BNL-229072-2025-TECH
EIC-ADD-TN-150

EIC ESR BEAM POSITION MONITORS THERMAL AND THERMOMECHANICAL STUDY PRELIMINARY DESIGN

F. Micolon

October 2025

Electron-Ion Collider
Brookhaven National Laboratory

U.S. Department of Energy
USDOE Office of Science (SC), Nuclear Physics (NP)

EIC ESR BEAM POSITION MONITORS THERMAL AND THERMOMECHANICAL STUDY PRELIMINARY DESIGN

F. Micolon†, D. M. Gassner, M. Mahoney, K. Matsushima, L. Skordis, M. Wendt

Brookhaven National Laboratory, Upton, New York, USA

Abstract

The Electron Ion Collider (EIC) Electron Storage Ring (ESR) Beam Position Monitors (BPM) are designed to monitor the electron beam orbit position on a turn-by-turn and bunch-by-bunch basis in the vacuum chamber. Large variations in ESR fill pattern and bunch intensity imposes a large dynamic range on the BPM system design. And given the large ESR beam current - up to 2.5 A with 1160 x 20 nC bunches – the heating by synchrotron radiation (SR) and beam impedance is a significant concern. The high energy of the electrons – up to 18 GeV – leads to scattering of the SR that produces high radiation doses and associated heating of structures away from the SR impact area. Because of this intense heating, and stringent position stability requirements, an in-depth engineering analysis was carried out. This paper will review the analysis made of the preliminary design and its main outcomes.

INTRODUCTION

The EIC ESR is 3,8 km storage ring for electron bunches injected on-energy on-orbit from the Rapid Cycling Synchrotron (RCS). It is designed to store polarized electrons with energies 5 GeV, 10 GeV and 18 GeV to reach the collision center-of-mass energy required by the EIC physics program [1]. Flat electrons beams will be stored with a vertical/horizontal emittance ratio of 11:1. Each of the 185 defocussing ESR quadrupole will be equipped with an adjacent BPM embedded in the beamline vacuum chamber, as well as some at the focussing quadrupole location downstream of the injection point for a total of ~220 [2].

ESR BPM REQUIREMENTS

ESR Beam Parameters

Table 1: ESR Beam Parameters at maximum current ([1])

Beam energy (GeV)	**5**	**10**	**18**
Number of bunches (-)	1160		290
Max bunch charge (nC)	27.55		9.93
Beam current (A)	2.5		0.23
RMS bunch length (mm)	7		9
Bunch spacing (ns)	10.15		40.6
Synchrotron radiation (MW)	3	10	10

The 7 mm rms long, intense ESR collision bunches, in contrast to the low intensity pilot bunch (Table 2), will impose a large dynamic range for the ESR BPM system. Performance requirements for the ESR BPM are summarized in Table 2.

Table 2: BPM System Design Requirements [3]

Requirements	**Pilot bunch**	**Store /BBA**
Bunch charge (nC)	1.6	27.6
Beam position range (mm)	+/-10	+/-3
Resolution turn-by-turn (µm)	≤ 100	≤ 30
Resolution multi-turn (µm)	-	≤ 2
Position drift - 1s window (µm)	-	≤ 1
Position drift - 8h window (µm)	-	≤ 5

As shown on Table 2, tight requirements are imposed on measurement drift of the BPM measurement. This translates into requirements both for the BPM electronics drift and the BPM pickup position stability.

BPM Center Position Requirements

While the ESR BPM can benefit from Beam-Based Alignment (BBA), requirements are placed on the BPM center position to ease commissioning pre-BBA.

Table 3 BPM mechanical center position requirements

	Tolerance
Determination of **BPM center position wrt BPM fiducials**	+/- 200 µm
Determination of **BPM Horiz/Vert plane angle wrt BPM fiducial**	+/- 20 mrad
Alignment of **BPM center wrt quadrupole center axis**	+/- 500 µm (TBC)
Alignment of **BPM Horiz/Vert plane wrt quadrupole H/V planes**	+/- 50 mrad (TBC)

Note that the requirements of Table 3 apply to the BPM mechanical center and not the electrical center. The Lambertson method may be used to determine the mechanical-electrical center offset if needed. BBA will help locate the BPM electrical center with respect to the adjacent quadrupole magnetic center. However adjusting the roll of the BPM measurement planes with respect to the adjacent quadrupole magnetic planes is important as errors will induce a false coupling between the two planes and cannot be measured and corrected electronically with BBA.

ESR BPM BUTTON DESIGN AND INTEGRATION

The ESR button preliminary design is largely based on the successful NSLS2 BPM button design [4][5]. Due to

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
† fmicolon@bnl.gov

their proximity (21 mm), the two Ø6 mm side-by-side buttons are embedded in the same flange (Fig. 1). Leak tightness of the flange is ensured by a Helicoflex® gasket.

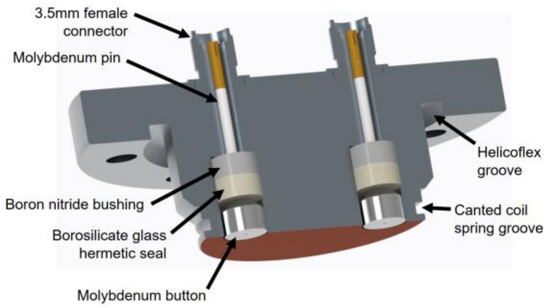

Figure 1 Cross section of the ESR BPM module preliminary design

The button and stem will be made of molybdenum given a good CTE match with the SiO_2 insulator, this helps minimize internal stress and crack propagation after many heating cycles. Heating considerations of the NSLS2 button prompted the use of a boron nitride bushing to help limit the button temperature, given the low thermal conductivity of the SiO_2 hermetic seal. The boron nitride is on the air-side in a tight-fit with the stem and the bore, so it is not in perfect thermal contact on either side. A radial gap - filled with air - will reduce its effectiveness. Given the 7 mm short ESR bunches (Table 1) the bunch RF spectrum extends up to 15 GHz. This imposes a tight radial gap between the Ø6 mm molybdenum button and the housing (0.25 mm nominal) to avoid electromagnetic fields resonance at frequencies corresponding to the bunch spectrum. Additional details on the design can be found in [6].

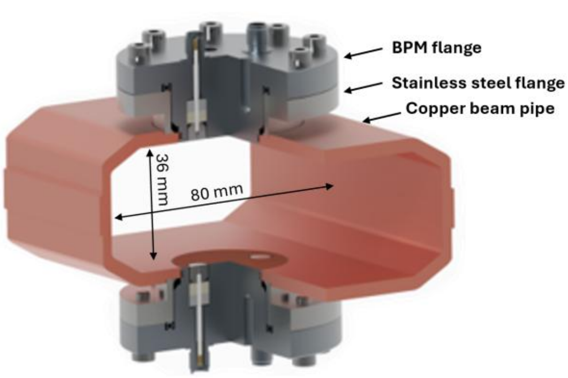

Figure 2 Cutaway of the ESR BPM in the vacuum chamber

The BPM module will be integrated in the water-cooled copper vacuum chamber of the ESR (Fig 2). The vacuum chamber is octagonal with main dimensions 80 mm horizontal and 36 mm vertical. Not represented on Fig 2 are the water-cooling channels located on each side of the vacuum chamber.

The BPM will be integrated in the vacuum chamber of the so-called "multipole" girder that is supporting the quadrupole, sextupoles and corrector magnets in the arcs. The beampipe support supporting the BPM is attached to the quadrupole lower support (Fig 3). The BPM support structure is made of invar bars and threaded rods for final position adjustment.

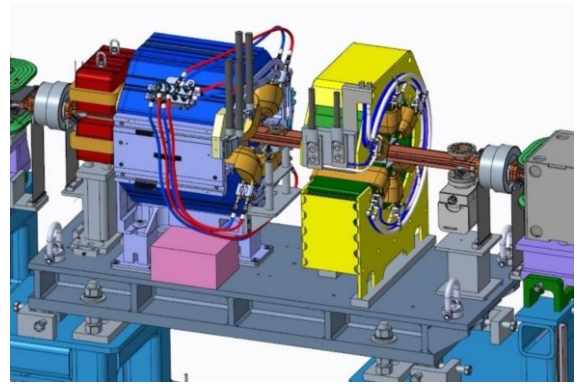

Figure 3 Multipole magnet girder

THERMAL ANALYSIS

The three main sources of heating of the BPM are:

1. Beam-induced RF heating
2. Direct synchrotron radiation
3. Scattered synchrotron radiation

Beam impedance

Each BPM button represents a discontinuity in the smooth vacuum chamber walls and alters the TEM field generated by the passing bunch. EM modes can penetrate in the geometric imperfections and resonate in the gaps as discussed in [7]. This produces eddy currents which, together with the bunch image current, translate into heating power. A CST model has been used to model and optimize the BPM button geometry to minimize the wakefield effect of a passing bunch. The total power dissipation on each BPM module amounts to 2.5 W while the Mo button only gets 0.165 W. Simulation details can be found on [8].

Direct synchrotron radiation

Due to the high beam current and electron energy required, the amount of synchrotron radiation handled by the ESR is among the highest ever seen in a collider (Ref. [1] Table 3.41). Synchrotron radiation from the upstream dipoles will be illuminating the vacuum chamber in the horizontal plane. While the SR power incident on the BPM itself is expected only around 0.14 W per BPM from Synrad simulation, the heating of the vacuum chamber will produce local heating and beam pipe distortion that are significant for the BPM performance. At the maximum SR power of 10 MW (table 1) the incident SR on the multipole vacuum chamber is expected to be 6.3 kW total or 3.5 kW/m [9].

Scattered synchrotron radiation

At high electron energy, the synchrotron radiation spectrum contains high energy photons that have the potential to scatter off when they interact with matter through photoelectric and Compton scattering. This produces secondary radiation that will penetrate the surrounding structures and heat them up. This scattered SR effect was evaluated with FLUKA both in the 10 GeV and 18 GeV (higher SR photon energy) beam scenario. Little difference was seen on power between the two scenarios. The BPM module receives about 0.4 W and the Mo button about 0.04 W.

Water and air cooling

The high synchrotron radiation in the ESR vacuum chamber imposes water-cooling channel with large cooling flow rate in close proximity to the SR incident point. The multipole girder is located immediately downstream of the water inlet point which minimizes water temperature elevation from the inlet temperature. The cooling water loop is designed to supply an inlet water temperature between 20°C and 30°C [10]. Previous design analysis of the vacuum chamber assumed a water flow rate up to 8 GPM, which results in an average water speed of 3 m/s over the ∅14 mm channels, a velocity beyond which copper erosion can become a concern. For this analysis, we have elected to use a mass flow rate of 6 GPM which gives a velocity of 2.3 m/s, a turbulent Reynolds number >40 000 and a convection coefficient of 9320 W/m^2.K with a 30°C water temperature. All surfaces exposed to air have a convection coefficient of 5 W/m^2.K to represent natural convection with an air temperature of 30°C.

Results

The model is a 0.2 m section of beampipe with the central supporting brackets modelled (Fig.4).

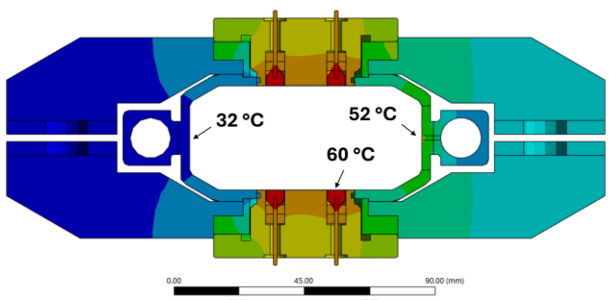

Figure 4 Resulting BPM temperature distribution

The temperature of the button reaches 60°C in the highest heating scenario analyzed (2.5 A with 27.55 nC bunches – 10 MW synchrotron radiation) which is acceptable. The button temperature elevation is +30°C of which +17°C (57%) is caused by the beam induced RF heating, +7°C (23%) is due to SR and +6°C (20%) from scattered SR. The heat extraction is done mostly by water (698.2W) and very little by air (4 W).

THERMO-MECHANICAL ANALYSIS

Disclaimer: the beamline support designs are not finalized. So, this study is a status and will guide the final design.

Table 2 summarizes the BPM readout drift requirement, which is a budget composed of BPM pickup position drift and electronics drift. Here we will be concerned only with the hardware distortion/displacement which results in a BPM center position drift.

The BPM center displacement is composed of a deformation of the entire multipole girder vacuum chamber (Figure 4) and a local distortion of the BPM module and its support under vacuum forces and uneven temperature distributions. The BPM support bracket is considered made of stainless steel to match the copper thermal expansion and avoid local thermomechanical stresses on the soft copper vacuum chamber. The threaded rods and supports are considered made of Invar to have a high temperature stability.

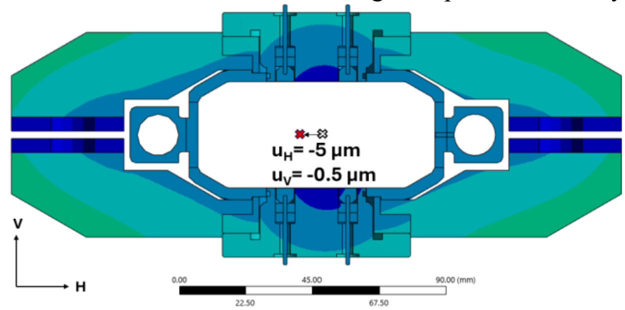

Figure 5 Distortion of the BPM module

Upon heating the hardware distortion will induce a motion of each pickup in various direction < 10 µm. As the BPM signal is processed as delta/sum, symmetrical displacement around the beam will not change the position readout. The BPM center displacement is then 5 µm horizontal away from the SR line and < 1 µm vertical.

The vacuum chamber overall distortion is particularly impacted by incident SR and is non-constant along the chamber length because of the photon absorber section downstream of the BPM. In the current design the chamber distortion at 10 MW SR heating results in an additional displacement of the BPM center 5 µm vertically and 6 µm horizontally [11]. The requirement on BPM center position drift of <5 µm over an 8-hour store is not fulfilled by the current design. However, the present displacement values are encouraging, and we are optimistic that some design modification will help fulfill this requirement.

For perspective the PEP-II BPM buttons had a 25 µm motion mostly due to "the bowing of the vacuum chamber" [12]. However, once in operation they had even greater overheating concerns [13].

BPM VIBRATION STABILITY

Table 2 mentions a maximum allowed position drift of +/- 1 µm over 1 s. As was measured in [14], some areas of the EIC tunnel have high levels of ground vibrations. The vibration spectrum from 100 Hz down to 1 Hz results in an integrated RMS displacement of 0.115 µm. Therefore, fulfilling this stability requirement is not trivial, and particular care must to be taken to ensure the ESR beamline vacuum chamber do not amplify the ground motion through resonances. High flow rate of cooling water in the vacuum chamber, needed to extract 10 MW of SR, can also produce a wide vibration excitation spectrum of the vacuum chamber. This excitation needs to be assessed.

CONCLUSION

The severe environment and relatively stringent requirement impose a careful analysis of the ESR BPM. This analysis show that, at the preliminary design phase, the expected operating temperature is acceptable and while the position drift requirements are not fulfilled, we have identified some design changes that are expected to successfully improve the design and match the requirements.

REFERENCES

[1] F. Willeke, “Electron-Ion Collider eRHIC Pre-Conceptual Design Report”, Office of Scientific and Technical Information (OSTI), Jul. 2019. doi:10.2172/1547019

[2] D. Gassner et al. “Design Status of the Electron-Ion Collider Beam Instrumentation” presented at IBIC’25, Liverpool, UK, Sep. 2025, paper MOPC017

[3] F. Zulferino et al. “Electron Storage Ring System Beam Position Monitor Button Assembly Performance Requirement Documentation” EIC Internal Report EIC-SEG-RSI-151 rev. 00 (October 2025)

[4] A. Blednykh *et al.*, “NSLS-II Storage Ring BPM Button Development”, in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 748-750. doi:10.18429/JACoW-IPAC2015-MOPMN021

[5] W. X. Cheng, B. Bacha, B. N. Kosciuk, S. Krinsky, and O. Singh, “Performance of NSLS2 Button BPM”, in *Proc. IBIC'13*, Oxford, UK, Sep. 2013, paper WEPC09, pp. 678-681.

[6] K. Matsushima “ESR BPM Pick-Up Mechanical Design” PDR presentation - October 2025 - Link : 04-K.Matsushima-ESR BPM Pick-Up Mechanical Design.pptx

[7] P. Cameron, A. Blednykh, B. N. Kosciuk, I. Pinayev, V. Ravindranath, and O. Singh, “BPM Button Optimization to Minimize Distortion due to Trapped Mode Heating”, in *Proc. PAC'09*, Vancouver, Canada, May 2009, paper TH5RFP011, pp. 3462-3464.

[8] M. Wendt “ESR BPM system overview”, PDR presentation - October 2025 - Link : 03-M.Wendt-ESR BPM System Overview.pptx

[9] C. Hetzel – Private communication

[10] HDR Basis of Design – BNL report BNL_EIC-FD100_IFB_BOD

[11] M. Mahoney – Private communication

[12] N. Kurita, D. Martin, S. Smith, C. Ng, M. Nordby, and C. Perkins, “Design of the Button Beam Position Monitor for PEP-II”, in *Proc. PAC'95*, Dallas, TX, USA, May 1995, paper MPQ25, pp. 2512-2514.

[13] S. P. Weathersby and A. Novokhatski, “BPM Breakdown Potential in the PEP-II B-factory Storage Ring Collider”, in *Proc. ICAP'09*, San Francisco, CA, USA, Aug.-Sep. 2009, paper THPSC057, pp. 363-366.

[14] F. Micolon and B. Podobedov, "Ground vibration studies in the RHIC tunnel in view of EIC", in Proc. NAPAC2025, Sacramento, CA, USA, Aug. 2025, pp. 884-887. doi:10.18429/JACoW-NAPAC2025-WEP097