Horn Optimization for nuSTORM
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nuSTORM Overview

WHO WE ARE, WHAT WE DO
Overview - Motivation

- 3.8 GeV/c muon decay ring (±10%) + near detector + far detector to study eV-scale neutrino oscillations and neutrino cross sections.
  - $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$, $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$
  - Well understood neutrino flux + flavor
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$ clean neutrino flux also utilizable
  - Provides a technology test bed for muon facilities;
  - Affordable
    - Old technology; Simple implementation
  - Now has FNAL Stage 1 approval.
Overview - Facility

- 100 KW target station
  - 120 GeV protons from MI;
  - Magnetic horn to collect $\pi^+$ or $\pi^-$;
  - Target material: graphite or Inconel;

- A total run exposure of $10^{21}$ protons over 4-5 years
  - $2.6 \times 10^{18}$ useful muon decays

- Pion beamline to transport and inject the pions, and to accept the muons from pion decay
  - No full-aperture fast kicker or separate pion decay channel needed. “Stochastic injection” used.
• Gold target produces the most pions— but not recommended (energy deposition in the horn)
  – Graphite is the baseline target material;
  – Inconel yields more pions, and energy deposition problem is more tolerable;
  – Simulation tool: MARS15

• Inconel used in our optimization study
Overview – Facility near site

Animation of the pions and muons in the facility

Photo courtesy of nuSTORM collaboration

Target+Horn

Decay Straight

Degrader

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Pion Beamline D&S

WHAT TO OPTIMIZE
The pion beamline consists of the transport beamline, the beam combination section (BCS), and the storage ring production straight shared by $\pi$ and $\mu$.

The pion beamline is designed with reference momentum $P_0=5$ GeV/c, the simulation was initially done using $\pi^+$ collected by a NuMI-like horn with slightly different lengths and target position, no full optimization.
Number of $\mu^+$ in 2000 $\mu$m needs to be maximized!

G4Beamline used as the tracking tool; Geant4 implemented
Muons from Pions at the End of the Pion Beamline (Cont’d)

The Momentum Distribution for PDGid: -13

Green: Ring momentum acceptance
Red: Extract for muon cooling studies

Number we need to maximize!

0.012 / POT

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Optimization Goal(s)

- **Single Goal:** Maximize muons in the transverse and momentum acceptance of the ring --
  - Why *not* directly use this criterion:
    - Phase space of pions from each horn design is different, need to re-match the optics;
    - Need full Monte Carlo simulation for each design;
    - Too much computing power and time

- **Alternative Goals:**

  For horns collecting pions, for which the optics can be matched,
  - Maximize muons within 3.8+-10% GeV/c, at the end of the production straight ($N_{\mu,\text{end}}$)
  - Maximize pions within 2000 $\mu$m at the end of the horn ($N_{\pi}$)

  They must be optimized *simultaneously* – No formula for the analytical correlation of the two.
• π+ after the horn are linearly distributed in 4-6 GeV/c (\( f_{p_{\pi}}(p_{\pi}) = ap_{\pi} + b \))

3.8±10% GeV/c from the \( N_0 \) π+ within \( P_0 x(1\pm m) \) GeV/c can be estimated. (\( m=\Delta P/P_0 \) and \( P_0=5 \) GeV/c)

\[
N_{\mu,\text{end}}(0.18) \sim 8.82 \times 10^2 N_0 \left( 1.8 \times 10^3 a + 0.36 b \right)
\]

MC tracking in G4BL well matches the estimation. (Both for Inconel and Graphite)

Maximum value found at \( m=0.18 \).
Maximizing $N_{\pi}$

- Different $\pi^+$ beams from different horn collections have very different phase space distributions
  
  - Distorted bivariate Gaussian in the phase space – must be fitted in order to obtain Twiss (Optics) parameters for matching;
  
  - $N_{\pi}$ obtained from counting $\pi^+$ in the fitted 2000 $\mu$m acceptance ellipse

- Large phase space area (more than 2000 $\mu$m) causes fitting bias
Maximizing $N_{\pi}$ (Cont’d)

- Direct statistics gives biased fit – red
- Iterative Gauss-Newton method – green
  - Iteratively discards particles with largest emittance until rms emittance reaches a specific value
- Better match to the core of the beam
Maximizing $N_{\pi}$ (Cont’d)

- Is a set of Twiss parameters ($\alpha$ and $\beta$) usable?
- A range of feasible Twiss from MADX:
  - Quad. gradient limit
  - Beam size limit in the beamline
  - Able to find a match?
  - Next set of parameters

Example: In the range
Directly use $N_{\pi}$

Example: Out of the range
Scale $N_{\pi}$
Find the closest distance
Multiple Objective Genetic Algorithm (MOGA)

HOW TO OPTIMIZE
A python-mpi code to run the Genetic Algorithm (GA), to improve the individuals

- Different individuals are different combinations of parameters
- They give different objective values
  - (Different horns yield different \( N_\pi \) and \( N_\mu,\text{end} \))
- Objectives to be maximized / minimized
  - (Max. \( N_\pi \) and \( N_\mu,\text{end} \))
- Parameter constraints;
  - (Current in horn, neck radius, etc.)

A scan of 5 different values for each parameter is 2 MILLION runs!

- An individual horn is a combination of the above parameters, and horn the current (9 parameters);
- Select parents based on the objectives, produce offspring;
- Parameters are treated like “genes” – genes of children are the crossover and mutation of the parents’ genes;
- Eventually, the whole population will be improved, i.e. gives larger \( N_\pi \) and \( N_\mu,\text{end} \)
MOGA process

GA starts, a number of random individual horns produced as the first generation

Model the B-field in the horns, based on the parameters of each horn

Track π+ in the individuals, calculate $N_\pi$ and $N_{\mu,\text{end}}$ for each case

Select the best individuals, make the offspring. A child generation is generated

When the maximum generation number is reached, or the population stops improving, stop the algorithm

Population size: 200;
Generation limit: 100;
CPUs used in each generation: ~1200

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Optimization Results

IT WORKS
Collection of $\pi^+$ from a 38 cm Inconel (2.5 interaction lengths)

$N_{\mu,\text{end}}$ increased by 14%; $N_{\pi}$ increased by 18%;
Then, Pion beamline re-matched; $\pi^+$ re-tracked;
$\mu^+$ in both 2000 $\mu$m and 3.8±10% GeV/c increased by 8.3%

Shorter (2 m) + lower current (225 kA) + narrower outer conductor!

Why not as high?
Higher-order effects not considered: Beta-beat, phase space difference for off-momentum particles, etc.

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Collection of $\pi^+$ from a 46 cm Inconel (3 interaction lengths)

$N_{\mu,\text{end}}$ and $N_{\pi}$ increased by $\sim20\%$; (If just changing the target length: $\sim5\%$)

Then, Pion beamline re-matched; $\pi^+$ re-tracked;
$\mu^+$ in both 2000 $\mu$m and $3.8\pm10\%$ GeV/c increased by $\sim16\%$

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Conclusions

IMPORTANCE OF THE OPTIMIZATION
Conclusions and Future

• nuSTORM benefits from the optimization:
  – Expect 8.3% more neutrino flux, with a 38 cm Inconel target;
  – Expect 16% more flux, with a 46 cm Inconel target.

• Other horn-based projects – e.g. LBNE:
  – Algorithm is expected to work if the objectives are known;
  – Algorithm may be less complicated and faster, if no beamline tracking is needed;
  – MOGA allows adding other constraints to obtain a more realistic design + optimization

• Future:
  – Modify the objectives based on further ring design studies;
  – Collaboration work with other projects if needed and interested.

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Thanks

YOUR COMMENTS ARE WELCOME
For the past decade, a lot of effort has been spent on neutrino oscillation physics.

8 channels accessible by νSTORM

\[
\begin{align*}
\mu^+ &\rightarrow e^+ \nu_e \bar{\nu}_\mu \\
\bar{\nu}_\mu &\rightarrow \bar{\nu}_\mu \\
\bar{\nu}_\mu &\rightarrow \bar{\nu}_e \\
\nu_e &\rightarrow \nu_e \\
\nu_e &\rightarrow \nu_\mu \\
\bar{\nu}_e &\rightarrow \bar{\nu}_e \\
\bar{\nu}_e &\rightarrow \bar{\nu}_\mu \\
\end{align*}
\]

- disappearance
- appearance ("platinum" channel?)
- appearance (atmospheric oscillation)
- disappearance
- appearance: "golden" channel
- appearance: "silver" channel
**Introduction-Facility**

- **100 KW target station**
  - 120 GeV protons from MI;
  - Magnetic horn to collect $\pi^+$ or $\pi^-$;
  - Target material: graphite or Inconel;
- **A total run exposure of $10^{21}$ protons over a period of 4-5 years**
  - $8 \times 10^{12}$ protons per pulse; cycle time 1.33 sec.
  - A total of $2.6 \times 10^{18}$ useful muon decays, updated from $1.9 \times 10^{18}$ useful muon decays in the proposal
- **Pion beamline to transport and inject the pions, and to accept the muons from pion decay**
  - No full-aperture fast kicker or separate pion decay channel needed
- **Gold target gives the most pion productivity but is not recommended** (intensive energy deposition in a horn)
  - Graphite is the baseline target material in the proposal;
  - Inconel yields more pions, but engineering challenges may rise, though better than gold;
- **Inconel used in the optimization study**
Maximizing $N_{\mu\text{,end}}$

- $f_{p_\pi}(p_\pi) = ap_\pi + b$

- e.g. $a = -1.46935529e-07$, $b = 1.23467765e-03$

- $a$ and $b$ changes only slightly w.r.t different horns (Usually a few percent)
Maximizing $N_{\mu,\text{end}}$

• The above implies that the maximum number of $\mu^+$ within 3.8±10% GeV/c generated is

$$N_{\mu,\text{end}}(m = 0.18) = 8.82 \times 10^2 N_0 \left[ 1.8 \times 10^3 a + 0.36b \right]$$

  – Assuming the phase space acceptance of the pion beamline $P_\Phi$ for different initial conditions is the same;
  – This has taken the momentum acceptance and decay kinematics into account.

• Horn variation gives slightly different coefficients $a$, $b$, and very different $N_0$
MOGA process

GA starts, a number of random individual horns produced as the first generation

Model the B-field in the horns, based on the parameters of each horn

Select the best individuals, make the offspring. A child generation is generated

Track π+ in the individuals, calculate $N_{\pi}$ and $N_{\mu,\text{end}}$ for each case

When the maximum generation number is reached, or the population stops improving, stop the algorithm

~40,000 core-hours used in each search