Thermal simulation of the HSR arc BPM Module for EIC

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Thermal simulation of the HSR arc BPM Module for EIC


Version

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<th>Version</th>
<th>Date</th>
<th>Main modification</th>
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<td>0.1</td>
<td>02/01/23</td>
<td>Initial draft</td>
</tr>
<tr>
<td>0.5</td>
<td>3/17/23</td>
<td>Corrections from co-authors.</td>
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I. 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 stripline beam position monitors (BPM) used for RHIC will not be compatible with the planned EIC hadron beam parameters that include higher intensity, shorter bunches, and some operational scenarios with large radial offsets of the beam in the vacuum chamber. To address these challenges, the existing RHIC stripline BPMs will be shielded, and a new BPM design using button pick-ups and integrated in a new vacuum interconnect/bellows assembly that will be installed adjacent to the existing BPMs.

A thermal analysis of the new arc BPM housing and button pick-up design has been conducted to assess the effects caused by beam induced resistive wall heating and signal propagation through the button pick-up cables for several operational scenarios. This report will describe the analysis results to quantify the heat transfer and temperature distribution that can be expected on the new HSR cryogenic arc BPM housings, button pick-ups, and cryo-signal cables.
1. Model setup

   a. System integration

   Fig. 1 shows the current integration of the stripline BPM and their coaxial cables on a RHIC CQS magnet. One end of the cables is connected to the BPM striplines through vacuum feedthroughs (noted 2 on Fig 1). The other end of the cables comes out of the vacuum vessel into the tunnel through vacuum feedthroughs located on the vacuum vessel instrumentation flanges (4 on Fig. 1). In between, the coaxial cables are inserted in aluminum channels that provide heat stationing at the heat shield temperature (3 on Fig. 1). More details are available in Ref. [1].

   Since the cables are in vacuum, no convection occurs, and the resistive heat will have to be conducted away. The current RHIC coaxial cables have a plastic dielectric, which limits the maximum beam intensity due to RF heating and limited operating temperature of the dielectric (see Ref. [2]). For EIC, we plan to use cables with a SiO2 dielectric which features a much higher operating temperature.

   For EIC, the existing stripline BPM will be shielded by the beam screen (see Ref. [3]) and new BPMs with button pick-up embedded in the interconnect modules will be installed adjacent (see Fig. 2).
Fig 2. Planned integration of the EIC HSR interconnect module (as of January 2023)

Fig 3. depicts a cross section of the button pick-up BPM implementation and their connectors.

II. Model geometry and materials

Model geometry

The finite element (FE) model contains all the BPM housing and ancillaries (pickup, insulator, flange) as well as the beam screen cooling pipe extraction module, and jaw assembly.

The beam screen RF flange (Fig. 3) is linked to the beam screen through an RF spring with limited contact. Thus, it is considered that no heat flows through that contact.
The RF fingers included in the interconnect module with the HSR BPM (see Fig.2) are thermally linked to the adjacent magnet, so they are not included in this model and will be treated by a separate analysis.

Fig. 4 lays out the geometry of the model.

Fig. 5 depicts the coaxial cable cross section modelled. The dimensions depend on the specific cable considered and are described in Appendix IV.

Figure 4 Model 3D geometry representation - 1/8 mode

Figure 5 Cross section of the BPM coaxial cable – dimensions used can be found in Appendix IV
Contacts

We assume a perfect contact along the radial direction of the coaxial cable between the dielectric material, inner and outer conductors (Fig 5). Fig. 6 represents the contact condition between the other parts of the BPM module model. In addition, the dashed line shows the heat propagation path from the cable to the cold sink (=beam screen).

Following updates from the button manufacturer, contacts with limited penetration have been implemented for the button assembly. The pickup/stem contact is laser welded with limited penetration, so it is only considered on the edge. The inner/outer flange are TIG welded on a depth of 0.5 mm (0.02”-0.03” specified by the manufacturer).

1. Boundary conditions

Heating: Thermal conduction

The heat coming from the cryostat BPM feedthrough, considered at room temperature (293 K), will be conducted through the cable to the BPM module. The cable is locally heat stationed to the heat shield (50 K - 80 K depending on the sector) to limit the thermal conduction from the tunnel side to the BPM module (see Appendix IV for details).

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. In this CST model, the beam chamber walls are divided in sectors of 20 degrees to get the heat
distribution for each of these sectors (Fig 7). The heat flux values are conservatively scaled for resistivity with a value of $\rho = 5E+8$ ohm.m (corresponding to a RRR10 copper at 50 K).

We will consider that the beam can be offset up to 23 mm horizontally and 2 mm vertically in the BPM (see details Appendix V for justification of these offset values).

![Figure 7 CST model for RWH and beam wall division](image)

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 - cell empty means a symmetry condition is used**

<table>
<thead>
<tr>
<th>Sector ID (see Fig 7)</th>
<th>Centered beam</th>
<th>Offset Radial +20 mm</th>
<th>Offset Radial +23mm/Vertical+2mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.69</td>
<td>29.24</td>
<td>60.28</td>
</tr>
<tr>
<td>2</td>
<td>1.49</td>
<td>7.58</td>
<td>11.01</td>
</tr>
<tr>
<td>3</td>
<td>1.16</td>
<td>1.89</td>
<td>1.79</td>
</tr>
<tr>
<td>4</td>
<td>3.77</td>
<td>1.85</td>
<td>1.35</td>
</tr>
<tr>
<td>5</td>
<td>4.84</td>
<td>0.84</td>
<td>0.53</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0.32</td>
<td>0.19</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>0.07</td>
<td>0.03</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>0.07</td>
<td>0.03</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td>0.14</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td>0.39</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
<td>0.82</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td>0.82</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td>4.25</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td></td>
<td>30.09</td>
</tr>
<tr>
<td><strong>Total heat RWH (mW)</strong></td>
<td><strong>42.1</strong></td>
<td><strong>83.9</strong></td>
<td><strong>111.9</strong></td>
</tr>
</tbody>
</table>
Equivalent linear heat flux (mW/m) | 339 | 548 | 731

Another CST model is used to evaluate the power deposited by RWH on the pickup surface as well as the pickup flange (Fig. 8) with the same beam conditions.

![Figure 8 CST model of the pickup RWH](image)

Table 2 depicts the heat deposited on the pickup surface and on the BPM flange because of leaking fields through the small gap ~ 500 microns between the pickup electrode (green) and flange (orange).

**Table 2 Heat flow from CST for the pickup and flanges –cell empty means a symmetry condition is used**

<table>
<thead>
<tr>
<th>Heat flow (mW)</th>
<th>Centered beam</th>
<th>Offset Radial +20 mm</th>
<th>Offset Radial +23mm/Vertical+2mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pickup 1</td>
<td>0.55</td>
<td>3.86</td>
<td>5.36</td>
</tr>
<tr>
<td>Flange 1</td>
<td>0.35</td>
<td>2.05</td>
<td>3.1</td>
</tr>
<tr>
<td>Pickup 2</td>
<td></td>
<td></td>
<td>2.03</td>
</tr>
<tr>
<td>Flange 2</td>
<td></td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>Pickup 3</td>
<td></td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>Flange 3</td>
<td></td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Pickup 4</td>
<td></td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Flange 4</td>
<td></td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Total RWH (inclusive of wall heating)</strong></td>
<td><strong>45.7</strong></td>
<td><strong>95.8</strong></td>
<td><strong>123.6</strong></td>
</tr>
</tbody>
</table>

Heating - Coaxial cable RF heating

The propagation of the voltage signal along the coaxial cable will generate heat by resistive and dielectric heating. A 1D model has been setup to evaluate this heating and the signal attenuation for a given cable temperature profile. This model is described in Appendix I.
The CST model depicted in Fig. 8 is also used to compute the fields excited by the beam, coupled to the BPM pickups and propagating along the coaxial cables (see Fig. 9).

![Figure 9 CST simulation BPM electric signal for various beam vertical offsets](image)

**Table 3 CST simulation peak voltage for various beam scenario**

<table>
<thead>
<tr>
<th>Signal peak voltage (V)</th>
<th>Centered beam</th>
<th>Radial +20 mm</th>
<th>Radial +23 mm Vertical +2 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.7</td>
<td>66.4</td>
<td>81.8</td>
<td></td>
</tr>
</tbody>
</table>

This signal is processed by the 1D cable heating model with the cable temperature profile (see Appendix I for more details) and gives a heating profile along the cable length.

**Heating – Pickup stem heating**

The pickup stem is made of Inconel. Its resistivity is higher than the copper conductor of the coaxial cable. This is computed as follows:

\[
R(T) = \rho(T) \cdot \frac{l}{2.\pi.r.\delta(T)}
\]

With:

\[
\delta(T) = \sqrt{\frac{2.\rho(T)}{\mu_0.2.\pi.f}}
\]

The term \( \rho(T) \) is evaluated for the temperature of the connection with the coaxial cable inner conductor. Overall, this represents 15-20 % of the total RF heating.
Table 4 Coaxial cable and stem heating and attenuation for different beam offset

<table>
<thead>
<tr>
<th>Max signal RF power (W)</th>
<th>Centered beam</th>
<th>Beam offset - radial +20mm</th>
<th>Beam offset - Radial +23mm Vertical +2mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.165 W</td>
<td>0.95 W</td>
<td>1.44 W</td>
</tr>
<tr>
<td>Cable type</td>
<td>0.141”</td>
<td>0.090”</td>
<td>0.141”</td>
</tr>
<tr>
<td>Max cable heating (mW)</td>
<td>8.9</td>
<td>12.5</td>
<td>51.7</td>
</tr>
<tr>
<td>Cable attenuation (dB)</td>
<td>-0.24</td>
<td>-0.35</td>
<td>-0.25</td>
</tr>
</tbody>
</table>

Table 3 shows the overall cable heating obtained through the 1D model. Max RF power and Max heating is the value for the pickup closest to the beam (for example Pickup 1 on Fig. 8).

Cooling – beam screen cooling circuit

Fig. 3 shows that the beam screen is pressed onto by the cooling jaw. The cooling jaw and beam screen are both metallic surfaces, so this is treated as a thermal contact conductance (TCC). The applied interface pressure with the current bolting pattern is estimated in the 40-60 MPa range at 2/3 of the bolt elastic limit.

With a Fukuoka correlation this gives TCC values in the range 2400-3300 W/m².K. We applied 2400 W/m².K (see Fig. 6) conservatively.

Note: Effective TCC are notoriously difficult to predict. Especially on large planar surfaces. Implementation an alternative load path is desirable as laid out in section i).

Cooling – magnet cooling line

The BPM interconnect module will be welded onto the end of the stripline BPM module. Some of the heat from this BPM module will be conducted to the magnet helium through the outer walls of the stripline BPM. A dedicated FE study of the stripline BPM obtained the equivalent thermal resistance of this conduction. This equivalent thermal resistance is implemented in the model as a solid with thermal conductivity worked out to represent the stripline BPM conductance (see Fig. 4).

Cooling – Heat shield heat stationing

To limit the conduction from the tunnel temperature, the BPM cables are heat stationed to the heat shield (50-80 K). The position of this heat station has been chosen to minimize the cryoplant operating cost (see Appendix IV for details). The model considers that the temperature of the cable outer conductor is fixed to 80 K, 350 mm after the tunnel feedthrough and for a length of 100 mm.

Cooling - Additional heat stationing

A subsequent study evaluated the advantage offered by heat stationing the last stretch of coaxial cable (close to the BPM module) or the BPM module itself to the beam screen cooling circuit with thermal straps.
These boundary conditions were treated as convective coefficient representative of the thermal straps thermal resistance (47 K/W for strap reference 69925K32). They were placed at the last 100 mm of coaxial cable (for the coaxial heat station) or on the top and bottom of the BPM module between two pickups.

Fig. 10 shows a schematic summary of the boundary condition discussed here.

III. Results and discussion

a. Nominal case

Fig. 11 shows the thermal distribution on the HSR BPM module using the coaxial cable dimensions of 0.141” for the centered beam.
In this case, the RWH is low (46mW - see Table 2) and the main source of heating is from the cable conduction from the tunnel feedthrough (see Fig 11 – case 2).

The following results will be sorted by heating case. Table 4 present the different conditions for the scenario simulated.

<table>
<thead>
<tr>
<th>Case</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.141” cable - No beam</td>
</tr>
<tr>
<td>2</td>
<td>0.141” cable - Centered beam</td>
</tr>
<tr>
<td>3</td>
<td>0.141” cable - Offset beam R+20mm</td>
</tr>
<tr>
<td>4</td>
<td>0.141” cable - Offset beam R+23V+2mm</td>
</tr>
<tr>
<td>5</td>
<td>0.141” cable - Offset beam R+23-V+2mm with cable Anchoring</td>
</tr>
<tr>
<td>6</td>
<td>0.141” cable - Offset beam R+23-V+2mm with module anchoring</td>
</tr>
<tr>
<td>7</td>
<td>0.090” cable - No beam</td>
</tr>
<tr>
<td>8</td>
<td>0.090” cable - Centered beam</td>
</tr>
<tr>
<td>9</td>
<td>0.090” cable - Offset beam R+20mm</td>
</tr>
<tr>
<td>10</td>
<td>0.090” cable - Offset beam R+23V+2mm</td>
</tr>
<tr>
<td>11</td>
<td>0.090” cable - Offset beam R+23-V+2mm with cable anchoring</td>
</tr>
<tr>
<td>12</td>
<td>0.090” cable - Offset beam R+23-V+2mm with module anchoring</td>
</tr>
</tbody>
</table>

Fig. 12 represents the model power input and output for each simulated scenario described in Table 4.
The power summary from Fig. 12 shows that for the 0.141” cable, the dominant source of heat is the tunnel feedthrough conduction. Most of this heat is intercepted by the heat shield stationing; however, even without beam (Fig 12 - case 1), the heat flux to the 4 K beam screen remains at 370 mW (501 mW with an offset beam at high intensity – case 4). The smaller 0.090” cable (case 7) allows a reduction of conducted heat flux to the beam screen to only 115 mW (case 7).

A similar reduction is seen for all comparable cases with the 0.141” cable and the 0.090” cable. The reduction in power to the beam screen cooling circuit is between 250 mW and 400 mW. Assuming about 200x interconnect are equipped with the 4x button BPMs, the resulting gain in heat flux to 4 K is between 50 W to 80 W. Associated savings in operating costs for EIC are estimated between $95k and $150k (see Ref.[4]).

When using the smaller 0.090” cable, the signal attenuation increases however (see table 3).

Fig. 13 shows a summary of the temperature reached on the BPM button face and the beam enclosure wall in the different cases.
A maximum temperature of 42.9 K is found on the BPM button face (Fig 13 - case 4) with the BPM module wall kept below 27.8 K. All other cases have lower temperature.

Ref. [5] shows that on a clean stainless surface H₂ has a degassing peak around 18 K. Other gases will not start significantly degassing before 30-40 K. Depending on the surface coating there, these peak temperatures may shift (see Ref.[5]).

Heat stationing the cables or the BPM module itself is an efficient method to reduce the beam wall temperature (see Fig 13 case 5,6,11,12). The tradeoff is an increase in cryogenic power to the beam screen cooling (see Fig. 12).

b. Stress test – extreme beam heat load

To assess the model behavior for an unexpectedly high beam heating case, we have doubled the heat loads from RWH and RF cable heating from the cases 4 and 10 (no heat stationing).

Fig. 14 depicts the power summary from these extreme cases.
From Fig. 14 we see that the increase in beam screen circuit loading is not equal to 2x the values for cases 4 and 10. Indeed a large proportion of the additional heat on the cable will be absorbed by the heat shield heat station.

The highest temperature is then reached on the button close to the beam and is 56.4 K for the 0.141” cable and 54.6 K for the 0.090” cable. The highest temperature on the module wall are 31.1 K and 26.8 K respectively.

The corresponding cable temperature profile is depicted on Fig. 15.
The temperature of the 0.141” cable is still close to the thermal conduction temperature profile. The 0.090” cable has higher “bumps” in the temperature profile because the cable lower cross section is less effective in conducting the heat away. In the extreme case of cable temperature elevation, this will lead to an increase in cable attenuation (-0.38 dB for the case R+23mmV+2mm and -0.47 dB when the heat flux is doubled).

One way to avoid the attenuation variation between cables, which can potentially degrade the BPM accuracy would be to heat station the cables together at around 0.4 m cable length to equalize their temperature and so their attenuation. By doing so the attenuation of the hottest cable becomes -0.38 dB while the attenuation for no beam is -0.35 dB (see table 4).

Even in this extreme case, the heat loading of the beam screen cooling circuit is reasonable.

IV. Conclusion
A thermal model to simulate the new HSR interconnect BPM has been setup and used in a variety of load cases. In the heating case expected for EIC operation, the expected heating of the BPM module beam surface is limited to less than 30 K and 40 K on the button itself.

The use of two different cables (0.141” and 0.090”) has been evaluated and for cryogenic purposes the smaller has better performance with the tradeoff of a slightly higher RF attenuation.

The power extracted by the beam screen cooling circuit has been evaluated and a method to heat station the BPM module directly to the beam screen cooling pipe (or manet pipe) has been proposed as an effective way to limit the BPM module temperature elevation further.
Acknowledgment

The author wishes to thank Medani Sangroula for providing all CST simulations described here. Charlie Hetzel, Douglas Holmes, David Gassner, Rob Hulsart, Igor Pinayev, Vadim Ptitsyn, Medani Sangroula, Joseph Tuozzolo and Silvia Verdu-Andres, for giving inputs throughout this work and also for reviewing this material.

References


Appendix I - Evaluating the loss in a cryogenically cooled RF coaxial cable.

Introduction

A coaxial cable carrying a RF signal power will be heated by attenuation. In the case of the BPM coaxial cables, these are surrounded by vacuum which suppresses convective cooling. The only way to evacuate its generated power becomes conduction which supposes a temperature elevation of the cable.

The RF heating is generally made available by the cable manufacturer at room temperature. However, the cryogenic losses are significantly different from the room temperature losses and this is less frequently documented.

Our aim is to get a tool that described the losses occurring in a coaxial cable for a given temperature profile and a given RF signal propagation. We will aim at discussing the model principles in this section.

Model principle

A finite difference 1D model is used to compute the resistive losses along the cable. These resistive losses are a function of the conductor material resistivity (temperature-dependent) and the conductor skin depth (depends on frequency of the RF signal and the resistivity).

This 1D model takes an initial temperature profile and will compute the loss in each segment of the cable. This can be used as an input to the ANSYS model containing all relevant boundary conditions. We can compare the new cable temperature profile with the one previously used for the cable heating model. If the temperature profiles are close, the result is considered as being converged. If not, another iteration is run until the result is converged.

Fig. 1 describes schematically the steps of the simulation process:

The same process is done independently for the inner and outer conductor.

We will described the operation done at each step described in the graph Fig. 1:
Step 1.1
We get a discretized temperature profile of the cable length from a previous ANSYS iteration (or we can manually input one). Note: A good starting point for the EIC cable simulation is the conduction only cable temperature profile or a point with a similar dissipated RF power.

Step 1.2
The cable temperature profile is translated into a copper resistivity for each cable segment. We use an interpolation of a resistivity curve for copper RRR50.

Step 2.1
We get the bunch RF time-dependent signal voltage \( V(t) \) from the CST simulation.

Step 2.2
We can determine the CST bunch signal energy \( E = \frac{1}{R} \int V(t)^2 \cdot dt \) and approximate this bunch with a sine signal of similar frequency. Then we adjust the amplitude to get an identical signal energy.

Note: The frequency approximation is used to work out the propagation skin depth (step 3.1). A higher frequency means a smaller skin depth (so higher cable heating). The reference frequency for room temperature has been determined to be around 660 MHz (see annex 2 for details). We selected a frequency of 1 GHz. This is conservative, with around 20% higher heating power.

Step 2.3
We can now extract the current integral from the sine approximation with the hypothesis that the match load is 50 ohms.

Step 2.4
We integrate this current squared.

Step 3.1
The skin depth is a function of resistivity and signal frequency:

\[
\delta(x) = \frac{1}{2\pi} \sqrt{\frac{\rho(x)}{f}}
\]

Step 3.2
The cable resistance \( R(x) \) is a function of the cable geometry (radius of the conductors), skin depth and resistivity:

\[
R(x) = \rho(x) \cdot \frac{\Delta x}{2\pi r \cdot \delta(x)}
\]
Step 4.1
We will now work out the power dissipated per bunch passing:

\[ E(x) = R(x) \int i^2 \, dt \]

Step 4.2
Knowing the machine filling pattern, we know how many bunches the BPM will see per second. With the 30.5 nC 6 cm RMS bunch we expect a maximum machine filling of 290 bunches (out of 315 buckets). With a bunch revolution period of 12.8 us this gives a bunch passing frequency of 22.7 MHz.

We can then multiply the energy deposited by bunch \( E(x) \) with the bunch passing frequency to get the deposited power \( P(x) \).

Note: the underlying assumption is that we can approximate a succession of bunches as a constant heating power by averaging.

Step 4.3
This power generated by the bunch RF signal is imported in ANSYS as a convection coefficient on the conductor surface. The ANSYS simulation is run with these new parameters.

Step 4.4
We can compare the cable temperature profile used to generate the previous iteration with the new cable temperature profile from step 4.3. If the differ by more than 1K the whole iteration must be repeated with this new temperature profile, as a higher cable temperature will mean a higher generated power. If not we will consider the solution as converged and acceptable.

A coaxial cable RF loss is composed of the resistive losses, computed above and the dielectric loss resulting from the motion of charges through the dielectric (then acting like a capacitor). These are usually neglected at low frequency however at 1 GHz they should be included.

The dielectric loss, although a minor portion of the overall RF loss, is computed using the manufacturer formula for room temperature. Knowledge of the evolution of the dielectric loss for sintered SiO2 at lower temperature has not been found in the literature.

Manufacturer’s attenuation formula at room temperature for the 0.141” cable:

\[ a(\frac{dB}{100 ft}) = 0.2923 \sqrt{f(MHz)} + 0.0011 \ast F(MHz) \]

Manufacturer’s attenuation formula at room temperature for the 0.090” cable:

\[ a(\frac{dB}{100 ft}) = 0.5642 \sqrt{f(MHz)} + 0.0011 \ast F(MHz) \]
Appendix II – Determination of the reference frequency for attenuation

CST studio is used to determine the bunch signal voltage. This voltage profile has a similar pattern irrespective of the bunch position within the beampipe (the bunch position offset will mostly affect the signal voltage). We can then use the Fourier transform of this voltage to study the frequency composition of the EIC bunch pattern.

The bunch RF signal power distribution can be obtained by multiplying the Fourier transform of the voltage by that of the current. Since voltage and current are in phase the pattern is similar to figure 1.

The cable attenuation has a resistive ($\propto \sqrt{f}$) and dielectric loss ($\propto f$). The manufacturer specifies coefficient for both contribution.

$$\alpha(f) = a.\sqrt{f} + b.f$$

<table>
<thead>
<tr>
<th>Attenuation (dB/100 ft)</th>
<th>a</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.090” cable</td>
<td>0.5645</td>
<td>0.0011</td>
</tr>
<tr>
<td>0.141” cable</td>
<td>0.2923</td>
<td>0.0011</td>
</tr>
</tbody>
</table>

We can then convolute the FT from the EIC bunch pattern to the cable attenuation to get an image of the cable loss vs. frequency for the EIC bunch signal. And from there we can plot the power integral for these FT (see Fig. 2).
As seen on figure 2, the frequency of median power dissipation is around 660 MHz. The same amount of power is dissipated at higher and lower frequency so this can be used as an average frequency to simplify further analysis.

Note: the attenuation characteristic used is given at room temperature. Its evolution at lower temperature is essentially linear (see annex IV) so this conclusion should be reasonable even at lower temperatures.
Appendix III – Comparison of the coaxial loss model with published data from the LHC

1. Introduction

To assess the reliability of the 1D model used to compute the RF losses along the BPM cables, we have compared its results to data available in the literature. An example of such data that is sufficiently detailed and in a relevant configuration is the paper from C.Bovet et al. “Measurement and modelling of the thermal dissipation of a cryogenic coaxial cable for LHC BPMs” (link).

In the following section we will compare the results from our simulation to the experimental results contained in the paper.

2. Simulation setup
   a. Geometry

To follow the conditions described in [1], we have made a FE model containing a 0.65m coaxial cable. The cable is made of an inner conductor made from stainless steel with a copper cladding. The dielectric is made from sintered SiO2 with an estimated density of 12.8%. The outer conductor is made from a stainless-steel jacket with an inner cladding of copper. The copper cladding are considered as having a RRR30 (see section “evaluating the copper cladding RRR”).

   Figure 19 FE Model geometry, materials and boundary conditions

   b. Boundary condition

The hot end of the cable is considered at 290K while the cold end is fixed at 4.5K.

The outer jacket of the coaxial cable will radiate in the thermal shield enclosure that is cooled at 20K. The emissivity retained for the stainless steel outer jacket is 0.07 (Ref.[2]).
The RF power dissipation will be computed using the 1D model. The reference frequency is 390 MHz as indicated in the [1].

c. Results and discussion

i. Temperature profile

The cable temperature profile has been computed for three different RF power rating, 0W (conduction only), 10W and 20W included in [1].

![Temperature Profile Graph]

Figure 20 Comparison of measured/simulation temperature profile for various RF power

Overall the evolution of the temperature profile is consistent with the experimental data. At mid cable (L=0.3 m) the temperature elevation for a P(RF)=20W is +60K measured and +47K simulated.

The mismatch observed, may be due to the room temperature elevation, the geometry of the cable being slightly different in the simulation than reported in [1] or the evaluation of the stainless emissivity that is likely to vary with temperature (considered constant at 0.07 in the simulation).

ii. Power evaluation

The paper [1] also reports on direct RF power dissipation evaluation on the cooled cable. On the graph Fig. 4 we will compare the values measured to the values obtained by simulation.
The simulated values match closely the measured values for RF power of 3W, 8W and 10W while being consistently slightly overestimated. The measured value for RF=20W (293 mW) is an outlier as mentioned in the paper [1]. It would correspond to an attenuation being halved abruptly (which is not credible unless this is the discovery some sort of RF superconductivity…) instead of a linear increase.

To confirm this hypothesis, the evolution of the outer jacket temperature profile (see Fig 3) is coherent to a RF power dissipation being about double at P=20W than at P=10W (about the same temperature difference between P=20W than at P=10W as between P=10W and P=0W).

3. Conclusion

The comparison between the simulated and measurement for the LHC type cable is consistent. The simulated temperature profile elevation for the cable is slightly underestimated however the power dissipation evaluation is consistent between simulation and measurement and the simulation seem always slightly conservative which is reassuring.

Reference


Appendix IV – Comparing the simulated attenuation to the manufacturer data

1. Introduction/context

At a later stage during this work, we managed to obtain cryogenic attenuation results from the proposed cable manufacturer company. We will report them here and describe how they compare with the data we have simulated previously.

2. Precisions on manufacturers data

The data obtained from the manufacturer did not describe the test setup in detail. After enquiry, the cable length used was close to 5 feet. We assume the temperature to be constant along these 5 feet without considering any end effects. Any warmer ends would tend to give a higher attenuation but without knowing the setup this cannot be estimated accurately.

The temperature tested range from 20 degC to -180 degC (~100K). The frequency tested range from 200 MHz to 1 GHz.

We have used our 1D cable model to work out the attenuation in the same conditions. While the resistive losses are evaluated at the relevant temperature the dielectric losses are considered as temperature independent in the 1D model and are always equal to the formula given by the manufacturer for their cable at room temperature (see Appendix I).

3. Results and discussions
   a. Attenuation

   ![Figure 22 Attenuation measured vs. simulation for a 1.3m long 0.141" cable](image)

   Figure 22 Attenuation measured vs. simulation for a 1.3m long 0.141" cable
Fig. 1 and Fig. 2 depicts the attenuation value measured by the manufacturer in solid line versus the simulation with the 1D model in dotted line. Fig.1 corresponds to a 0.141” cable while Fig.2 refers to a 0.090” cable.

For the 0.141” cable (Fig. 1) at 20°C the data are consistent with a maximum difference of 0.050 dB for the high frequency. For the 0.090” cable the data at 20°C are very consistent.

At cold, both in for the 0.141” and 0.090” cables, the measured attenuation is higher than the simulated attenuation. This difference is even higher when the RF frequency is high.

Since the dielectric attenuation is $\propto f$ while the resistive attenuation is $\propto \sqrt{f}$ the fact that the difference is higher at higher frequency points to a dielectric attenuation higher than expected by the model. Another possible explanation would be that some portion on the ends of the 5’ cable was used to transition from room temperature to cryogenic temperature. Since we simulate an homogeneous temperature along a 5’ cable this can explain the attenuation divergence with the experiment at lower temperature.

The difference between the measurement and the simulation can reach 30% at 100 K. However, since most of the attenuation is going to be in the warm section of the cable, the overall impact of this divergence is expected to be limited.

a. Power dissipation
While the power dissipation data are very consistent at room temperature, their differ at cold temperature like the cable attenuation. The observation and proposed explanation is similar than with the attenuation graphs. Note that a 20% overestimation was done when selecting a reference frequency, this should cover some of this underestimation at lower temperature (while still being conservation at higher temperatures).
Appendix V – Thermal conduction and placement of the heat shield thermalization

Introduction

The RF coaxial cable planned to be used for EIC will produce significantly more heat conduction that the cable used for RHIC mostly because of the material used.

We will aim at describing the initial heat conduction analysis leading to the study of the thermalization placement in this section.

Heat conduction

Material and dimensions

<table>
<thead>
<tr>
<th>Material (ID/OD)</th>
<th>RHIC</th>
<th>EIC – 0.141” cable</th>
<th>EIC – 0.090” cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer conductor</td>
<td>304L (ID 3.58mm/OD 3.57mm)</td>
<td>304L (ID 3.58mm/OD 3.57mm)</td>
<td>304L (ID 1.78mm/OD 2.29mm)</td>
</tr>
<tr>
<td>Outer conductor plating</td>
<td>/</td>
<td>Cu RRR30 (Thickness 0.114mm)</td>
<td>Cu RRR30 (Thickness 0.025mm)</td>
</tr>
<tr>
<td>Dielectric</td>
<td>Tefzel (ID 3.07mm/OD 0.81mm)</td>
<td>Si02 (ID 3.07 mm/OD 1.09 mm)</td>
<td>Si02 (ID 1.78 mm/OD 0.64 mm)</td>
</tr>
<tr>
<td>Inner conductor</td>
<td>Cu RRR100 (OD 0.81mm)</td>
<td>Cu RRR100 (OD 1.09mm)</td>
<td>Cu RRR100 (OD 0.64.mm)</td>
</tr>
</tbody>
</table>

1D thermal conduction comparison

Using the materials and dimensions above, we worked out the linear thermal conduction along the cable in mW.m. We can get an estimated conduction power in multiplying by the actual cable length.

The cable is divided in two stages:

The “hot” stage links the tunnel feedthrough (300K hot sink) to the thermalization piece cooled to the heat shield temperature. The heat shield helium will vary between 50K and 80K depending on the magnet position along the circuit.

The “cold” stage links the thermalization piece (50K to 80K) to the BPM module (considered at 4K).
From Fig. 1 and Fig. 2 we see that overall, the 0.090” EIC cable will conduct slightly less heat to the cryogenic circuits than the RHIC cable did. The EIC 0.141” cable however conducts about 3x times more heat to the cryogenic circuit as the RHIC cable for an identical implementation.

Placing the thermalization for EIC
As depicted on Fig. 1 and Fig. 2 the heat flow can be evaluated at the different heat station as a function of the length between these heat stations. We can then work out the placement the heat shield heat station along the cable length to minimize the overall load at the cryoplant.

The length of the cable is considered fixed at 1.3 m. Fig. 3 and Fig. 4 depict the effective heat load at the cold point in function of the distance between the thermalization and the tunnel feedthrough.

![Heat flow graph](image1)

**Figure 28 Heat conduction to the heat shield for the EIC 0.141" cable for two heat shield temperature (80K or 50K)**

![Heat flow graph](image2)

**Figure 29 Heat conduction to the 4.5K cooling circuit for the EIC 0.141" cable for two heat shield temperature (80K or 50K)**

We will try to place the thermalization to minimize the cryoplant working load. The cryoplant is assumed to follow a Carnot thermodynamic cycle with a 20% efficiency (discussion with R. Than). Fig 5 depicts the cryoplant power to extract 1W of heat at different cold temperature.
Using this and the heat flow as a function of the thermalization position (Fig. 3 and Fig. 4) we can then work out the power required at the cryoplant as a function of the thermalization placement. Shifting the thermalization toward the hot sink (tunnel feedthrough) will decrease the heat load to the BPM module (4.5K) but increase the heat load on the heat shield (80K/50K). We will strive the place the thermalization where the cryoplant cooling load (= operating cost) is minimized.

As seen on Fig. 6 we should ideally place the thermalization between 0.2 and 0.4 m from the tunnel feedthrough to minimize the operating costs.
Appendix VI – Minute of the 16th Dec 2022 meeting on worst HSR BPM beam misalignment

Following is the minute of the meeting held on Dec 16th 2022 where the worst beam misalignment in the HSR BPM was determined.

From: Micolon, Frederic
Sent: Friday, December 16, 2022 10:41 AM
To: Blednykh, Alexei <blednykh@bnl.gov>; Gassner, David M <gassner@bnl.gov>; Hetzel, Charles <chetzel@bnl.gov>; Verdu Andres, Silvia <sverdu@bnl.gov>; Sangroula, Medani <msangroul@bnl.gov>; Liu, Chuyu <cliu1@bnl.gov>; Robert-Demolaize, Guillaume <grd@bnl.gov>; Ptitsyn, Vadim <vadimp@bnl.gov>; Berg, J Scott <jsberg@bnl.gov>
Subject: [Minute] RE: Discussion on worst HSR BPM misalignment

Dear all,

Here is a tentative summary of what we discussed today. Please correct if I got something wrong. I want to be sure we have a common understanding/agreement.

• Presentation by Frederic:
In order to complete the engineering thermal analysis of the HSR BPM module, we need to define credible maximum value for the beam/BPM offset. They should be conservative but not too much at the risk of having to rework a design that is close to completion for no valid reason.

The maximum nominal orbit offset is 21 mm radial, 0 mm vertical.

The beam orbit control values was set at 1 mm following discussions with Silvia.

The CQS beampipe end max misalignment is considered to be 0.85 mm horizontal and 0.8 mm vertical.

Past RHIC surveys have shown magnets with vertical offsets of 1 mm wrt their neighbors. We will take this as possible magnet position drift in the tunnel.

This adds up to 23.85 mm max Beam/BPM center offset and 3.8 mm Beam/BPM center vertical offset.

• Discussion
It is mentioned by Vadim and Chuyu that the orbit feedback control system will use the correctors to force the beam in the center of the BPMs (or with the nominal beam offset desired). → This 1 mm magnet misalignment was taken out of the distance table.

It is mentioned by Chuyu that the beam orbit feedback system can provide a closed orbit with residuals below 0.2 mm. → The orbit uncertainty comes down from 1 mm to 0.2 mm.

Unlike RHIC, the BPM will not be well aligned with the quadrupole/sextupole magnetic center. The offset can reach 0.85mm (beampipe end offset). Assumption is that we want the orbit control feedback system to position the beam with respect to the quad/sextupole magnetic center and not the BPM center. So this 0.85 mm BPM misalignment is left in the table.

It is mentioned (by Alexei ?) that the BPM will also have calibration errors and Igor should be the best placed to give input on the expected calibration error.
Guillaume mentions that the design peak offset is 21mm but at the level of the BPM the excursion will be less, by at least 0.8 mm.

Chuyu mentions that the beam scenario computed by Medani (290 bunches 0.7A) does not match the operational scenario at 21 mm high offset so this analysis will be conservative.

We agree that a scenario with **23mm radial offset and 2mm vertical offset** must be conservative. So if the thermal response is satisfactory there should be no further issues.

Scott mentions that the beam has transverse dimensions, while CST models a strictly linear beam. Since the BPM heating is not linearly proportional to its distance to wall, the particles closer to the wall will have a proportionally greater heating than the ones far from the beam center. Beam transverse size could be in the order of 1mm.

It is considered that when the actual beam position is known, expecting it will not be as bad as the conditions we settled on (R+23mm/V+2mm) we can look again with the beam dimensions and decide if we should worry and run new simulations.

The worst case scenario from today on is a beam/BPM offset of **R+23mm/V+2mm**.

The resulting table is attached

Thanks for attending!

Frederic

<table>
<thead>
<tr>
<th>Justification</th>
<th>Value horizontal (mm)</th>
<th>Value vertical (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSR nominal beam offset</td>
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</tr>
<tr>
<td>Beam orbit control tolerance</td>
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<tr>
<td>Beampipe end misalignment</td>
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<td>0.8</td>
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<tr>
<td>BPM calibration uncertainty</td>
<td>?</td>
<td>?</td>
</tr>
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<td>Magnet misalignment</td>
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<td>±1</td>
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<tr>
<td><strong>Total</strong></td>
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<td><strong>2</strong></td>
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