Cooling Demonstrator Target Study

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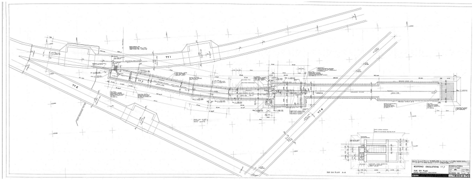
Outline

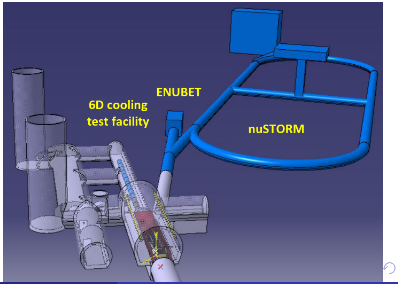
- Siting and proton beam options
- Baseline target and capture
- Pion yield energy dependence
- First pass target optimisation
- Capture challenges & optimisation
- Muon yield estimates
- Conclusion and next steps

Demonstrator facility siting options at CERN

Two siting options currently considered. Overaching aim of the study - explore pion production options

- Intersection Storage Rings (ISR) complex
    - In the TT7 extraction line
    - Proton beam from the PS
    - At surface level, radiation concerns require a lower proton beam energy, 14 GeV (10 kW beam power)
- TT10
    - Pion production system shared with the nuSTORM facility
    - Proton beam from the PS (26 GeV) or SPS (100 GeV)
    - Underground, beam power up to 80 kW

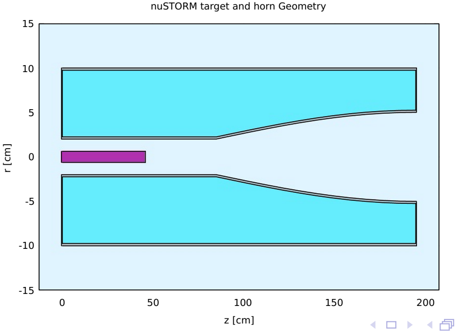




Baseline Target & Capture System

Derived from the FNAL nuSTORM horn optimization study [1]

- Target: Inconel, cylindrical, $L = 46\ \mathrm{cm}$ (3 interaction lengths), $r = 0.63\ \mathrm{cm}$
- Capture: Magnetic horn, optimised to deliver 5 GeV pions (!) from a 120 GeV proton beam impinging on the target
- Currently under study @nuSTORM



Magnetic Horn Focusing

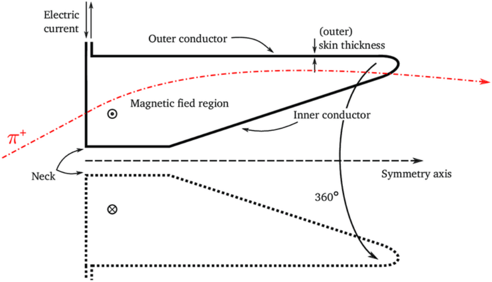
Toroidal magnetic field generated between the inner and outer conductors

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

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

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

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



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 geometries derived from code provided by John Back (nuSTORM GitHub repository)
- Particle position and momentum recorded at:
  - the downstream end of the horn, within the outer conductor radius
  - the target surface

π^+ yield comparison for different proton energies

- Simulated 10^6 protons-on-target for three proton beam energies (14, 26 and 100 GeV, all with $\sigma_{x,y} = 2.67$ mm)
- Horn current: $\mathrm{I} = 220$ kA
- Estimated the yield of π^+ with momenta in the 270 - 330 MeV/c range and within a transverse acceptance cut of 2 mm rad

π^+ yield comparison for different proton energies

Table: Pion yield in the 270 - 330 MeV/c range

E_0 [GeV]	14	26	100
At target [/POT]	0.10	0.15	0.35
At horn exit [10^{-2}/POT]	1.06	1.63	4.01
Within 2 mm rad [10^{-4}/POT]	3.24	5.16	13.75
Energy normalised [10^{-5}/POT/GeV]	2.31	1.99	1.38

- Number of pions produced at target scale with the proton beam energy.
- Pion yield per proton energy largest at 14 GeV.
- N.B. Capture efficiency to be improved by optimising/redesigning the horn/capture system

π^+ at target: Angle Distribution

π^+ in the 270-330 MeV/c momentum range

Angle: $\theta = arctan(p_T/p_z)$

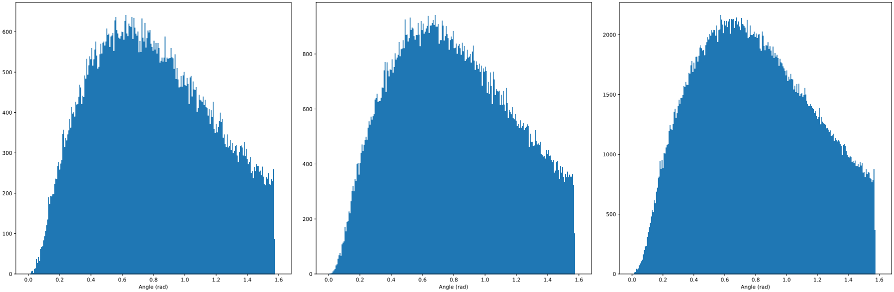


Figure: (left) 14 GeV, (middle) 26 GeV, (right) 100 GeV proton beam energy

π^+ at target: Longitudinal Position Distribution (z)

π^+ in the 270-330 MeV/c momentum range

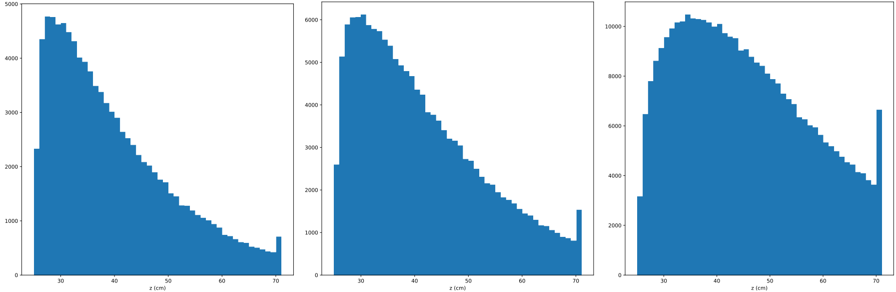


Figure: (left) 14 GeV, (middle) 26 GeV, (right) 100 GeV proton beam energy

At lower proton beam energies, more pions are emitted towards the upstream end of the target. Might inform capture system design.

π^+ yield comparison for different proton energies - graphite

Choice of material motivated by the extensive knowledge and use of graphite targets.

- Target: Graphite, cylindrical, $L = 80\ \mathrm{cm}$ (1.78 interaction lengths), $r = 0.63\ \mathrm{cm}$
- Capture: Horn, I = 220 kA

Table: Pion yield in the 270 - 330 MeV/c range

E_0 [GeV]	14	26	100
At target [/POT]	0.07	0.09	0.16
At horn exit [10^{-2}/POT]	0.79	1.05	2.07
Within 2 mm rad [10^{-4}/POT]	2.80	4.27	7.53
Energy normalised [10^{-5}/POT/GeV]	2.00	1.64	0.75

Pion momentum range

Can we improve the muon yield by capturing a wider pion momentum window?

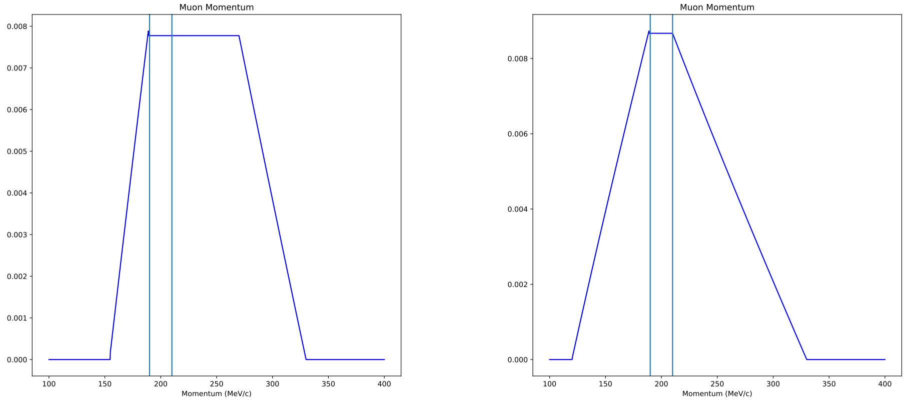


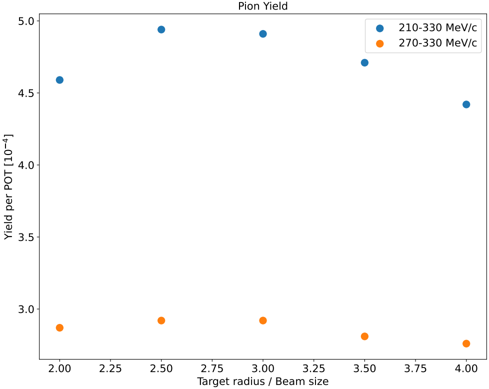
Figure: Muon distribution from a (left) 300 ± 30 MeV/c and (right) 270 ± 60 MeV/c pion beam.

Pion momentum range

- The wider momentum range (2x) provides $\sim$ 70% more captured pions in the transverse phase space of interest (2 mm rad)
- Further study required
    - Consider transfer line & cooling channel acceptance. The 190-210 MeV/c muon sample will contain muons that decay backwards and sideways in the pion rest frame. Muons that decay orthogonally to the pion momentum will have a divergence of $\sim$ 150 mrad ($p_T \approx 30$ MeV/c)
    - PID implications?

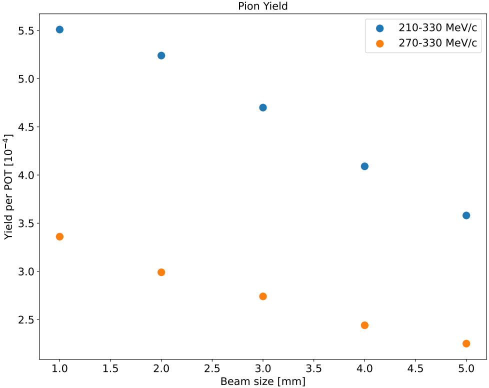
Graphite target: radius/beam size optimisation

- Proton beam: E = 14 GeV, $\sigma_{x,y} = 2.67$ mm
- Target: Graphite, cylindrical
- Target radius varied between 2 and 4 times the beam size
- Capture: Horn, I = 220 kA
- Simulated 5.0×10^6 POT for each configuration



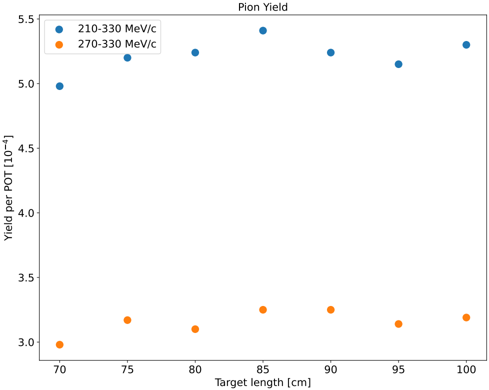
Graphite target: proton beam size optimisation

- Proton beam: E = 14 GeV
- Target: Graphite, cylindrical, $r = 3\sigma_{x,y}$
- Proton beam size varied between 1 and 5 mm
- Capture: Horn, I = 220 kA
- Simulated 2.0×10^6 POT for each configuration

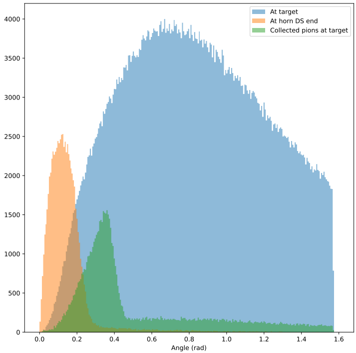


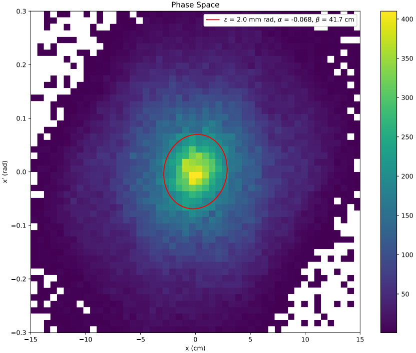
Graphite target: Length optimisation

- Proton beam: E = 14 GeV, $\sigma_{x,y} = 2\ \mathrm{mm}$
- Target: Graphite, cylindrical, $r = 3\sigma_{x,y}$
- Capture: Horn, I = 220 kA
- Simulated 5.0×10^6 POT for each configuration



Capture - challenges

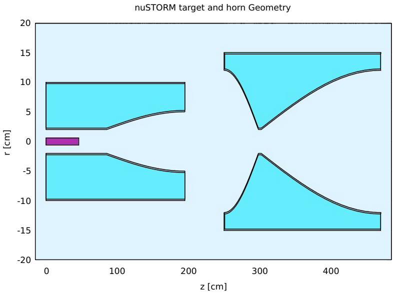


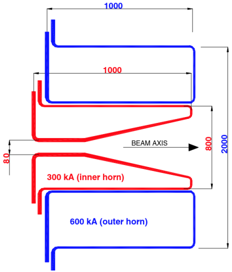


- Large pion angles, with a majority of pions produced outside the effective angular acceptance of existing horn
- Small fraction of captured pions useful for producing muons within the transverse emittance required

Capture - optimisation

- Can we achieve the required muon bunch intensity using only one horn? → currently under study
- Two horns

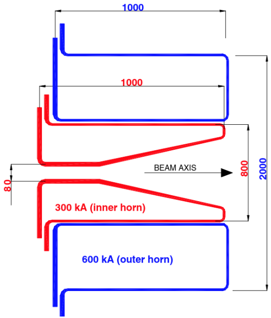




- Solenoid - synergy with Muon Collider, but more challenging (and expensive) technology

Neutrino Factory horn prototype

- Simone Gilardoni thesis
- Proton beam: E = 2.2 GeV, $\sigma_{x,y} = 2.2$ mm
- Target: Mercury, cylindrical, L = 30 cm, r = 0.75 cm
- Yield for pions in 200-800 MeV and 4.2 mm rad transverse acceptance:
  - 1.4×10^{-3} π^+/POT
  - 0.6×10^{-3} π^+/POT/GeV
- Yield for the TT7 option – 10 kW (14 GeV) proton beam, graphite target, one horn 220 kA – in the same momentum and transverse acceptances:
  - 1.9×10^{-2} π^+/POT
  - 1.4×10^{-3} π^+/POT/GeV



Muon yield estimation: Horn Capture

How many muons / POT in 190-210 MeV/c?

TT7 - Graphite

- Proton beam: E $= 14$ GeV, $\sigma_{x,y} = 2\ \mathrm{mm}$
- Target: Graphite, L $= 80$ cm, $r = 3\sigma_{x,y}$
- Horn: I $= 220$ kA

For a pion momentum bite of 210-330 MeV/c:

- 2 mm rad $\rightarrow 5.2 \times 10^{-4}\ \pi^{+}$/POT $\rightarrow 0.91 \times 10^{-4}\ \mu^{+}$/POT

N.B.

- Bunch time structure not considered yet
- Pion capture efficiency can be improved

Muon yield estimation: Horn Capture

TT10 (nuSTORM) - Inconel

- Proton beam: E = 100 GeV, $\sigma_{x,y} = 2.67\ \mathrm{mm}$
- Target: Inconel, L = 46 cm, r = 0.63 cm
- Horn: I = 220 kA

For a pion momentum bite of 270-330 MeV/c:

- 2 mm rad $\rightarrow 13.8 \times 10^{-4}\ \pi^{+}/\mathrm{POT} \rightarrow 2.4 \times 10^{-4}\ \mu^{+}/\mathrm{POT}$

N.B.

- Bunch time structure not considered yet
- Pion capture efficiency can be improved

Conclusion and Next Steps

- 10 kW (14 GeV) proton beam option and graphite target feasible provided adequate capture
- Efficient capture is challenging due to the large pion angles
  - Dedicated capture system required
  - Priority is horn-based capture, with a solenoid comparison study also in mind (to asses performance and feasibility, e.g. cost, physical constraints - narrow tunnel, not much space available for capture and decay in TT7)
- Muon yield estimates are $\mathcal{O}(10^{-4}/POT)$. Further work required to account for:
  - Bunch time structure
  - Pion and muon losses during transport to the cooling channel

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!