ELECTROMIGRATION ISSUES IN HIGH CURRENT HORN*

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Abstract

The secondary particle focusing horn for the AGS neutrino experiment proposal is a high current and high current density device. The peak current of horn is 300 kA. At the smallest area of horn, the current density is near 8 kA/mm^2. At very high current density, a few kA/mm^2, the electromigration phenomena will occur. Momentum transfer between electrons and metal atoms at high current density causes electromigration. The reliability and lifetime of focusing horn can be severely reduced by electromigration. In this paper, we discuss issues such as device reliability model, incubation time of electromigration, and lifetime of horn.

INTRODUCTION

In the proposed Brookhaven AGS Super Neutrino Beam Facility, a magnetic horn will be used to focus the secondary beam. Much attention has been given to physics and mechanical properties of the horn. The electrical and electromechanical issues have not been considered as serious design limitations. All horn problems have been regarded as mechanical failures, material strength limitations, etc. These conclusions are correct in most situations. Our interest is to broaden the investigation and gain understanding of the electro-mechanical aspect of horn design.

HORN BASIC ISSUES

The basic physics consideration of horn design is its geometry to capture and focus of secondary particles. The neutrino beam produced will have to travel more than 2500 kilometers to reach the detector at far end. To reduce beam loss, it is desirable to have an ultra thin wall horn to make it as transparent as possible to the secondary beams. The horn geometry is shown in Figure 1.

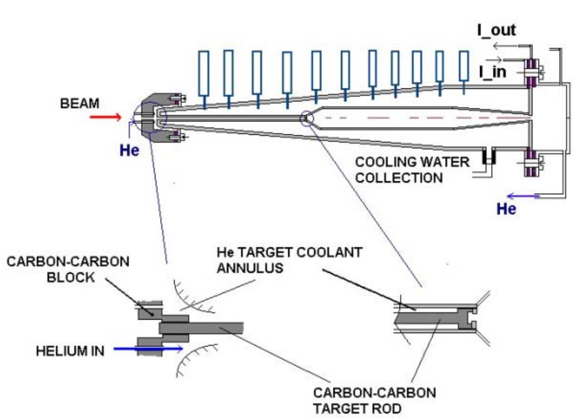

Figure 1. Target and horn configuration.

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Mechanical issues related to target and horn design have been well recognized. These include: horn material selection, the horn and target integration, the thermal distribution of horn, the heat removal mechanism, the material swell due to irradiation, material corrosion, material fatigue, etc.

HORN ELECTROMIGRATION ISSUES

The nominal horn current is 250 kA of half sine wave, with 1.2 ms base width. The design maximum is 300 kA. This is a very high current pulsed power system. The stored energy will be on the order of 36 kilo-joules. An unintended and uncontrolled current interruption or release would cause severe damage to the device, power supply and transmission system. Furthermore, the horn and target radiation level will be very high during beam operation. Hence, the frequency of horn replacement during operation, the integrity and reliability of horn as well as all other devices and subsystems are of great concern.

Until now, the electrical issues have been more on the high voltage pulsed power design and high current generation and transmission. However, with horn of ultra thin walls, the current density might be above the threshold of electromigration.

The simplified horn geometry is shown in Figure 2. Its parameters are listed in Table I.

Table I Horn Parameters

Section	Inner Diameter	Wall Thickness	L
L1	14 mm	2.5 mm	800 mm
L2	14 mm minimum	2.5 mm	100 mm
	120 mm maximum		
L3	120 mm	2.5 mm	800 mm
L4	120 mm maximum	1.0 mm	400 mm
	12 mm minimum		

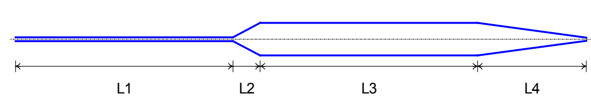

Figure 2 Simplified Horn geometry

At the fundamental frequency, 833 Hz, of the current pulse, the skin depth is 3.574 mm. The wall thickness of the horn is less than the skin depth. Therefore, we assume the wall is fully saturated by pulse current. At peak current level of 300 kA, the current density can reach as

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high as 7.3456 kA/mm^2. Figure 3 and 4 show the current conducting area and current density distribution alone horn axial.

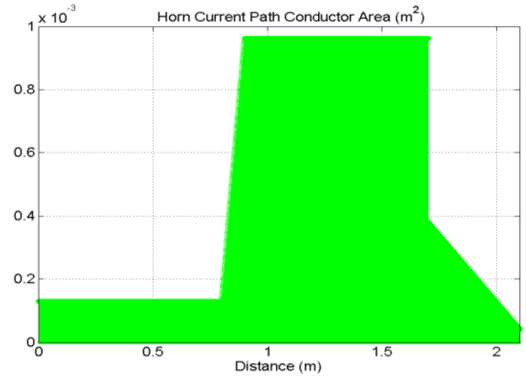

Figure 3. Horn current path area

Notice that in the neck area, where the target is contained, and at the tip of the horn the conducting areas are very small.

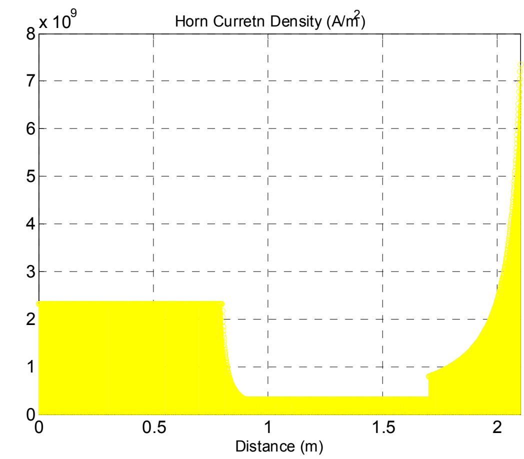

Figure 4. Horn current density

According to various literatures, the discovery of electromigration was more than hundred years ago. The electromigration is due to momentum exchange of electrons and metal atoms. At high current density massive electrons collide with metal atoms, and the effect becomes noticeable. It happens at the place of material voids, impurities, and grain boundaries, etc. Although the electromigration force is proportional to the current density, the electromigration failure rate is proportional to higher orders of the current density. One famous result is the Black's equation, which relates the electromigration mean time to failure to the inverse square of the current density:

$$t_{50} = c\frac{e^{\frac{E_a}{kT}}}{J^2} \ . \qquad (1)$$

Where t_{50} is mean time to failure, c is a constant determined from experiment, E_a is the activation energy, k is Boltzmann's constant, T is temperature, and J is the current density.

The Black's equation was an empirical result obtained in the sixties. There have been many explanations based on different theories. Most researches are based on experimental results of various materials, different sample geometry, and laboratory setups. A modified version of Black's relation is often used as:

$$\tau \propto \frac{e^{\frac{E_a}{kT}}}{J^n} \ . \qquad (2)$$

Where τ is device lifetime, and n is to be determined by experiment.

Aluminum material will be used for horn construction. Experimental results of aluminum material show a wide range of n from 1.8 to 16 depending on many other variables. However, in the current density range being considered, we might assume n=2.

Other factors may also affect the overall reliability of the horn device. In summery, commonly concerned factors include:

- Current density,
- Ambient temperature,
- Resistive Joule heating,
- Water and moisture,
- Environment,
- Material swell caused by ionized radiation,
- Soldering joints,
- Material fatigue due to electromagnetic force,
- Material defects,
- Surface condition,
- Mechanical stress due to structural factors, etc.

It should be pointed out that the joule heating is an important parameter associated with lifetime of device. Under operating condition of 240 kA, 1.2 ms pulse width, 2.5 Hz repetition rate, the temperature at the tip of horn can reach as high as 470 K. This would mean the area with highest temperature is much more likely to induce electromigration than the area of relative low temperature of 144 K. Using Black's equation, this temperature difference of 326 K will reduce device lifetime by a factor of 3.67×10^{14} in the high temperature region.

The tip of horn is also the area of highest current density. The ratio of its current density to the area with lowest current density is about 23.5 times. When current density square rule is used, it will imply that the device lifetime at horn tip is 555 times less than the large straight section L3.

The activation energy of the particular aluminum material shall also be determined empirically. For the purpose of discussion, we use the lattice activation energy of 1.4 eV, and grain boundary activation energy of 0.6 eV for aluminum alloy [9]. Considering that protons enter target area have particle momentum of 28 GeV, it's reasonable to believe any uncontrolled spray of primary beam onto the aluminum wall could cause metal atoms to dislocate. The secondary beam travel through thin wall of horn may also cause material activation. Therefore the beam itself is a contributing factor to electromigration.

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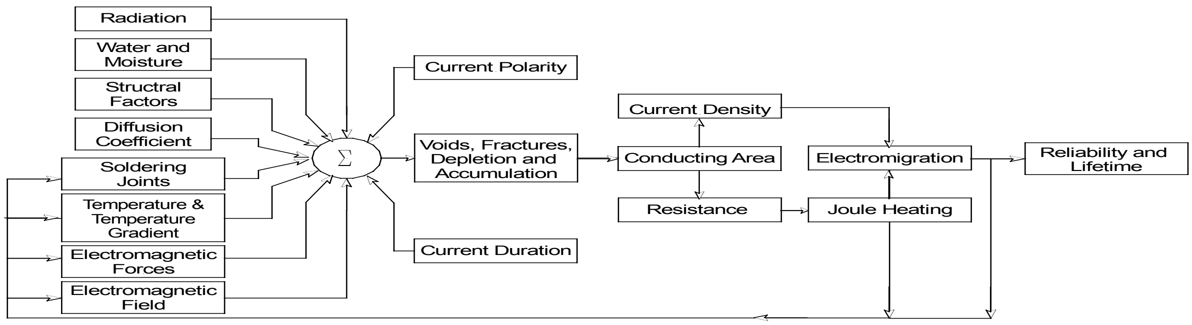

Figure 5. Electromigration and reliability model.

Table II lists horn parameters for comparison. It can be seen that the maximum current density of proposed AGS horn is 14.37 to 24.48 times of other devices. The electromigration due to the current density square factor alone would mean a 206 to 500 times degradation in device lifetime.

Table II Horn current and pulse lifetime

Experiment	I_{peak}	J_{peak}	T_{pulse}	F	N_{design}
	kA	A/mm^2	μs	Hz	pulses
NuMi	200	?	2600	0.54	1×10^7
MiniBooNe	170	447	143	5.00	1×10^8
K2K	250	511		0.50	11×10^6
Nufact prototype	300	300	81	50.00	2×10^8
CNGS	150	363		0.33	42×10^6
AGS Superbeam	300	7345	1200	2.50	8×10^6

Other studies have shown that the electromigration incubation time factor, bipolar current effect, wet effect, etc. The incubation time is related to void growth, extrusion, edge displacement, and more importantly the flux divergence. The electromigration is a process of mass transfer. It requires discrete time to cause an event to occur. The accumulated pulse time is a production of the number of pulses and pulse duration. Therefore short pulse duration might have advantage of longer horn lifetime.

The force of bipolar current tends to carry the metal atoms back and forth. It has been demonstrated by others that the metal sample tested under the same current density condition last longer with alternative current than direct current. It prompts us to consider if a bipolar wave shape is better rather than half sine.

However, the short pulse width implies higher voltage, and bipolar current is related to bipolar voltage waveform. It will make the high voltage design very difficult, especially under ionized environment.

We are interested on the technology that could extend the horn lifetime and benefit the physics experiment as well. Nano-material bonding has been one of the considerations, and it certainly deserves more research and development. A simple model, as shown in Figure 5, to study the horn device reliability and electromigration is derived from a collection of related research works [2-10].

CONCLUSION

While this device is in proposal stage, we would like to extrapolate the lifetime of other horn devices to estimate the frequency of horn replacement during operation. This shall aid the planning and decision of remote automated horn handling capability and storage facility.

We are interested in explore new design method, new material composition, and simulation model as well as test approach. More than forty references are used in this work, only a few can be listed due to space limitations.

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