Cooling Demonstrator Design Studies

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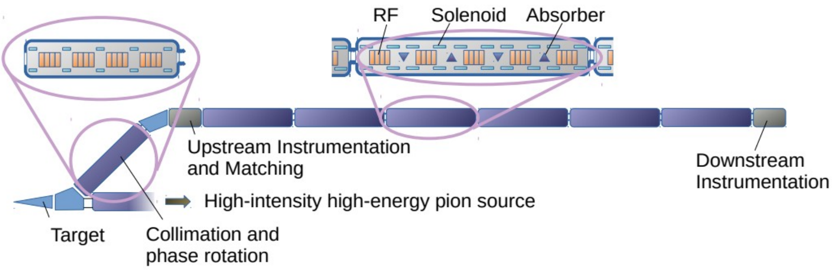
Muon Cooling Demonstrator

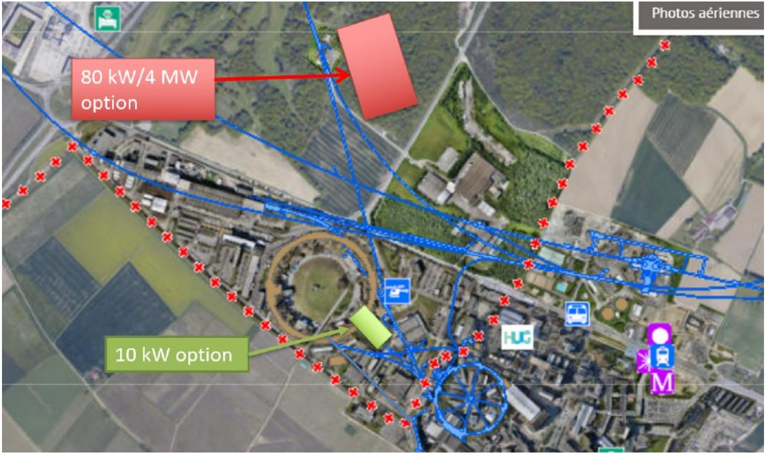
- Ionisation cooling proof-of-principle demonstrated by MICE (2020)
    - Only one pass through an absorber
    - No acceleration
    - Transverse (4D) cooling only
- Study of 6D cooling a natural follow-up
    - Demonstrate 6D cooling
    - Stage multiple cooling cells
    - Accelerate with RF cavities
    - Achieve suitable cooling performance

Muon Cooling Demonstrator



- Design in progress
  - Preliminary cooling cell - done (C. Rogers)
  - Preliminary phase rotation & collimation - done (C. Rogers)
  - Muon (pion) production and transport - work in progress
    - Design informed/impacted by the siting options

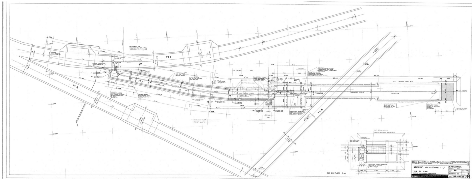
Demonstrator facility siting options at CERN

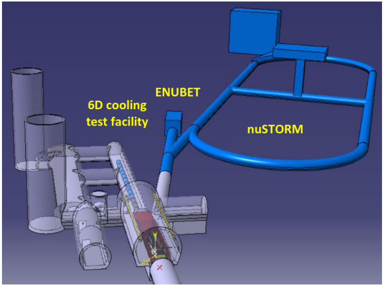


Demonstrator facility siting options at CERN

Two siting options at CERN are currently considered

- Intersection Storage Rings (ISR) complex
  - In the TT7 extraction line
  - Proton beam from the PS
  - Near surface level, lower proton beam power required (10kW), 14 GeV
- TT10
  - Pion production system could be shared with the nuSTORM facility
  - Proton beam from the PS (26 GeV) or SPS (100 GeV)
  - Underground, beam power up to 80 kW (first phase)



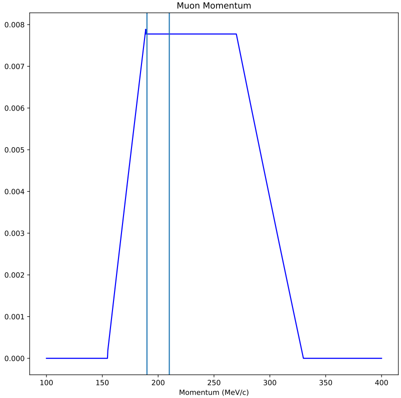


Target & Capture System

- Protons impinge on a target → pions → muons
- Muon yield can be improved by:
  - Choosing a suitable target geometry and material
  - Improving the pion capture efficiency
- Pion capture usually achieved using:
  - Magnetic horns
  - Solenoid channel

Pion momentum range

- Aim to produce muons with 190-210 MeV/c momentum
- Which pions are we interested in?



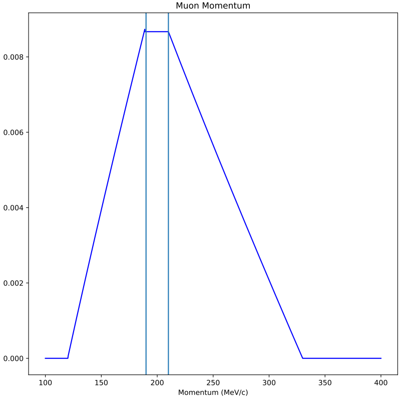
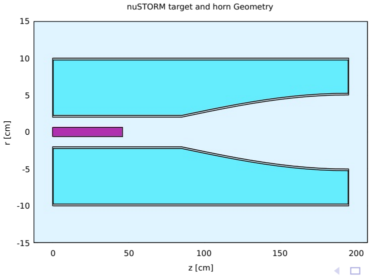


Figure: Muon distribution from a (left) 270-330 MeV/c and (right) 210-330 MeV/c pion beam.

Target & Capture System - Magnetic Horn

Baseline target and horn design derived from the FNAL nuSTORM horn optimization study [1]

- Target: Inconel, cylindrical rod, $L = 46\ \mathrm{cm}$ (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



π^+ yield: different proton beam energies

- Simulated 10^6 protons-on-target for the three proton beam energies considered at CERN:
  - 14, 26 and 100 GeV (all with $\sigma_{x,y} = 2.67$ mm)
- Horn current: 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: different proton beam 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

π^+ at target: Angle Distribution

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

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

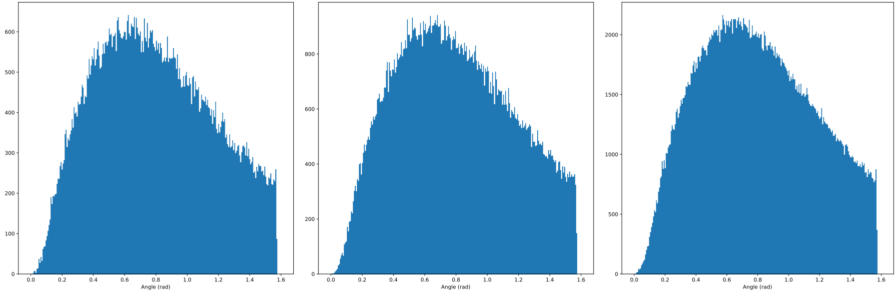


Figure: (left) 14 GeV, (middle) 26 GeV, (right) 100 GeV proton beam energy

π^+ yield: different proton energies - graphite

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

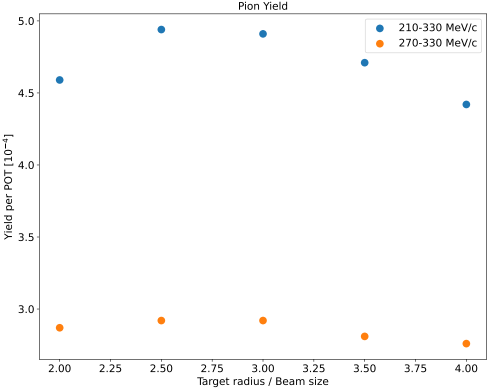
- Target: Graphite, cylindrical, $L = 80$ cm (1.78 interaction lengths), $r = 0.63$ cm
- Capture: Horn, I = 220 kA

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

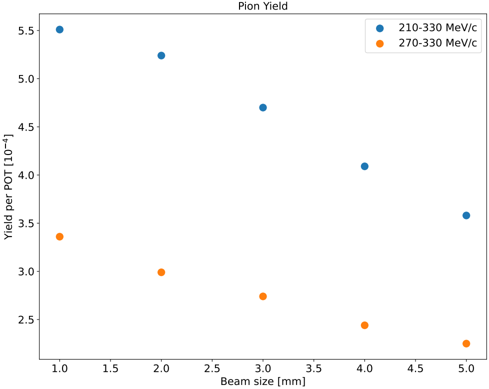
Graphite target: radius/beam size optimisation

- 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



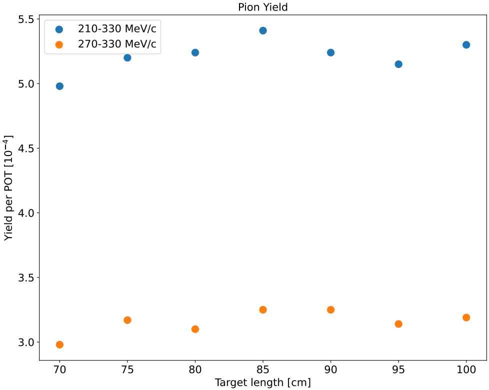
Graphite target: proton beam size optimisation

- 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

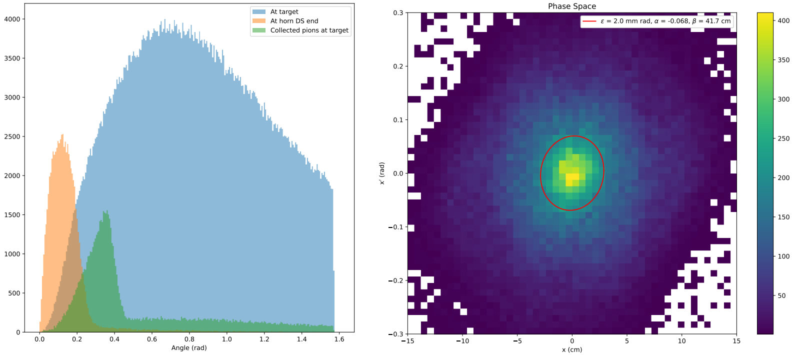


Graphite target: Length optimisation

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



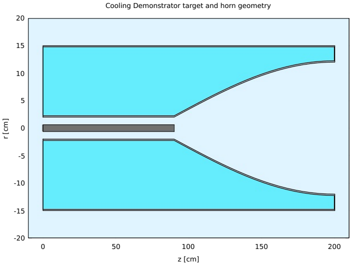
Capture: challenges

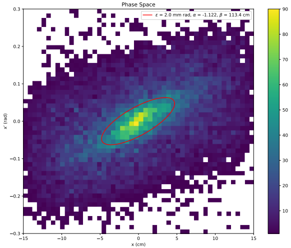


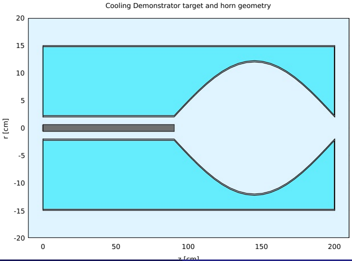
- Large pion angles, with a majority of pions produced outside the effective angular acceptance of existing horn
- Small fraction of captured pions useful for producing muons within the transverse emittance required

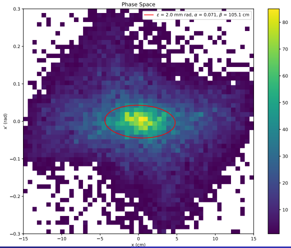
Capture: optimisation

- Horn geometry can be further optimised → currently under study





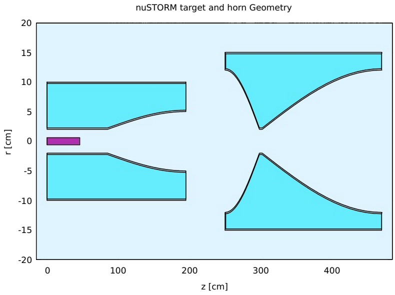


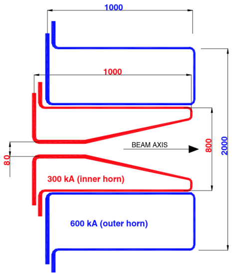


Capture: optimisation

Can pursue higher yields using:

- Multiple horns

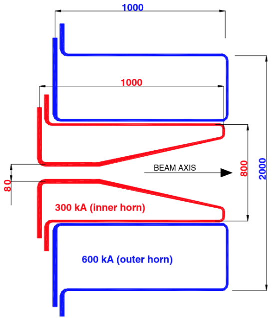




- Solenoid capture - more challenging for the low power option (and expensive regardless)
  - To be explored

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:
  - $1.4 \times 10^{-3}\ \pi^+/\mathrm{POT}$
  - $0.6 \times 10^{-3}\ \pi^+/\mathrm{POT}/\mathrm{GeV}$
- Yield for the TT7 option – 10 kW (14 GeV) proton beam, graphite target, one horn 220 kA – in the same momentum and transverse acceptances:
  - $1.9 \times 10^{-2}\ \pi^+/\mathrm{POT}$
  - $1.4 \times 10^{-3}\ \pi^+/\mathrm{POT}/\mathrm{GeV}$



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:

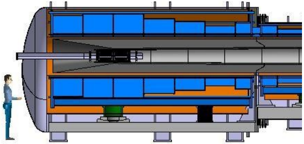
- 2 mm rad $\rightarrow 7.9 \times 10^{-4}\ \pi^{+}$/POT $\rightarrow 1.53 \times 10^{-4}\ \mu^{+}$/POT

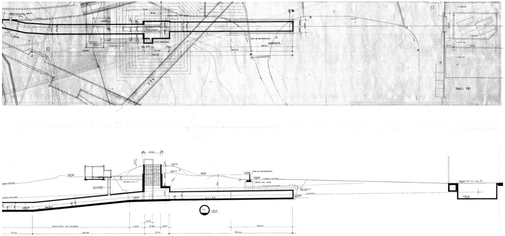
N.B.

- Bunch time structure not considered yet
- Expect to produce 5 - 10 100 ps bunches from a ~ 7 ns pulse

Next Steps: solenoid capture

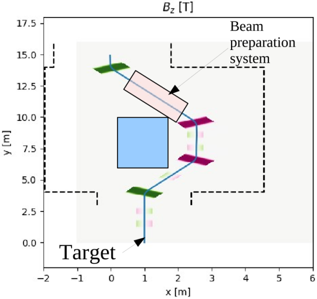
- Comparative study with the magnetic horn
- Some space concerns:
  - Tunnel only about 2.8 m wide
  - Solenoid + decay channel may require 10 - 20 m in length
  - Current assumption is that the beam dump (and chicane) will be located in the chamber in the middle region of the tunnel → target in region where the tunnel has an incline?

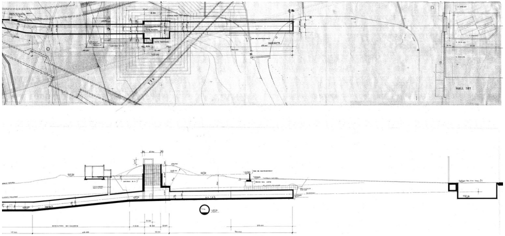




Next Steps: beam transport

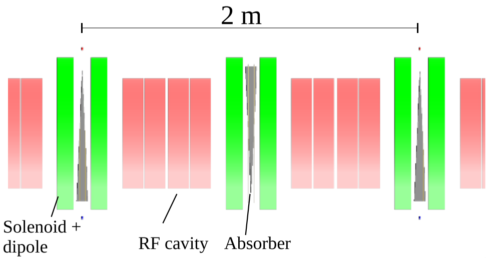
- Transport: target → beam preparation system → cooling stage
  - Finalize design, integrate in one simulation





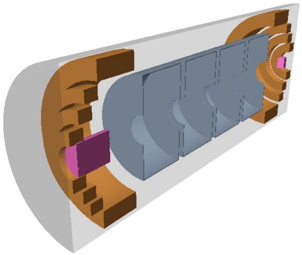
- Ideally pions would decay into muons before the chicane → can we place the target further upstream?

Next Steps: cooling cell



Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH

- Implement preliminary cooling cell lattice design (C. Rogers) in BDSIM
- Study performance and iterate design
- Integrate in a start-to-end simulation



Summary

- Target & capture preliminary design done
  - 14 GeV proton beam option feasible for TT7 option provided adequate capture
  - Efficient capture is challenging due to the large pion angles
  - Priority is horn-based capture, with a solenoid comparison study to follow
- 190 - 210 MeV/c muon yield $\sim \mathcal{O}(10^{-4}/POT)$ for a few ns pulse. Further work required to account for:
  - Bunch time structure
  - Pion and muon losses during transport to the cooling channel
- Plans to develop a cooling channel model in BDSIM and integrate it in a start-to-end demonstrator simulation

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!

Back-up

Magnetic Horn Focusing

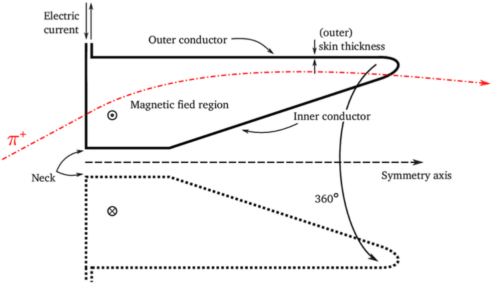
Toroidal magnetic field generated between the inner and outer conductors

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

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^+ at target: Longitudinal Position Distribution (z)

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

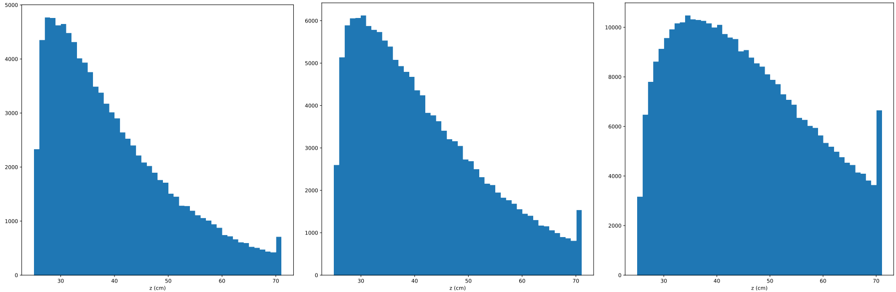


Figure: (left) 14 GeV, (middle) 26 GeV, (right) 100 GeV proton beam energy

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

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?

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

N.B.

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