MAX IV: Lessons learned

Magnus Sjöström on behalf of the MAX IV team

2022 LEL workshop

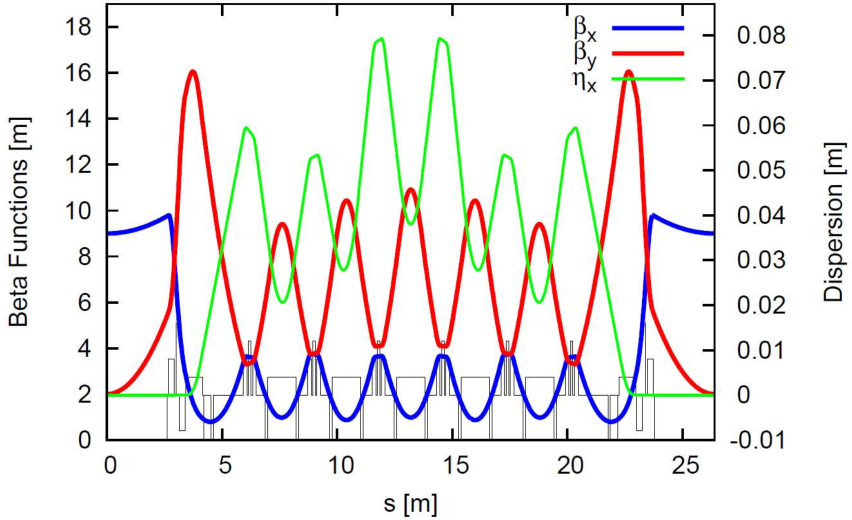
Outline

- Overview
- Dynamic aperture
- Vacuum system performance
- Collective issues
- Stability and noise
- Practical issues

Overview: MAX IV 3 GeV ring lattice

Original lattice design updated continuously in feedback loop with magnet design

Periodicity	20
Circumference	528 m
Horizontal tune ν_x	42.20
Vertical tune ν_y	16.28
Natural horizontal chromaticity ξ_x	-49.984
Natural vertical chromaticity ξ_y	-50.198
Momentum compaction (linear) α_c	3.06×10^{-4}
Horizontal damping partition J_x	1.8471
Bare lattice emittance ε_0	0.328 nm rad
Bare lattice energy loss per turn	363.8 keV
Bare lattice natural energy spread σ_δ	0.769×10^{-3}
Bare lattice horizontal damping time τ_x	15.725 ms
Bare lattice vertical damping time τ_y	29.047 ms
Bare lattice longitudinal damping time τ_E	25.194 ms
Horizontal beta function at center of LS β_x^* (bare lattice)	9.00 m
Vertical beta function at center of LS β_y^* (bare lattice)	2.00 m

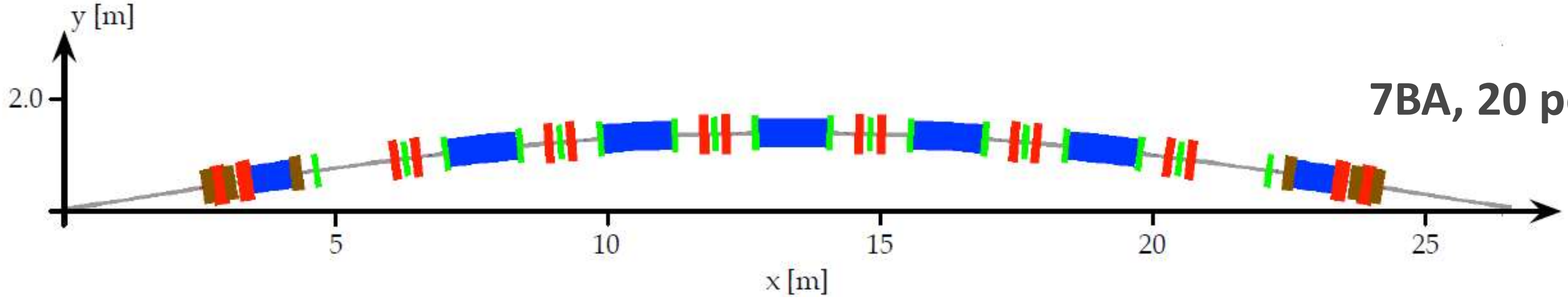


S. C. Leemann, "Updates to the MAX IV 3 GeV storage ring lattice", internal note 20121107

Overview: 3 GeV ring performance

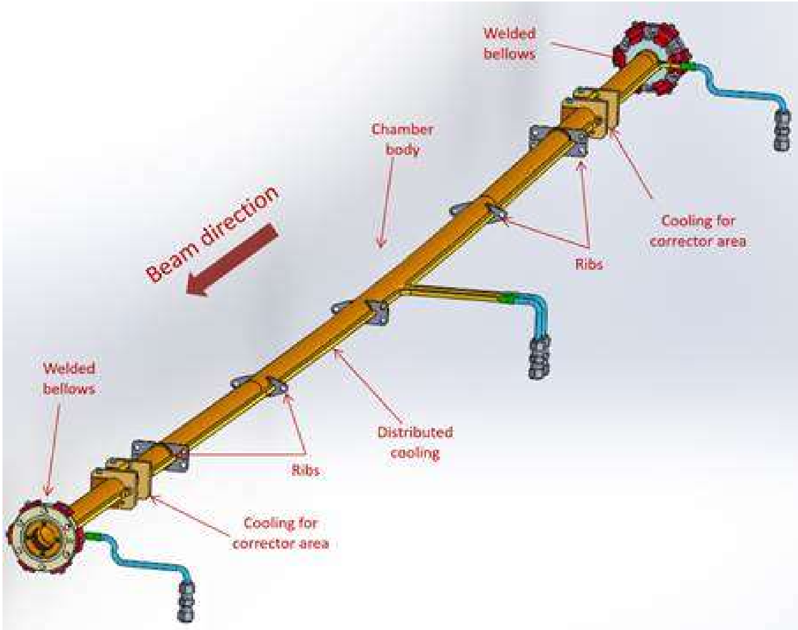
- 500 mA stored current in multibunch mode demonstrated during accelerator studies
  - Regular delivery to beamlines at 300 mA
  - ~9 mA stored current in single-bunch mode.
- ~39 Ah Iτ product from gas scattering
- $\gtrsim$ 90% injection efficiency
- Emittances:
  - ε_x = 320 ± 18 pm rad
  - ε_y = 6.5 ± 0.1 pm rad (down to 2 pm rad observed, cranked up to 7.5 – 8 pm rad during delivery)
- RMS orbit stability (up to 100 Hz) well below 10% of beam size (H/V) passively without Fast Orbit Feedback
- Typical Δβ/β in 2-3% (peak-to-peak), or roughly 0.5% (RMS)
- Typical residual η_y around 0.6 mm RMS

Overview: technology



7BA, 20 periods

100 MHz RF passive HC



Circular NEG-coated Cu chambers

Compact magnets

Dynamic aperture: magnet quality

Summary field errors
int. B' DIP: $\sigma = 1.1 - 1.5 \cdot 10^{-3}$
int. B' DIPM: $\sigma = 9 \cdot 10^{-4}$
Others typically $1 - 3 \cdot 10^{-3}$

Summary multipole errors
Largest higher order term (as fraction of main term @ r = 10 mm) in the $3.0 - 12.3 \cdot 10^{-4}$ span

Summary alignment errors
Block internal roughly equal to design assumption of 25 μm RMS, 2σ cut-off
Girder-to-girder separate question...

Overview

M. Johansson et al., "Magnet design for a low-emittance storage ring", Journal of Synchrotron Radiation 21, 884-903, 2014.

Alignment data (internal to the blocks)

J. Björklund-Svensson, M. Johansson, "Relative alignment within the MAX IV 3 GeV storage ring magnet blocks", IPAC'15, Richmond, VA, USA.

Field errors

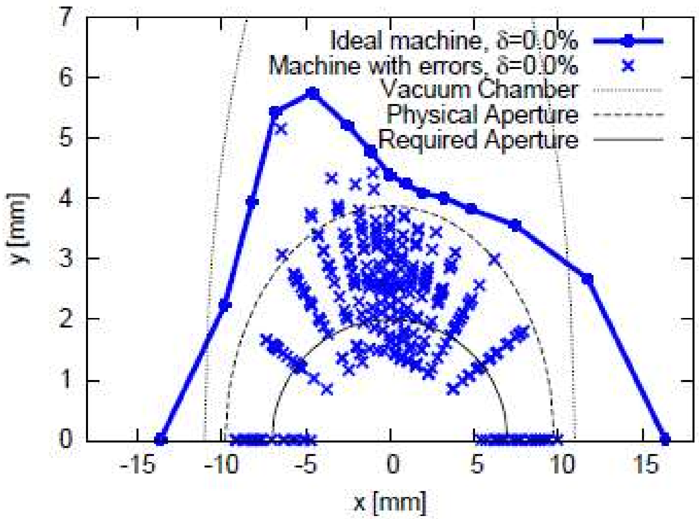
M. Johansson et al., "MAX IV 3 GeV storage ring magnet block production series measurement results", IPAC'15, Richmond, VA, USA.

Multipole errors

M. Johansson et al., "MAX IV 3 GeV storage ring magnet block production series measurement results", IPAC'16, Busan, Korea.

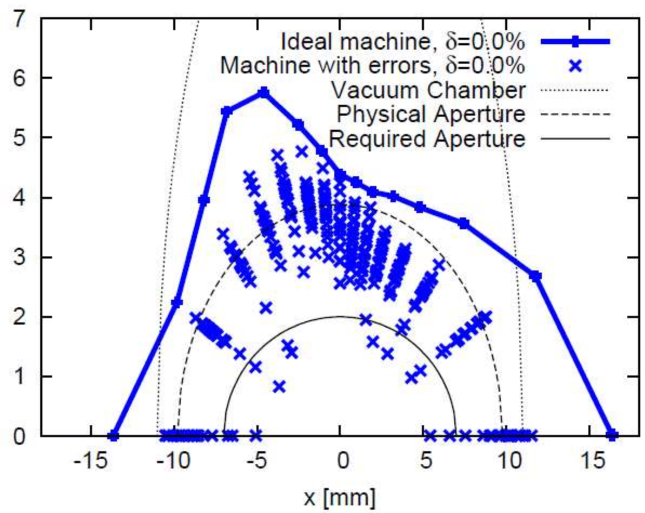
Dynamic aperture: 2014 simulations

Bare lattice DA @ long straight center (β_x = 9 m, β_y = 2 m)
20 seeds including alignment, field and multipole errors; three different scenarios



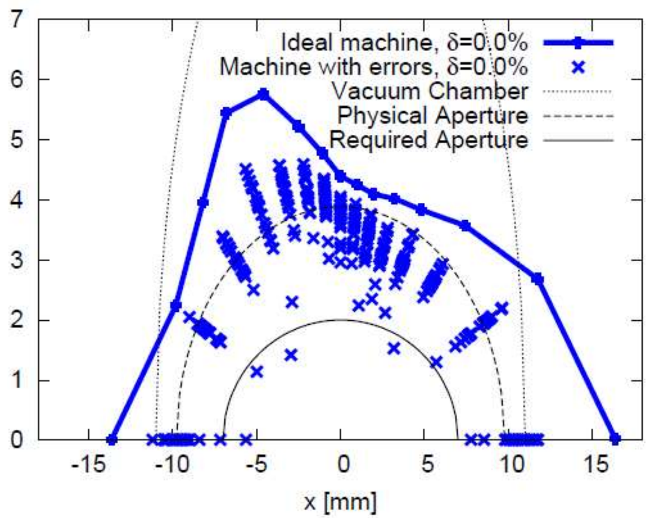
"Start of commissioning" scenario
Block alignment: 100 μm, 0.4 mrad (RMS)
Field errors on 10^{-3} level (coarse shunting)
Orbit corrected

Beta-beat: 3.4% / 12.7%



Block alignment: 50 μm, 0.2 mrad roll (RMS)
Field errors on $5 \cdot 10^{-4}$ level (fine shunting)
Orbit corrected
LOCO deployed

Beta-beat: 2.1% / 6.6%



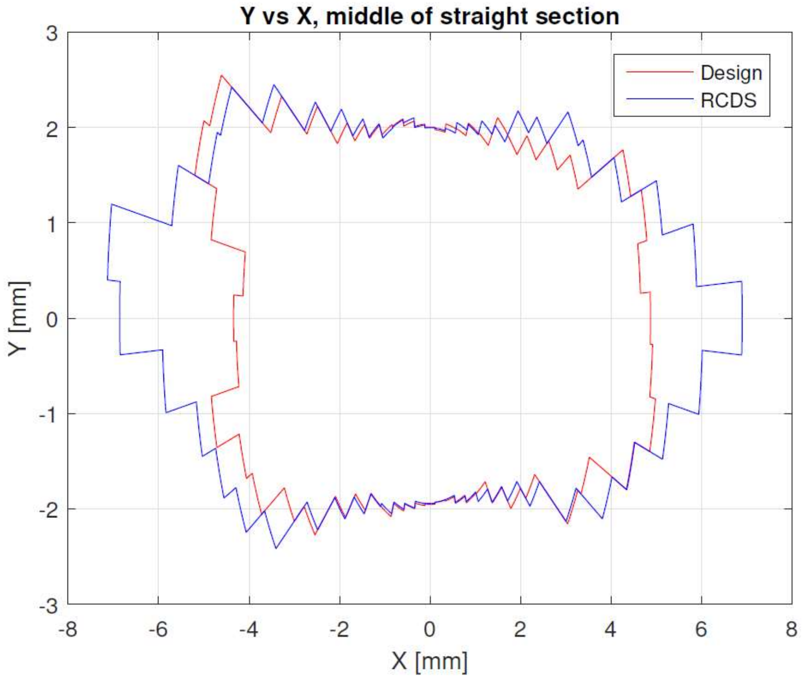
Block alignment: 25 μm, 0.1 mrad (RMS)
Field errors on $5 \cdot 10^{-4}$ level (fine shunting)
Orbit corrected
LOCO deployed
Ring re-aligned

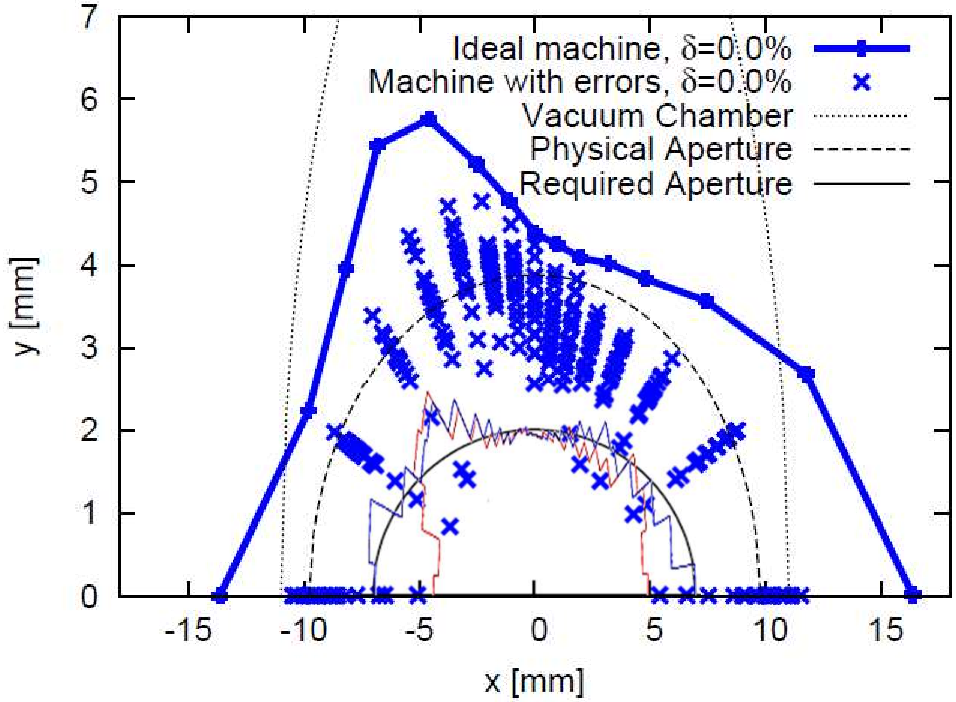
Beta-beat: 1.9% / 5.6%

S. C. Leemann, "Updates to the MAX IV 3 GeV storage ring lattice", internal note 20121107 (revised 2014)

Note: Post-LOCO correction regularly achieves beta-beats around 2% (both planes)

Dynamic aperture: 2018





Orbit correction and LOCO deployed.

”Design” sextupole family currents calculated from manufacturer excitation curve data.

No re-alignment was done, nor any individual magnet shunting.

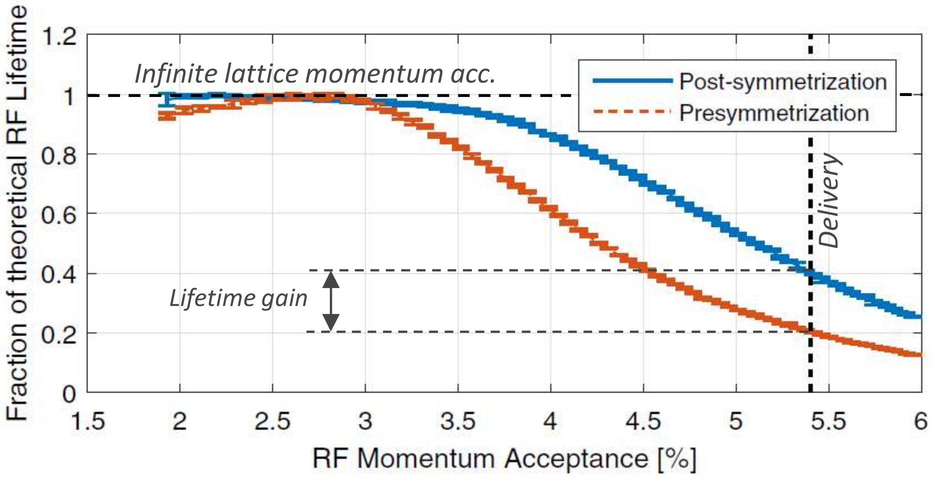
RCDS optimization of sextupole settings was used to improve the horizontal dynamic aperture

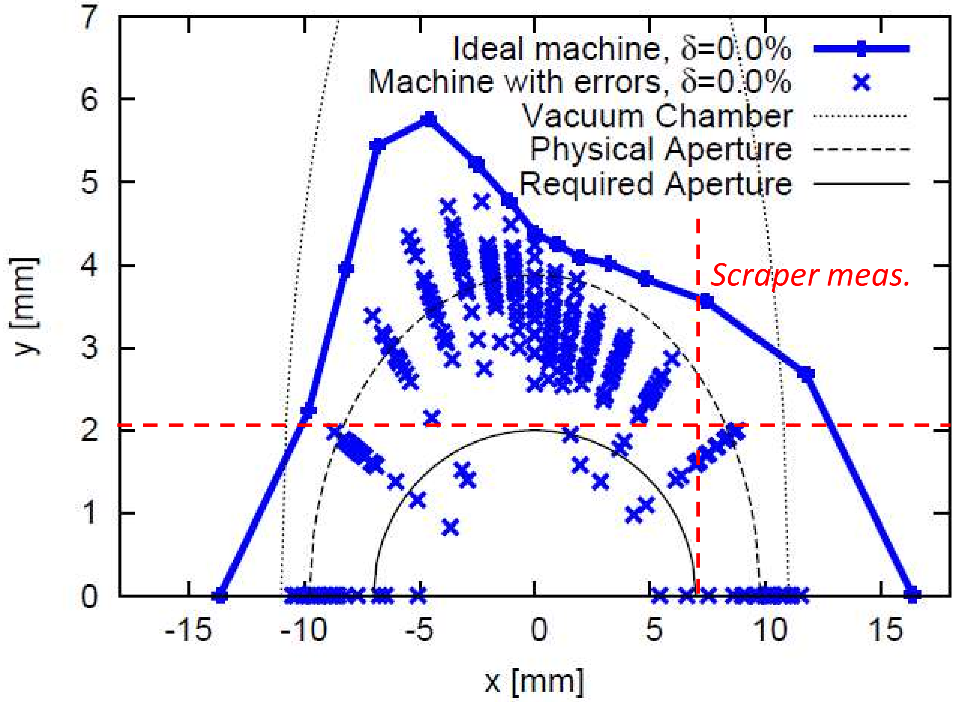
Unfortunately the lattice performance with the optimized sextupole settings degraded over time relatively quickly. Work continued...

D. Olsson et al., ”Online optimisation of the MAX IV 3 GeV ring dynamic aperture”, IPAC’18, Vancouver, Canada

S. C. Leemann, ”Updates to the MAX IV 3 GeV storage ring lattice”, internal note 20121107 (revised 2014)

Dynamic aperture: 2020





Development and deployment of NOECO procedure to calibrate sextupole circuit field errors.

Lifetime (total) @ 250 mA, improvement 11 h → 19 h

Scraper measurement showed dynamic aperture improvements:

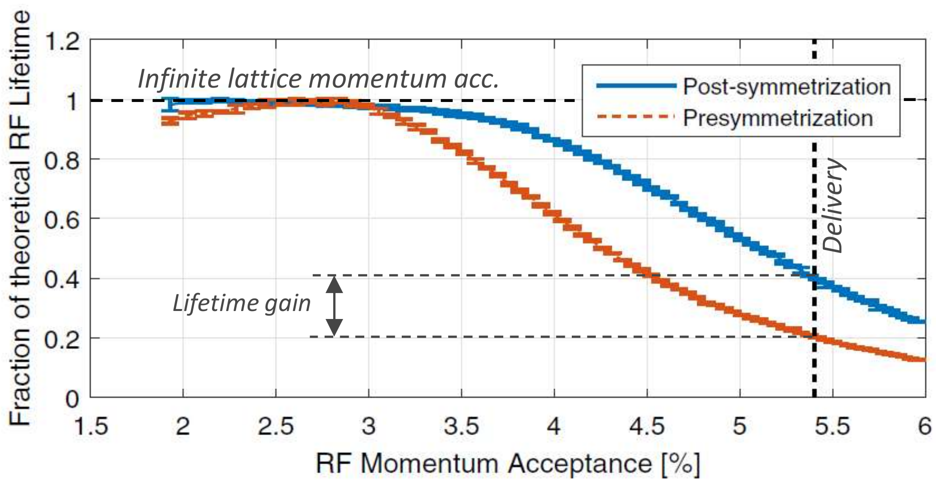
A_x 3.7 → 5.6 mm mrad

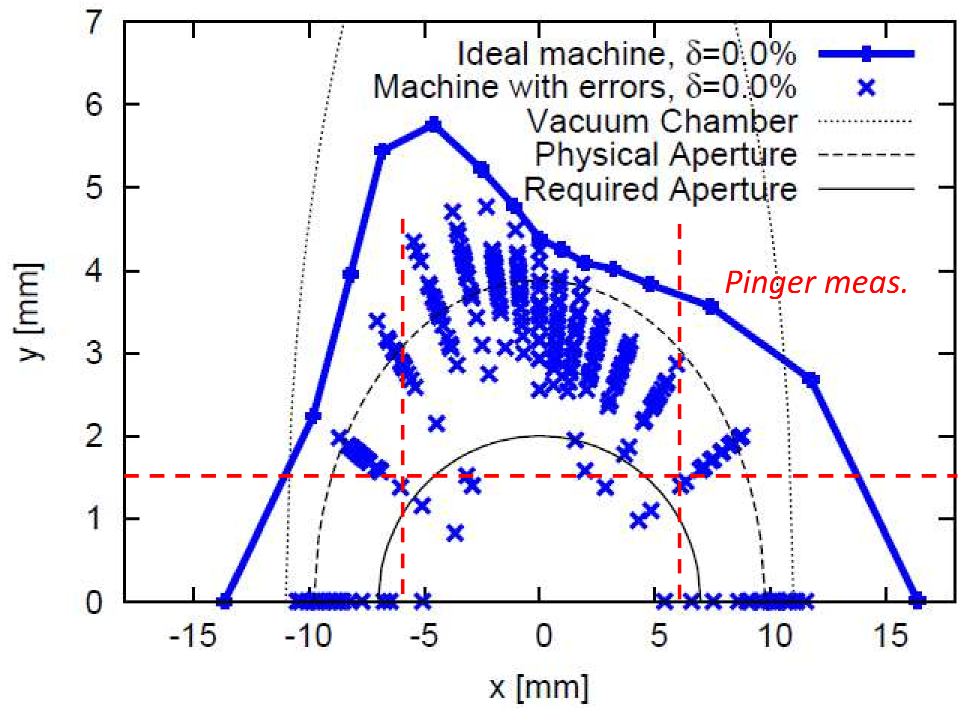
A_y 1.6 → 1.9 mm mrad

D. Olsson et al., "Nonlinear optics from off-energy closed orbits", Phys. Rev. Acc. Beams 23 (2020)

S. C. Leemann, "Updates to the MAX IV 3 GeV storage ring lattice", internal note 20121107 (revised 2014)

Dynamic aperture: 2020





Development and deployment of NOECO procedure to calibrate sextupole circuit field errors.

Lifetime (total) @ 250 mA, improvement 11 h → 19 h

Pinger measurement showed acceptance changes (limit 1% loss rate / kick):

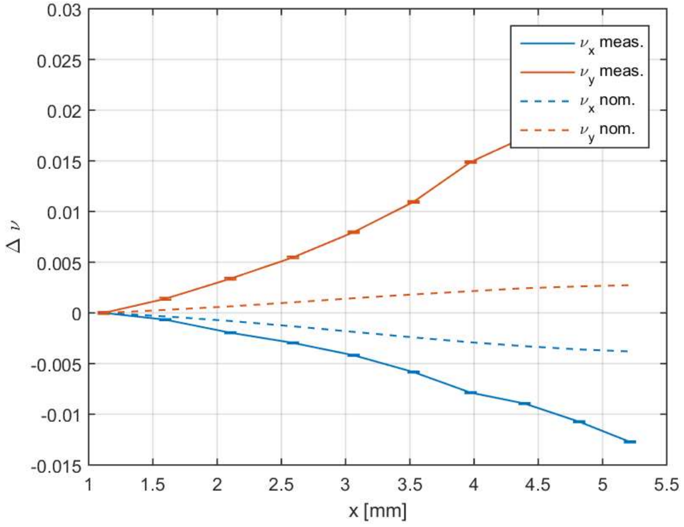
A_x 2.1 → 3.9 mm mrad

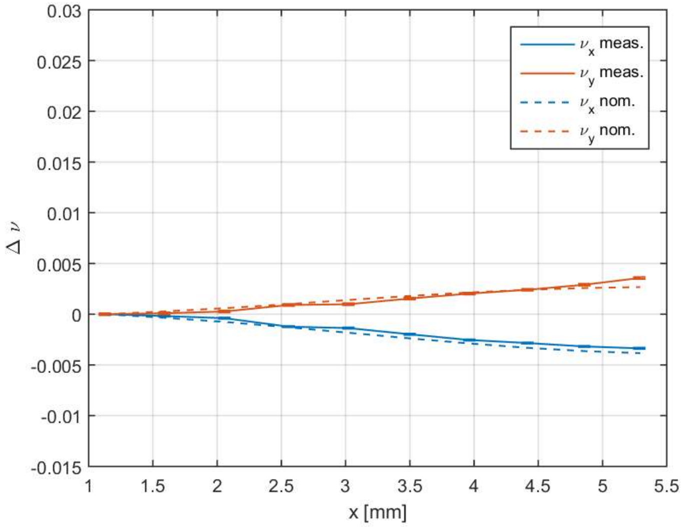
A_y 2.1 → 1.2 mm mrad

D. Olsson et al., "Nonlinear optics from off-energy closed orbits", Phys. Rev. Acc. Beams 23 (2020)

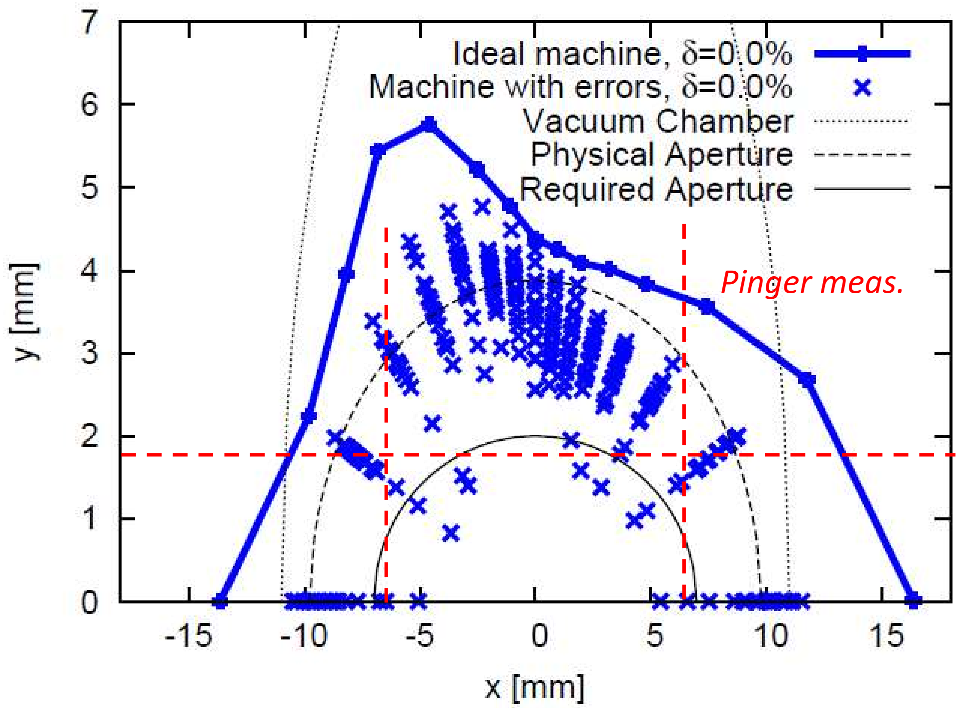
S. C. Leemann, "Updates to the MAX IV 3 GeV storage ring lattice", internal note 20121107 (revised 2014)

Dynamic aperture: 2022 (ongoing)





Results and graphs above by D. Olsson



Octupole optimization trials via RCDS, trying to:

a) minimize ADTS difference to design, or

b) maximize Iτ

Pinger measurement so far show a roughly 5-10% improvement in dynamic aperture (limit 1% loss rate / kick)

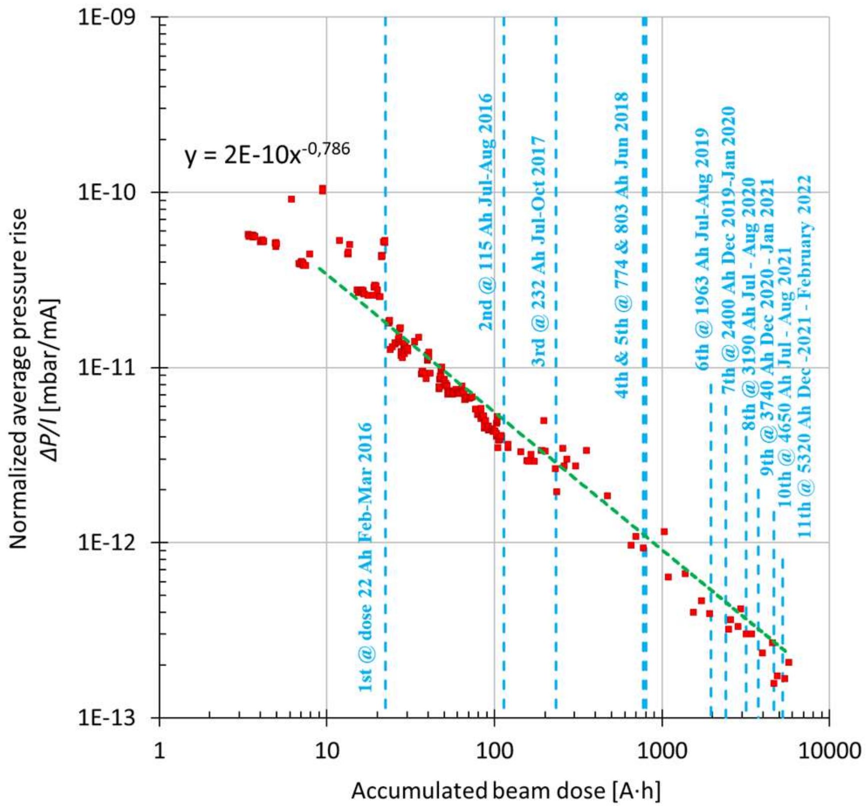
S. C. Leemann, "Updates to the MAX IV 3 GeV storage ring lattice", internal note 20121107 (revised 2014)

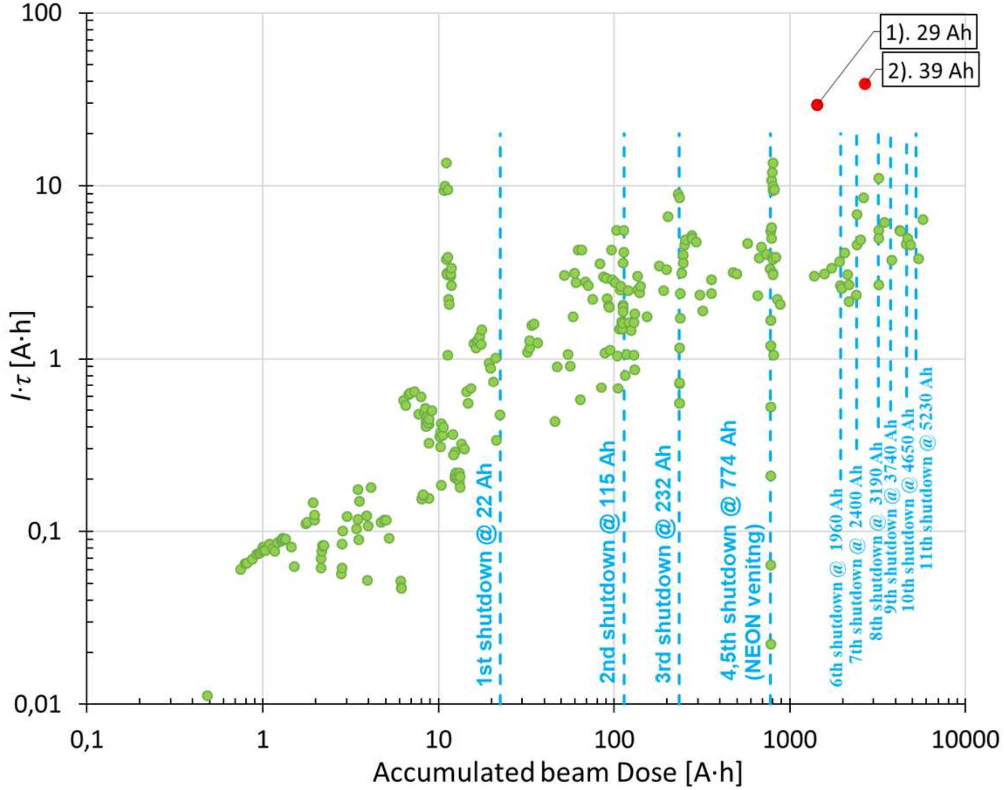
Dynamic aperture: 2022

- Experience is it tends to degrade with time
  - DA optimization settings found via RCDS were quite sensitive
  - NOECO-calibrated settings survive better
  - Single dipole kicker injection quite sensitive to the degradation
  - MIK (prototype installed in 2017, final version in 2019) essentially removed stored beam DA requirement during injection
  - Causes for degradation still under investigation. Candidates include thermal drift, power supply issues, power supply replacements (differences in absolute calibration between units), et.c.
- Minimum twice-yearly campaigns, i.e. post-startup:
  - BBA, i.e. recalibrating BPM offsets
  - LOCO → recalibrating circuit gradient and skew gradient errors
  - NOECO → recalibrating sextupole circuits
- Calibration of ADTS via octupole optimization ongoing
- Beam-based re-alignment of magnet blocks still not done:
  - Higher threshold now due to user delivery. Beamline source points introduce boundary conditions (likely manageable, see e.g. M. Apollonio, ”First transparent realignment tests at the Diamond storage ring”, IPAC’15)
  - At this point a prioritization issue; current lattice works well

Vacuum system: performance

- **Fully NEG coated system stands the test of time.**






research papers

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Commissioning and operation status of the MAX IV 3 GeV storage ring vacuum system

Marek Grabski* and Eshraq Al-Dmour

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Slide by Å. Andersson

Vacuum system: rest gas composition

- **Model based rest gas composition far too pessimistic**

Table 1
Selected partial pressures as measured by the RGA in achromat 17-L at accumulated beam doses of 450 and 705 A h at no stored beam and at 170 and 200 mA stored beam

			Mass (gas species)				
RGA location	**Beam current (mA)**	**Accumulated beam dose (A h)**	**2 (H_2)**	**16 (CH_4)**	**18 (H_2O)**	**28 (CO)**	**44 (CO_2)**
17-L	0	450	98.7%	0.2%	0.1%	0.8%	0.1%
	170	450	94.7%	0.4%	<0.1%	4.2%	0.3%
	0	705	98.9%	0.2%	<0.1%	0.8%	0.1%
	200	705	95.5%	0.3%	<0.1%	3.9%	0.1%

Table 5
Comparison of simulated and measured total pressures and gas compositions at S1 locations at a dose of 100 A h and a beam current of 100 mA

				Mass (gas species)				
	Beam current (mA)	**Accumulated beam dose (A h)**	**Pressure (mbar)**	**2 (H_2)**	**16 (CH_4)**	**18 (H_2O)**	**28 (CO)**	**44 (CO_2)**
Simulated	100	100	1×10^{-9}	16%	2%	0%	36%	46%
Measured	100	100	1.3×10^{-9} (H_2 equivalent)	90%	0.8%	<0.1%	7.7%	0.2%

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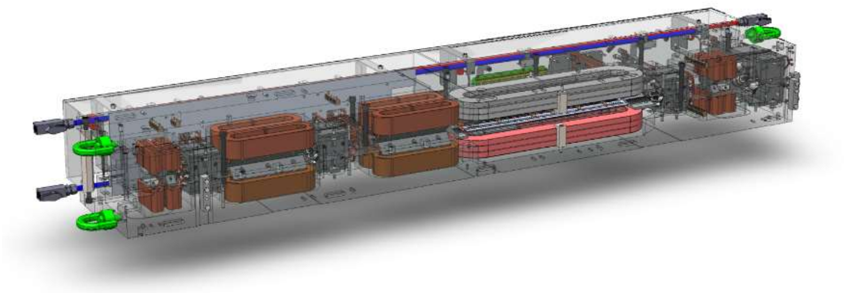
Slide by Å. Andersson

Collective effects: lessons learned

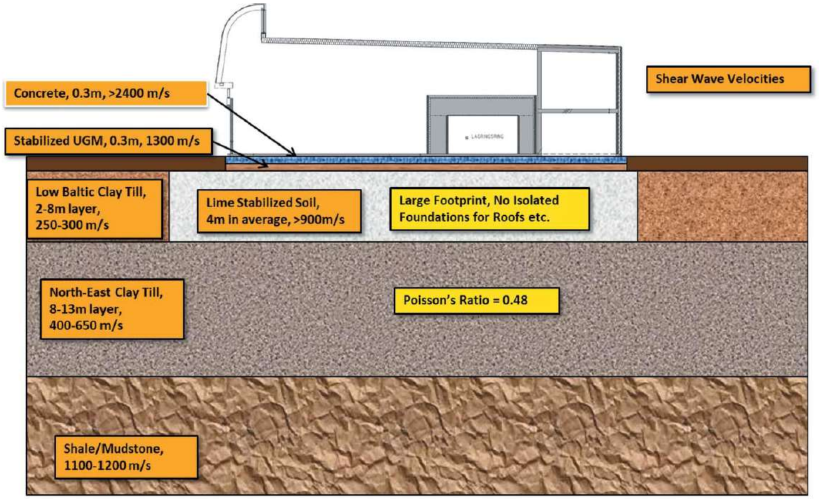
1. A mode-0 damper system is a must (more in F. Cullinan's talk tomorrow)
2. Mode 1 can be a real limitation to harmonic-cavity bunch lengthening and should be properly evaluated (more in F. Cullinan's talk tomorrow)
3. An accurate HOM model based on RF measurements and beam measurements at low current is the most efficient way of finding the optimum operating temperatures for cavities.
4. Landau cavities can be used as a method to stabilise the beam against longitudinal HOM-driven instabilities
5. Impedance models based on E-M simulations of vacuum components underestimated Im $Z_{||}/n$ and Im Z_y considerably (a not uncommon issue, see V. Smaluk https://www.sciencedirect.com/science/article/pii/S0168900218300640)
6. The nonlinear dynamics of the lattice can have a large impact on the transverse mode-coupling instability (more in F. Cullinan's talk tomorrow)
7. Due to the small vacuum chamber aperture, the long-range resistive wall impedance was expected to be the limiting factor at low chromaticity but so far HOM-driven instabilities have dominated (neither are present at delivery current and at nominal chromaticity)
8. A good vacuum system and a low RF frequency is sufficient to avoid ion trapping and fast-ion instabilities

Stability and noise

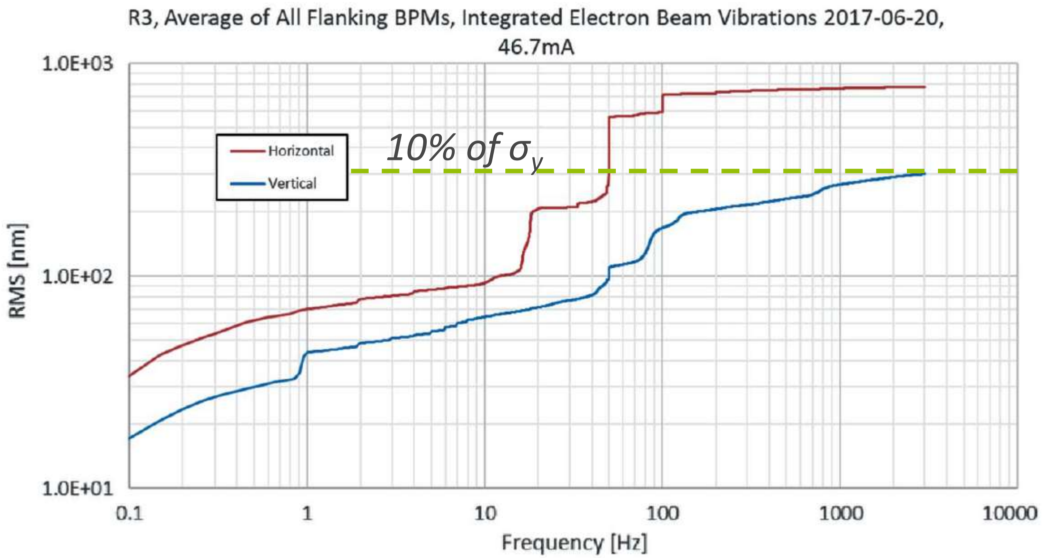


Main philosophy

- Reduce sensitivity to vibrations
- Use passive systems as far as possible
- Increase correlation of movement (common girders, stiffen the soil to increase wavelength, etc.)



P. F. Tavares et al., "Commissioning and first-year operational results", Journal of Synchrotron Radiation (2018)

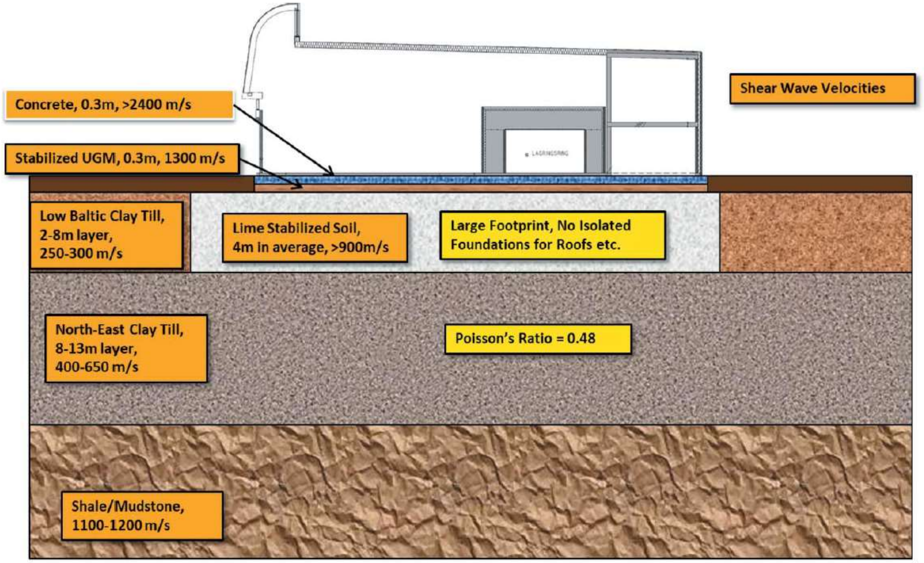


Pictures and data by Brian N. Jensen

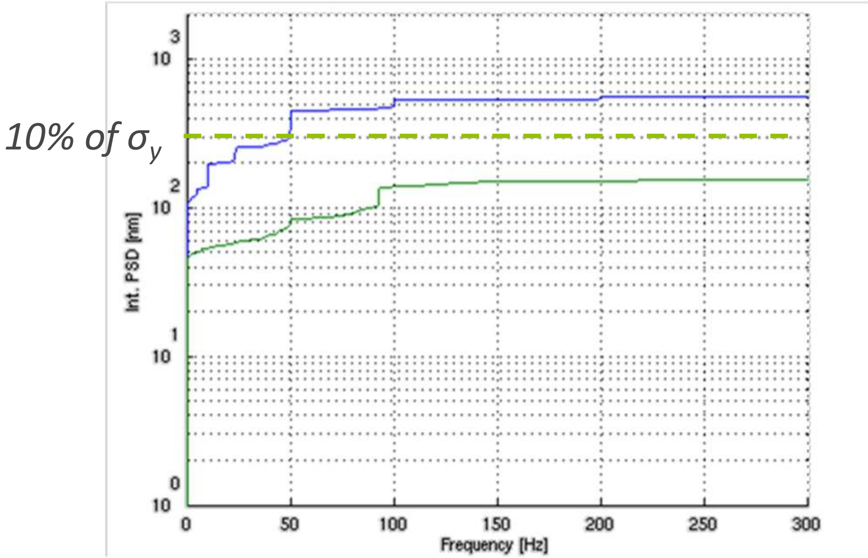
Fast Orbit Feedback not required! Until someone changes their ID gap or equipment misbehaves...

Stability and noise

- Reduce sensitivity to vibrations
- Use passive systems as far as possible
- Increase correlation of movement (common girders, stiffen the soil to increase wavelength, etc.)



P. F. Tavares et al., "Commissioning and first-year operational results", Journal of Synchrotron Radiation (2018)

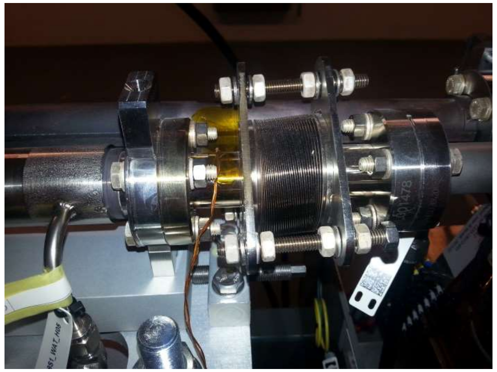


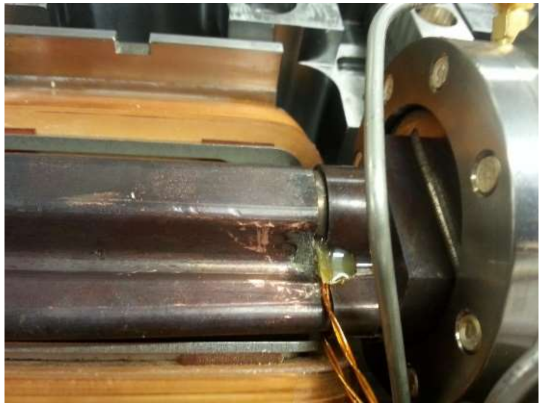
Integrated PSD for beam motion at BPMs flanking NanoMAX ID, with no FOFB.

Fast Orbit Feedback not required! Until someone changes their ID gap...

Practical issues

- Short-circuited pole-face strips (used to adjust the dipole field gradient)
- Badly placed glue spots deforming some vacuum chambers
- Absorber outside mechanical tolerances
- Misaligned vacuum chambers → early injection trouble → later hot spots when ramping up current
- Insufficient cavity conditioning
- New control system
- ... and so on



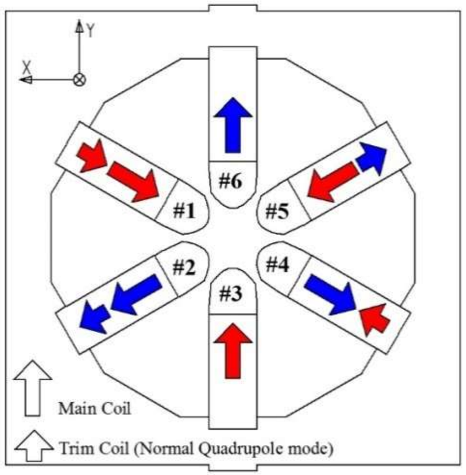


As always:

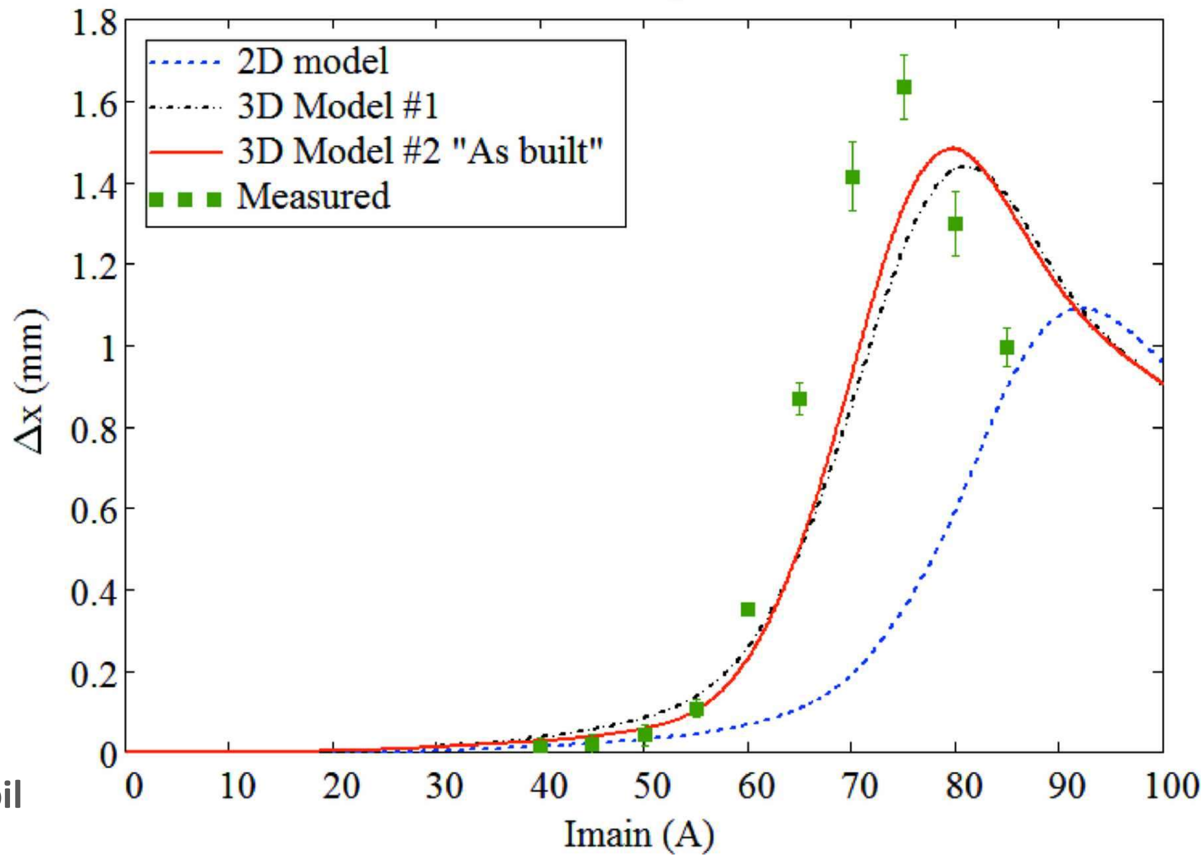
1. Thorough subsystem tests required
2. Commissioning planning needed
3. Murphy does not care about pt. 1 and 2, re-planning *will* happen.

In the end the main commissioning challenges at MAX IV were related to ”simple” problems that risked slowing down progress rather than fundamental issues

Practical issues: BPM calibration



Picture by Alexey Vorozhtsov



(Right) 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

JOURNAL OF SYNCHROTRON RADIATION

Tavares *et al.*

Volume 25 | **Part 5** | September 2018 | Pages 1291–1316 | 10.1107/S1600577518008111

Practical issues: BPM calibration

Some BBA numbers

- Offset amplitudes: roughly 100 µm RMS, major contribution electrical rather than mechanical
- Offset stability:
  - 6 / 8 µm (H/V) drift over 1 month, post-startup from cold tunnel
  - Avoid measuring if magnets are cold. Thermalization period 24-48 h, design-dependent
- Offset reproducibility: 2-3 µm RMS, ignoring outliers when people bump into cables etc.
- BPM offsets are function of current, up to 10 µm jumps observed during early commissioning. Primary cause is button RF-chain attenuators switching in/out to manage S/N ratio. Survivable.

More details in "Review of beam-based calibration of BPM offsets", Karlsruhe

SUMMARY

Summary

Dynamic aperture

- Restrictions persist inside the ”required” aperture but do not represent an issue for standard operation and user delivery. Managed via:
  - Use of MIK (does not disturb stored beam)
  - Shift of operating point (when using dipole kicker injection) and empirical tricks
- Continuous improvements over the past years via tuning of higher order elements (NOECO for chromatic sextupoles, work ongoing on octupole trimming to reproduce desired ADTS) → doubling of lifetime

Vacuum

Once initial issues with the fully NEG-coated vacuum system were resolved (compressed and misaligned chambers, hotspots, etc.) performance has been excellent.

Collective effects

- Mode 0 damper has proven to be a required system
- Longitudinal HOMs managed via cavity temperature tuning and HC bunch elongation

Stability & noise

While MAX IV site sufficiently quiet that beam position noise passively within stability criterion a Fast Orbit Feedback system still a necessity due to ID gap motion and, on occasion, misbehaving equipment

THANK YOU FOR YOUR ATTENTION!

Extra slides

In case of questions...

Field error model

Error model

Field errors at first assumed to be Gaussian w. 2σ cut-off, $\sigma = 5 \cdot 10^{-4}$

Table 2: Spread in Strength at Nominal Current, per Magnet Element Type for the Full Series of 140 Magnet Blocks

magnet element	No [pcs]	in magnet blocks[6]	min. [%]	max. [%]	rms [%]
DIP B_0	80	U1,2,4,5	-0.15	0.17	0.07
DIP B_0	20	U3	-0.41	0.19	0.16
DIPm B_0	40	M1,2	-0.13	0.14	0.06
DIP B’	80	U1,2,4,5	-0.27	0.23	0.11
DIP B’	20	U3	-0.46	0.23	0.15
DIPm B’	40	M1,2	-0.18	0.20	0.09
QDend	40	M1,2	-0.45	0.48	0.19
QF	80	U2,4	-0.38	0.32	0.16
QF	80	U3	-0.41	0.43	0.25
QFend	40	M1,2	-0.38	0.35	0.14
QFm	80	U1,5	-0.36	0.33	0.15
SD	160	U1,2,4,5	-0.57	0.79	0.25
SD	40	U3	-0.37	0.25	0.16
SDend	40	M1,2	-0.46	0.39	0.17
SFi	40	U3	-0.38	0.77	0.21
SFm	40	U1,5	-0.50	0.68	0.27
SFo	40	U2,4	-0.41	0.54	0.21
OXX	38	M1,2	-0.57	0.58	0.29
OXY	38	M1,2	-0.24	0.93	0.27
OYY	40	M1,2	-0.33	0.38	0.15

M. Johansson et al., ”MAX IV 3 GeV storage ring magnet block production series measurement results”, IPAC’16, Busan, Korea.

Multipole error model

Multipole errors

Multipole errors used in simulation based on unscaled BINP measurement data taken with SLS magnets.

Magnet family	Error type	Order	Maximum multipole component (relative to main field component) Upright	Skew
Quadrupoles	Systematic	6	0.5×10^{-4}	—
		10	0.5×10^{-4}	—
		14	0.1×10^{-4}	—
Sextupoles	Systematic	9	0.5×10^{-4}	—
		15	0.5×10^{-4}	—
		21	0.5×10^{-4}	—
Quadrupoles	Random (rms)	2	2.5×10^{-4}	—
		3	2.8×10^{-4}	2.9×10^{-4}
		4	1.9×10^{-4}	1.4×10^{-4}
		6	1.3×10^{-4}	—
		10	3.0×10^{-5}	—
Sextupoles	Random (rms)	3	5.0×10^{-4}	—
		4	5.2×10^{-4}	4.9×10^{-4}
		5	3.5×10^{-4}	—
		9	8.0×10^{-5}	—
		15	5.0×10^{-5}	—

E.I. Antokhin et al., "*Precise Magnetic Measurements of the SLS Storage Ring Multipoles: Measuring System and Results*", Proceedings of the Second Asian Particle Accelerator Conference, Beijing, China, 2001, p. 209–211.

Table 3: Rotating coil results per magnet type, strength of main term series average, and largest higher order term (in 1E-4 of main term at r = 10 mm) series min/max/rms.

magnet	No [pcs]	block	int. strength at nom I.	harm. cont. [1E-4] min	max	rms
QFend	40	M1,2	-8.209 T	-10.4	7.3	3.0
QDend	40	M1,2	6.032 T	-9.6	8.0	3.1
QFm	80	U1,5	-5.918 T	-16.0	11.0	4.2
QF	80	U2,4	-6.117 T	-18.1	13.6	4.4
QF	80	U3	-6.250 T	-8.4	8.5	3.1
SDend	40	M1,2	182.1 T/m	-17.5	17.6	6.5
SFm	40	U1,5	-180.0 T/m	-19.6	23.9	10.9
SD	160	U1,2,4,5	126.8 T/m	-42.2	35.5	9.8
SD	40	U3	130.0 T/m	-19.4	18.3	6.2
SFo	40	U2,4	-187.1 T/m	-25.4	44.5	12.3
SFi	40	U3	-211.7 T/m	-17.2	8.4	5.5
OXX	38	M1,2	3230.9 T/m^2	-22.4	29.4	9.3
OXY	38	M1,2	-6497.1 T/m^2	-26.8	34.6	9.0
OYY	40	M1,2	2793.2 T/m^2	-13.3	14.5	4.7
corr x	200	all	3.8 Tmm			
corr y	178	all	-3.7 Tmm			

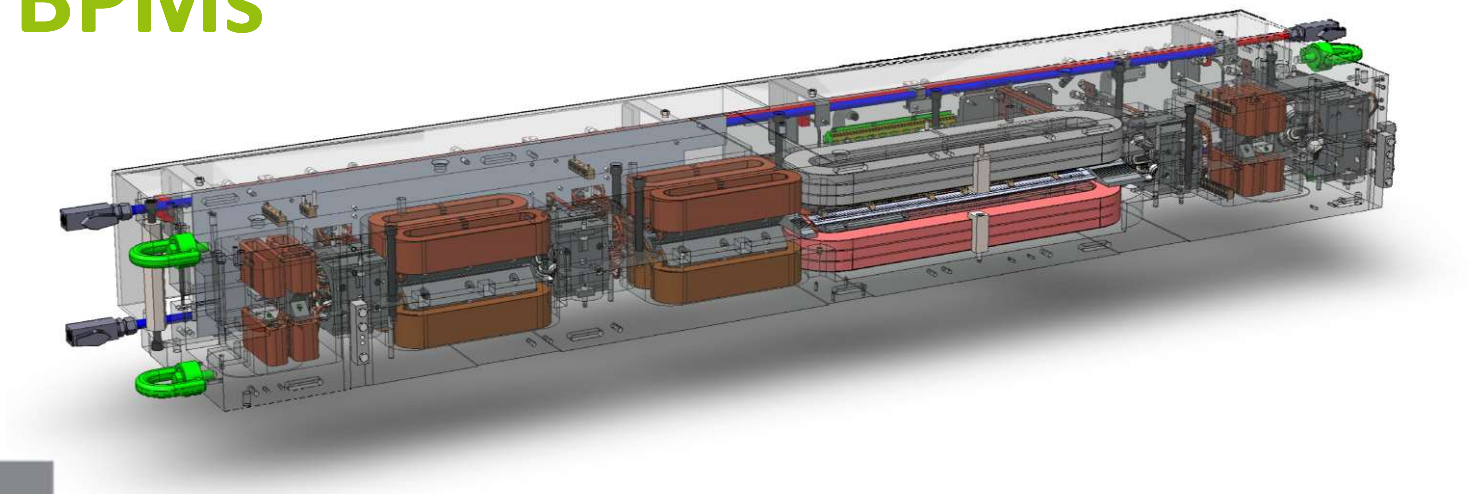
M. Johansson et al., "MAX IV 3 GeV storage ring magnet block production series measurement results", IPAC'16, Busan, Korea.

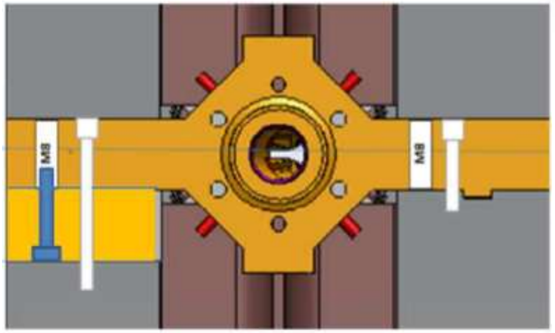
Commissioning Lessons Learned

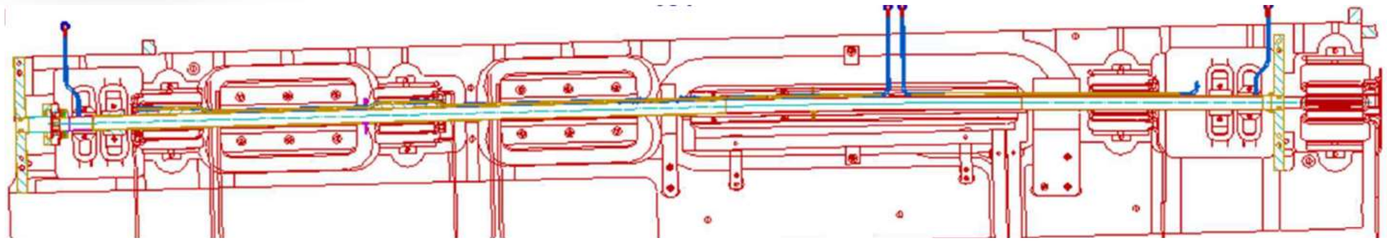
- Invest time and effort in sub-system testing ***prior*** to beam commissioning.
- Perform subsystem-tests as much as possible using the **final control system configuration** and GUIs. Use subsystem-tests as an opportunity to drive the control system development and deployment schedule.
- Design subsystem tests to reproduce as much as possible real operating conditions.
- Allow time for correcting errors found during those tests.
- Make sure radiation safety understands and agrees to the commissioning plan.
- Allow plenty of time for RF cavity conditioning.
- Have spare parts on-site during commissioning.
- Have an on-line model of the accelerator for quick testing.
- **Be ready to improvise !**

Slide by P. F. Tavares

MAX IV BPMs

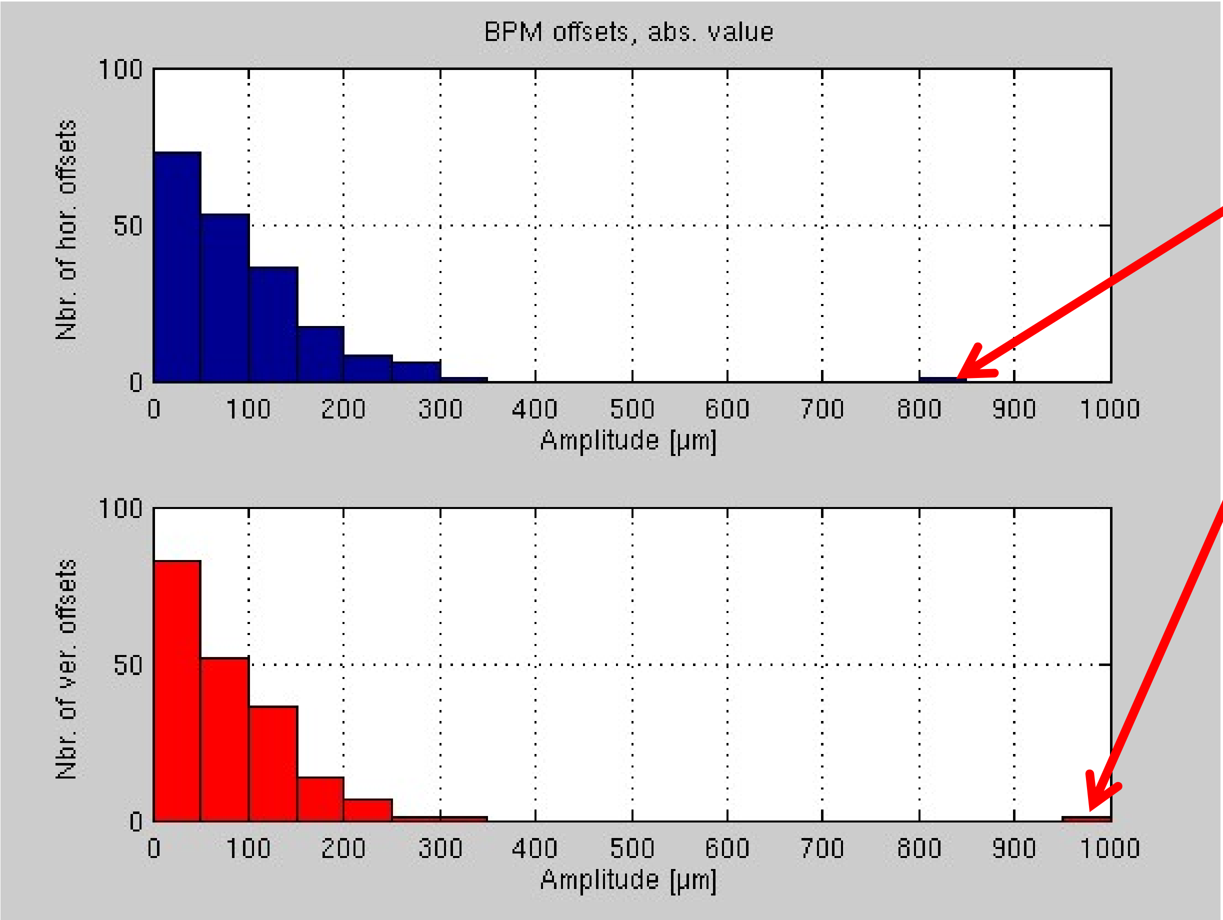






- Fixation vs. magnets (midplane, clamped to the solid body that contains the magnet)
- BPM and sextupole/octupole magnets positioned using CNC-machined grooves in the block → mechanical positioning given by CNC accuracy (+-20 µm)
- Libera Brilliance+ electronics
- Capacitive button BPM (scaled ALBA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

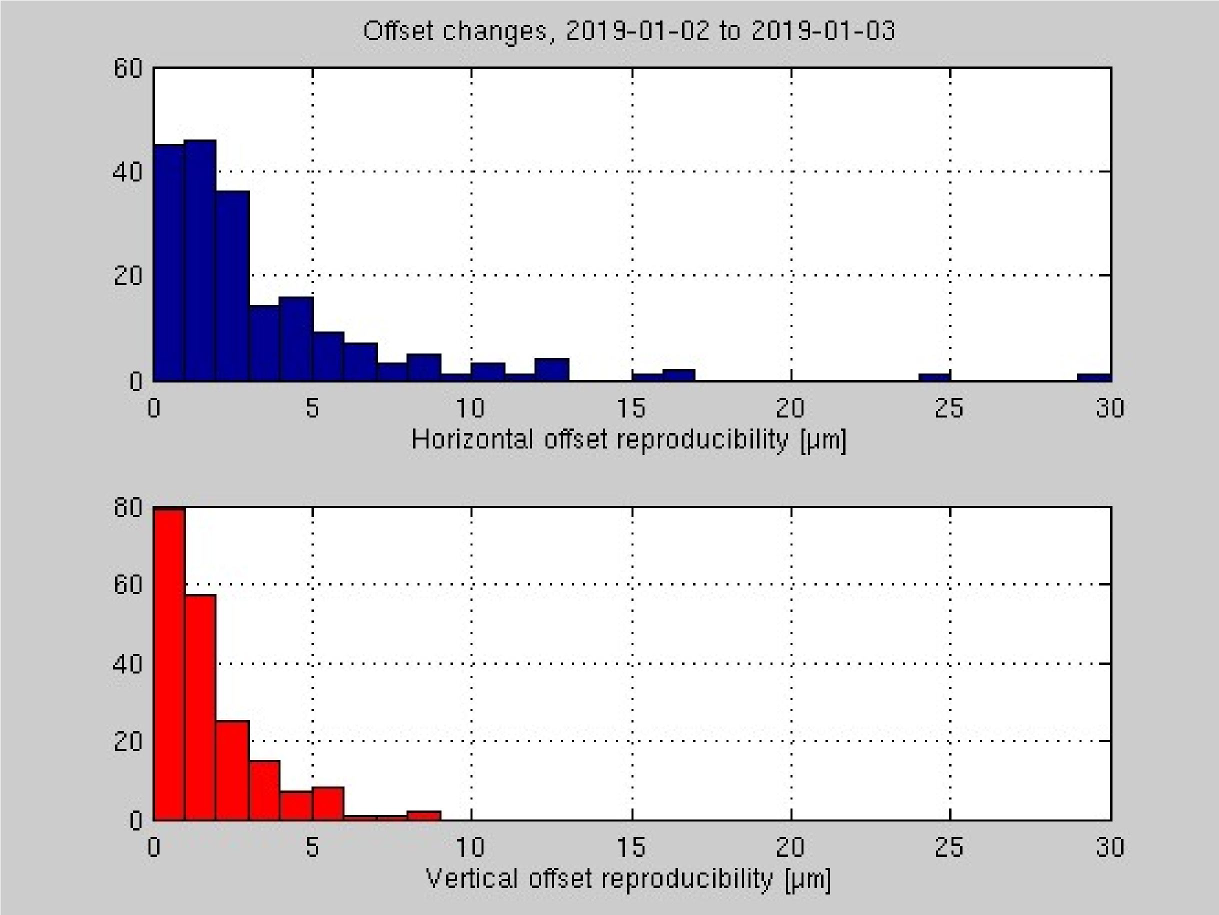
Offsets, absolute size



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.*

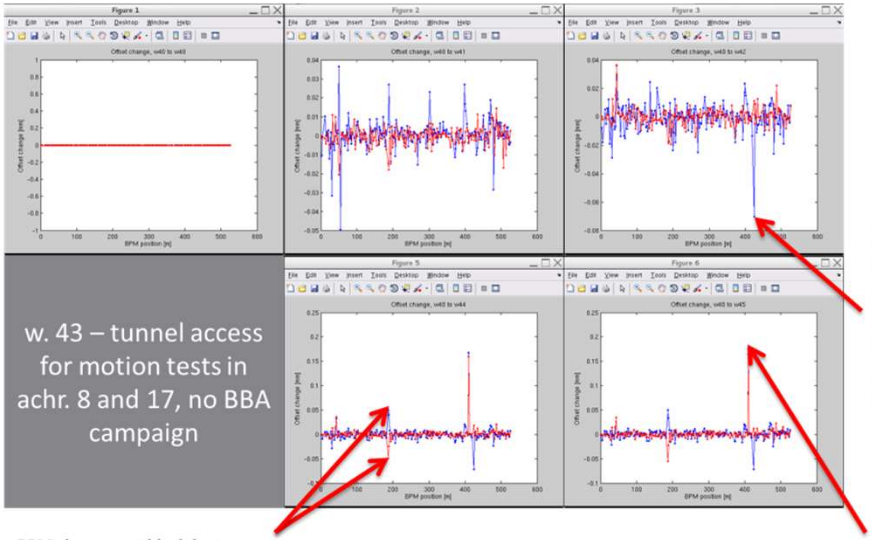
Offset reproducibility



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



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

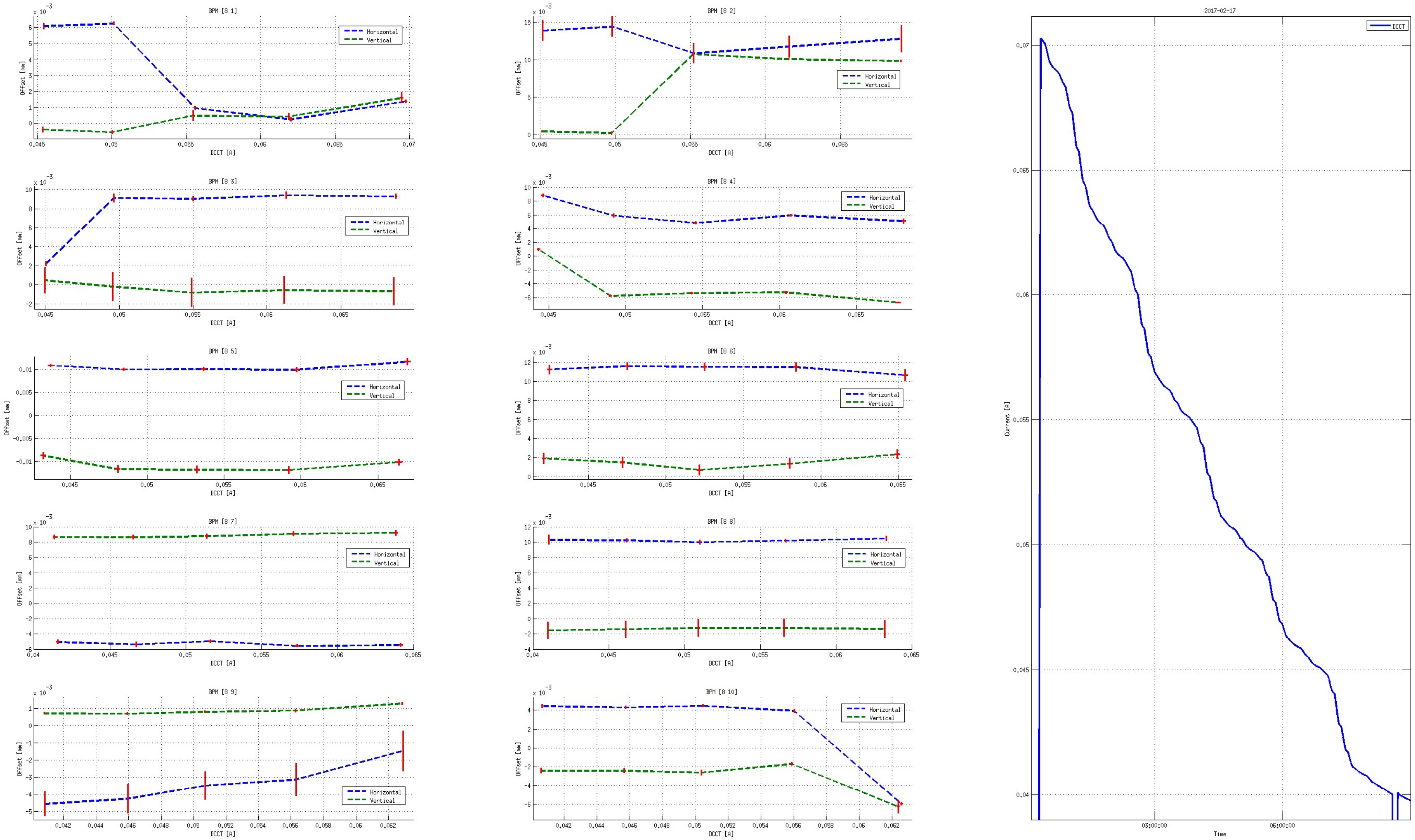
BPMs in magnet block just downstream of BALDER ID (achr. 8)

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

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* ***)***

Current dependence 0 – 65 mA *(2016 results, not revisited)*



Measurement, analysis and plots by R. Svärd