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FELICIA – A PROBE TO SURVEY THE RHIC MAGNET BEAMPIPE DIAMETER FOR EIC BEAM SCREEN INSERTION

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Abstract

The Electron Ion Collider (EIC) Hadron Storage Ring (HSR) will reuse many of the existing superconducting (SC) magnets of the RHIC storage rings. To comply with the beamline vacuum requirements in more demanding operational scenarios, the beampipe of the RHIC SC magnets will be equipped with low surface impedance, low secondary electron yield (SEY) beam screens. The installation of these beam screens will be done with the SC magnets as installed today, thus making it a critical operation for a timely EIC installation. The beam screen inner dimensions must be maximized to retain enough aperture to the beam. On the other hand, keeping enough clearance between the screen and the beampipe is critical to ensure a smooth beam screen installation. A survey probe was designed and built to measure the inner diameter of several RHIC SC magnets in-situ and provide critical data for the beam screen design optimization. This paper reports on the design of the probe and the results from the survey campaign.

MOTIVATION AND REQUIREMENTS

Featuring shorter bunches than RHIC [1] and large radial offsets for certain beam energies [2], the EIC hadron beams would produce an unacceptable heating on the current stainless steel RHIC beampipe. The solution adopted is to install a low impedance beam screen in the beampipes of the RHIC SC magnets [3]. Conceptual designs for this beam screen have evolved from a passively cooled solution [3] to an actively cooled beam screen with circulation of helium in a welded capillary (see Fig. 1).

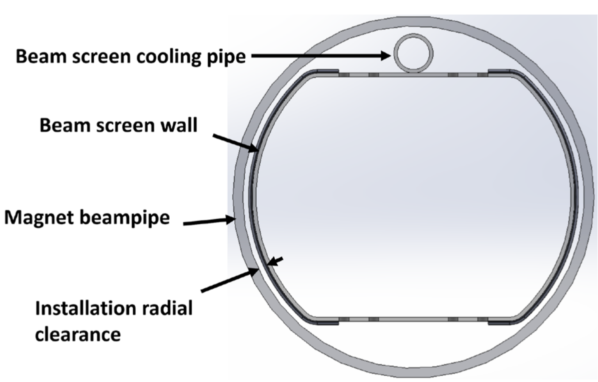

Figure 1 View of Actively Cooled BS Cross Section.

The radial clearance between the beam screen and the beampipe diameter must be carefully set. A too tight clearance would lead to installation issues by interference with the beampipe while a too large clearance would reduce the beam aperture unnecessarily. So the knowledge of the actual beam pipe diameter is a crucial prerequisite to a sound beam screen design.

Most magnets in the RHIC arcs have a nominal beampipe diameter of Ø69.1 mm except for the snakes and spin rotators. The RHIC arc cold masses have lengths between 3 m and 12 m.

The aim of this work was to design a survey probe that can measure the diameter of a complete magnet beampipe with a precision better than +/- Ø0.1 mm.

DESIGN OF A SURVEY PROBE

The survey probe is based on a touch probe principle. Stainless steel balls are pushed against the beampipe inner diameter, and the position of these balls is measured with linear potentiometers. The balls are fixed on a tilt module. When tilting down, this module pushes against a spring-loaded linear potentiometer (see Fig. 2). Opposite to the tilt module is another touch ball positioned on a fixed arm. The potentiometer extension is therefore an image of the distance between the fixed ball and the tilt ball (i.e. pipe diameter). Each main module is equipped with four touch balls constituting two perpendicular measurements each with a tilt ball and a fixed ball.

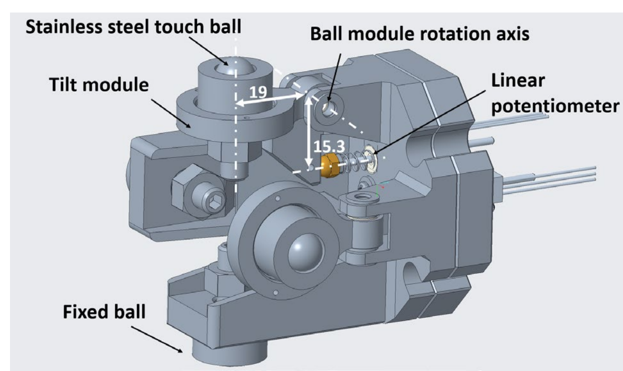

Figure 2 Probe Measurement Module.

The allowable diameter measurement range is 66 mm to 72 mm. The potentiometer shaft displacement for this range is about 5 mm corresponding to about half the potentiometer total linear range. The potentiometer voltage is read by a 15-bits ADC which allows a readout resolution of 0.34 µm on the touch ball position through the assembly tilt.

The complete survey mole is equipped with two main measurement modules, one at its front and the other at its back (see Fig. 3). The main body of each module is 3D-printed while the tilt modules use bronze bushing joints and stainless-steel pins. Friction in the linear potentiometer induced a hysteresis effect due to the distortion of the 3D-printed module. This was a key factor in the overall probe

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precision. So these modules were reinforced with epoxy glued thin stainless steel sheets to stiffen the assembly and limit the amplitude of the distortion hysteresis.

To go through the 12 m long beampipe with a controlled longitudinal sampling rate, the probe has been fitted with an onboard motor and a driving wheel. The motor displaces the probe in steps of around 10 mm and stop 0.2 s at each step to make redundant potentiometer recordings. Even a small amount of dirt in the beampipe was found to hinder the smooth motion of the stainless touch balls eventually. Adopting a back-and-forth motion at each step has solved the problem by avoiding dirt accumulation in the stainless ball assembly.

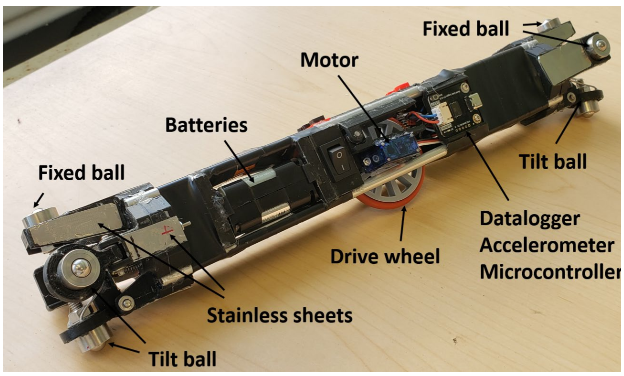

Figure 3 Assembled Survey Probe.

To keep track of the mole orientation in the beampipe, the probe is equipped with a three-axis accelerometer. The potentiometer ADC and accelerometer readout are stored in an onboard memory. The probe actuation and data are handled through an open-source Arduino® microcontroller.

RESULTS AND DISCUSSION

Probe Resolution, Repeatability, and Accuracy

The calibration of the mole was done in a short pipe pinched with a C-clamp. The clamp was loaded and unloaded by steps of 0.15 mm and the potentiometer readout was recorded. A very good response linearity is achieved. The measured resolution is between 0.29 µm and 0.32 µm. The repeatability is measured between +/- 24 µm and +/- 38 µm.

The probe accuracy was evaluated by making use of a machined cylindrical plug of precise diameter. The C-clamp was used to distort the pipe inner diameter snugly around the plug outer diameter and the probe diameter readout was compared to the round plug OD. This has shown that, at worst, the probe diameter readout is 0.27 mm lower than the actual diameter. Overall, the probe accuracy was found always Ø0.05 to Ø0.27 mm under the actual diameter. This is thought to be linked with assembly misalignments of the opposing touch balls.

In summary, the precision and accuracy of the different measurements are summarized in Table 1.

Table 1 Summary of Measurement Precision and Accuracy

Potentiometer	V front	V back	H front	H back
Precision +/- (mm)	0.030	0.024	0.038	0.036
Accuracy (mm)	-0.16	-0.26	-0.27	-0.05

RHIC Arc Dipoles Beampipe Survey

The probe was used to measure the beampipes of a total of 12 RHIC arc dipoles (DRG) stored as spare. The dipole beampipe has three main sectors: a short sector running out of the magnet, another sector running through the end volumes where the magnet leads and superconducting bus expansion loops are connected, and then the sector within by the coils where the beam is subject to the magnetic field. The end volume and end pipe are also present on the other side of the coil section.

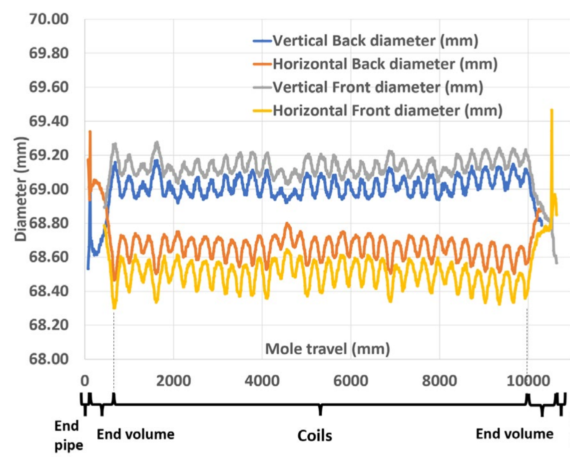

Figure 4 ID Survey of RHIC Dipole DRG567

As shown in Fig.4, the beampipe ID at the coil segment displays an oscillating pattern in both horizontal and vertical planes. This pattern is consistent for all dipoles. Here the amplitude measured is around 0.3 mm and the horizontal and vertical oscillations are 180° out of phase. The horizontal ID is consistently lower than the vertical ID.

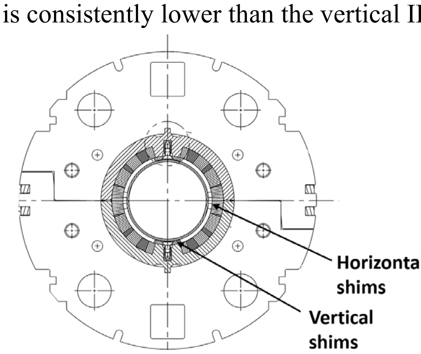

Figure 5 Cross Section of a RHIC Dipole [5]

The oscillation pattern (wavelength, amplitude, and relative phase) is explained by the way the dipole magnets are assembled. The collaring of RHIC dipoles is done by

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pressing the two parts of the yoke together to apply a pre-stress on the coil (see Fig. 5).

The dipole yoke is then bent to imprint a horizontal sagitta to the magnet and the cold mass outer shells are welded on [4]. The beampipe is centred in the yoke by means of locating shims. These locating shims are placed about 0.3 m apart. Horizontal and vertical shims are staggered. The imprint of these shims explains the oscillation wavelength, amplitude and relative phase seen of Fig 4.

The average minimum diameter and standard deviation (σ) for the beampipe of a sample population of 12 dipoles are used to determine the lower bound beampipe diameter that is likely to allow a smooth beam screen insertion. Under the assumption that the sample population is representative of the magnets installed in RHIC and that the assembly tolerance conforms to a normal distribution, we elected to subtract 3σ to the average diameter to determine the maximum beam screen OD that should fit through 99.8% of all dipoles. Values are summarized in Table 2.

Table 2 Dipole Diameter Summary

Dimensions in mm	Horizontal	Vertical
ΦAverage	68.44	68.46
Std dev σ	0.10	0.28
ΦAverage – 3σ	68.14	67.62

From the dipole diameter analysis (see Table 2), the maximum OD recommended for the beam screen assembly is 68.14 mm horizontal and 67.62 mm vertical.
Adding the manufacturing tolerance and beam screen wall thickness gives a minimum horizontal beam aperture of 63 mm. For high energy beams with large orbit excursions, this was found to correspond to an expected available beam aperture within 9 – 10 σ.

RHIC DU Survey

In the RHIC straight sections, drift spaces are filled with dummy (DU) sections that ensure the vacuum lines, cryogenic lines and electrical bus continuity.

By design the long RHIC DU sections have welds on the beampipe that lead to the protrusion of the weld bead into the beampipe. In some instances, a pinch of the beampipe attributed to the through bolts in the aluminium I-beams has been seen during our surveys (see Fig. 6).

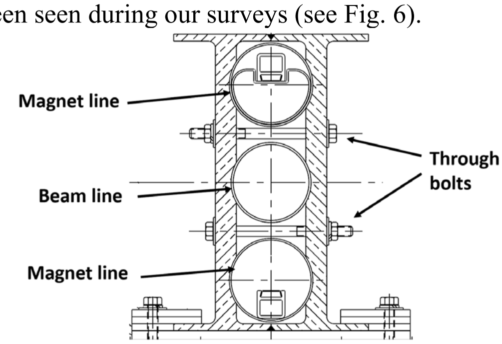

Figure 6 DU Section Cold Mass Cross Section

These features lead to significant distortions along the beampipe. Inner weld beads and through bolt pinches in the beampipe have been found to reduce the beampipe diameter to values as low as Ø66.83 mm and Ø67.50 mm, respectively. RHIC contains a limited number of DU sections, so including these values in the beam screen diameter analysis would have led to an unreasonable diameter constraint on all magnets, and further reduced the beam aperture. Therefore, the ID of each DU beampipe will be surveyed individually ahead of beam screen insertion and specific measures will be adopted on a case by case.

RHIC CQS Survey

In the arcs, the RHIC dipoles alternate with a CQS assembly which can contain a quadrupole, a corrector and either a sextupole or a trim magnet. The CQS cold mass is collared and welded before the insertion of the straight beampipe. So there is sufficient clearance for insertion of the beampipe through the coils and no interference is expected. Survey of a CQS beampipe confirmed that the CQS cold mass has a smooth beam pipe ID upstream of its stripline BPM module [5].

WHY FELICIA?

Felicia was the name of a ferret working at FNAL in the late 1960s. She was working to check for blockage and clean the beam aperture of the FNAL accelerators beampipe. [6] This is a tribute to a brave ferret.

CONCLUSION

One of the early challenges of the EIC beam screen installation was getting a precise knowledge of the beampipe diameter profile to set its dimensions correctly. To this end, a survey mole was engineered, assembled, and calibrated in the second half of 2022. A series of survey runs in RHIC spare magnets has led to recommendations on the beam screen assembly OD to maximise both the beam aperture and the chances of a smooth installation.

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