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Electromigration Issues in Pulsed Power System*

W. Zhang, J. Sandberg (Brookhaven National Laboratory)

Abstract

Electromigration issue caught our attention during a recent effort to design and develop a high current and high current density pulsed power system. 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 pulsed power device can be severely reduced by electromigration. In this paper, we discuss issues such as device reliability model, incubation time of electromigration, lifetime of device, and design tradeoffs.

Keywords: electromigration, pulse power systems, accelerators, current density.

1. Introduction

In pulsed power system design and development, source and load are often treated as separate building blocks. However in a high current pulsed power system with inductive load, the reliability of load directly affects performance of source. Load failure could suddenly interrupt high current flow and produce high voltage spikes. As a result, it could induce serious damages to the pulsed power supply. To exam the limitations and tradeoffs could help to identify critical areas and plan advanced R&D efforts.

During the design study of the secondary particle focusing horn and horn pulsed power supply system for the AGS neutrino experiment proposal we encountered such scenario. In the proposed design, the peak current of horn is 300 kA. At the smallest area of horn, the current density would reach near 8 kA/mm^2. This high current density will likely induce electromigration phenomena. This led to our investigation of electromigration issue.

2. Electromigration

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.

According to various literatures, the discovery of electromigration was more than hundred years ago. 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.

In pulsed power system, current density correlated problems might happen at internal connection of pulsed capacitors, soldering point, pulse transmission lines,[2] mechanical joint of high current path, internal conductor of solid state device,[3] [4] and high current density load. Common factors affect the overall reliability of the pulsed power device and system 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,
- Ionizing radiation,
- Mechanical stress due to structural factors, etc.

3. An Example of Design Study

In neutrino beam facilities, magnetic horns are used to focus the secondary beam, and high voltage and high current power supply system are used to drive focusing horns through a set of transmission lines.

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

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than 2500 kilometers to reach the detector at far end.[1] 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.[1]

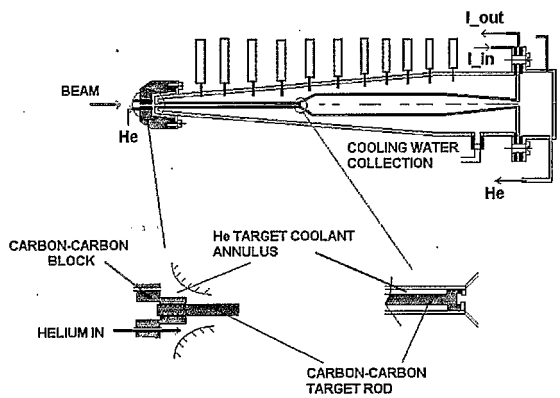

Figure 1. Target and horn configuration.

The simplified horn geometry is shown in Figure 2. Its parameters are listed in Table I.[1) 5)]

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		

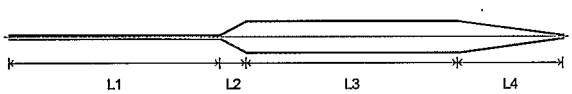

Figure 2. Simplified Horn geometry

A key question was asked at last year's International Neutrino Beam Instrumentation Workshop, NBI-2005. Is there any limitation in current capacity of horn (metal)? Actually, several physics experiments have been facing challenging issues of horn lifetime. However, almost all horn problems have been regarded as mechanical failures, material strength limitations, etc. These conclusions are correct in most situations.

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.

Electrical issues have been more focused on the high voltage pulsed power design and high current generation and pulse power transmission. Basic design considerations include high voltage design, high current transmission, high energy storage, low resistive and low inductive design, high radiation environment, device availability, device survivability, system fault tolerance, electrical, mechanical, and radiation safeties, and high noise immunity of control system, etc.

The electromechanical issues have not been considered as serious design limitations, while failure phenomena seem to correlate with electromigration. With horn of ultra thin walls, the current density might be above the threshold of electromigration.

In proposed horn design the fundamental frequency of the current pulse is 833 Hz. Its corresponding skin depth is 3.574 mm. The wall thickness of the horn, as listed in Table I, 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 high as 7.35 kA/mm^2. Figure 3 and 4 show the current conducting area and current density distribution alone horn axial.

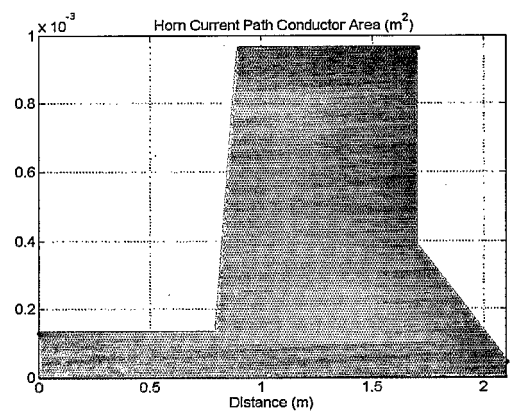

Figure 3. Horn current path area

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

In the proposed design, several parallel subsystems with solid state switches and capacitive energy storage will drive the load through a set of parallel plate transmission lines. 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 pulse 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.

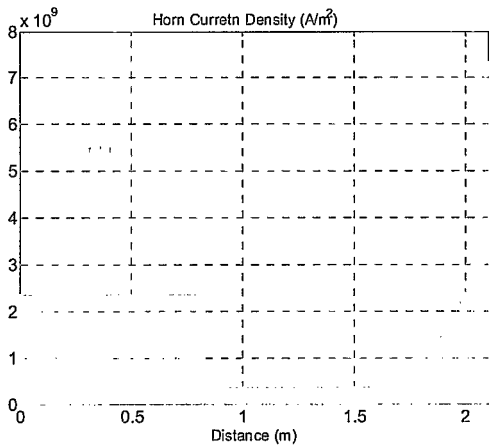

Figure 4. Horn current density

Solid-state devices are vulnerable to high voltage spikes. Therefore, high voltage arcing and pulse reflections at load and transmission path can cause massive damage to power supply system, control system, and diagnostic 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.

4. Design Comparison and Tradeoffs

We will use Black's equation to evaluate the design and compare it to existing devices. 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. A literature search of experimental results of aluminum material shows a wide range of n from 1.8 to 16 depending on many other variables. However, in the current density range being considered, we assume that n equals to 2.

4.1 Joule heating and device lifetime

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.[5] 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.[5] 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.

4.2 Current density and device lifetime

In the proposed horn design, tip of horn is 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.

4.3 Ionizing radiation and material activation

Another issue is the horn (or aluminum) damage associated with high level ionizing radiation. Usually, the activation energy of the particular aluminum material shall 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.[6] Considering that protons enter target area have particle momentum of 28 GeV, it is 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.

4.4 Extrapolation

Extrapolation can be used to evaluate a design based on known parameters. 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

4.5 Pulse polarity

Most Pulsed power system delivers uni-polar pulses. There have been some studies suggest bipolar pulses could reduce electromigration effect. 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. The proposed horn current waveform is a half sine pulse. It prompts us to consider if a bipolar wave shape is better rather than half sine.

4.6 Cooling method

Several cooling methods were considered for horn design, such as water, helium gas, and circulating oil. High pressure water cooling has been the preferred method for low cost and high efficiency. However, wet environment could accelerate electromigration. Insulating oil and helium gas have no known association to electromigration phenomena. In addition, the conductive nature of water could cause high voltage arcing, while insulating oil and gas have the advantage of high voltage withstanding. Therefore, we believe that they are better cooling agents in high voltage and high current systems.

4.7 Pulse width and incubation time

The electromigration is a process of mass transfer. It requires discrete time to cause an event to occur.[14] The incubation time is related to void growth, extrusion, edge displacement, and more importantly the flux divergence. 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. 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.

4.8 Pulse repetition rate

Several studies have linked the device lifetime to the pulsed repetition rate.[15) 18)] Both low repetition rate and high repetition rate might induce more electromigration damage. It challenges common believe of using higher repetition rate for accelerated lifetime test.

4.9 An enhanced model

An enhanced model, as shown in Figure 5, to study the horn device reliability and electromigration is derived from reference 10 and other related research works in reference 6-18.

5. Conclusion and Acknowledgement

Electromigration in metal conductor can become the limitation of the high current pulsed power system. Alternative material like Carbon Nano-tube (CNT) can handle several magnitudes higher of current density than metal. It can be used under much higher temperatures and has high mechanical strength. It would be interesting to see the application of CNT in future pulse power systems.

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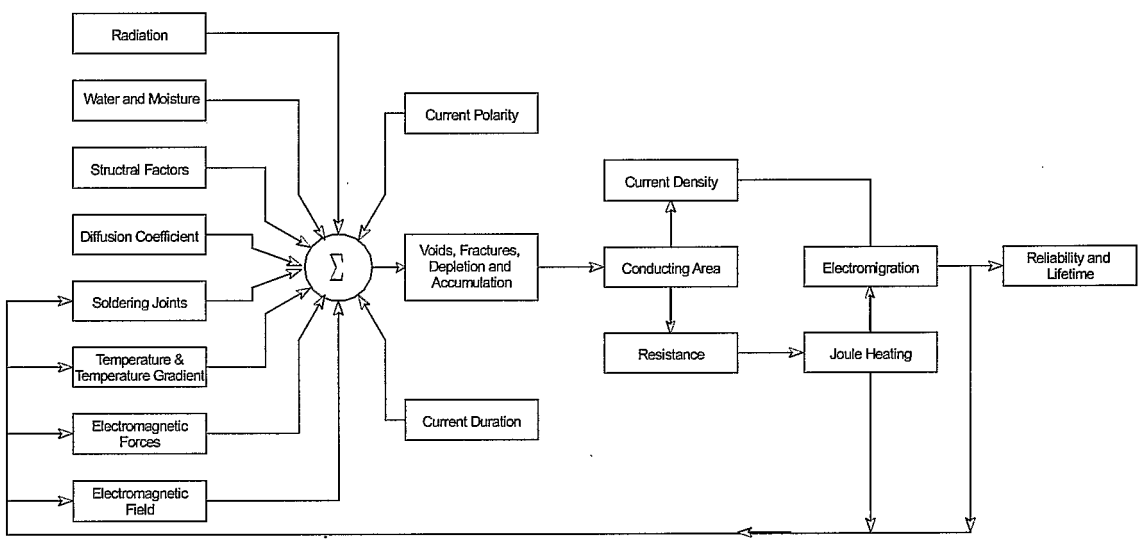

Figure 5. An enhanced electromigration and device reliability model

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