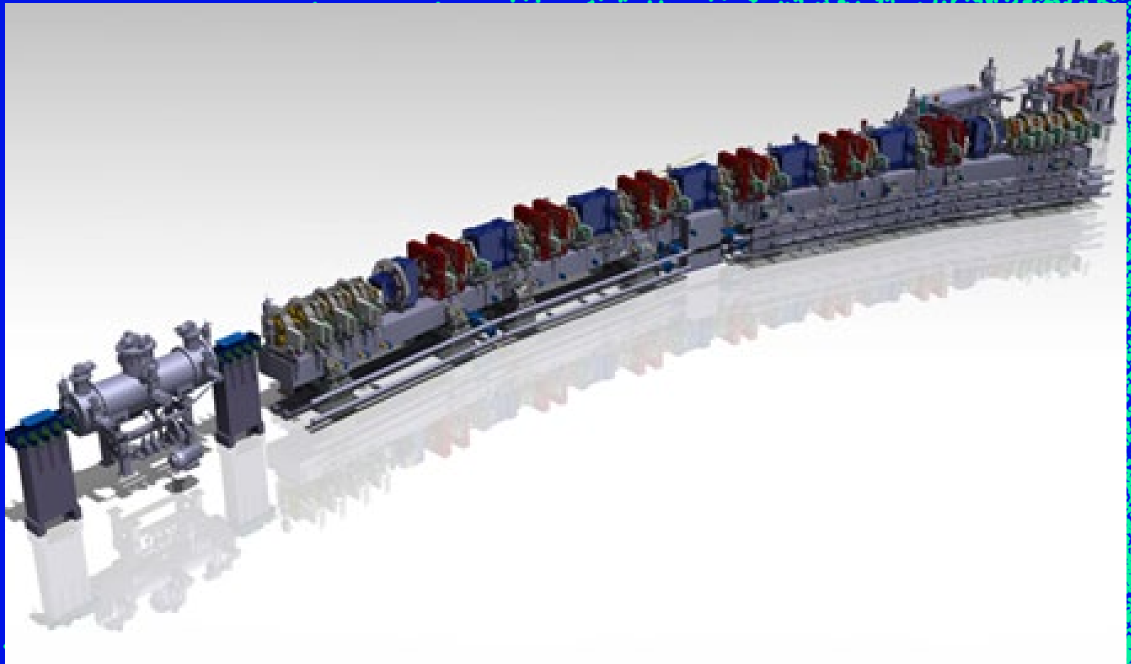
Lessons Learnt in the Commissioning of Swiss Light Source 2.0



M. Aiba on behalf of SLS 2.0 team

08.10.2025

Low Emittance Ring Workshop

DESY, Hamburg, Germany

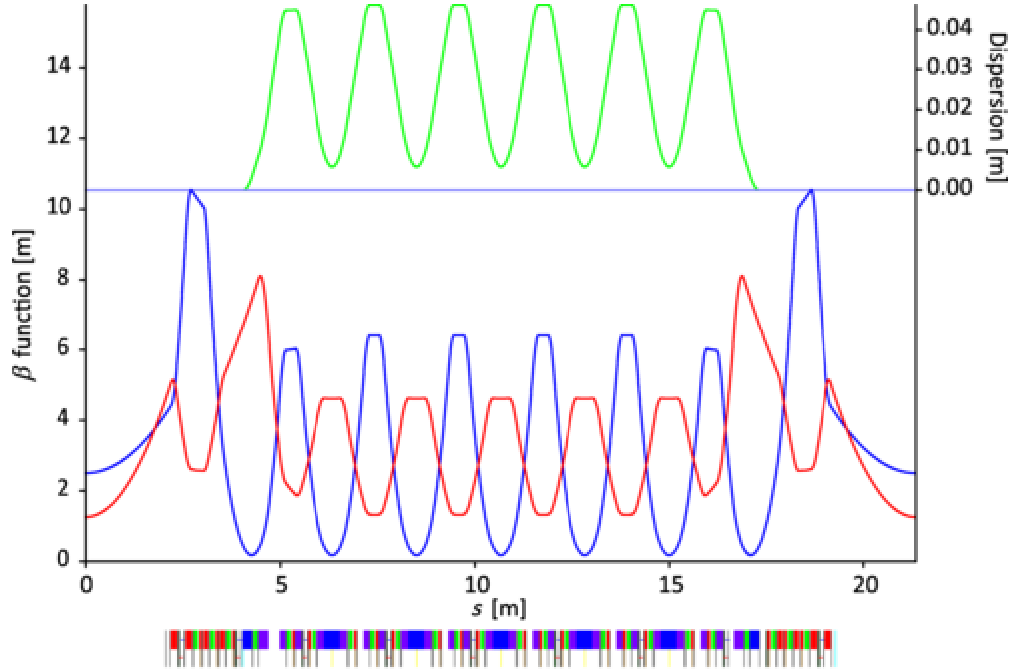
Overview of SLS 2.0

- New 4GLS storage ring
- Primary goals
  - Emittance, 40 times lower
  - Hard X-ray, 100 times brighter
- Key parameters
  - C: 288 m, reusing building and injector
  - Natural emittance: 158 pm w/o ID
  - Beam energy: 2.4 GeV → 2.7 GeV
    came with negative α → positive α
- Key technologies
  - NEG coating
  - Permanent magnet (PM)
  - HOM damped cavity
- Challenges
  - Compact lattice, 7BA with PM
    → Mechanical integration
    → Feasible?
  - Short dark time, tight schedule
    → All systems ready on Day-1

Parameters	SLS today	SLS upgrade
Lattice type	TBA	7-BA
Number of arcs	12	12
Circumference (m)	288	288
Gross straight length (m)	79.9	83.6
Total bending angle (deg)	374.69	430.08
Working point Q_x/Q_y	20.43/8.74	39.37/15.22
Momentum compaction factor, first/second order (10^{-4})	6.04/36.3	1.05/7.94
Natural chromaticity ξ_x/ξ_y	−67.3/−21.0	−99.0/−33.4
Vertical emittance (pm)	≈10	10
Chromaticity in operation	5	1.0–1.5
Energy (GeV)	2.411	2.700
Natural emittance (pm)	5630	158 (135)
Energy spread (10^{-3})	0.88	1.16 (1.04)
Radiation loss per turn (keV)	549	688 (915)
Damping partition $J_x/J_y/J_s$	1.0/1.0/2.0	1.83/1.0/1.17
Damping time $\tau_x/\tau_y/\tau_s$ (ms)	8.65/8.67/4.34	4.14/7.58/6.47
Beam current (mA)	400	400
Maximum rf voltage (MV)	2.6	2.2
Harmonic number	480	480
Number of bunches	390–420	450
Beam lifetime (h)	≈10	≈9

More details
- Talk on SLS2.0 upgrade project by H. Braun, this session
- Talk on SLS2.0 magnets by G. Montenero, Thursday afternoon

7BA lattice



- Permanent magnets
  - Longitudinal Gradient Bend
  - Reverse bend
- Electromagnets
  - Matching quad
  - Sextupole
  - Oct. + Normal & Skew Qs (0.32 T)
  - Orbit correctors (800/600 urad)

- Orbit and linear optics along the achromat are entirely based on permanent magnets!
- Pseudo-symmetry: same phase advance for S, M and L straights
- Limited corrector strength
- Significant magnetic crosstalk compensated by magnet optimization/tuning (backup slide)

Machine commissioning plan: 7 Phases

- Phase 1: Injector / 2024 Dec
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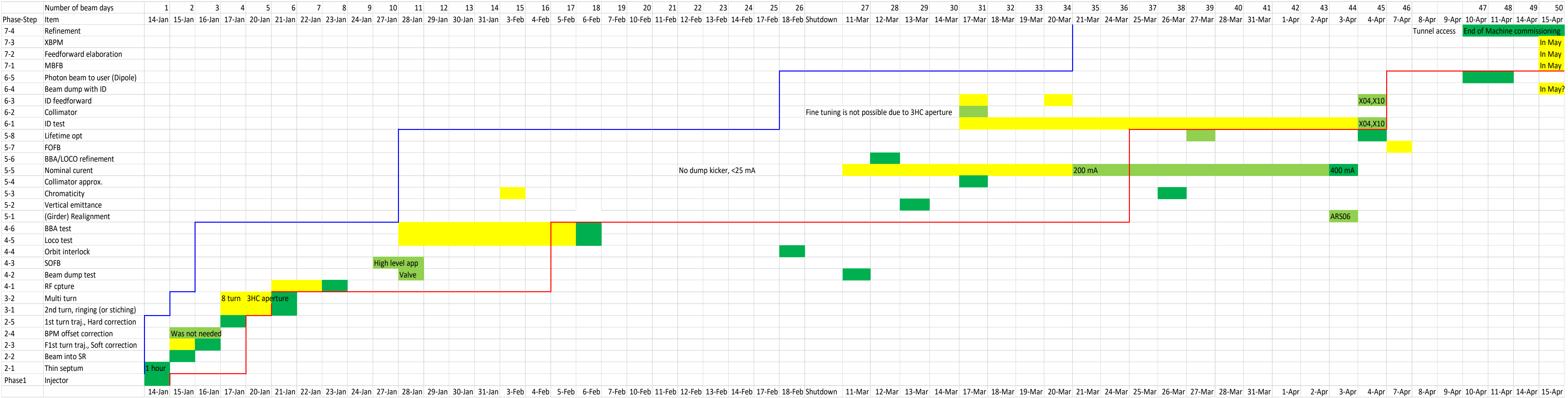
- Phase 7: Finalization, Elaboration / Open end

- Shift plan was one (long) shift per weekday, and vacuum conditioning over night and weekend as long as we were on schedule
- No weekend shift was needed in reality

Actual progress



- Machine commissioning is completed almost as planned
  - First electron into storage ring on 14th January
  - First stored beam on 23rd January
  - Design beam current, 400 mA, on 3rd April
  - First light to dipole beamlines on 10th/11th April
- We made it within 50 beam days!

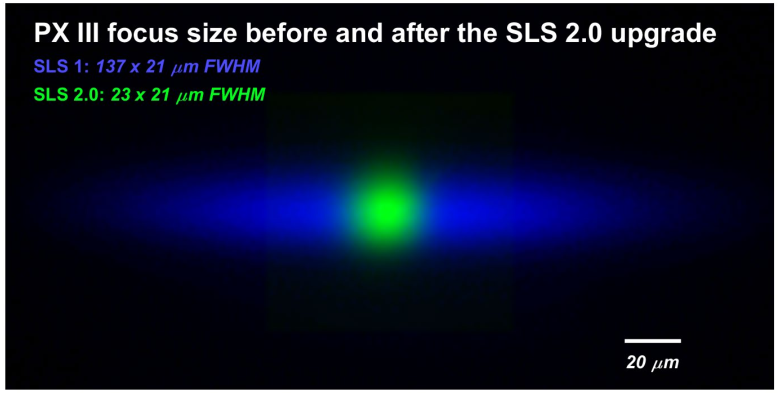


Figure by courtesy of B. Rösner
Thanks to PX beamline colleagues

Getting first stored beam

- 14th Jan: Injector restart. Beam going through the thin septum
- 15th Jan: Beam going through first three sectors. Sector-4 BPMs were not triggered…
- 16th Jan: LGB realignment (correcting "known misalignments"), almost one turn
- 17th Jan: One turn and shortly after 8 turns achieved, but not more…
- 20th Jan: 5 turns but not more…
- 21st Jan: Taper into 3HC was blocking the injected beam, and realigned, ~40 turns
- 22nd Jan: Sextupole/Octupole ramped up, orbit correction, ~125 turns
- 23rd Jan: RF capture and stored beam! Individual cavity phasing was needed

* BPM commissioning was undergoing in parallel during these first days

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Orbit threading

- Procedure
  - Beam launch into the storage ring
    - Injected beam was centered at the first two BPMs (pseudo-on-axis injection) using K3 and K4 in H plane and transport-line vertical correctors in V plane
  - Threading based on model matrix
    - 1^{st} turn correction without cutting many eigenvalues was possible, Xmax/Ymax ~1 mm
    - BPM electronic offsets were corrected before commissioning
      - 300 um (assumed in simulation) vs 228/116 um (BBA in Phase 4)
  - “Stitching”
    - Correctors upstream of the septum were manually adjusted with all four bump kickers ON

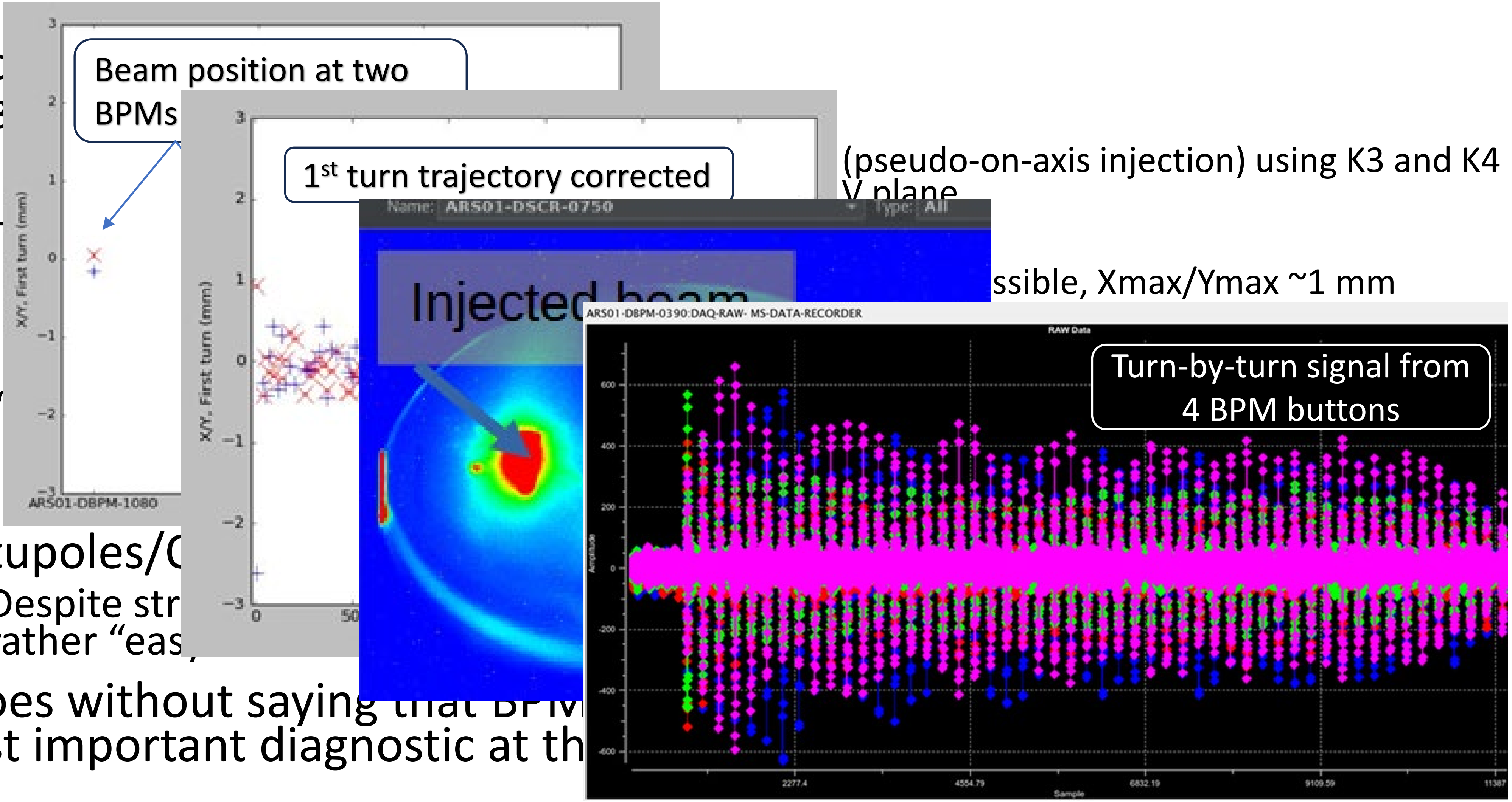
      → Multi turns achieved, and switching to the orbit mode
- Sextupoles/Octupoles were OFF
  - Despite strong focusing MBA lattice, transporting the beam through *linear lattice* is rather “easy”
- It goes without saying that BPM in turn-by-turn mode was essential and most important diagnostic at this stage.

Orbit threading

- Proc
  - B
  - T
  - “

(pseudo-on-axis injection) using K3 and K4
V plane

ssible, Xmax/Ymax ~1 mm



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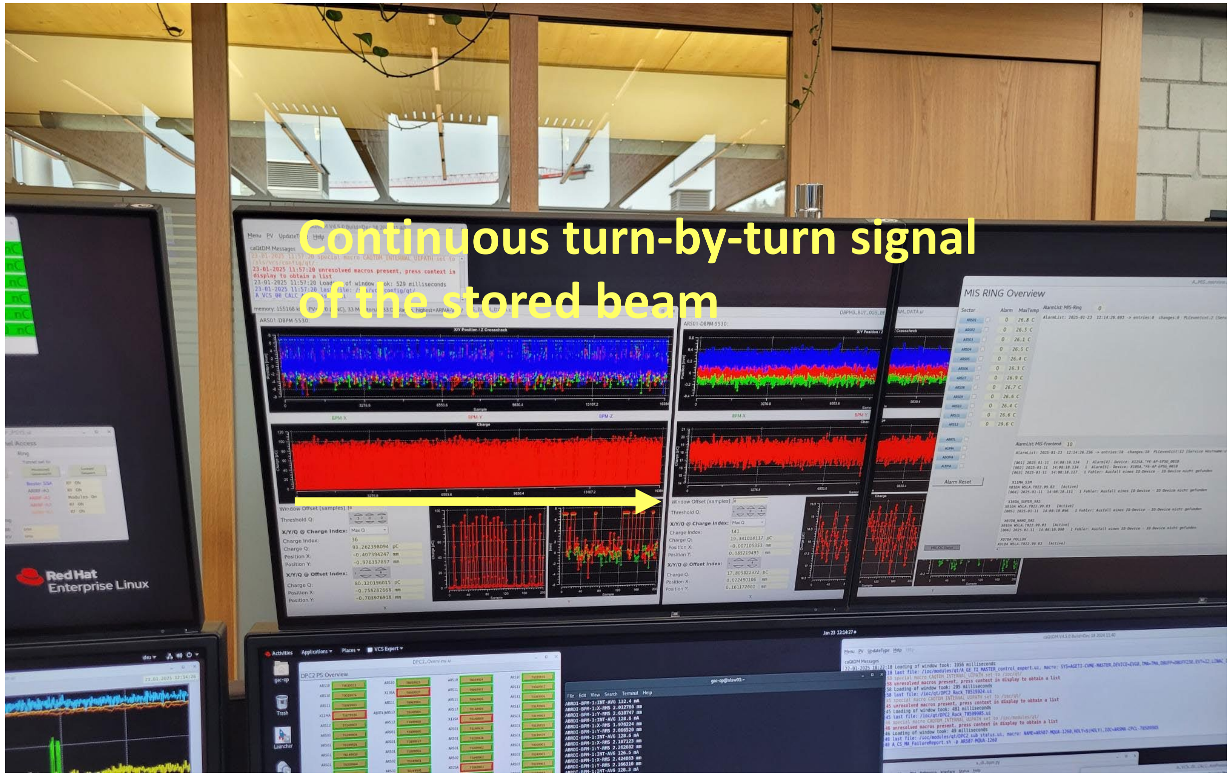
First stored beam

- Sextupoles/Octupoles ON
- RF capture
  - Phase scan, cavity by cavity
    - On-crest phase ↔ Maximum turn
  - Phases were set to the synchronous phase

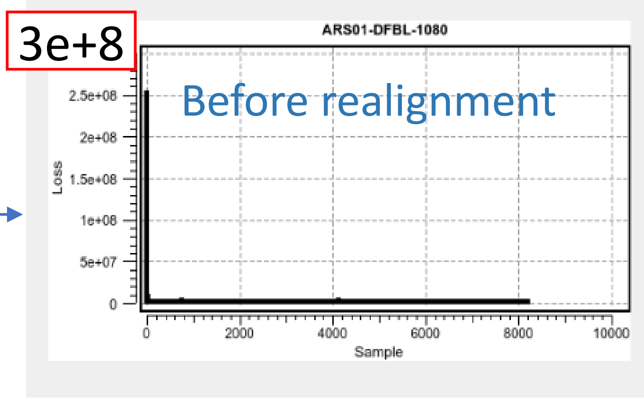
    → Beam captured!

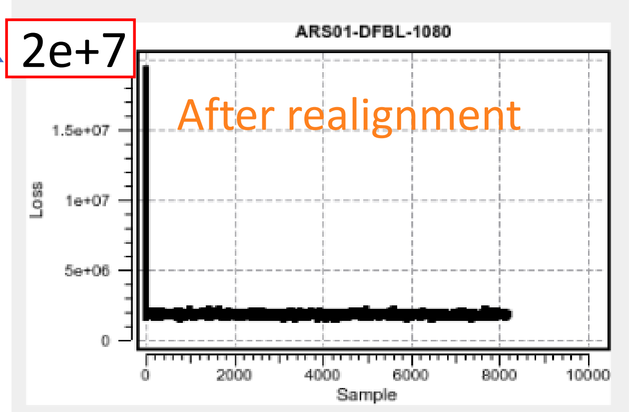


Injection

- Kicker bump injection (SLS1 kickers reused)
  - Easy to start with
  - Overdriven until the first stored beam (no accumulation possible)
  - Accumulation right after the first stored beam by switching to nominal setting
- Injection efficiency
  - Vacuum chamber downstream of the thin septum was largely misaligned, very poor efficiency
  - After realignment, ~80% efficiency achieved (Transfer line ICT vs Ring PCT)
  - New 3HC taper with bellows installed,
    ~100% efficiency achieved (Transfer line ICT vs Ring PCT)
- In Phase 7
  - Booster extraction and Transfer line tuning mitigated the residual beam loss, ~100% efficiency achieved (Booster PCT and Ring PCT)
  - Keeping ~100% efficiency is next challenge; sometimes it drops to <90% though >90% most of time.
- Plan for Aperture sharing/Quasi-on-axis injection
  - Stripline kicker, 20ns/2 ns pulse, is under development; PSI contribution to iFAST WP7
  - Prototype tested at ESRF-EBS
  - Prototype final test in this month → Kicker design to be finalized

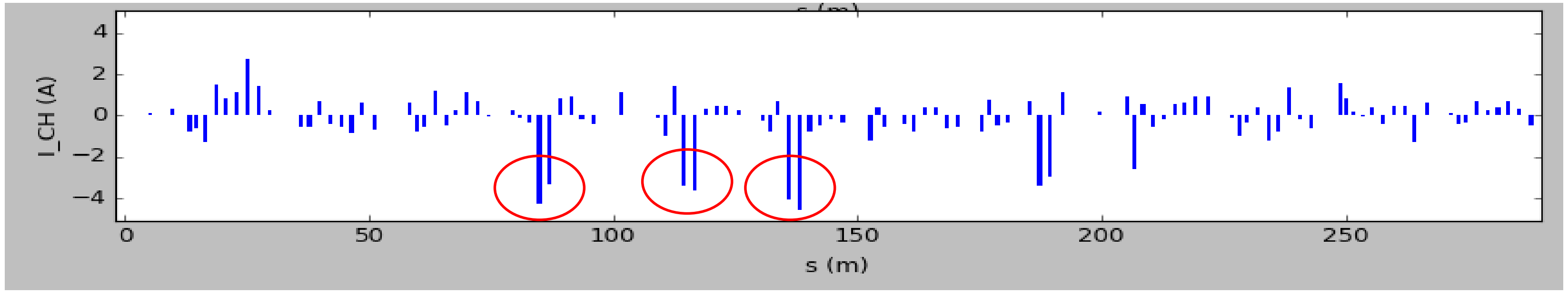
Turn-by-turn signal from BLM (Libera) in the injection straight



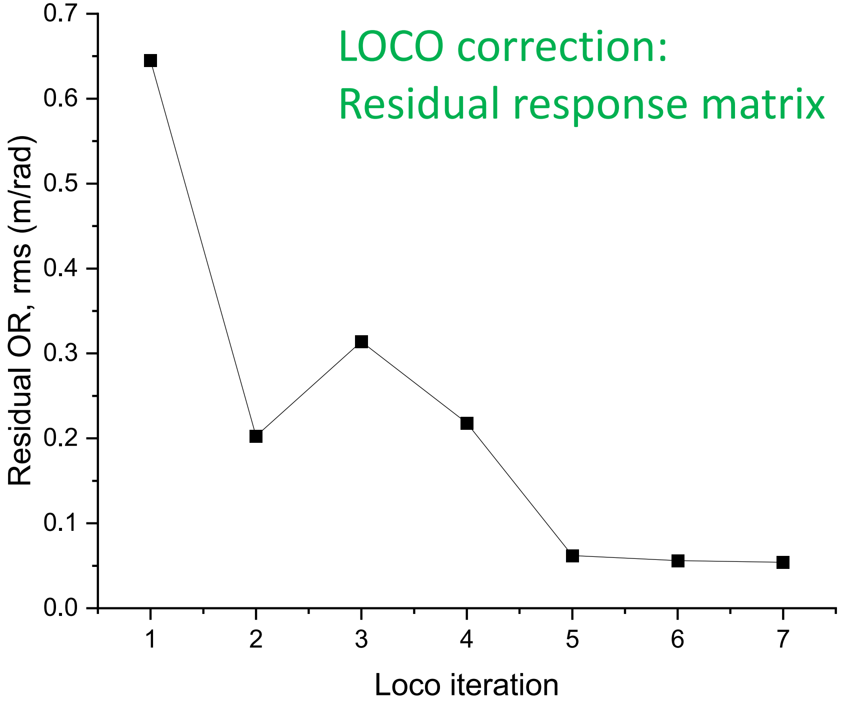


Orbit correction

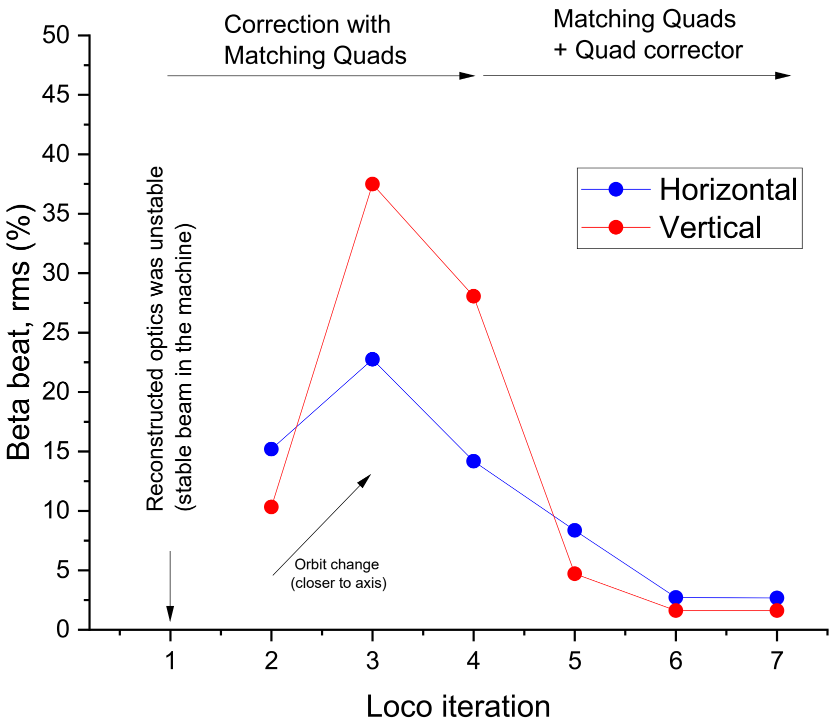
- BPM (quick) beam-based alignment
  - 115 BPMs aligned within about 10 um. Can be done in about 3 hours.
- No problem in V plane: Correctors within ±4 A while the limit is at ±5 A
- In H plane, **not enough corrector strength**
  - BBA constant (BPM offset) was manipulated in Sector 4, 5 and 6 by 200 um or so, to prevent the corresponding correctors from reaching to their limit
  - Fixed in Phase 7



Linear optics correction



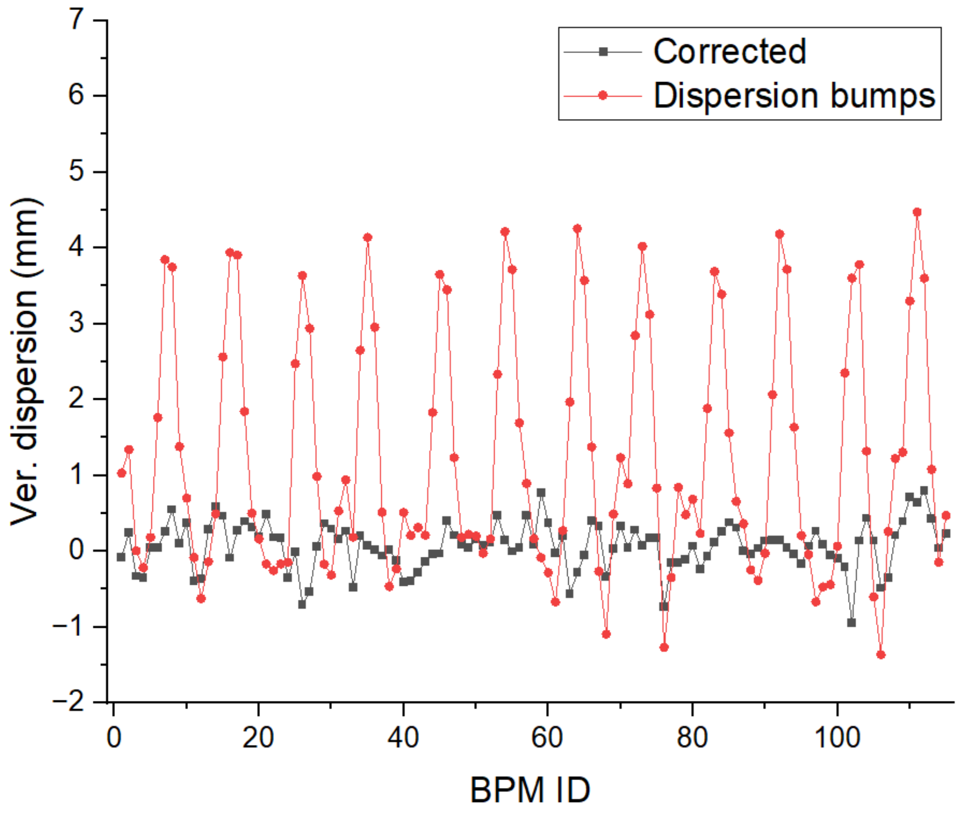
Beta beat from reconstructed machine



- Correction with only matching quadrupoles, and then the quad correctors were included
- Dispersion correction (backup slide)

Vertical emittance control

- Coupling and V dispersion were corrected first using skew quads
- Vertical dispersion bumps was introduced to control V emittance
  - This static approach is convenient for the early stage of commissioining
  - Emittance dilution utilizing bunch-by-bunch Feedback is considered
- Nominal V emittance = 10 pm



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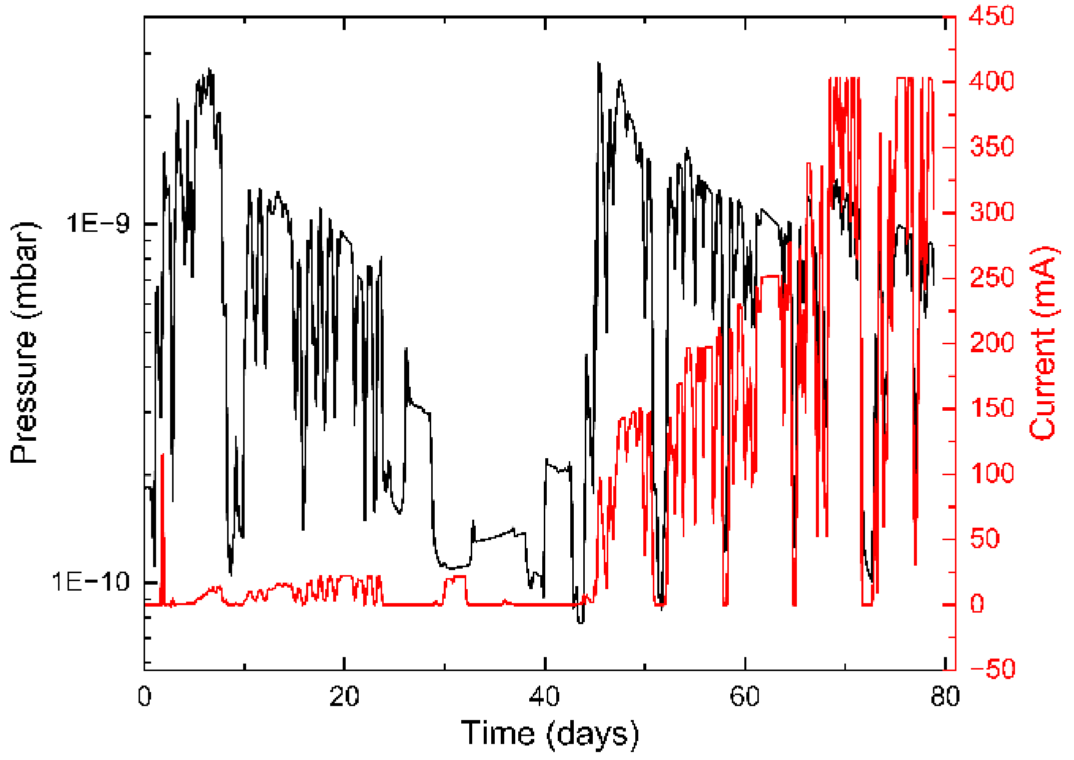
Reaching 400 mA and vacuum conditioning/scrubbing

- <25 mA until the beam dump kicker was installed
- Two scenarios were considered in the planning:
  - Scenario A: No need to close the bunch-by-bunch feedback (BBBF) loop
  - Scenario B: Coupled bunch mode instability requires BBBF, increasing chromaticity or 500 MHz cavity tuning…
- Thanks to the new HOM damped cavities, Scenario A was the case. This made our life much easier!
  - Ion instabilities observed as expected with >100 mA. Otherwise, no instabilities observed up to 400 mA
- Some hot spots observed with temperature sensors at 400 mA…
  - Additional water cooling where necessary
- About 160 A.hours provided by April 15th
  - No aggressive scrubbing applied; Vertical pinger at 3 Hz
  - Beam lifetime of 8 hours was achieved → ~12 h in July

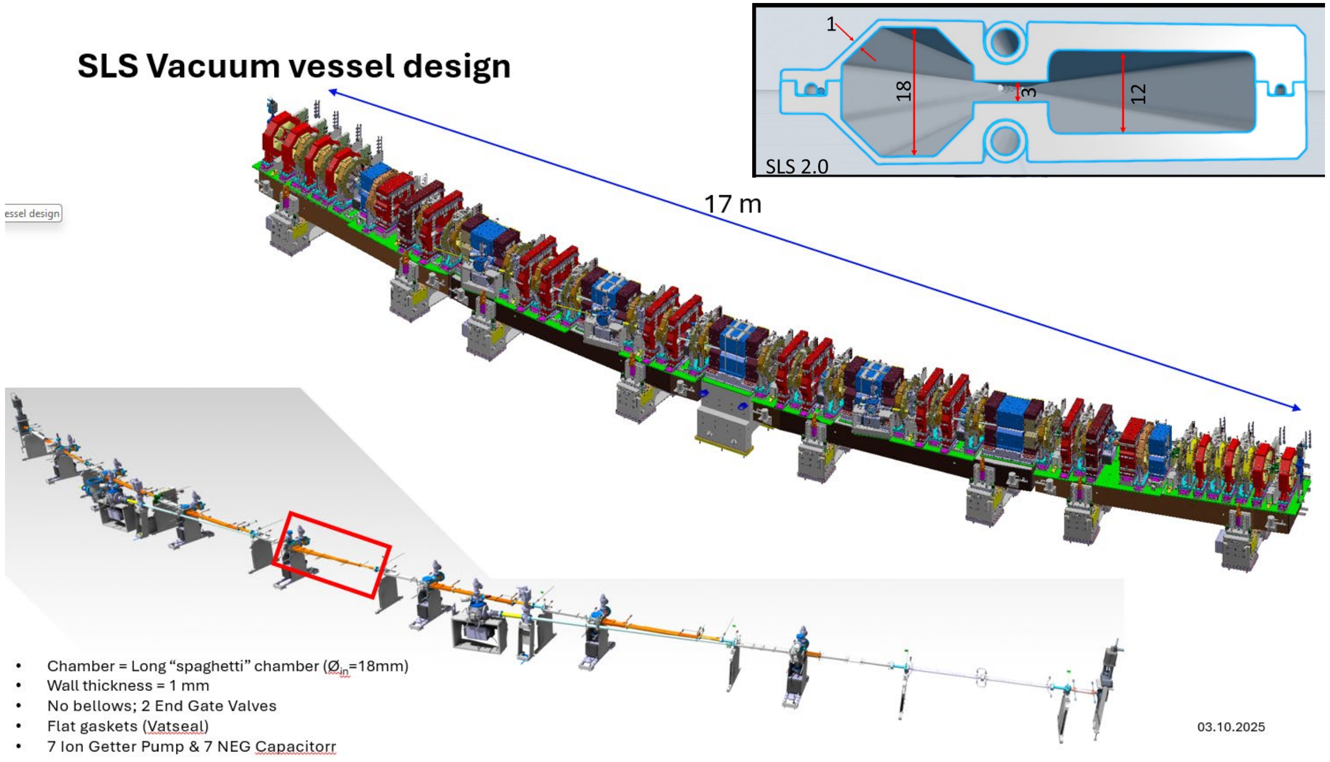


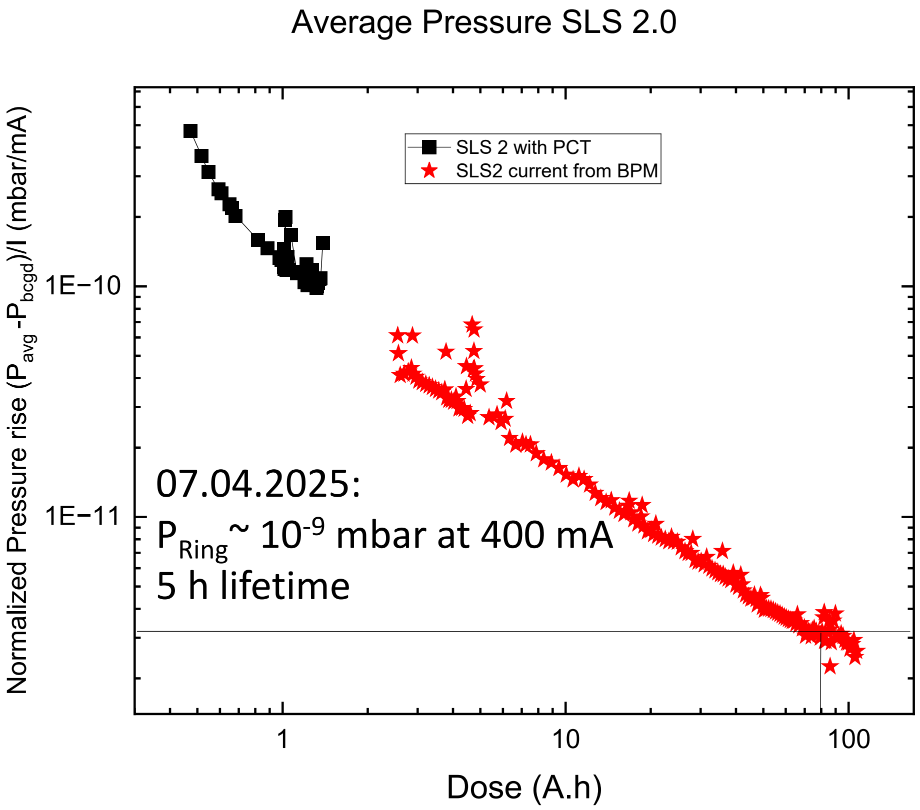
Average pressure and Beam current

January 25th to April 15th 2025

Figure from R. Ganter

Vacuum system

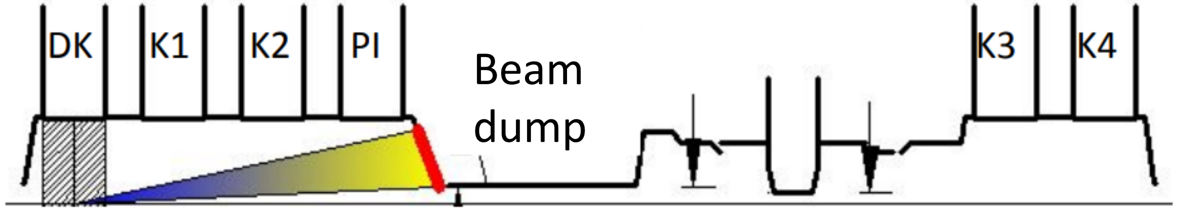


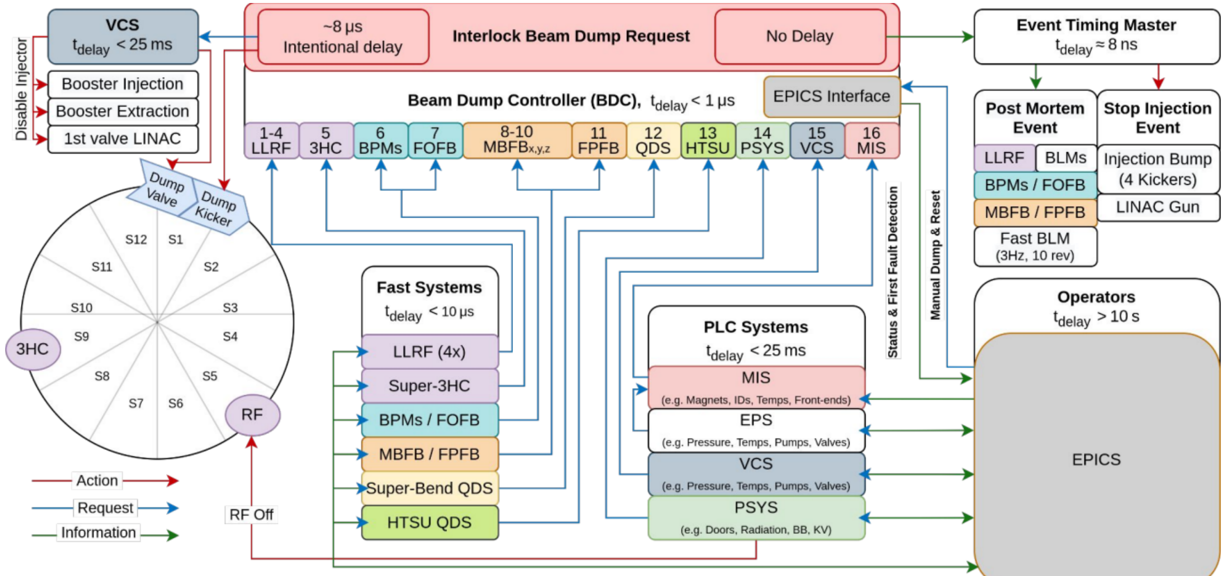


- Aggressive design "no bellows over 17 m"
- Beam dose of 100 A.hour → Minimal conditioning
- Pressure better in the arc chamber with NEG (< 1e-9 mbar) than some other parts not coated (>1e-9 mbar)

Beam dump and Machine protection

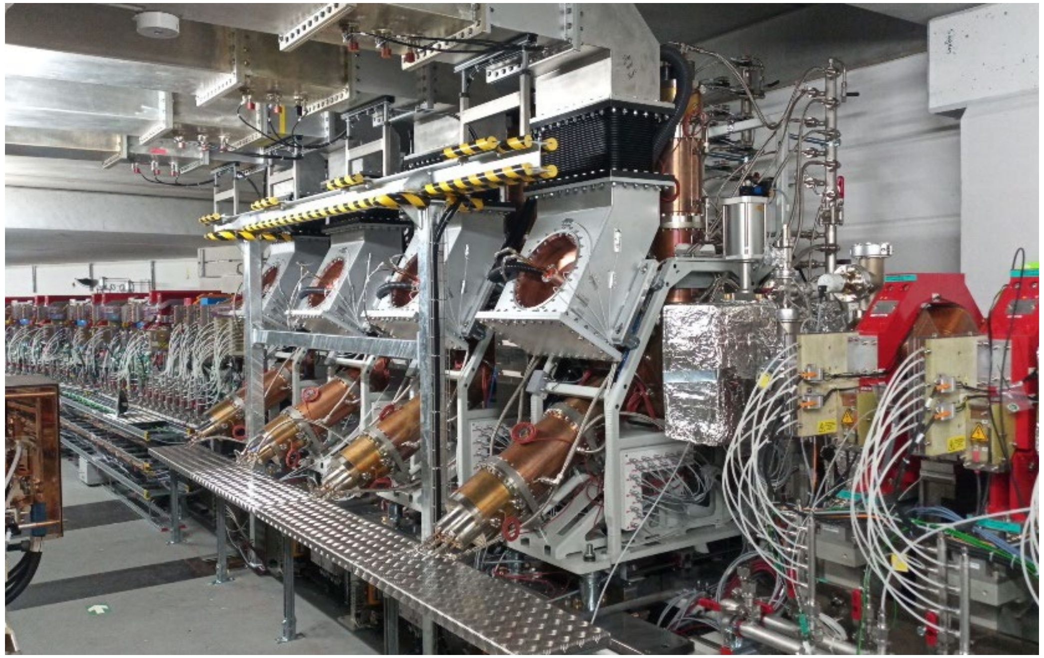
- Machine protection system
  - Protect thin vacuum chambers, IDs, ring permanent magnets, etc.
  - Designed to react within ~100 us
  - Beam is safely dumped even for the worst event, i.e., power cut
- Dump kicker and internal beam dump
  - Integrated into the injection straight
  - Slope of the sinusoidal kicker pulse spread the bunch train on the beam dump surface





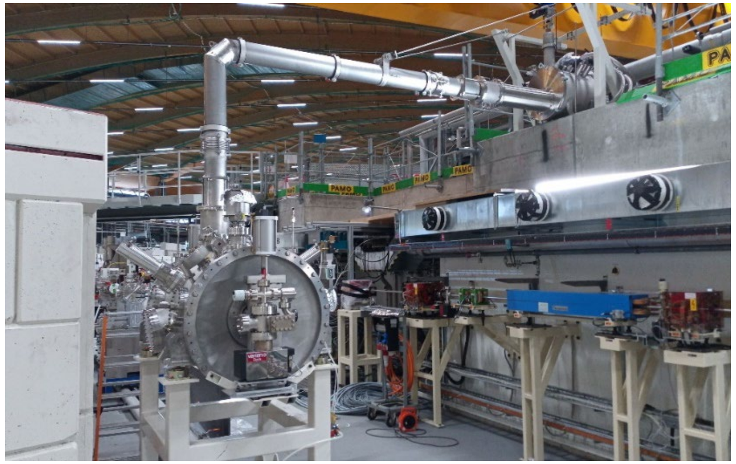
500 MHz RF system

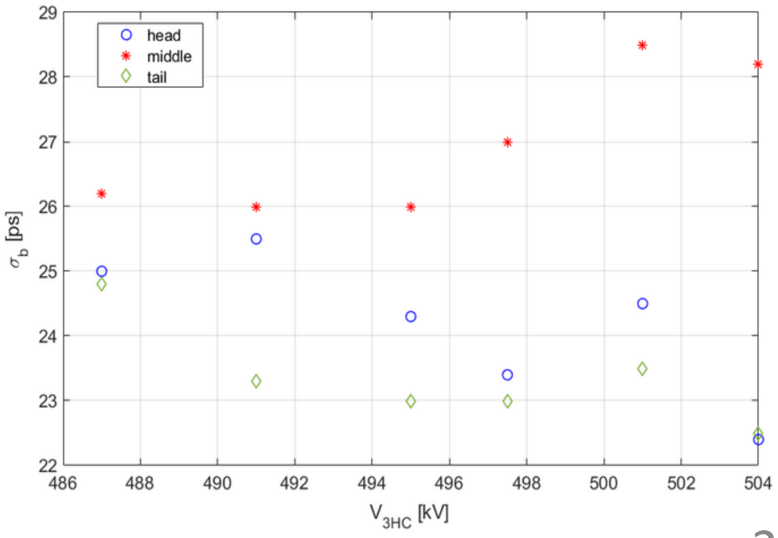
- New HOM damped cavities
  - Large beta functions at the RF location
  - New digital LLRF system
  - Pre-conditioning at test stand
    - Sophisticated tool was available since commissioning Day-1: beam recovery after beam damp as quick as possible
  - Harmonic number = 480
    - Nominal filling = 450 bunches uniform
    - Two gaps or 50-bucket long gap to avoid ion instability when it was necessary
  - No coupled bunch mode instability up to 400 mA



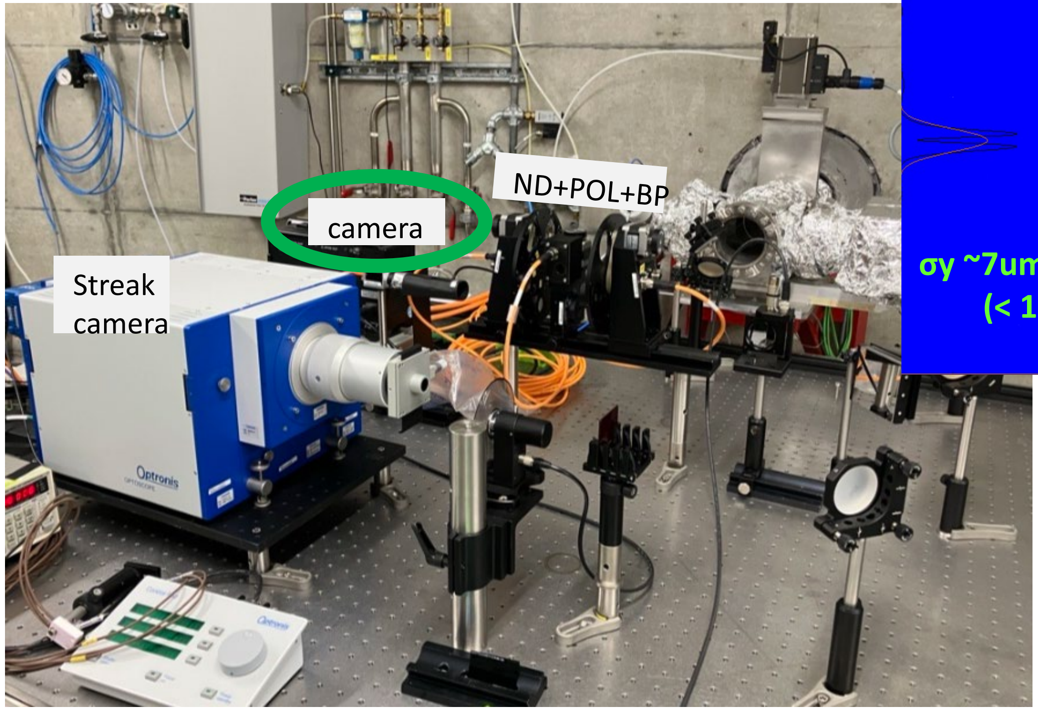
Third harmonic cavity, passive SC

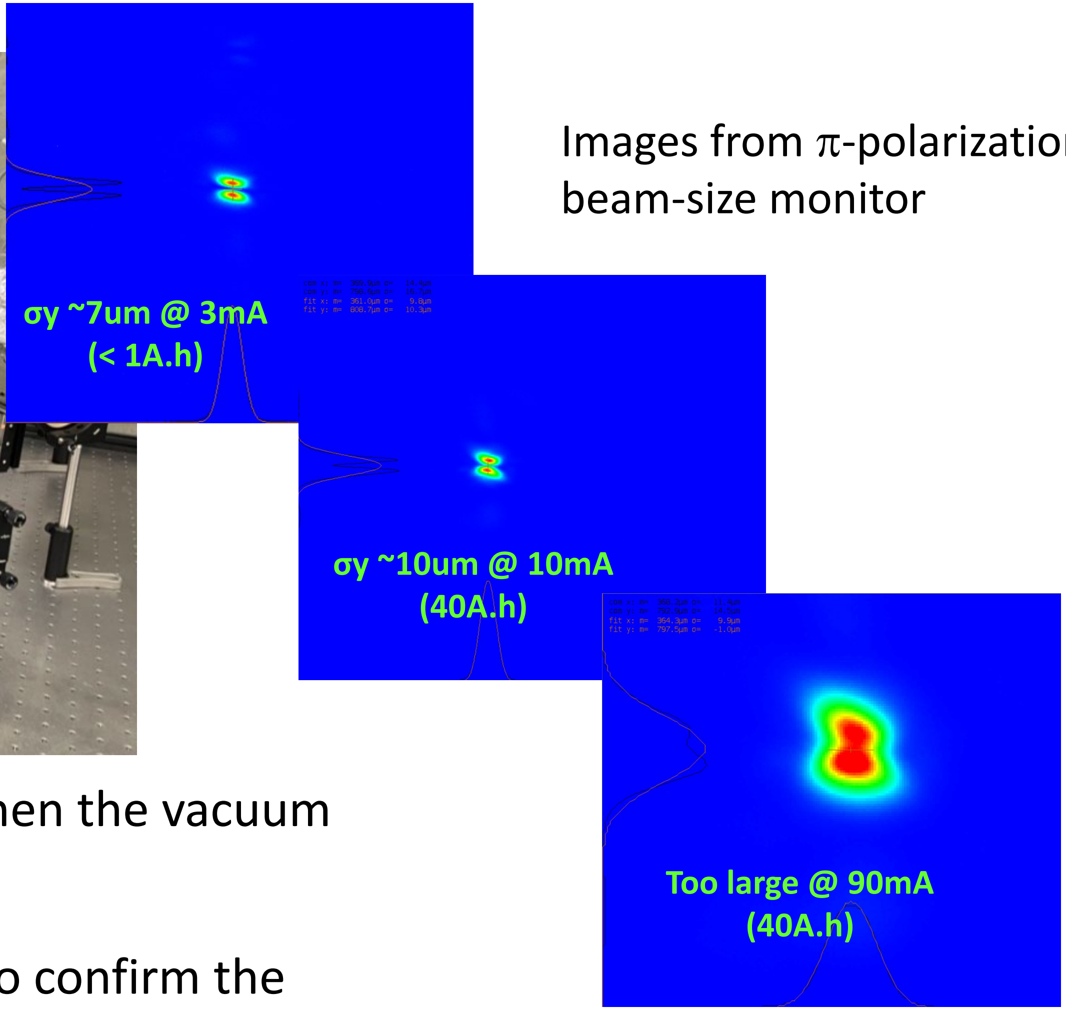
- SLS1 3HC cavities reused
  - Tuning system and cryo-plant upgraded
- Approximately tuned during the beam current increasing
- In Phase 7, further tuning with streak camera
  - Operating point: ~501 kV
  - Bunch length: ~10 ps w/o HC vs ~25 ps average with HC





Beam size measurement with visible light





Images from π-polarization beam-size monitor

- Significant V beam size increase was observed when the vacuum pressure was high
  - Small-angle/multiple scattering with residual gas (?)
- Later, with good vacuum, the monitor was used to confirm the vertical emittance control

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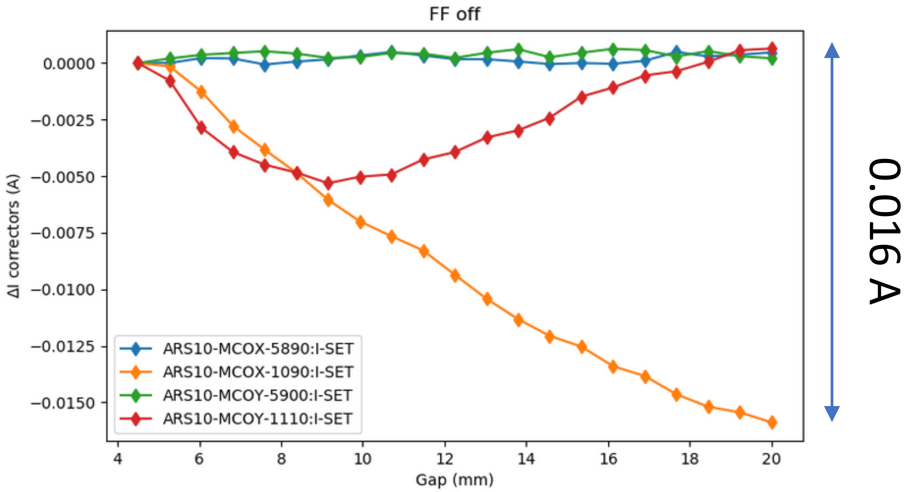
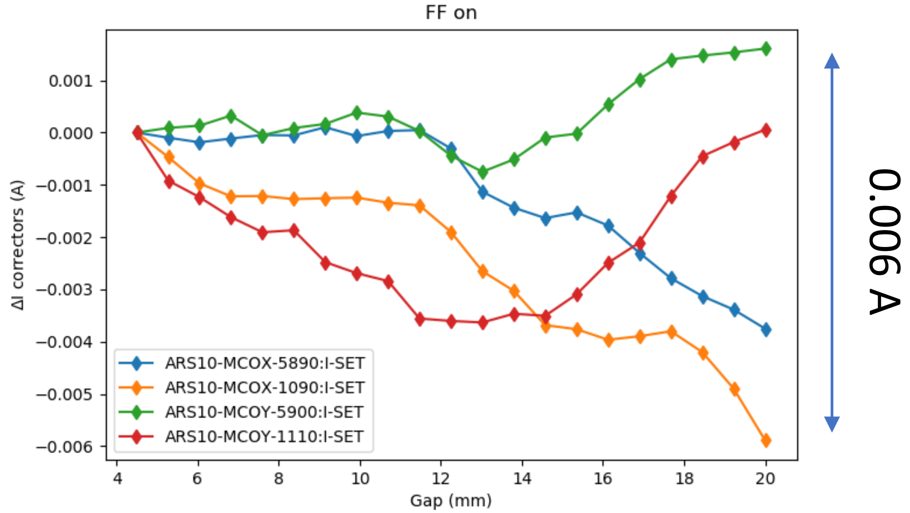
Preparation for ID beamline commissioning

- Beamline vacuum conditioning
  - Before starting ID beamline commissioning, ID gaps have been closed to condition the vacuum up to the photon shutter
- Orbit feedforward tables have been measured and applied
  - 4 correctors are attached to undulator (H/V/upstream/downstream)
  - Gap dependence of the orbit feedback correctors is reduced
- Tune and coupling feedforward are considered





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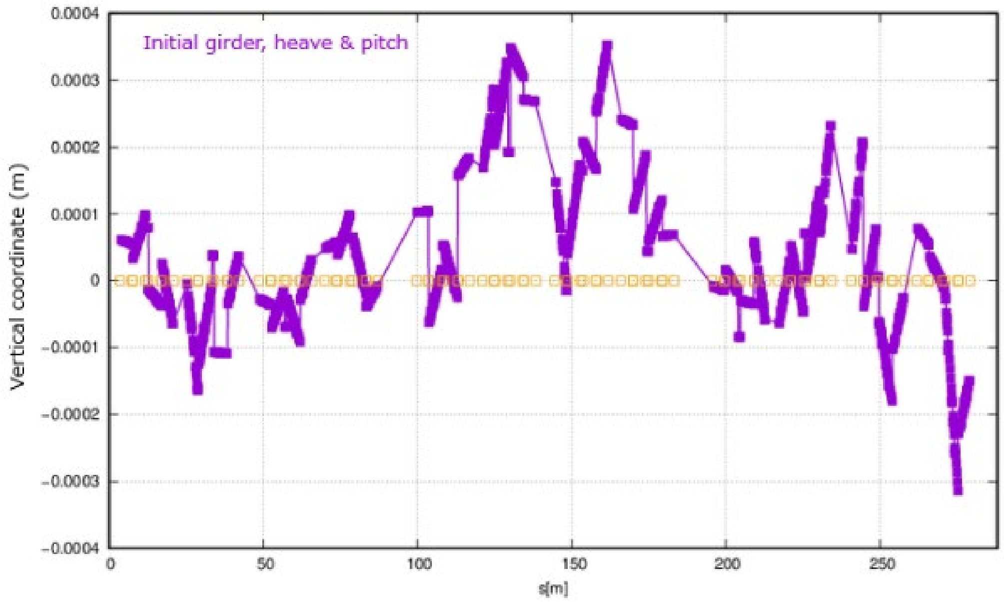
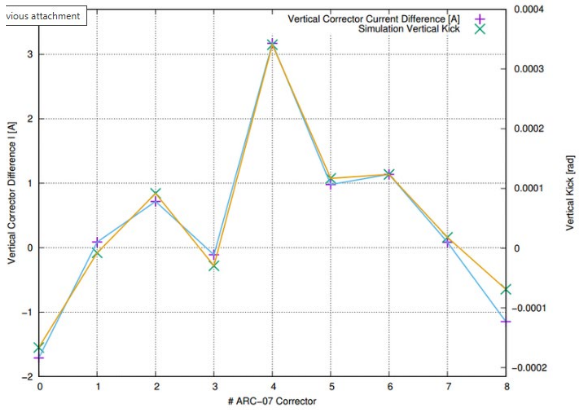
Realignment campaign (1)

- Vertical girder alignment
  - Girders are motorized and can be remotely aligned from the control room
  - Beam Assisted Girder Alignment (BAGA)
    - <u>Girders were moved with stored beam and FOFB running</u>
    - New corrector setting is obtained immediately
    - All girders were aligned to the reference (Y=0)
- Horizontal girder alignment
  - Manual alignment in the tunnel; not motorized in H plane
  - Girders in Sector 5 were aligned during the last shutdown in August
  - It is not necessary to align all the girders; horizontal alignment is planned for a few more locations
- Some beamline components need to be realigned
  - Difficulty to establish smoothly-connected alignment network between the machine and the beamline

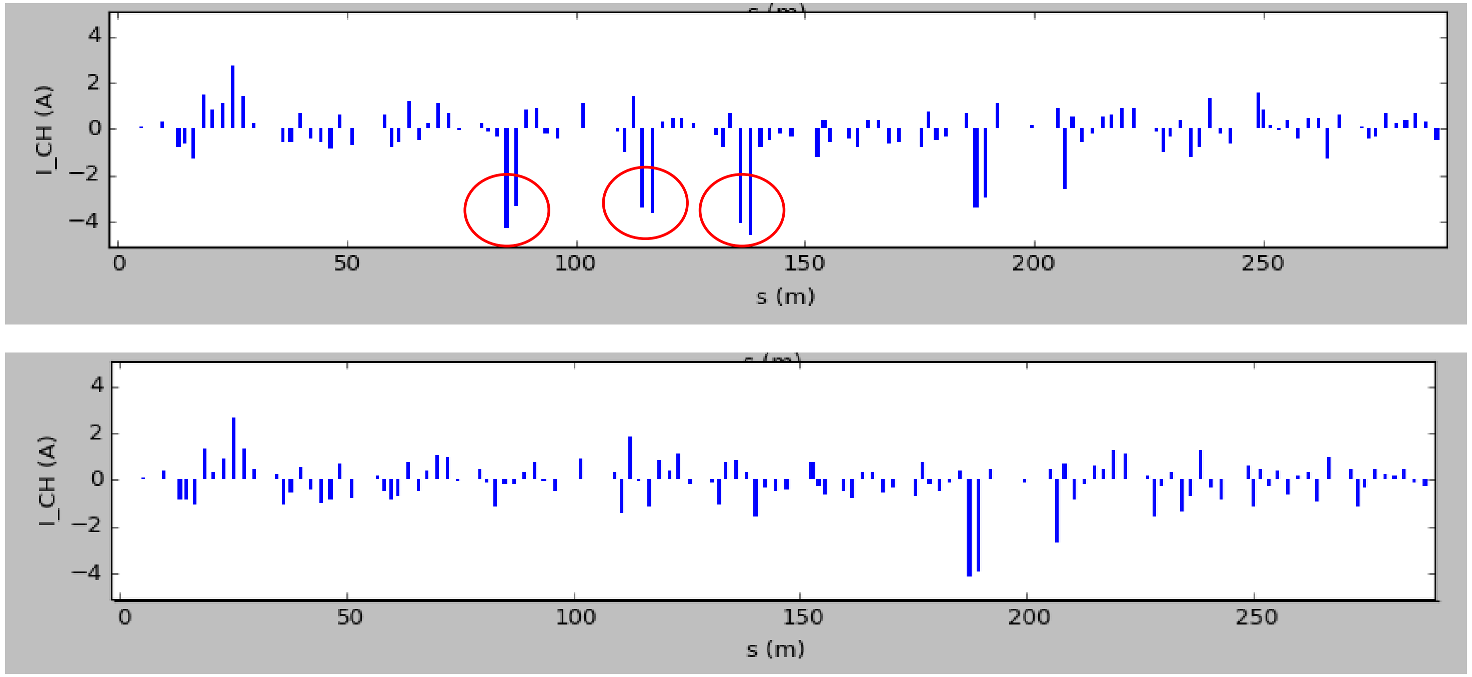




Simulated and actual vertical corrector changes. Good agreement indicates well-corrected optics.

Realignment campaign (2)

- LGB in Sector 6 and Reverse bends in Sector 4, 5 and 6 were shifted, up to 500 um, to regulate the horizontal corrector current…

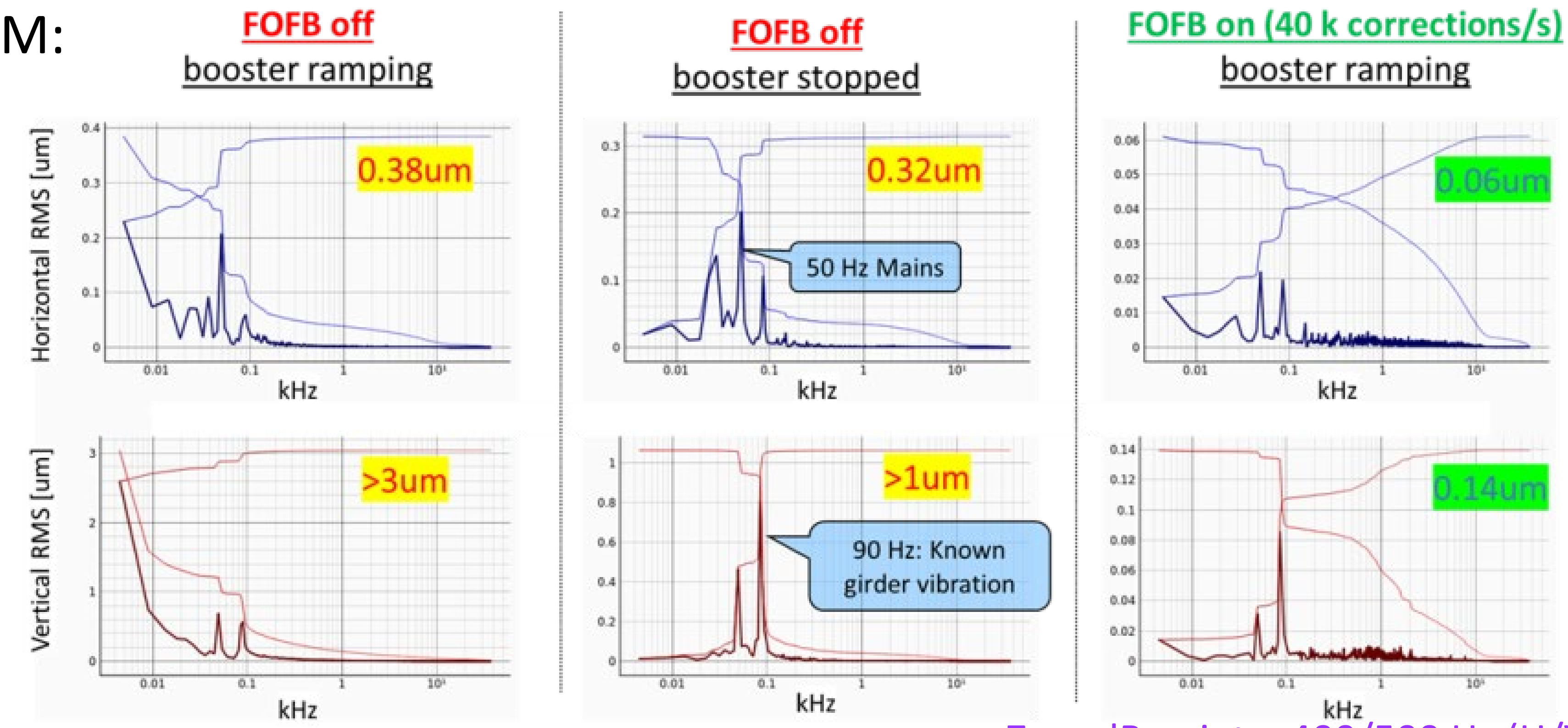


Status of feedbacks

- Fast orbit feedback (postponed from Phase 5 to Phase 7)
  - Slow orbit feedback was running since Phase 4 and good enough for beamline commissioning
  - FOFB loop is currently running at 40 kHz, possibly pushed to 80 kHz if better
  - RF frequency correction is included in FOFB; Low alpha machine, α~1e-4
- Filling pattern feedback is in-progress
- Bunch-by-bunch feedback is ready
- Tune feedback is not demanded
  - Manual tune correction from time to time

Orbit stability

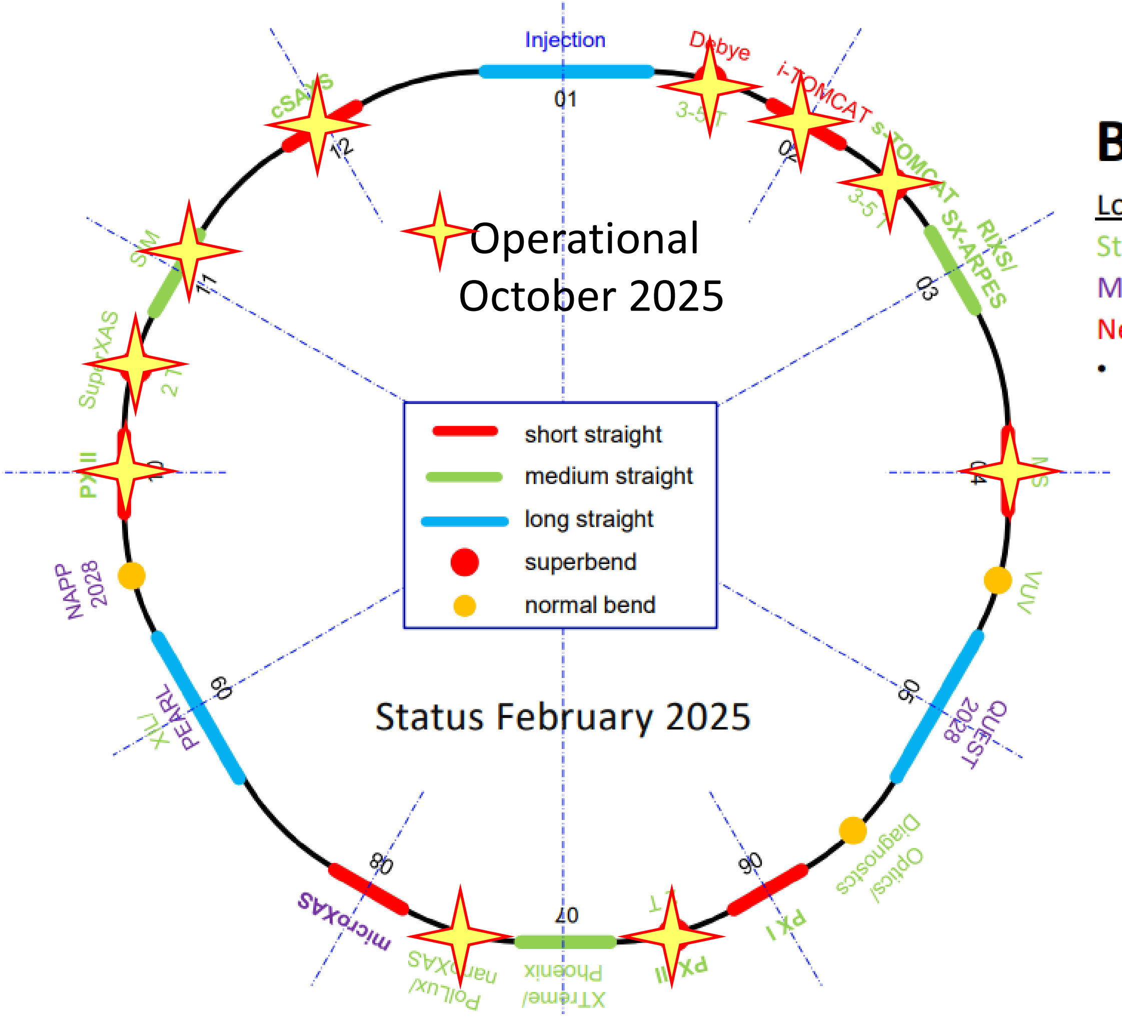
Reference BPM:



Zero dB point ~ 400/500 Hz (H/V)

All BPMs: 144/91 um in H/V

Beamline commissioning



Beamline portfolio

Locations

Stays

Moves

New

- **Boldface** indicates major upgrade

ID list

2: 1-m U10 (U15 single module interim)

3: 4-m UE36 knot

4: 2-m U14

5: 4-m UE90 knot

6: 3-m U17 (U19 interim)

7: 2-m UE38

8: 3-m U17

9: U70

10: 3-m U17 (U19 interim)

11: 2 x 2-m UE36 knot

12: 3-m U17 (U19 interim)

Lessons learnt (and known)

- Importance of preparation
  - Planning, hardware tests, magnet polarity check, high level applications, virtual accelerator, etc.
- Importance of beam diagnostics
  - BPM was the most important diagnostics to establish stored beam, and later for orbit correction and fast orbit feedback
  - Enhanced BLM system was useful to localize beam losses
- Excellent new devices
  - Thin septum: Injection efficiency close to 100% achieved
  - HOM damped cavity; no instability observed except for ion instabilities
- Vacuum conditioning/scrubbing
  - 100 A-hour is a good measure
  - Increased beam size gave us extra time for optics refinement; Lifetime was dominated by gas scattering when the pressure was high
- Beam lifetime longer than expected, 9 hours in design vs ~12 hours
  - Gas scattering lifetime might be underestimated with 1.0e-9 mbar CO assumed
  - Robust beam optics with pseudo-symmetry lattice design
  - Planar undulators including CPMU14 (3.8 mm gap) had no significant impact on the lifetime. Apple type undulators to be examined.
- Compact MBA based on permanent magnet is feasible
  - Orbit and linear optics correction were fine with limited correctors (proof for crosstalk compensation) ← This was the grave concern from beam dynamics point of view!
  - Excellent job done by magnet and alignment groups
  - No issues with large number of power supplies for matching quads + multipoles + Q/D correctors

When we made the first stored beam…

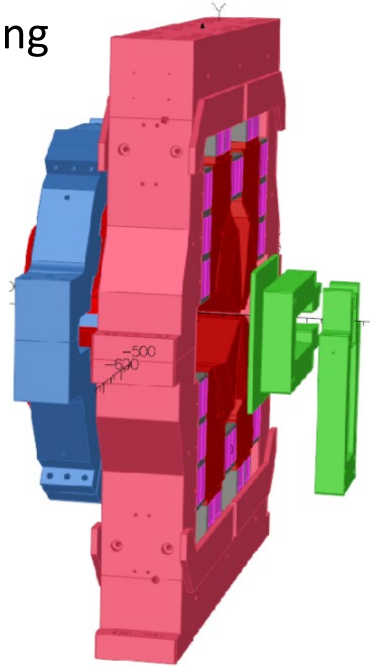
Special thanks for the input:
F. Armborst, S. Bettoni, M. Böge, H. Braun, A. Citterio,
M. Dehler, R. Ganter, B. Keil, G. Montenero, C. Ozkan,
L. Stingelin, P. Willmott, M. Wurm
Thanks to all PSI colleagues who contributed to SLS2.0

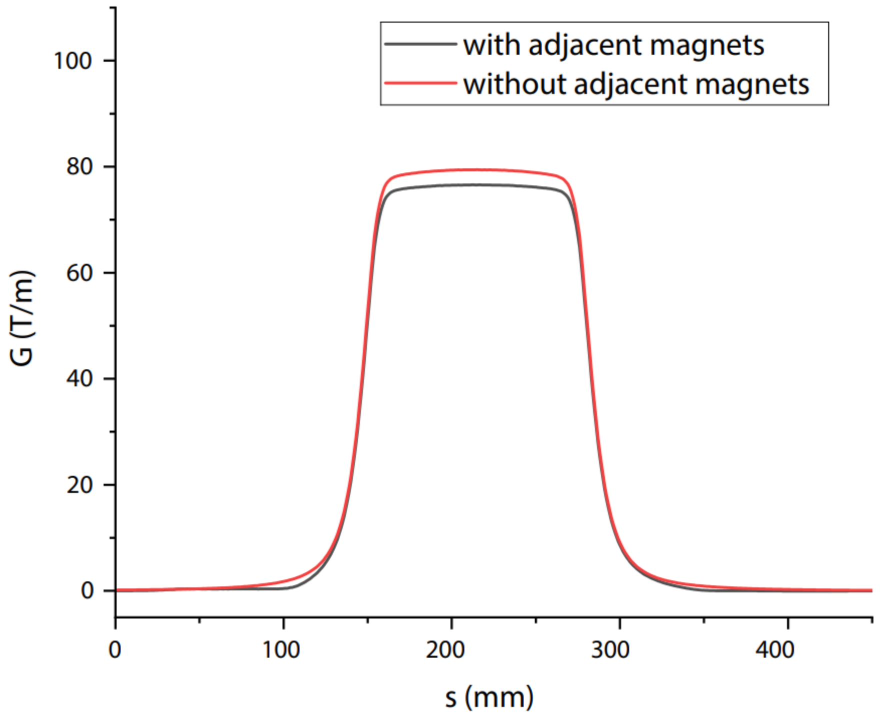
Thank you for your attention!

© Photo by Takashi Tomizaki

Magnetic crosstalk

Sextupole+Reverse Bend+Correctors
FEM modeling



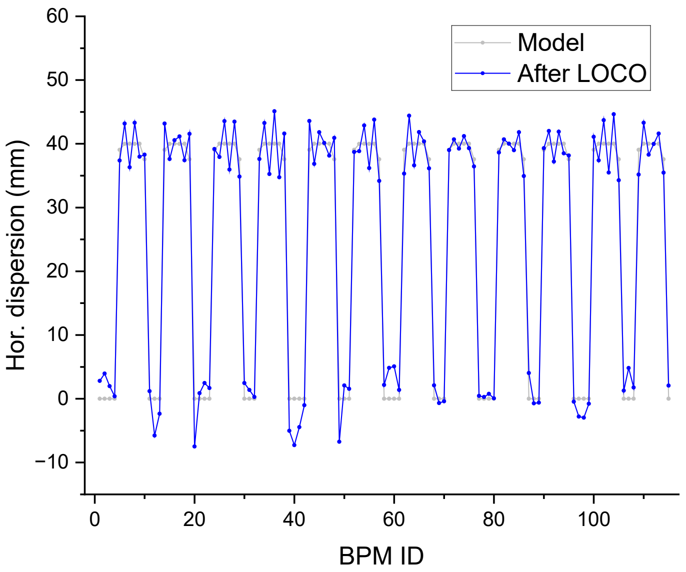


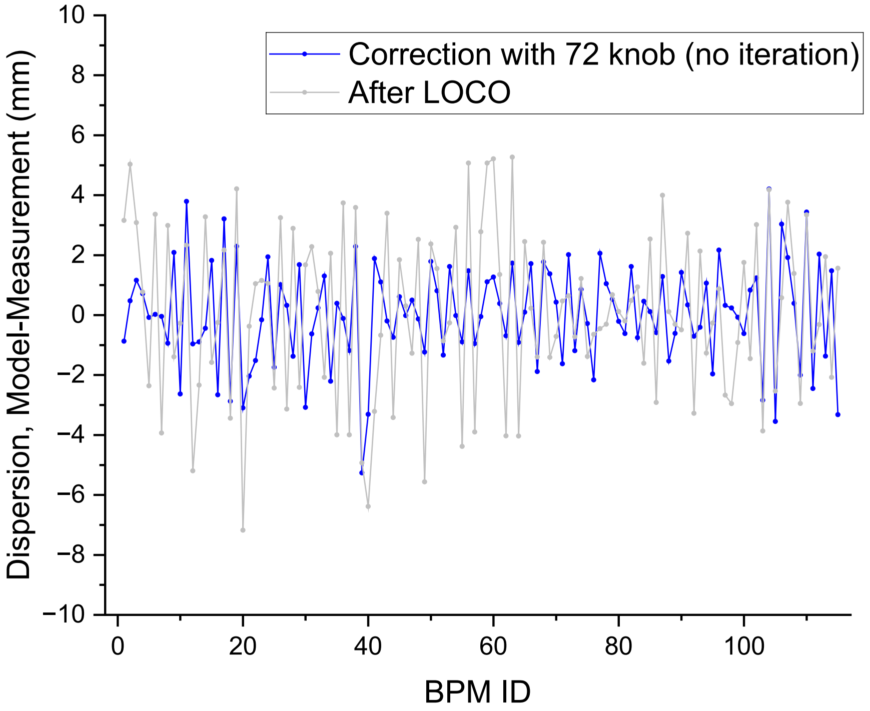
Reverse bend field attenuation 4.6%...

All permanent magnets were measured and tuned to compensate for crosstalk

Linear optics correction, Dispersion

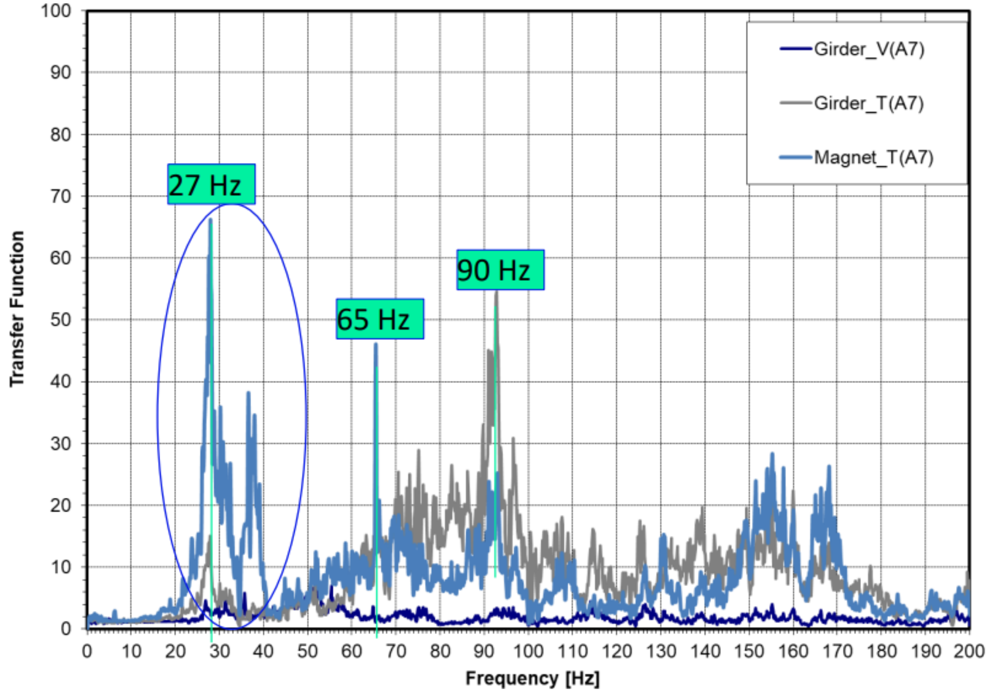
- Dispersion was not well corrected with LOCO (not expected)
- "Dispersion knob" applied
  - One dispersion knob consists of 6 quad correctors
  - Almost transparent to beta function
  - 72 dispersion knobs applied





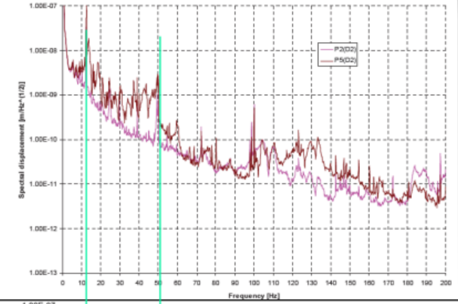
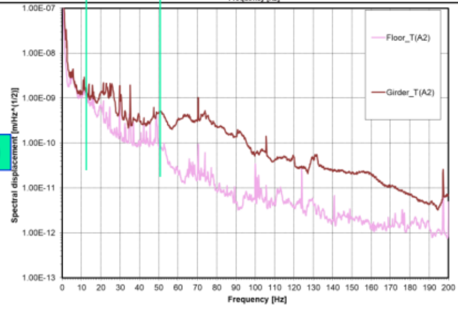
Girder and Ground vibration

Transfer function over frequency



- Most distinct Magnet amplification at 27Hz (Also seen in beam measurement)
- Girder Motion at 90 Hz is not amplified to the Magnets

Comparison to SLS 1

PSD vertical	Integrated RMS Girder	Natural frequency	Girder Style
SLS 	vertical 32nm horizontal 56nm	1st EF ~15Hz	• Mover System • 5 DOF
SLS 2.0 	vertical 7 nm horizontal 8 nm	1st EF ~25Hz	• Wedge Design • 2 DOF