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Beam-based alignment tests at the Cooler Synchrotron (COSY)

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Abstract The Jülich Electric Dipole moment Investigation (JEDI) Collaboration works on a measurement of the electric dipole moment (EDM) of charged hadrons using a storage ring. Such a dipole moment would violate $\mathcal{CP}$ symmetry, providing a possible option for physics beyond the Standard Model. The JEDI experiment requires a small beam orbit root mean square (RMS) in order to control systematic uncertainties. Therefore an ongoing upgrade of the Cooler Synchrotron (COSY) at Forschungszentrum Jülich is done in order to improve the precision of the beam position. The first results of the beam based alignment method, that was tested with one quadrupole in the ring, will be discussed.

Keywords Beam-based alignment · Quadrupole · Cooler Synchrotron · COSY

1 Introduction

There is an observable matter-antimatter asymmetry in the universe. In order to explain that, there are more $\mathcal{CP}$ violating effects needed [1] than contained in the Standard Model already. One candidate for that is a non vanishing electric dipole moment (EDM) of subatomic particles, as permanent EDMs of subatomic particles violate parity and time reversal symmetry. Thus they also violate $\mathcal{CP}$ symmetry, in case the $\mathcal{CPT}$ theorem holds. The predictions of the EDM of the Standard Model are orders of magnitude too small to explain the dominance of matter in the universe. The discovery of a larger EDM would hint towards physics beyond the Standard Model and contribute towards an explanation for the dominance of matter.

It is possible to measure the EDM of subatomic particles by observing the interaction of their spin with strong electric fields. As the Jülich Electric Dipole moment Investigation (JEDI) Collaboration aims to measure the EDM of charged

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Table 1 Explanation of the parameters in equation 1.

Parameter	Meaning
Δx	Orbit change
s	Measurement position
s_0	Position of quadrupole
Δk	Change in quadrupole strength
$x(s_0)$	Position of the beam with respect to the magnetic center of the quadrupole
l	Length of quadrupole
$B\rho$	Magnetic rigidity of the beam
k	Quadrupole strength
β	Beta function
ν	Betatron tune
ϕ	Betatron phase

subatomic particles, namely protons and deuterons, one needs to have a very precise storage ring for those measurements [2]. In order to improve the precision of the Cooler Synchrotron (COSY) with the beam-based alignment method, it was tested with one quadrupole.

2 Theoretical description of beam-based alignment

When one varies the strength of one quadrupole it affects the closed orbit all around the ring. This change of the closed orbit depends on the offset of the beam inside that specific quadrupole. The change of the orbit [3] can be described by

$$\Delta x(s) = \frac{\Delta k \cdot x(s_0)\ell}{B\rho} \cdot \frac{1}{1 - k\frac{\ell\beta(s_0)}{2B\rho\tan\pi\nu}} \cdot \frac{\sqrt{\beta(s)}\sqrt{\beta(s_0)}}{2\sin\pi\nu}\cos[\phi(s) - \phi(s_0) - \pi\nu], \quad (1)$$

where the parameters used are explained in table 1.

Out of equation 1 one can extract that the orbit change $\Delta x(s)$ is a linear function of the offset of the beam with respect to the magnetic center of the quadrupole $x(s_0)$. This is very beneficial, as most of the parameters in that equation are not perfectly known. Due to the linear dependence one can define a simple merit function in order to extract the optimal position out of the measured data. The merit function used for this measurement is

$$f = \frac{1}{N_{\mathrm{BPM}}}\sum_{i=1}^{N_{\mathrm{BPM}}} (x_i(+\Delta k) - x_i(-\Delta k))^2 \propto (\Delta x)^2 \propto (x(s_0))^2. \quad (2)$$

For that merit function one takes two measurements for each point. Once the orbit is measured with slightly increased quadrupole strength $(+\Delta k)$ and once with slightly reduced quadrupole strength $(-\Delta k)$. The difference of the positions x_i for both measurements is calculated and added in quadrature for all beam position monitors (BPM). If one has a look at the merit function one can see that it is proportional to the offset of the beam with respect to the magnetic center of the quadrupole $x(s_0)$ squared. Thereby one can take multiple measurements at different positions and find the minimum of the merit function. This way one can determine the optimal position inside the quadrupole.

3 Experimental technique and results

For the measurement it is necessary to change the strength of one individual quadrupole. This is not easily possible at COSY, as all the quadrupoles are powered in families of four. In case one changes the strength of one quadrupole by adjusting the power supply, also the other three will change accordingly and the measured effect will be a superposition of all four. This is not wanted, thus a different approach was used. As some of the quadrupoles in COSY have additional windings on the poles of the magnet, there is another way to change the strength. When one powers the additional coils on the poles in addition to the main coils one has two quadrupoles superimposed on top of each other. It was checked that the behavior is the same as one quadrupole with changed strength. As this was the case one can effectively change the strength of that specific quadrupole without affecting the other quadrupoles of the same family.

During the measurement multiple different bumps were introduced into the closed orbit at the quadrupole position. This leads to different magnitudes of the measured effect on the closed orbit. Thereby multiple points could be scanned in horizontal and vertical direction to find the optimal beam position inside the quadrupole.

The result of the test measurement in November 2017 for one quadrupole is, that the optimal position was determined to be $(-1.98 \pm 0.01)\,\mathrm{mm}$ in horizontal direction and $(1.15 \pm 0.01)\,\mathrm{mm}$ in vertical direction. The measured data points can be seen in figure 1. In addition one can see the fitted function (colored plane) to determine the minimum of the merit function. The minimum is indicated by a red dot in the figure. The error on the value of the optimal position was determined by the fit, where during the calculation of the values of the merit function an error of $10\,\mu\mathrm{m}$ was assumed for the relative BPM precision. This measurement was a first proof of principle measurement in order to show that it is possible to determine the optimal position of the beam inside a quadrupole.

4 Conclusion

The method to determine the magnetic center of a quadrupole has been proven to work at COSY. It was possible to determine the optimal position inside one specific quadrupole. The change of quadrupole strength with the use of additional windings on the poles of the quadrupoles was used successfully. In the future this measurement will be done for more than one quadrupole at COSY in order to determine the overall offsets of the quadrupoles and correct for these offsets.

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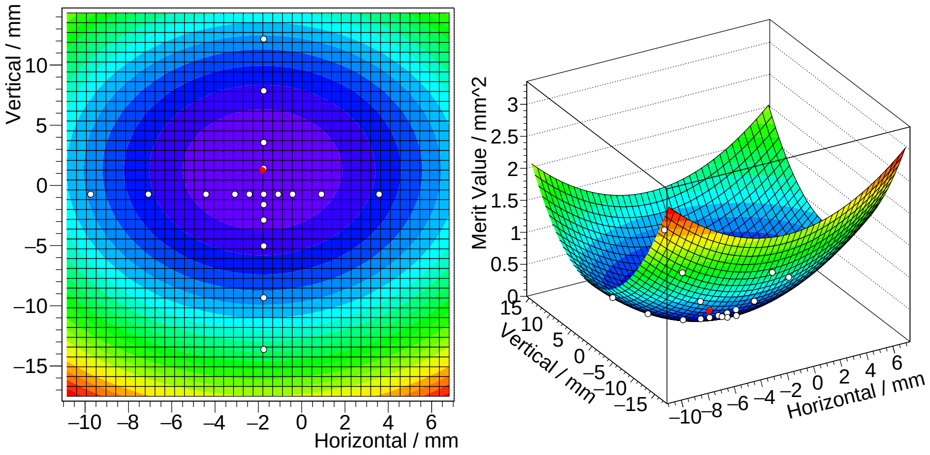

Fig. 1 Result for the beam-based alignment of quadrupole QT12. The left plot shows a top view of the right one. In the left plot one can see the positions where the data points were measured. Those are indicated by the white points. The colored layer is a function fitted to the data points in order to determine the minimum of the function. The red dot is the position of the minimum. On the right side one can see the plot in three dimensions, where the expected parabola shape in both horizontal and vertical direction is easily visible.

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