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Analysis of DIII-D Upgraded Neutral Beamline Bending Magnet Thermal Shields

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***Abstract*—The ion bending magnets in the DIII-D neutral beamlines are protected by 12.7 mm thick copper thermal shields. These shields are inertially cooled by single pass water lines. After years of operations, these shields have suffered from thermal cracking, which once initiated, can propagate through a water cooling line causing water leaks into the beamline. The cracks in the thermal shields are always in the same area. Recent modeling of the beam ion distribution across the thermal shields shows very uneven heating. This modeling shows peak heat fluxes (on the order of 6 MW/m^2) and very high stresses near the crack locations.**

In addition to the concentrated heat flux, another possible factor affecting bending magnet thermal shield failure is beam pulse power modulation. In recent years, the beam source power has been rapidly cycled on and off to enable feedback regulation of beam injection power at less than full power operation. Beam divergence is largest at startup, and as a result of the frequent startups produced by modulation, the heat flux to the bending magnet thermal shields may be increased. Test results of the impact from rapid beam modulation on heat flux to the thermal shields will be discussed.

An improved design thermal shield, which minimized a stress concentration feature near the failure area, was developed and installed in two of the four the beamlines in 2005, but it was not designed for increased duration beam pulses. To allow for an increase in the allowable high power pulse duration, the bending magnet thermal shields are being replaced with an upgraded design. The upgraded design is centered on improved cooling in the peak heat flux region. A small panel insert in the larger shield plate is considered with numerous small water channels using cooling technology from the laser diode industry. The insert panel is designed to maintain a low surface temperature (less than 200°C) and to keep the temperature rise of the cooling water under 40°C. The remainder of the upgraded thermal shield is inertially cooled with water lines spaced to return the shield to initial temperature during the 600 second cool-down period.

Details of the bending magnet thermal shield heat flux modeling, the new long pulse shield design and the effect of beam pulse modulation are presented.

I. INTRODUCTION

DIII-D has four neutral beamlines, each with two ion beam sources (Fig. 1). These ion beams are neutralized and the neutral particles are injected into the plasma (2.5 MW per source of injected power). The current beam pulse length is limited to 3 s at maximum power. The internal components of the beam line are protected by water-cooled copper collimators and thermal shields. The only thermal shields or collimators that have failed inside of a beam line are the thermal shields protecting the magnet poles of the ion bending magnet. The ion bending magnet bends the ions that were not neutralized back towards an ion dump to prevent charged particles from impacting unshielded surfaces.

The magnet thermal shields are large, single piece oxygen free copper (OFC) plates, which are approximately 1565 x 711 x 12.7 mm. These shields are inertially cooled and are instrumented with nine thermocouples (TCs). The cooling is passive and achieved by a long single-pass cooling tube which is capable of returning the shield to its initial temperature after a 600 s between-pulse interval. In recent years, the neutral beams have been modulated (rapid on/off cycling) frequently. This beam pulse modulation was believed to have contributed to the failure of the thermal shields.

While these shields have survived some years of operations at current pulse durations, it is desired to upgrade the beamlines to longer duration pulses (10 s) in the future. These thermal shields are the weakest of the internal components because of their relative thinness and uneven heat flux exposure. Initial evaluations have shown that these thermal shields will require active cooling to survive longer high power pulses without damage.

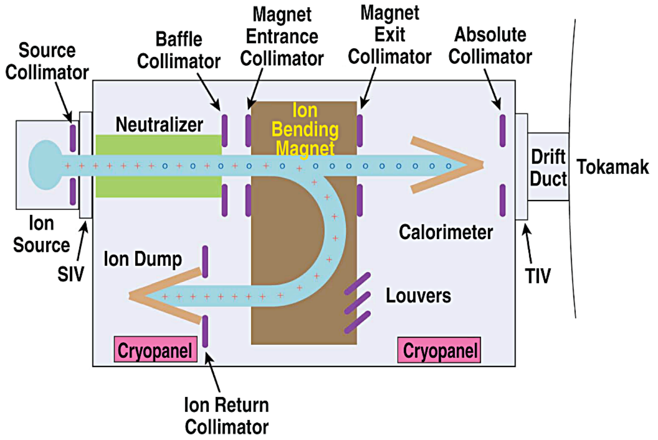

Figure 1. Beamline horizontal section view showing ion bending magnet location.

II. EXISITNG THERMAL SHIELD FAILURES

A. Failure Location

All of the damaged thermal shields have shown damage in the same area. This area is shown in Figs. 2 and 3 and is located close to the sharp corner edge of a thermocouple routing channel (located on opposite side of that shown in Figs. 2 and 3). The sharp corner edge of the channel introduces a stress concentration factor and has been the initiating location for all cracks in the thermal shields. An improved thermal shield design installed in 2005 rounded this sharp corner and minimized the stress concentration there. Typically the failure mode has been cracking, but warping of the plate with no cracking has also been observed.

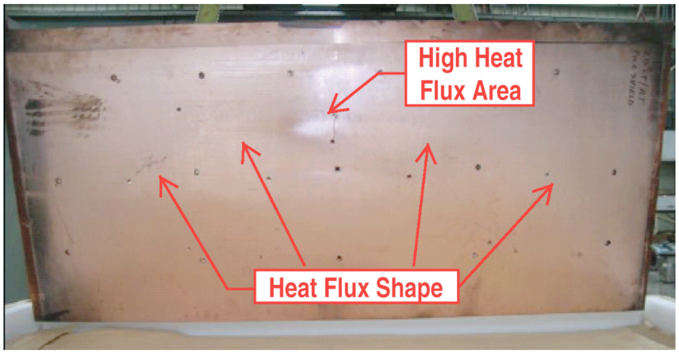

Figure 2. Thermal shield showing crack and heating pattern.

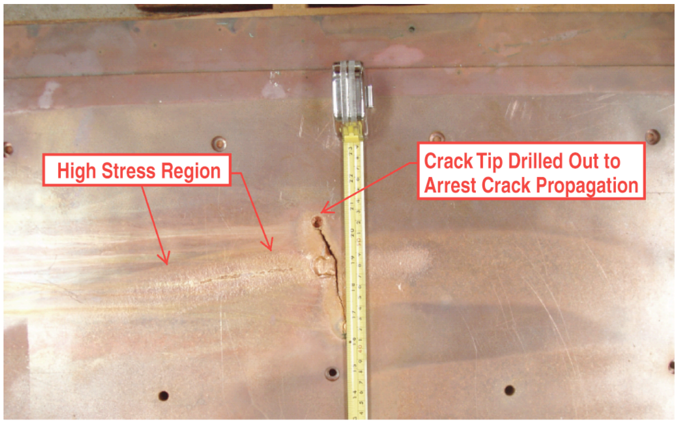

Figure 3. Visible heat flux damage and cracking of plate.

B. Failure History

The bending magnet thermal shields that were designed and installed in 1986, were in use in 2003 when a crack in a shield resulted in a water leak in the beamline (referred to as 30L). Prior to this incident, no thermal shield damage had been seen during annual beamline inspections. After the shield failure, all beamline thermal shields were inspected and 11 of 16 (69%) were found to be damaged (2 of the undamaged shields had seen limited use as the 30R ion source had only been in operation for approximately half of the time the other sources had been operating). The thermal shields from the 30L source were replaced with the shields from the 30R source since it was no longer in use. For the other thermal shields, the crack tips were drilled out to minimize the probability of continued crack propagation and water line rupture. Operation of the beamlines was then resumed until a one year shutdown began in April 2005. Following the shield replacement, the maximum beam pulse length was reduced by 10%.

In 2005, all eight of the thermal shields in the 150 and 210-deg beamlines were replaced with improved design shields (three of the existing shields that were removed were not cracked). In 2008, a thermal shield failed that had not shown damage in 2003. This failure resulted in a water leak in the beamline (330-deg left), as a crack in the shield propagated through a water line. After this incident, all of the thermal shields were inspected and damage was discovered on the 30-deg left source shields as well as on the 330-deg right source shields. Two new thermal shields without any thermocouple channels were rapidly manufactured and installed in the 30-deg left beamline and the three undamaged thermal shields that had been removed from the 210 and 150-deg beamlines in 2005 were put into the 330-deg beamline. Of the 14 bending magnet thermal shields currently in use, 8 are of the improved design installed in 2005, 2 are of the simplified and improved design installed in 2008, and 4 are of the original design.

III. HEAT FLUX MODEL

A charged wire was used to measure the orbit path of charged ions across the bending magnet (wire orbit model). This mapping of the ion orbit paths was used in the development of a heat flux model. An assumption was made that energy from the ions was deposited uniformly along the orbit paths and that all of the orbits had equal energy deposition per unit length. The total energy deposited by the ion orbit paths was set equivalent to the total power deposited on the thermal shield based on water flow calorimetry measurements. As the orbits were plotted, a high heat flux region that has nearly all of the ion orbits crossing it was evident as can be seen in Fig. 4. The calculated heat flux in this region is approximately 6 MW/m^2. The effects of this high heat flux region can be clearly seen on the thermal shields in Figs. 2 and 3.

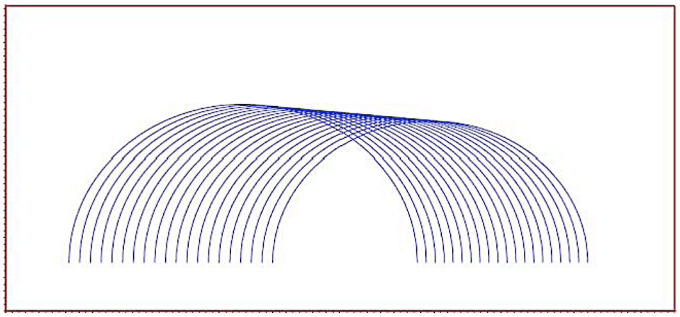

Figure 4. Ion orbits across bending magnet face.

IV. EXISTING THERMAL SHIELD ANALYSIS

The heat flux model described in the preceding section was used in a finite element model of a simplified existing thermal shield. The maximum calculated temperature on the thermal shield was 319°C for a pulse of 3 s duration (Fig. 5). Large temperature gradients were present in the model as the heat flux from the ion orbits has a very large gradient, going from near maximum energy deposition to zero energy deposition across a very short distance. These sharp temperature gradients generated high thermally induced stresses (Fig. 6). The inner heated region of the plate is thermally expanding against the colder outer region of the plate. The thermal shield plate had been fully annealed in the course of manufacture during the brazing of the cooling water tubes. The yield strength for annealed OFC is approximately 34.5 MPa. The calculated stresses in the plate are approximately 7 times the allowable stress of the OFC in compression and 1.5 times the allowable stress in tension (allowable stress for thermally induced stress being twice yield stress). These stresses are highest in the region where the plates had cracked at the thermocouple groove. In plates where no crack is present, the high stress region is characterized by out of plane warping and/or surface texture change.

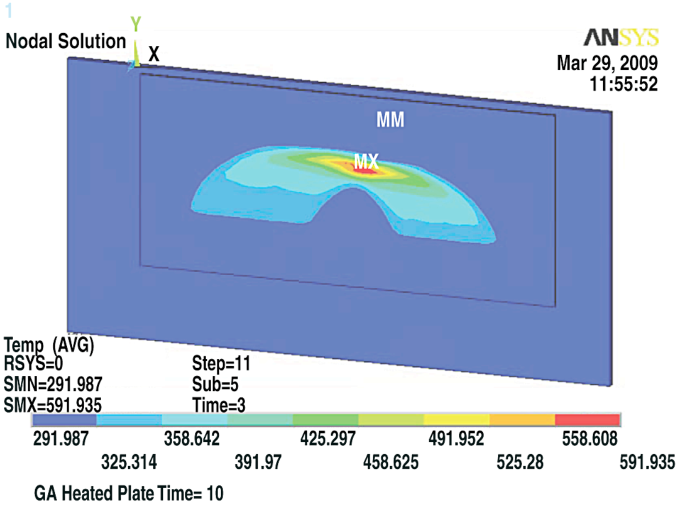

Figure 5. Temperature (Kelvin) distribution on thermal shield after 3 s shot.

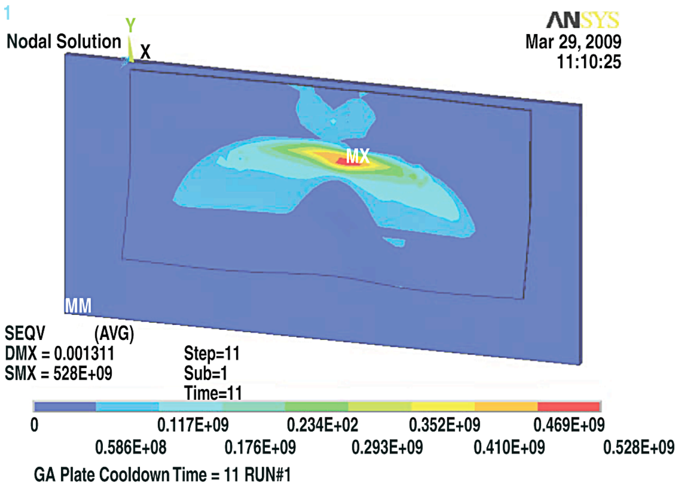

Figure 6. Von Mises stress (Pa) distribution on thermal shield (deformed shape not to scale).

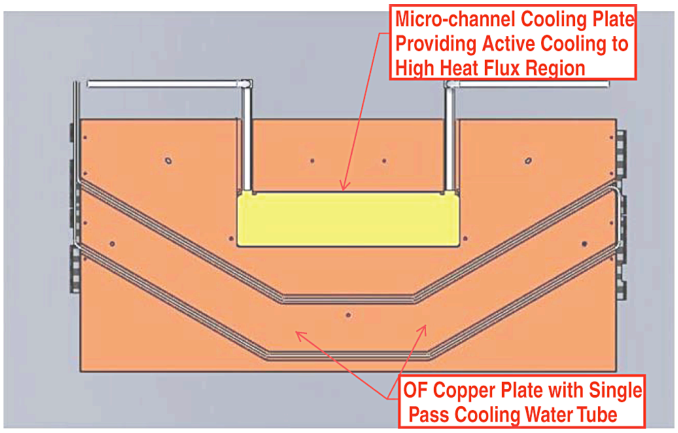

Figure 7. Upgraded thermal shield design (non-heated side shown).

V. NEW THERMAL SHIELD DESIGN

In evaluating the current thermal shield design for longer pulse (10 s) operation, it was determined that the surface temperature of the shield would approach the melting temperature of the OFC. Increasing the thermal shields beyond the current 12.7 mm thickness was not an option due to geometry constraints in the beamline. Active cooling was determined to be necessary to keep the surface temperature of the thermal shield below the melting temperature of the copper. To achieve active cooling, a micro-channel cooling plate was employed. The micro-channel cooling plate is approximately 610 x 152 x 12.7 mm. This plate is filled with numerous small cooling passages which are approximately 0.13 mm wide. The technology is used often in laser diode cooling applications. This plate has numerous small cooling passages approximately 0.13 mm wide, fed in parallel. The technology is used often in laser diode cooling applications. This plate is designed for a peak surface temperature of less than 140°C to minimize thermal stresses. The plate has a water flow rate of approximately 1 L/s.

The upgraded thermal shield design is split into three parts. These parts are (see Fig. 7) the large base plate (inertially cooled OFC), the micro-channel cooling plate (actively cooled Glidcop®) and the small OFC plate (uncooled). The small OFC plate is not expected to receive any significant amount of heating and will be conductively cooled by the bending magnet.

Using the heat flux model from Section 3, a 10 s pulse was applied to the large base plate of the upgraded thermal shield. The maximum temperature was calculated to be 309°C (Fig. 8). The thermally induced strains in this upgraded design are approximately 25% lower than the original shield (Fig. 9). The new large OFC plates will utilize a flame spray process for thermally attaching the cooling tubes to prevent annealing of the plate (existing thermal shields were annealed during the brazing of the cooling tubes) and maintain its strength. The new lower strains combined with the new unannealed thermal shield plates result in acceptable stresses for a 10 s pulse.

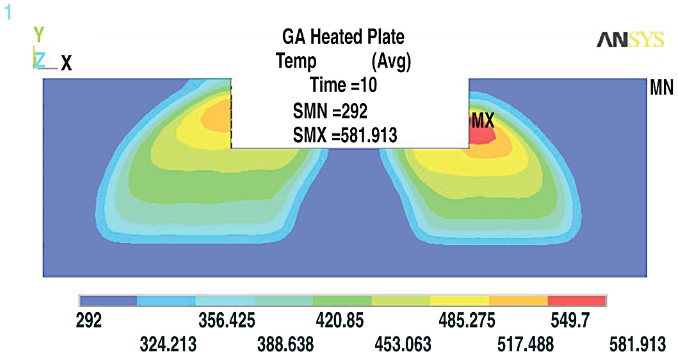

Figure 8. Temperatures in upgraded thermal shield (K).

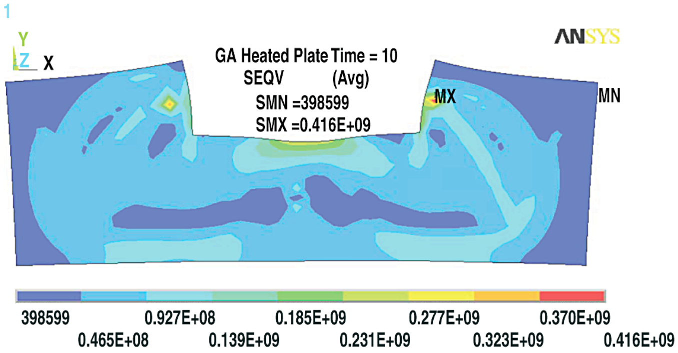

Figure 9. Von Mises stresses in upgraded thermal shield (Pa) (deformed shape not to scale).

VI. BEAM PULSE MODULATION EFFECTS

The practice of modulating the neutral beams began around 2001. Modulation is the rapid on and off cycling of the ion source (e.g., 50 ms on/50 ms off repeated). This allows the beam pulse to be used to generate diagnostic beam blips without injecting too much energy and it enables the use of feedback control of the beams where the average injected power is regulated by controlling the modulation duty cycle. Modulation of the beamlines has become very common during DIII-D operation. Approximately 80% of all experiments during the most recent DIII-D operation period used modulated beams. Since beam optics are worst (and therefore divergence is largest) in the first millisecond of a pulse, it was thought that modulation would lead to greater heating of the thermal shields due to the many beam turn-on phases of a modulated injection pulse train. Testing revealed that the magnet entrance collimators just upstream of the bending magnets did receive approximately 65% greater heating during modulated pulses for a given injected energy level. The bending magnet thermal shields, however, did not see increased heating, but actually saw anywhere from a 5%–40% decrease (data was not uniform) in heating. This testing of the modulated beam pulses showed that the bending magnet thermal shields were not receiving greater heating from the frequent startups occurring during modulation, perhaps because the power was not present continuously and had more time to disperse across the thermal shield. The data gathered from beam pulse modulation testing revealed that if anything, beam modulation would likely reduce the stresses and temperatures on the bending magnet thermal shields.

VII. CONCLUSION

Analysis of the existing thermal shields reveals that the shield failure was caused by large stresses resulting from non-uniform heating. The upgraded thermal shield is designed to manage non-uniform heat loads. A 10 s pulse length requires active cooling to avoid shield damage. A micro-channel cooling plate will be able to provide the necessary active cooling in the highest heat flux region. The remainder of the upgraded thermal shield has been strengthened through a new process of water cooling line attachment.

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