1.2 MW LBNE Horns

9th International Workshop on Neutrino Beams and Instrumentation

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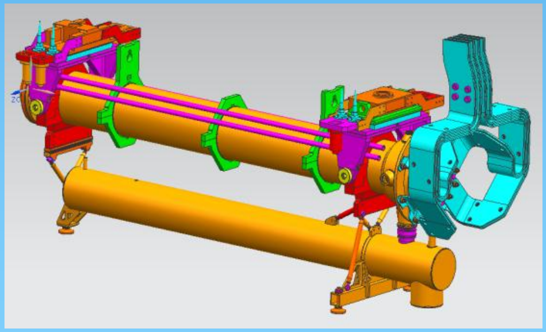

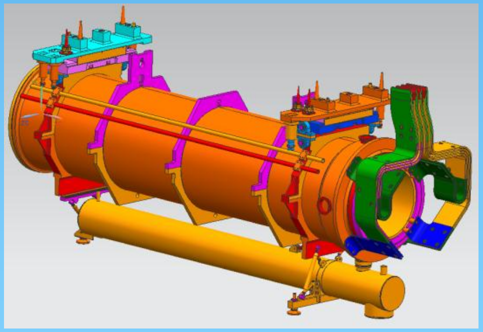

Outline

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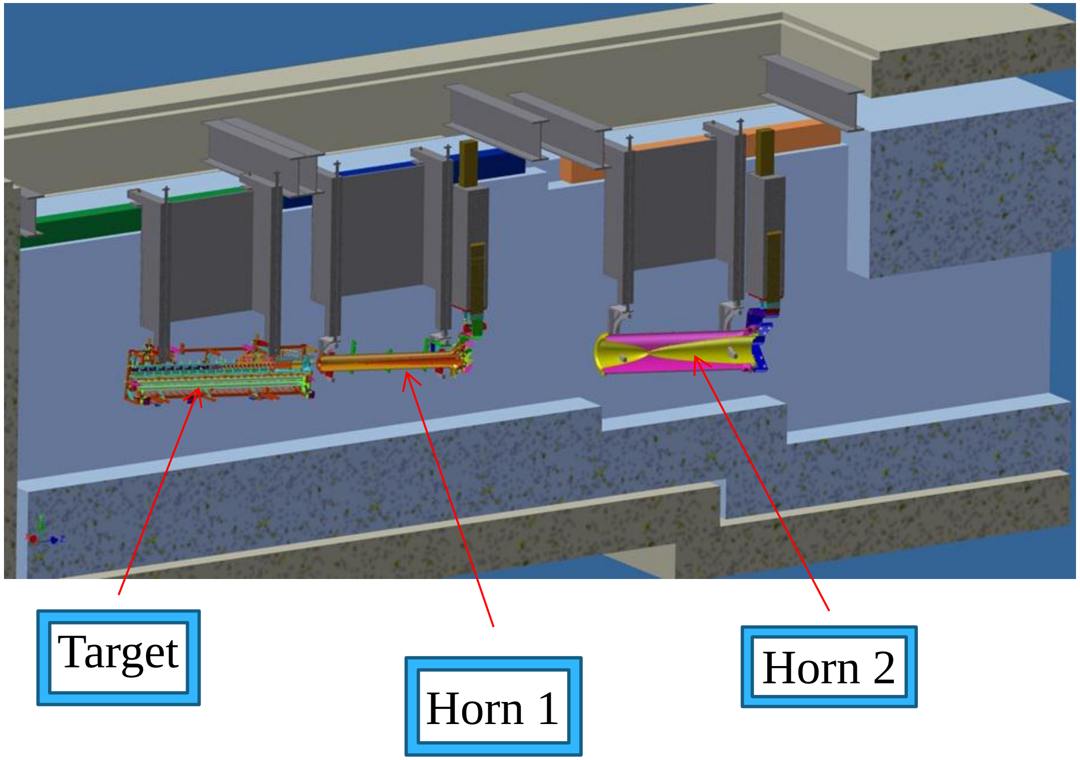
Position in LBNF Target Hall

- Horns sit downstream of the NuMI style target and carrier, supported by modules which rest on steel crossbeams.
- The target will be inserted into the inner conductor of Horn 1, which is followed by Horn 2 further down the beamline.
- These disposable components are top-loaded and sit level as opposed to NuMI / NOvA where the entire target hall follows the beamline angle.
  - Will help with ease of assembly as opposed to sitting at a steeper angle.
  - Allows for easier movement of shielding and robust, newly designed alignment mechanisms

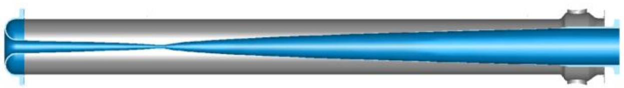


Horn Systems - Requirements

- Horn systems must have connections that are able to be made or unmade remotely
  - Necessary for remote handling operations.
  - Possible horn repairs or decommissioning require access to major fasteners & components.
- Design for long-term reliability
  - Must provide reliable operation for at least 2 years or 30 million pulses due to spare production capacity restraints.
  - All materials must withstand a radioactive, corrosive environment, at elevated temperatures.
    - Aluminum
    - Stainless Steel
    - Titanium
    - Alumina ceramics
    - Zirconia ceramics
  - Derived production parameters
    - Must use radiation-hard materials.
    - Inner conductors must utilize electroless nickel plating for increased fatigue life and corrosion resistance.
    - Outer conductors & brackets must utilize Type III Hard-coat anodizing for corrosion resistance.

Conductor Design

- Two-horn focusing system.
- Geometrical shape of Horn 1 & 2 conductors are identical to the NuMI / NOvA horn design.



660cm

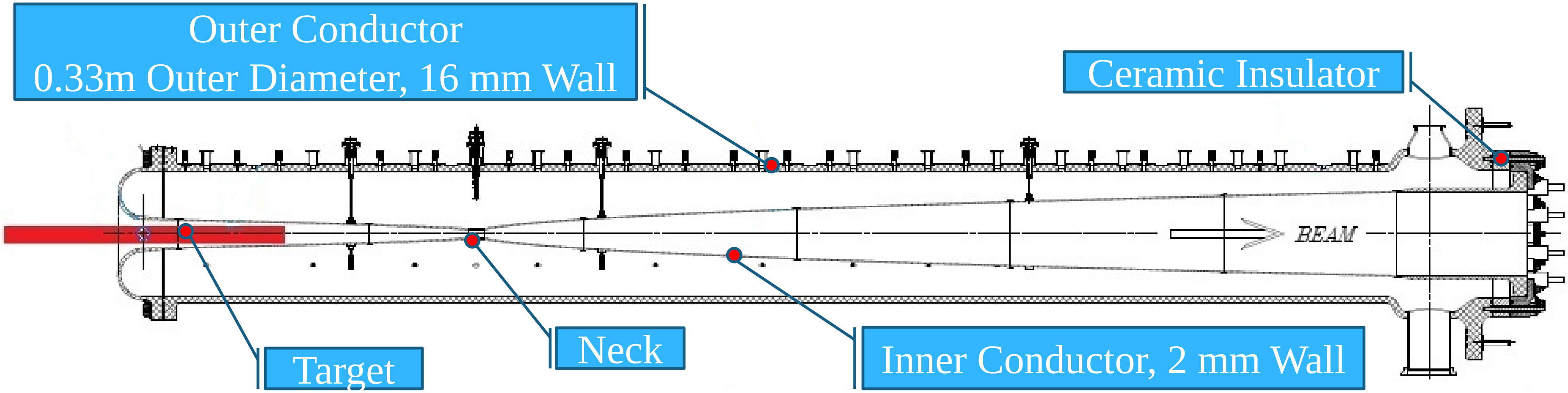
LBNE Horn 1

LBNE Horn 2

- NuMI / NOvA Horn designs have an extensive operational history.
- Conductor and subsystem designs have been validated over millions of pulses.
- Allows significant cost savings over redesigning and prototyping a new horn system.

Conductor Design Cont.

Horn 1 has a double-paraboloid inner conductor, with the upstream parabola surrounding the target, followed by the downstream parabola after the neck region.



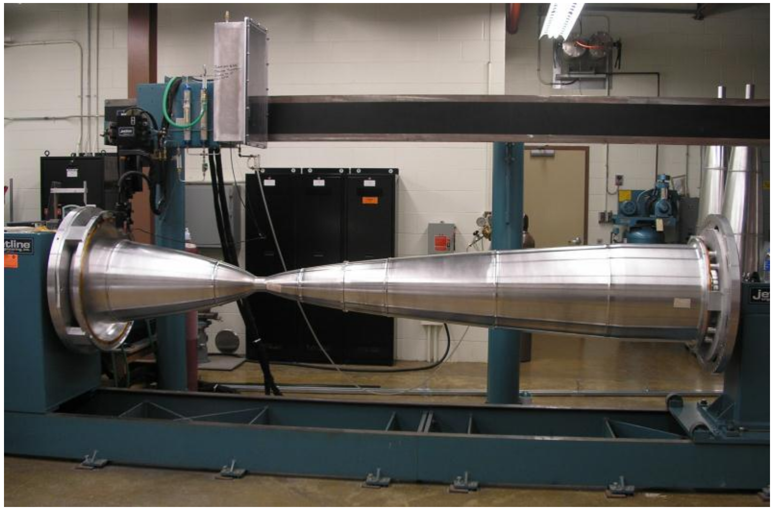
- Target must fit in horn with adequate clearance so as to not touch the inner conductor during operation. Optimal clearance is ~2mm.
- Horn 2 layout follows that of Horn 1, although the inner and outer conductors have slightly thicker walls due to their size, and lessened effects from beam heating compared to Horn 1.

Manufacturing Considerations – Conductor Fabrication

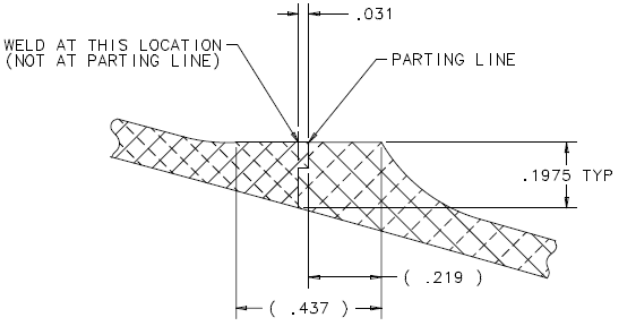
- Our experience is that outer conductors are generally straightforward to fabricate and can be trouble free if proper attention is given during production.
- Inner conductor segments can be problematic depending upon optics requirements and/or physics constraints.
  - Large, thin walled designs have a tendency to spring after machining and can be impossible to assemble.
  - Generally conductor wall thickness will be tied to the required diameter.
  - Horn 1 I.C. thickness is 2mm based on a diameter range of ~ 3cm - 20cm, while Horn 2 I.C thickness is 3mm based on a diameter range of 10cm – 60cm.
  - Resistive heating from current pulse also contributes to designed thickness.

Manufacturing Considerations – Welding

- Current Capabilities:
  - With in-house CNC TIG welding, we are able to achieve circularity and concentricity of ±0.015” (~.5mm), with voids <0.010” (.25mm).
  - Must utilize clean handling & tight tolerances to control internal weld porosity.
  - These steps can yield a NAS 1514 Class 1 Weld.

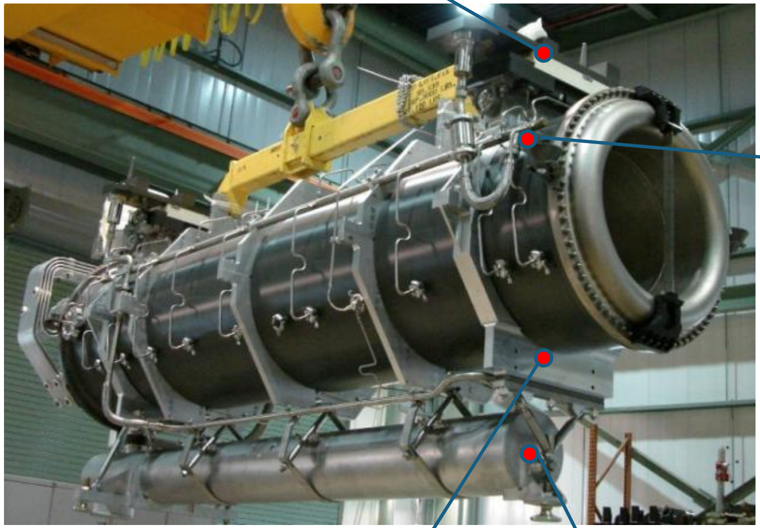


- Thoughts for future designs:
  - Minimizing number or complexity of conductor segments can significantly reduce welding & straightening time.
  - Long, slender horns will require more support rings & thicker weld regions.



Horn Subsystems

Hanger to remotely plug into module



Water manifolds

Support clamps for water tank and manifold mounting points

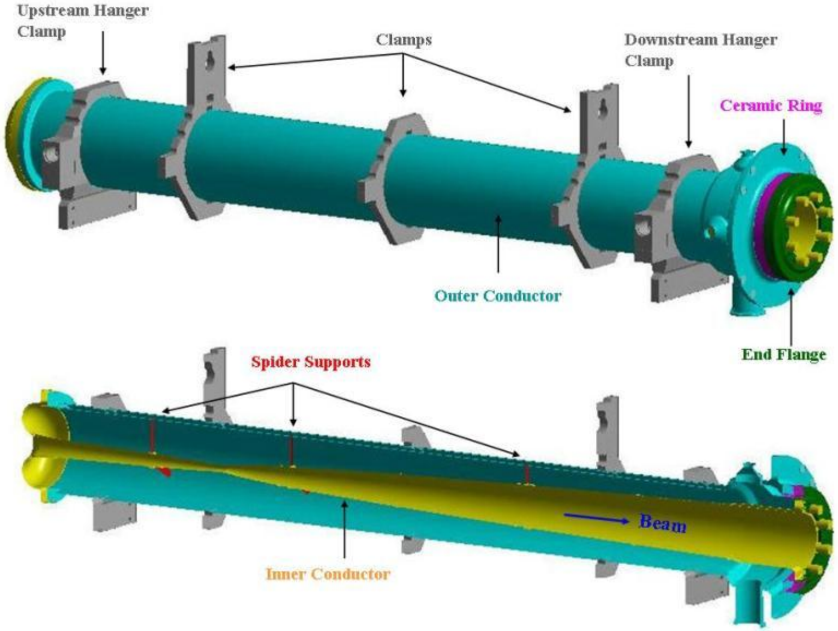
Water tank & horn assembly supports

- Experiences and technologies from NuMI / NOvA Horns will be implemented.
  - All subsystems have had a very good operational record.
  - Minor issues with the water manifolds and striplines were experienced early in NuMI.
    - Electrical breaks
    - Stripline hardware
  - FNAL designed & fabricated electrical breaks have been used for several years without failure.
  - Revised stripline fabrication to use higher quality, corrosion resistant hardware.

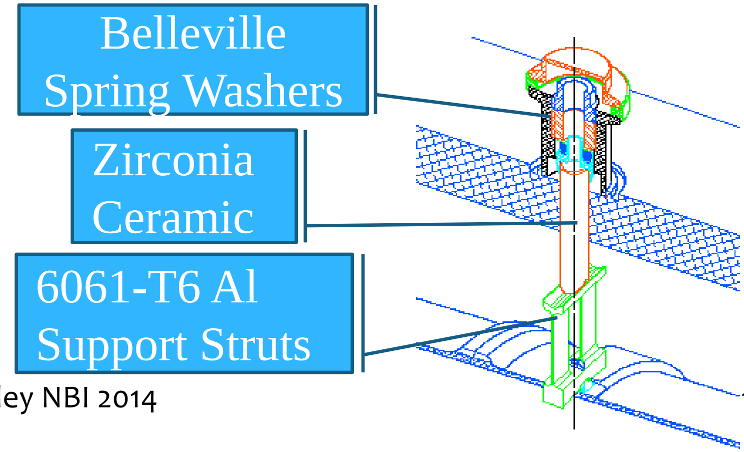
Ancillary Components

Horn Crosshairs

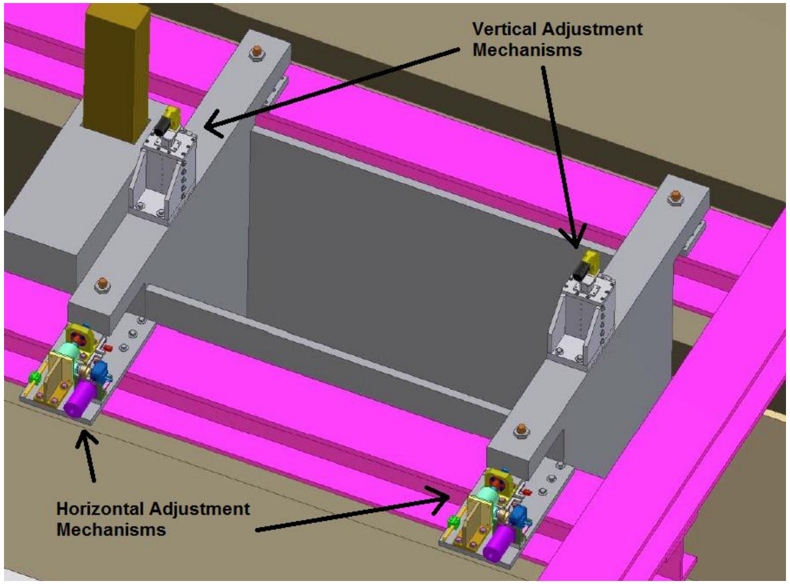
- Crosshair placement and design will remain the same.
  - Horn 2 crosshairs might need to be upgraded to beryllium due to energy deposition and / or temperature & stress concerns

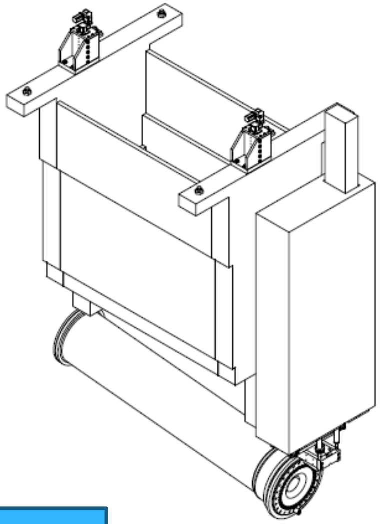


Spider Supports



Horn Support Structures

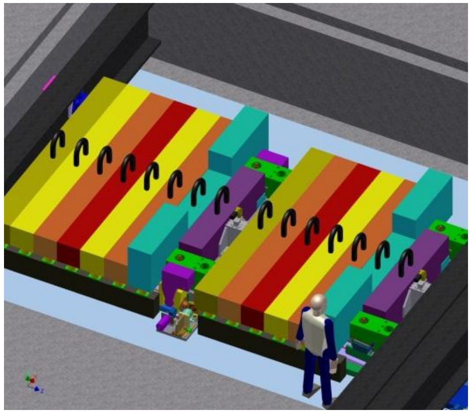




- Module mainframes and Stripline blocks require radiation labyrinths
- Necessary for dose rate reduction and technician protection while servicing

- The horn support structures will be the primary interface between the horns and all other systems.

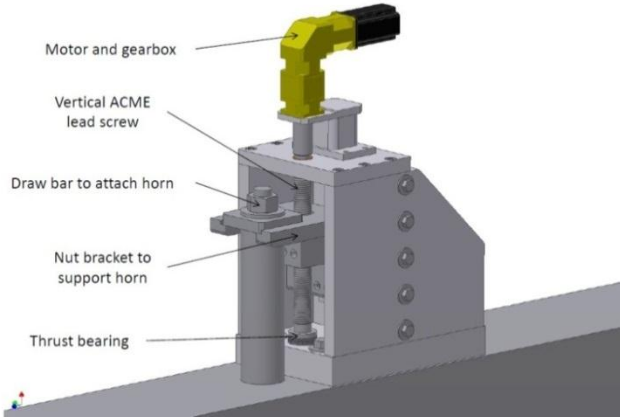
- Target Chase
- Instrumentation
- Cooling Water
- Electrical Supply
- Shielding Blocks

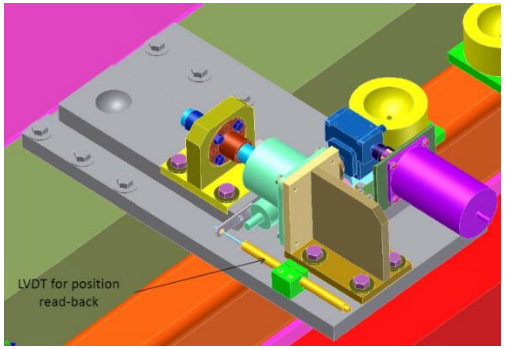


Horn Support Structures Cont.

- Stripline block will be derived from NuMI / NOvA design.
- Will require replaceable fan or ductwork assembly to provide cooling air to enclosed conductors

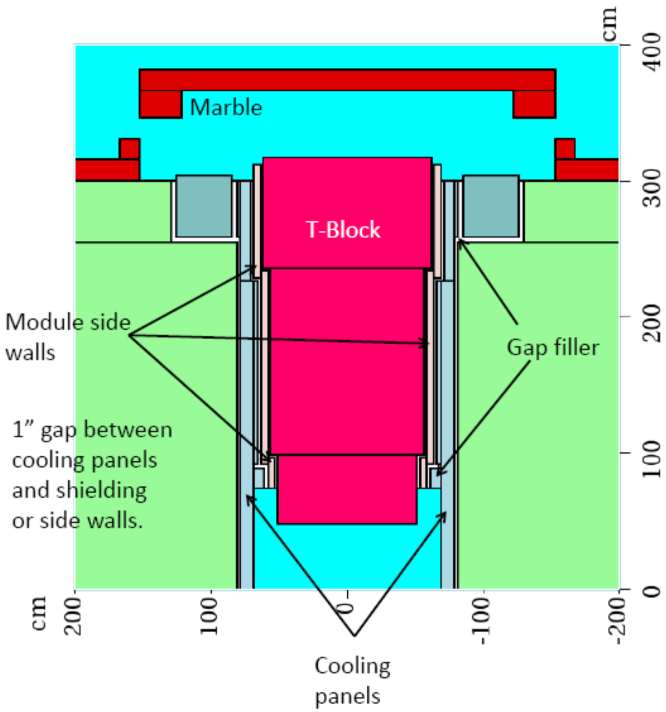
- Vertical adjustment mechanisms located on upstream and downstream end walls will allow yaw for both horns.
- Motor and reduction gearbox must drive a screw to complete this.
- Screw material will be primarily INVAR 36 for thermal stability.





- Horizontal adjustment mechanisms will allow fine tuning to the pitch of both horns.
- These will move the entire module with horns attached.
- Allows very ridged connection between horn and module mating points.

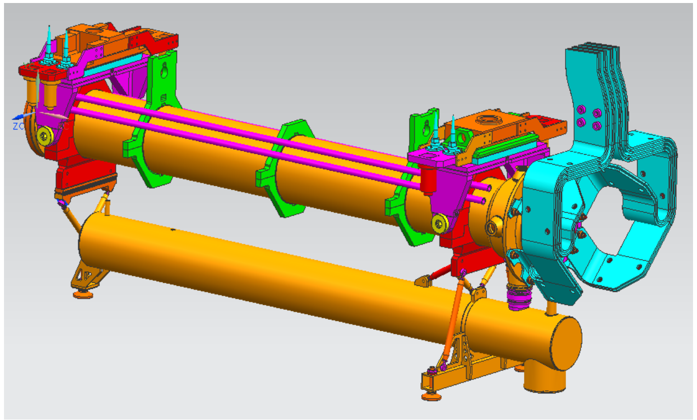
Module EDEP



- Internal heating from beam energy deposition and heat absorption from internal shielding "T" Blocks will cause horn alignment problems if the module is left un-cooled.
- INVAR 36 vertical support rods are only meant to attenuate expansion. There will still need to be active cooling.
- This will certainly be a problem at 2.3 MW, and is believed to be a concern at 1.2 MW.
- Our current plan is to have modules cooled from the start of operation for any beam power.
- Understanding where support structure hot spots are is essential to determining module cooling panel & manifold placement.

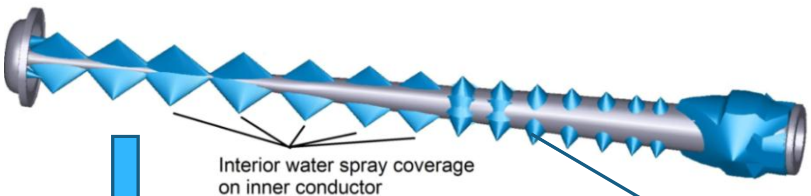
- Must ensure minimal connections / welds, as each is a possible failure point.
- Modules are designed for the life of the facility, and need to built accordingly.
- Must consider possible hot handling work for repairs if needed.

Horn 1 Analysis

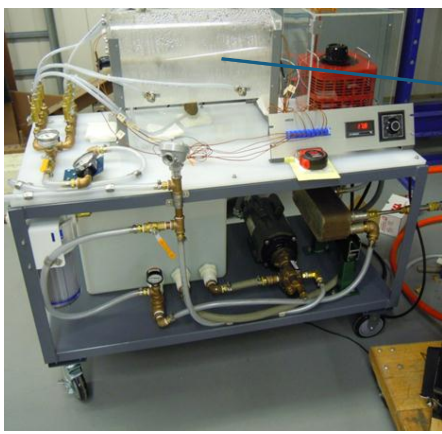


- It was understood early on that 1.2 MW operation of a NuMI / NOvA Horn 1 was a potential issue due to the existing design limits.
  - Temperature (Must stay below 100 C).
  - Fatigue life of inner conductor (Need to reach 30 million pulses or higher).
- Driving factors for operating temperature, stresses, and the resultant fatigue life are beam heating and resistive (joule) heating.
  - Beam energy deposition could not be lowered due to target design requirements.
  - Resistive heating from the NOvA power supply with a pulse width of 2.3ms would cause high temperatures and premature failure.
- It was thought (and later verified) that we would be able to keep horn current at 230kA, if we were able to reduce the current pulse width to 0.8ms.
  - Drawback is that new power supply is required.

Horn 1 Analysis Cont.

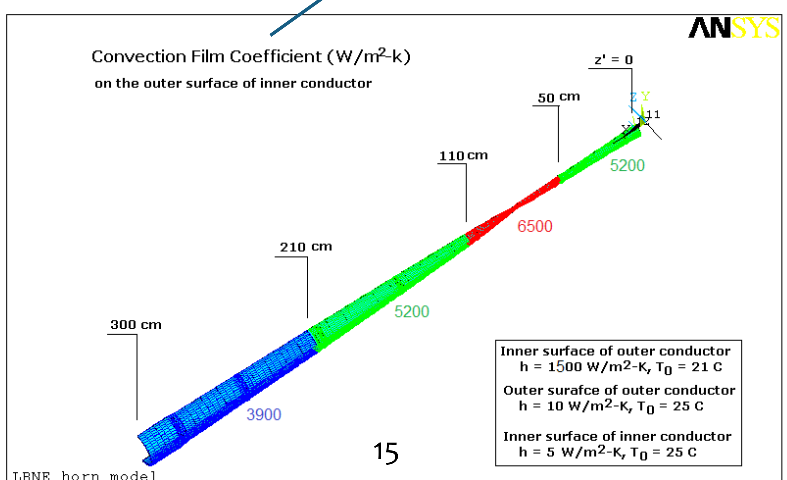


Model spray pattern



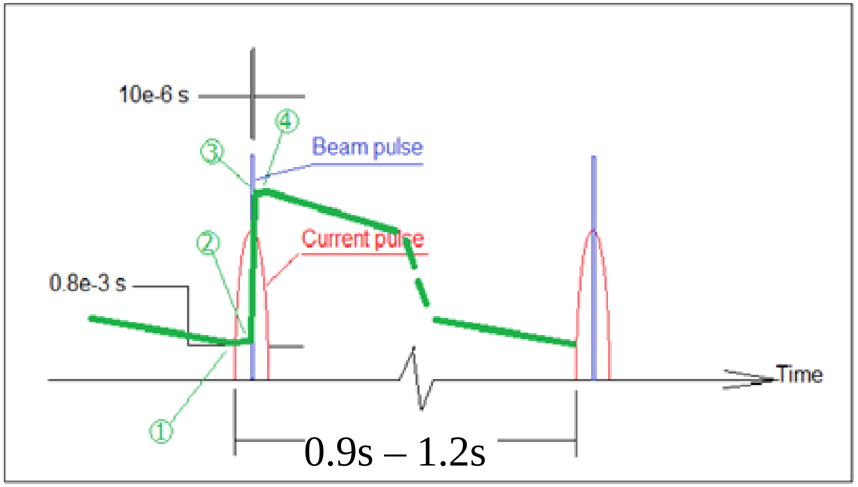
Build test assembly

Apply results to analysis



- The first step:
  - Find a conservative heat transfer coefficient for the horn analysis.
- Discovered that additional cooling would be required for the outer conductor.
- Will need to increase flow rates from existing design to meet cooling needs.

Horn 1 Analysis Cont.



* Analysis work was performed independently, on 2 separate machines with 2 separate models to verify results.

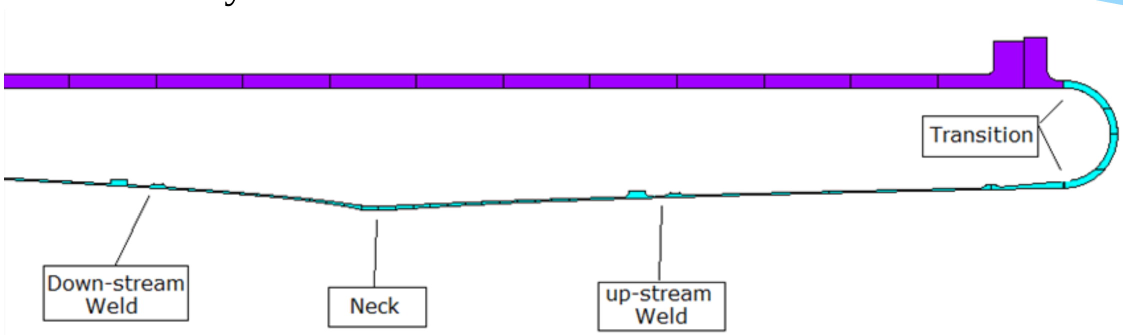
- Analysis was set up for both 120 GeV and 80 GeV operation, varying only energy deposition and cycle time.
- *Ang Lee and Zhijing Tang from FNAL Studied 4 scenarios:
  - Normal operation (beam & current pulse).
  - Test stand operation (current pulse only).
  - Horn off operation (beam pulse only).
  - Cyclic operation (normal running for 1 minute, horn off for 10 seconds & repeat).

Pulse Parameters For 80 GeV	
Horn peak current, I (kA)	230
Half-sine current pulse length, t (ms)	0.8
Cycle time, T (s)	0.9
Protons Per Spill	7.5E+13

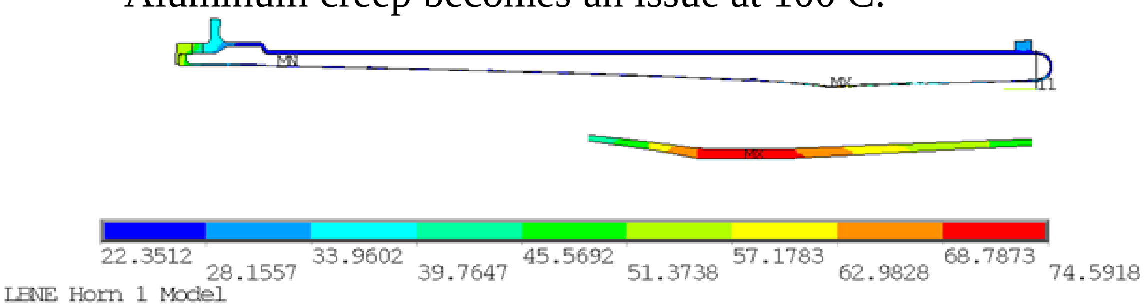
Pulse Parameters For 120 GeV	
Horn peak current, I (kA)	230
Half-sine current pulse length, t (ms)	0.8
Cycle time, T (s)	1.2
Protons Per Spill	7.5E+13

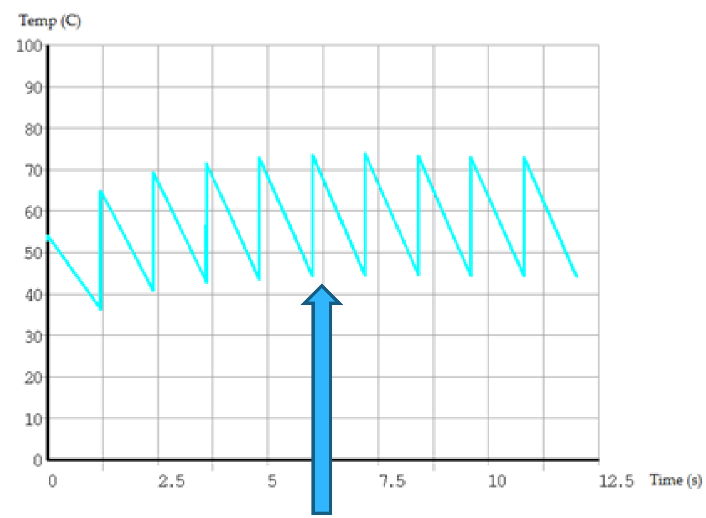
Horn 1 Analysis Cont.

- Primary areas of concern:



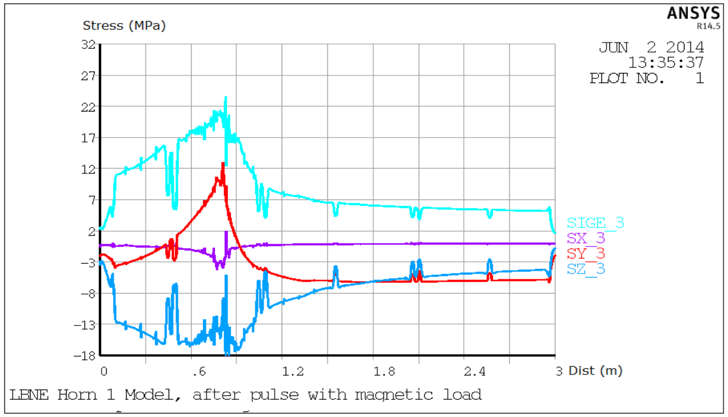
- Largest temperature increase can be seen at neck region as expected. Steady state temperature of 59 C and maximum transient temperature of 75 C is acceptable.
- Aluminum creep becomes an issue at 100 C.

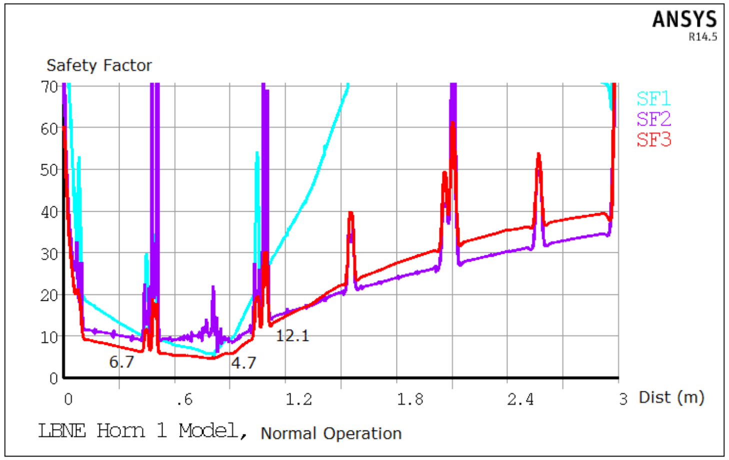




- Instantaneous temperature rise of 30 C creates the high alternating stress that is of concern for fatigue life.

Horn 1 Analysis Cont.





- Component stresses were evaluated, as was equivalent stress. Equivalent stress is the highest stress for all areas of concern, and therefore was used in the fatigue life calculation for a conservative analysis.
- Fatigue life was calculated with the Goodman Equation

$$\frac{S_a}{S_f} + \frac{S_m}{S_u} = \frac{1}{SF}$$

- Assuming a 6061-T6 aluminum fatigue strength of 14KSI (from BPVC), and an ultimate strength of 45KSI, safety factors could be calculated.
- Calculated safety factors were then reduced due to:
  - Welded regions (cut S.F. by 50%)
  - Corrosion concerns (cut S.F. by another 25%)

Horn 1 Analysis Cont.

- 120 GeV operation will be the most demanding due to beam energy deposition.
- NuMI / NOvA style horns must keep pulse width as low as possible to reduce resistive heating while not creating high voltage problems.
- Minimum Safety Factor (S.F.) of 2.5 is acceptable with stringent quality control.
- Will continue to improve QA processes

Safety Factor for 120 GeV Operation

	Safety Factor			
Operation Condition	Up-stream Weld	Neck	Down-stream Weld	Transition
Normal Operation	**2.5**	**3.5**	4.5	9.2
Test Operation	2.9	4.65	5.3	12.7
Horn-off Operation	7.5	12.7	10.9	36.8
On-off Operation	2.5	3.5	4.5	9.2

Safety Factor for 80 GeV Operation

	Safety Factor			
Operation Condition	Up-stream Weld	Neck	Down-stream Weld	Transition
Normal Operation	**2.55**	**3.6**	4.65	10.3
Test Operation	3.4	5.1	4.6	10.3
Horn-off Operation	9.4	15	13	25.9
On-off Operation	2.55	3.6	4.65	10.3

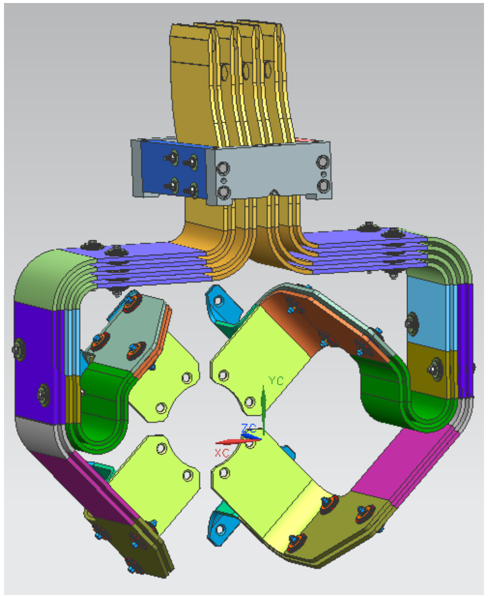
Power Supply

- Current NOvA power supply was designed to provide a pulse width of roughly 2.3ms with a maximum current of 240kA.
- Although it can provide sufficient horn current, the pulse width cannot be modified, and therefore a new supply is required for LBNF Horns.
- This is due to the excessive resistive heating caused by the long pulse width.
  - A current pulse longer than .8ms will reduce fatigue life of the horns to an unacceptable level.
  - Conversely, a shorter current pulse will introduce high voltage concerns. We still need to complete a high voltage potential test to at least 4kV

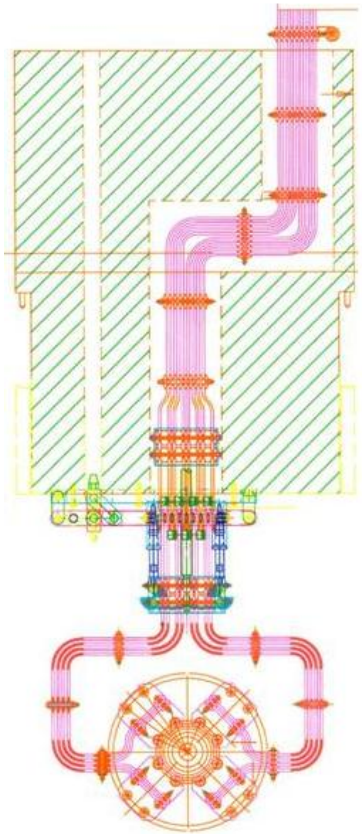
- The existing design plan is to build a new power supply, with Horn 1 and 2 wired in series, which provides the following benefits:
  - Can use a single power supply
  - Requires a single set of controls
  - Peak current occurs at the same time for both horns.
  - Ensures identical current across horns.
- Building a new power supply is a calculated trade off as opposed to redesigning Horn 1.

* Specific inquiries can be answered by Ken Bourkland, FNAL

Stripline Studies

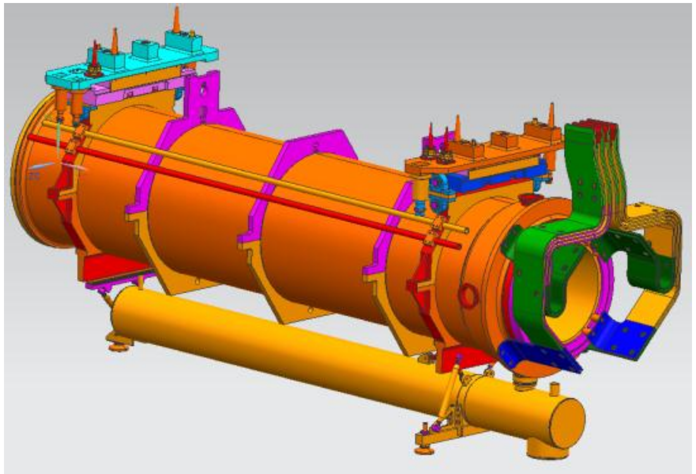


- Horn 1 stripline model has been generated and is currently being modified for analysis.
- Analysis will focus on operational temperatures & stresses, with a thorough vibration study using knowledge obtained from test stand pulsing of spare NOvA horn 1 (PH1-05).
- It is critical to understand stripline vibration at both 120 GeV and 80 GeV.
- Repetition rates are faster than NOvA and we have confirmed that not all frequencies have rung out even at the current rep rate of 1.33 seconds.



- Stripline labyrinth is also a concern due to enclosed geometry.
- This must be cooled to sufficiently remove resistive heat, as well as radiated heat from energy deposition in the stripline block.
- The modules will be cooled, however the stripline block is not. We need to do an analysis to identify if thermal expansion will cause issues with the connection between the labyrinth stripline and the horn stripline.

Additional Studies – Horn 2



- Conductor model has been generated and is being prepared for analysis.
- The NuMI / NOvA Horn 2 is a very robust design, utilizing large conductor segments with large cross sectional areas.
- Resistive heating is not much of a concern on Horn 2. It is of primary concern what effects the beam energy deposition has on the inner & outer conductor.
  - Will the O.C. need to be thinned?
  - Could reduce wall thickness from 1" (25mm) to 3/4" (19mm) or 5/8" (16mm); similar to NOvA Horn 1.

- Must study same operating conditions as Horn 1 (120 GeV & 80 GeV).
- Stripline study will have to be replicated as well due to slight design differences from Horn 1.
  - Does it experience the same effects?
  - Cooling profile and resistive heating is different which could be significant.
  - **What** is the primary stress?
  - **Where** is the primary stress?

Conclusion

- Analysis shows that a NuMI / NOvA style horn 1 can successfully meet the operational requirements of the LBNF beamline for 1.2 MW.
  - We have a comfortable current limit of 230 kA, with a pulse width of 0.8ms.
  - Modified NuMI style graphite target design works well with the horn and does not produce unacceptable levels of beam energy deposition into the horn conductors.
- A thorough study is needed on the effects of a 1.2 second & 0.9 second repetition rate on the horn 1 and 2 stripline design.
- The horn 2 analysis will begin shorty and we do not anticipate any results that would indicate it needs to be significantly redesigned. We will wait to see if the outer conductor wall thickness needs to be reduced until all results are in.
- Horn support modules are progressing in design and are well defined at the conceptual level. Work will continue on preliminary design, primarily encompassing a temperature and deformation analysis to understand alignment issues, and modeling of utilities and supports to accept a 2.3 MW Horn 1.

ANY QUESTIONS?