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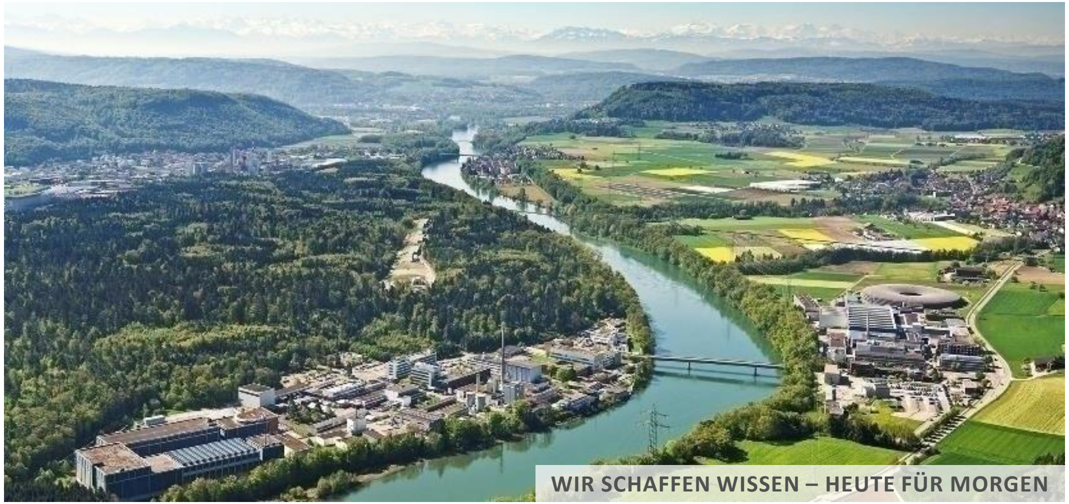

Boris Keil for the SLS 2.0 BPM & Orbit Feedback Team :: GFA :: Paul Scherrer Institute

SLS 2.0 BPM And Fast Orbit Feedback System

iFAST Low Emittance Rings Workshop, CERN, Geneva, Feb. 13, 2024

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Contents

Swiss Light Source Upgrade Project: SLS 2.0

SLS 1.0:

- 3rd generation synchrotron light source
- User operation since 2001
- Last beam Sept. 30, 2023

SLS 2.0:

- 1st beam 1/2025
- New storage ring: >40x higher hard X-ray brilliance
- Replace ageing hardware (BPM electronics from 2001, ...)
- Keep linac, booster

SLS 2.0

Parameter	Units	SLS 1.0	SLS 2.0
Circumference	m	288	
Beam Current	mA	400	
Injection Charge	nC	~0.15 (Single Bunch Top-Up @ 3 Hz)	
Beam Energy	GeV	2.4	2.7
Main RF	MHz	499.637	499.654
Harmonic No.	#	480	
Hor. Emittance	pm	5030	131-158
Vert. Emittance	pm	5-10	10
Ring BPMs	#	75	136
Ring Beam Pipe		Stainless Steel	Copper (NEG)

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SLS 2.0 BPM Requirements

σ_Y ~ 5 µm nominal, may be reduced/adjusted

Parameter	Goal	% of σ_Y
Position Noise (0.1 Hz - 1 kHz BW), 400 mA	**<50 nm RMS**	1%
Position Noise (0.1 Hz - 0.5 MHz BW), 400 mA	<1 µm RMS	20%
Position Noise (0.5 MHz BW), 0.15nC, 1 Bunch	<50 µm RMS	-
Electronics Drift (400mA beam, constant)	<100 nm / hour	2%
	<400 nm / week	8%
	<1 µm / year	20 %
Overall Drift (Electronics + Cables + Mechanics)	<250 nm / hour	5%
	<1 µm / week	20%
	<2.5 µm / year	50%
Beam Current Dependence (Const. Fill. Patt.)	<100 nm / 4 mA	2%

Contents

SLS 2.0: BPM Types & Beam Pipe

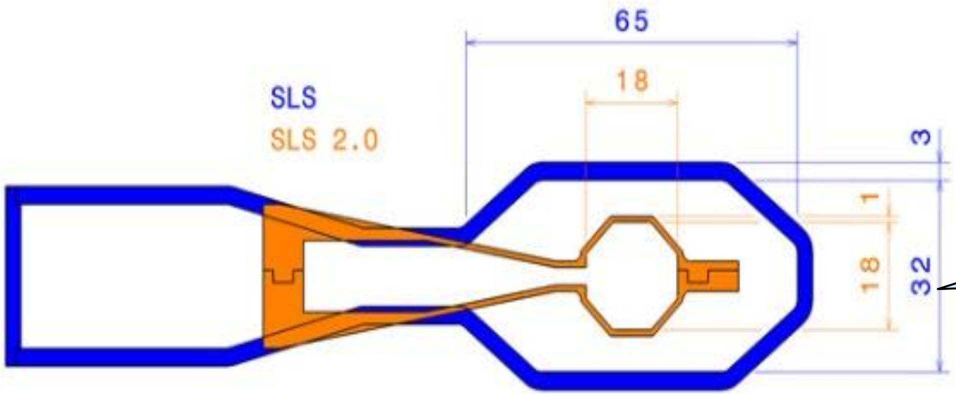
Decaying 500 MHz sine

All: 4 diagonal electrodes A,B,C,D

X[mm] ~ k_x * (A-B-C+D)/(A+B+C+D)

Location	BPM Type	geometry factors k_x/k_y [mm]
Linac & Transfer Lines	Resonant Stripline	various
Booster	Button	8.3/7.7
SLS 1.0 Ring	Button	16.7/14.3
SLS 2.0 Ring	Button	**7.1/7.2**

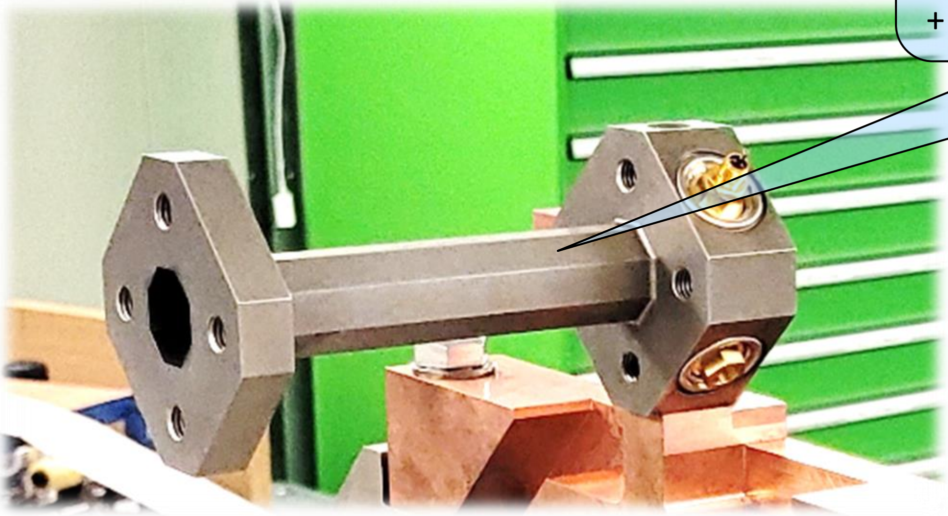
Same BPM electronics has >2x better resolution at SLS 2.0 compared to SLS 1.0

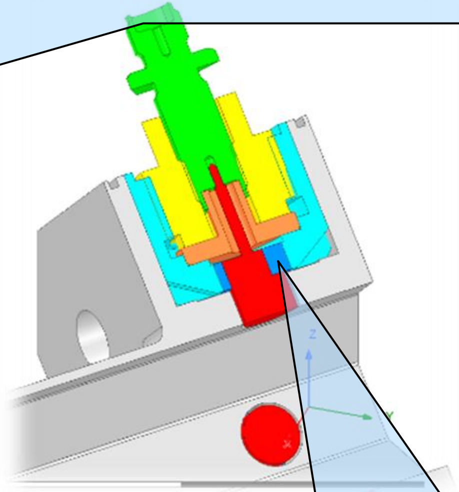


Dimensions [mm]

SLS 2.0 Button BPM

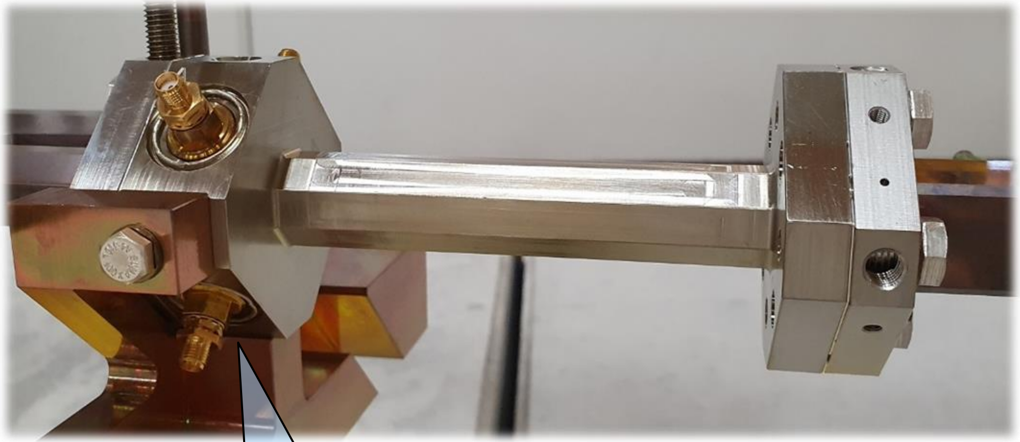
Combined BPM + orbit corrector dipole magnet beam pipe (taper 18→21 mm = synchrotron radiation shielding). 0.5 mm steel + 5 µm Cu + 0.5 µm NEG)

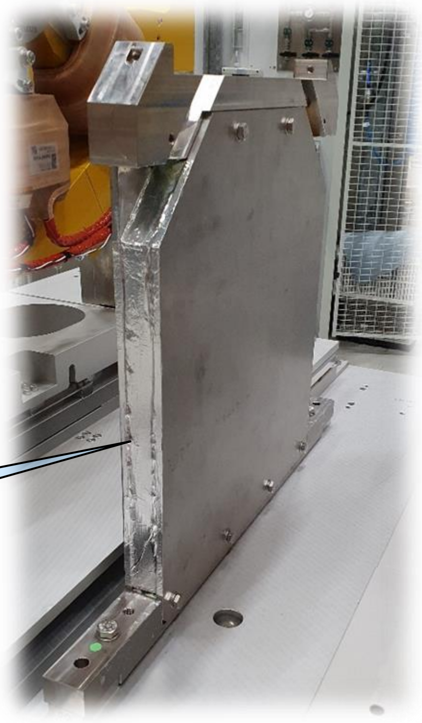




Borosilicate glass (dark blue): Inner conductor (red) with coaxial asymmetry → HOM power reduction & spectral spreading

BPM Mechanics: Support

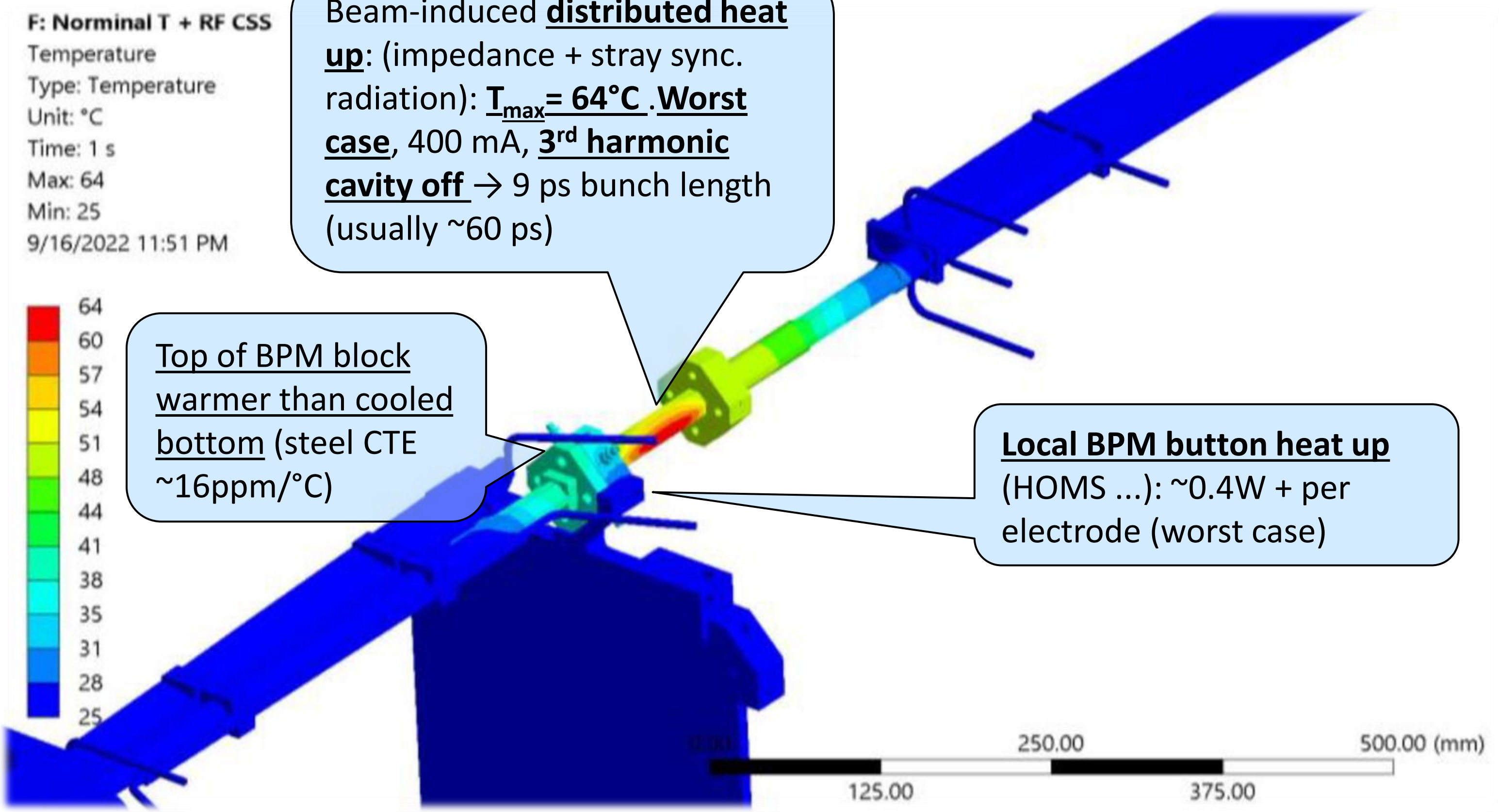




Water cooled copper block reduces position drift

Double steel plates, filled with sealed compound of balsawood & viscoelastic glue

BPM Mechanics: Temperature Simulation



Beam-induced **distributed heat up**: (impedance + stray sync. radiation): **T_{max}= 64°C .Worst case**, 400 mA, **3rd harmonic cavity off** → 9 ps bunch length (usually ~60 ps)

Top of BPM block warmer than cooled bottom (steel CTE ~16ppm/°C)

Local BPM button heat up (HOMS ...): ~0.4W + per electrode (worst case)

BPM Mechanics: Performance

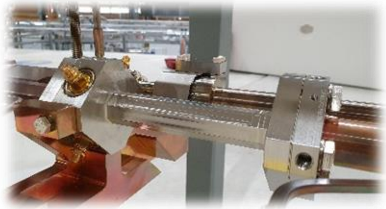
Center of BPM block would move even if bottom side did not: Stainless steel CTE ~16 ppm/°C → distance of ~30 mm & dT ~ 10°C causes dY ~ 5 µm.

Simulated beam-induced BPM pickup *center* motion	**ΔX [µm]**	**ΔY [µm]**
Motion from **0 mA to 400mA** beam current	-11.3	4.7
Motion @ **Top-up injection (400...404mA)**	< 0.1	<0.05

- Assume worst case (400 mA, 9 ps bunch length, 3HC off)
- Additional drift due to air & water:
  - Simulation: ΔY ~ 5 µm/°C water temperature change
  - SLS 1.0 water often ~0.03°C peak-peak (→150nm), but not always ...
  - Being improved for SLS 2.0 (variable RPM for cooling machines, ...)
- Beam, air & water cause common drift of all BPMs → less critical (X-ray angle ...)

BPM Mechanics: Production Status

- All BPM electrodes produced
- Most BPM blocks produced
- Beam pipe assembly in progress
- No vacuum problems so far



Contents

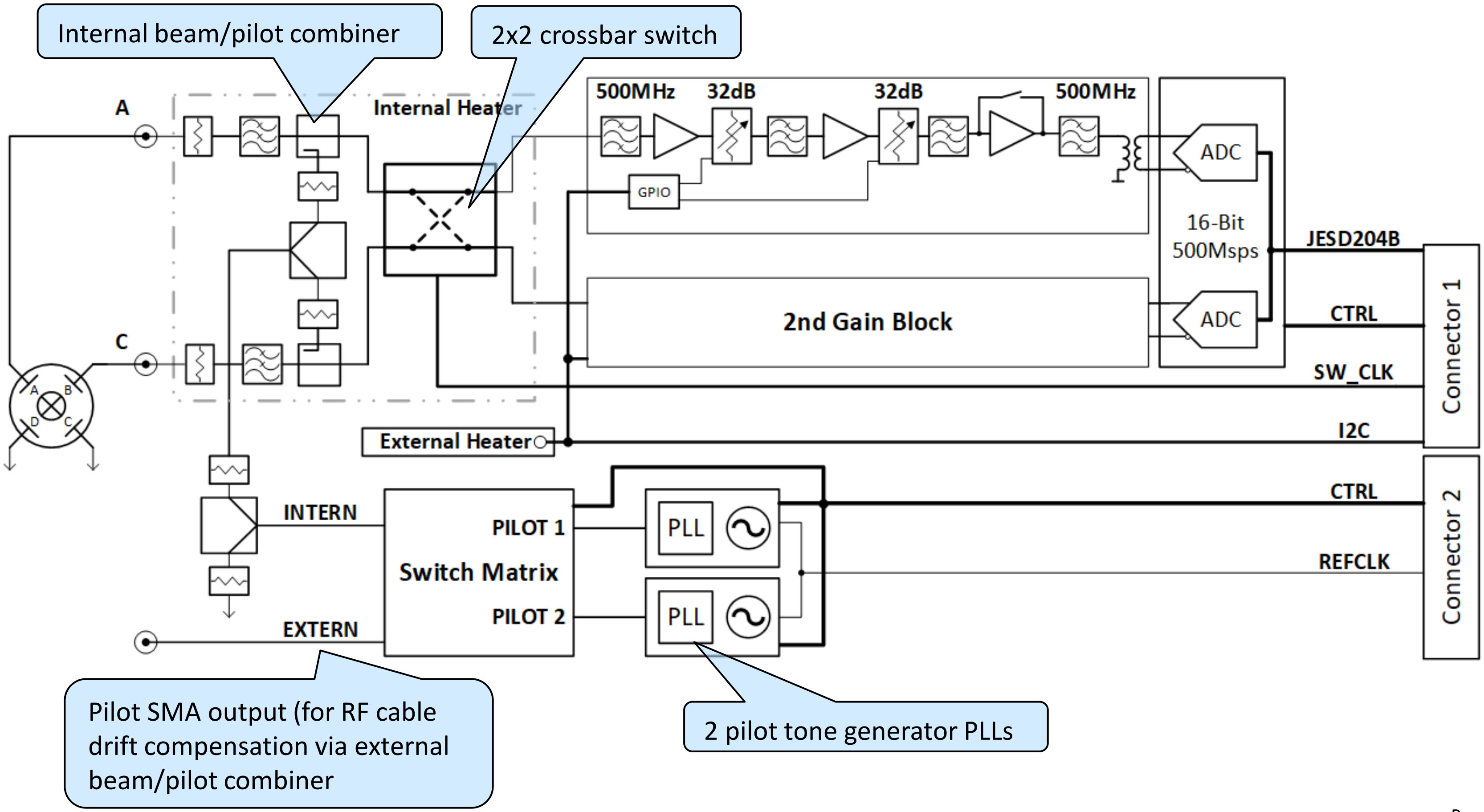
SLS2 BPM Electronics: "DBPM3" (PSI Design)

Generic 19'' back-end (AMD/Xilinx **Zynq UltraScale+ MPSoC: CPUs & FPGA on same chip**), already used in SwissFEL (IBIC'22 TUP12)

SLS 2.0: **3 RF Front-End** (RFFE) modules per unit, **integrated ADC** (JESD204B)

Redundant power supply module

DBPM3 SLS 2.0 RFFE Block Schematics



SLS 2.0 BPM Position Drift Suppression

Mechanics → stable air & water & beam current (top-up).

RF cables (differential drift relevant):

- Passive methods:
  - Equalize cable properties (measure & sort by TOF/attenuation)
  - Thermal cable bundle isolation
  - Cable trays below floor (lower temp. variation)
- Active methods (so far):
  - Pilot tone

Electronics: Pilot tone, crossbar switch, active temp. regulation (DBPM3: 14 heating zones per RFFE ...), choose low-drift components, ...

All: Optional feed-forward correction on temperature & humidity sensors

Contents

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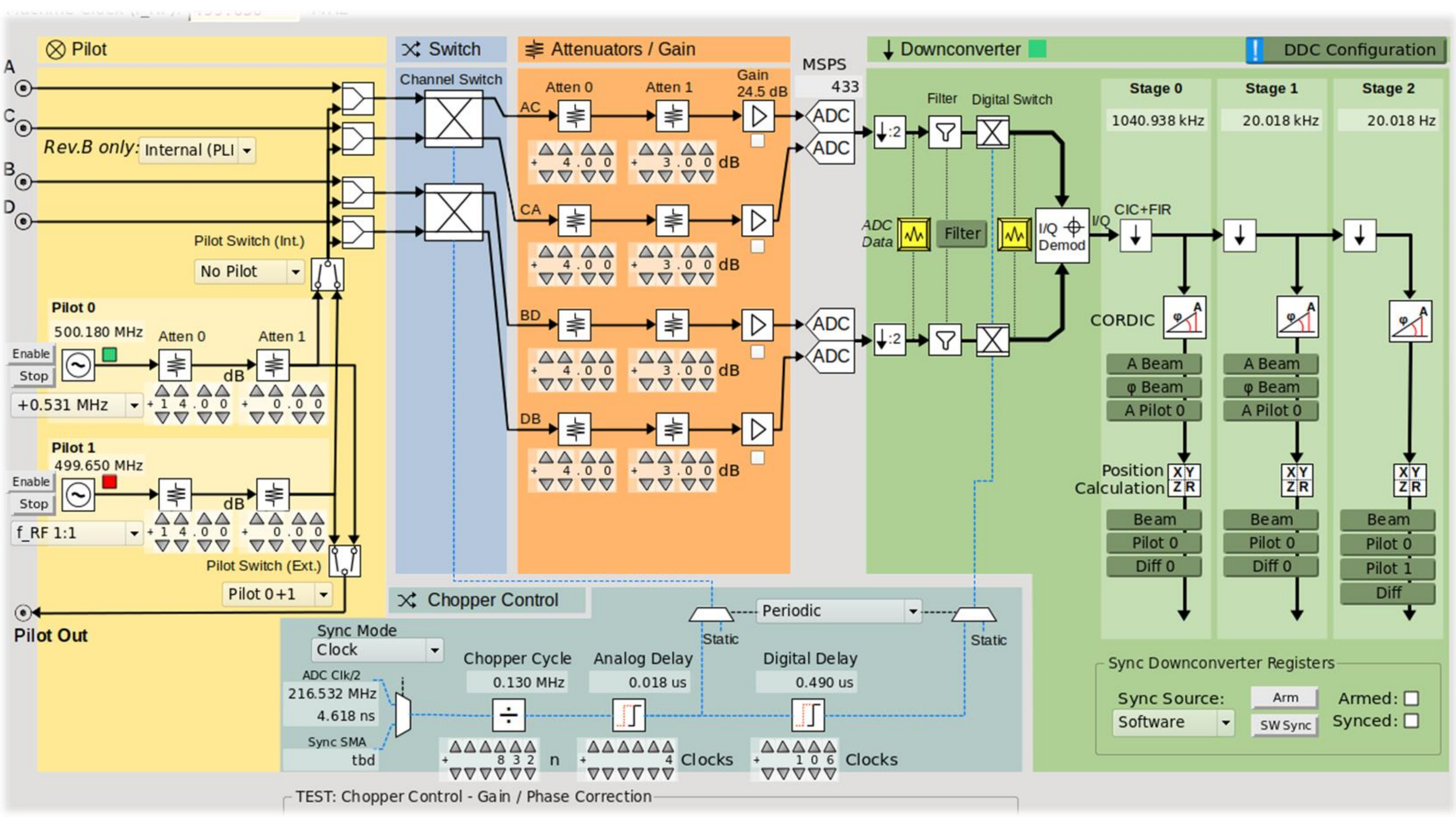
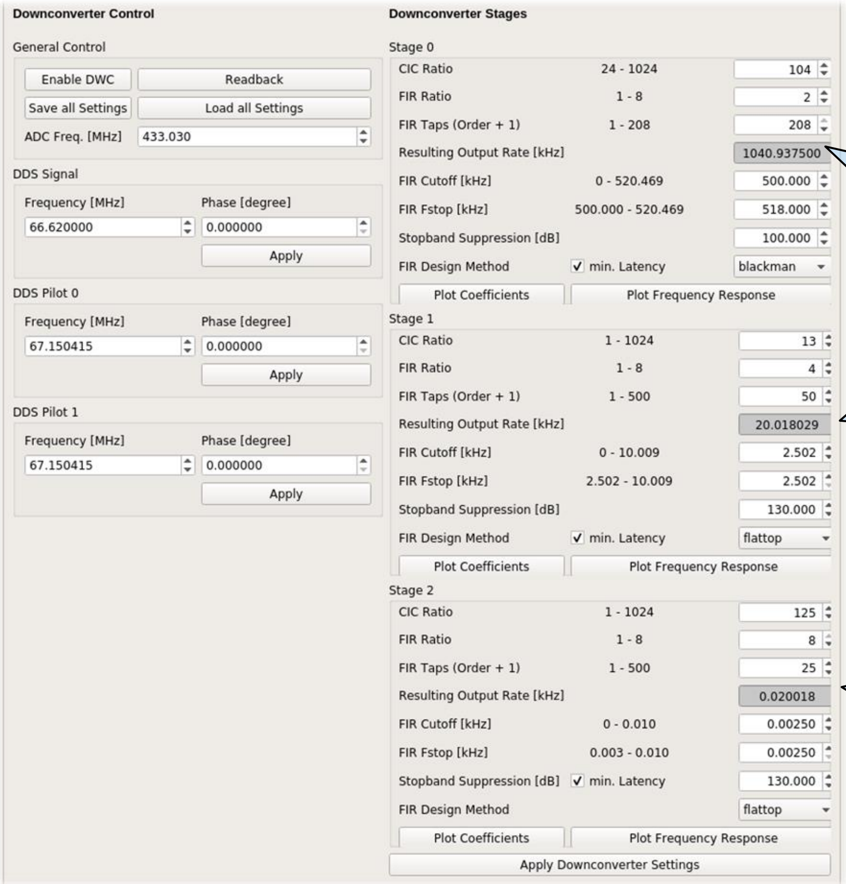
GUI: Settings for DBPM3 Test @ SLS 1.0 Ring

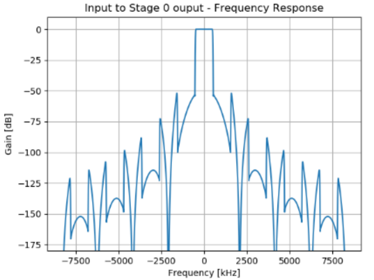


Python GUI: DBPM3 DDC Filters

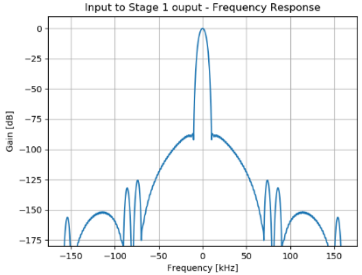
Programmable during operation via EPICS ...



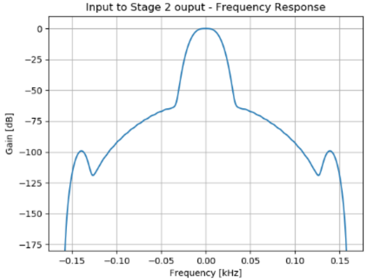
DDC **Stage 0**: 1.04 MSPS (= turn-by-turn), **0.5 MHz BW**



DDC **Stage 1**: 20 kSPS, **3.3 kHz BW** ("fast orbit feedback data").



DDC **Stage 2**: 20 SPS, **11 Hz BW** ("slow data")

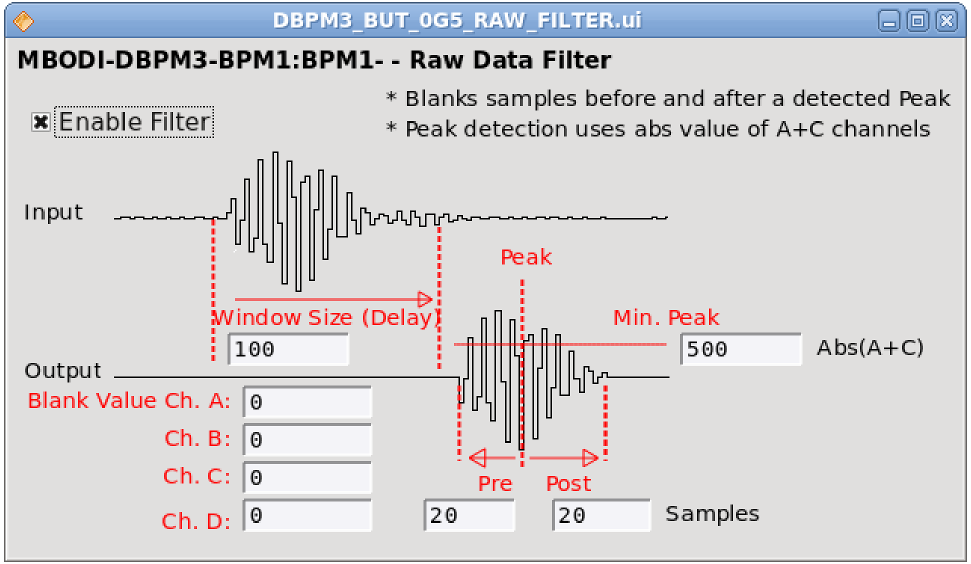


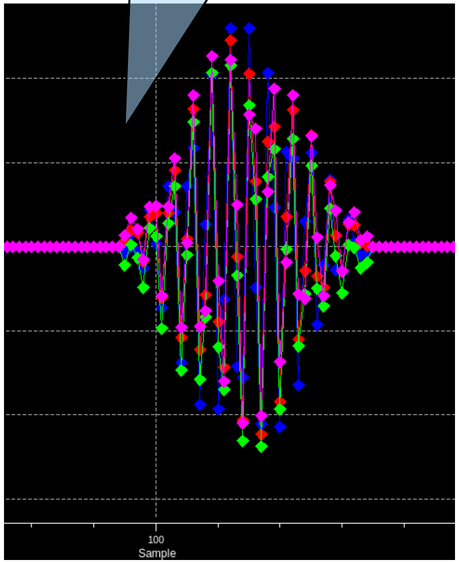
DBPM3 Electronics: 1-Bunch Position Resolution

DBPM3 electronics beam test @ SLS 1.0

- Booster (button BPMs): ~36µm RMS noise @ 0.15nC
- Transfer line (res. striplines): ~9µm RMS @ 0.15 nC

Special single bunch mode: DBPM3 firmware can zero ADC data outside signal peak area → improves resolution using normal DDCs





DBPM3 Electronics Test @ SLS Storage Ring

Test Setup:

- DBPM3 RFFE Rev. C (received 8/2023): First version with pilot output
- 400 mA SLS 1.0 ring BPMs beam signal (last beam 9/2023)
  - Sum signal of 4 buttons combined with DBPM pilot output
  - Then split to 4 RFFE channels (test electronics drift only → short cables)
  - Simulates centered beam
- 1 pilot , $f_{pilot} = f_{beam} + 0.531$ MHz
- ADC: 433 MSPS, 50% full scale (25% beam + 25% pilot)
- 2x2 crossbar switches @ 130 kHz
- k_x/k_y = 7.1mm/7.2mm (SLS 2.0 ring)
- Water cooled 19'' rack

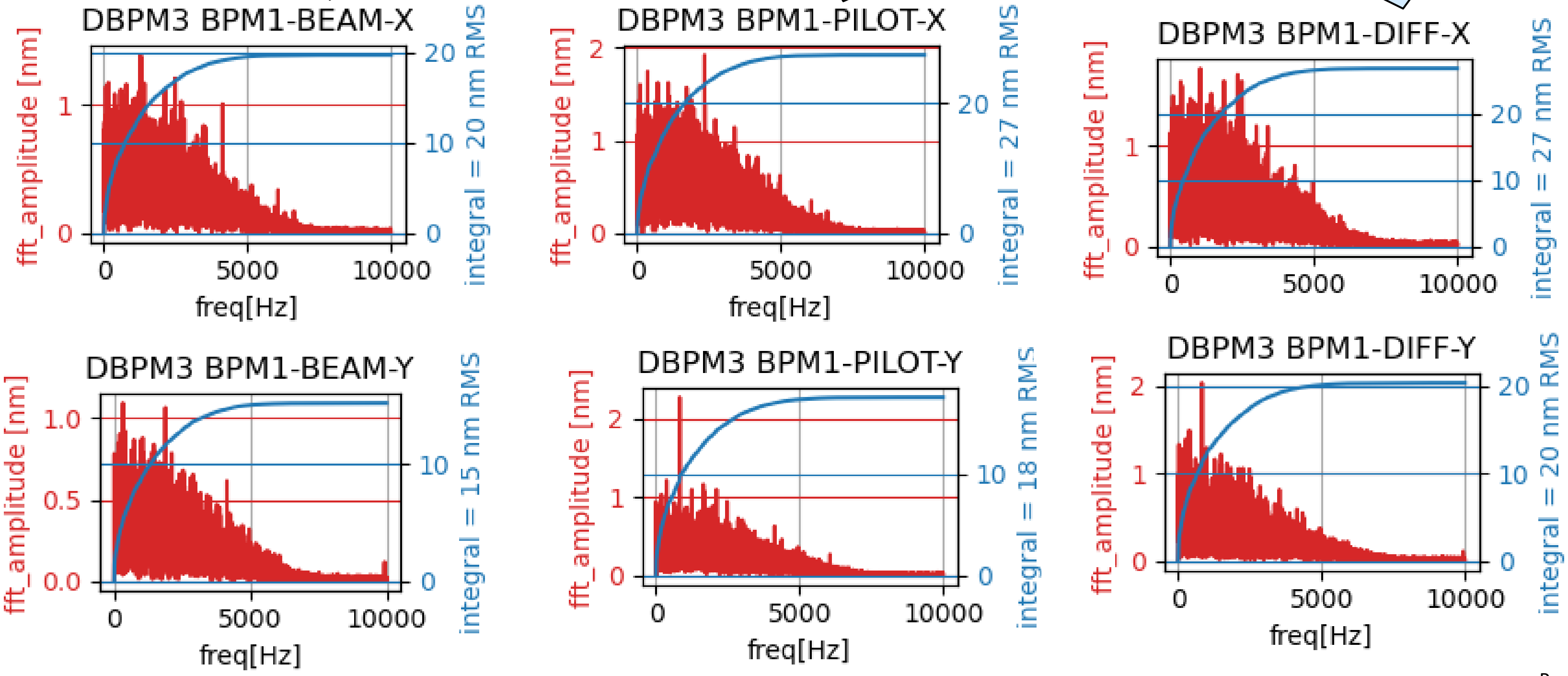
DBPM3 Electronics: RMS Position Noise

20 kSPS, 3.3 kHz bandwidth

Beam signal only:
20 nm (X) / 15 nm (Y)

Pilot signal only:
27 nm (X) / 18 nm (Y)

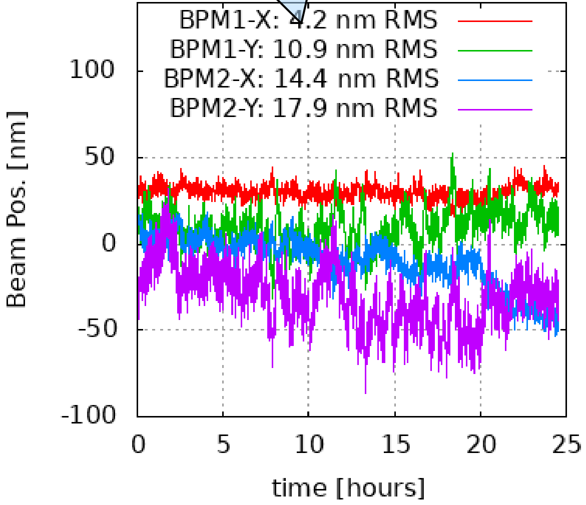
Beam minus Pilot:
27 nm (X) / 20 nm (Y)



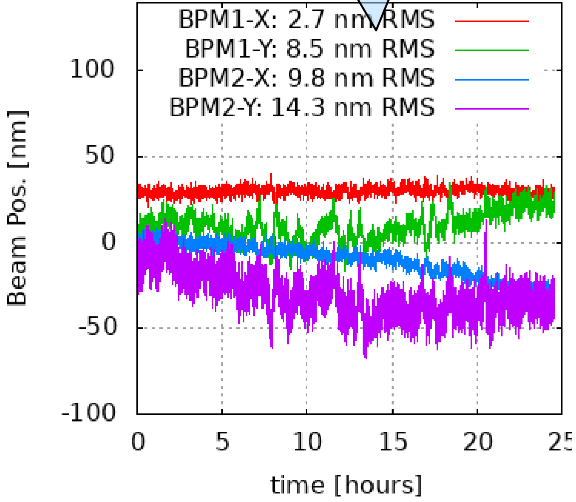
DBPM3 Electronics: 24 Hour Position Drift

20 SPS, 11 Hz bandwidth, 1 plot point per 30s recorded, no smoothing

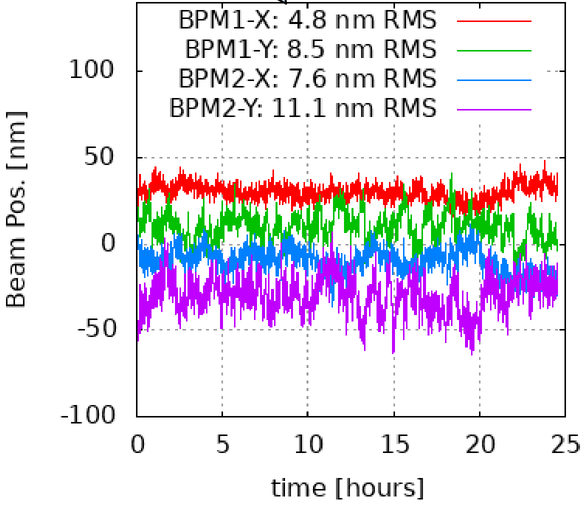
Beam signal only:
< 17.9 nm RMS



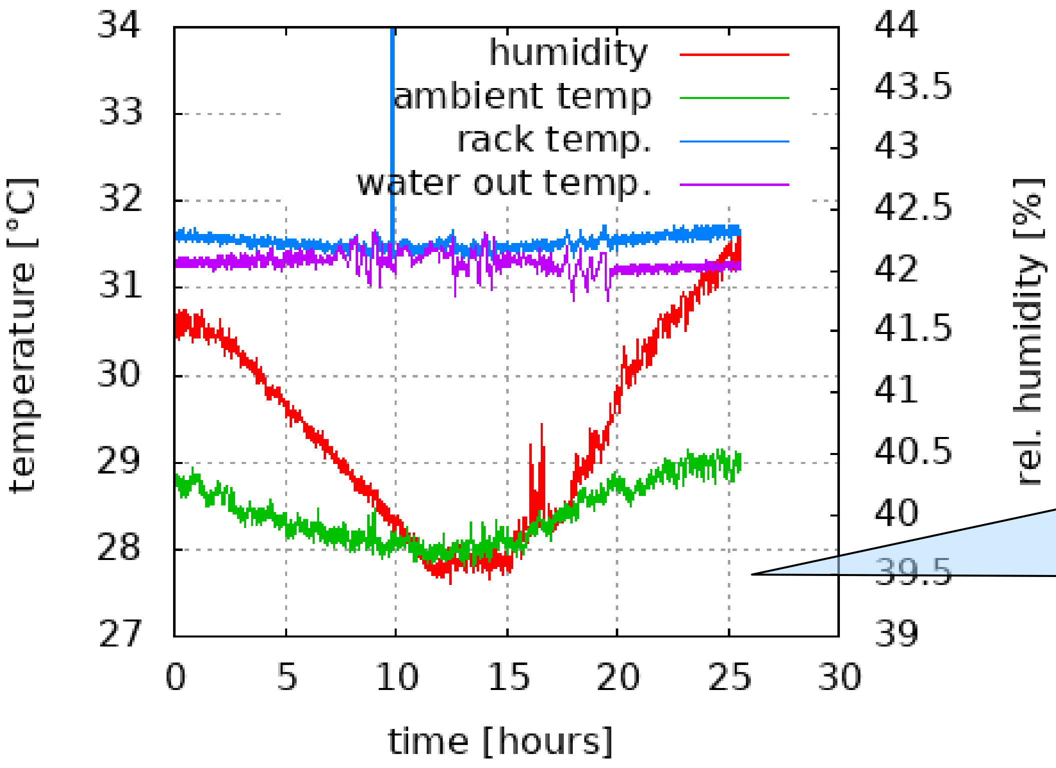
Pilot signal only:
< 14.3 nm RMS



Beam minus Pilot:
< 11.1 nm RMS



DBPM3 Drift Test: SLS Hall Ambient Conditions



Test in SLS 1.0 building. Expect similar/better conditions in SLS 2.0 (rack PID temp. controller & cooling water to be improved ...)

Contents

SLS 2.0 Ring Fast Orbit Feedback (FOFB)

FOFB Feature	**Units**	**SLS 1.0**	**SLS 2.0**
BPMs in FOFB Loop	#	73	115+
Horizontal Dipole Correctors	#	73	115+
Vertical Dipole Correctors	#	73	115+
Corrector Magnet Type		Sextupole Add-on Coil	Separate Dipoles
Min. Beam Size @ BPM	µm	~5	~5
Data Network Topology		Ring (12 DSP Engines)	**Tree (Central Engine)**
BPM Bandwidth	kHz	0.8*	**~3***
Corrector Power Supply Bandw.	kHz	~3	**3-5****
Correction Rate	kHz	4	**20-100**
Loop 0dB Bandwidth	Hz	~100	**~350…400 *****

* BPM bandwidth programmable (Hz … MHz)

** Magnet + beam pipe bandwidth >> 10 kHz. SLS 2.0 magnet power supply: Bandwidth programmable (within limits …)

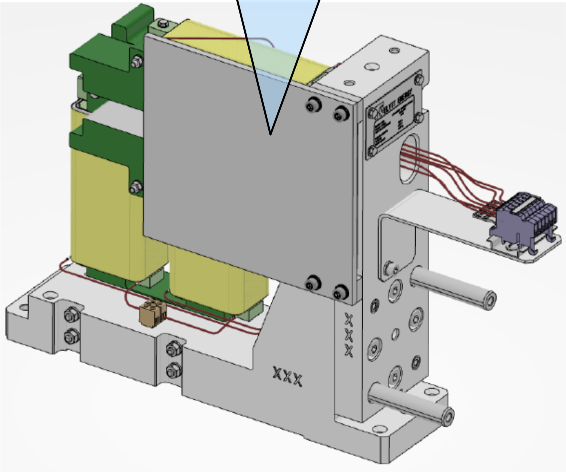
*** Depending on programmed BPM & magnet PS bandwidth.

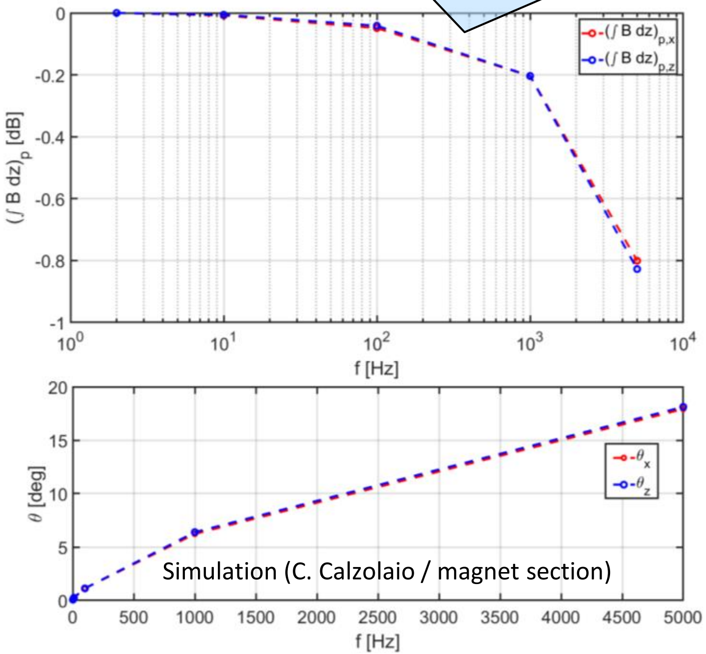
SLS 1.0 experience: **No significant perturbations > 150 Hz**, but higher BPM & corrector bandwidth adds more noise to beam -> targeting 350 Hz 0dB bandwidth, little motivation to go higher (and space/cost constraints …).

FOFB Dipole Corrector Magnets

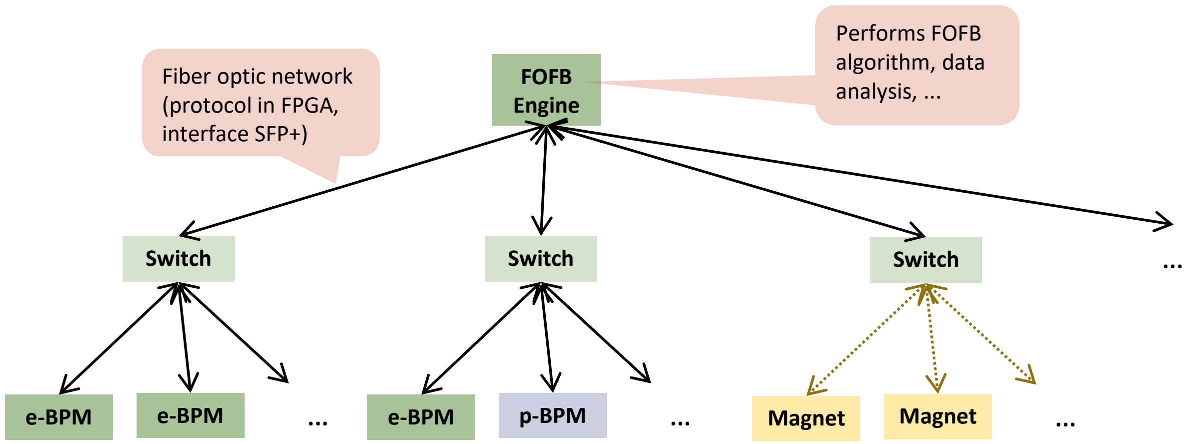
SLS 2.0: Magnets very close (price for keeping old tunnel & circumference …)
→ laminated shield to minimize inter-magnet field crosstalk

Magnet bandwidth ~ inverse square of **lamination thickness**.
SLS 2.0: **0.35mm** -> bandwidth limited by power supply (trade-off strength vs. noise), not magnet/beam pipe





SLS 2.0 FOFB System Topology



Data transfer from/to "FOFB Engine": Tree topology

- Can be scaled/extended (size, performance)
- Allows mix of different monitors & actuators (e-BPM, photon BPM, magnet PS, ...)
- Uses fiber optic links (50MBaud POF for magnet PS, 5-10 Gbps SFP+ for everything else, PSI custom protocol)

Contents

Summary & Outlook

BPM Status:

- Mechanics: Production nearly finished, installation in progress.
- Electronics:
  - Latest version: Promising results, but only few pcs tested at SLS 1.0 shortly before dark time
  - Forced to change PCB soldering company (old one shut down CH site …)
  - Risk reduction: Want more time for test & possible improvements of final version.
    - Production of 1st generation of new BPM electronics has started, use for most ring BPMs in 2025, keep old SLS 1.0 BPM electronics in uncritical booster/linac/TL one more year
    - Produce 2nd generation in 2025 & install in ring 2026, move 1st generation to booster/linac/TL, get rid of old SLS 1.0 hardware.

FOFB Status:

- Magnets and power supplies produced, installation starting
- New central SLS 2.0 FOFB engine & fiber links to BPMs/PS successfully tested at SLS 1.0 with beam
  - So far algorithm in software (CPU of Zynq UltraScale+ MPSoC) → 4 kHz correction rate @ SLS1
  - Presently moving algorithm to FPGA part of MPSoC → expect 20+ kHz corr. rate for SLS 2.0

Thanks to:

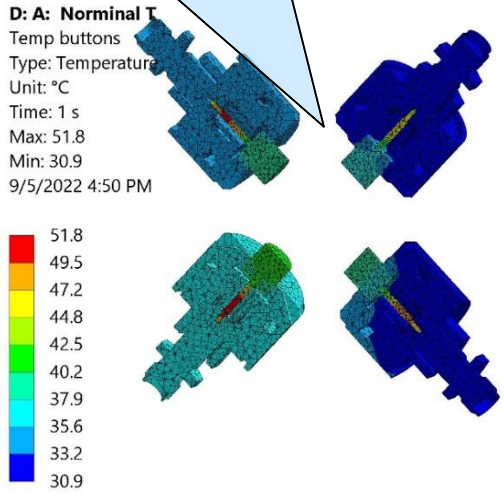
F. Marcellini (Pickup/RF)
M. Roggli (RF Front-End)
M. Rizzi (RF/Electronics)
R. Ditter (Crate/Back-End)
J. Purtschert (Firmware/Software)
G. Marinkovic (SW/FW/HW)
X. Wang (Mechanics/Simulations)
D. Stephan (Vacuum/Mechanics)
C. Calzolaio (Magnets)
...
and many others in the SLS 2.0 project team & PSI support groups

Appendix: Supplementary Slides …

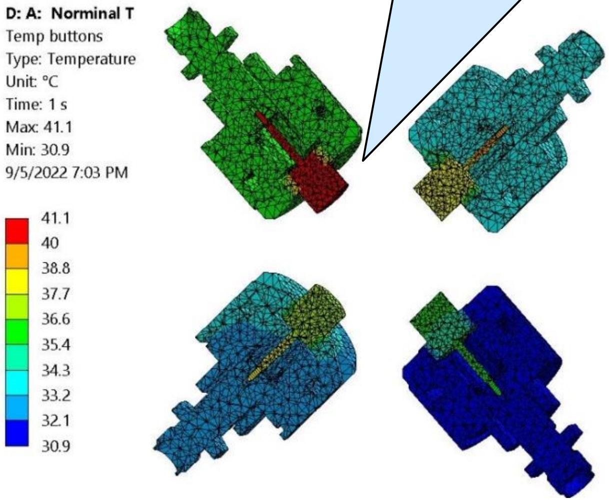
BPM: Button Temperature

Simulation of button electrode temperature (rare worst case: 400 mA, 3HC off, 9 ps bunch length)

Inconel button (= **standard for our production company** BC-Tech) + borosilicate glass isolator: **52°C max.** -> **O.K.**



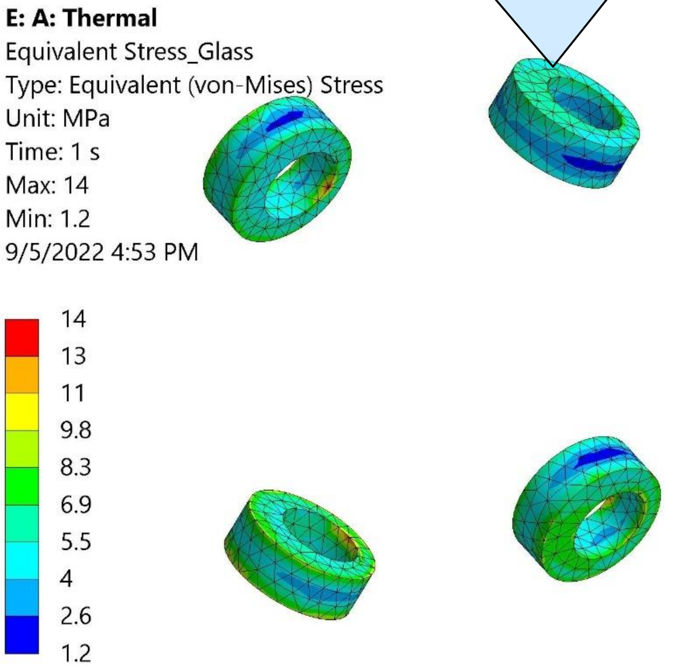
Alternative: Molybdenum button. Temperature only **11°C lower** (button temperature **dominated by glass, not metal).**

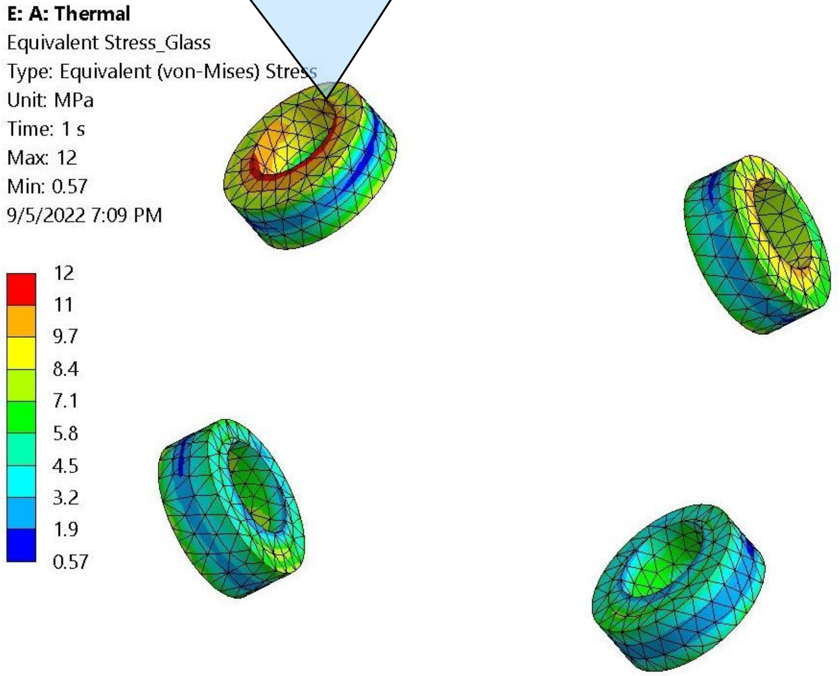


BPM: Thermal Stress of Borosilicate Glass

<u>Inconel button</u>: Stress = 14 MPa (values < 50 MPa uncritical) for worst case (400mA, 9ps bunch length)

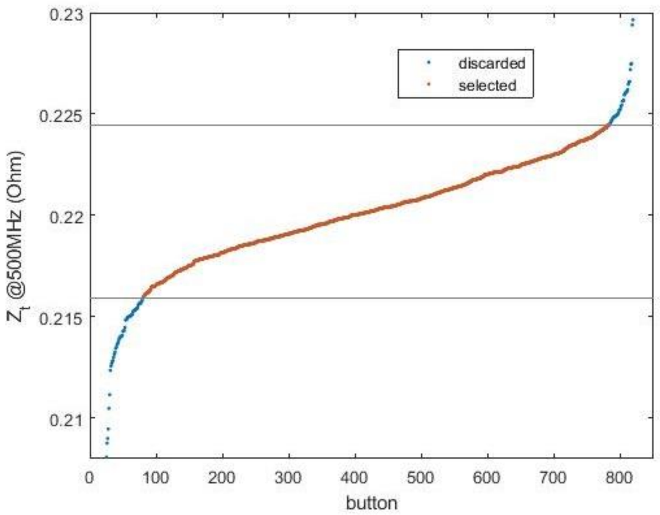
<u>Molybdenum button</u>: 12 MPa (values < 50 MPa uncritical) → **<u>not much better, but BC-Tech never used it → schedule risk → keeping Inconel</u>** for SLS 2.0

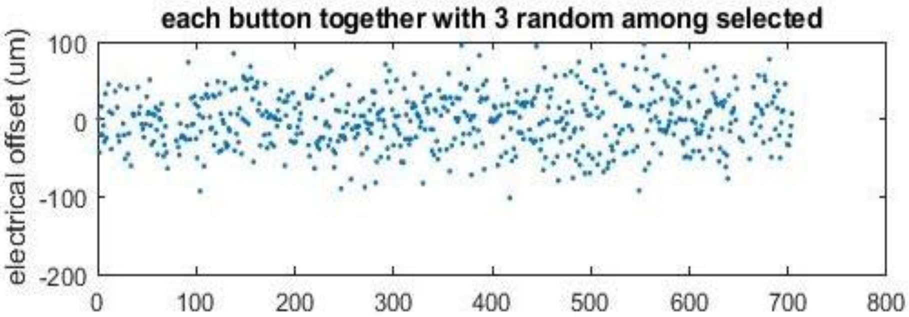


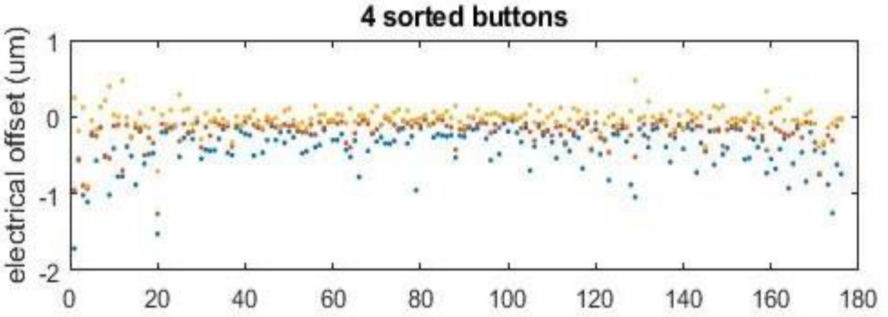


BPM Button Electrode Sorting

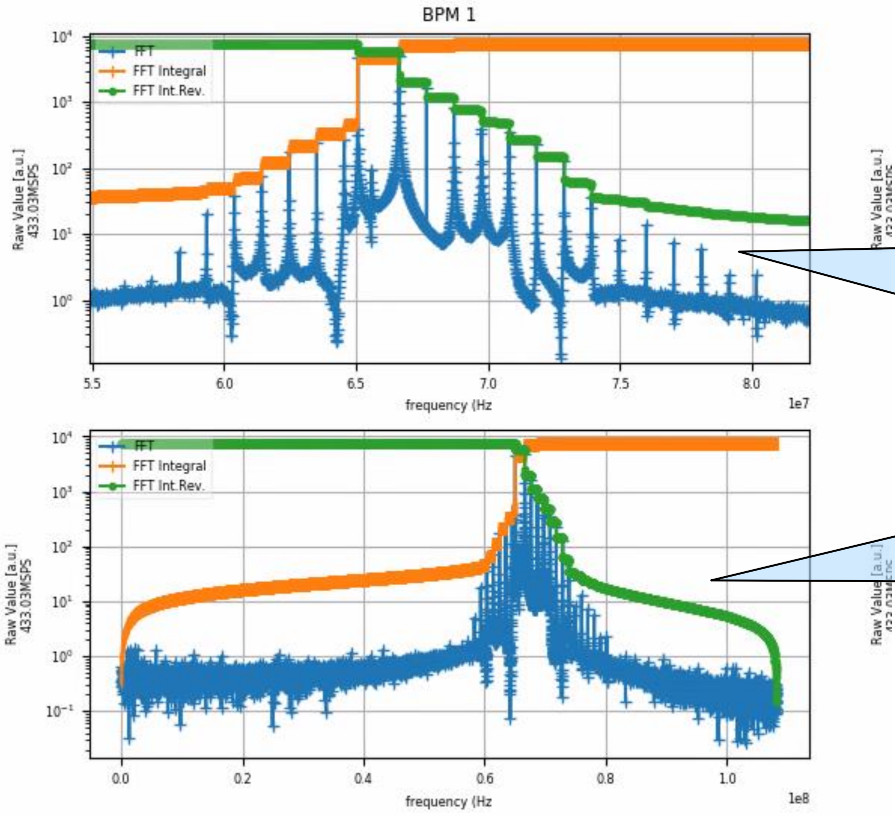
- <u>Transfer impedance</u> of all button electrodes <u>measured pre-welding</u>
- <u>Sorted</u> by impedance: <u>Reduce</u> contribution to position <u>offset</u> from ~50 µm to <u>~1 µm</u>







SLS2 BPM Electronics: Prototype Test @ SLS1



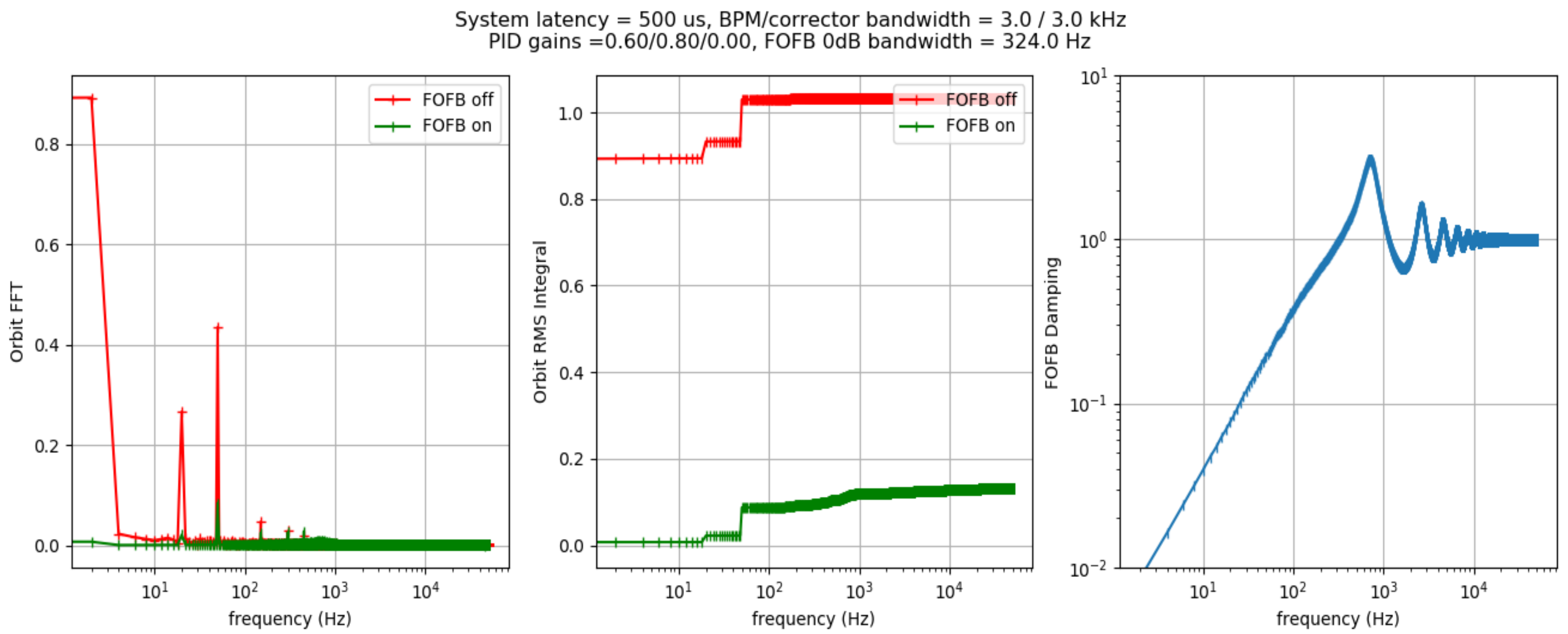
ADC signal spectrum:
~500 MHz beam signal undersampled at ~433MSPS -> beam signal visible at ~66.6 MHz

Bandwidth of RFFE band pass filters limit/damp of revolution harmonics seen by ADC

FOFB Bandwidth & Noise Considerations

- Higher FOFB 0dB bandwidth improves damping of high-frequent perturbations, but also adds noise to beam
- Perfect machine: No perturbations → best orbit stability when FOFB is off ☺
- Real-world machine: Optimal choice of FOFB bandwidth depends on perturbation spectrum
- SLS 1.0: Little perturbations > 150 Hz, mainly 50 Hz harmonics & sub-100 Hz vibrations
- SLS 2.0: Space & cost & time constraints → choice of single dipole orbit corrector used both for static and dynamic orbit corrections
    - Corrector must be strong enough for larger static corrections (to be reduced by mechanical realignment)
    - Corrector must be fast (for FOFB) but not add to much noise to beam
    - Expect 350 Hz 0dB bandwidth to be good compromise between damping perturbations & adding noise.

FOFB Bandwidth Simulation



Simulation of SLS 2.0 FOFB correction bandwidth of 324 Hz, assuming 3 kHz BPM and corrector bandwidth, and 0.5ms system latency (= conservative assumptions, may get better). 0dB bandwidth can be increased > 400 Hz, at expense of adding more noise to beam.