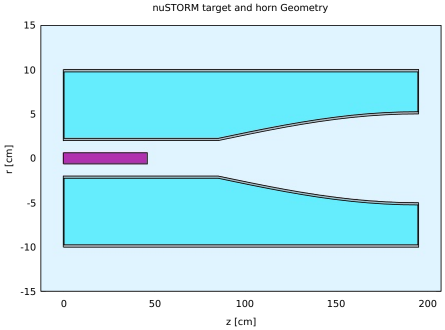


Baseline Target & Horn Design

Derived from the FNAL optimization study [1]

Optimised to deliver 5 GeV/c pions from a 120 GeV proton beam impinging on a 46 cm-long cylindrical Inconel target

- Target: Inconel, L = 46 cm, r = 6.3 mm
- Horn current: tunable; 219 kA optimal for 5 GeV/c pions



FLUKA simulation

- Used FLUKA to simulate the proton-target interaction and tracking of the secondary particles in the magnetic field of the horn
- Horn and target geometry derived from code provided by John Back (nuSTORM GitHub repository)
- Proton beam: E $= 100$ GeV (SPS), $\sigma_{x,y} = 2.67\ \mathrm{mm}$
- Particle position and momentum recorded at:
  - the downstream end of the horn, within the 10 cm outer conductor radius
  - the target surface
- Overarching aim of the study - characterise horn performance and optimise over the $\sim$ 1-8 GeV/c pion momentum range

Pion capture - horn current scaling

- For each pion momentum studied current scaled as $I(p_\pi) = \frac{219}{5} p_\pi$
- Scaling roughly preserves the phase space structure of the captured pions
- Studied one current polarity only (to capture π^+)
- Simulated 10^6 protons-on-target for each current setting

Table: Horn currents

p_π [GeV/c]	1	1.32	2	2.64	4	**5**	6	7.2
Current [kA]	43.8	57.8	87.6	115.6	175.2	**219**	262.8	315.4

Current scaling - phase space

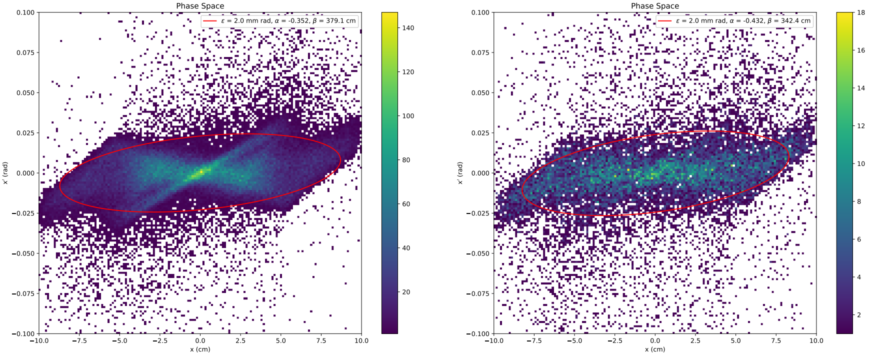


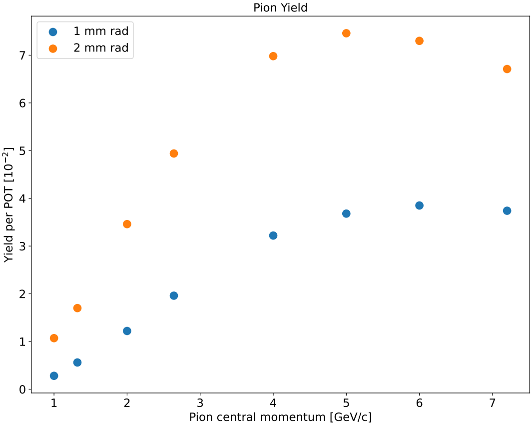
Figure: $x - x'$ phase space for (left) 5 GeV/c and (right) 1 GeV/c pions captured within the $\pm$ 10% momentum acceptance.

Current scaling - yields

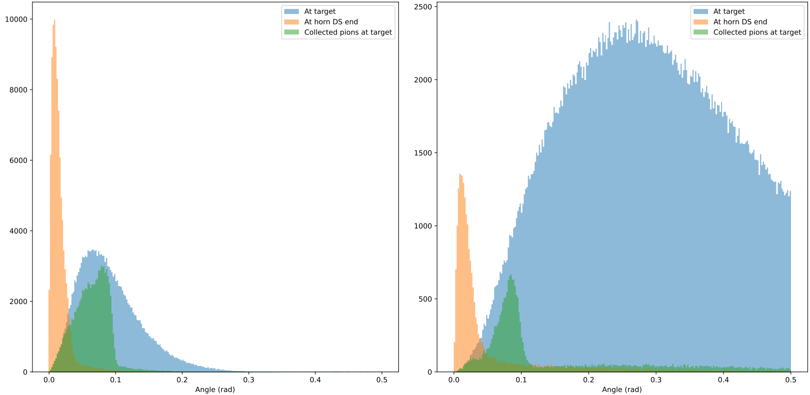
Selected pions within:

- $\pm$ 10% momentum acceptance
- 2 mm rad transverse acceptance (1 mm rad also considered)

Lower yields observed at lower pion momenta ($\leq$ 2.64 GeV/c)



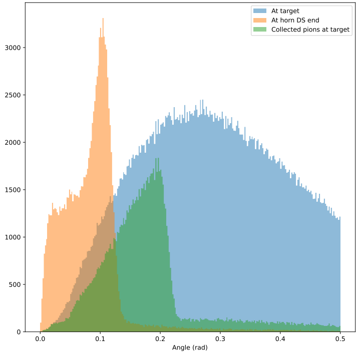
Low-momentum challenge

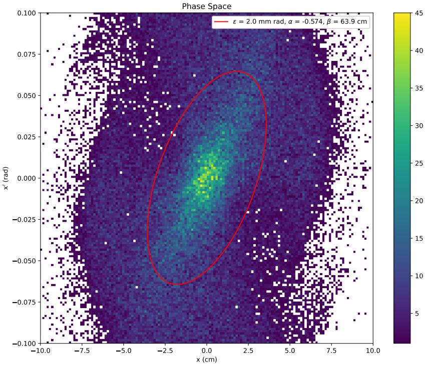


At lower momenta, the pion angle ($\theta = \arctan(p_T/p_z)$) distribution shifts to larger values $\rightarrow$ outside the horn effective capture acceptance

Low-momentum - current tuning

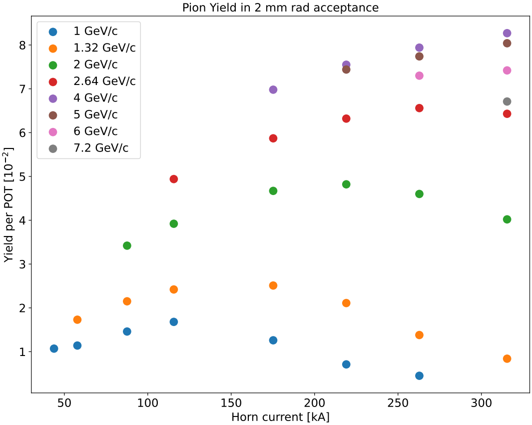
- First obvious solution - increase the horn current ($\nearrow$ horn acceptance)
- E.g. capture 1 GeV/c pions using 219 kA (up from 43.8 kA)
- Phase space structure changes
  - Smaller fraction of captured pions within the transverse acceptance
  - Study required to assess if beam can be matched into the pion beamline





Horn current optimisation

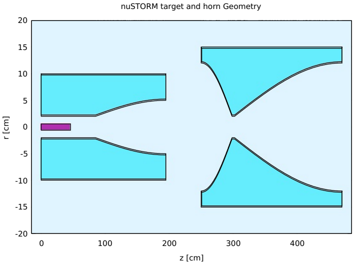
For (almost) every pion momentum setting, estimated the yield using horn currents higher than its corresponding scaled current value



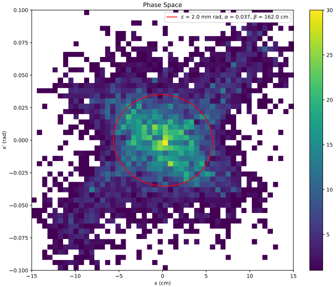
Optimal currents larger than the scaled values; further checks needed to asses if matching into the pion beamline is achievable

Low-momentum - second horn

Further pion yield improvement may be achieved by using an additional horn, placed downstream of the first one



- First horn used to maximise collected pions
- Second horn used to reduce the angular divergence of the under- and overfocused pions
- Initial results for 1 GeV/c pions:
  - Yield $\nearrow$ by $\sim$ 70% (2 mm rad)
  - Yield $\nearrow$ by $\sim$ 105% (1 mm rad)
- Further multi-parameter optimisation required



Production straight - muon transmission

BDSIM study by Tiago Alves

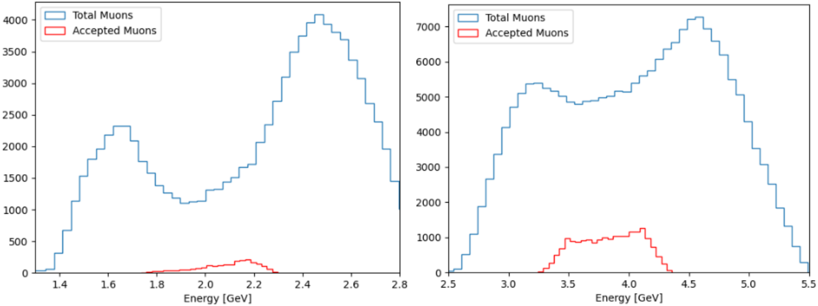
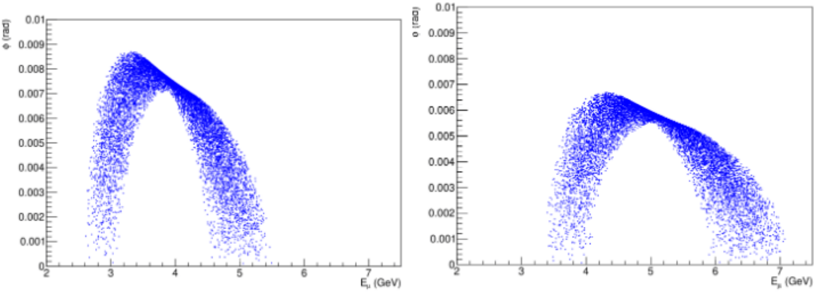


Figure: Muon distribution at the end of the production straight from a (left) 2.64 GeV/c and (right) 5 GeV/c pion beam (± 10%).

The mirror OCS samples muons from the middle of the range, where the transmission in the production straight decreases at lower energies

Production straight - pion decay

Study by Sittha Jeamburaset



(a) $E_\pi = 5$ GeV (b) $E_\pi = 6.5$ GeV

Muons in the middle of the energy range have a large divergence, which leads to losses in the beam pipe. The effect is expected to accentuate with decreasing energy.

Conclusion and Next Steps

- Horn capture performance can be improved by tuning the horn current
  - Pion yields of $\sim 6.5 - 8.5 \times 10^{-2}$/POT achievable for $p_\pi \geq 2.64$ GeV/c with current horn
  - Study required to match the captured pions into the beamline
- Capture challenging for $p_\pi < 2$ GeV/c, a factor of ~ 3 drop in yield observed
  - Further improvement at low p_π likely requires a second horn
  - Encouraging initial results using two horns, improvement required. Second horn optimisation ongoing.
- Further studies required to understand the lower muon transmission in the production straight observed at low momenta
  - Track the FLUKA-generated beams to end of production straight using BDSIM
  - Identify potential solutions (e.g. OCS, production straight magnets)
  - Contribute to the flux normalisation update

References

A. Liu, A. Bross, and D. Neuffer.
Optimization of the magnetic horn for the nustorm non-conventional neutrino beam using the genetic algorithm.
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 794:200–205, 2015.

Thank you!