Review of beam based calibration of BPM offsets

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Beam-Based Alignment (*or beam-based BPM offset calibration*)

- Literature survey with focus on
  - Storage Rings
  - Beam-based calibration methods (no actual movement of magnets of BPMS)
- Most publications date from the late 90's.
- Methods are considered "standard" procedure now.
- Resolution/Accuracy improved from ~100-200 µ down to ~10-20 µm over the past 20 years.
- Focus in recent work on developing faster methods.

References

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Accelerator	Magnet used as reference	Method	Accuracy [μm]	Ref	Year
MAX I	Quadrupole	Quad shunt resistors	65	1	1994
ALS	Quadrupole	Individual power supplies	50	2	1995
KEK TRISTAN	Quad. trim on sextupole	Modulation of quad trim coils	50	3	1995
BESSY I	Quadrupole	Individual power supplies		4	1996
SPEAR	Quadrupole	Quad shunts	50	5	1996
PLS	Quadrupole	Shunts	170	6	1998
DELTA	Quadrupole	Auxiliary power supplies	150	7	1998 (?)
KEK B	Quad. trim on sextupole	Quad trim coil Sextupole Physically moved	100	8	2000
BEPC	Quadrupole			9	2000
SPRING 8	Quadrupole	Fourier Analysis	150	10	2001
HERA	Quadrupole	Quad families	300	11	2002
KEK-ATF	Quadrupole	Individual power supplies	<10	12	2004
RHIC	Quadrupole	Quad families	100-200	13	2005
SOLEIL	Various	Various		14	2006
NSLS	Quadrupole families	Multiple kick fits	200	15	2007
SSRF	Quadrupole	Individual power supplies		16	2009
SLS	Quadrupole	Individual power supplies	5 - 10	17	2011
INDUS II	Quadrupole	Active shunts	14	18	2015
JPARC	Quadrupole	Individual power supplies		19	2015
ALBA	Quadrupole	Fast correctors, Individual quads	10 - 50	20	2018

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Methods

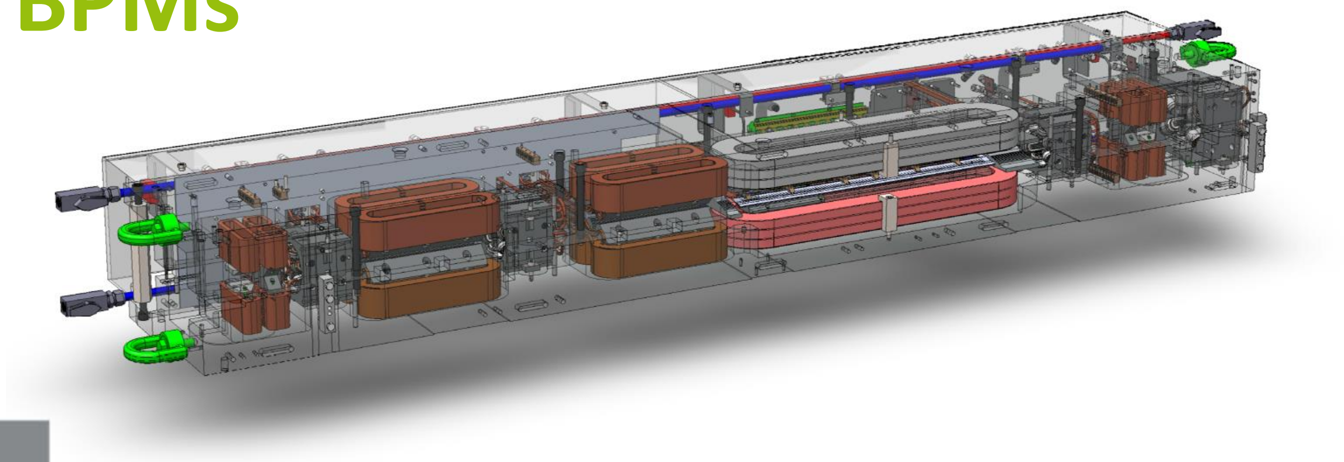
K-variation, classification borrowed from ALBA paper [20]:

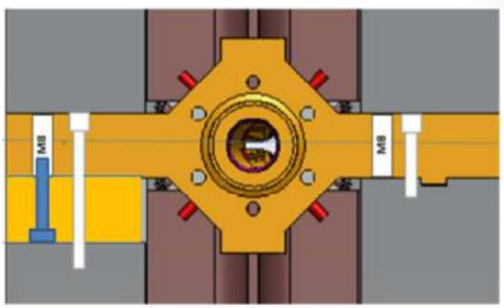
- ***Beam-to-BPM:*** largely model independent, requires individual PS/shunts for a neighbouring quadrupole field. Often time consuming.
- ***Beam-to-quad:*** requires machine function knowledge (e.g. HERA [11], RHIC [13], NSLS [15]). Orbit shifts and hysteresis must be compensated for as a result. Can be used without individual quadrupole knobs.

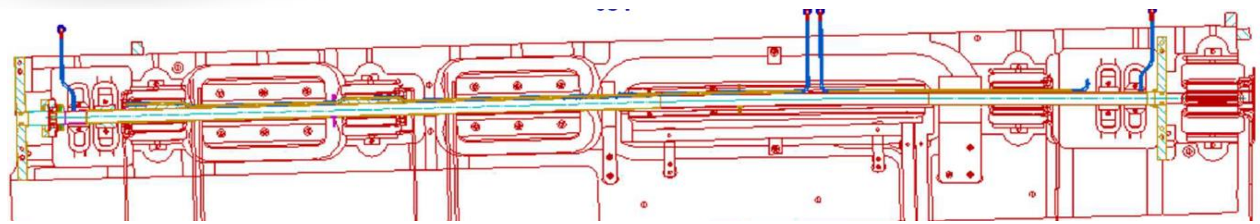
AC/DC:

- ***Steady state:*** ”classical” version with many implementations, magnet settings kept fixed while readings are taken
- ***Modulate quad field:*** apply a sinusoidally varying quad field, minimize orbit oscillations by moving the orbit (e.g. KEK TRISTAN [3])
- ***Modulate corrector:*** drive orbit oscillations using dipole correctors and vary a quadrupole field. Offset in both planes can be measured simultaneously (e.g. ALBA [20]).

MAX IV BPMs







- Fixation vs. magnets (midplane, clamped to the solid body that contains the magnet)
- BPM and sextupole/octupole magnets positioned using CNC-machined grooves in the block → mechanical positioning given by CNC accuracy (+-20 µm)
- Libera Brilliance+ electronics
- Capacitive button BPM (scaled ALBA design)

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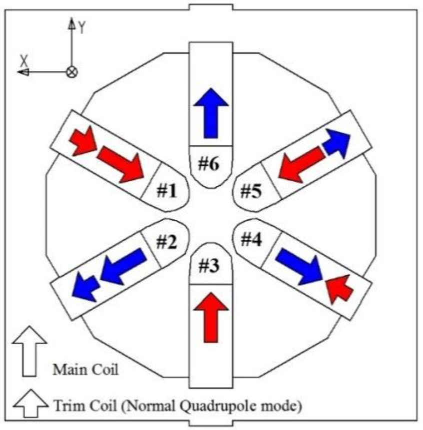
MAX IV BPMs offset calibration

- BBA using **quadrupole trim coil on sextupole w. individual PS** (similar to KEK but there modulation was used)
  - **Design assumption:** simulations indicated difference to be sub-micron. Hence for practical purposes quad field center and sextupole field center coincides. ***BUT!*** not quite true when both coils powered (saturation, see next slide)
  - **Motivation is limiting feed-down in strong sextupoles:** beam goes through centre of OXX, SDE, SFI, SFO, SFM families
  - **Limited BPMs:** Off-centre passage through SD, OXY and OYY
- **Design simulation assumption for error seeds:** "In addition a BPM calibration accuracy of 10 μm rms [5 μm rms] is assumed" (MAX IV DDR 2.4 – Lattice errors and correction). *No systematic error component was assumed!*
- **Standard quad variation measurement method**, using slightly adjusted quadcenter MML routine by G. Portmann:
  - Offset measurement campaigns done at cold beam (< 3 mA) w. 10 Hz data
  - 200 BPMs, 2 planes → **8-10 hr per campaign** → only done after shutdowns or reported issues

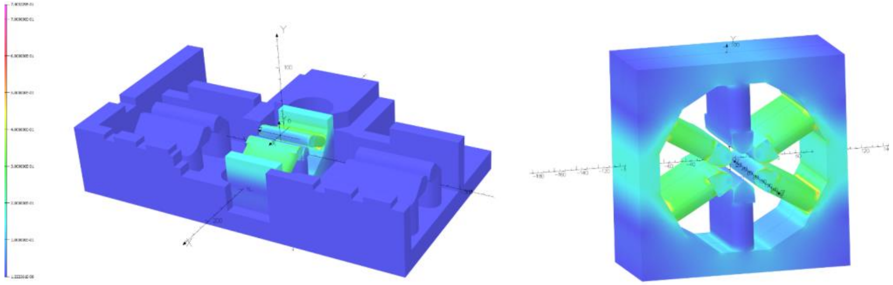


Picture by Alexey Vorozhtsov

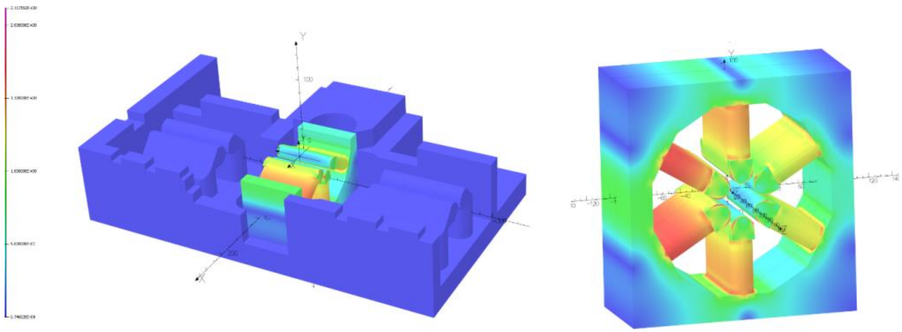
MAX IV BPM offset calibration, cont.

- Iron saturation effects resulted in offset shifting depending on main coil current, trim coil excitation, unipolar vs. bipolar, etc.
- Saturation was suspected early on, but 2D simulations could not explain the magnitude of the effect
- Experimental results (Robin S.) agree with theory, although 3D required (Alexey V.) (next slide)
- ***Solution:*** zero main coil during the measurement! Luckily, possible for all magnets w. BBA trims without losing the entire dynamic aperture.

Only Trim Coils ON



Trim Coils + Main Coils ON



Calculations and pictures by Alexey Vorozhtsov

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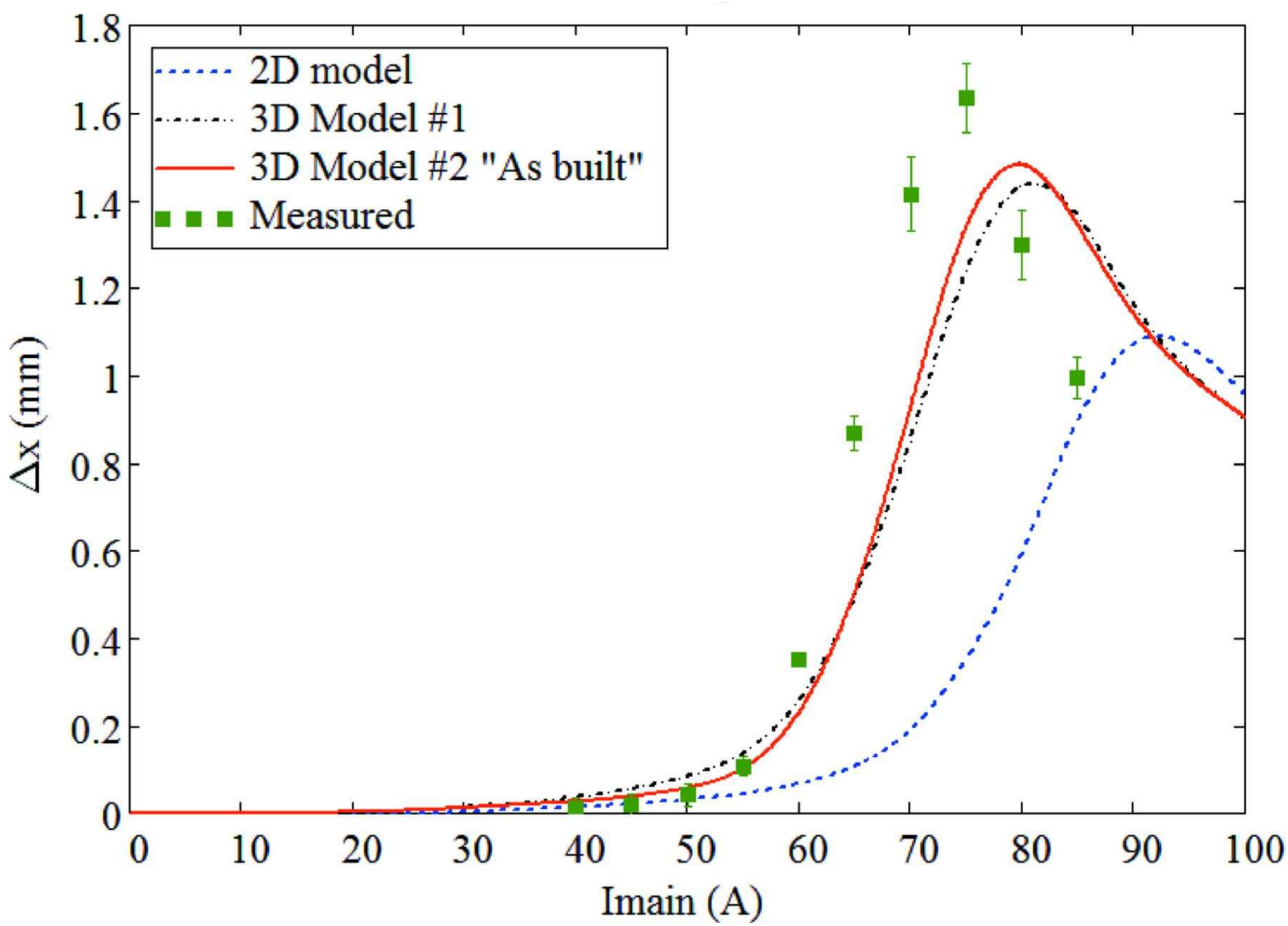
Calculated and measured horizontal offset value (mm) as a function of the sextupole main coil current at fixed value of the trim coil of 5 A. See Appendix A for details about the various models



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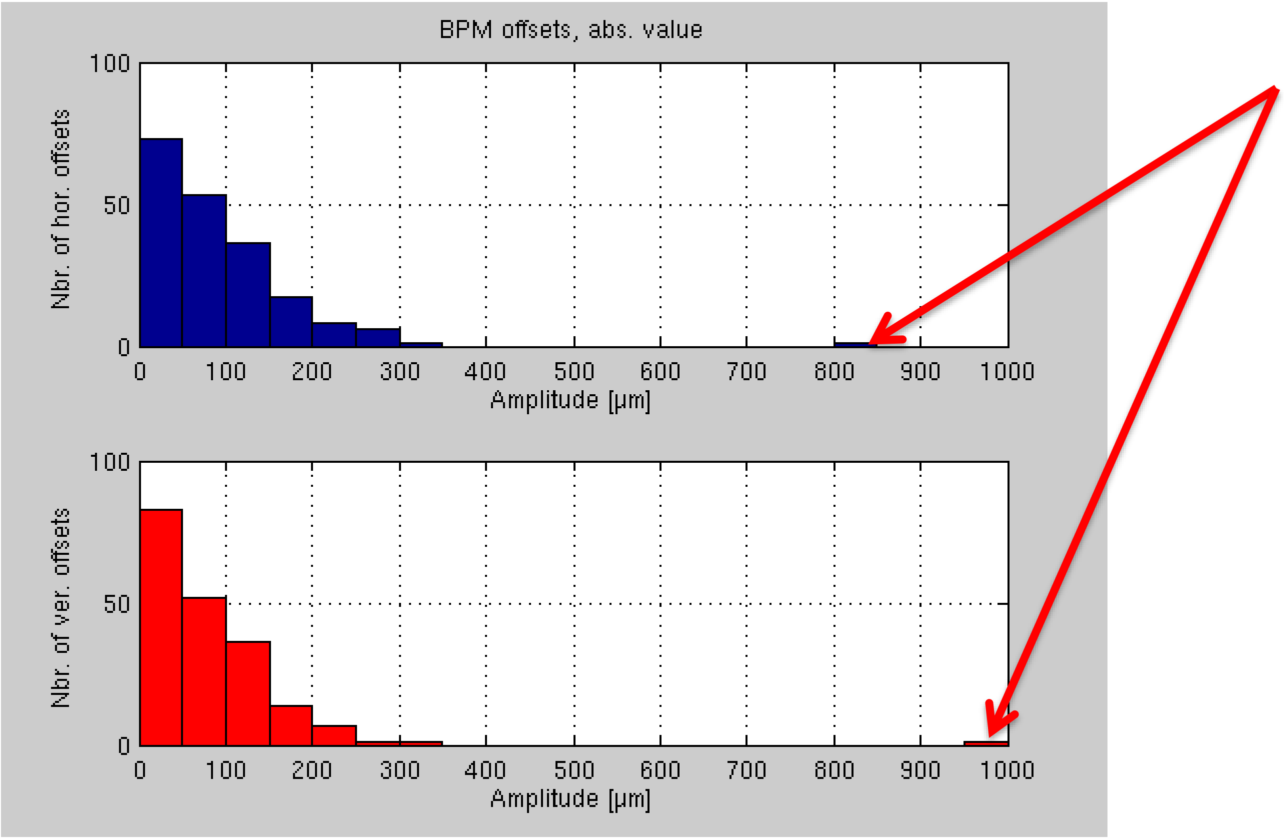
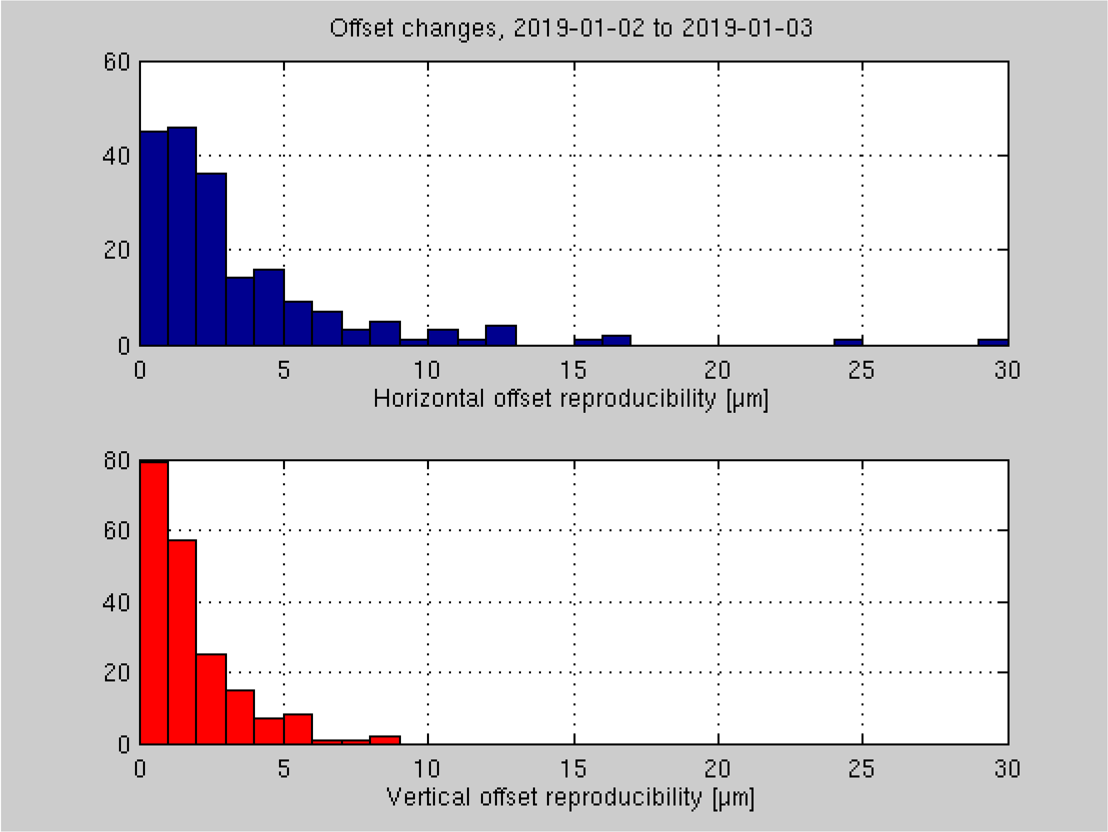
Offsets, absolute size



Problem child BPM:
"R3-316U3/DIA/BPM-02"

Above: *current offsets in 3 GeV ring, established after a campaign during 2019-01-02 to 2019-01-03.*

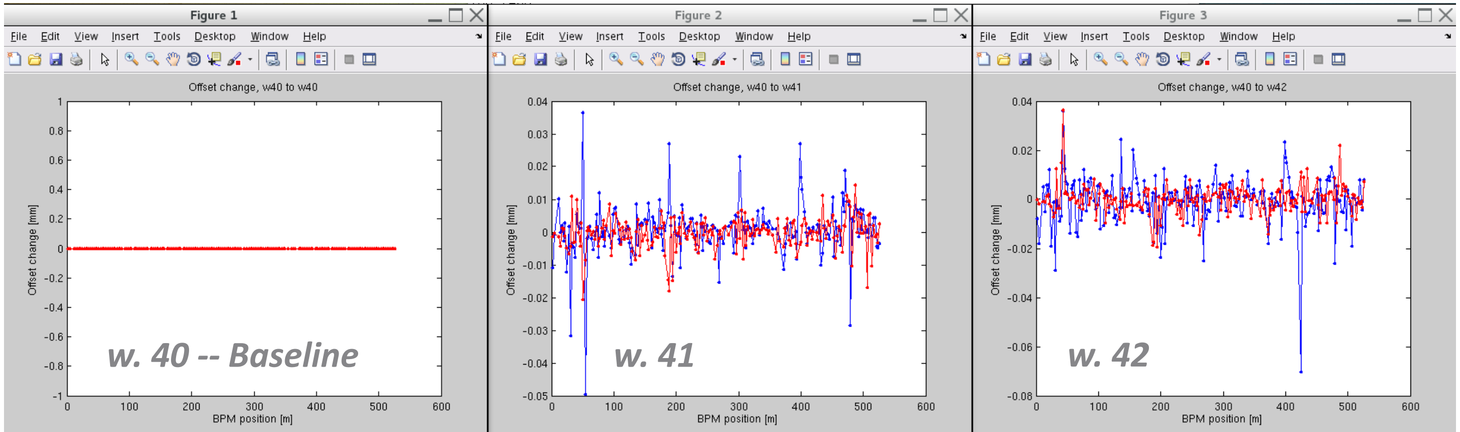
Offset reproducibility



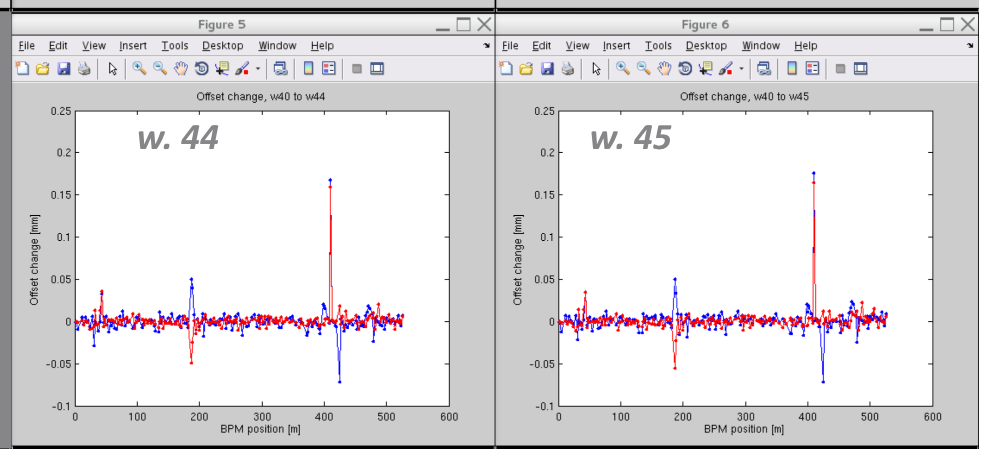
Possible to estimate random component by repeated measurements (recent start-up campaigns, post-thermal stabilization)

Above: *variation in offsets (STD) between two full campaigns performed back-to-back during 2019-01-02 to 2019-01-03.*

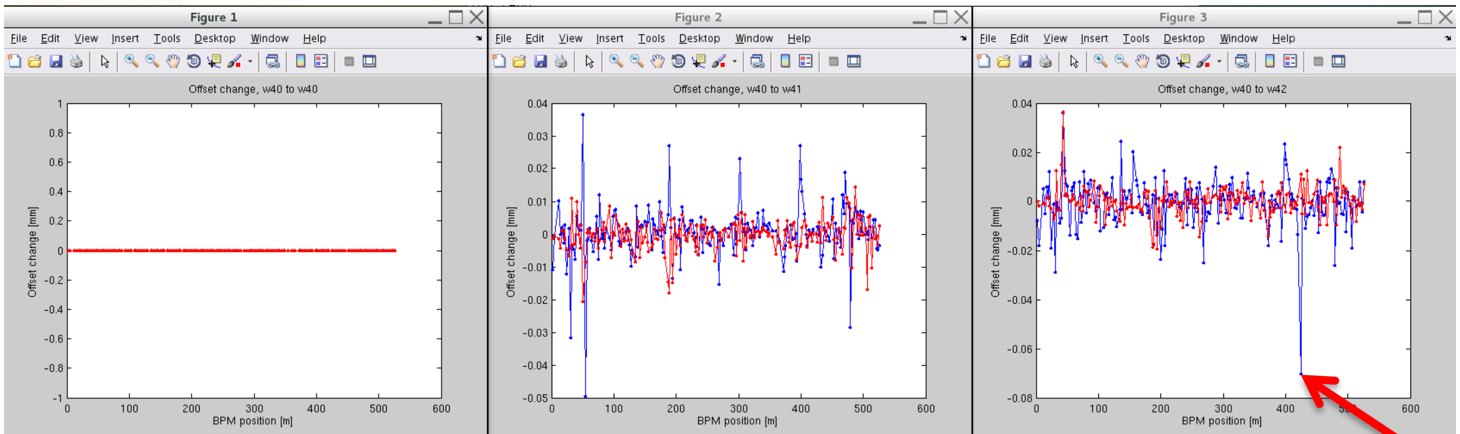
Offset stability, month-scale



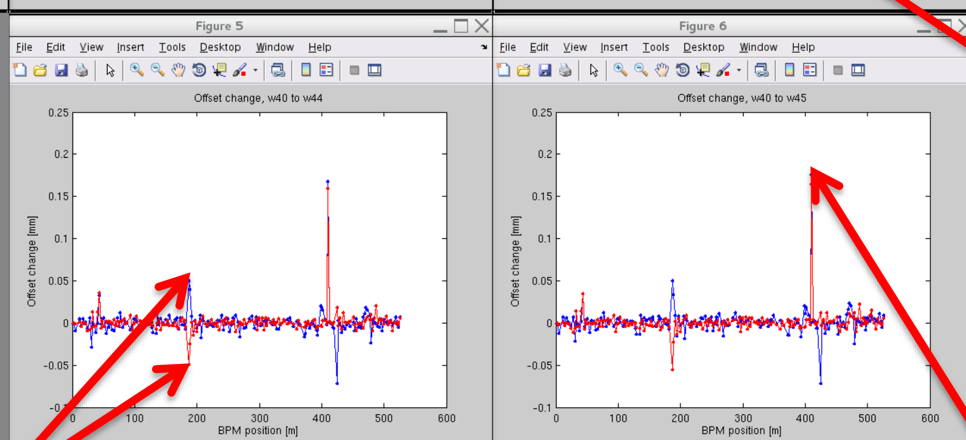
2016 w. 43 – tunnel access for motion tests in achr. 8 and 17, no BBA campaign



Offset stability, month-scale



2016 w. 43 – tunnel access for motion tests in achr. 8 and 17, no BBA campaign



BPM just downstream of HIPPIE ID (achr 17.) Significant installation work during the morning, exact cause unknown (water flow adjustments, etc.)

BPMs in magnet block just downstream of BALDER ID (achr. 8)

Problem child BPM: R3-316U3/DIA/BPM-02

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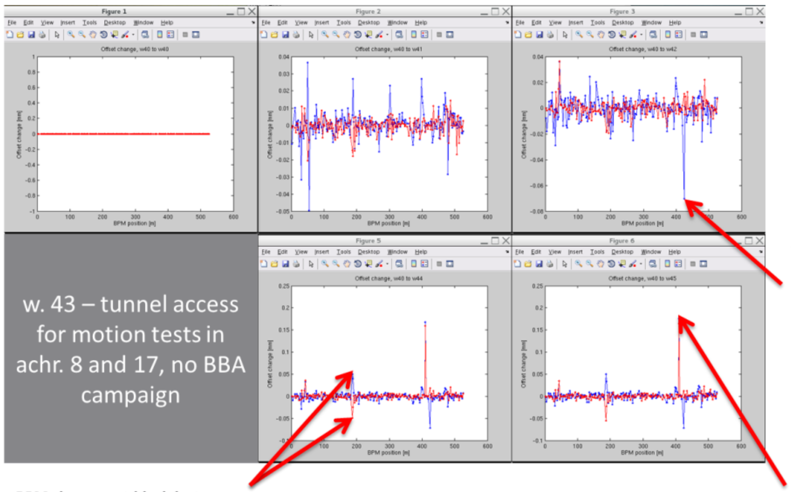
Offset stability, month-scale

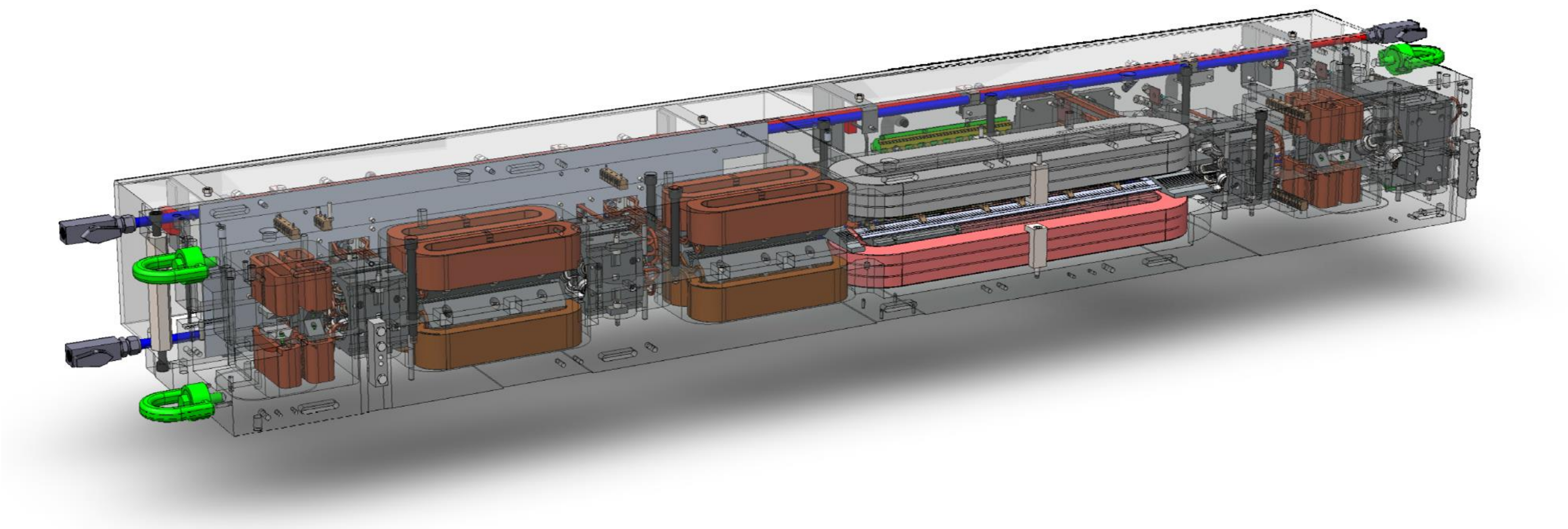


Looking at changes over 5 week period, ignoring the outliers:

- Peak hor. offset RMS changes < 8 µm
- Peak ver. offset RMS changes < 6 µm
- Majority of the shifts took place in period 2016 w. 40-42, during which period the machine was warming up from the summer shutdown ***(NB!** Temperature stability in the tunnel rely on large thermal inertia and passive control where the temperature of air flowing into the tunnel is regulated so as to minimize the flow of power into or out of the tunnel due to the ventilation**)***

Offset stability, days

- Offsets drifting if magnets have been shut off during Tuesday maintenance stops; thermal effect, stabilizes after 24-48 hours at which point offsets have recovered.
- Effect not fully understood, but easily managed (safety can be maintained without shutting off magnets).



Conclusions

Methods:

- Methods are considered ”standard” procedure now.
- Resolution/Accuracy improved from ~100-200 µ down to ~10-20 µm over the past 20 years.
- Focus in recent work on developing faster methods.

MAX IV:

- Magnet/BPM/vacuum design has achieved good long-term (1 month) stability → reduced need for frequent campaigns
- Achieved reproducibility of offset measurements is in line with or better than the design assumption of 5 µm RMS.
- Don’t forget iron saturation, if using trim coils on a higher order magnet!

That's all folks…

THANK YOU FOR YOUR ATTENTION!