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STATUS OF THE EIC HSR COLD BEAM POSITION MONITORS MECHANICAL DESIGN AND INTEGRATION*

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Abstract

The Electron Ion Collider (EIC) Hadron Storage Ring (HSR) aims to leverage as much hardware from the Relativistic Heavy Ion Collider (RHIC) storage ring as possible. However, the RHIC stripline beam position monitors (BPM) used in the superconducting magnet (SC) cryostat will not be compatible with the planned EIC hadron beam parameters that include shorter bunches, higher beam current and operation of the beam with a radial offset in the vacuum chamber. A new cryogenic BPM design using button pick-ups, integrated in a new interconnect bellow assembly, will be installed next to the decommissioned and shielded RHIC stripline BPMs. This paper will review some of the challenges faced in the design of the BPM pick-ups ahead of their procurement.

INTRODUCTION

The EIC HSR is designed to leverage the existing collider infrastructure from the RHIC project including instrumentation [1] and SC magnets [2]. However early studies found that the new beam structure, with shorter bunches and higher beam current, would not allow reusing the RHIC striplines BPM due to integration and heating concerns, especially at large horizontal beam offset [3, 4]. A new BPM pick-up design has been developed in the last years [5, 6]. This paper will cover some aspects driving the mechanical design and its integration in the SC magnets interconnect space.

SYSTEM REQUIREMENTS

HSR Beam Parameters

The EIC HSR hadron beam parameters will be significantly more challenging than for RHIC (see Table 1).

Table 1: Proton Beam Parameters for High Center of Mass (E_{cm}) and High Luminosity ($\mathscr{L}$) Collisions (From [7, 8])

	RHIC achieved	EIC HSR E_{cm}	EIC HSR $\mathscr{L}$
Number of bunches (-)	111	290	1160
Beam current (A)	0.28	0.69	1.00
RMS bunch length (cm)	60	6	
Bunch spacing (ns)	108	40.6	10.2

The short and intense HSR proton bunches will impose a challenging dynamic range for the BPM system. So an important design aspect was the trade-off between signal sensitivity and heating concerns. Accelerator physics requirements for the HSR BPM are summarized in Table 2.

Table 2: BPM System Design Requirements as of 2025

Requirements	Pilot bunch	Store
Bunch charge (nC)	5	30.6
Bunch length (mm rms)	1500	60
Beam position range H/V (+/- mm)	5/5	23/2
Beam position range H (aperture)	16 %	72 %
Resolution turn-by-turn (mm)	2	0.2
Resolution integrated 1s (mm)	0.2	0.02

Note: these are still being finalized at the time of writing.

As seen on Table 2 the BPM system needs to perform through a large dynamic range, between a long (1500 mm rms) low-intensity 5 nC gold pilot bunch and a ~20x shorter train of 30.6 nC store bunches. To keep the synchronicity between ultra-relativistic electron and only moderately relativistic hadron bunches at all beam energies, the hadron beam pathlength must be adjusted by shifting the beam radially in the beampipe up to ±20 mm close to the focusing quadrupoles [9] which represents 72 % of the beampipe aperture.

BPM Center Position Accuracy Requirements

The EIC HSR BPM system can unfortunately not benefit from Beam-Based Alignment (BBA) in the arcs because the SC circuit does not allow powering of each SC quadrupole magnet separately. While BBA can be done in the interaction regions [10], the arcs BPM will have to rely on a careful fiducialization during installation and the resulting BPM center position will be hard coded in the beam control system.

Table 3: BPM System Position Accuracy Requirement

Requirement	Positional requirement (mm)
Vertical (mm RMS)	0.3
Horizontal (mm RMS)	0.6

The EIC HSR physics program puts a special emphasis on the collision of polarized beams. Beam polarization is very sensitive to vertical deflections which must be minimized. Therefore, a careful quadrupole magnet alignment then becomes critical, as well as a precise fiducialization of the BPMs, especially in the vertical plane (see Table 3). The requirement of Table 3 refers to the position accuracy of BPM electrical center relative to the quadrupole magnetic center.

BPM BUTTON INTEGRATION

The HSR BPM button will be integrated in the new beamline interconnect module between superconducting

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magnets (Fig. 1). This area is cooled by the beam screen cooling circuit held between 4.5 K to 9 K by a flow of supercritical helium. During magnet cooldown, this circuit will be cooled with a delay, so the cryo-condensation of residual gas will occur mostly on the SC magnet cold bore. This will help limit beam-stimulated gas desorption on the BPM button. This new interconnect module is planned to be welded to the existing magnet beampipe, so its position cannot be tightly controlled given the assembly clearances and weld-induced distortions. This misalignment can increase the beam offset at the BPM location, as the hadron beam horizontal offset for pathlength adjustment is done in reference to the quadrupole center (Table 2). A provision for this misalignment was done in the thermal simulations .and the maximum beam offset considered is 23 mm [11].

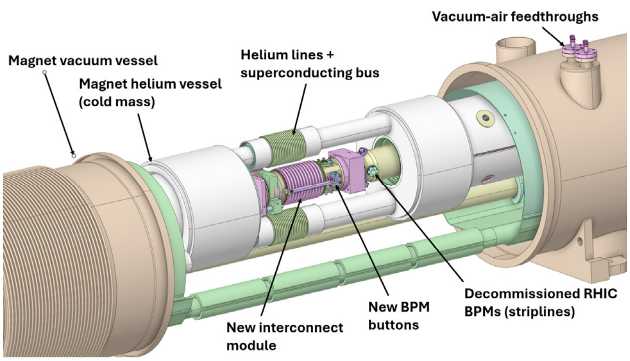

Figure 1: HSR SC magnet interconnect integration.

While the configuration initially preferred for the BPM button placements was 30° above horizontal mid-plane (Fig. 2) to mitigate button heating concerns, recent design studies prompted the reconsideration of a orthogonal button orientation (top, bottom, left, right). Indeed, for large beam offsets (Table 2) the BPM resolution decreases substancially both for the orthogonal or "corner" arrangement of the BPM buttons [6]. This coupled with strong non-linearity in the sensitivity, puts at risk the system accuracy and its ability to meet the resolution requirements (Table 2).

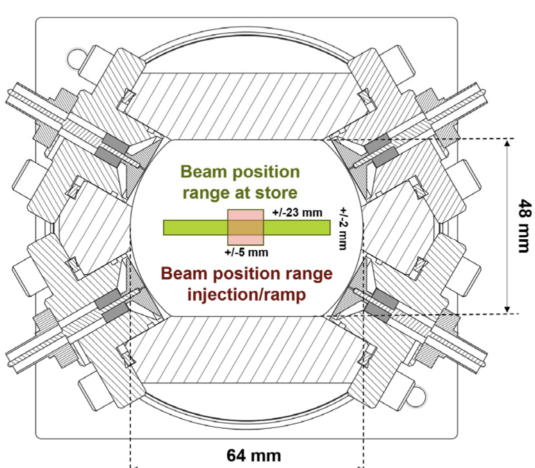

Figure 2: Cross-section of BPM module integration.

Fortunately, an orthogonal button configuration allows defining a "virtual center" electrode as the sum of the vertical buttons for Δ/∑ signal processing and increase the system resolution and accuracy for large horizontal offset beam displacements [6].

New SiO_2 insulated coaxial cables have been chosen to extract the RF signal from the cryostat volume through feedthroughs. A thermal analysis of these cables was made to ensure that thermal runaway is not a concern [11, 12] as could have been the case for RHIC at higher intensity [4].

BPM BUTTON DESIGN

The BPM button will be assembled to the beamline BPM housing with a bolted flange, similar to the LHC cold button design [13].

The 18 mm diameter pickup itself will be made of OFHC copper to mitigate beam-induced resistive wall heating (RWH) concerns [12] with an overlay of amorphous carbon to mitigate electron cloud generation [14]. A sleeve is designed around the button and will help with button positioning tolerance during fabrication and provide protection during handling (see Fig. 3).

The shorter HSR bunches (Table 1) will generate a higher frequency beam spectrum and so radial clearance between the button and the body was minimized to reduce beam-excited trapped resonant modes of the electromagnetic field. With elevated signal voltage expected at top design parameters, this can lead to high electric field gradient between the button and housing.

The button stem is designed in Inconel, while the heat generated on the stem at high RF signal power becomes significant, a stiff and strong material is required to support the RP-3.5 mm male connector. A RP-3.5 mm connector was chosen to avoid annealing the delicate female petals during vacuum firing prior to installation.

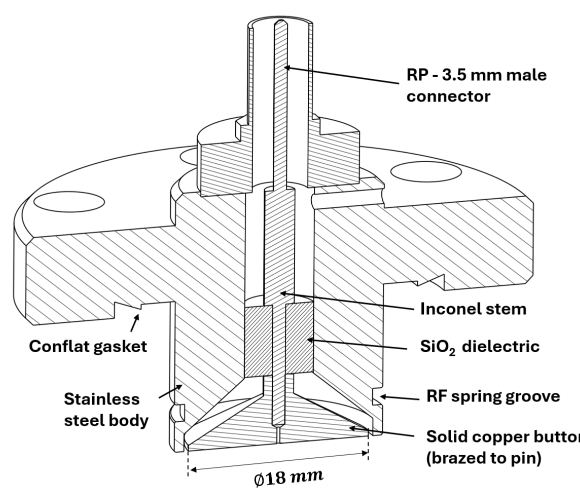

Figure 3: Cross section of the proposed button design.

Tight fabrication tolerances are crucial for this design to maintain a well-matched RF characteristic impedance and to make sure the electrical center of the 4x buttons can be defined accurately for accurate position determination (Table 4). The insulator and hermetic seal proposed is a SiO_2 dielectric material which has a favorably low dielectric constant but is also a poor thermal conductor. It was

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nevertheless found acceptable through thermal simulations [12]. Al_2O_3 is considered as an acceptable alternative.

Due to the variety of material employed, high temperature during the assembly process combined with cryogenic thermal cycles during operation will make this design sensitive to thermal expansion mismatch and possible fatigue crack growth leading to vacuum leaks.

Thermomechanical studies have been carried out and a series of cryogenic cycling tests, followed by helium leak checking are planned for reception testing of the first units.

BPM ALIGNMENT STRATEGY

As discussed earlier, the careful fiducialization of these BPMs will be crucial for the beam orbit feedback system to avoid inadvertent deflections to the polarized beam. The BPM module electrical center position will need to be measured and related to the quadrupole magnet center position with the required accuracy (Table 3).

Unlike the RHIC BPM, which benefited from direct measurement of their electrical center and of the quadrupole magnetic center thanks to a survey antenna [15], the assembly sequence foreseen here will not allow this procedure and will have to rely on survey fiducialization only.

The SC quadrupole magnet center position in the magnet fiducials reference frame has been recorded for RHIC and stored in the magnet database. The accuracy of the magnetic field center determination with the survey antenna was reported as ±60 microns in [16]. The BPM electrical center needs to be measured and projected in the coordinate system of the BPM module fiducials. This can be done with a stretched-wire RF measurement or using the Lambertson method combined with a Coordinate-Measuring Machine (CMM) or a 3D scanner for the mechanical center determination. This later approach has more steps which could increase the error budget. The precision of the chosen approach will be tested at reception and measurement of the first units. Finally, the relative position of the magnet fiducial reference frame and BPM fiducial reference frame will need to be measured with a laser tracker in the tunnel and recorded. Table 4 summarizes the expected errors of each step.

Table 4: Estimate Tolerance Breakdown for BPM Position Determination

	Est. tolerance (microns rms)
Electrical center fiducialization[1]	150*
BPM-to-magnet reference frame relative positioning	50*
Magnet center fiducialization	60
Total RSS/Arithmetic sum	169*/260*

[1] *Can be done in a single step for RF stretched wire measurement. Lambertson needs an extra step.*

**These are estimating values at the time of writing and will need to be confirmed through initial testing.*

Based on these estimates it seems that the position accuracy requirements can be fulfilled (Table 3). However, the real measurement accuracies will need to be obtained through testing and comparing different methods. After HSR beam commissioning, the fiducialization values can be compared with BBA measurements for all the straight section quadrupoles from Q9 to Q1 which have trim powering circuits.

BPM POSITION STABILITY

While fiducialization is performed at room temperature during assembly, it is important that operation conditions do not move the BPM-to-quadrupole center away from their initial relative position. Possible sources of displacement identified during operations include:

- Transverse loading from the magnet bellow
- Pressure loading from the helium circuit line
- Vibration resonance of the BPM module
- Uneven temperature profile

The new interconnect module will be welded at the end of a cantilevered beamline which is welded to the cold mass (Fig. 4). Applying the maximum expected bellow misalignment load, the displacement at the BPM location level is estimated about 16 µm. This is an order of magnitude lower than the position accuracy required (Table 3).

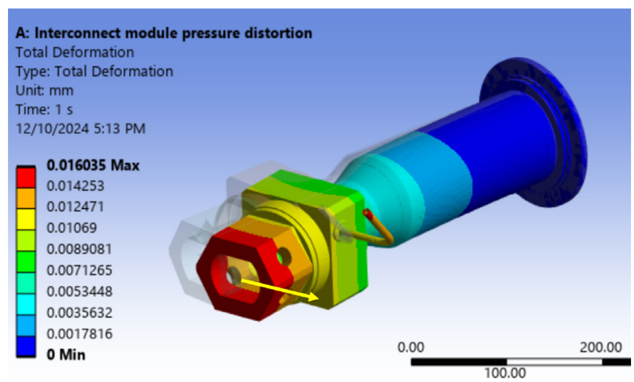

Figure 4: Simulation of BPM distortion with transverse bellow load (displacement displayed in mm).

The first-order resonance of the cantilever assembly is simulated at 720 Hz, at this high frequency the ground vibration will be very small [17] and it is assumed that the helium-flow induced vibration is also negligible.

Uneven temperature distribution of the BPM module should not be a concern as under 50 K the integrated thermal expansion of metals is almost asymptotic, and the cantilevered beam is covered with MLI to avoid uneven radiation loading from room-temperature components in the interconnect space.

CONCLUSION

The design of the EIC HSR BPM buttons has made steady progress and the procurement has started. Selected vendors will be allowed propose design adaptations from our reference design. These adaptations will be carefully studied to ensure the design requirements are fulfilled. An in-depth testing campaign is planned at the reception of the design verification units.

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