BEAM-BASED ALIGNMENT AT THE COOLER SYNCHROTRON (COSY) AND BEYOND

March 31, 2021 | Tim Wagner | IKP-2, Forschungszentrum Jülich

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- What is beam-based alignment?
- How does it work?
- What are the results at COSY?
- How is it done at other accelerators?
- How to include it in future accelerator designs?

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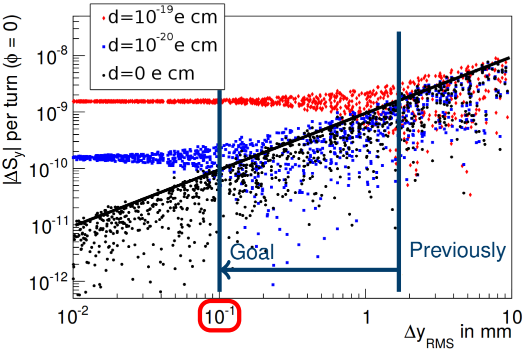
Why is beam-based alignment needed and what is it?

- For an EDM measurement the orbit has to be as good as possible
- Orbit RMS should be lower than 100 µm
  $\rightarrow$ Orbit Control
- Goal is to go central through all magnets (i.e. quadrupoles)
- Thus BPM to quadrupole offset has to be known
  $\rightarrow$ Beam-based alignment

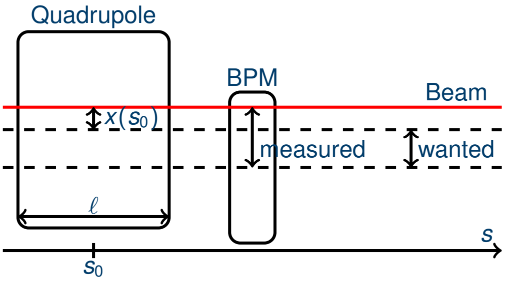


M. Rosenthal, PhD thesis (modified)

Principle of beam-based alignment

- Use beam to optimize the beam position

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



Dispersion not included in this equation.

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Principle of beam-based alignment

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

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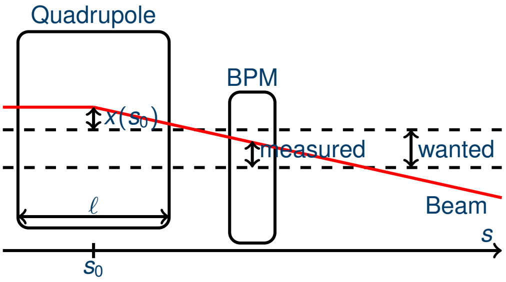

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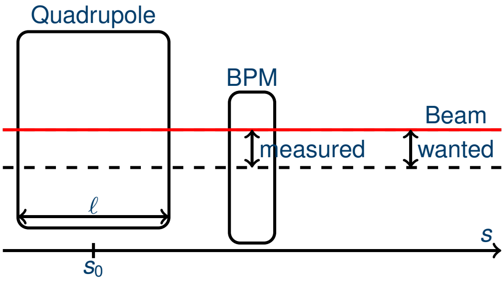

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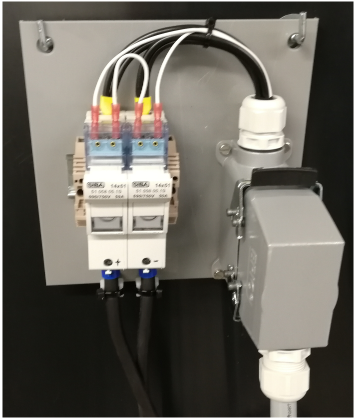
Measurement Procedure

- Vary quadrupole strength with additional power supplies connected in parallel to an individual quadrupole



Measurement Procedure

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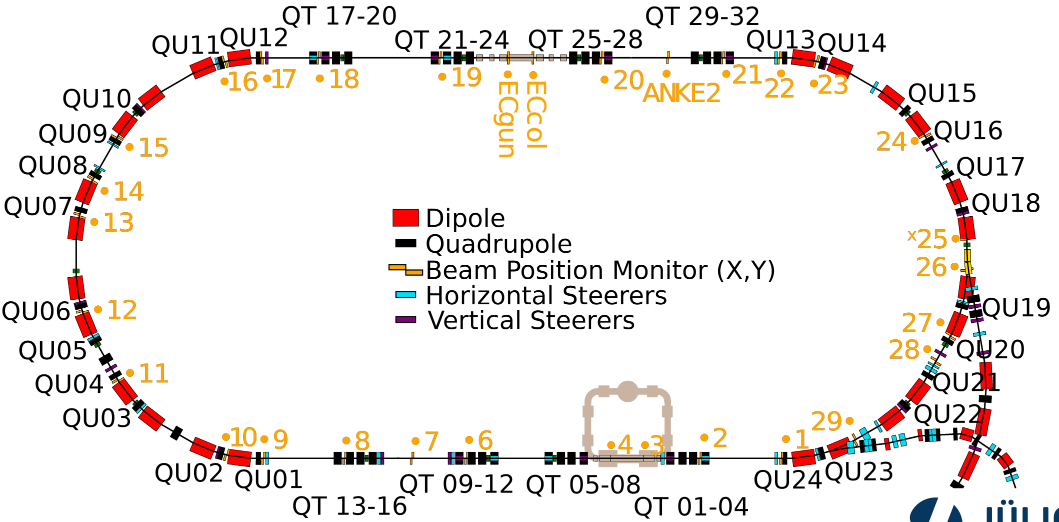
$$\Delta x(s) = \frac{\Delta k \cdot x(s_0) l}{B\rho} \cdot \frac{1}{1 - k \frac{l\beta(s_0)}{2B\rho \tan \pi\nu}} \cdot \frac{\sqrt{\beta(s)}\sqrt{\beta(s_0)}}{2 \sin \pi\nu} \cos[\phi(s) - \phi(s_0) - \pi\nu]$$

- 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

Cooler Synchrotron COSY



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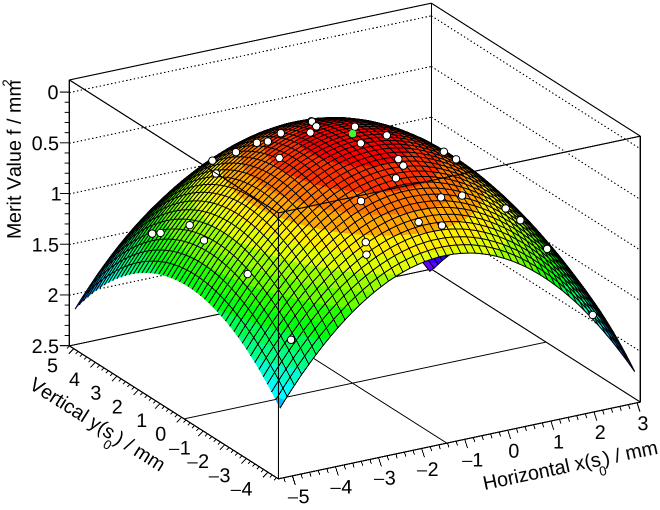
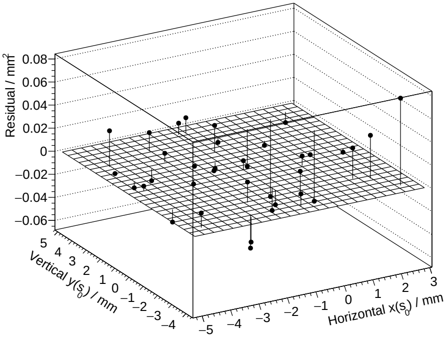
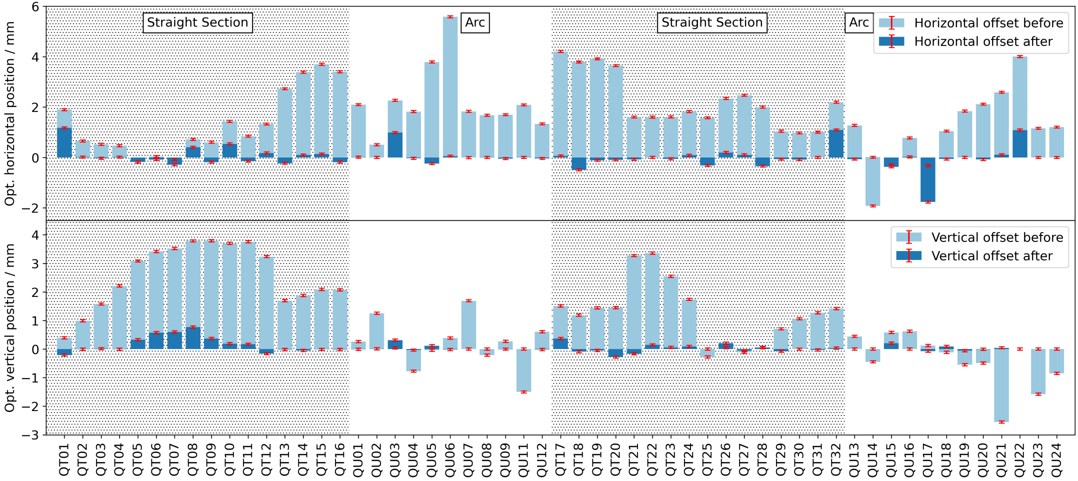
Example for one quadrupole (QU17)





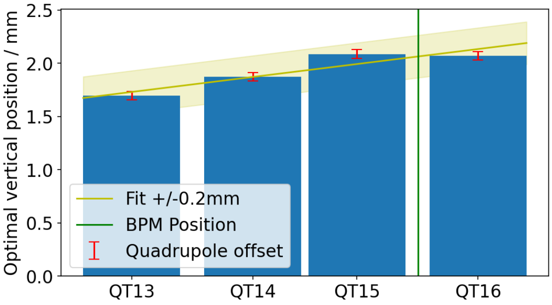
Optimal positions in all quadrupoles

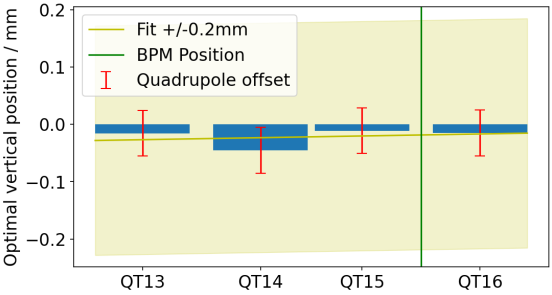


This result has been published in [1].

Alignment of quadrupoles

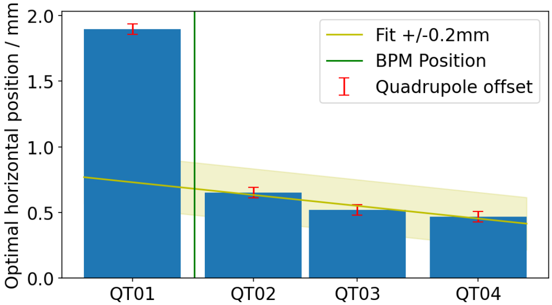
Example 1 (QT13 - QT16) - Good Alignment

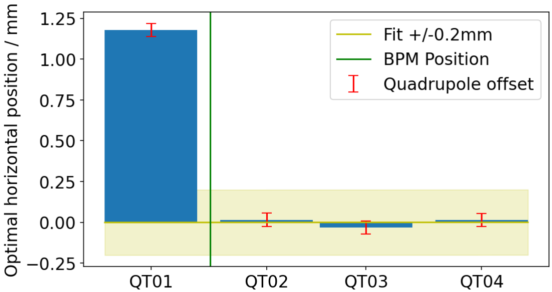




Alignment of quadrupoles

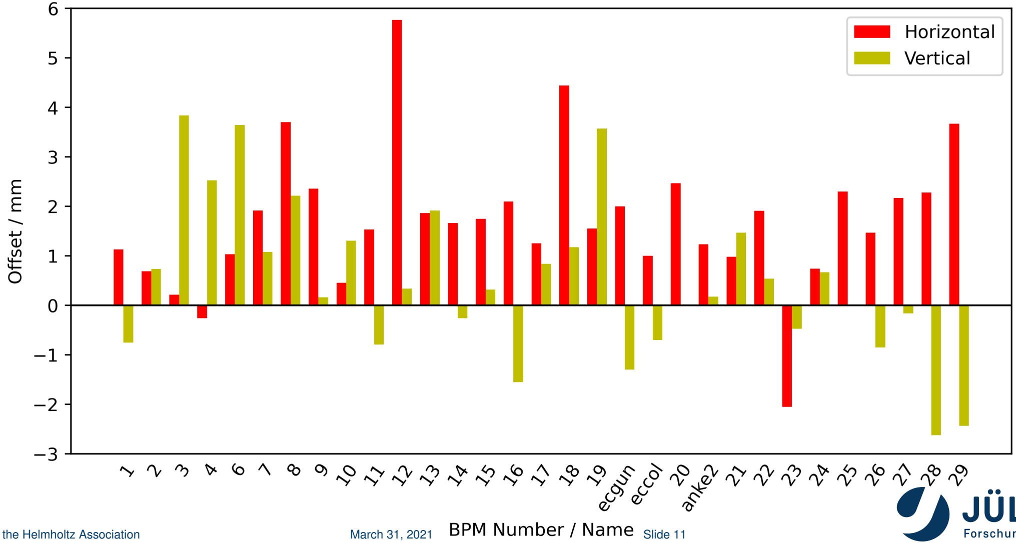
Example 2 (QT01 - QT04) - Bad Alignment





- Quadrupoles, where such an offset has been detected, have been remeasured with a laser tracker and it confirmed these offsets

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.

Beam-based alignment in other acelerators

- Options to modify the quadrupole strength
  - Individually powered quadrupoles: ALS [2], SuperKEKB Linac [3]
  - Back-leg windings: LEP [4, 5]
  - Shunt resistors: MAX 1 [6]
  - Shunt power supplies: RHIC [7], INDUS-2 [8]

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- Interesting examples: LEP [5] and ALBA [9]
  - LEP used sinusoidal quadrupole exitations to induce beam oscillations
  - From the FFT of the beam oscillations the Fourier strength was used to determine the offset in the quadrupole
  - ALBA uses AC excitations of corrector magnets and high sampling rate BPMs (10 kHz) to accelerate the beam-based alignment process

Considerations for future accelerators

- Essential to incorporate a method for beam-based alignment into the design of the acellerator components
- Attaching measurement markers to as many accelerator elements as possible for mechanical alignment, especially the BPMs
- With markers for mechanical alignment it is possible to reduce the number of beam-based alignment measurements
- For COSY one could implement a feedback system continuously monitoring the quadrupoles to improve the precision of the beam-based alignment

Summary

- Beam-based alignment was performed at COSY and improved the orbit correction performance
- Several misaligned quadrupoles were identified
- Improved the COSY model for simulations and allows better comparison of the simulation to measurements
- Different methods of quadrupole strength variation for beam-based alignment
- Future accelerators should be planned with beam-based alignment in mind

Further Reading I

[1] 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].

[2] G. Portmann, D. Robin, and L. Schachinger. “Automated beam based alignment of the ALS quadrupoles”. In: Conf. Proc. C 950501 (1996), pp. 2693–2695.

[3] S. Ogur et al. “Beam-based alignment of the SuperKEKB linac quadrupoles”. In: Nucl. Instrum. Meth. A 925 (2019), pp. 199–211. DOI: 10.1016/j.nima.2019.02.018.

[4] I. Barnett et al. “Dynamic beam based alignment”. In: AIP Conf. Proc. 333 (1995). Ed. by G. H. Mackenzie, B. Rawnsley, and J. Thomson, pp. 530–535. DOI: 10.1063/1.48033.

Further Reading II

[5] B. Dehning et al. "Beam based alignment at LEP". In: Nucl. Instrum. Meth. A 516 (2004), pp. 9–20. DOI: 10.1016/j.nima.2003.07.039.

[6] Peter Röjsel. "A beam position measurement system using quadrupole magnets magnetic centra as the position reference". In: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 343.2 (1994), pp. 374–382. ISSN: 0168-9002. DOI: https://doi.org/10.1016/0168-9002(94)90214-3.

[7] J. Niedziela, C. Montag, and T. Satogata. "Quadrupole beam-based alignment at RHIC". In: Conf. Proc. C 0505161 (2005). Ed. by Charlie Horak, p. 3493.

[8] Saroj Kumar Jena et al. "Beam based alignment and its relevance in Indus-2". In: Rev. Sci. Instrum. 86.9 (2015), p. 093303. DOI: 10.1063/1.4930277.

Further Reading III

[9] Zeus Martí et al. “Fast beam-based alignment using ac excitations”. In: Phys. Rev. Accel. Beams 23 (1 Jan. 2020), p. 012802. DOI: 10.1103/PhysRevAccelBeams.23.012802.

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