Magnetic Focusing Horns for Neutrino Experiments

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Outline

1. Introduction of neutrino beam experiments at Fermilab \( (p3-6) \)
   - NuMI, NOvA and LBNE
   - Neutrino beam production and focusing

2. Focusing horns \( (p7-15) \)
   - Engineering challenges and on-going issues
   - NuMI Horn subsystems

3. Finite element thermal and structural analysis
   - LBNE Horn1 inner conductor \( (p16-27) \)
   - NO\(\nu\)A Horn1 power supply stripline \( (p28-32) \)
NuMI – Neutrino at Main Injector

- Provides neutrinos for MINOS (Main Injector Neutrino Oscillation Search)
- Using protons (400 kW) from Main Injector
- is currently in operation since March 2005

NuMI Facilities at Fermilab

(30 – 100 m underground)

- Provides neutrinos for MINOS (Main Injector Neutrino Oscillation Search)
- Using protons (400 kW) from Main Injector
- is currently in operation since March 2005

Located underground shielded from cosmic backgrounds
NO\(\nu\)A – NuMI Off-axis \(\nu_e\) Appearance Experiment

An upgrade of NuMI beam intensity from 400 kW to 700 kW
- Recycler becomes an 8 GeV proton storage ring (new kickers)
- Main Injector cycle time reduced (more RF)
- NuMI beamline: new Medium Energy target, relocate Focusing Horn #2

<table>
<thead>
<tr>
<th></th>
<th>NuMI</th>
<th>NO(\nu)A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Power to Target</td>
<td>400 kW</td>
<td>708 kW</td>
</tr>
<tr>
<td>Repetition time, s</td>
<td>1.89</td>
<td>1.33</td>
</tr>
<tr>
<td>(\nu) Energy spectrum</td>
<td>1-5 GeV</td>
<td>3–10 GeV</td>
</tr>
<tr>
<td>Number protons per pulse</td>
<td>4.0 x 10(^{13})</td>
<td>4.9 x 10(^{13})</td>
</tr>
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</table>

Detectors are located off (14 mrad) of the neutrino beam axis
- narrows the spread of neutrino energies hitting the detector – for \(\nu_e\) appearance measurement

October 2009 – received DOE construction approval
2013 – detectors expected to collect data

[Map of NO\(\nu\)A and Soudan locations with 810 km distance]

[Graph showing Medium Energy Tune with on-axis and off-axis tunings]
LBNE – Long-Baseline Neutrino Experiment

Jan., 2010 – DOE approved the Mission Need of the project (Critical Decision 0)
Sep., 2011 -- DOE review for conceptual design and a cost estimate
Oct., 2020 -- Beam commissioning, expected to operate for 20 years

Far detector at DUSEL, SD

Start with a 700 kW beam, and then upgraded to 2.3 MW available with Project X
120 GeV protons hit target to produce $\pi^+$

magnetic horn to focus $\pi^+$

$\pi^+$ decay to $\mu^+\nu$ in long evacuated pipe

left-over hadrons shower in hadron absorber

rock shield ranges out $\mu^+$

$\nu$ beam travels through earth to experiment

Neutrinos have no charge – use magnetic horns to steer $\pi^+$
How the Horn Works to Focus the Neutrino Beams

- Pulse current running from the outer conductor to inner conductor to produce toroidal magnetic field
- The charged pions are then focused by this magnetic field
- Two-horn focusing system, geometrical shape of conductors and distance are optimized to maximize the neutrino event rate in the far detector

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<th>LBNE</th>
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<tr>
<td>Proton beam power to target</td>
<td>400 kW</td>
<td>700 kW</td>
<td>708 kW</td>
</tr>
<tr>
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<td>1.89</td>
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<tr>
<td>Horn peak current, kA</td>
<td>200</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>Half-sine current pulse length, ms</td>
<td>2.3</td>
<td>2.3</td>
<td>1</td>
</tr>
</tbody>
</table>
Horn Engineering Challenges

Assure long-term reliability

Must withstand repetitive thermal and magnetic loadings over millions of pulses in a radiation and corrosive environment – fatigue issue

Heating – 1. Electrical resistive heating
   2. Beam heating due to secondary particle interactions in the material

Magnetic pressure – Lorentz force

Meanwhile, thickness of the inner conductor is minimized to reduce absorption and scattering of secondary particles in the conductor material

Require full analysis of the stresses to ensure a robust design

Assure alignment tolerance and mechanical stability

Inner conductor straightness tolerance ~ 0.5 mm -- high quality of field symmetry

Assure reparability and personnel safety

horn will eventually become very radioactive – remote handling in the event of a replacement/repair
Horns On-going Issues

**NuMI** – spare horn production, predicted lifetime of horns – 1~2 years due to high radiation damage and fatigue issue
  - 1 ½ production cycle

**NOvA** – Horn upgrade, to handle increased heating
  - FEA
  - Modifications to reduce heating and improve cooling

**LBNE** – Conceptual design
  - FEA
  - Maximize the neutrino flux while making a robust horn design
Horn Conductors

- Inner conductor - 3~4 mm thickness Al, parabolic shape
- Minimize material in secondary particle path -- reduce π absorption and scattering
- Conductor material easy to machine/weld, and corrosion resistance – Al 6061-T6
- Adequate water cooling, inner conductor erosion control– electroless nickel coating
- Corrosion barrier coating for outer conductor - Type III hardcoat anodize

Spider support centers inner conductor, flexes in beam direction

Number and location of spider supports were determined with vibration analysis
Horn Support Structure

Intensely radiation environment – components receive ~ 10 to 100 Giga-Rad/year (NuMI)
Residual rates of components 10 to 100 rem/hr (NuMI) – remote handling
Radiation in humid air creates nitric acid and Ozone – accelerated corrosion on materials
If fatigue doesn’t kill a horn, corrosion is the second biggest killer of horns
Power Supply Stripline

Electrical connection is provided by the stripline, flexible
- allows for remote motor controlled horn alignment
- allows horn/transmission lines thermal expansion/contraction

Connect to Horn power supply transmission line

Stripline block/remote control clamp
Shaft toggles clamp to provide pressure for good electrical connection

Flares out to connect to Horn inner/outer conductors, to supply 200 kA current (NuMI)
Remote Handling

Through support module

- aligns horn
- allows the mounting and dismounting of feed-through connections from the top of the module away from the most highly activated areas (cooling water, instrumentation cabling and the horn stripline)

Calibration of horn position to module

Motors to drive main shafts
For vertical adjustment

Motorized screw jacks to control horizontal adjustment
Horn Cooling System

Waterline Electric Isolator
Original design had ceramic-invar brazed joints
Leaked, responsible for 3 out of 4 horn failures

Water manifolds

Replaced with SS-Ceramic shrink-fit joints
Ensure horn long-term reliable operation
Inner Conductor CNC TIG Welding

6~7 segments, welded with in-house CNC TIG welding machine

Strict straightness requirement
- high quality of field symmetry
- we are able to achieve an overall Inner conductor straightness ~ 0.5 mm, with void in welds <0.25 mm

Welds at low stress location with thicker wall to compensate reduced strength in heat-affected-zone

Single pass, full penetration to minimize distortion

Clean handling & tight tolerance to control internal weld porosity
Finite Element Analysis were carried out to predict the temperatures, alignment stability, study thermal and magnetic stresses, and to assess the fatigue strength.

Present here:
- LBNE Horn1 inner conductor (p16-27)
- NOvA Horn1 stripline (p28-32)
LBNE Horn1 Thermal and Structural Analysis

**Steady state thermal analysis**
- FEA model and Boundary conditions
- heating loads
- Temperature distribution

**Transient thermal analysis**
- Heating loads during a single pulse
- Temperatures at steady state, mid-pulse and end-pulse

**Structural analysis**
- Magnetic forces
- Stresses at steady state, mid-pulse and end-pulse

**Fatigue analysis of Horn1**
- Stress fluctuation
- Prediction on fatigue strength
- Transient thermal stress

**Stress components study**
- Axial, hoop, radial stresses
- Thermal loading only at mid-pulse
- Magnetic loading only
FEA Model and Boundary Conditions

Heating load density varies along the length of Horn

Horn FEA model is divided into 10-cm-long segments
  – Beam heating is a function of radial and axial position
  – Resistive heating is inversely proportional to the square of radius and wall thickness

\[ P_j \propto \frac{1}{A^2} \]

Boundary condition of heat transfer coefficient (W/m²-C)
  -- determined through cooling tests
  -- varies, depending on water coverage
Calculation of Heating Loads

1. Electrical resistive heating:

\[
P_j = \frac{\sigma_T I^2 t}{2 A^2 T}
\]

Material resistivity:
\[
\sigma_T = \sigma_0 [1 + a(T - T_0)]
\]

Skin depth:
\[
\delta = \sqrt{\frac{2\sigma}{\omega \mu}} = 4.5 \text{mm}
\]

All charge should be distributed quite uniformly across 2-5mm wall thickness

2. Beam energy deposition in material, calculated with Monte Carlo code MARS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Horn peak current, I (kA)</td>
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<td>Half-sine current pulse length, t (ms)</td>
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<tr>
<td>Cycle time, T (s)</td>
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<tr>
<td>Beam Energy, GeV</td>
<td>120</td>
</tr>
<tr>
<td>Number protons per pulse, ppp</td>
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</table>

MARS outputs (Edep) are expressed in GeV/g per proton. They are converted into average power density in W/m^3 for load input in the FEA model.
Calculated Horn1 Temperature @ Steady State

Three time scales:  
1. Length of proton beam pulse -- 10 micro-seconds  
2. Length of current pulse – 1 ms  
3. Time of repetition rate – 1.33 s

Max. 40 °C @ Horn1 Neck

Heating loads on inner conductor

Heat Load Density (W/m3)

Distance from Front Face MCzero (cm)

- Resistive Heating
- Beam Heating
- Total Heating

Max. 40 °C @ Horn1 Neck
Transient Thermal Analysis

Transient thermal analysis for a single pulse after horn reaches equilibrium

Temperature @ Neck rises by 25 °C during each pulse, then gradually returns to equilibrium temperature (40 °C) before next pulse.
Temperatures at Steady state, Mid-pulse and End-pulse

Large temperature fluctuation would occur only in a 0.7 m long section

Surface temperature of the horn would be below the phase change temperature of water
Avoid creating radioactive vapor or accelerated oxidation of the conductor surface
Stress calculations for **steady state, mid-pulse and end-pulse**

-- Temperature solution from thermal analysis was loaded as **thermal loading**

-- For **mid-pulse**, immediately after beam spill, **magnetic pressure** was applied in addition to thermal loading

\[
P_{\text{max}} = \frac{\mu_0 I^2}{8\pi^2 R^2}.
\]

**Max. pressure 2.71 MPa on Neck pointing inward**

**Thermal gradients** → **compressive stress** on the IC

**Electromagnetic forces** → **compressive circumferential/radial stresses** and **tensile axial stress**
Thermal and magnetic loading may augment or compensate each other, resulting in a range of stress magnitudes at different locations and times.

**Stress < 26 Mpa** – a safety factor of 10 with regard to material yield strength (270 MPa at 100 C for $10^5$ hrs). However, there is a fatigue issue.
Fatigue Analysis

Cyclic thermal and magnetic loading over millions of beam/current pulses may lead to microscopic physical damage to the inner conductor material, even at stress well below the ultimate strength (310 MPa) – evaluate the fatigue strength

Used stress-based approach to analyze the fatigue strength

-- with the calculated maximum and minimum stresses, the alternating stress and mean stress are obtained

For constant-life line of $10^7$ cycles

$S_{\text{endurance}} = 12 \text{ KSI} = 82.7 \text{ MPa}$

$S_{\text{ultimate}} = 44 \text{ KSI} = 303.4 \text{ MPa}$

Using modified Goodman relation

$$\frac{\sigma_a}{S_{\text{e}}} + \frac{\sigma_m}{S_{\text{ut}}} = \frac{1}{n}$$

to calculate the fatigue safety factor
Fatigue Safety Factor of Horn1 Inner Conductor

### Steady state
- **US Cap**
  - Max. stress: 25.9 MPa
  - Min. stress: 4.8 MPa
  - Mean stress: 15.4 MPa
  - Alternating stress: 10.6 MPa
  - Safety factor: 5.6

- **Neck**
  - Max. stress: 27.2 MPa
  - Min. stress: 8.6 MPa
  - Mean stress: 17.9 MPa
  - Alternating stress: 9.3 MPa
  - Safety factor: 5.8

- **Weld**
  - Max. stress: 23.4 MPa
  - Min. stress: 7.6 MPa
  - Mean stress: 15.5 MPa
  - Alternating stress: 7.9 MPa
  - Safety factor: 6.8

### Mid-pulse
- **US Cap**
  - Max. stress: 25.9 MPa
  - Min. stress: 4.8 MPa
  - Mean stress: 15.4 MPa
  - Alternating stress: 10.6 MPa
  - Safety factor: 5.6

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  - Max. stress: 23.4 MPa
  - Min. stress: 7.6 MPa
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  - Alternating stress: 7.9 MPa
  - Safety factor: 6.8

### End-pulse
- **US Cap**
  - Max. stress: 25.9 MPa
  - Min. stress: 4.8 MPa
  - Mean stress: 15.4 MPa
  - Alternating stress: 10.6 MPa
  - Safety factor: 5.6

- **Neck**
  - Max. stress: 27.2 MPa
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  - Max. stress: 23.4 MPa
  - Min. stress: 7.6 MPa
  - Mean stress: 15.5 MPa
  - Alternating stress: 7.9 MPa
  - Safety factor: 6.8

**Consider welding correction factor, 0.5**

Except the welds, the fatigue safety factor over the inner conductor would be higher than 5.5
Taking into account a 0.5 welding correction factor, the fatigue safety factor at neck weld would be 3.4
In order to understand the stress conditions and to optimize the design, FEA were performed to study the stress components under different scenarios:

- Thermal loading only
- Magnetic loading only

<table>
<thead>
<tr>
<th>Normal beam operations</th>
<th>Magnetic Loading only</th>
<th>Thermal Loading only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before pulse</td>
<td>Mid-pulse</td>
<td>End-pulse</td>
</tr>
<tr>
<td>( \sigma_{\text{Axial}} )</td>
<td>-8.8 ~ -4.9</td>
<td>-10.1 ~ 2.9</td>
</tr>
<tr>
<td>( \sigma_{\text{Hoop}} )</td>
<td>-1.9 ~ 1.6</td>
<td>-27.4 ~ -17.4</td>
</tr>
<tr>
<td>( \sigma_{\text{Radial}} )</td>
<td>-0.18 ~ 0.12</td>
<td>-4.5 ~ 0.55</td>
</tr>
<tr>
<td>( \sigma_{e} )</td>
<td>5.8 ~ 8.1</td>
<td>13.9 ~ 23.5</td>
</tr>
</tbody>
</table>

“+” -- tensile stress
“-” -- compressive stress

Max. compressive axial stress 23.9 MPa would occur at end-pulse – thermal loading
Max. compressive hoop stress 27.4 MPa would occur at mid-pulse – magnetic loading
Tensile axial magnetic stress would compensate the compressive axial thermal stress, resulting in a lower overall axial stress

Similar analysis were performed for other scenarios: current pulsing without a beam, beam cold start-up, and with beam without current pulsing, in order not to overlook the worst scenario

FEA helped design optimization
NOvA Horn1 Stripline Thermal & Structural Analysis

NOvA is an upgrade of NuMI from 400 kW to 700 kW. Horn is analyzed and modified, to handle the increased heating. Stripline is cooled with air, but the flare portion is hidden from forced air.

<table>
<thead>
<tr>
<th>Concerns due to high temperature</th>
<th></th>
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<tbody>
<tr>
<td>Increase in electrical resistance</td>
<td></td>
</tr>
<tr>
<td>Loss of electrical contact</td>
<td></td>
</tr>
<tr>
<td>Thermal stress</td>
<td></td>
</tr>
<tr>
<td>Reduction in material strength</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Heating sources</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Joule heating</td>
<td>3.4 kW</td>
</tr>
<tr>
<td>Beam heating</td>
<td>1.4 kW</td>
</tr>
<tr>
<td>Thermal radiation heating</td>
<td>0.3 kW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cooling</th>
<th></th>
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<tbody>
<tr>
<td>Forced air</td>
<td></td>
</tr>
<tr>
<td>Stagnant air</td>
<td></td>
</tr>
<tr>
<td>Conduction to water cooled Horn</td>
<td></td>
</tr>
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</table>

<table>
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<tr>
<th>Modifications</th>
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<tr>
<td>Move inner strips outwards</td>
<td></td>
</tr>
<tr>
<td>Increase water coverage on Horn DS</td>
<td></td>
</tr>
</tbody>
</table>

Air in narrow channel

Forced air
NOvA Horn1 Stripline Modification

With improved cooling flared out stripline geometry, the max temp is reduced < 100C as desired.
In order to give a more accurate estimation of stripline temperature, experiments were performed on a spare horn on test stand to empirically benchmark heat transfer coefficients used in ANSYS.

Fiber-optic thermometer sensors were placed on different locations to measure temperature under different air flow conditions.

On test stand, the resistive heating is the only heating source.
Sensitive Check of Heat Transfer Coefficients

In temperature calculations
Several sets of heat transfer coefficients of stagnant air
-- $h_{\text{out}}$ for air around outside surfaces, 1 - 10 W/m$^2$-C
-- $h_{\text{in}}$ for air in gap between strips, 0.5 - 1 W/m$^2$-C

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$h_{\text{out}}$</th>
<th>$h_{\text{in}}$</th>
</tr>
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<tbody>
<tr>
<td>b</td>
<td>2.5</td>
<td>0.5</td>
</tr>
<tr>
<td>c</td>
<td>2.5</td>
<td>1</td>
</tr>
<tr>
<td>d</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>e</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>f</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>g</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>
Comparison of Calculated Temperature with Measurement

<table>
<thead>
<tr>
<th>Scenario ((h_{out}, h_{in}))</th>
<th>No air flow</th>
<th>Measured Temperature Rise (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (\text{Measured})</td>
<td>6.3</td>
<td>9.6</td>
</tr>
<tr>
<td>2 (b (2.5, 0.5))</td>
<td>10.4</td>
<td>16.1</td>
</tr>
<tr>
<td>3 (c (2.5, 1))</td>
<td>7.2</td>
<td>9.5</td>
</tr>
<tr>
<td>4 (d (1, 0.5))</td>
<td>17.1</td>
<td>19.5</td>
</tr>
<tr>
<td>5 (e (5, 0.5))</td>
<td>6.1</td>
<td>13.3</td>
</tr>
<tr>
<td>6 (f (5, 1))</td>
<td>4.6</td>
<td>8.4</td>
</tr>
<tr>
<td>7 (g (10, 1))</td>
<td>2.1</td>
<td>7.1</td>
</tr>
</tbody>
</table>

Conclusion: Reasonable heat transfer coefficient of stagnant air
\[h_{out} = 5 \text{ W/m}^2\text{-C}\]
\[h_{in} = 2 \text{ W/m}^2\text{-C}\]