PROCEEDINGS OF SCIENCE

Rogowski Beam Position Monitor

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The Jülich Electrical Dipole Moment Investigations (JEDI) Collaboration performed the first direct measurement of a charged hadron Electric Dipole Moment (EDM). These investigations were carried out using polarized deuteron beams at the COoler SYnchrotron (COSY) located at the Forschungszentrum Jülich in Germany. The search for an EDM demands high precision measurements, separating the true EDM signal from the background. As a next step, a prototype electrostatic EDM ring will be designed to increase the sensitivity of the measurement. Here the necessity of a near ideal beam closed orbit requires a system of many compact and highly sensitive Beam Position Monitors (BPM). A new type of BPM has been developed based on a segmented toroidal Rogowski coil. These Rogowski BPMs are highly compact requiring only about 10 centimeters of free space for installation while providing a resolution of a few micrometers. The Rogowski BPMs compete with other BPM types in order to provide the best resolution and Signal-to-Noise Ratio (SNR), while using as little space as possible.

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1. Introduction

The glaring absence of antimatter is one of the pressing questions that challenge our current understanding of the observable universe [1]. One explanation for this matter-antimatter asymmetry is the presence of CP violating processes in addition to the ones accounted for in the Standard Model [2]. A charged particle Electric Dipole Moment (EDM) is a source of CP violation. EDM can be searched by measuring the interaction of particle spin with electric and magnetic fields using a storage ring. The JEDI collaboration is working on a magnetic ring conducting such high-precision measurements. Current measurements are taking place at COSY, Forschungszentrum Jülich [3]. The next step will be to build a prototype storage ring employing a combination of electric and magnetic fields. The final goal is to produce an electric storage ring which provides the necessary precision for such EDM measurements.

For these future experiments, a high-quality beam is necessary; thus, a high-precision Beam Position Monitor (BPM) is required. The Rogowski BPM is a candidate for this role and is currently being tested in the laboratory and preliminary results from the tests inside COSY show that the BPMs have a resolution of a few micrometres over 1 second sampling duration [4]. This, along with its compact profile, makes the Rogowski BPM an excellent choice for the future electric storage ring.

2. Rogowski BPM

A Rogowski coil is made by winding a wire around a non-conducting core in a toroidal manner [5]. The Rogowski BPM is made up of four Rogowski coil segments. A coiled segment is a quadrant. A signal is induced in the coil when the beam passes through the BPM (Electromagnetic Induction principle [6]). This signal is then used to determine the position of the beam. The Rogowski BPM's performance is yet to be quantified, and one way to do it is by determining the signal-to-noise ratio (SNR). The first step is to measure the system's noise floor; for this, various experiments are conducted. Then the data is fed into the SNR model of the BPM system.

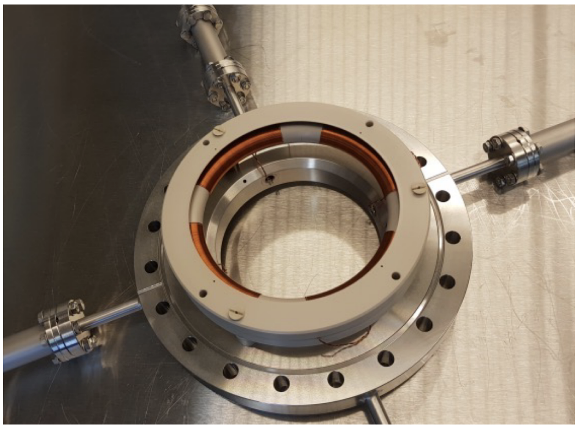

Figure 1: A Rogowski Beam Position Monitor installed inside a vacuum apparatus.

3. Experiments

3.1 Noise Measurements

The Rogowski BPM setup is made up of the following components: Rogowski coil segments, pre-amplifier, cables and lock-in amplifier. These components are found in the laboratory setup and the setup deployed at COSY. To measure the noise profile of the Rogowski BPM setup, a measurement of the noise profile of its components is a must. For all the experiments, the noise is measured using the lock-in amplifier. The input of the device under test (DUT) is capped off using a 50 Ω load, and the output is connected to the lock-in amplifier. A sweep is then performed over the selected frequency range. The results from these experiments are seen in Figure 2.

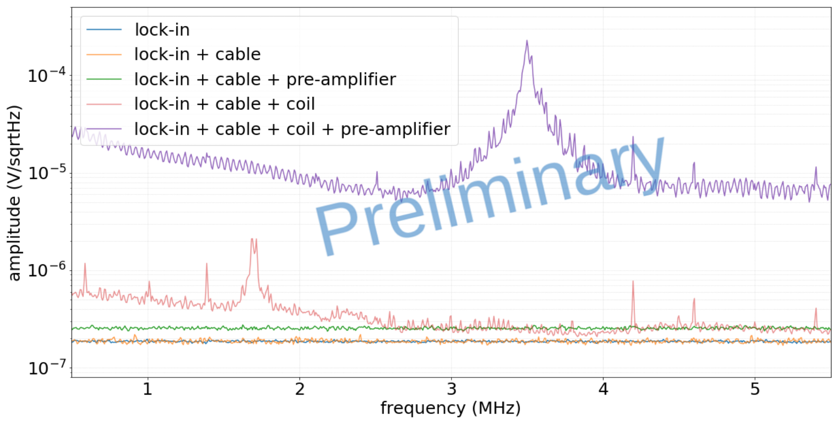

Figure 2: Noise profile of different components at 1V input range.

At the 1 V input range, the noise contributions of the lock-in amplifier and the lock-in amplifier—cable system (Figure 2, curves 1 and 2) are similar at $\sim 200\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$, implying that the contribution from the cable is minimal. Introducing the pre-amplifier (see curve 3) increases the noise floor to $\sim 280\,\mathrm{nV}/\sqrt{\mathrm{Hz}}$. The two noise profiles of the system with coils (Figure 2, curves 4 and 5) have their resonance peaks at different frequencies. Curve 4 has a resonance peak at approximately 1.8 MHz, whereas curve 5 has a resonance peak at about 3.5 MHz. This difference in the resonant frequencies can be explained by the involvement of the pre-amplifier in the circuit at the time of the measurements. When the measurement is conducted without the pre-amplifier, the capacitance of the cable brings down the circuit's resonant frequency.

3.2 Impedance Measurement

In order to determine the coil parameters R, L and C, a vector network analyzer was used for impedance measurement of the coil segment. The network analyzer is calibrated before the measurements are performed and thus provides values of the parameters which correspond to a higher resonant frequency. The following resonant function is used to determine the parameters:

$$F(\omega) = \frac{1}{\sqrt{\left(1 - \omega^2 LC + \frac{R}{R_{\mathrm{out}}}\right)^2 + \left(\frac{\omega L}{R_{\mathrm{out}}} + \omega RC\right)^2}}. \quad (1)$$

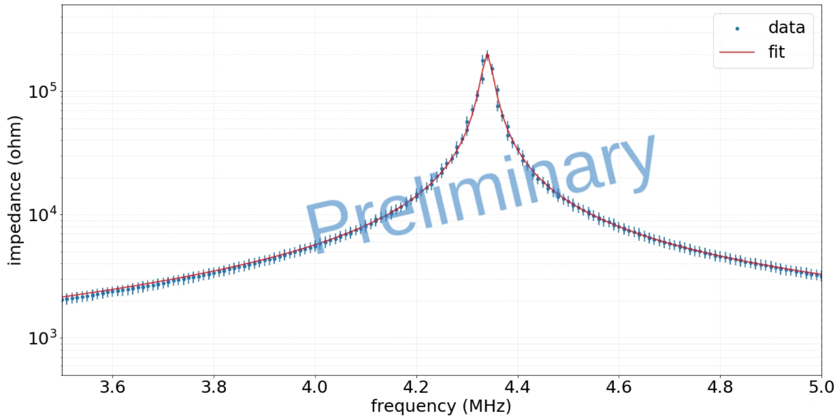

Figure 3: Impedance profile of the Rogowski coil segment.

parameter	value
$R[\Omega]$	4.26 ± 0.24
$L[\mu\text{H}]$	34.09 ± 1.97
$C[\text{pF}]$	39.45 ± 2.28

Table 1: Values of R, L and C parameters from the impedance measurement.

The values in Table 1 are obtained by fitting the resonant function to the experimental data. The network analyzer's calibration negates the cable's capacitive effects; however, a splitter box purpose-built to facilitate this measurement introduces a capacitive component that was not calibrated out, leading to a resonant frequency of $\sim$ 4.35 MHz, as seen in Figure 3. The results from all these experiments are then used in the SNR model to produce the SNR curve.

4. Noise Model Result

The SNR model consists of two parts: signal and noise. The signal component in the numerator is modelled using the frequency-dependent resonant function in the previous section and other parameters like beam intensity and the input impedance of the pre-amplifier. The noise component is calculated by quadratically adding the noise values of all the components of the Rogowski BPM system. The following is the SNR model:

$$\text{SNR} = \frac{U(\omega)}{U_{\text{total}}^{\text{noise}}\sqrt{2\Delta f}}, \tag{2}$$

where

$$U(\omega) = g \cdot \omega \cdot F(\omega) \cdot \Phi. \tag{3}$$

Here g is the pre-amplifier gain and Φ is the magnetic flux due to the beam. Figure 4 describes the SNR profile of a Rogowski BPM coil segment as a function of frequency for a 100 μA beam current. It is observed that the performance of the system improves drastically around the resonant frequency of the coil segment. The curve shows a general resonance circuit-like behaviour in the frequency range that has been investigated.

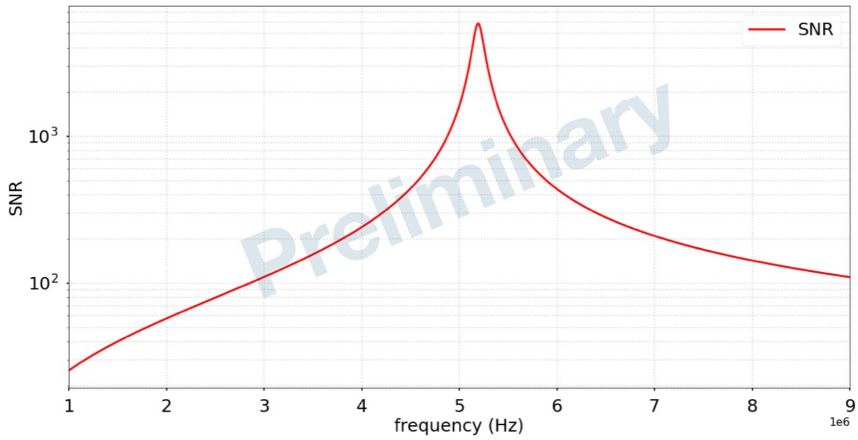

Figure 4: The SNR profile of the Rogowski Beam Position Monitor.

5. Conclusion and Outlook

The result from the SNR model of the Rogowski BPM is very promising, and a similar experimental equivalent is also being performed. As expected, the SNR shows the best values at the system's resonant frequency. This means that the best performance can be obtained by tuning the resonant frequency of the BPM setup to the beam's revolution frequency, for example, when deployed in a storage ring where the revolution frequency of the beam is fixed. Better measurement techniques need to be investigated to exclude unwanted interference peaks from the noise measurements.

References

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