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ELECTROMAGNETIC AND THERMAL SIMULATIONS FOR THE SWITCH REGION OF A COMPACT PROTON ACCELERATOR

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ELECTROMAGNETIC AND THERMAL SIMULATIONS FOR THE SWITCH REGION OF A COMPACT PROTON ACCELERATOR*

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Abstract

A compact proton accelerator for medical applications is being developed at Lawrence Livermore National Laboratory. The accelerator architecture is based on the dielectric wall accelerator (DWA) concept. One critical area to consider is the switch region. Electric field simulations and thermal calculations of the switch area were performed to help determine the operating limits of SiC switches. Different geometries were considered for the field simulation including the shape of the thin Indium solder meniscus between the electrodes and SiC. Electric field simulations were also utilized to demonstrate how the field stress could be reduced. Both transient and steady-state thermal simulations were analyzed to find the average power capability of the switches.

INTRODUCTION

A compact proton accelerator based on the concept of dielectric wall accelerator (DWA) with field gradients as high as 100 MV/m is being developed [1,2]. The objective of this project is to determine the feasibility of making a compact proton accelerator for cancer therapy treatment. The existing proton treatment facilities are very large and costly. A compact proton machine will not only reduce the cost, but also can be used in most hospitals. One critical area to consider in the design is the switch region. The switches considered for this application are SiC photoconductive switches. They are compact switches capable of operating at high electric field and high peak current at elevated temperature with long lifetime. Maximum switch critical field is limited by bulk breakdown strength of SiC and field enhancement of switch electrodes. In order to operate at 100 MV/m field gradient in SiC switch material, field enhancement at electrode edges needs to be minimized. In this study, electric field stresses on different geometries were simulated to demonstrate how the field stress could be reduced. In addition to the field simulations, thermal calculations were performed to help determine the operating limits of SiC switches.

ELECTRIC FIELD SIMULATION

Figure 1 shows the two-dimensional view of a SiC switch. A SiC layer is sandwiched between two electrodes. Between the electrode and SiC layer is a very thin layer of Indium solder meniscus.

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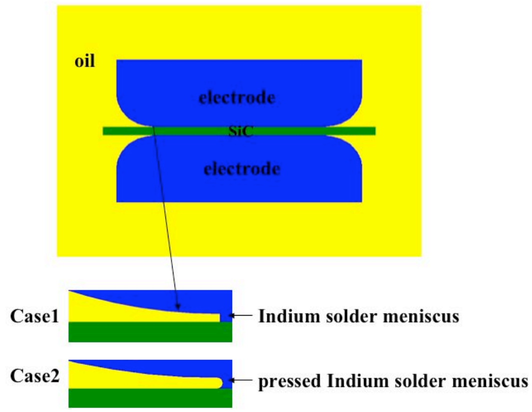

Figure 1: Two-dimensional configuration of a SiC switch. The bottom pictures show an enlarged view of the area between the electrode and SiC layer.

Since during the manufacturing process, Indium solder meniscus could be pressed to have curved edges (Case 2 in Figure 1), electric field simulations were performed to study the effects on the field enhancement. In the simulation, the top electrode is charged to 11 kV while the lower electrode is at ground. Magnitude of electric field along the interface of SiC and Indium solder meniscus for Case 1 and 2 are displayed in Figure 2 and 3, respectively. For both cases, the two peaks occur at the edges as expected. For case 1, the peak field is about 80 MV/m and is below the breakdown strength of SiC selected (around 200 MV/m). However, for Case 2, the peak field stress is three times the peak field stress of Case 1 and is above the breakdown threshold of SiC selected. Therefore, SiC switches can fail at a lower voltage than expected. The results explain what has been observed in the experiment.

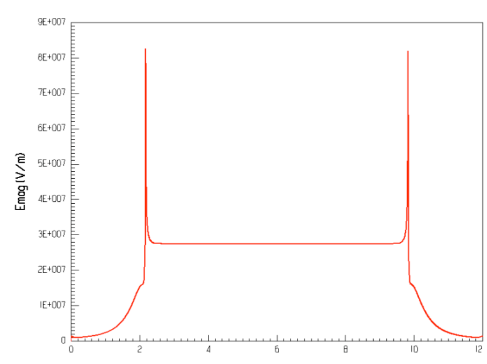

Figure 2: Magnitude of electric field along the interface of SiC and Indium solder meniscus for Case 1.

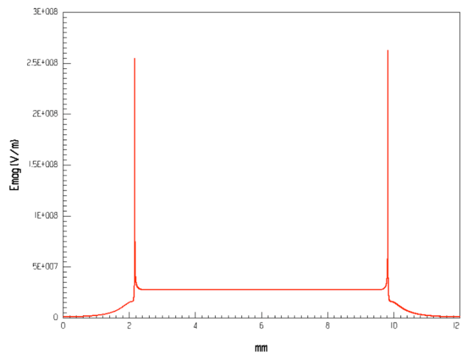

Figure 3: Magnitude of electric field along the interface of SiC and Indium solder meniscus for Case 2.

The maximum stress for Case 2 can be greatly reduced using the nanoparticle composite filler (Figure 4). The plot of electric field magnitude along the interface of SiC and Indium solder meniscus is displayed in Figure 5. The result shows the maximum field stress is reduced to one fifth of the field stress in the original configuration.

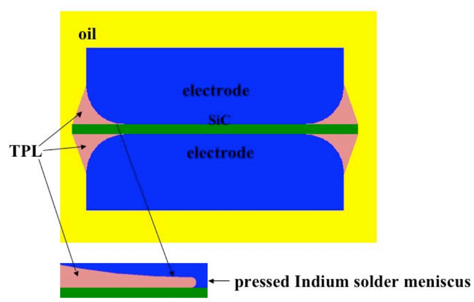

Figure 4: Two-dimensional configuration of a SiC switch with nanoparticle composite filler. The bottom picture shows an enlarged view of the area between the electrode and SiC layer.

THERMAL LOAD CALCULATION

To calculate the thermal load on SiC switches, a three-dimensional thermal transient analysis was performed to obtain the temperature variation as a function of time and position inside the structure. The configuration for the simulation is shown in Figure 6. A SiC layer is sandwiched between two copper sheets. Teflon layers are on the other sides of copper sheets and also next to the SiC layer. One side of the SiC layer is in contact with the oil. For the simulation, it is assumed all energy stored in the Blumleins to be dissipated in the switches. The power density inside SiC is 4.7e6 W/m^3 at 10 Hz.

Thermal transient simulations were performed for two cases. One is with the power on for 100 seconds. The second case is assuming the power to be on for 3000 seconds. The room temperature is assumed to be 25 degrees Celsius. Figure 7 shows the average temperature of SiC as a function of time with the power on for 100 seconds. The average temperature in SiC increases when the power is on and reaches 61 degrees Celsius before the power is turned off at t = 100s. After the power is off, the average temperature inside SiC decreases as we have expected.

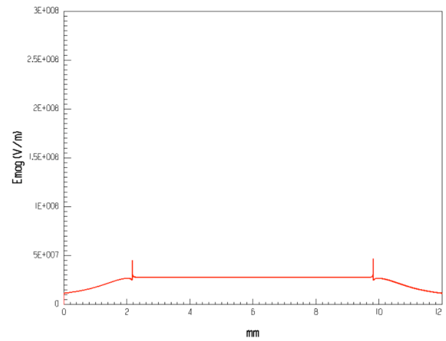

Figure 5: Magnitude of electric field along the interface of SiC and Indium solder meniscus for the case with nanoparticle composite filler.

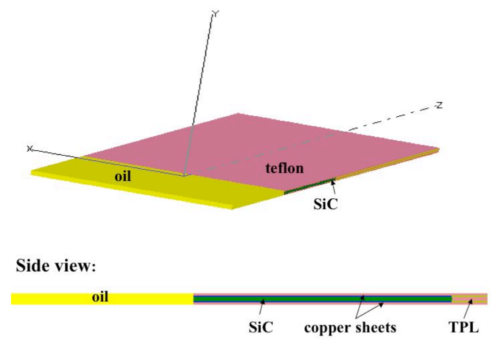

Figure 6: Configuration for the thermal analysis of SiC switches. The bottom picture shows the two-dimensional side view of the geometry.

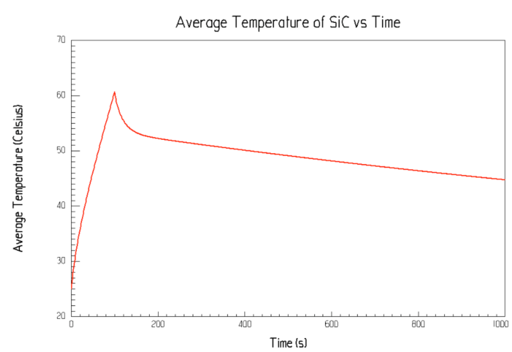

Figure 7: Average temperature of SiC versus time with the power on for 100 seconds.

As a function of time, the average temperatures in Teflon and oil have the similar trend as the temperature in SiC. Temperature in teflon reaches 57 degrees Celsius before the power is turned off at t = 100s while oil gets to about 32 degrees. Figure 8 shows the temperature along the z-axis at t=100s.

To see how high the temperature gets when the power is on for a long time, transient simulations were performed for the case where the power is on for 3000 seconds. Figure 9 shows the average temperature of SiC as a function of time with the power on for 3000 seconds. The average temperature in SiC and teflon reaches 540 degrees Celsius before the power is turned off at t = 3000s while oil gets to about 230 degrees Celsius.

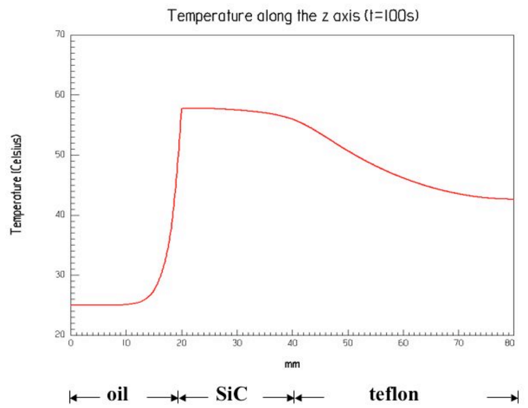

Figure 8: Temperature along the z-axis at t=100s (with the power on for 100 seconds).

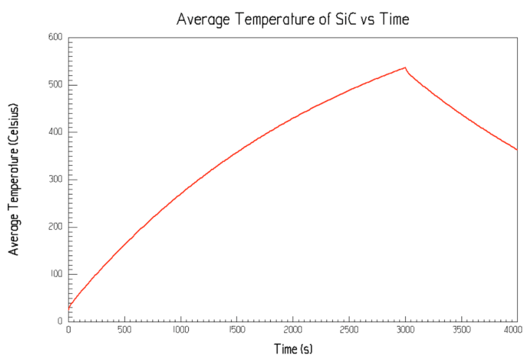

Figure 9: Average temperature of SiC versus time with the power on for 3000 seconds.

To further reduce the temperature, a configuration with oil surrounding the structure is considered (Figure 10). Two cases are also simulated for this configuration. The first case is with the power on for 100 seconds. The average temperature in SiC reaches 58 degrees Celsius before the power is turned off at t = 100s. It's only about 3 degrees lower than the temperature obtained for the first configuration (without the surrounding oil). Temperature in teflon reaches 51 degrees Celsius while oil gets to about 36 degrees. The average temperature of the oil is a little higher because more oil is helping to dissipate the heat in a short period of time.

The second case simulated for the new configuration is with the power on for 3000 seconds. The average temperature in SiC reaches only 180 degrees Celsius before the power is turned off at t = 3000s. It's about 360 degrees lower than the temperature obtained for the first configuration (without the surrounding oil). Temperature in teflon also only gets to 170 degrees Celsius (compared to 540 degrees in the first configuration) while oil reaches to about 85 degrees. The results show that the new configuration will help reduce the heating especially if the power is on for a long time.

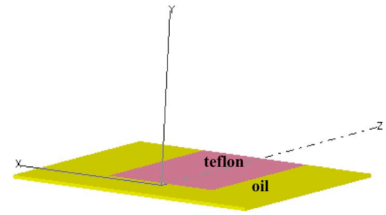

Figure 10: Geometry for the thermal analysis of switch.

Transient simulations were also performed for different power densities in SiC. The power is assumed to be on for 100 seconds. The results of peak temperature rise as a function of power density inside SiC are summarized in Figure 11. The design with one switch described earlier is with power density of 4.7e6 W/m^3 inside SiC. If we consider the temperature below 200 degrees Celsius to be in the conservative safe operating region, temperature rise in SiC switches will allow 6 times higher repetition rate than the current design.

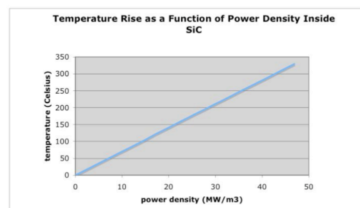

Figure 10: Peak temperature rise as a function of power density inside SiC after 100 seconds.

SUMMARY

To help determine the operating limits of SiC switches, electric field simulations and thermal load calculations of the switch area were performed. The electric field simulation results show that the maximum field stress can be larger than expected depending on the shape of the Indium solder meniscus. Using TPL nanoparticle composite filler, the maximum field stress can be greatly reduced. A three-dimensional thermal transient analysis was performed to calculate the temperature variation as a function of time and position inside the structure. Several cases were considered. The results show that the new configuration with oil surrounding the structure will help reduce the heating especially if the power is on for a long time.

REFERENCES

[1] G. J. Caporaso, et al., "High Gradient Induction Accelerator", PAC'07, Albuquerque, NM, June 2007.

[2] Y-J Chen and A. C. Paul, "Compact Accelerator for Cancer Therapy", PAC'07, Albuquerque, NM, June 2007.