SIMULATIONS OF HIGH CURRENT MAGNETIC HORN STRIPLINES AT FERMILAB

T. Sipahi, S. V. Milton[2], S. G. Biedron[1,2], Department of Electrical & Computer Engineering, Colorado State University (CSU), Fort Collins, CO, 80523, USA
[1]also at Faculty of Electrical Engineering, University of Ljubljana, Slovenia
[2]also at Element Aero, Chicago, IL 60643 USA
R.M. Zwaska, J. Hylen, FNAL, Batavia, IL 60510, USA

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 that 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 future LBNF program. We evaluated the two existing high-current striplines for NuMI and NOvA at Fermilab by producing Electromagnetic simulations of the magnetic horns and the required high-current striplines. In this paper, we present the comparison of these two designs using the ANSYS Electric and ANSYS Maxwell 3D codes with special attention on the critical stress points. 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 the LBNF experiment.

GENERAL CONCEPT

Neutrino beam production from proton accelerators can be described as follows. First, the protons are accelerated to a suitable energy in a particle accelerator. 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. This pions subsequently decay to muons and the muons decay into an intense neutrino beam. The horns are fed high current, necessary to generate the required field, through striplines as shown in Fig. 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.

In this paper our main interest is focused on the evaluation of the existing fatigue failure of the 700-kW high-current stripline and comparision of it with the 400-kW design. Each of these two stripline designs were operated on horn 1 for the NuMI and NOvA at Fermilab experiments.

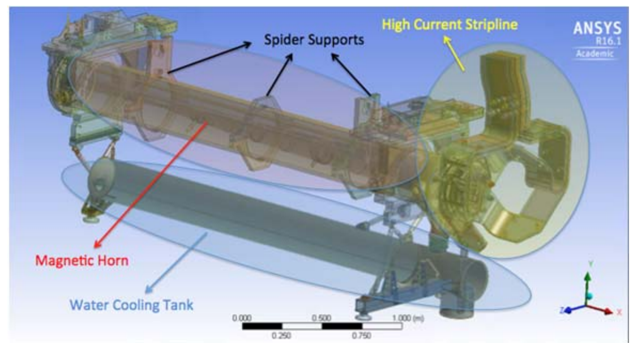

Figure 1: 3D model of the attached magnetic horn 1 (red section), the 700-kW high current stripline (yellow section), water cooling tank (blue section) and spider supports.

400 kW AND 700 kW HIGH-CURRENT STRIPLINE GEOMETRIES

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 Fig. 2 (400-kW design) is an older and larger version; it has proven itself durable in fatigue resistance and overall robustness. The stripline shown in Fig. 3 (700-kW design) has been designed as a more compact structure to accommodate a larger radius on 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 Figs. 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 needs to evaluate this magnetic field and determine its effect on the striplines.

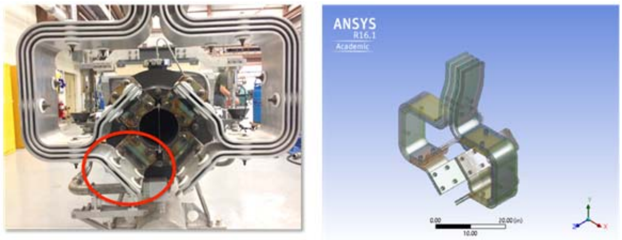

Figure 2: The 400-kW high-current stripline for NuMI.

Figure 3: The 700-kW high-current stripline for NOvA.

The 700 kW high-current stripline failed in service at the 90 degree bend in the so-called “flag plate” (Fig. 4). The simulations were done to see if the magnetic induced stresses were the primary source of the failure at this specific location.

Figure 4: Fatigue failure location of the flag part of the 700-kW high-current stripline [1].

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.

Four conductors are used to conduct the 200 kA into and out of the inner and outer conductor of the horn. This was shown previously in Fig. 2. In Fig. 5 the total current density simulation result of the 400-kw design stripline is shown using half symmetry model. 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, and the current flows with a polarity of + - - +.

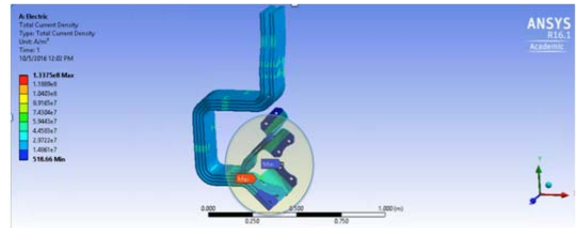

Figure 5: The current density simulation of 400-kW, high-current stripline using (half symmetry) using ANSYS Electric.

When the identical currents is applied in opposite directions at the flag plate (the 90 degree bend) that includes the bolt holes, the current density at the inner corner is ~4 times larger than the nominal two straight plates case shown in Fig. 6.

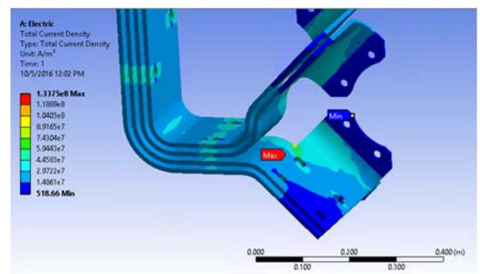

Figure 6: The current density simulation of the flag plate of 400-kW high-current stripline using (half symmetry) using ANSYS Electric.

When the identical current is applied to the flag plate of the 700-kW, high-current stripline, the current density at the inner corner is ~3 times larger than the nominal two straight plates case (Fig. 7).

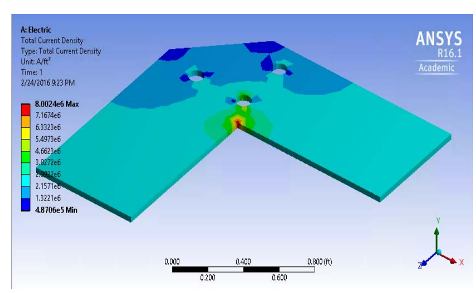

Figure 7: ANSYS Electric result for total current density of flag plate of 700-kW design carrying 50-kA, DC each in the opposite direction (+ -).

MAGNETIC PRESSURE COMPARISION OF FLAG PARTS FOR 400 KW AND 700 KW HIGH-CURRENT STRIPLINE DESIGNS USING ANSYS MAXWELL 3D

In our previous study [2] magnetostatic and electric related simulation results both for the straight sections and at the flag part location of the 700- kW, high-current stripline design were performed. As a cross check we used both LANL’s magnetostatics simulation kit [3] and the commercial ANSYS suite of codes [4] along. Both simulations used an accurate representation of the stripline and horn geometries to calculate the fields and forces generated.

Here, we compare the 400-kW and 700-kW, high-current stripline designs that were attached and used with magnetic horn 1 for the NuMI and NoVA at Fermilab experiments.

Simulations show that for the 700-kW design the magnetic field at the inner most corner is much larger than in the straight sections as shown in Fig. 8. The average pressure on the flag plate is found to be ~ 3.1 x10^4 N/m^2; however, at the inner corner section this pressure is ~ 8.8 x 10^4 N/m^2. The related result is shown in Fig. 9.

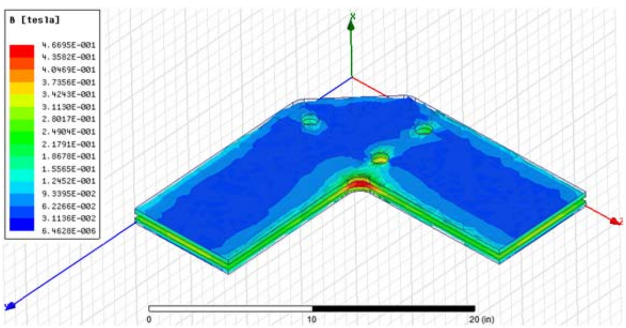

Figure 8: ANSYS Maxwell 3D result for magnetic field map of flag plate of 700-kW design each carrying 50-kA, DC in the opposite direction (+ -).

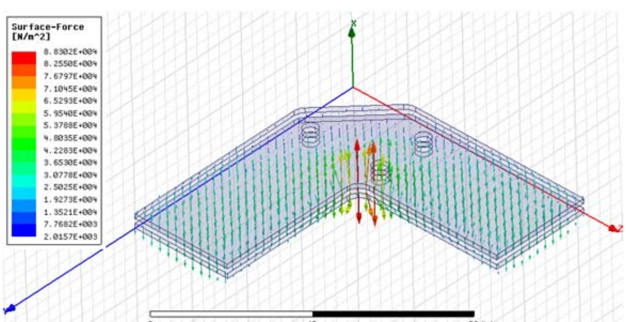

Figure 9: ANSYS Maxwell 3D result for the pressure distribution of flag plate of 700-kW design each carrying 50-kA, DC in the opposite direction (+ -).

For the 400-kW design the magnetic field at the inner most corner is much larger than in the straight sections as shown in Fig. 10. The average pressure on the flag plate is found to be ~ 2.5 x10^4 N/m^2; however, at the inner corner section this pressure is ~ 9.6 x 10^4. N/m^2. The related result is shown in Fig. 11.

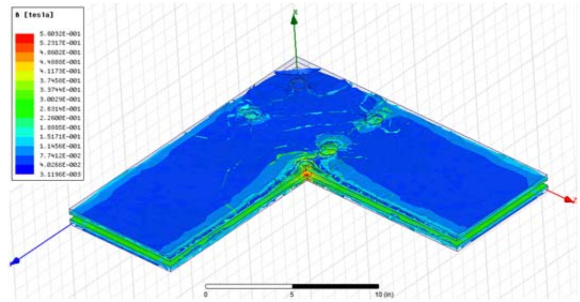

Figure 10: ANSYS Maxwell 3D result for magnetic field map of flag plate of 400-kW design each carrying 50-kA, DC in the opposite direction (+ -).

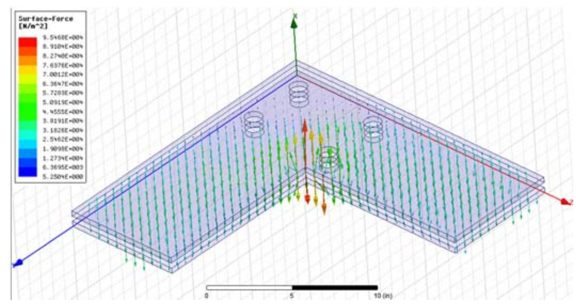

Figure 11: ANSYS Maxwell 3D result for the pressure distribution of flag plate of 400-kW design each carrying 50-kA, DC in the opposite direction (+ -).

CONCLUSION

The current densities and forces at the critical locations of the flag plate part were evaluated both for 400-kW and 700-kW high-current stripline designs. According to these results the 700-kW design has lower current density pressure values at the inner corner of the flag part. Inclusion of the chamfering and bolt holes effected the current density and forces, but not critically. The results for the current density, magnetic field and the pressure were evaluated for real stripline flag plates. The results were presented for each high current stripline design. The values were found to be a little smaller for the 700-kW one. 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 the future LBNF experiment. 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 is enlarged for the higher current required in the next designs.

ACKNOWLEDGMENT

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