Center for Accelerator Science and Engineering

Vibrating-Wire Magnetic-Axis Measurement of SLS2.0 Multipole Magnet

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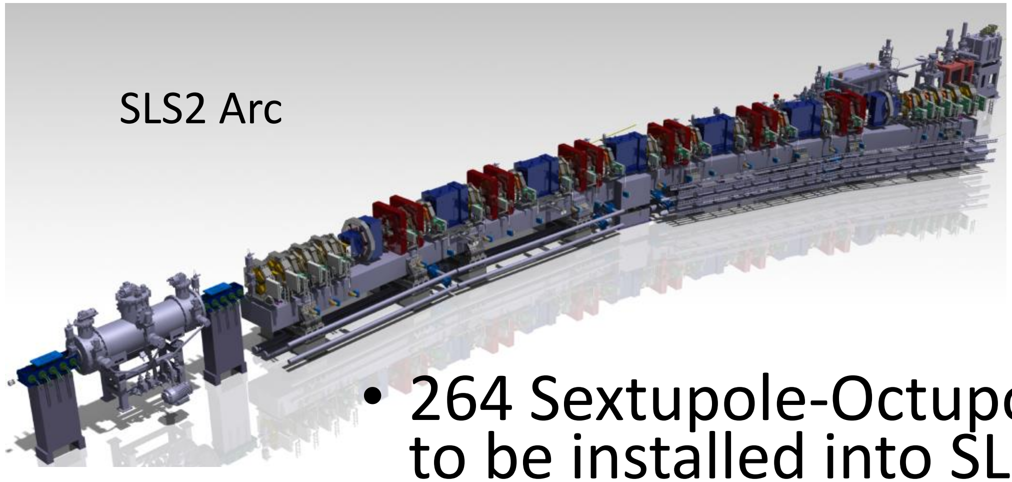
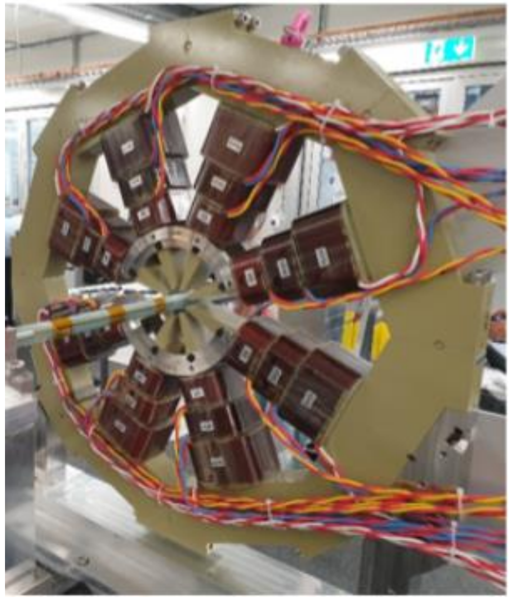
23rd IMMW
Bad Zurzach, Switzerland
08.10.2024

Introduction: Magnets to measure

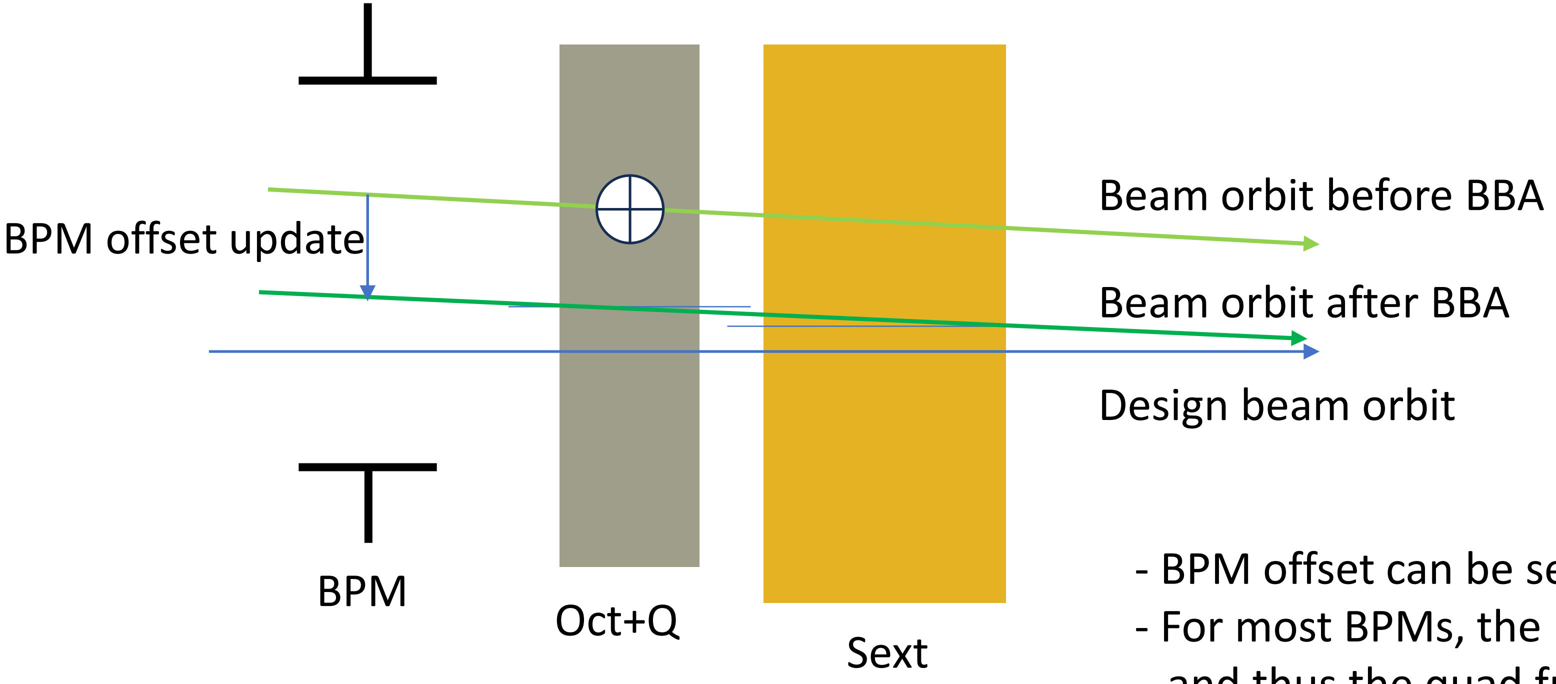


- 264 Sextupole-Octupole pairs (+24 Sextupole) to be installed into SLS2.0 storage ring
  - Transverse alignments of the sextupoles are important to mitigate optics error sources
  - Octupole yoke accommodates three functions: Octupole, normal and skew quadrupoles
  - Beam-based alignment using normal quadrupole function
  - *Magnet-axis measurement with vibrating-wire technique → Sextupole and Octupole relative alignment*



Beam-based alignment (BBA)

- BPM offset w.r.t. neighboring quadrupole is measured and subtracted from BPM reading: *No physical alignment* is to be applied



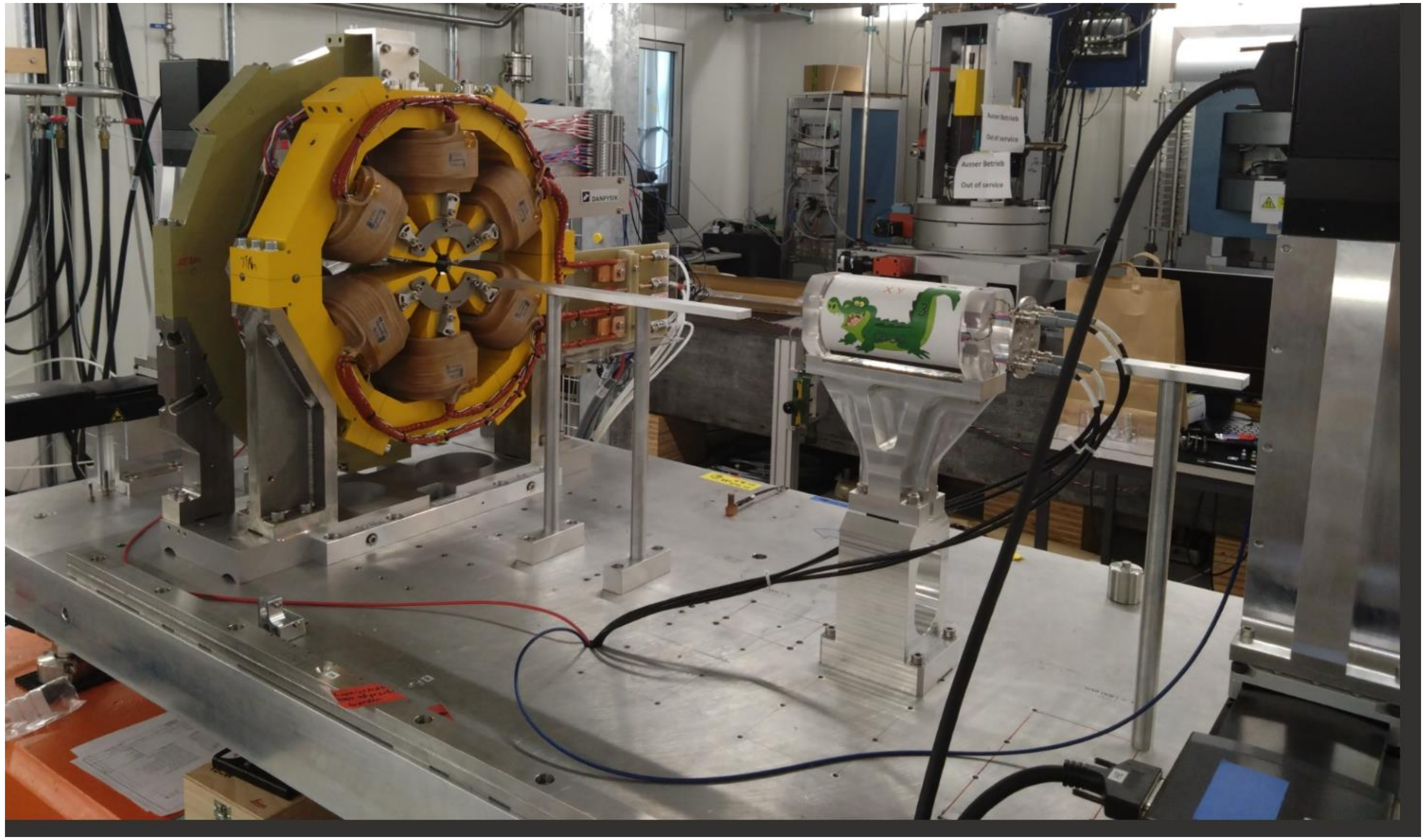
⊕ Quad field on the beam orbit

→ Beam orbit shift

→ BPM offset w.r.t. Q-axis is found

- BPM offset can be several 100 μm before BBA
- For most BPMs, the neighboring quad is permanent magnet, and thus the quad function is implemented into the octupole

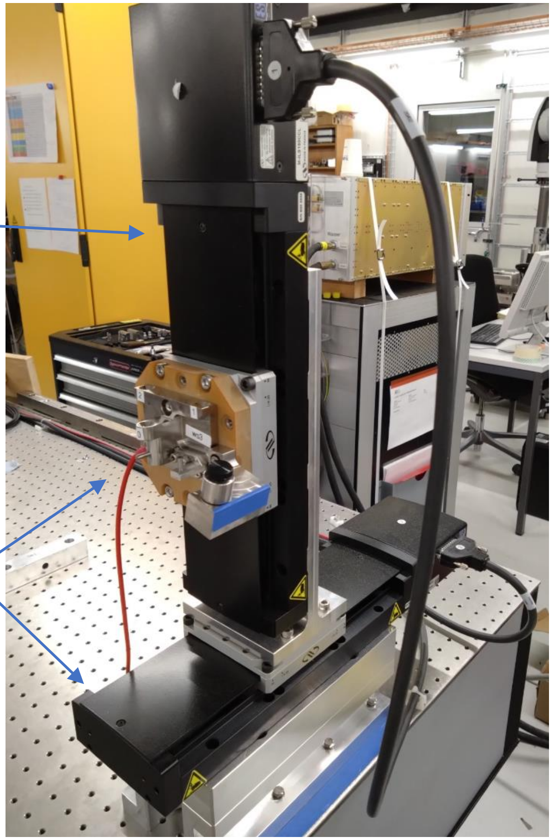
Measurement bench



The measurement system achieved a precision of axis measurement of a few μm
(estimated from repeated measurements)

Wire mover: Motorized linear stages

X-Y mover



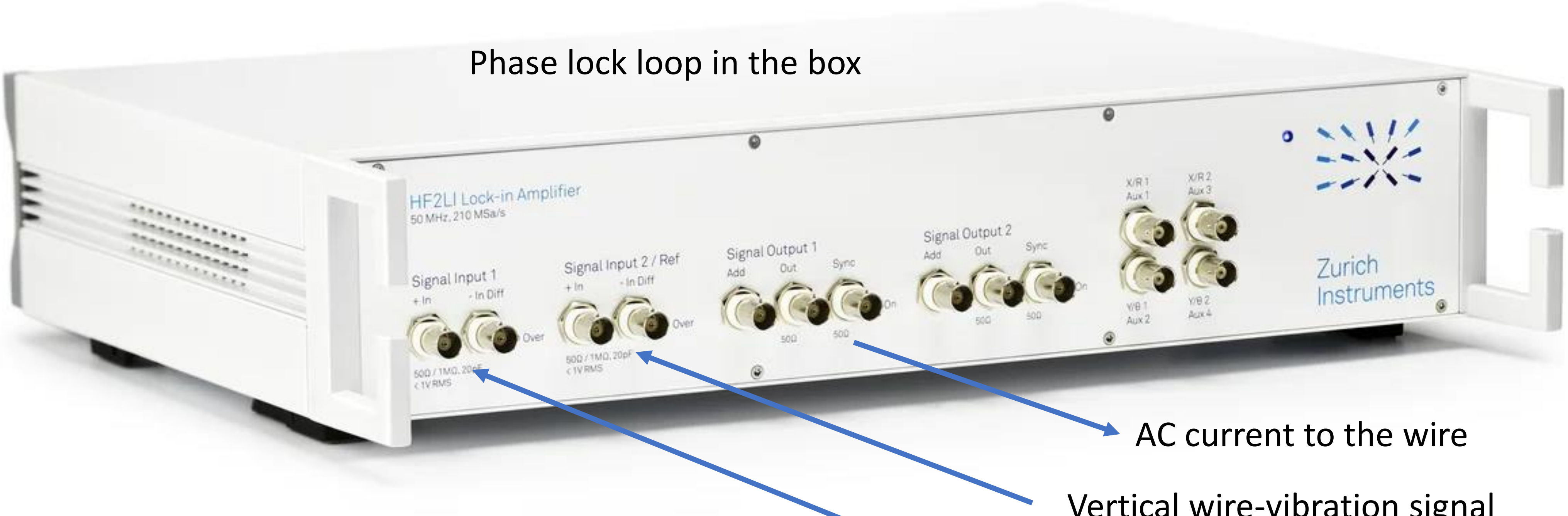
Wire holder
with fiducialization points

Newport: https://www.newport.com/

PSI

Lock-in amplifier

Phase lock loop in the box



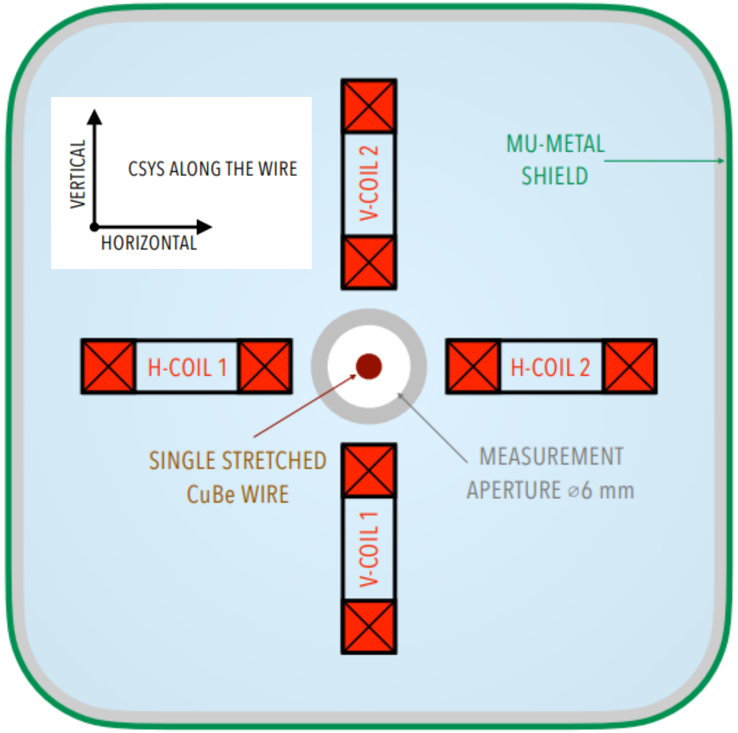
AC current to the wire

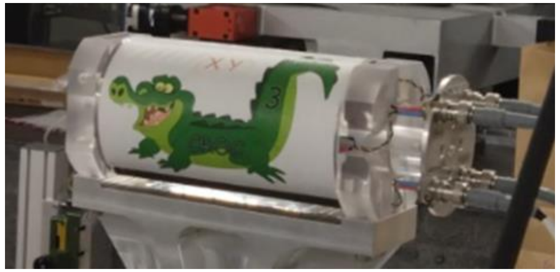
Vertical wire-vibration signal

Horizontal wire-vibration signal

Zurich Instruments: https://www.zhinst.com/

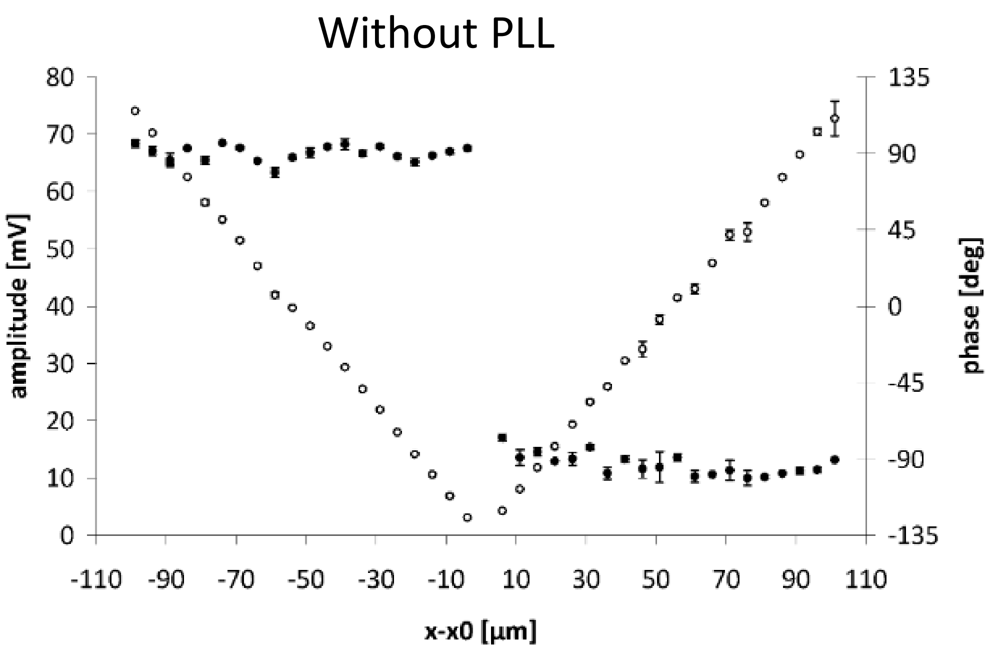
Vibration detector

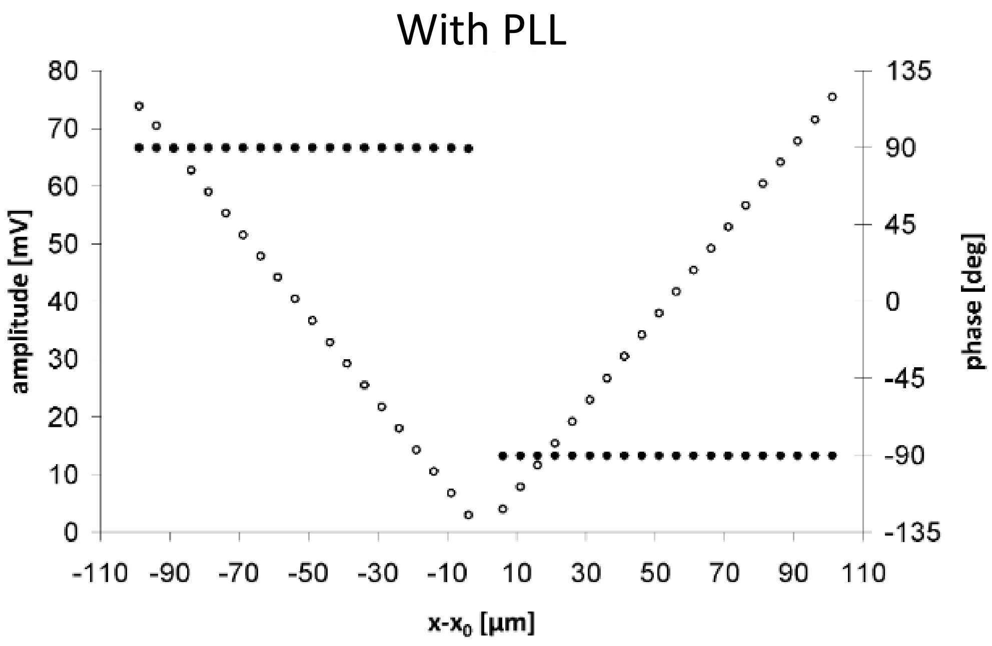




- detector with two orthogonal pairs of pick-up coils; wound with Cu wire ⌀ 0.070 mm, >10'000 windings; coils electrically connected to pairs for differential readings; Mu-metal shield over the whole detector body length 140 mm
- pairs connected to two channel lock-in amplifier (ZI HF2LI); H-coils pair to channel 1, V-coils pair to channel 2
- measurement with ⌀ 0.125 mm CuBe single stretched wire
- wire AC 50-100 mA, reference frequency f_{REF} is set to the double of the wire resonance frequency f_0, thus avoiding vibrations stemming from the earth and environment fields
- in field the wire vibrates with the same AC frequency f_{REF}

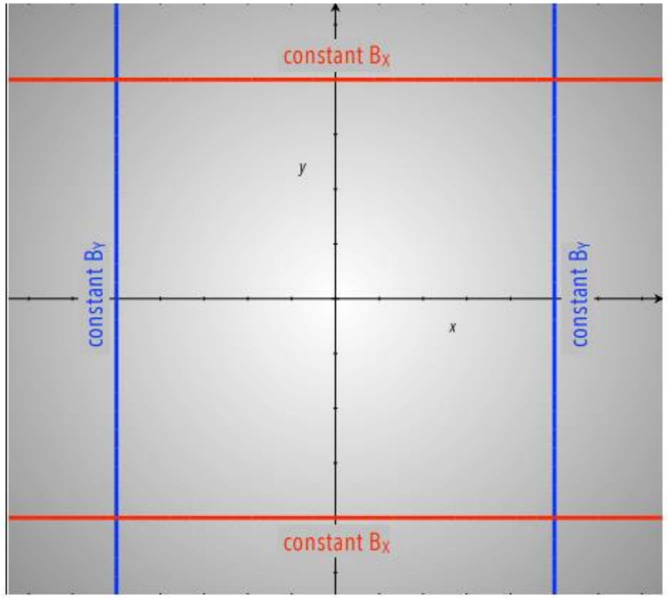
PLL improves signal-to-noise ratio



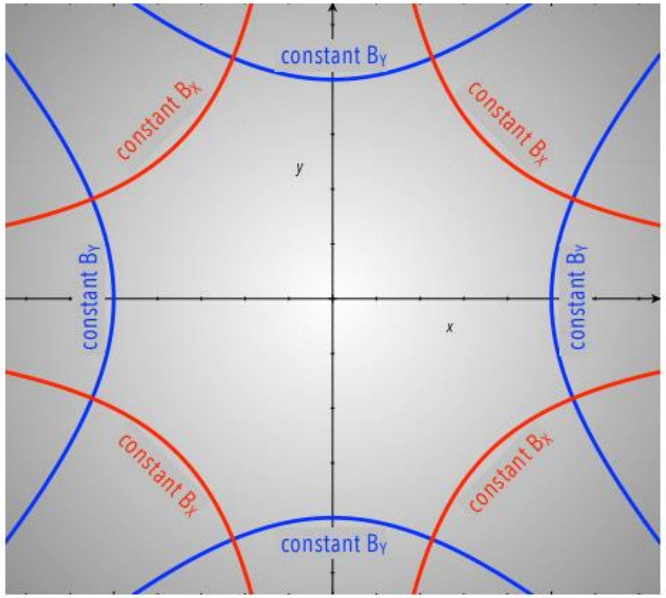


Figures from SwissFEL quadrupole measurement:
C. Wouters, M. Calvi, V. Vrankovic, S. Sidorov and S. Sanfilippo,
``Vibrating Wire Technique and Phase Lock Loop for Finding the Magnet Axis of Quadrupoles'',
Proceedings of the 22nd International Conference on Magnet Technology, 4KP1-1 (2011)

Axis measurement (1)



Quadrupole Equipotential Lines

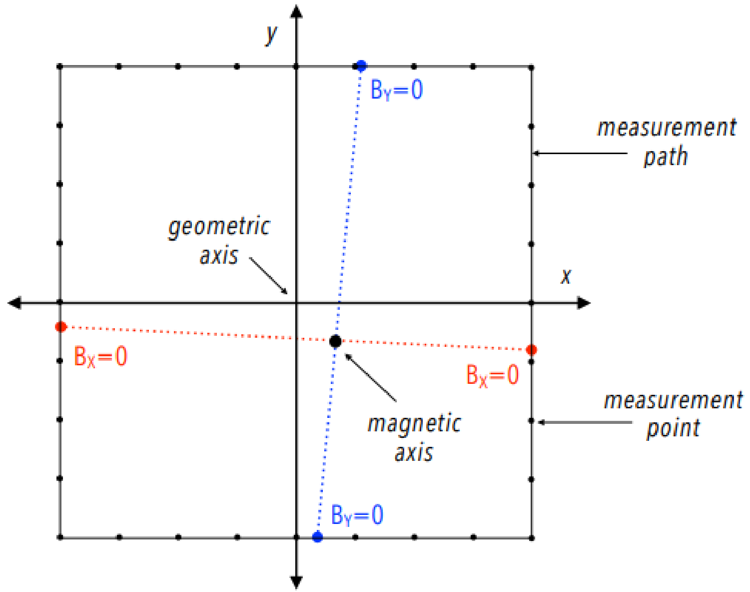


Sextupole Equipotential Lines

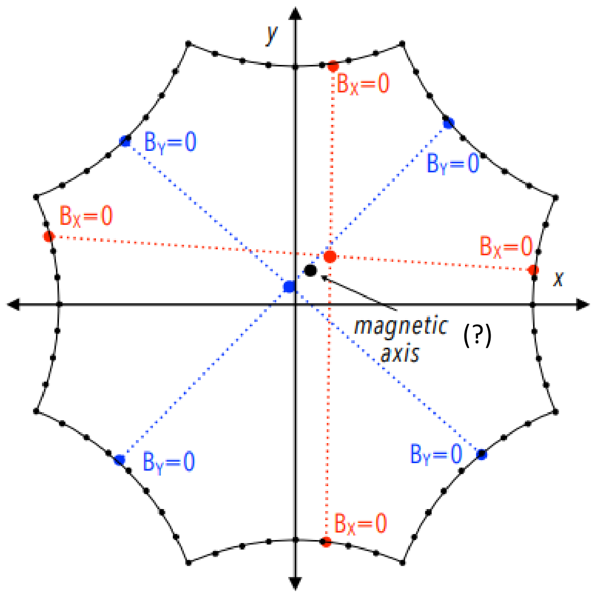
- PLL can work only on a signal that does not change its phase shift considerably
- in multipole magnets the magnetic field components are constant on the equipotential lines; in perfect quadrupole they are straight lines, in perfect sextupoles they are hyperbolas

➡ PLL is applied on the channel measuring the constant field component, while the measurements are taken from the other channel, searching for the position where the signal changes polarity

Axis measurement (2)



Quadrupole (4 measurement paths)

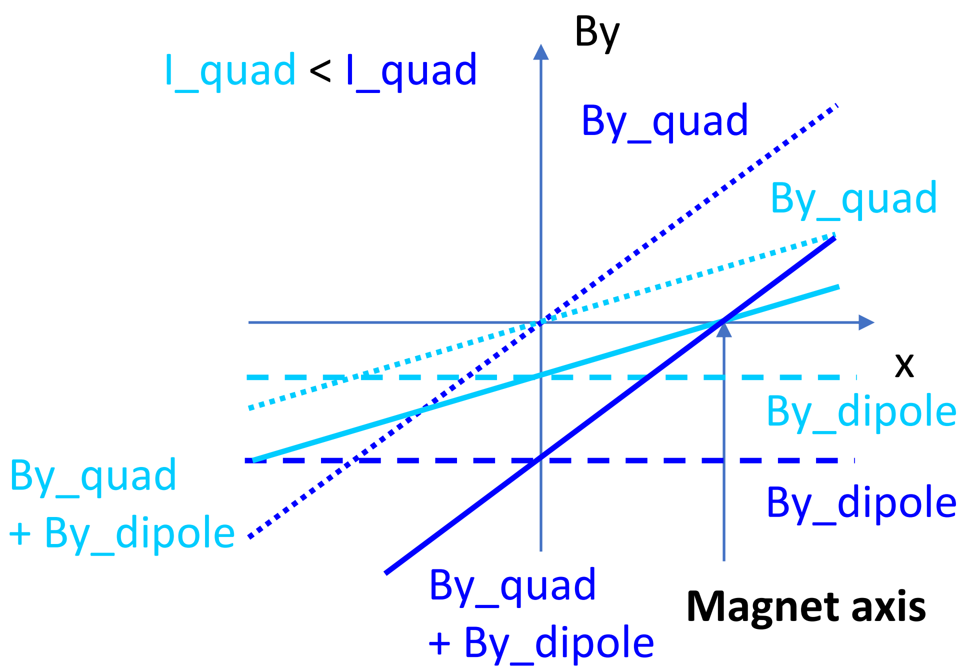


Sextupole (8 measurement paths)

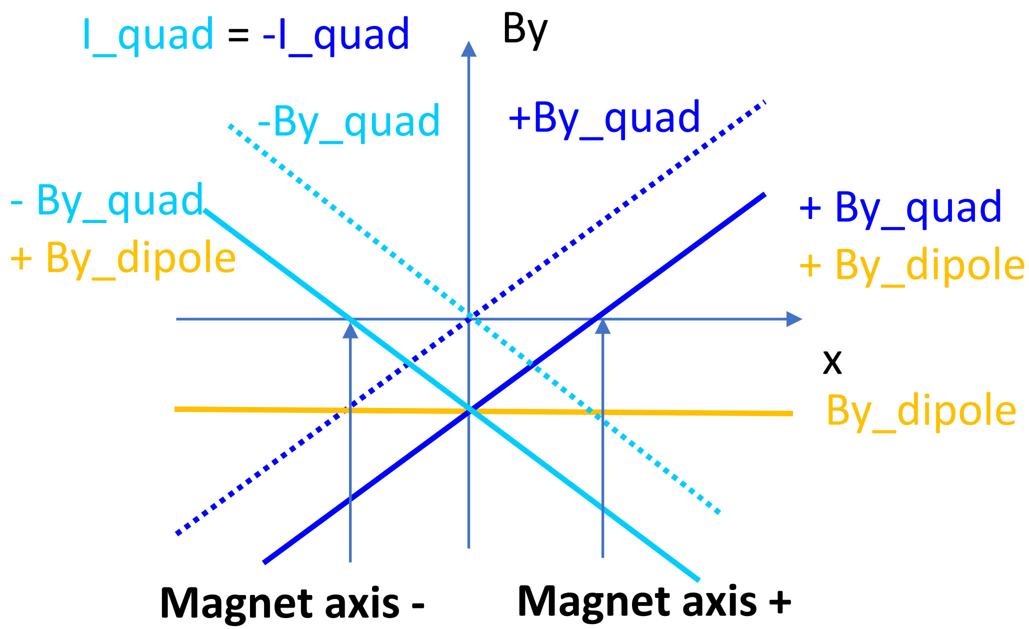
- interpolate the vibration amplitudes from the measurement points on every measurement path and find positions with zero field components
- connect the zero field component positions from the opposite paths and find the intersection point;
  for quadrupole this point defines the magnetic axis
  for sextupole there are 2 intersection points and their average defines the magnetic axis
- repeat the same procedure one more time, now along smaller paths centred around the magnetic axis;
  this cancels out the spurious measurements

Remark on the quadrupole magnet axis

Dipole error proportional to quad field

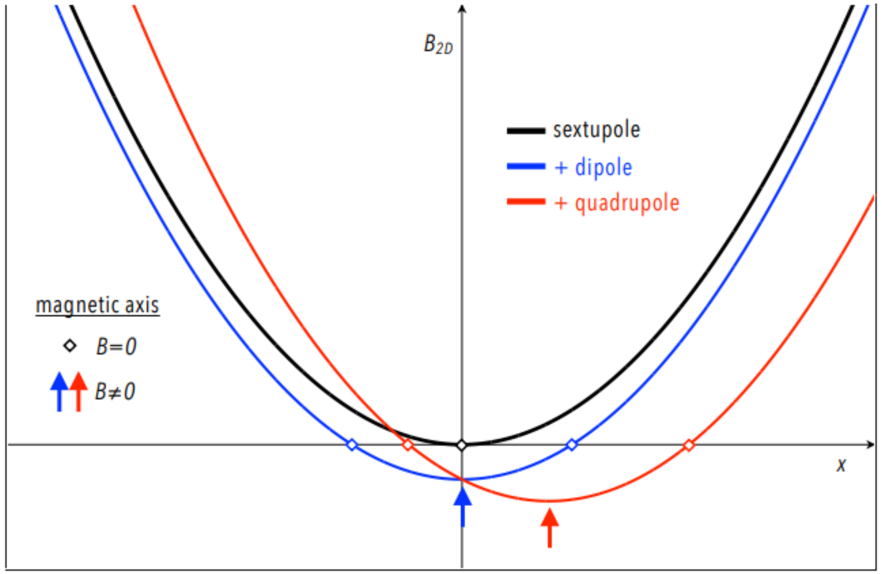


Constant dipole error



- Dipole proportional to quad field → Axis shift is constant and transparent to BBA
- Constant dipole → The axis depends on the quad current → BBA with positive and negative quads current and take an average

Remark on the sextupole magnet axis



magnetic axis is where B=0?

- true, perfect sextupole has only one point in space where the field is zero and this is the magnetic axis
- but, sextupoles with multipole errors have two zero field points and average between these points is the magnetic axis - however, at this point the field is not zero;
  this point is captured though by the used methodology

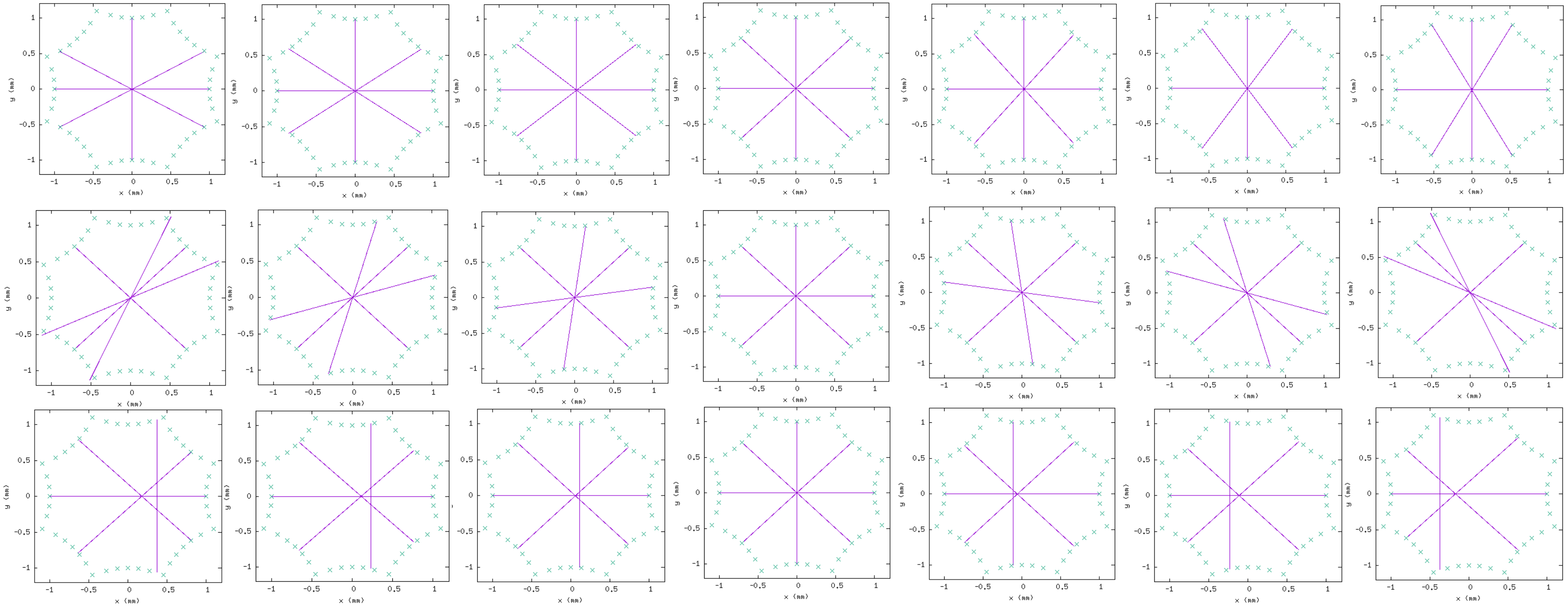
Impact of dipole/quad errors on sext-axis measurement

Error - ← Ideal sext. → Error +

Normal dipole

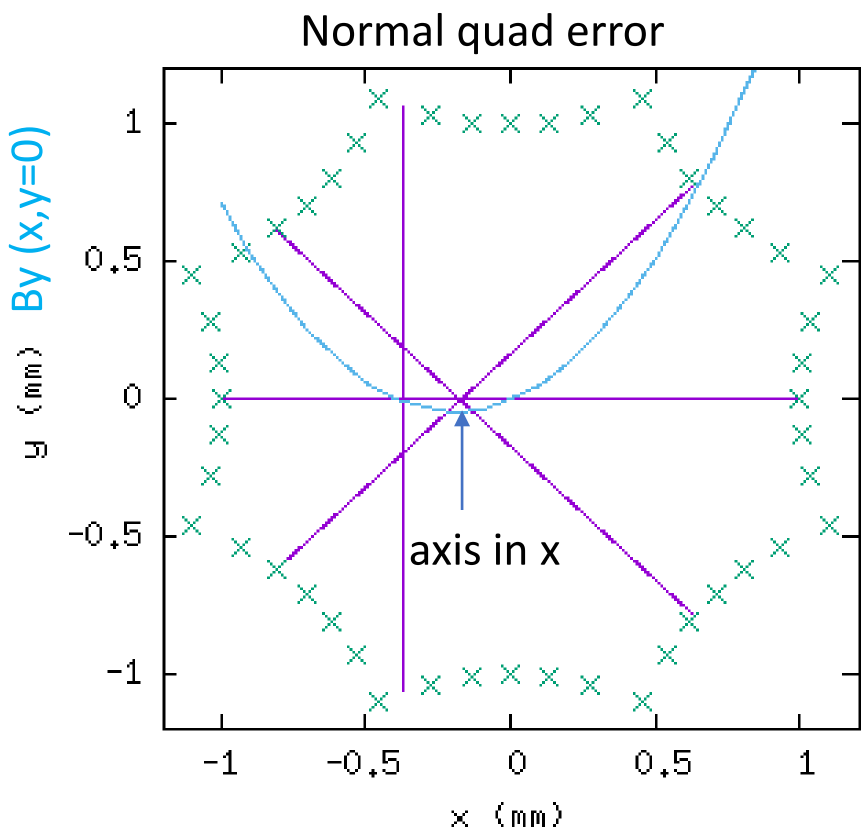
Skew dipole

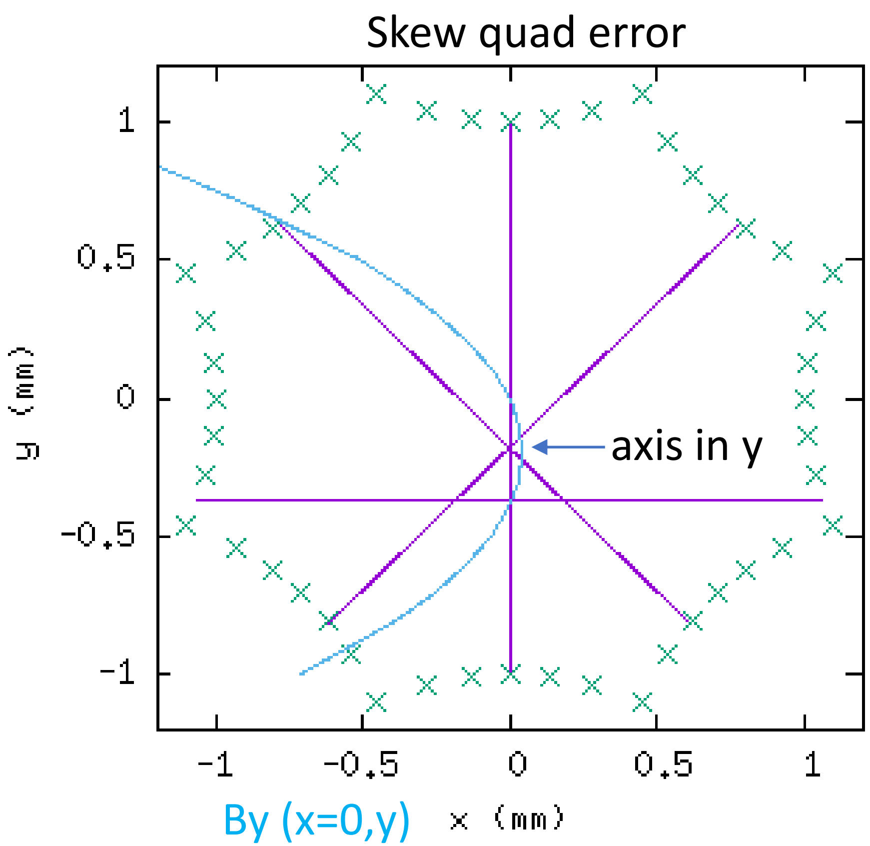
Normal quad



Dipole error → No impact on the measured axis
Quad error → See next slide
Higher multipole → Negligible impact; Field is weak at wire positions

Impact of quad errors on sext-axis measurement

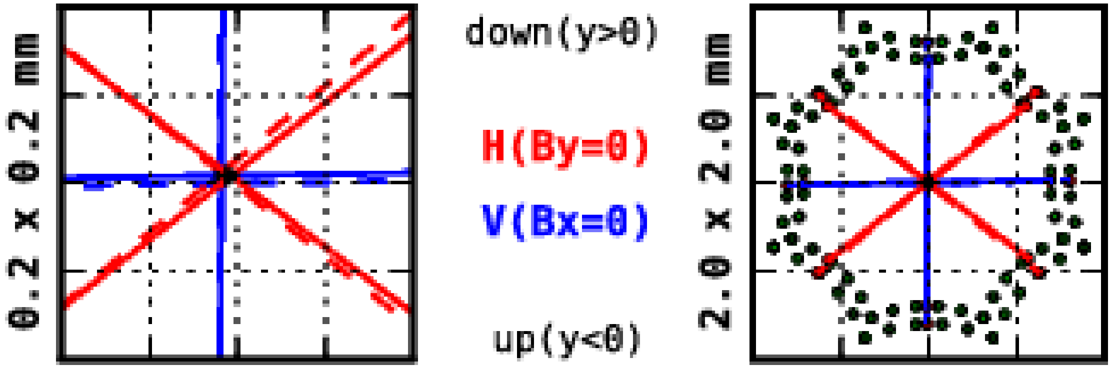




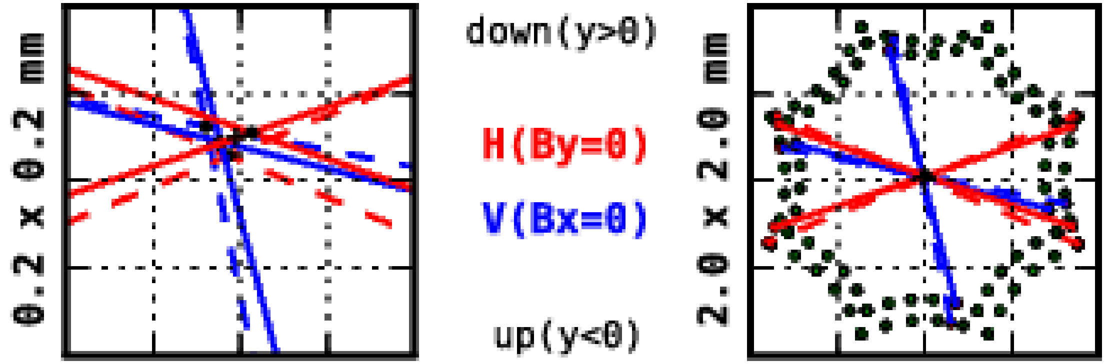
- Sextupole axis is shifted by normal/skew quad but it can be found
- The shift is normally < 10 µm; Quad error in sextupole is not significant

Typical sext-axis measurement data

Good sextupole



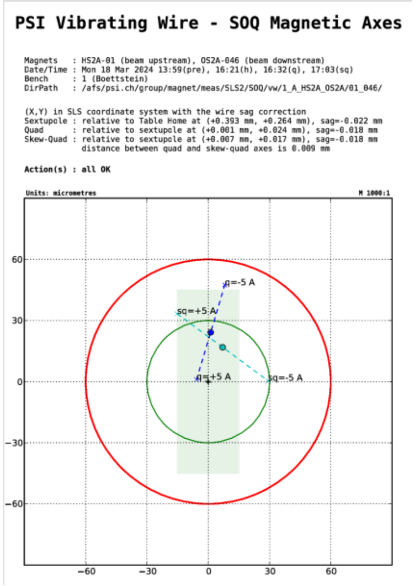
A sextupole
with D+Q errors



Relative alignment

- Shifting octupole yoke horizontally, and lifting sextupole yoke vertically with spacer shims based on axis measurements
- Iteration of measurement and alignment to achieve relative alignment 15 µm and 45 µm in H and V; 6 ~ 9 hours

Report generated at the end of each SOQ measurement



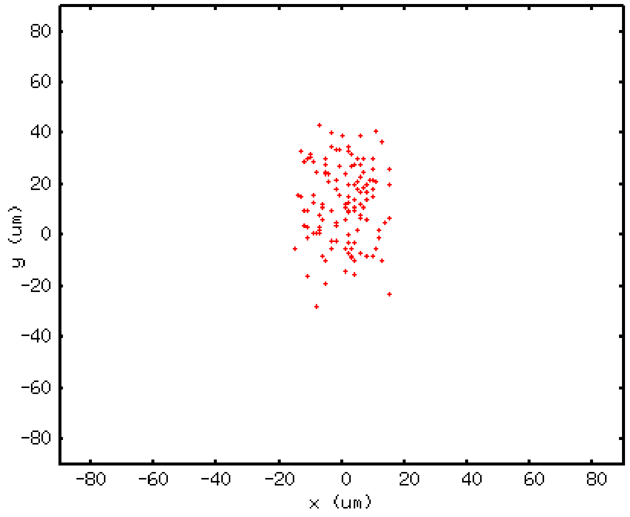
PSI Vibrating Wire - SOQ Magnetic Axes

```
Magnets   : HS2A-01 (beam upstream), OS2A-046 (beam downstream)
Date/Time : Mon 18 Mar 2024 13:59(pre), 16:21(h), 16:32(q), 17:03(sq)
Bench     : 1 (Boettstein)
DirPath   : /afs/psi.ch/group/magnet/meas/SLS2/SOQ/vw/1_A_HS2A_OS2A/01_046/

(X,Y) in SLS coordinate system with the wire sag correction
Sextupole : relative to Table Home at (+0.393 mm, +0.264 mm), sag=-0.022 mm
Quad      : relative to sextupole at (+0.001 mm, +0.024 mm), sag=-0.018 mm
Skew-Quad : relative to sextupole at (+0.007 mm, +0.017 mm), sag=-0.018 mm
            distance between quad and skew-quad axes is 0.009 mm

Action(s) : all OK
```


Quad axes from all SOQs

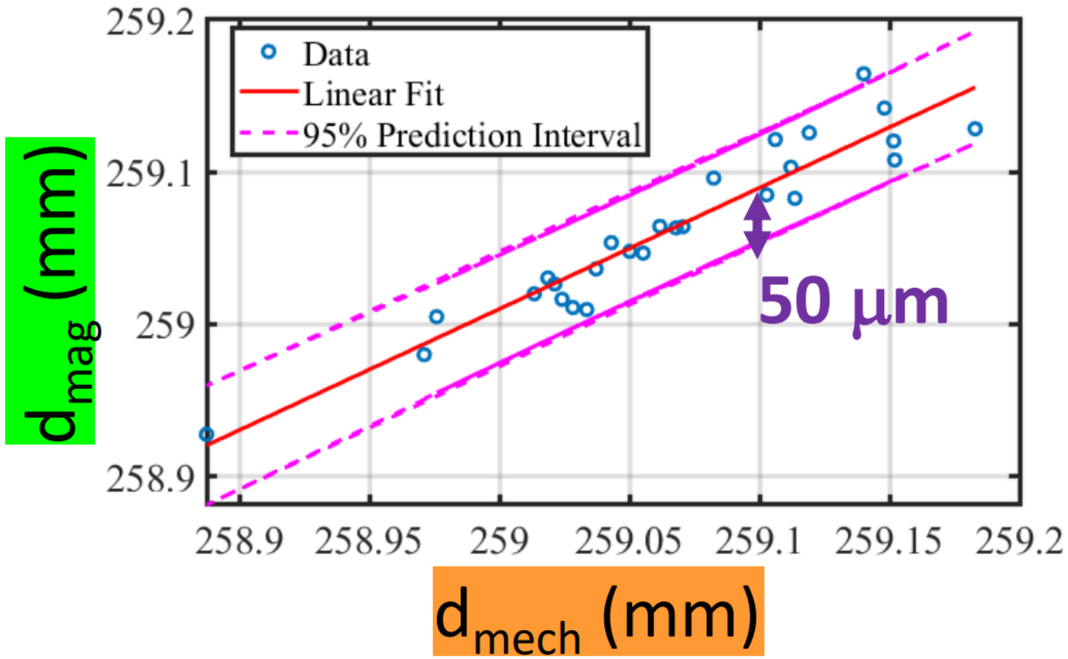


Implementation into Online model

```
# Quad_x, Quad_y, Skew_x, Skew_y [mm]
self.OctShift['ARS01-MOCT-1230']=[0.003, -0.008, 0.02, 0.009]
self.OctShift['ARS01-MOCT-1330']=[-0.004, 0.021, -0.002, 0.024]
self.OctShift['ARS01-MOCT-1440']=[-0.012, 0.004, -0.007, -0.001]
self.OctShift['ARS01-MOCT-1840']=[-0.005, 0.025, 0.007, 0.035]
self.OctShift['ARS01-MOCT-1950']=[-0.011, -0.001, -0.005, -0.002]
self.OctShift['ARS01-MOCT-2230']=[0.013, 0.037, 0.059, 0.038]
self.OctShift['ARS01-MOCT-2360']=[0.004, 0.011, 0.012, 0.018]
self.OctShift['ARS01-MOCT-2450']=[0.002, 0.02, 0.009, 0.019]
self.OctShift['ARS01-MOCT-2730']=[-0.001, 0.034, 0.015, 0.041]
.
.
.
```

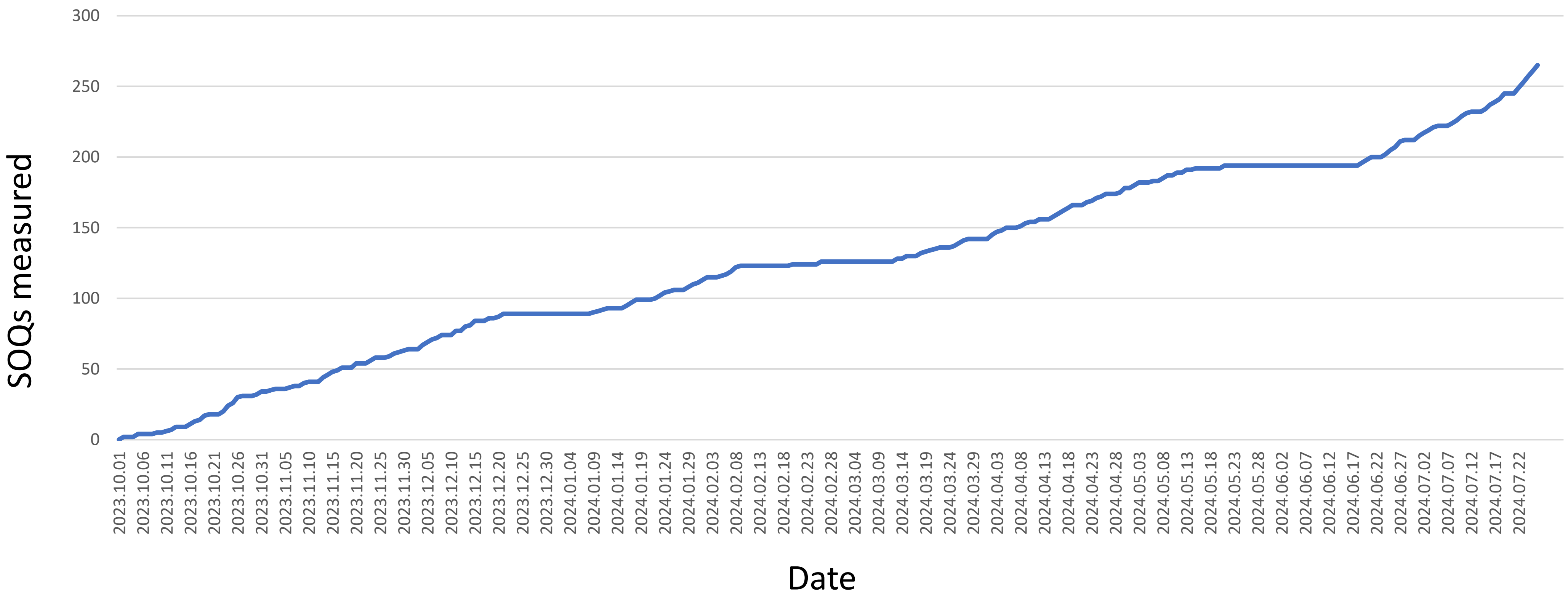
Residual offsets between Quadrupole (of octupole) and Sextupole are taken into account in BBA

Sextupole axis: CMM vs Vibrating Wire (VW)



- The sextupole axis found from VW is measured with a laser tracker w.r.t. the fiducialization points on the top surface of the sextupole yoke
- Sextupole axis from CMM and Vibrating wire measurement showed a good agreement → Double checking the laser tracker fiducialization

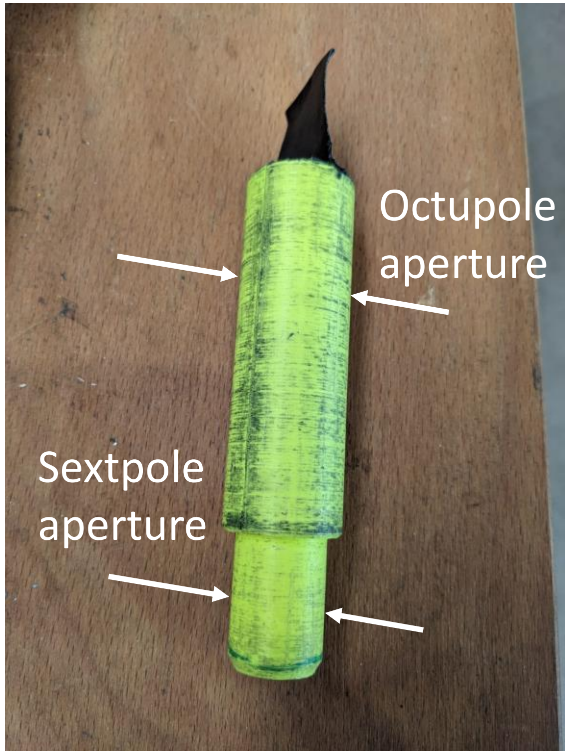
Progress curve
Series measurement over 10 months



- Approximately, 2 SOQs/working-day
- Three breaks: Christmas and waiting for the delivery of octupoles

Further topics

- Measurement and alignment is easier when the initial offset between Sextupole and Octupole is small
  - A 3D-printed tool was used to achieve a good initial alignment
- One octupole had an additional winding with wrong polarity (1 of 8 skew-quad coils)
  - The wrong polarity was found with a hall probe and fixed by R. Deckardt
- Measurement is performed at PSI while the magnets are stored in a remote building
  - Next generation light source storage ring consists of a large number of magnets, and thus the effort required for the logistics and book-keeping should not be underestimated



3D-printed alignment tool
by Y. Studer

Summary

- The magnet axes of sextupole and octupole pairs were measured, and the relative alignments of the pairs were completed
  - There are various approaches to find the magnet axis; we determined the magnet axis by measuring the field along equipotential lines
  - A phase-lock loop was employed and closed during the measurement to improve signal-to-noise ratio
  - Series measurement of 264 pairs was completed, and most magnets have been installed into the accelerator tunnel!

Many colleagues were involved in the measurement:
Special thanks to P. Chevtsov, R. Deckardt, K. Dreyer, T. Ernst, R. Felder, A. Gabard, M. Gregorio, R. Riccioli, S. Sanfillipo, S. Sidorov, R. Stefani, Y. Studer, V. van de Vijfeijken, G. Wang, C. Zoller