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Thermal Analysis and Simulations of the Abort Kicker Magnets Systems for the Electron-Ion Collider

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DISCLAIMER

Thermal Analysis and Simulations of the Abort Kicker Magnets Systems for the Electron-Ion Collider*

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Abstract

The Abort Kicker Magnets system used in the current Relativistic Heavy Ion Collider (RHIC) to steer the circulating beam into the dump will be subjected to higher heat loads in the Electron-Ion Collider (EIC). After analyzing the existing abort kicker magnets and running thermal simulations in ANSYS it was concluded that they may not be suitable for use as-is in the future EIC due to heat and impedance concerns in the magnets.

Possible solutions include adding a round titanium-coated ceramic beam tube to help solve the heat and impedance concerns, but this will reduce the limiting aperture of the kicker magnet. Another possible solution to meet all the performance requirements for EIC would be to add titanium-coated ceramic plates with water-cooling and tapered transitions that significantly improve the impedance and lower the heat in the magnets with less reduction to the aperture.

INTRODUCTION

In 2014, the ferrite material used in the abort kicker magnets was changed from CMD5005 to CMD10, and an active ferrite cooling loop was installed to prevent heating. The cooling circuit was designed for a 1 KW heat load in each of the five abort kicker magnets, but the estimated heat load for EIC is 5 kW per abort Kicker [1]. The thermal properties of CMD10 measured at CERN [3] were used for thermal simulations on the kicker for a heat load of 5kW per abort kicker.

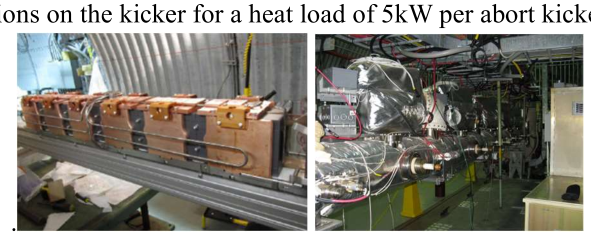

Figure 1: Abort Kicker Magnets System in RHIC

MECHANICAL DESIGN

The Abort Kicker Magnets System is composed of 3 chambers that each have 5 magnets. The full length of a chamber is about 25 ft.

Figure 2: Chamber of Five Kicker Magnets' Assembly

Each kicker module is made up of 6 ferrite blocks (Fig.3 - in purple and brown) assembled in a square with a high-voltage busbar inserted in their center. The busbar is the coil of the magnet made of Stainless Steel 304 (Fig.3 - in white). The ferrite blocks are cooled through pressed-contact with copper plates installed all around the magnet (Fig.3 – in orange), cooling tubes made of Stainless Steel 316 are clamped unto the copper plates and used to provide water cooling to the magnet structure.

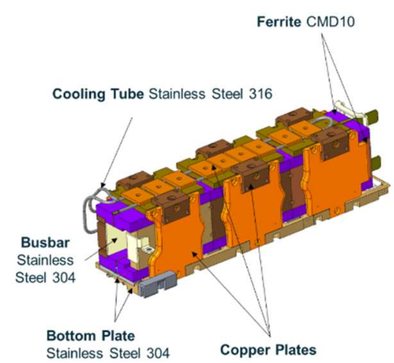

Figure 3: Materials in a Kicker Module

The ferrite material used in each kicker module is commonly referred to as CMD10 which is a Ni-Zn alloy used for fast pulse applications. This material has a high relative permeability which guides the magnetic field, ensures field homogeneity in the aperture of the kicker module while reducing the amount of pulse current required [3]. An essential property of this material is its Curie Temperature that is the temperature above which there is a sudden drop in the ferrite's permeability which might cause the kicker to lose kicking strength due to a loss of its magnetic properties. It is then required to keep the temperature in the kicker's ferrite below the curie temperature to ensure its safe operation. For CMD10, the curie temperature is estimated to be 250°C [2].

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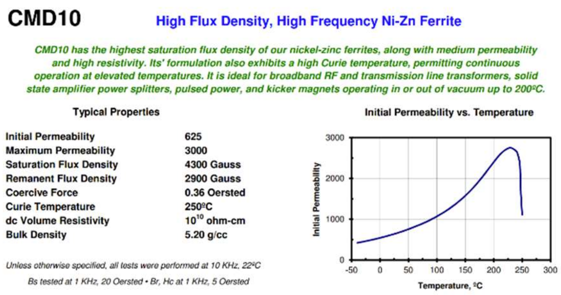

Figure 4: Magnetic Properties of the CMD10 Ferrite

COOLING CIRCUIT

The cooling circuit installed on the abort kicker magnets system in 2014 is a continuous water loop that ends with a knife edge flange for external connection [4].

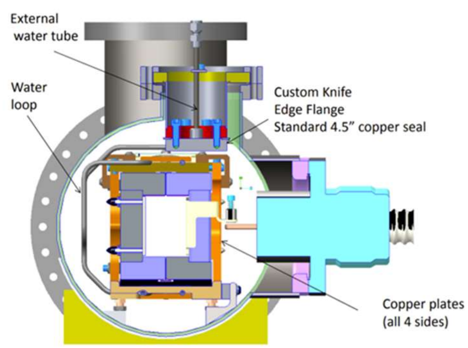

Figure 5: Cross-Section of the Abort Kicker System with the Water Loop

Water is supplied to the magnet through cooling pumps that are connected to a reservoir tank. Between the cooling pump and the reservoir tank there is a heat exchanger, a filter, a gear pump and an AC Motor that regulates the amount and speed of water flowing to the magnets.

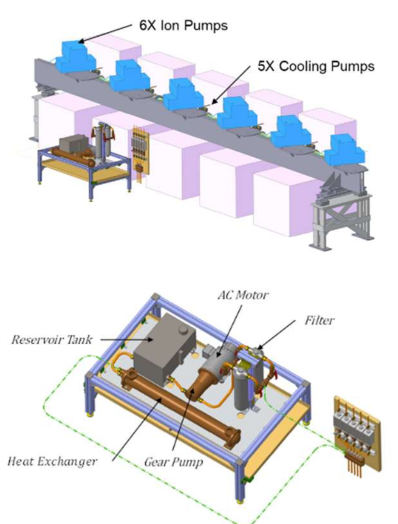

Figure 6: Cooling Circuit of the Abort Kicker System

THERMAL SIMULATIONS IN ANSYS

Two main types of thermal simulations were performed in ANSYS. The first is a best-case scenario that assumes all the materials in the kicker module are in perfect thermal contact. The other case was more conservative and helped provide a worst-case scenario in which the contact between Ferrite to Copper or Ferrite to Steel material is very rough leading to the highest temperature gap between the materials. This worst-case scenario was modeled in ANSYS by adding an estimated Thermal Contact Conductance (TCC) of 1500 $\mathrm{W/m^2 \cdot K}$, the lowest TCC value for contact between ceramic and metal materials. At first, thermal simulations were done for the kicker as it is in RHIC to ensure that the right boundary conditions are being used in the analysis.

The water-cooling guidance from EIC infrastructure provides a supply temperature greater than 86 F (30 ℃), a water temperature rise greater than 10 F (5 ℃) between the water inlet and outlet. The cooling water should flow at a rate between 5 ft/s (1.524 m/s) and 10 ft/s (3.048 m/s) to decrease the erosion in the cooling pipe. The pressure drop throughout the system should be less than 45 Psi. From these values, the boundary conditions of the thermal analysis were computed and summarized in the table below:

System		RHIC	EIC
Water Temperature	Inlet Temp.	22 ℃	30 ℃
	Outlet Temp.	28 ℃	53 ℃
	Avg Temp.	25 ℃	41.5 ℃
Cooling Pipe	Outer Diameter	1/4 "	
	Inner Diameter	3/16 "	
	Full Length	296.506 "	
ANSYS Input	Heat Load	1000 W	5000 W
	Mass Flow Rate	0.0409 kg/s	0.0534 kg/s
	Volumetric Flow Rate	0.65 GPM	0.85 GPM
	Flow Velocity	7.56 ft/s	9.93 ft/s
	Heat Transfer	11378.3939 W/ (m2.K)	16468.87 W/ (m2.K)
Water Pressure Drop		**16.91 Psi**	**25.69 Psi**

Table 1: Thermal Analysis Boundary Conditions

Due to the symmetry in the kicker, thermal simulations were performed in ANSYS using half of the kicker and heat loads of 500W for RHIC and 2500W for EIC.

RHIC THERMAL SIMULATIONS

Thermal simulations were performed with 1KW heat load to benchmark the thermal simulations done by C. Pai in 2014 during the kicker upgrades [4]. In his analysis C. Pai got a maximum temperature in ferrite of 65.5 ℃ which is very close to the maximum temperature of 64.022 °C shown in the pictures below.

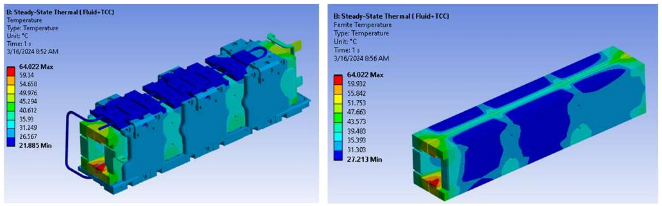

Figure 7: Temperature in Kicker Magnet 1KW Heat Load

EIC THERMAL SIMULATIONS WITH PERFECT CONTACT

Assuming perfect contact between all the materials in the assembly, thermal simulations were performed for a heat load of 5KW heat load per kicker magnet. Temperatures in the ferrite were much higher than the thermal simulations with the RHIC parameters. The maximum temperature in the ferrite was 193.220 °C which is lower than its Curie Temperature making the magnet safe to operate, even though this is not recommended.

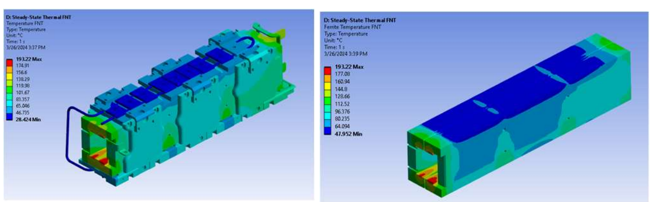

Figure 8: Temperature in Kicker Magnet 5KW Heat Load (Perfect Contact)

EIC THERMAL SIMULATIONS WITH BAD CONTACT (WORST CASE SCENARIO)

Adding a thermal contact conductance of 1500 $W/m^2 \cdot K$ between Ferrite-Copper and Ferrite-Steel materials, helped simulate a more realistic behavior of the thermal contact and temperature difference between dissimilar materials.

In this case, the maximum temperatures in the ferrite were found to be around 277.63°C. Knowing these values exceed the Curie Temperature of CMD10 shows that depending on the contact between the materials, the ferrite in the kicker could temporarily lose its electromagnetic properties and cause the kicker to misfire due to the heat in the magnet.

Through a time-dependent analysis, the time constant of the kicker was estimated to be 8 min 40 s. This is the time it would take to reach 67% of its maximum temperature. Under a heat load of 5KW, the ferrite in the magnet will take approximately 1 hour 28 min 33 s to reach its Curie temperature. This is shorter than the expected EIC beam store duration so we cannot take credit for thermal inertia.

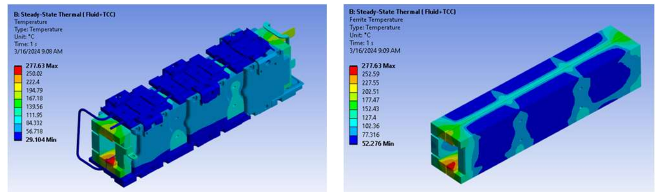

Figure 9: Temperature in Kicker Magnet 5KW Heat Load (Worst-Case Scenario)

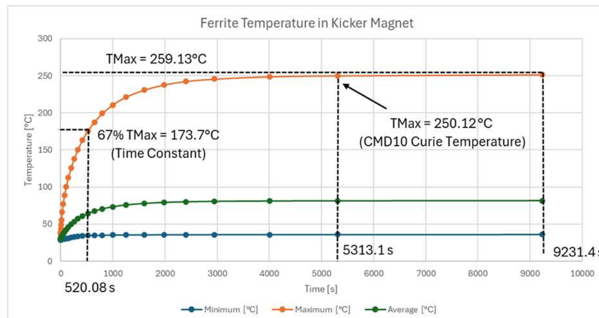

Figure 10: Temperature in Ferrite vs Time 5KW Heat Load (Worst-Case Scenario)

POSSIBLE SOLUTION TITANUM-COATED CERAMIC PLATES

The permeability of a ferrite material is a physical property that describes its ability to respond to a magnetic field meaning that a ferrite material with higher permeability would be easier to magnetize. Magnetic permeability is usually expressed as the ratio between the material's permeability and the permeability of free space which is why it is dimensionless and commonly referred to as relative permeability. Unfortunately, ferrite materials with higher curie temperatures tend to have a lower initial permeability. The initial permeability and curie temperature of CMD5005 are respectively 2100 and 130 °C . For CMD10 they are 625 and 250°C. Any ferrite material with a Curie temperature higher than 250 °C, will have an initial permeability lower than 200 which may reduce the strength of the kicker. Changing the ferrite material, as it was done in 2014 was not considered a viable solution.

The heating in the ferrite could be reduced by improving the cooling capacity. This can be done by increasing the diameter of the cooling pipe, maximizing the flow rate of the coolant, increasing the area of the copper insert in the magnet, increasing the contact force and pressure between materials, and lowering the coolant's inlet temperature.

Although these solutions may help with the heating of the kicker, there is still a need to improve its impedance for EIC. A solution to solve both the heat and impedance issue in the kicker magnet would be to add a round beam tube in the kicker but this would significantly reduce the aperture of the kicker. Therefore, it was suggested to add Titanium-Coated ceramic plates that would reduce the kicker's aperture by less than 10% while improving its impedance through tapered transitions without disturbing the integrity of the magnetic field. More thermal simulations were conducted in ANSYS to understand how adding the ceramic plates would affect the temperature of the ferrite in the kicker.

Through thermal simulations in ANSYS it was estimated that without water-cooling, adding the titanium-coated ceramic plates brings the maximum temperature of the ferrite down to 160℃ which is less than its curie temperature. If water cooling were to be added to the ceramic plates, these temperatures would go down to 73℃ and the time constant of the magnet would be about 7 seconds. These are ideal operational values which would meet all the performance requirements for the abort kicker magnets system in EIC.

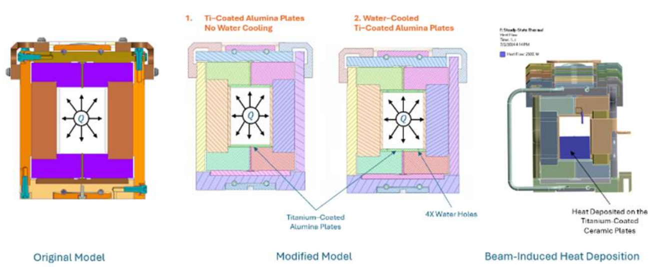

Figure 11: Modifications to the Model

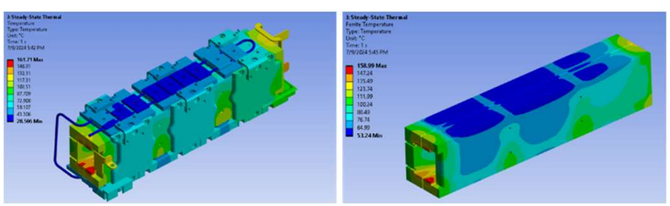

Figure 12: Temperature in the Kicker Magnets 5 KW Ti-Coated Plates without Water-Cooling

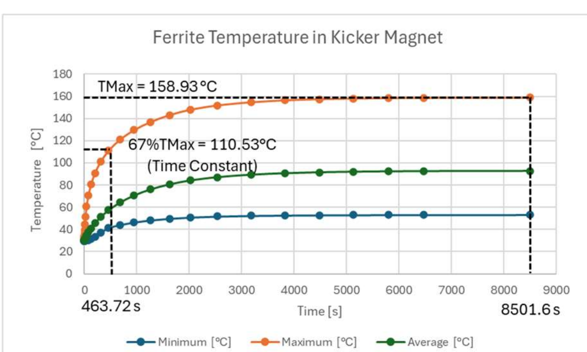

Figure 13: Temperature in the Ferrite vs Time Ti-Coated Plates without Water-Cooling

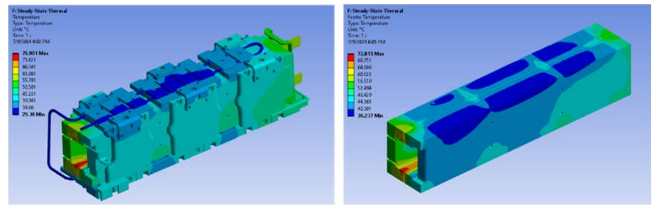

Figure 14: Temperature in the Kicker Magnets 5 KW with Water-Cooled Ti-Coated Plates

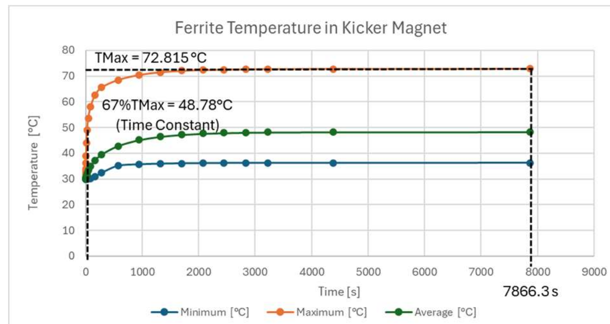

Figure 15: Temperature in the Ferrite vs Time with Water-Cooled Ti-Coated Plates

PATH FORWARD

A better understanding of exact beam-induced heat deposition on the kicker magnet is needed to perform more accurate thermal simulations. Furthermore, knowing the current temperature profile of the profile kicker magnets could help understand how the thermal simulations compare to the actual temperatures in the magnet. Also, understanding the aperture requirement of the magnet is needed to find the most optimal solution to the heat and impedance concerns. The abort kicker magnets could be redesigned to lower the temperature in the ferrite, but this would require electromagnetic analysis to understand how changes made to the kicker would affect the magnetic field and strength of the kicker.

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