DEVELOPMENT OF NEW BEAM POSITION MONITORS AT COSY

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Abstract

The existence of permanent Electric Dipole Moments (EDMs) of fundamental particles would violate parity and time reversal symmetry. Assuming the CPT-theorem, this leads to CP violation, which is necessary to explain the matter over antimatter dominance in the Universe. Thus, a measurement of a non-zero EDM would be a hint to new physics beyond the Standard Model. The JEDI collaboration (Jülich Electric Dipole moment Investigations) has started investigations towards a direct EDM measurement of protons and deuterons at a storage ring. To measure an EDM signal, systematic effects have to be controlled with high precision. One way of studying systematic effects is the use of new Beam Position Monitors (BPMs) based on a Rogowski coil as a magnetic pick-up. The main advantage of such coil is their high response to an RF signal, i.e. the particle bunch frequency, and their compactness. In a first step the BPMs have been benchmarked in a laboratory test system. In the next step the calibrated BPMs have been installed and tested at the storage ring COSY (Cooler Synchrotron) at Forschungszentrum Jülich. First measurement results are presented.

INTRODUCTION

The JEDI collaboration investigates the feasibility of measuring EDMs of charged particles, namely protons and deuterons, in the magnetic storage ring COSY [1, 2]. The method of choice is the usage of an RF Wien Filter to introduce a build-up of the vertical polarization, which is proportional to the EDM of the particle [3, 4]. A measurement of the orbit is necessary to control systematic effects, which contribute to a polarization build-up which is not related to the EDM [5]. The existing orbit control system, including electrostatic BPMs [6, 7], has to be improved to reduce systematic effects. One step of this improvement is an update of the existing BPM readout electronics [8]. In addition, new BPMs are being developed. These BPMs are magnetostatic pick-ups in a Rogowski coil configuration [9]. In industry the Rogowski coil is a well known device to measure alternating currents (ACs). The primary concept of a torus wound with a wire to measure the current, is modified towards a device which measures the centroid of the current. The spatial sensitivity is reached by winding the torus in parts and measuring the induced voltages in these parts. One advantage of the new device is its thickness of 1 cm compared to the length of the existing BPMs of 13 cm. Due

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to its small dimension the BPM can be installed at various places in the storage ring.

DESIGN OF ROGOWSKI PICK-UP COILS

The presented concept is based on the idea of determining the position of the beam by measuring the magnetic field induced by the particle flux. The developed Rogowski coil BPM consists of a torus with the following geometric parameters:

- Radius of the torus $R = 40\,\mathrm{mm}$

- Radius of the tube $a = 5\,\mathrm{mm}$.

The tube of the torus is wound with one layer of cooper wire with a diameter of $150\,\mu\mathrm{m}$. The geometric form of the wiring determines the field of application. A full winding is sensitive to the AC beam current going through the torus. Cutting the wiring into two equal halves leads to a measurement of the beam position in one direction of the transversal plane. Dividing the wiring into four segments allows to determine the beam position in both directions of the transversal plane. Figure 1 shows the Rogowski coil in a halved and a quartered configuration. The depicted coordinate system is used in the following mathematical derivation. The two halves of the coil are labeled R and L. The four quarters are labeled R, U, L and D.
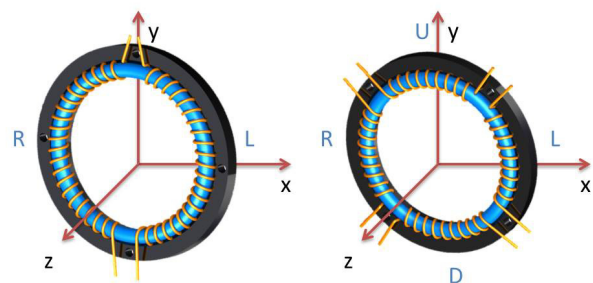

Figure 1: Half and quarter wound Rogowski coils in our coordinate system. The configuration shown on the left hand side permits a position measurement in x-direction. The configuration shown on the right hand side facilitates a measurement of the beam displacement in both directions: x and y.

Magnetic Field of the Particle Beam

The beam current assumed to be a pencil current in z direction perpendicular to the torus. The position with respect

to the center of the torus is given by

$$\vec{r_0} = x_0\vec{e_x} + y_0\vec{e_y} = r_0\cos\varphi_0\vec{e_x} + r_0\sin\varphi_0\vec{e_y}.$$

The magnetic field $\vec{B}$ induced by a particle beam with a current $\vec{I}$ is described by the Biot-Savart law:

$$\vec{B} = \frac{\mu_0}{2\pi}\vec{I}\times\frac{\vec{r'}}{|\vec{r'}|^2} \qquad \text{with} \quad \vec{r'} = \vec{r} - \vec{r_0},$$

where μ_0 is the vacuum permeability, $\vec{r_0}$ is the beam center and $\vec{r}$ is the position of the point where the magnetic field is measured. The magnetic flux through the Rogowski coil can be calculated by:

$$\Phi = \int_A \vec{B}d\vec{A}, \tag{1}$$

where $\vec{A} = A\vec{e_\varphi}$. For convenience, first the projection of the magnetic field to the $\vec{e_\varphi}$ direction is calculated. The expansion of the projected magnetic field in a Taylor series up to second order for small position deviations from the center of the torus ($r_0/R \ll 1$) leads to:

$$\vec{B}\cdot\vec{e_\varphi} = \frac{\mu_0 I}{2\pi}\frac{1}{r}\left[1 + \cos(\varphi - \varphi_0)\frac{r_0}{r}\right.$$
$$\left.+ \cos(2\varphi - 2\varphi_0)\left(\frac{r_0}{r}\right)^2 + O\left(\frac{r_0}{r}^3\right)\right]. \tag{2}$$

Induced Voltages

Solving the integral Eq. 1 by using Eq. 2, multiplying the result with the number of windings N and calculating the time derivative lead to the induced voltage in the coil:

$$U_{\text{ind}} = -N\frac{d\Phi}{dt}.$$

For a fully wound coil the induced voltage is:

$$U_{\text{ind},1/1} = \mu_0 N\frac{dI}{dt}\left(R - \sqrt{R^2 - a^2}\right).$$

The result is the same as an analytical solution of Eq. 1 without using a Taylor expansion of the magnetic field [10]. The induced voltage for one half of the coil reads:

$$U_{\text{ind},1/2} = \frac{U_{\text{ind},1/1}}{2}\cdot\left(1 - \frac{2}{\pi\sqrt{R^2 - a^2}}x_0\right),$$

if the full coil is cut in the two halves along the y-direction. The induced voltage of a quartered coil features additional terms including $x_0 \cdot y_0$, x_0^2 and y_0^2:

$$U_{\text{ind},1/4} = \frac{U_{\text{ind}1,1}}{4}\cdot\left(1 - \frac{2\sqrt{2}}{\pi\sqrt{R^2 - a^2}}x_0 + O\left(x_0 y_0, x_0^2, y_0^2\right)\right).$$

The position of the particle beam can be computed by calculating the difference and the sum of the voltages of two opposite halves:

$$x_0 = \frac{\pi\sqrt{R^2 - a^2}}{2}\frac{\Delta U_{\text{ind},1/2}}{\Sigma U_{\text{ind},1/2}}. \tag{3}$$

For two opposite quarters the corresponding term features non-linear corrections:

$$\frac{\Delta U_{\text{ind},1/4}}{\Sigma U_{\text{ind},1/4}} = \frac{2\sqrt{2}}{\pi\sqrt{R^2 - a^2}}x_0 + O\left(x_0\cdot y_0, x_0^2, y_0^2\right).$$

Figure 2 shows the calculation of the difference over sum ratio of two quarters for a beam position in the range of $-35\,\text{mm} < x_0, y_0 < 35\,\text{mm}$. The center of the two quarters are at $x_R = -R$ and $x_L = R$. This configuration leads to a sensitivity to the position x_0 of the particle beam. Using the two other quarters ($y_D = -R$ and $y_U = R$) leads to an equivalent sensitivity for y_0 displacements. The color-coded
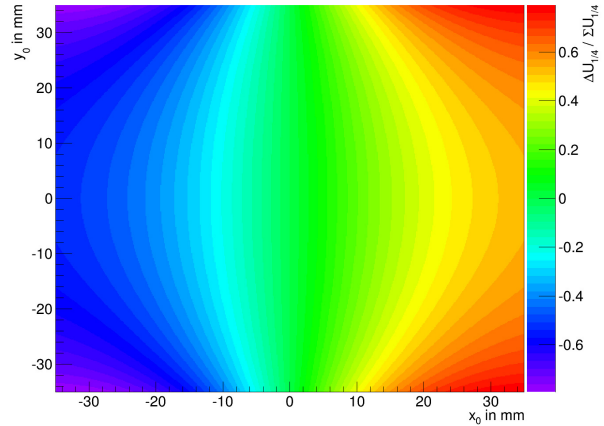

Figure 2: Calculated response signal of a quartered Rogowski coil BPM to the position of an ideal particle beam.

z-axis is the calculated ratio $\frac{\Delta U_{1/4}}{\Sigma U_{1/4}}$, which to first order is proportional to x_0. The influence of the higher-order terms increases with the distance to the torus center.

LABORATORY MEASUREMENTS

A first test of the measurement principle described was carried out in a laboratory setup [11]. With a live wire representing the particle beam. This wire is connected to two $x - y$ micro tables, one at each end. The current parameters are chosen to represent a typical Gaussian bunched particle beam in COSY. The frequency was set to $750\,\text{kHz}$, the intensity corresponds to 10^{10} particles and the width of the longitudinal bunch profile is chosen to be $\frac{\Delta T}{T} = 10\,\%$. The first measurement with this setup was done with a quartered Rogowski coil, aligned as sketched in the right hand side of Fig. 1.

With this installation two measurements were performed. One with the wire centered at $y_0 = 0\,\text{mm}$ and moved along x-direction in the range $x_0 = -30\,\text{mm}$ to $30\,\text{mm}$ and the second one under the conditions: $y_0 = 15\,\text{mm}$ and $x_0 = -30\,\text{mm}$ to $30\,\text{mm}$. For both measurements the induced voltages of the two quarters L and R are measured. The calculated ratio $\frac{\Delta U_{LR}}{\Sigma U_{LR}}$ is plotted against the position of the wire in Figs. 3 and 4.

Both measurements show that a position determination using the Rogowski coil BPM is possible. The sensitivity of
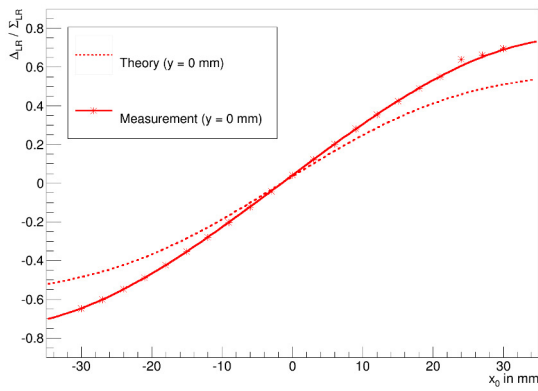
Figure 3: The ratio $\frac{\Delta U_{\mathrm{LR}}}{\Sigma U_{\mathrm{LR}}}$ for the wire positioned at $y_0 = 0$ mm and $x_0 = -30$ mm to 30 mm. The dotted line represents the theoretical expectation, the solid line is a fit to the data points.
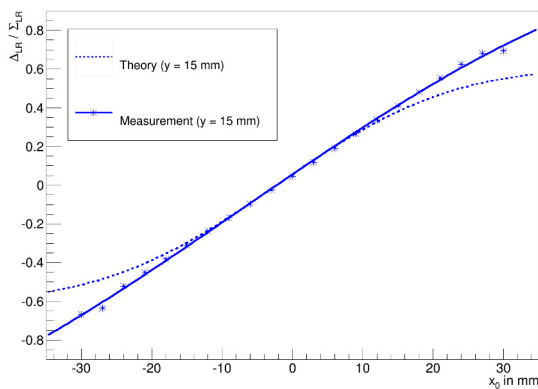

Figure 4: The ratio $\frac{\Delta U_{\mathrm{LR}}}{\Sigma U_{\mathrm{LR}}}$ for the wire positioned at $y_0 = 15$ mm and $x_0 = -30$ mm to 30 mm. The dotted line represents the theoretical expectation, the solid line is a fit to the data points.

the BPM, the linear term of the measurement, is around 10% higher than the expected value. In addition the non-linear corrections seem to be smaller than those calculated by using the described Taylor expansion. These discrepancies are under investigation and will be analyzed by using a new test bench. This test bench is specially designed to characterize the Rogowski coil BPM for further developments within the EDM experiment of the JEDI collaboration.

MEASUREMENTS AT COSY

Accelerator Setup

To test the measurement principle in a real accelerator environment, a halved Rogowski coil was installed at COSY. The measurements were performed with a bunched deuteron beam with a momentum of 970 MeV/c and a revolution frequency of 750 kHz. One series of measurements was dedicated to the response to a horizontal orbit shift of the beam at the position of the Rogowski coil BPM. This response was induced by applying a local orbit bump. The deflection

of the bump was controlled by the change of two corrector magnets. A deuteron beam of about 10^9 particles was injected, accumulated and accelerated to its final momentum. After 33 s the orbit bump with a certain strength was applied. The beam position was measured before and after the orbit bump. The first measurement probed the reference orbit, the second the orbit after the bump. The difference between both measurements is the displacement of the beam, induced by the corrector magnets. Two fills were taken for each bump strength. After these two fills the bump strength was varied and the measurement repeated. Figure 5 illustrates the measurement sequence for two different corrector strengths.
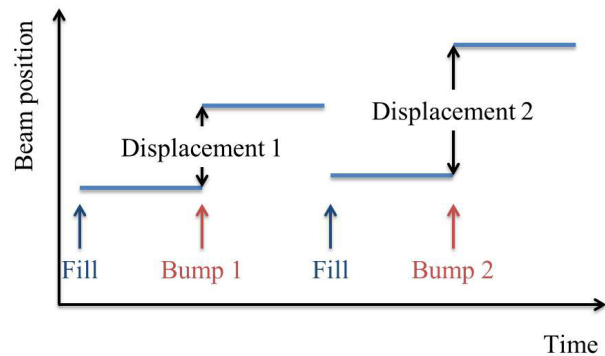

Figure 5: Schematics of the measurement sequence with two different local orbit bumps.

Readout Scheme

Each pick-up coil of the BPM is connected to a pre-amplifier with a high input impedance with an amplification of 13.5 dBm. The pre-amplified signals are fed into a two channel lock-in amplifier[1]. The reference frequency of the lock-in is the beam revolution frequency, defined by the bunching cavity. Figure 6 shows a schematic drawing of the wiring. The chosen 3 dB filter width of the lock-in amplifier was 15.7 Hz. This filter leads to an effective averaging time of 10.2 ms. The sampling rate of the device was set to 225 Sa/s.
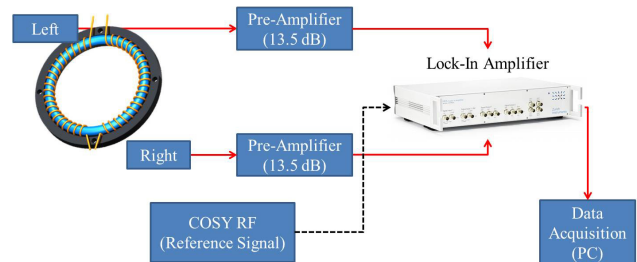

Figure 6: Readout scheme for the signals of the two halves of the Rogowski coil.

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

Analysis of the Data

The displacement of the beam induced by the orbit bump is determined by using two measurement intervals. Each interval has a length of 4.45 s. For each data point the beam position is calculated using Eq. 3. The measured beam position $P_{1,2}$ at each interval is calculated by averaging the 1000 data points. The statistical error of the measured beam position is $\sigma_{P_{1,2}} = 3\,\mu$m for each interval. The difference of these two measurements corresponds to the displacement:

$$\Delta P = P_2 - P_1 \pm \sqrt{2} \cdot \sigma_{P_{1,2}}. \qquad (4)$$

In addition to the statistical uncertainty a systematic uncertainty is estimated from the variations of the measured displacement ΔP_{fill} from the first fill to the second fill for constant magnet settings. The variations of the change in the displacement is plotted in Fig. 7. The RMS value
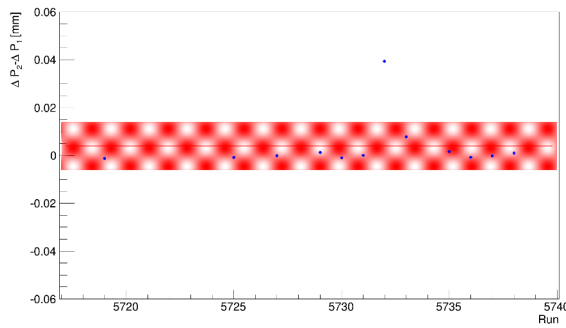

Figure 7: Displacement variations from fill to fill for constant magnet settings. The width of the colored band represents the RMS of the shown variations.

$\sigma_{var} \approx 10\,\mu$m of this variation is considered as an additional source of uncertainty. In summary, the uncertainty is given by:

$$\sigma_{\Delta P}^2 = 2 \cdot \sigma_{P_{1,2}}^2 + \sigma_{var}^2 \approx 10\,\mu\text{m}. \qquad (5)$$

Measurement Results

The performance of the Rogowski coil BPM is analyzed by plotting the measured displacements ΔP against the change of the strength of the two corrector magnets. Figure 8 displays the corresponding plot for 13 different settings of the corrector magnets. The data suggest a complete linear dependence on the beam position over a range of about ±8 mm. The linear fit describes the given data points very well, the reduced $\chi^2 = 9/11$ confirms the expected linear behavior. In addition the residua show no significant systematic effect, they are uniformly distributed.

Since the existing BPM system at COSY does not provide a measurement of the beam position at the shown accuracy, a calibration against the existing system isn't done. An absolute calibration will be carried out with the new test system, described before.

In addition to the precisely linear sensitivity of the BPM, the influence by a change of the particle beam perpendicular
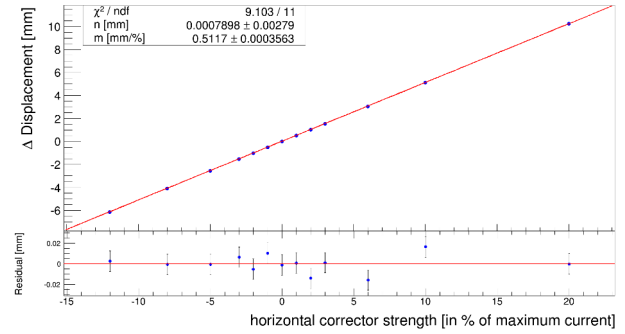
Figure 8: Test of the linearity of the BPM response to the corrector magnet excitation, which is proportional to a horizontal beam displacement at the BPM.

to the measurement direction is studied. The measurement principle is similar to the one used for the horizontal measurement: The beam is moved in y-direction with a vertical orbit bump, induced by two corrector magnets. The strength of the magnets is directly proportional to the vertical beam displacement at the position of the Rogowski coil. With a perfectly aligned BPM and no vertical-horizontal coupling, the measured displacement should be independent of the change of the beam position in y-direction. The corresponding measurement result is shown in fig. 9.
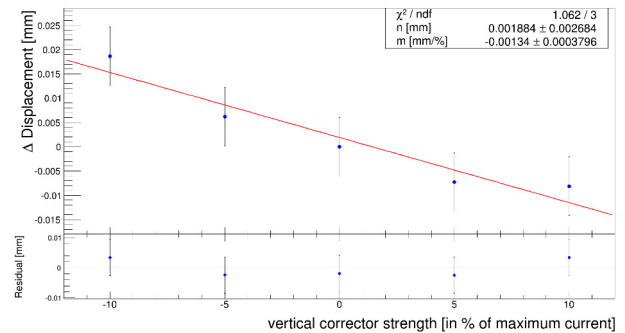

Figure 9: The measured horizontal beam displacement plotted against the corrector strength, which is proportional to the vertical beam movement.

A linear function is fitted to the data points. The slope is $m = (1.3 \pm 0.4)\,\mu$m/%, which is 3σ larger than 0. This small deviation from 0 can be driven from tilts in the magnets or from a tilt of the BPM itself. Both these effects may be distinguishable with an upgraded BPM system. In comparison to the horizontal case, the vertical sensitivity is about 400 times smaller.

SUMMARY

A new concept of a magnetostatic BPM, described by a simple mathematical model, is presented. First measurements in a laboratory demonstrate the applicability of Rogowski coils as BPMs for bunched particle beams.

For a Rogowski coil BPM wound with two wires, each covering an angle of 180°, the spatial sensitivity of the coil is completely linear. This prediction has been proven by a first operation of the BPM in an accelerator environment. In the measured range of ±8 mm, the sensitivity was found to be completely linear. In addition the measured sensitivity to the perpendicular axis is at least 400 times smaller and can be regarded as negligible within the confidence interval. All in all, the Rogowski coil BPM in the configuration with two opposite windings allows a precise measurement of the beam position in one direction, independent of the beam position in the second, perpendicular direction. In future work, the Rogowski coil BPMs will be analyzed in more detail in a new test bench which is specially designed to calibrate the BPMs. After the calibration, the BPMs will be installed in COSY in the vicinity of a new RF Wien Filter to enable an alignment of the particle beam with respect to the center of the Wien Filter. This configuration allows a study of systematic effects relevant for EDM measurements.

Outlook toward Future Developments

To reduce the noise of the measured voltages and the resulting position uncertainty, the coils can be cooled down. By changing the geometric form of the windings, the pickups may be used for measurements of higher moments of the beam distribution. Further sensitivity improvement can be achieved by fabricating the coils from superconducting wire and couple them to a SQUID magnetometer.

ACKNOWLEDGMENT

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