Beam-based alignment at the Cooler Synchrotron COSY

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Motivation

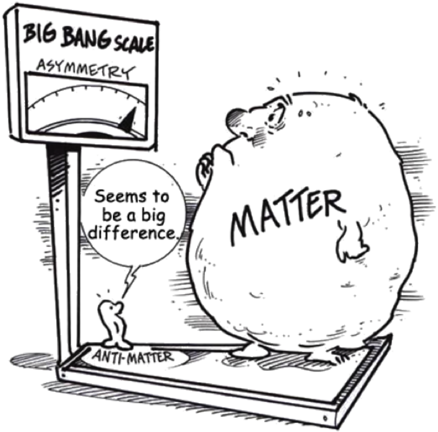
Baryon asymmetry

	Observed	Standard Model
$\frac{n_B - n_{\bar{B}}}{n_\gamma}$	6×10^{-10}	$\approx 10^{-18}$

Criteria for the asymmetry

- Baryon number violation
- No thermodynamic equilibrium
- **$\mathcal{C}$ and $\mathcal{CP}$ violation**

Sakharov (1967) [1]



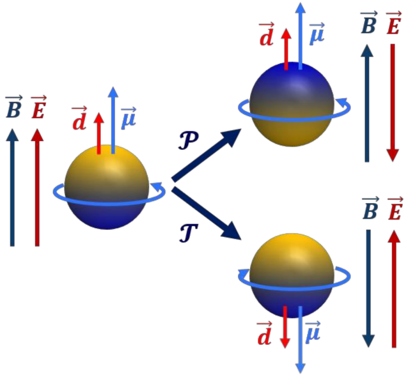
Electric Dipole Moment (EDM)

- Permanent EDMs of hadrons are $\mathcal{T}$ and $\mathcal{P}$ violating
- $\not{\mathcal{T}} + \mathcal{CPT}$ theorem $\rightarrow \not{\mathcal{CP}}$ violation
- Standard Model expectation: $d_{\text{hadron}} \approx 10^{-31}\,\text{e cm}$

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

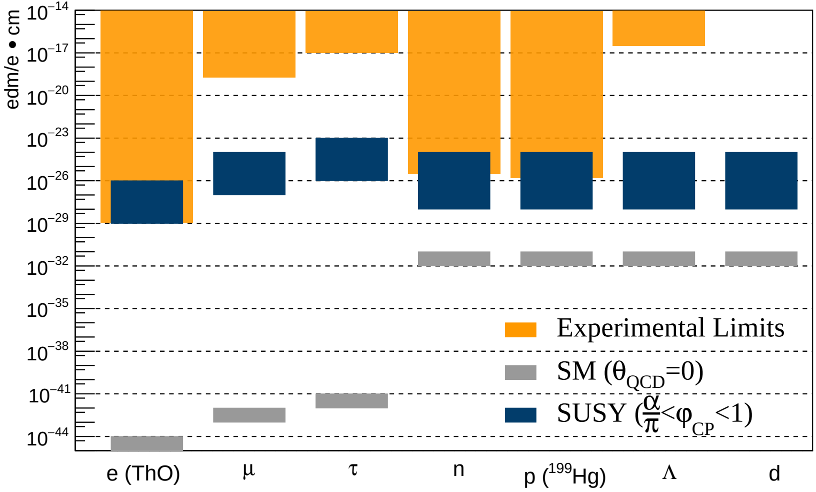
$$\mathcal{P} : \mathcal{H} = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$

$$\mathcal{T} : \mathcal{H} = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$



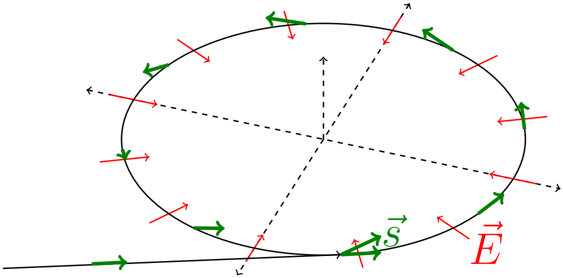
$$\vec{\mu} = g \cdot \frac{q}{2mc}\vec{S} \qquad \vec{d} = \eta \cdot \frac{q}{2mc}\vec{S}$$

Electric Dipole Moment (EDM)



EDM measurement of charged particles

Principle: Observe the interaction of the EDM with the electric fields



$$\frac{d\vec{S}}{dt} \sim d\vec{E} \times \vec{S}$$

Buildup of vertical polarization

$d \propto$ Spin rotation angle

COSY

Cooler Synchrotron - COSY

- 184 m circumference
- Polarized protons and deuterons
- Current experiment uses deuterons with $p = 970\,\mathrm{MeV\,c^{-1}}$
- 10^9 to 10^{10} particles
- Electron cooling
- Spin manipulation

Systematic limit to the EDM measurement

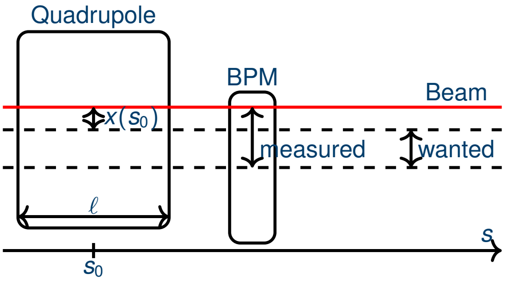
- For an EDM measurement the orbit has to be as good as possible
- Goal is to go central through all magnets (i.e. quadrupoles)
- Orbit Control software corrects the beam to the Beam Position Monitor (BPM) zero position
- Thus BPM to quadrupole offset has to be known $\rightarrow$ Beam-based alignment

Orbit y_{RMS}	"Fake" EDM
1.3 mm	$\sim 10^{-19}$ e cm
0.16 mm	$\sim 10^{-20}$ e cm

M. Rosenthal, PhD thesis [2]

Principle of beam-based alignment

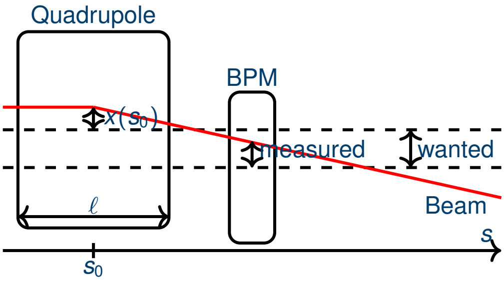
- Use beam to optimize the beam position



Principle of beam-based alignment

- Use beam to optimize the beam position
- Vary quadrupole strength
- Observe and then minimize orbit change

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



Dispersion not included in this equation.

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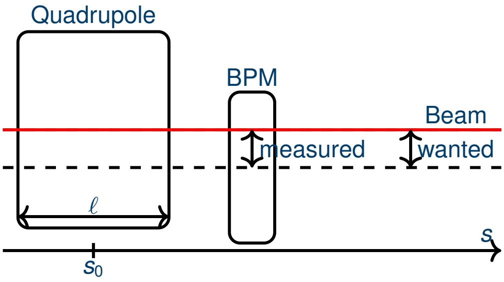

Dispersion not included in this equation.

Measurement Procedure

- Vary quadrupole strength Δk of an individual quadrupole

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

- Not possible to calculate $x(s_0)$ due to lack of precise knowledge of all other parameters

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

- By finding the minimum ($f \to 0$) the optimal beam position can be found

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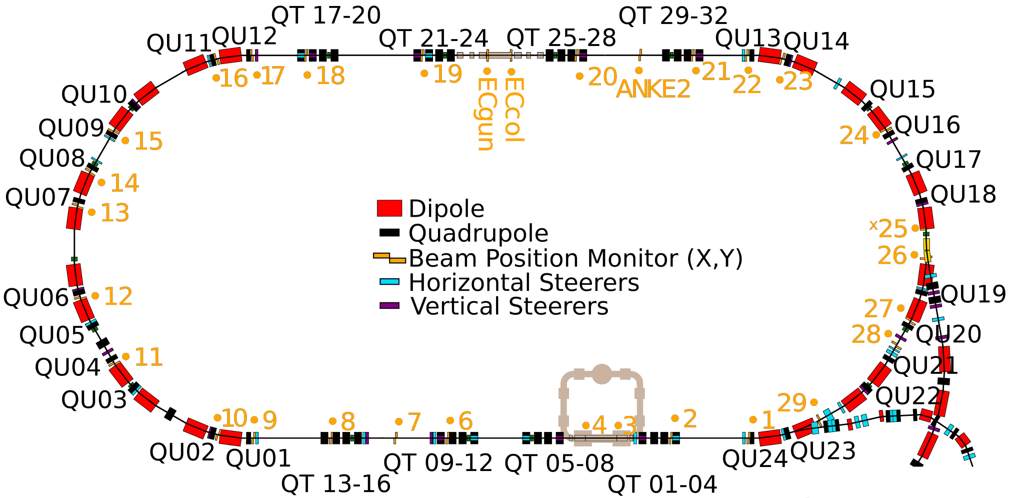
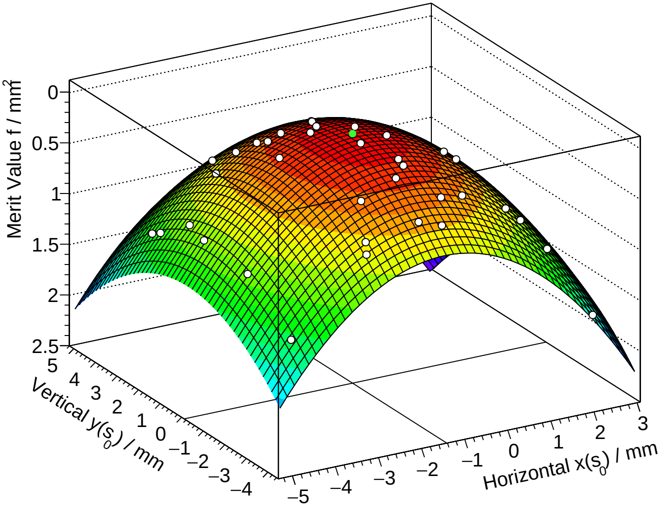
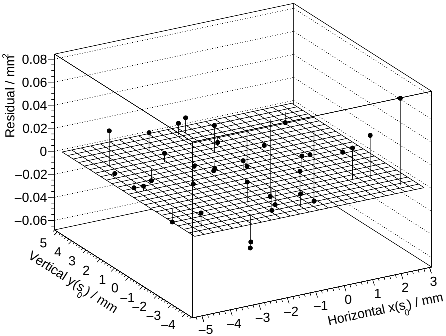
Cooler Synchrotron COSY

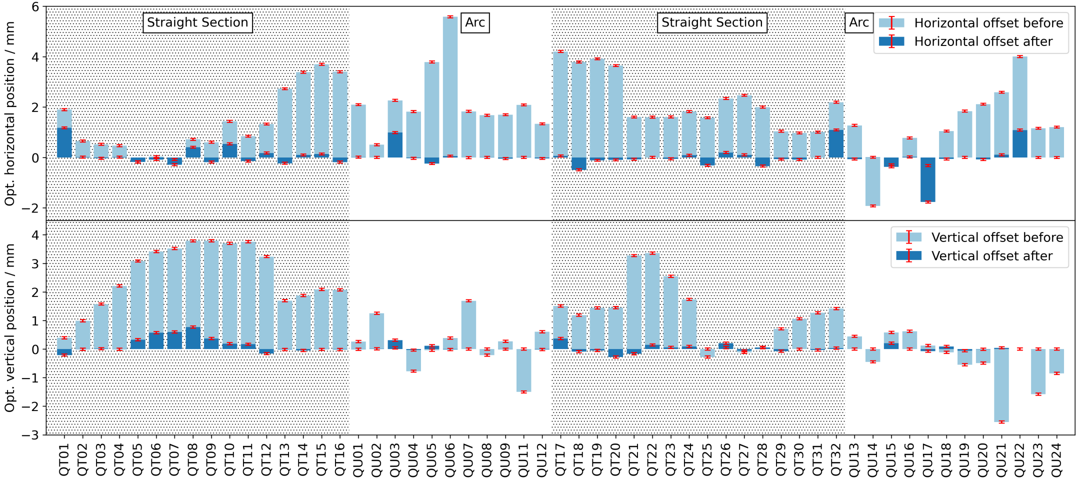


Example for one quadrupole (QU17)



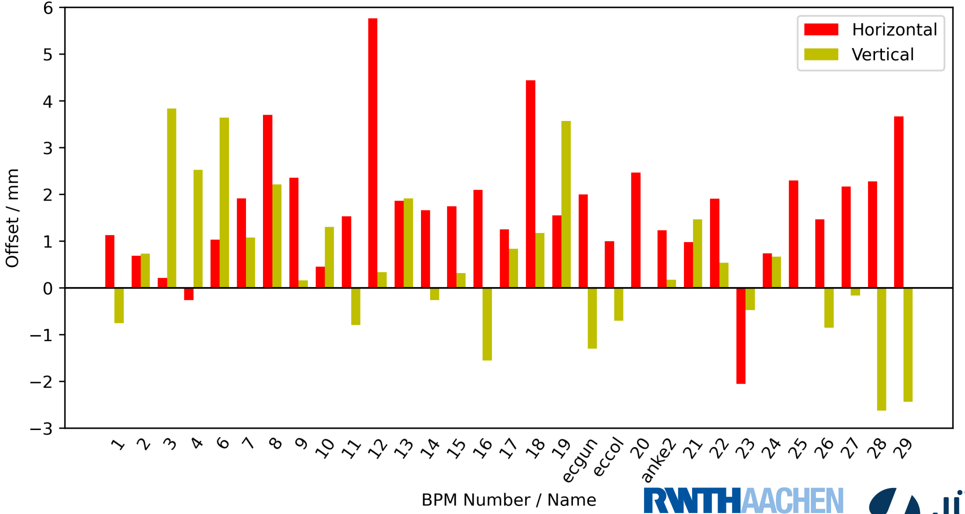


Optimal positions in all quadrupoles



This result has been published in [3].

COSY BPM offsets



Orbit improvement

Orbit corrected twice, once with offsets before BBA and once with offsets after BBA

	Orbit RMS		Steerer RMS	
	Horizontal	Vertical	Horizontal	Vertical
Before BBA	2.27 mm*	1.09 mm	5.03 % / 0.63 mrad*	4.39 % / 0.25 mrad
After BBA	3.26 mm*	0.52 mm	3.90 % / 0.49 mrad*	0.79 % / 0.05 mrad

Vertical orbit is better by a factor 2 while also needing fewer steerers by a factor 5.

*For this orbit correction four steerers around the electron cooler were excluded from the orbit correction. Thus, that part could not be corrected well and the horizontal orbit was 10 mm off in that straight section. This leads to these high RMS values and is not representative of the actual performance.

Summary

- EDM measurement needs a good orbit in the accelerator
- Beam-based alignment can determine the offset between the BPMs and the quadrupoles
- It was performed at COSY and improved the orbit correction performance
- Improved the COSY model for simulations and allows better comparison of the simulation to measurements

Further Reading I

[1] A. D. Sakharov. “Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe”. In: Pisma Zh. Eksp. Teor. Fiz. 5 (1967), pp. 32–35. DOI: 10.1070/PU1991v034n05ABEH002497.

[2] M. S. Rosenthal. “Experimental Benchmarking of Spin Tracking Algorithms for Electric Dipole Moment Searches at the Cooler Synchrotron COSY”. PhD thesis. RWTH Aachen University, 2016.

[3] T. Wagner et al. “Beam-based alignment at the Cooler Synchrotron COSY as a prerequisite for an electric dipole moment measurement”. In: JINST 16.02 (2021), T02001. DOI: 10.1088/1748-0221/16/02/t02001. arXiv: 2009.02058 [physics.acc-ph].

Equation with Dispersion

$$\Delta x(s) = \frac{\Delta k \cdot x(s_0)\ell}{B\rho} \cdot \frac{1}{1 - k \cdot \frac{\ell}{B\rho}\left[\frac{\beta(s_0)}{2\tan(\nu\cdot\pi)} + \frac{D(s_0)^2}{\eta\cdot L_0}\right]} \times \left[\frac{\sqrt{\beta(s)\beta(s_0)}}{2\sin(\nu\cdot\pi)}\cos(\phi(s) - \phi(s_0) - \nu\cdot\pi) + \frac{D(s)D(s_0)}{\eta\cdot L_0}\right]$$

As $\Delta x(s)$ is still proportional to Δk and $x(s_0)$, one does not need to explicitly consider dispersion for the beam-based alignment measurement.

Derivation can be looked up in the JEDI Internal Note 8/2018.