

SIMULATIONS OF HIGH CURRENT NUMI MAGNETIC HORN STRIPLINES AT FNAL

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Abstract

Both the NuMI (Neutrinos and the Main Injector) beam line, that has been providing intense neutrino beams for several Fermilab experiments (MINOS, MINERVA, NOVA), and the newly proposed LBNF (Long Baseline Neutrino Facility) beam line which plans to produce the highest power neutrino beam in the world for DUNE (the Deep Underground Neutrino Experiment) need pulsed magnetic horns to focus the mesons which decay to produce the neutrinos. The high-current horn and stripline design has been evolving as NuMI reconfigures for higher beam power and to meet the needs of the LBNF design. The CSU particle accelerator group has aided the neutrino physics experiments at Fermilab by producing EM simulations of magnetic horns and the required high-current striplines. In this paper, we present calculations, using the Poisson and ANSYS Maxwell 3D codes, of the EM interaction of the stripline plates of the NuMI horns at critical stress points. In addition, we give the electrical simulation results using the ANSYS Electric code. These results are being used to support the development of evolving horn stripline designs to handle increased electrical current and higher beam power for NuMI upgrades and for LBNF.

GENERAL CONCEPT

Neutrino beams from proton accelerators are produced as follows. First, the protons are accelerated in a typical particle accelerator such as a synchrotron. The energy of the protons, along with the geometry of the beamline determines the energy of the neutrinos. The accelerated protons are extracted from the accelerator and directed on to a target where the protons interact with the target material, producing a large number of secondary pions among other particles. Shaped magnetic fields created by focusing horns are used to select out pions of the preferred charge, and focus them into a collimated beam. These horns are fed high current through striplines as shown in Figure 1.

Realistic simulations of the horns and striplines are required. These will be used to study both the performance of the system as well as the potential for stress induced structural damage to the striplines and the horn structure.

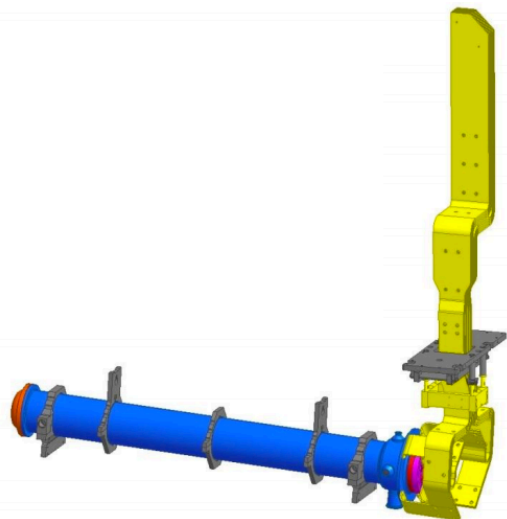


Figure 1. 3D model of the attached magnetic horn (blue section) and the high current stripline (yellow section).

In this paper our main interest is focused on the evaluation of the existing high-current striplines at Fermilab.

Stripline Geometry

Figures 2 and 3 show two different geometries for the connections between the striplines and the horns and each have their advantages and disadvantages. The stripline shown in Figure 2 is an older and larger version; it has proven itself durable in fatigue resistance and overall robustness. The stripline shown in Figure 3 has been designed as a more compact structure at larger radius to the beam axis, reducing beam heating and increasing air cooling. In comparison to the older design this new design exhibits less symmetry. Also the L-shaped flag plates have been changed to chamfered plates in the new design.

As seen in Figures 2 and 3 the high-current striplines are constructed as parallel conductors to minimize the magnetic fields external to the horn. However, this electric current does create a local magnetic field and force that has a significant impact on the long-term performance of the striplines; therefore, one need to evaluate this magnetic field and determine its effect on the striplines.

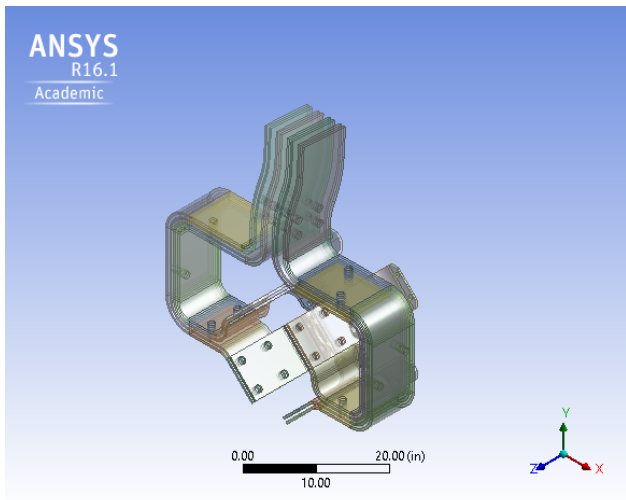


Figure 2. The older version robust high current stripline for the NuMI horn.

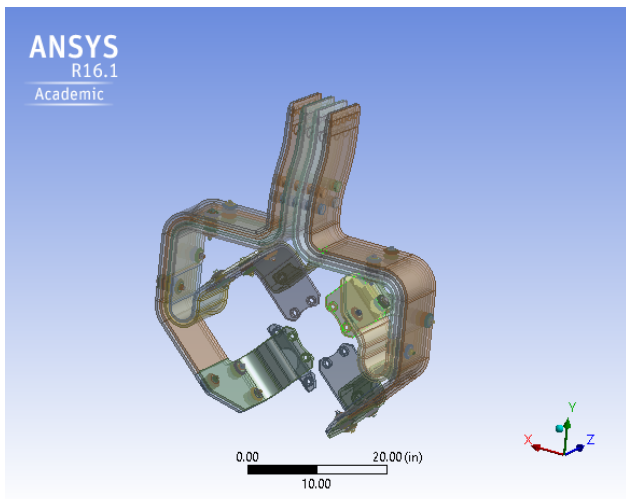


Figure 3. The new generation, compact, high-current stripline for the NuMI horn for higher beam power.

LANL'S MAGNETOSTATICS AND ANSYS MAXWELL 3D SOLVERS

We use both LANL's magnetostatics simulation kit [1] and the commercial ANSYS suite of codes [2] along with an accurate representation of the stripline and horn geometries to calculate the fields and forces generated.

Four conductors are used to conduct the 200 kA into and out of the inner and outer conductor of the horn. This was shown in previously in Figures 1, 2 and 3 previously. The cross-section of all plates are 8 inches by 0.375 inches, and the distance between each plate is 0.375 inches. Each carry an applied current of 50 kA pulsed, and the current flows with a polarity of + - + -. As such simulations were done for both relevant current polarity cases, ++ and + -, Figures 4 and 5.

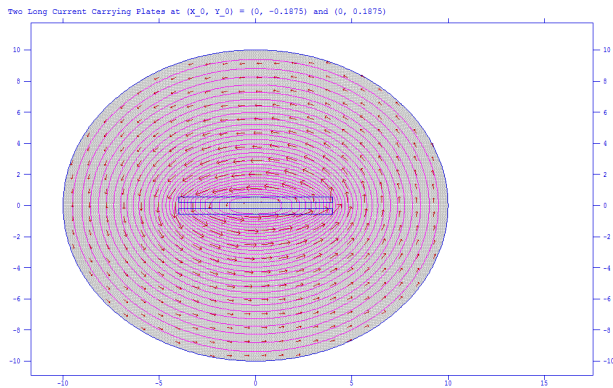


Figure 4. Poisson result for the magnetic field map of cross section of parallel plates in x-y planes carrying 50 kA DC each in the same direction (++) .

As an example, two striplines carrying opposing current generate magnetic fields that when coupled to the current generate a repulsive force between the two striplines. With 50 kA of current in each stripline the magnetic force between the two striplines is found to be 6186 N/m from Poisson (Figure 5) and 6192 N/m as calculated by ANSYS Maxwell 3D (Figure 6).

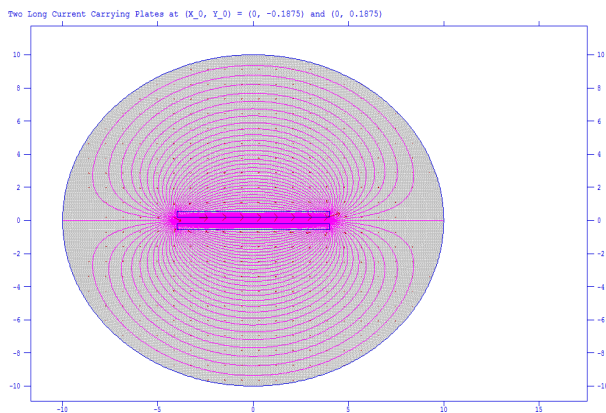


Figure 5. Poisson result for the magnetic field map through a cross section of parallel plates in x-y planes carrying 50 kA DC each in the opposite direction (+ -) .

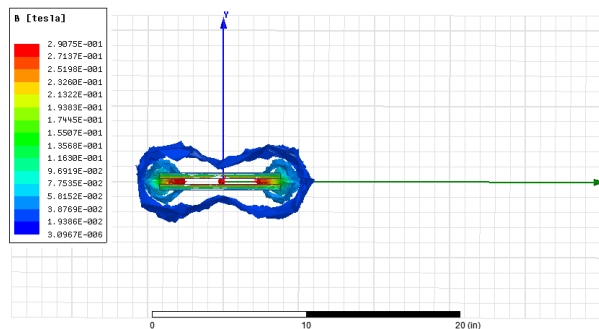


Figure 6. ANSYS Maxwell 3D result for the magnetic field map of two parallel plates of the high current stripline carrying 50 kA DC each in the opposite direction (+ -) .

The newer version of the stripline failed in service at the 90 degree bend in the so-called “flag plate” (Figure 7). Using the same methodology, simulations were done to see if the magnetic induced stresses were the primary source of the failures at this point.

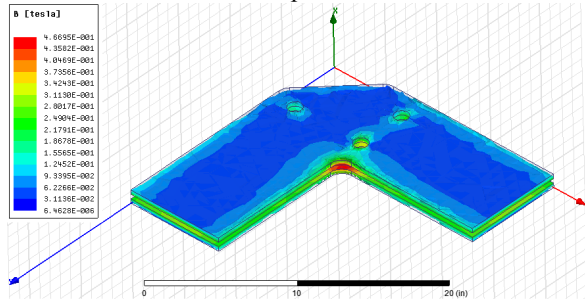


Figure 7. ANSYS Maxwell 3D result for magnetic field map of chamfered L-shaped two parallel plates of the high current stripline with bolt holes carrying 50 kA DC each in the opposite direction (+ -).

Simulations show that the magnetic field at the inner most corner is much larger than in the straight sections. The average pressure on the flag plate is found to be $\sim 3.1 \times 10^4$ N/m²; however, at the inner corner section this pressure is $\sim 8.8 \times 10^4$ N/m². The related result is shown in Figure 8.

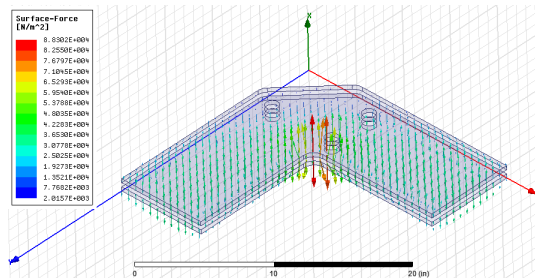


Figure 8. ANSYS Maxwell 3D result for the pressure distribution of chamfered L-shaped two parallel plates of the high current stripline while carrying 50 kA DC each in the opposite direction (+ -).

While these are high pressures, it is not enough to, in itself, cause structural damage, and so the damage is most likely coming from a combination of heating and vibrational effects.

ANSYS ELECTRIC RESULTS FOR CURRENT DENSITY

The electric current density calculations were performed using the ANSYS Electrical code. 50 kA of current was applied to the flag plate to evaluate the current density in critical stress locations. As a reference point the current density for the simple straight sections is 2.4×10^6 A/ft². When the identical current is applied to the chamfered L-shaped flag plate that includes the bolt holes, the current density at the inner corner is ~ 3 times larger than the nominal two straight plates case (Figure 9).

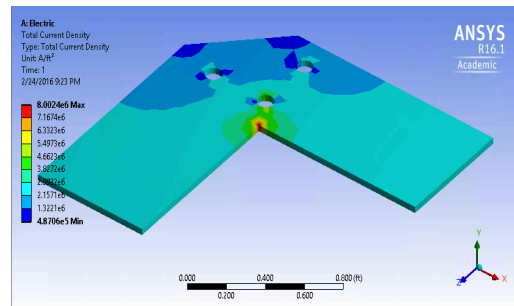


Figure 9. ANSYS Electric result for total current density of chamfered L-shaped flag plate of the high current stripline including bolt holes. 50 kA was applied.

CONCLUSION

The current densities and forces at the critical locations of the flag plate part were evaluated. Inclusion of the chamfering and bolt holes effected the current density and forces, but not critically. The results for the magnetic field and magnetic force were shown for straight plates. The straight section characteristics agreed well with theory. Additional magnetic field related effects such as the local pressures and current densities were evaluated for real stripline flag plates. The magnetic field was found to be ~ 2 times larger at the inner corner of the plates (Figure 7) as compare to the straight plates case (Figure 6). The pressure was found to be $\sim 8.8 \times 10^4$ N/m² at the highest point which was ~ 2.5 times higher than seen on average shown in Figure 8. The current density is found to be ~ 3 times larger in the corners (Figure 9). These results are not high enough to cause the stress fracture and these fractures are more likely related to repetitive heating and/or vibrational effects cause by the current and magnetic forces respectively. These results are being implemented in the on-going design upgrades of the magnetic horn stripline designs to handle increased electrical current and higher beam power for NuMI upgrades and for future LBNF. The corner sections need to be evaluated not only mechanically and thermally but also considering electromagnetic contributions. It is better if the inner corner radius of the plate will be enlarged for the higher current required in the next designs.

ACKNOWLEDGMENT

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REFERENCES

- [1] J. Warren, et al., “POISSON/SUPERFISH Reference Manual,” Los Alamos National Laboratory report LA-UR-87-126 (1987).
- [2] ANSYS Academic Research, Release 16.