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Thermal simulation of the EIC HSR interconnect module - RF fingers

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Version

Version	Date	Main modification
0.1	12/6/2023	Initial draft
0.2	3/8/2024	Geometry update – new results

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Introduction

The Electron Ion Collider (EIC) Hadron Storage Ring (HSR) will reuse most of the existing superconducting magnets from the RHIC storage ring. However, the existing beam vacuum chamber and stripline BPMs will not be compatible with the planned EIC hadron bunches that will have a 3x higher intensity and be 10x shorter, and some operational scenarios with large radial offsets of the beam in the vacuum chamber. To address these challenges, a copper coated beam screen will be implemented, the existing RHIC stripline BPMs will be shielded and an interconnect module design, including new BPM will be installed adjacent to the existing BPMs.

A thermal analysis of the new arc BPM interconnect housing has been conducted to assess the heating caused by beam induced resistive wall heating and electron cloud heating. An analysis of the BPM module has been made and reported separately [1][2]. This report will focus on the other side of the interconnect module, containing the RF fingers.

System integration

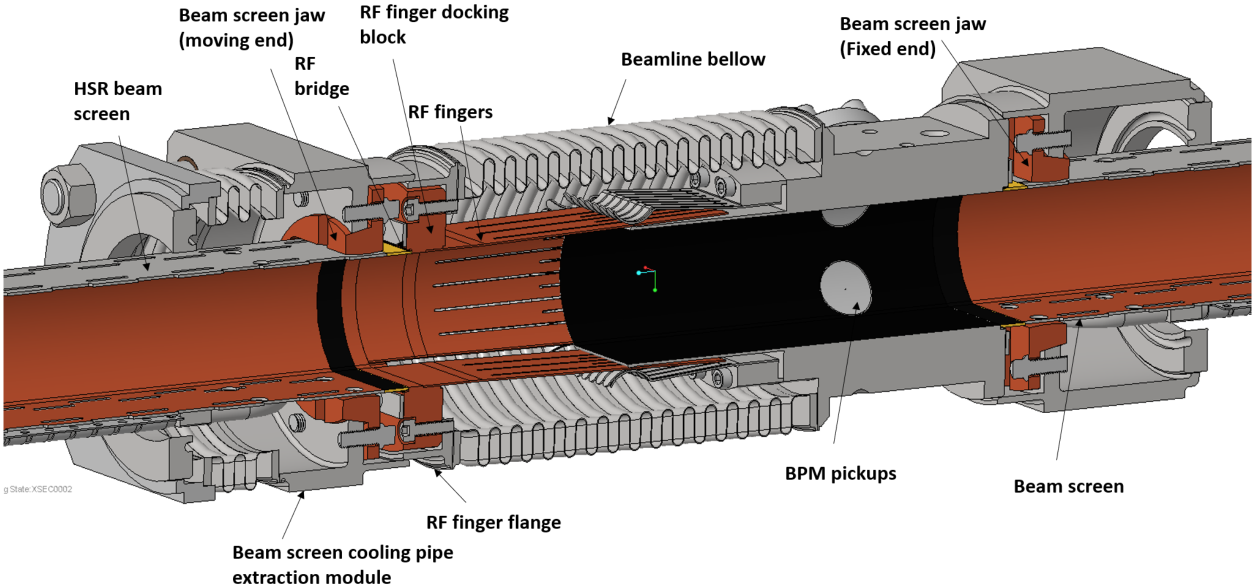


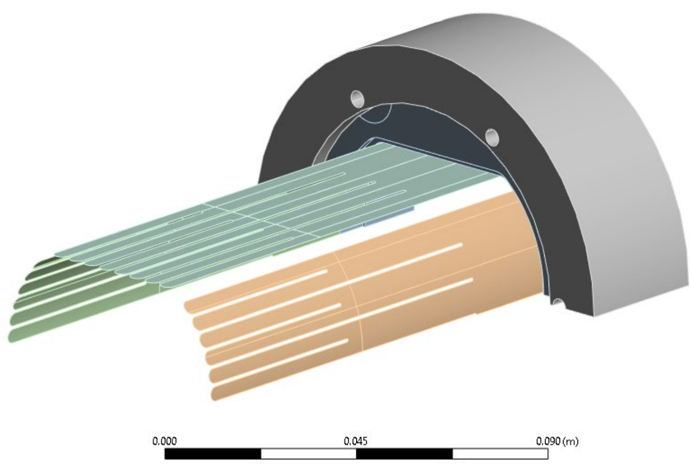
Figure 1 EIC HSR interconnect module design (as of August 2023)

Fig 1 shows the current integration of the HSR standard interconnect module.

Model setup

1. Geometry and materials

Fig 2. depicts the simplified model used for this FE simulation:



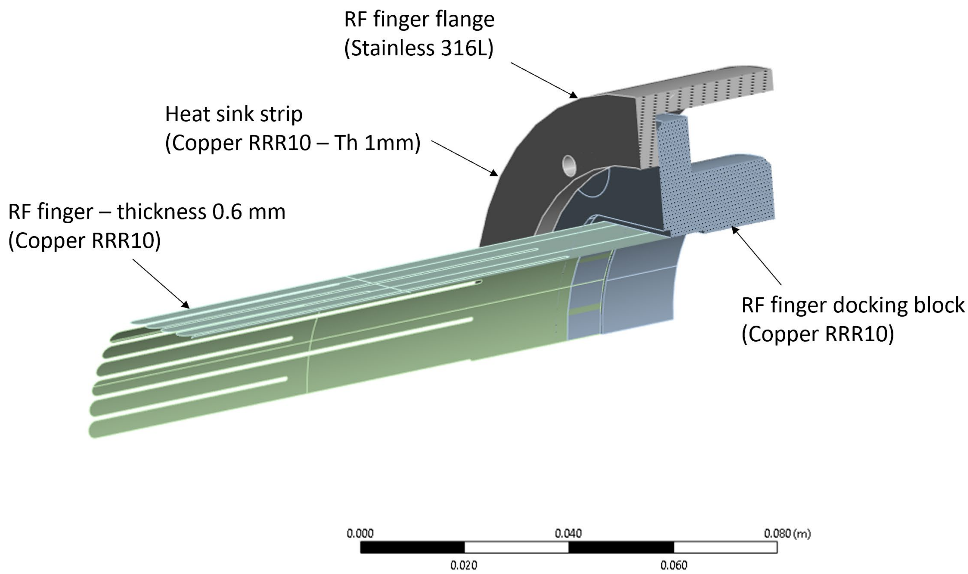


Figure 2 Layout of the model and materials

The model contains three main bodies. The RF fingers (0.6 mm thick) and docking block are planned to be made from Glidcop Al-15. Measurement of the RRR were conducted [3] and a RRR 10 was obtained. So we will consider here material properties consistent with copper with RRR10.

The RF finger flange is made of stainless steel 316L. A heat sink is proposed as a thin strip of copper overlayed onto the 316 flange and pressed or brazed to it (the analysis without heat sink is available in appendix 1).

2. Contact definition

The RF finger will be brazed to the copper docking block they are considered as a perfect thermal contact. The RF finger docking block will be bolted to the stainless steel flange. The thermal contact will then be localized around the bolt heads only (Fig 3) .

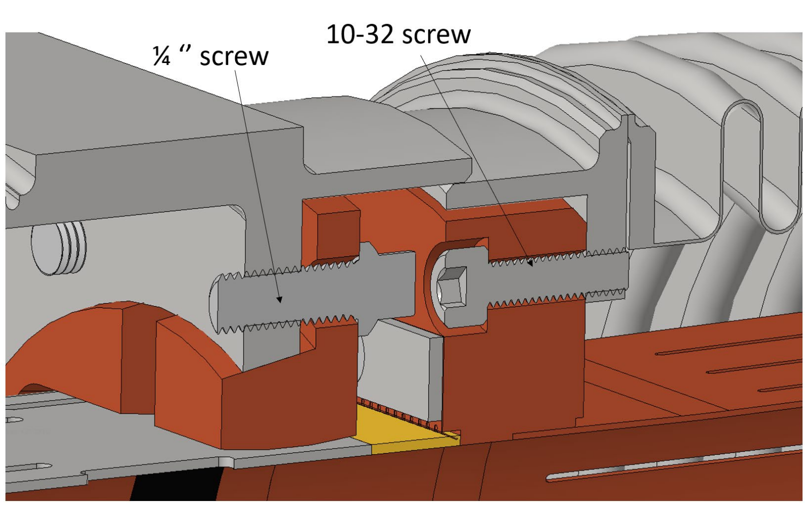


Figure 3 Cross section of the docking block to flange bolted interface

The bolt (blue in Fig 3) is a 10-32 stainless steel bolt. Assuming a tightening up to ½ of the tensile strength (350 MPa) we will get 4500 N of tightening force per screw ($S_{tensile}$=11.3 mm^2).

This force will squeeze the copper docking block against the stainless-steel flange and yield the soft copper until enough pressed surface is created to match the bolt tightening force.

$$F_{bolt} = (P.S)_{interface}$$

Assuming at the interface soft copper is going to be essentially plastically yielded the pressure is equal to the copper yield strength (~35 MPa for pure copper) :

$$S_{interface} = \frac{F_{bolt}}{P_{Yield}}$$

$$S_{interface}(mm^2) = \frac{4500\ N}{35\ MPa} = 128\ mm^2$$

This is equivalent to a circle of radius 13.6 mm around each bolt head. In practice the strain hardening of copper will limit the interface surface to possibly smaller value. Since the copper is a very soft material and the interface is plastically yielded, we will consider this as a perfect thermal contact.

3. Boundary conditions

Heating: Beam-induced resistive wall heating

The CST Wakefield Solver is used to simulate the beam-induced resistive wall heating (RWH) from a proton beam with 290 bunches with bunch charge of 30.5 nC and rms bunch length of 6 cm [4][5]. In this CST model, the beam chamber walls are divided in sectors of 20 degrees to get the local heat distribution for each of these sectors (Fig 7). The heat flux values are conservatively scaled for resistivity with a value of ρ = 5E+8 S.m (corresponding to a RRR10 copper).

We will consider that the beam can be offset up to 20 mm horizontally.

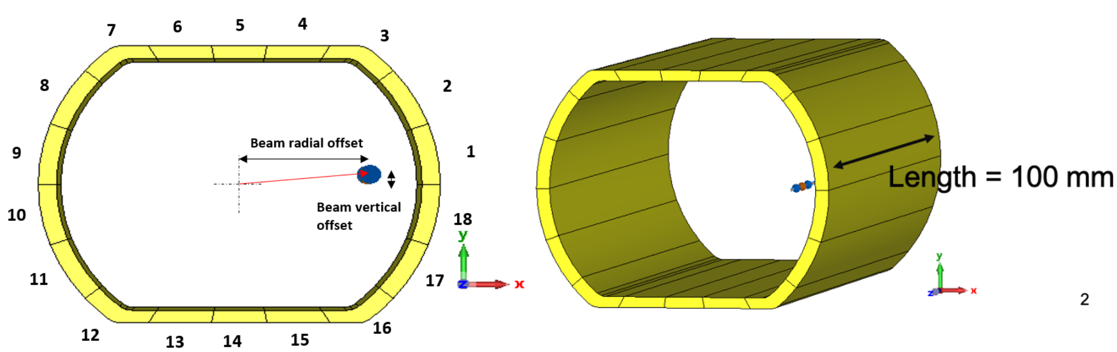


Figure 4 CST model for RWH and beam wall division

Table 1 gives the results from this CST simulation on the wall of the beam vacuum chamber.

Table 1 – Heat flow from CST for beam chamber walls (150 m long) – From [4] - Updated to reflect copper RRR10

Sector ID (see Fig 7)	Centered beam	Offset Radial +20 mm
1	1.69	29.24
2	1.49	7.58
3	1.16	1.89
4	3.77	1.85
5	4.84	0.84
6	-	0.32
7	-	-0.07
8	-	0.07
9	-	0.07
Equivalent linear heat flux (mW/m)	**281**	**560**

Heating : Electron clouds

Electron clouds heating has been computed in Ref. [6]. Fig. 5 represents the electron cloud heating expected in the interconnect region (no magnetic field) for various Secondary Electron Yield (SEY) values of the beam wall surface.

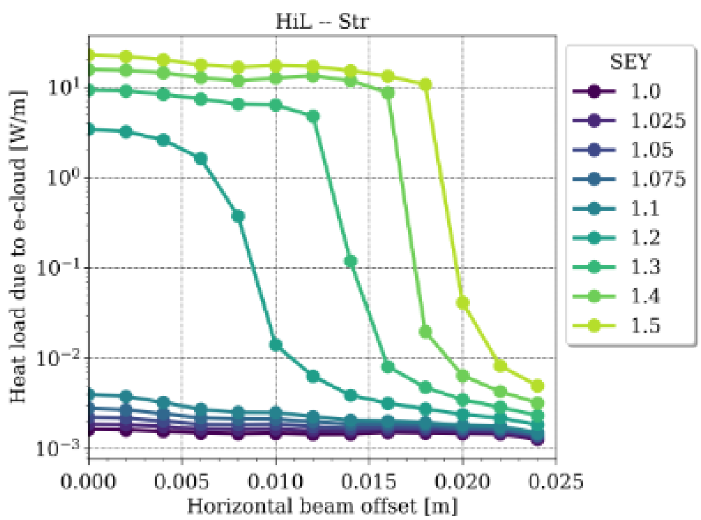


Figure 5 Electron cloud heating vs. SEY. Adapted from [6]

As seen on Figure 5, the electron cloud heating is most significant with the centered beam. An offset beam will produce less heating by about three orders of magnitude. A distribution of eClouds heating has been obtained and is depicted in Figure 8.

The coordinate X is the distance across the racetrack profile of the vacuum chamber.

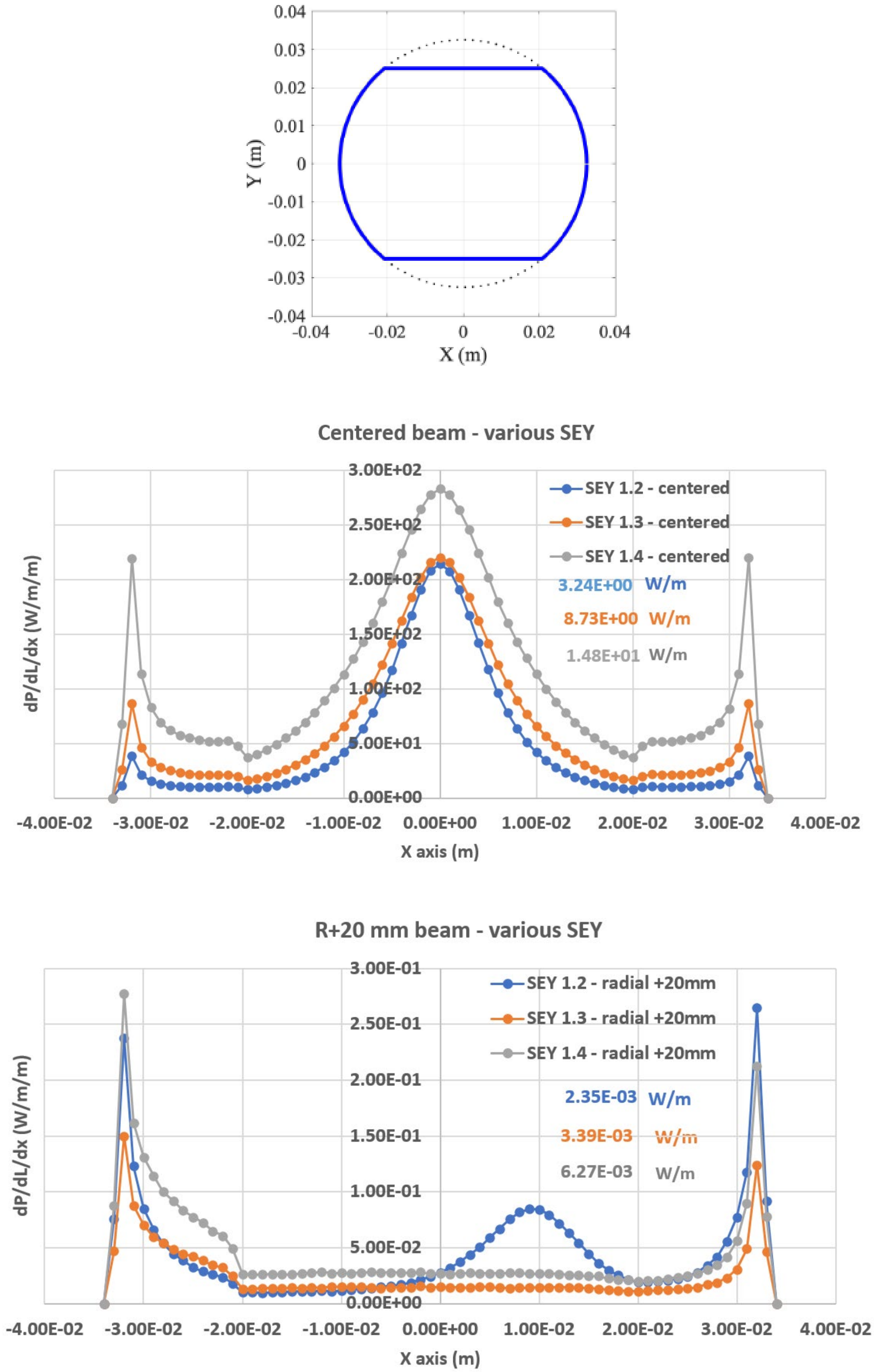


Figure 6 Electron cloud heating distribution (Top) racetrack profile (center) centered beam (Bottom) offset beam +20 mm Integrated linear heating values are represented on the graphs in color

Two configurations are considered here. In the first configuration, the entire assembly sees eCloud heating with the SEY considered. The length exposed to electron clouds is the entire 0.14 m length of the module.

In the other configuration we assume the fingers to be covered with a very-low SEY coating (amorphous carbon for example) while only the tip of the fingers, the area rubbing against the other interconnect end (Fig 1), sees a higher SEY. The length of finger with a higher SEY extends 0.053 m from the fingertip.

Note : The discretization of the ecloud heat flux in X instead of (x,y) lead to an overestimation of the eclouds heat flow in ANSYS when highly peaked on the edges. This is due to the ANSYS interpolation algorithm from 1D data to 3D model. The overestimation can reach +20% in the centered beam at high SEY (high edge peaking). It is even larger at R+20 mm but the negligible heat flux makes this noncritical.

Heating : Heat load summary

The total heating RF finger module equivalent length is 0.14 m.

The total heat deposited on the RF finger module is tabulated in table 2 :

Table 2 Heqt loqd summary when the entire module has a "high" SEY

	Centered beam			**R+20 mm beam**		
Resistive wall heating (W)	0.042			0.084		
SEY	**1.2**	**1.3**	**1.4**	**1.2**	**1.3**	**1.4**
Eclouds heating (W)	0.454	1.223	2.065	3e-4	5e-4	9e-4
Total (W)	**0.513**	**1.283**	**2.124**	**0.117**	**0.118**	**0.118**

Table 3 Heqt loqd summary when only the finger ends have a "high" SEY (0.053 m from tip)

	Centered beam			**R+20 mm beam**		
Resistive wall heating (W)	0.059			0.117		
SEY	**1.2**	**1.3**	**1.4**	**1.2**	**1.3**	**1.4**
Eclouds heating (W)	0.175	0.463	0.783	1e-4	2e-4	3e-4
Total (W)	**0.234**	**0.522**	**0.842**	**0.117**	**0.117**	**0.117**

Note : this thermal analysis considers two cases, centered and offset 20 mm. It is to be noted however that the lateral offset of the beam orbit may be more than 20 mm. Analysis have shown that the dipole ends can have a large offset with respect to their centered position, up to 7 mm see [6]. For this analysis, the case with a centered beam has a higher heating so the worst lateral offset case is neglected.

4. Cooling – Heat extraction

As described in Appendix 1, a thermal heat sink of the module is required.

We will consider the heat sink to be directing the heat to the beam screen cooling line. So its temperature will be considered held stable at 9 K.

In order to favor a good distribution of the heat extraction we proposed brazing or pressing a copper strip on the outside of the stainless-steel flange. A copper braid can then be soldered or brazed or pressed against this copper strip and onto the beam screen cooling pipes in the interconnects. The thermal resistance of these joints will be neglected.

Assuming a copper braid 5” long, 1” wide, 1/8” (MacMaster Type 69925K42) the wire gauge equivalent will be AWG1 (cross section of wires 42.4mm^2). Assuming a copper wire thermal conductivity of k=470 W/m/K at 10K (RRR30). The braid thermal resistance will be 3.35 K/W.

In the worst case, the heat load can reach a few W (see Table 2). To avoid generating a significant temperature elevation of the module because of the braid conduction itself, we recommend using two such braids or a thicker braid to increase its cross section.

For the rest of this work, we will assume 84.8 mm^2 of copper cross section for the braid. Thermal resistance 1.68 K/W (applied as a convection coefficient to the surface in yellow (fig 9) this equates to 53 W/m^2.K).

Also the heat sink interface of the beam screen cooling line will have to be designed long enough to avoid significant local heating from the helium convection.

Fig. 9 summarizes the boundary conditions applied to the model.

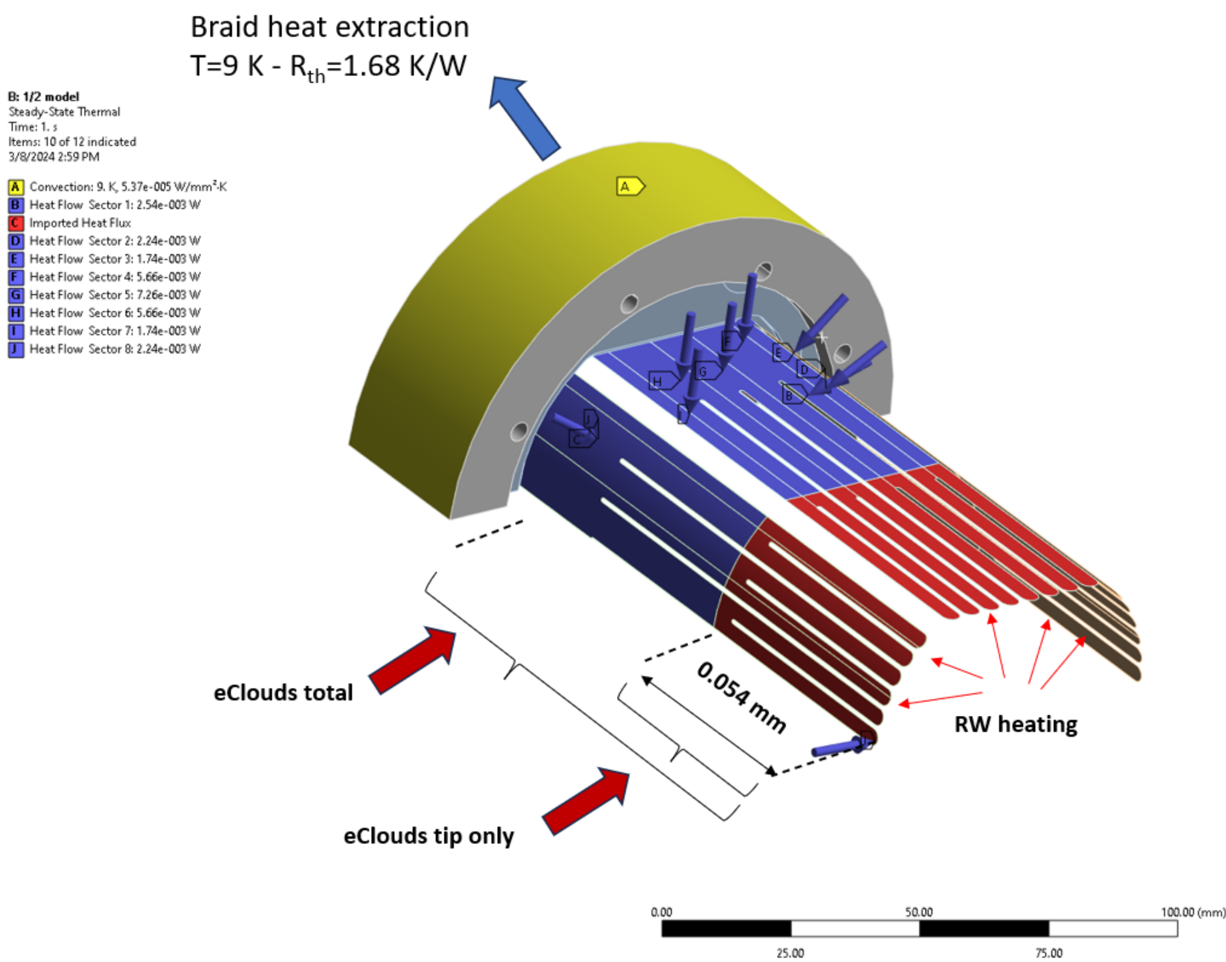


Figure 7 Summary of the boundary conditions for the thermal simulation

Results and discussion

1. Centered beam

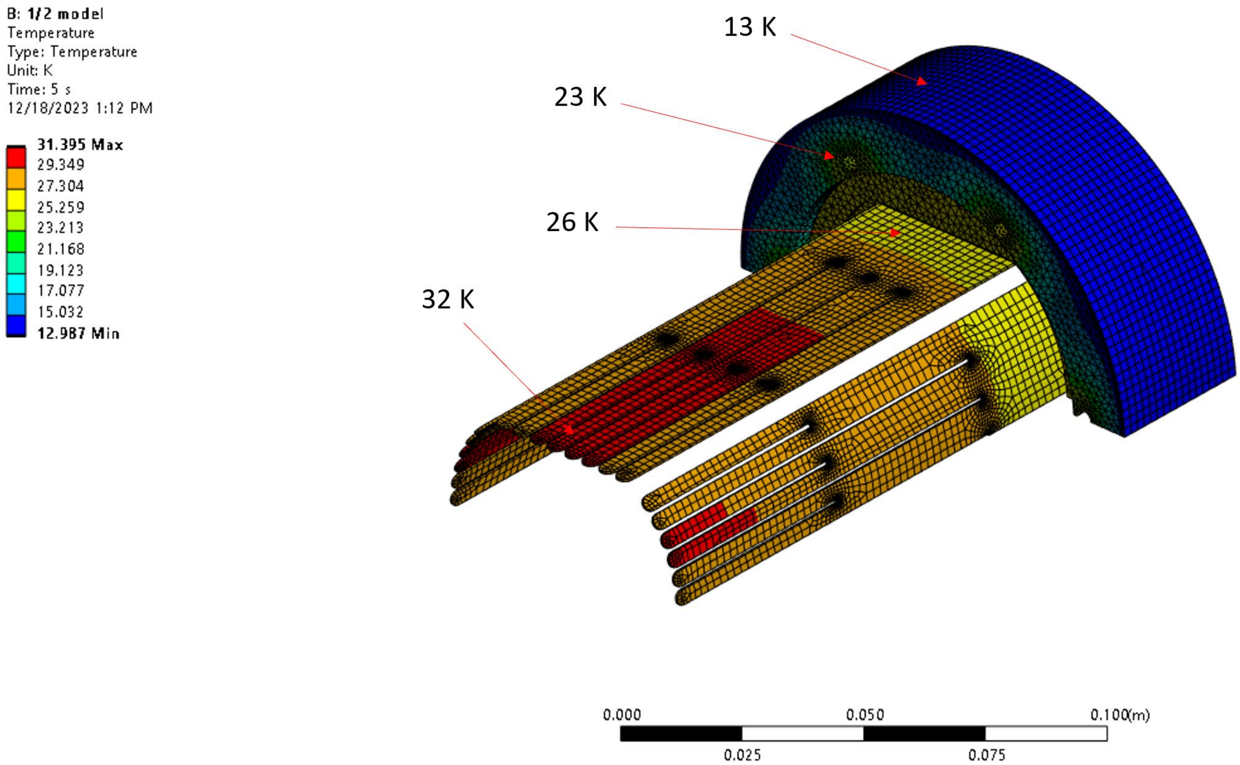


Figure 8 Result of the centered beam - SEY 1.4 - Full length eclouds exposure

As seen on Fig 10 the total temperature elevation is about 23 K in the worst SEY (Max temp 32 K - heat sink at 9 K). A significant portion of the heat elevation is due to the constriction of the heat flow though the bolt area (13 K out of 23 K). So increasing the number of bolts to distribute the heat flow better will improve this situation.

Table 4 summarizes the temperature reached by the model in the different scenarios and the simulated heat extracted by the beamscreen cooling line.

Note: this simulated power includes a slight interpolation overestimate mentioned previously. The reference power values are in table 2 and 3.

Table 4 Energy/Temperature in the various situations for a centered beam

Case	**Full-length ecloud**			**54 mm finger ecloud**		
SEY	**1.2**	**1.3**	**1.4**	**1.2**	**1.3**	**1.4**
Total ½ model heat (W)	0.24	0.68	1.26	0.09	0.24	0.44
Max Temperature (K)	**16.5**	**23.5**	**29.4**	**13.6**	**18.1**	**21.2**

From [8], keeping the surfaces of the vacuum chamber below 30 K will keep us clear of significant gas desorption from the aC coated surfaces. However, binding energies can be less on metallic surfaces or other materials and lead to a lower desorption temperature.

When the beam is centered the beam is driven by the eClouds heating, the beam RWH is secondary. This is consistent with table 2 and 3.

2. R +20 mm offset beam

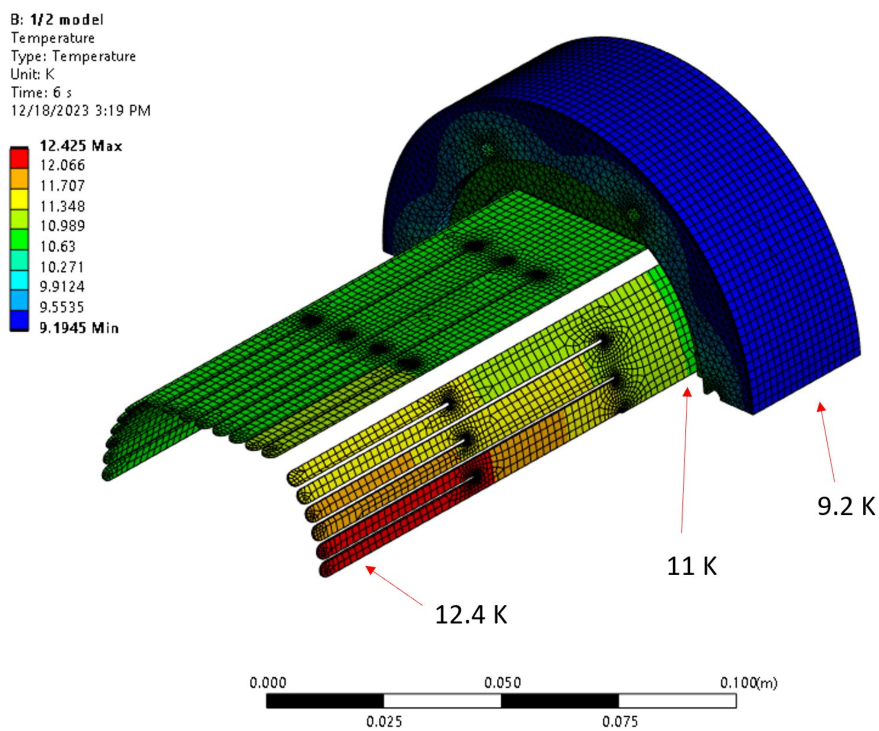


Figure 9 Results of the 20 mm offset beam - SEY 1.4 - Full length finger eclouds

As seen on Fig 11 the total temperature elevation is about 23 K in the worst SEY (Max temp 32 K - heat sink at 9 K). A significant portion of the heat elevation is due to the constriction of the heat flow though the bolt area. Increasing the number of bolts to distribute the heat flow better will improve this situation.

Table 5 Energy/temperature in the R+20 mm offset beam scenario

	Full finger ecloud			54 mm finger ecloud		
SEY	1.2	1.3	1.4	1.2	1.3	1.4
Total ½ model heat (W)	0.04	0.04	0.04	0.04	0.04	0.04
Max Temperature (K)	**11.3**	**11.4**	**11.4**	**11.1**	**11.3**	**11.4**

When the beam is offset, the model temperature is driven be the beam RWH and not the eClouds. This is consistent with table 2 and 3.

Conclusion

A thermal model to simulate the new HSR interconnect finger has been set up and used in a variety of load cases. In the heating case expected for EIC operation, the expected temperature of the fingers is limited to less than 30 K provided that the finger SEY is below 1.4 and a heat sink of the interconnect module is implemented.

References

[1] Micolon, Frederic, Gassner, David, Hetzel, Charlie, Pinayev, Igor, Sangroula, Medani, & Verdú-Andrés, Silvia. "*Thermal simulation of the HSR arc BPM Module for EIC*" https://doi.org/10.2172/1969913

[2] F.Micolon et al. "Thermal engineering of the cryogenic beam position monitors for the EIC hadron storage ring" Cryogenic engineering conference (CEC23) proceedings. Publication pending.

[3] S. Nayak – Private conversation

[4] Sangroula, Medani, et al. *BEAM INDUCED HEATING ANALYSIS UPDATE FOR THE EIC VACUUM CHAMBER COMPONENTS*. Technical note: BNL-224903-2023-TECH. https://doi.org/10.2172/2203271

[5] S. Verdú-Andrés, M. Sangroula "Beam-induced heat deposited in the EIC HSR screens " - Technical note: BNL-224980-2023-TECH https://doi.org/10.2172/2205643

[5] S. Verdú-Andrés *et al.*, "Electron cloud thresholds at the arcs of the Electron-Ion Collider hadron storage ring" - Technical note: BNL-224588-2023-TECH https://doi.org/10.2172/1992863

[6] F.Micolon *et al.*, "Evaluation of the maximum credible transverse offset for an HSR beamline through an interconnect " - Technical note: BNL-224466-2023-TECH - EIC-ADD-TN-061

[7] R. Salemme et al. "Vacuum Performance of Amorphous Carbon Coating at Cryogenic Temperature with Presence of Proton Beams", in Proc. 7th Int. Particle Accelerator Conf. (IPAC'16), Busan, Korea, doi:10.18429/JACoW-IPAC2016-THPMY007

Appendix 1 – Simulation without heat sink

In order to investigate the need for heat sink a full thermal model was set up. The heat extraction is then the beam screen and the welded cooling line.

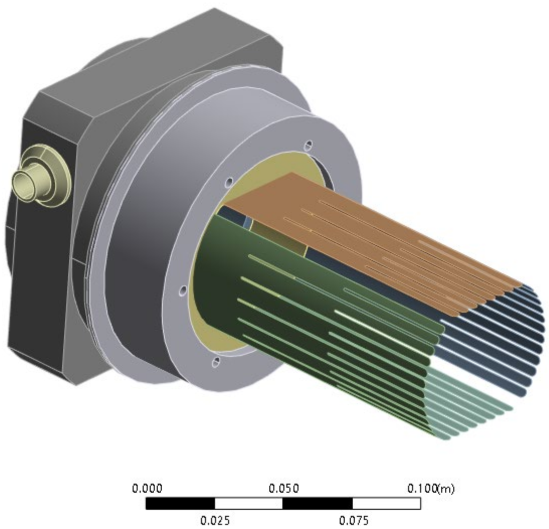
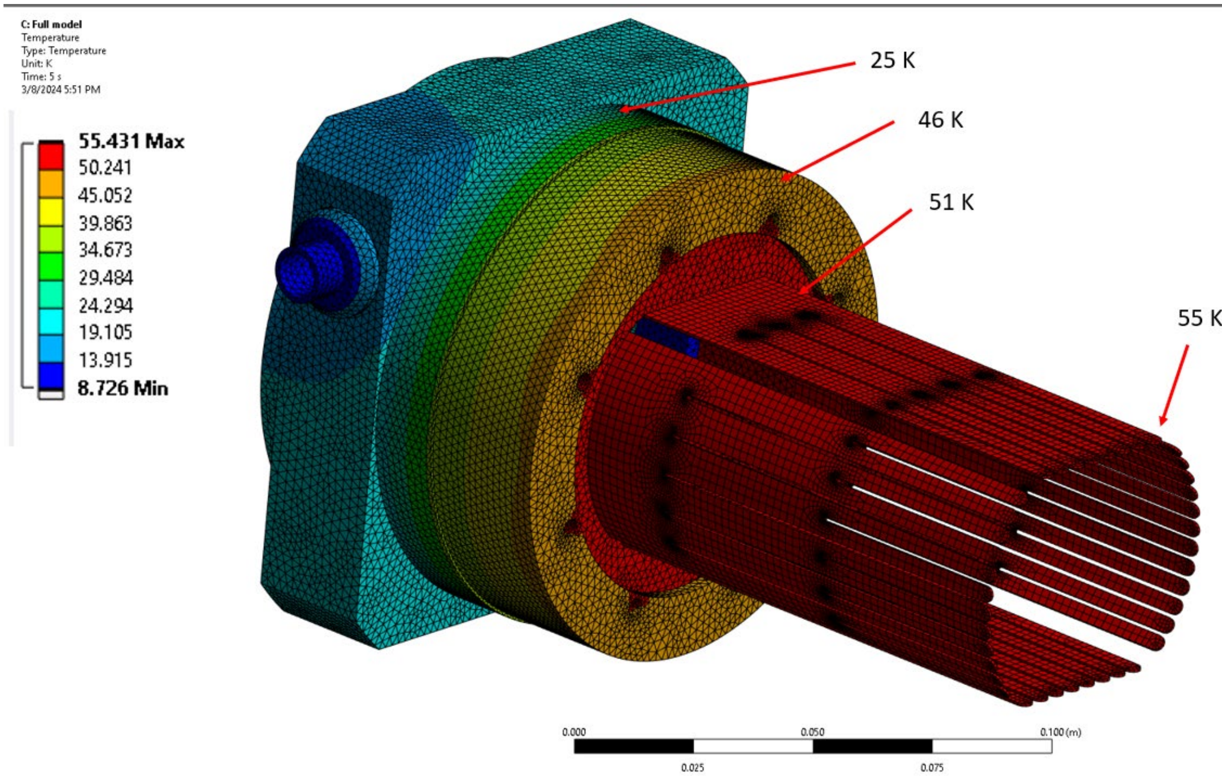


Figure 10 Full model geometry

The set of boundary conditions are similar to those described in this report.



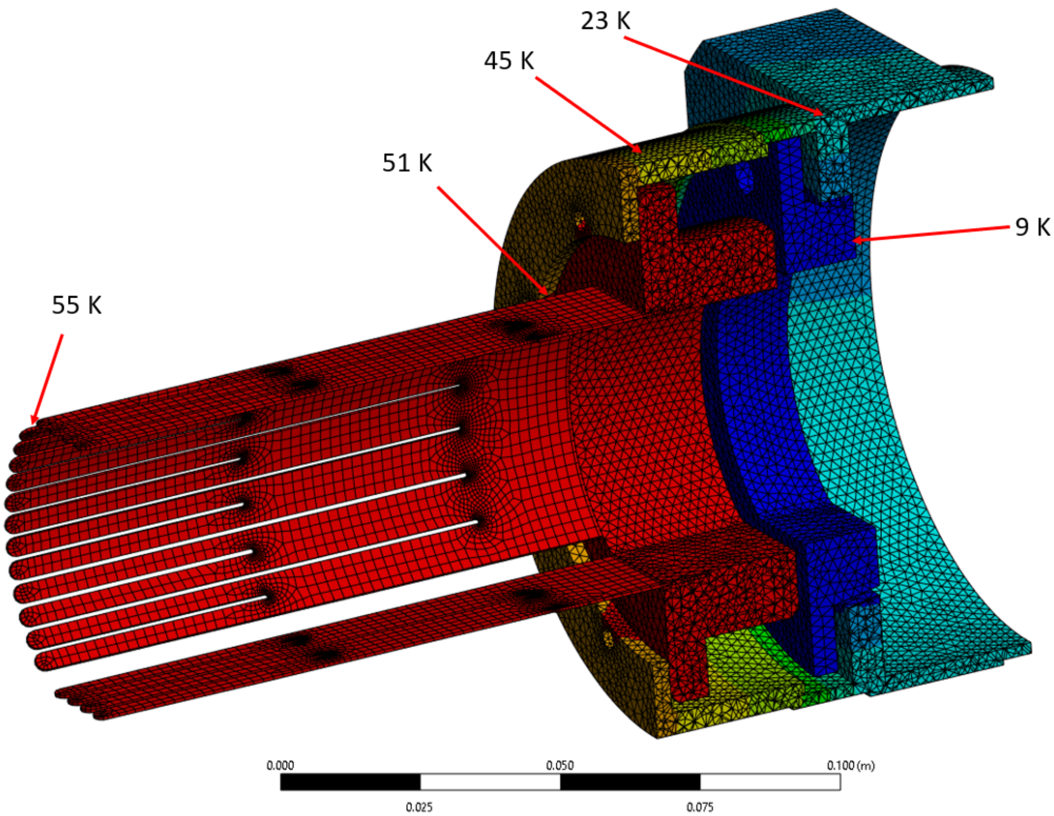


Figure 11 Full model temperature - SEY 1.4 – Temperature

Table 6 Energy/Temperature in the various situations for a centered beam

	Full finger ecloud			54 mm finger ecloud		
SEY	1.2	1.3	1.4	1.2	1.3	1.4
Total model heat (W)	0.55	1.50	2.75	0.22	0.54	0.95
Max Temperature (K)	**26.3**	**42.2**	**55.4**	**19.0**	**27.4**	**35.2**
Temp elevation (K)	17.3	33.2	46.4	10	18.4	26.2

Table 7 Energy/temperature in the R+20 mm offset beam scenario

	Full finger ecloud			54 mm finger ecloud		
SEY	1.2	1.3	1.4	1.2	1.3	1.4
Total model heat (W)	0.12	0.12	0.12	0.12	0.12	0.12
Max Temperature (K)	**15.6**	**14.7**	**14.7**	**14.0**	**15.7**	**14.8**
Temp elevation (K)	6.6	5.7	5.7	5	6.7	5.8

With this arrangement, even a relatively low SEY cannot ascertain a temperature below 30 K on the beam vacuum walls. The effectiveness of heat extraction through the beam screen docking jaw is also largely uncertain. A non-symmetrical heating can also distort the interconnect module.

For these reasons we recommend implementing a heat sink as described previously in the report.