BEAM BASED CALIBRATION OF A ROGOWSKI COIL USED AS A HORIZONTAL AND VERTICAL BEAM POSITION MONITOR

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Abstract

Electric Dipole Moments (EDMs) violate parity and time reversal symmetries. Assuming the CPT-theorem, this is equivalent to CP violation, which is needed to explain the matter-over-antimatter dominance in the universe. The goal of the JEDI collaboration (Jülich Electric Dipole moment Investigations) is to measure the EDM of charged hadrons (p and d). Such measurements can be performed in storage rings by observing a polarization build-up, which is proportional to the EDM. Due to the smallness of this effect many systematic effects leading to a fake build-up have to be studied. A first step on the way towards this EDM measurements is the investigation of systematic errors at the storage ring COSY (COoler SYnchrotron) at Forschungszentrum Jülich. One part of these studies is the control of the beam orbit with high precision. Therefore a concept of Beam Position Monitors (BPMs) based on pick-up coils is used. The main advantage of the coil design compared to electric-pick-up BPMs is the stronger response to the bunched-beam frequency and the compactness of the coil itself. A single Rogowski BPM measures the beam position in horizontal and vertical direction. Results of such a BPM in an accelerator environment are presented.

INTRODUCTION

The goal of the JEDI collaboration is to measure the EDMs of charged particles (p and d) at the storage ring COSY [1, 2]. To create an EDM signal an RF Wien filter introduces a vertical polarisation build-up of the stored polarized particles. This signal is proportional to the particles' EDM [3, 4]. To handle systematic effects, it is important to control the orbit with high precision. These systematic effects can contribute to an unwanted polarization build-up, which may erroneously be interpreted as an EDM signal [5]. The existing orbit control system at COSY will be improved to fulfil these requirements [6]. Furthermore, an investigation started with the goal to develop a prototype of a SQUID-based BPM [7]. For this SQUID-based BPM Rogowski coils are used as magnetic pick-ups [8]. This SQUID-based BPM development is divided into different steps. A first step is the test of a Rogowski coil, which is used as a BPM. The Rogowski coil consists of a torus, which is divided into four segments. Each segment is wound with a thin copper wire to measure the voltage, induced by the bunched beam. With this configuration it is possible to measure the beam position in the horizontal and the vertical plane. An advantage of the Rogowski coil BPM is its thickness of only 1 cm compared to the length of the existing BPMs with an extent of about 13 cm for one plane. This allows for installations in places with tight spatial constrains.

DESIGN OF ROGOWSKI PICK-UP COIL AND COSY INSTALLATION

The idea to measure the beam position with a segmented Rogowski coil is based on the measurement of the magnetic field induced by the particle flux. The geometry can be characterised by two radii. The radius R defines the distance from the centre of the tube to the centre of the torus and the radius a is the radius of the torus itself. In the presented setup the radius R is 40 mm and the radius a = 5 mm. The sketch of the different segments of the Rogowski coil BPM is shown in figure 1. Each segment is wound with a thin copper wire, which has the diameter of 150 μm. The number of windings for each segment is about 350. The depicted coordinate system is used in the following mathematical derivation. The segments are labelled with the numbers 1 to 4. The torus consist of vespel, which is vacuum-proofed.

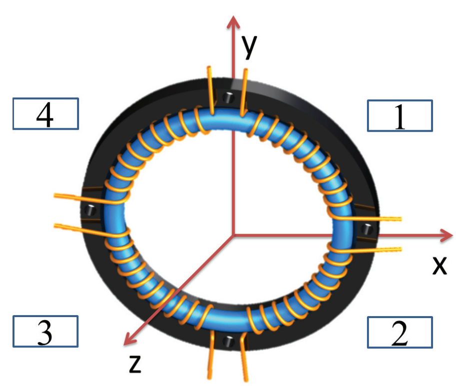

Figure 1: Sketch of a Rogowski coil BPM arrangement, which measures the horizontal and vertical beam position.

Two Rogowski coil BPMs with a distance of 13.3 cm to each other were installed in COSY storage ring to measure beam positions in the horizontal and in the vertical plane. The front Rogowski coil is installed on a fixed frame to use it as a reference BPM to suppress systematic effects like cycle to cycle orbit changes. The rear Rogowski coil is placed on a piezo table. The travel range is from −20 mm to 20 mm in horizontal and vertical plane. The resolution of the piezo

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tables is 1 μm. With this setup it is possible to move the Rogowski coil BPM to certain positions and to perform a calibration of this BPM in an accelerator. The whole setup is shown in figure 2.

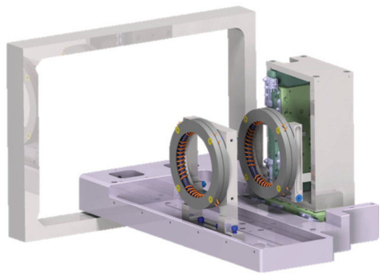

Figure 2: Schematics of the measurement setup, which was installed in the accelerator COSY. Front Rogowski coil BPM is mounted to a fixed frame. The rear one is mounted on a piezo table, which can be moved in horizontal and vertical direction.

Position Determination

In [9] the theoretical description of the magnetic field generated by a particle beam and the induced voltage for a horizontal or vertical Rogowski coil BPM is derived. The formula to calculate the horizontal (x) and the vertical (y) beam position with a Rogowski coil BPM divided into four segments is given by the following equations:

$$\begin{aligned} x &= \frac{\pi\sqrt{R^2-a^2}}{2}\,\frac{(U_1+U_2)-(U_3+U_4)}{U_1+U_2+U_3+U_4}, \\ y &= \underbrace{\frac{\pi\sqrt{R^2-a^2}}{2}}_{m}\,\frac{(U_1+U_4)-(U_2+U_3)}{U_1+U_2+U_3+U_4}. \end{aligned} \tag{1}$$

The sensitivity m is given by $\frac{\pi\sqrt{R^2-a^2}}{2}$ and depends only on the torus parameters R and a. The induced voltage in the corresponding segment is denoted by U_i (compare figure 1).

MEASUREMENTS AT COSY

Accelerator Setup

The measurement is performed with a bunched deuteron beam (about 10^9 particles) with a momentum of 970 MeV/c and a revolution frequency of 750 kHz. The measurement time of one cycle amounts to 220 s. As preparation for the measurement, the piezo table is moved to a certain position, before the beam is injected. Subsequently the induced voltages are measured with the two Rogowski coil BPMs after each applied trigger signal. In total 38 trigger signals are used for the data acquisition in one cycle.

Readout Scheme for one Rogowski coil BPM

Each pick-up segment of the BPM is connected to a preamplifier with a high input impedance (0.5 MΩ) with an amplification of 13.5 dB. The pre-amplified signals are fed into two synchronized lock-in amplifiers[1]. The four voltages are measured and recorded with the data acquisition, when a trigger signal is sent. The reference frequency of the lock-in amplifier is the beam revolution frequency, defined by the bunching cavity. Figure 3 shows a schematic drawing of the wiring. The COSY RF signal is converted into a TTL pulse and sent to the lock-in amplifier. The chosen 3 dB filter width of the lock-in amplifier is 15.7 Hz. This filter leads to an effective averaging time of 10.2 ms (≈8000 turns). The sampling rate of the device is set to 225 Sa/s.

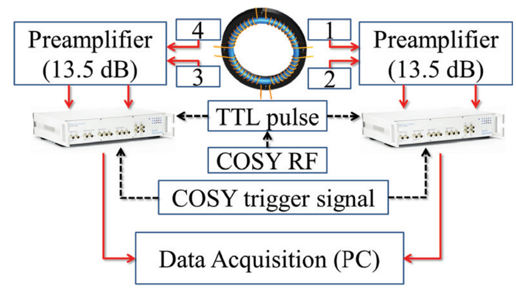

Figure 3: Readout scheme for the signals of one Rogowski coil BPM.

ROGOWSKI COIL CALIBRATION METHOD

The goal of the Rogowski coil BPM calibration is to compare the piezo table resolution with the resolution of the Rogowski coil BPM itself. A calibration of the Rogowski coil BPM increases the accuracy of beam position determination. The main idea of the calibration algorithm is taken from [10]. At first a grid measurement is performed with the help of the installed piezo tables. Before the particle beam is injected, the Rogowski coil BPM 1, placed on the piezo table, is moved to one defined position. Then the beam is injected and the voltages of Rogowski coil BPM 1 and Rogowski coil BPM 2 are measured after each trigger signal. This procedure is repeated at several positions as shown in the 2D graph of figure 4 (left). A sketch of the applied piezo table positions is shown in figure 4 on the left side. With this measurement grid the beam position resolution of the Rogowski coil BPM 1 is determined. But the measured beam positions are not coincide with the applied table positions. Therefore, a Rogowski coil BPM calibration is performed to reduce systematic effects like offsets or a rotation of the torus. The Rogowski coil BPM is calibrated with respect to the electrical centre of the system. The right sketch in figure 4 illustrates the coordinate system of the piezo table (x_T, y_T) and the coordinate system of the Rogowski coil BPM (x'', y''), which is rotated by the angle φ to the electrical centre (x', y'). The calibration algorithm minimizes the χ^2:

$$\chi^2 = \chi^2_x + \chi^2_y. \tag{2}$$

The χ^2 is split into a horizontal and vertical components. These components are defined in equation 3. The χ^2_x con-

[1] HF2LI from Zürich Instruments (`http://www.zhinst.com/`)

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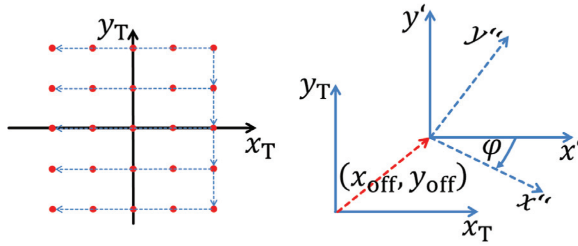

Figure 4: Left: coordinate system of the piezo table system. The dots show schematically the applied grid positions. Right: sketch of the coordinate system of the piezo table (x_T, y_T) and the coordinate system (x'', y'') of the Rogowski coil BPM, which is rotated with respect to the electrical centre by the angle φ. x_{off} and y_{off} define the offset to the electrical centre (x', y').

siders the square of the horizontal beam position correction defined by the terms $x'\cos(\varphi) - y'\sin(\varphi)$ minus the table position x_T and the offset to the electrical centre x_{off}. The numerator is weighted by the square of the errors on the horizontal and vertical beam position with respect to the rotation angle φ and fluctuation of the beam itself $\sigma_{x,\,fluc}$ and $\sigma_{y,\,fluc}$.

$$\begin{aligned} \chi_x^2 &= \frac{(x'\cos(\varphi) - y'\sin(\varphi) - x_T - x_{off})^2}{(\sigma_x\cos(\varphi))^2 + (\sigma_y\sin(\varphi))^2 + (\sigma_{x,\,fluc})^2} \\ \chi_y^2 &= \frac{(y'\cos(\varphi) + x'\sin(\varphi) - y_T - y_{off})^2}{(\sigma_y\cos(\varphi))^2 + (\sigma_x\sin(\varphi))^2 + (\sigma_{y,\,fluc})^2} \end{aligned} \quad (3)$$

The vertical component is calculated analogously. The orbit fluctuates by 23 μm in horizontal plane and 32 μm in vertical plane for each cycle and represents the orbit stability of the accelerator COSY. This variation is measured with the Rogowski coil BPM 2 on the fixed frame.

With equation 4 the horizontal and vertical beam position is determined. The factors g_2, g_3 and g_4 are calibration factors and weight the measured voltage with respect to induced voltage U_1. In this way different numbers of windings for each segment and different pre-amplification are taken into account. The factors m_x and m_y correct possible manufacturing errors of the torus radii.

$$\begin{aligned} x' &= m_x \cdot m \cdot \frac{U_1 + g_2U_2 - g_3U_3 - g_4U_4}{U_1 + g_2U_2 + g_3U_3 + g_4U_4}, \\ y' &= m_y \cdot m \cdot \frac{U_1 + g_4U_4 - g_2U_2 - g_3U_3}{U_1 + g_2U_2 + g_3U_3 + g_4U_4}. \end{aligned} \quad (4)$$

After minimization and calculation of the calibration factors ($g_2, g_3, g_4, x_{off}, y_{off}, \varphi, m_x, m_y$) the horizontal and vertical beam position is determined with equation 5.

$$\begin{aligned} x_{cor} &= x'\cos(\varphi) - y'\sin(\varphi) - x_{off} \\ y_{cor} &= y'\cos(\varphi) + x'\sin(\varphi) - y_{off} \end{aligned} \quad (5)$$

All measured voltages from each trigger signal with the corresponding piezo table position are used as input data for the minimization.

Data Analysis

The beam position in horizontal and vertical directions are calculated with and without the calibration factors for each trigger signal. One measurement consists of 38 trigger signals for one applied table position. A linear fit is applied to the 200 s cycle to calculate the mean position over the cycle. An example of this procedure is shown in figure 5 for one horizontal displacement, where the calibration factors are applied.

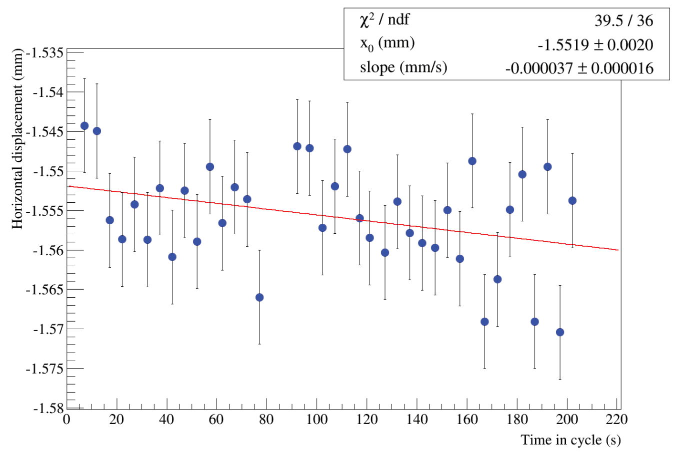

Figure 5: Corrected horizontal beam position. A linear fit is applied to determine the mean position of the cycle. The slope reflects possible drifts of the beam position during the cycle.

The mean position is given by the parameter x_0. The slope reflects possible drifts of the beam position during the cycle. Each position has a position accuracy of around 5 μm. In figure 6 the mean horizontal (x_0) against the mean vertical beam position (y_0) without calibration factors is shown. The Rogowski coil BPM detects the beam in horizontal and vertical direction with respect to the applied piezo table positions, but the data points suggest a rotation to the electrical centre. There is also an offset to the applied piezo table positions.

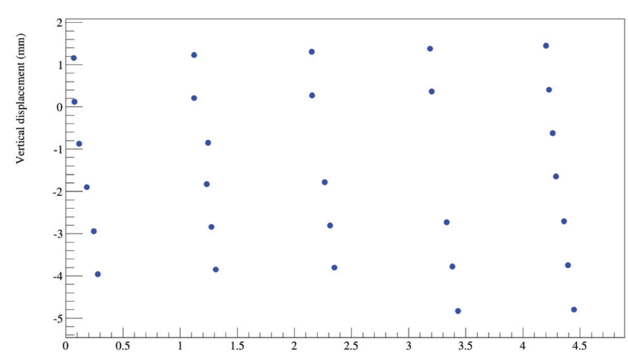

Figure 6: Measured beam position without calibration factors.

After minimization the calculated calibration factors are applied to the measured data. Table 1 presents the deter-

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mined and applied calibration factors and the corresponding χ^2.

Table 1: Calibration Factors After Applying the Minimization Algorithm

Calibration factor	value	error
x_{off} (mm)	+3.5166	± 0.0004
y_{off} (mm)	-8.8333	± 0.0006
g_2 (%)	96.437	± 0.041
g_3 (%)	102.128	± 0.002
g_4 (%)	109.261	± 0.046
φ (mrad)	-47.08	± 0.21
m_x (%)	96.765	± 0.025
m_y (%)	97.192	± 0.027
χ^2	1.48	

Figure 7 represents the measured data points after using the calibration factors. In addition the applied piezo table positions are shown. The corrected points are marked with blue dots and the table positions with boxes. The result shows that the calibration method works and there is a good agreement between adjusted table positions and corrected beam positions. The error on the beam position in horizontal direction is around 24 μm and for vertical direction 33 μm. It includes the fluctuation of the beam after each injections ($\sigma_{i,fluc}$) and the accuracy of beam position determination (σ_{i_0},).

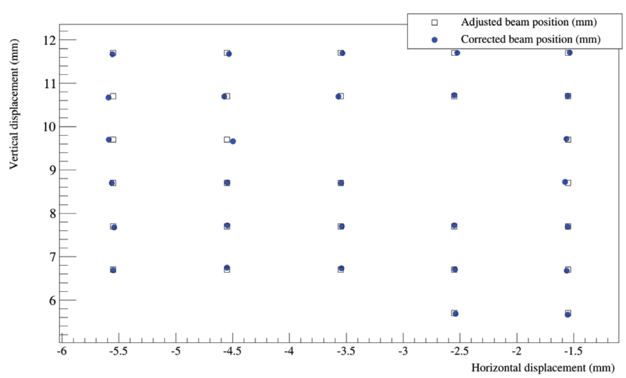

Figure 7: Corrected beam position with respect to the applied piezo table positions.

SUMMARY

A new concept of a magnetostatic BPM, which detects the beam position in horizontal and vertical beam position, is presented. A beam based calibration method is explained and applied. The results demonstrate the possibility to measure with one Rogowski coil BPM the horizontal and vertical beam position. With the help of the introduced calibration method it is possible to correct the measured beam position to the applied table positions and also to improve the accuracy of the beam displacement measurement.

Outlook toward Future Developments

In future work, two calibrated Rogowski coil BPMs will be installed in the vicinity of a new RF Wien Filter at COSY. This enables an alignment of the particle beam with respect to the centre of the Wien Filter. This configuration allows for studies of systematic effects relevant for EDM measurements. For a next beam time a calibrated Rogowski coil BPM will be installed to see the performance of a pre-calibrated system and to improve the accuracy of the position determination. Also a next step on the way to the SQUID-BPM will be the reduction of the coil temperature to decrease the noise level of the induced voltages.

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REFERENCES

[1] R. Maier, "Cooler synchrotron COSY — Performance and perspectives", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 390*, pp. 1–8 (1997) http://dx.doi.org/10.1016/S0168-9002(97)00324-0

[2] C. Weidemann, F. Rathmann, H. Stein, *et al.*, "Toward polarized antiprotons: Machine development for spin-filtering experiments", *Physical Review Special Topics - Accelerators and Beams 18*, 020101 (2015) http://dx.doi.org/10.1103/PhysRevSTAB.18.020101

[3] F. Rathmann, A. Saleev, N.N. Nikolaev, "The search for electric dipole moments of light ions in storage rings", *Journal of Physics: Conference Series 447*, 012011 (2013) http://dx.doi.org/10.1088/1742-6596/447/1/012011

[4] W. M. Morse, Y. F. Orlov, Y. K. Semertzidis, "rf Wien filter in an electric dipole moment storage ring: The 'partially frozen spin' effect", *Physical Review Special Topics - Accelerators and Beams 16*, 114001 (2013) http://dx.doi.org/10.1103/PhysRevSTAB.16.114001

[5] M. Rosenthal, A. Lehrach, "Spin Tracking Simulations Towards Electric Dipole Moment Measurements at COSY", *in Proceedings 6th International Particle Accelerator Conference*, IPAC'15, Richmond, VA, USA (2015). http://jacow.org/IPAC2015/papers/thpf032.pdf

[6] C. Böhme, M. Bai, F. Hinder, *et al.*, "Studies for a BPM Upgrade at COSY", TUPB017, IBIC'15, Melbourne, Australia (2015).

[7] H. Ströher, "Search for electric dipole moments using storage rings", *Horizon 2020 proposal, Excellent Science Call: ERC-2015-AdG, Type of action: ERC-ADG Proposal number: 694340* http://collaborations.fz-juelich.de/ikp/jedi/public_files/proposals/Proposal-SEP-210276270.pdf

[8] W. Rogowski, W. Steinhaus, "Die Messung der magnetischen Spannung", *Archiv für Elektrotechnik 1*, pp. 141–150 (1912) http://dx.doi.org/10.1007/BF01656479

ISBN 978-3-95450-177-9

[9] F. Hinder, H. Soltner, F. Trinkel, *et al*., "Development of New Beam Position Monitors at COSY", *in IBIC 2015 International Beam Instrumentation Conference Proceeding*, TUPB015, IBIC'15, Melbourne, Australia (2015) `http://ibic.synchrotron.org.au/papers/tupb015.pdf`

[10] M. Tejima, "BEAM BASED CALIBRATION FOR BEAM POSITION MONITORS ", *in IBIC 2015 International Beam Instrumentation Conference Proceeding*, TUPB015, IBIC'15, Melbourne, Australia (2015) `http://ibic.synchrotron.org.au/papers/tubla01.pdf`

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