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PROTOTYPE AND HIGH-POWER TEST OF SIC HOM*

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Abstract

In the EIC Electron Storage Ring (ESR), there will be beam currents up to 2.5 A, which will excite massive Higher-Order-Modes (HOM) power in the 17 single-cell 591 MHz Superconducting Radio Frequency (SRF) cavities. To damp the HOM power in the ESR SRF cavities is a challenge. A room temperature cylindrical shell shape Silicon Carbide (SiC) Beamline HOM Absorber (BLA) was chosen as the baseline design, due to its broadband and high-power capability, and previous demonstrations at other accelerator facilities, albeit at much lower power. Because the EIC BLA HOM power dissipation is significantly greater than the previous applications, it is imperative to carry out high power testing to determine the maximum device performance levels achievable for thermal transport, RF breakdown, and mechanical stress, prior to finalizing the design. A SiC HOM absorber with state-of-the-art geometry size was prototyped to verify shrink-fit technique, test outgassing rate, and high-power handling capability. This paper presents the HOM damper's prototyping and test results.

INTRODUCTION

Figure 1 shows, geographically, the RF systems in the EIC [1,2]. In the EIC ESR, there will be 17 single-cell 591 MHz SRF cavities to compensate for up to 10 MW of synchrotronic radiation loss in the EIC ESR. The beam current, bunch length, cavity voltage, and HOM power for different operation scenarios in EIC ESR are listed in Table 1. The most challenging scenario for HOM damping is to damp the 72.7 kW HOM power in the 10 GeV case, which has the shortest bunch length and highest beam current. Therefore, the 10 GeV case is the focus of the HOM damper design.

The EIC SiC HOM damper will use a cylindrical shell shape, which is similar to the applications in KEKB [3], APS-U [4], Cornell [5], and TRIUMF [6]. These solid cylindrical shell shape SiC HOM dampers are based on the shrink-fit technique and use water-cooling jackets to remove the heat energy. The failure limit of the HOM absorber's power handling capability is determined by the absorber assembly's thermal transport properties and the temperature profile for the given geometry. Therefore, we will use the HOM absorbing power flux to determine the SiC HOM absorber's maximum power handling capability. The power flux will provide design guidance for future BLAs. Previous SiC HOM damper testing [4, 7] found a power flux up to 0.2 W/mm^2 to be tolerable, however, there is no credible data on the maximum power flux of a SiC BLA. This paper will present the BLA prototype HOM damper test results.

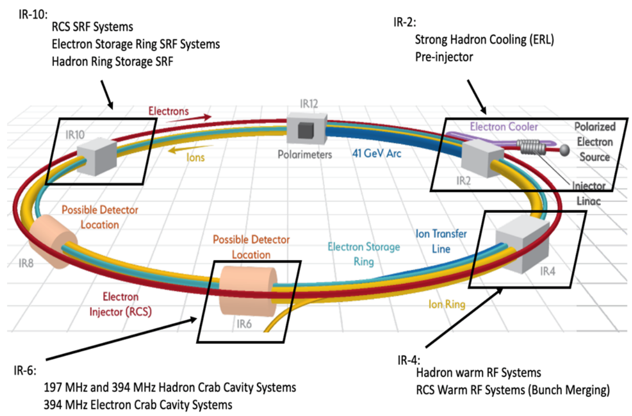

Figure 1: EIC RF systems.

Table 1: EIC Operation Scenarios

Beam parameters	Scenarios #1	Scenarios #2	Scenarios #3
Beam energy (GeV)	5	10	18
Beam current (A)	2.5	2.5	0.227
Bunch charge (nC)	27.6	27.6	10
RMS bunch length (mm)	9.6	7.7	8.7
Number of bunches	1160	1160	290
Cavity voltage (MV)	0.57	1.27	3.62
Total HOM power per cavity (kW)	65.1	72.7	2.4

HOM DAMPER DESIGN FOR EIC ESR SRF CAVITY

Figure 2 shows the HOM power flow for ESR SRF cavity [8, 9], where both SBLA and LBLA are 240 mm. Detail dimensions and power of the BLAs are listed in Table 2.

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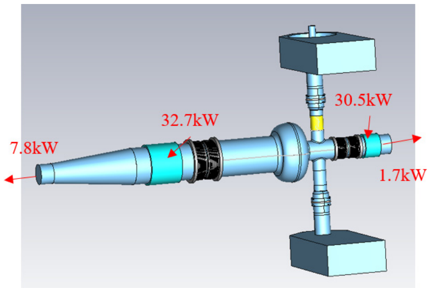

Figure 2: HOM power flow in EIC ESR SRF cavity.

Table 2: EIC Operation Scenarios

	LBLA	SBLA
Radius (mm)	137	75
Length (mm)	240	240
HOM power (kW)	34.4	38.3
Power flux (W/mm^2)	0.19	0.34

HOM DAMPER PROTOTYPE

Manufacture Process

The manufacture process of the SiC HOM damper is illustrated in Figure 3. A SiC housing assembly was brazed together from two flanges, one copper cylinder with water cooling channel on it and a stainless-steel housing. The SiC housing assembly was heated up to 145 ºC in an air oven, with estimated diametral expansion to be about 0.7 mm. The SiC housing was then removed from the oven and the SiC cylinder was inserted into the housing.

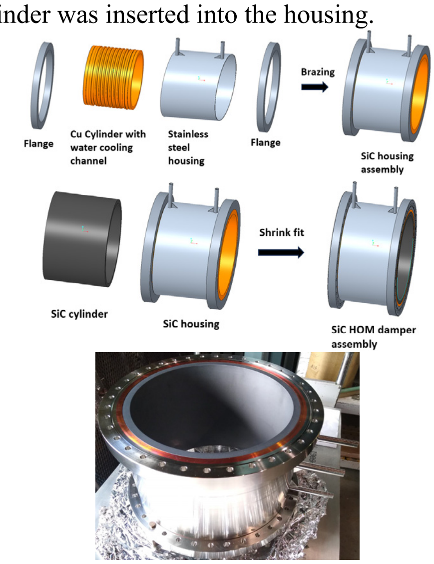

Figure 3: HOM BLA manufacture process.

Outgassing Test

Prior to the high-power RF testing, outgassing test was carried out to measure the outgassing rate of the HOM absorber assembly. This is important because the shrink-fit process may trap air between the SiC and the copper cylinder, causing the HOM absorber to act as a virtual leak. The system was baked at 200 ºC for 96 hours. The outgassing rate was measured to be 2.2E-10 Torr-Liters/sec-cm², which satisfies the high vacuum need for the ESR SRF cavity. It is worthwhile to mention that the surface finish wasn't specified when the SiC was ordered for this test. The surface finish was about Roughness Average (Ra) 3.2 µm. For the EIC SRF cavities' HOM damper, the surface finish for both copper and SiC will be specified to be Ra 0.8 µm, which would further lower the outgassing rate.

HIGH POWER TEST RESTULS

High Power Test Setup

The high-power test setup for SiC HOM damper is shown Figure 4. The high-power test was carried out in the air. RF breakdown voltage in the air is much lower than in the high vacuum environment, which could potentially be a limiting factor for the thermal stress test. Should that be the case, the test setup will be improved to mitigate such an issue. RF power provided by a 704 MHz 1 MW CW klystron is delivered to the BLA with WR 1500 waveguides. Two low insertion loss (~ 0.06 dB) transitions make connections between the WR 1500 waveguide and the SiC HOM BLA. There is a directional coupler in the downstream and upstream of the SiC HOM damper. A high-power RF phase shifter is placed before the shorting plate to adjust the RF field in the BLA for balancing the RF heating along the BLA axial direction, which is determined by the temperature profiles on the BLA flanges. On the SiC HOM damper flanges, there are 6 Resistance Temperature Detector (RTD) sensors attached to each flange and each of them is 60 degrees apart. There are three arc detectors near the HOM absorber: one on each transition and one on the shorting plate. There is an Infrared Radiation (IR) camera located on the shorting plate looking into the left side of the SiC surface while an IR detector is pointed to the opposite side of the SiC surface. Figure 5 (right) shows a typical IR camera photo when RF is on. The hottest area is the SiC surface. The temperatures measured by IR detector and IR camera are consistent with each other.

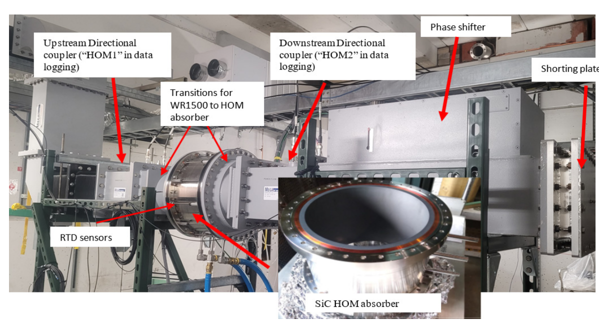

Figure 4: SiC HOM damper high power test setup.

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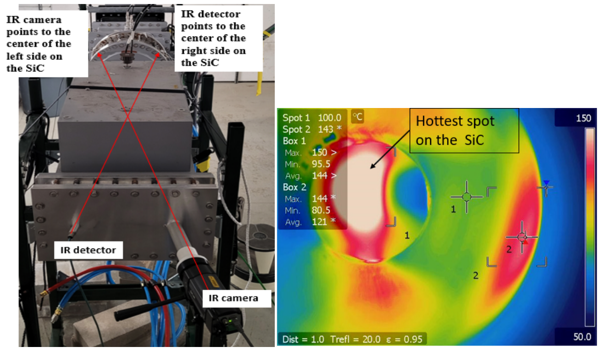

Figure 5: Left: IR camera and detector, right: Typical IR camera when RF power is on.

High Power Test Results

It is noticeable that the fundamental transverse mode (TE10) propagates in the WR1500 waveguide, and it transitions to TE10 mode in the cylindrical SiC HOM damper. Thus, RF heating in the horizontal plane (the narrow side of rectangular waveguide) is much stronger than the vertical plane (the wide side of the rectangular waveguide). Therefore, the thermal stress in the test is much worse than what is expected in the case for EIC ESR SRF cavity. This is because the RF heating caused by axial symmetrical longitudinal modes will be uniform on the SiC HOM damper surface. So, the results from this test are conservative, in terms of the thermal stress caused by RF heating.

The absorbing power is measured in two ways. The first way is to use the water flow and water temperature rise. The water flow inlet and outlet have about < 2% of discrepancy due to reading error in the water flow switch, which causes less than 2% of error in the absorbing power calculation. The other way to get the absorbing power is by RF power measurement in the directional couplers, with the consideration of insertion loss in the transition (~ 0.06 dB) and power loss on the waveguide. The formula for the absorbing power calculation is written as follows:

$$P_{absorbing} = (P_{HOM1Forward} - P_{HOM2Forward}) + (P_{HOM2Reflect} - P_{HOM1Reflect}) - 4xP_{transition\_loss} - 2xP_{directionalcoupler\_loss}$$

The high-power RF test was carried out in CW mode and the power was raised slowly by observing the thermal signals measured by RTDs. The RF was left on overnight (> 15 hours) at multiple power flux levels: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 W/mm^2. On the way up in RF power, the HOM absorber was taken apart to be inspected when the power flux reached 0.44 W/mm^2 and no sign of damage was found. The RF power continued to rise until two arcing events happened at a power flux of 0.65 W/mm^2. Figure 6 shows the temperature, RF power and water-cooling power for the last two days. Nothing abnormal can be seen from the RF and temperature signals. Additionally, the IR camera didn't show any differences before and after arcing as well. After the second arcing, the HOM absorber was taken apart and damage on the SiC was found. Figure 7 shows the cracks found in the SiC surface after two arcing events. Cracks were found both inside the SiC. As there was not a singular thermal stress point in the cylindrical SiC, it was likely that the crack inside the SiC was caused by thermal stress while crack on the edge was caused by arcing. Although there is a hypothesis that the thermal stress caused crack may happen prior to arcing or between 0.44 W/ mm^2 and 0.64 W/ mm^2, there is confidence that the SiC HOM absorber's limit power flux is above 0.44 W/ mm^2 because no damage was found during visual inspection at this level. Thus, for the EIC ESR SRF cavity HOM damper, it was determined to use the 240 mm long SBLA, which has a power flux of 0.34 W/mm^2, providing > 30% of margin.

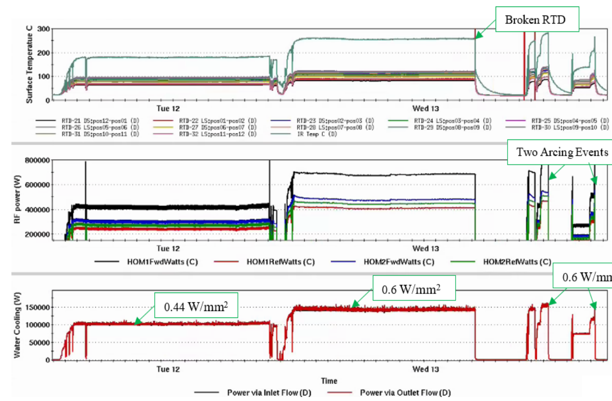

Figure 6: High power test.

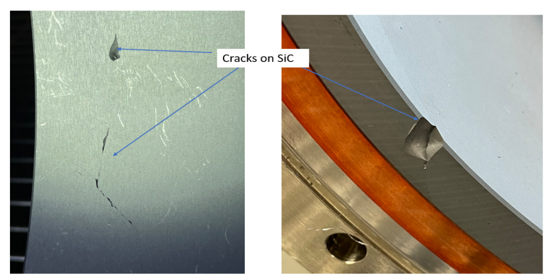

Figure 7: Crack found inside the SiC (left) and on the edge (right).

SUMMARY AND PLAN

HOM damping is crucial for the EIC ESR SRF systems due to the high beam current operating scenarios. A cylindrical shell shape SiC BLA was chosen for the EIC HOM damper. To test the feasibility of the SiC HOM damper, an HOM damper prototype was manufactured and tested. After the HOM absorber assembly was manufactured successfully, an outgassing test was carried out and was demonstrated to satisfy the SRF cavity application. The high-power test results found the power flux limit (> 0.44 W/mm^2) to be at least two times higher than what was expected (0.2 W/mm^2). These results showed that the LBLA design for a power flux of 0.19 W/mm^2 has > 100% of margin, and the SBLA design for a power flux of 0.34 W/mm^2 has > 30 % of margin.

More testing will be carried out in the future to continue to characterize the SiC BLA power flux and other properties. All the HOM absorbers for EIC SRF cavities will go through high power test, prior to the installation to the EIC SRF cryomodules.

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