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

Development of the SLS 2.0 BPM System

IBIC 2023, Sep. 11, 2023, Saskatoon, Canada

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	
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)

SLS 2.0: BPM Types & Beam Pipe

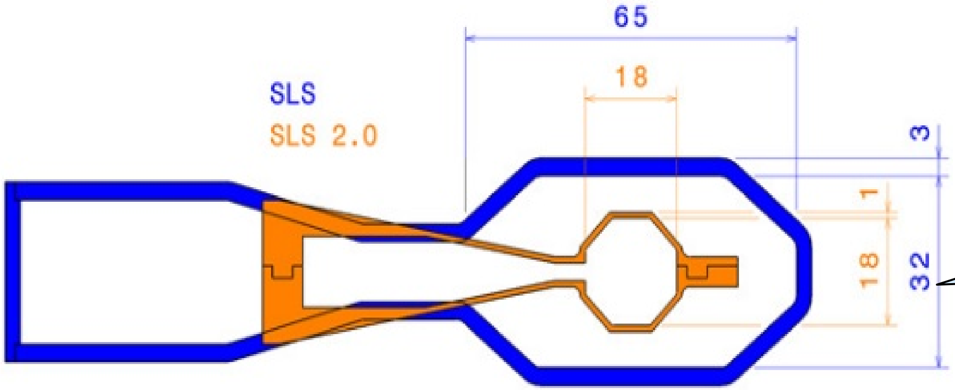
Decaying 500 MHz sine

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]

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SLS 2.0 BPM Requirements

σ_Y~5µm 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	<1000 nm RMS	20%
Position Noise (0.5 MHz BW), 0.15nC, 1 Bunch	<50 um RMS	-
Electronics Drift (400mA beam, constant)	<100 nm / hour	2%
	<400 nm / week	8%
	<1000 nm / year	20 %
Overall Drift (Electronics + Cables + Mechanics)	<250 nm / hour	5%
	<1000 nm / week	20%
	<2500 nm / year	50%
Beam Current Dependence (Const. Fill. Patt.)	<100 nm / 4 mA	2%

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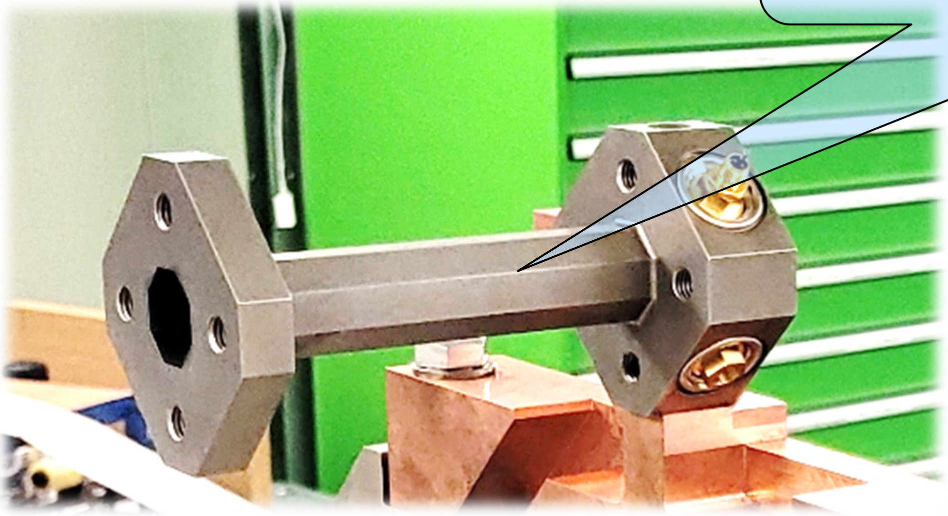
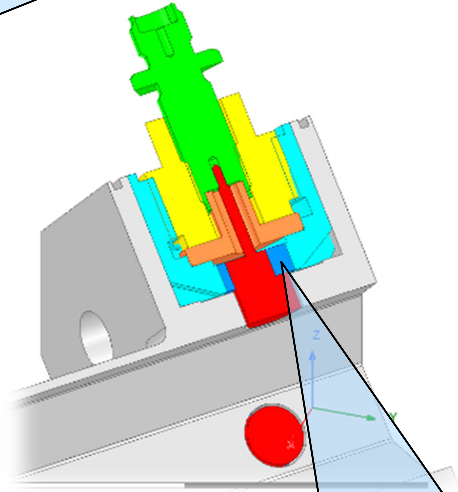
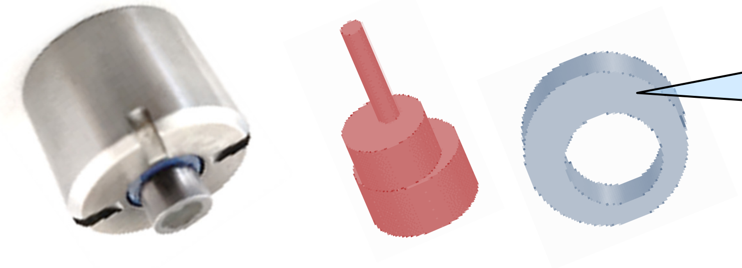
BPM Mechanics

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)

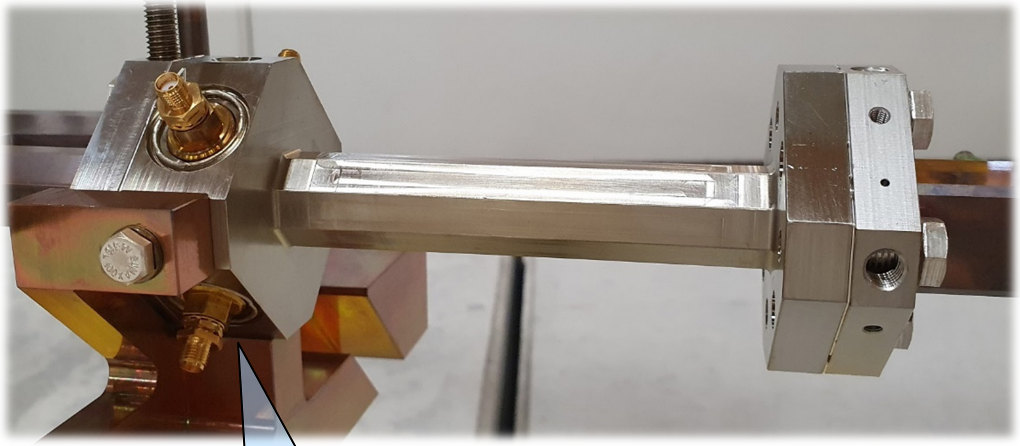






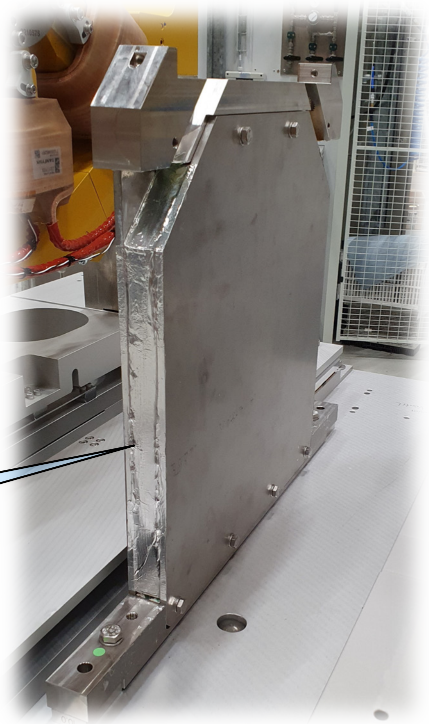
Borosilicate glass (dark blue): Inner conductor (red) with coaxial asymmetry → HOM power reduction & spectral spreading

BPM Mechanics: Support

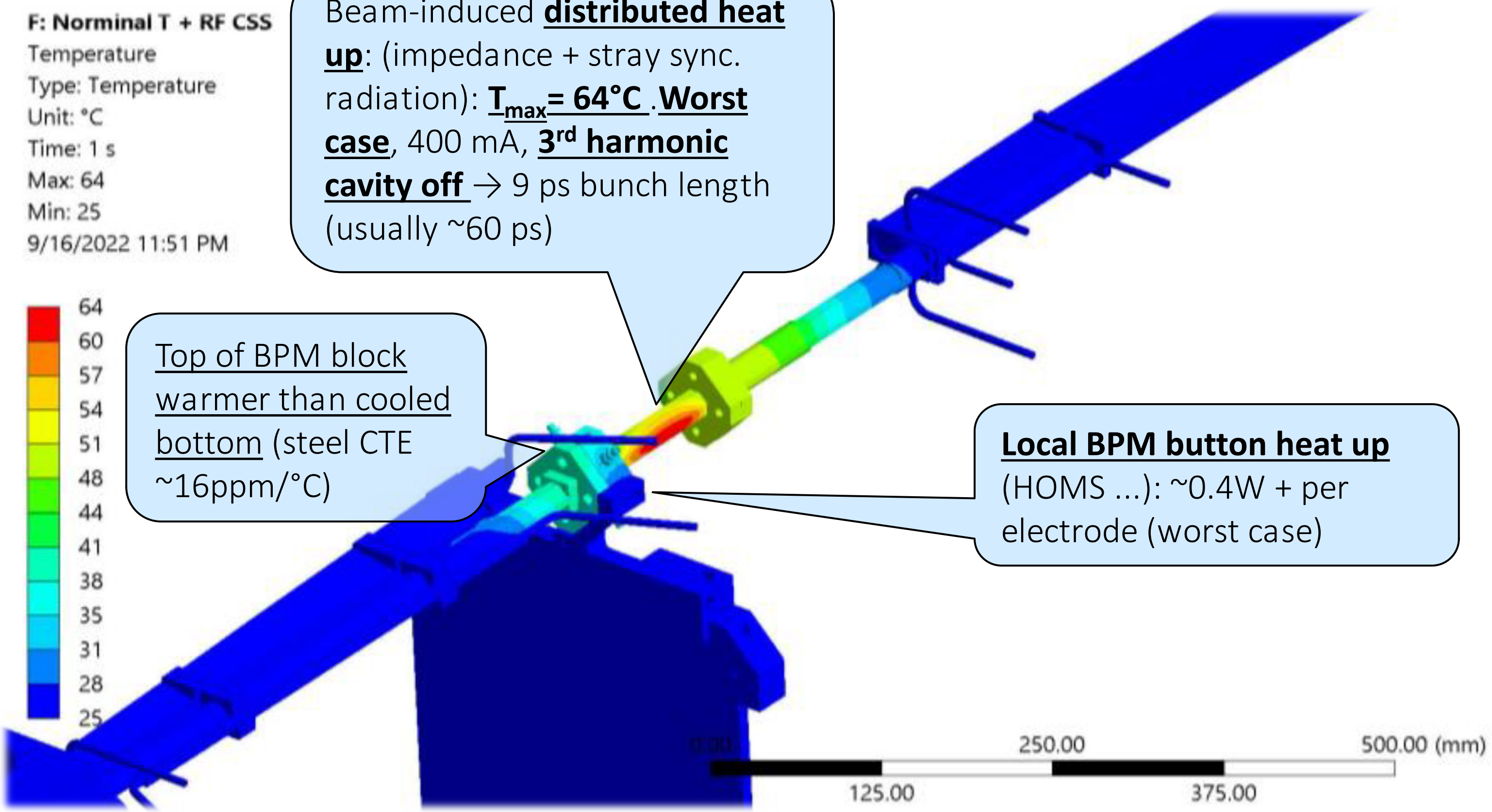


Water cooled copper block reduces position drift

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



BPM Mechanics: Temperature Simulation



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

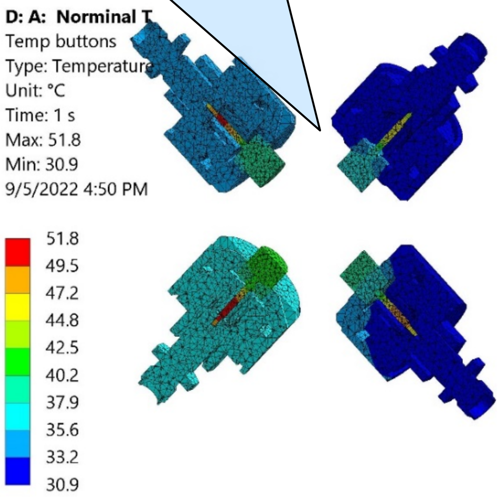
<u>Top of BPM block warmer than cooled bottom</u> (steel CTE ~16ppm/°C)

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

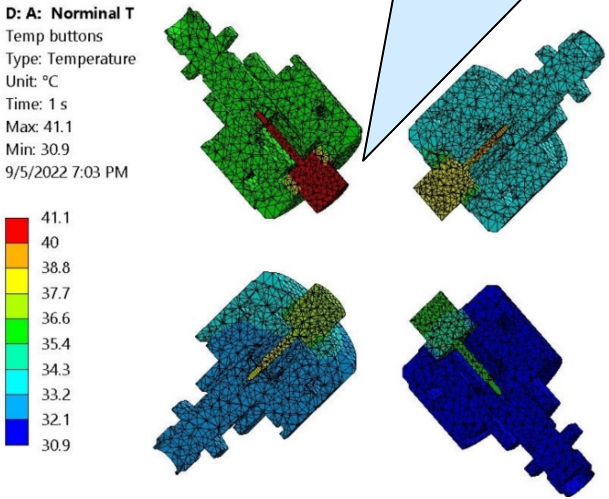
BPM: Button Temperature

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.**



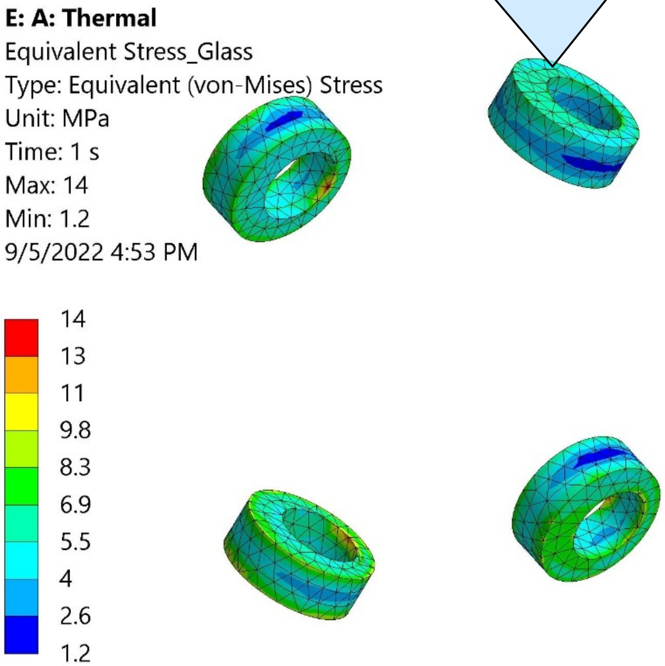
Alternative: Molybdenum button. Temperature only **11°C lower** (button temperature **dominated by glass, not metal).**

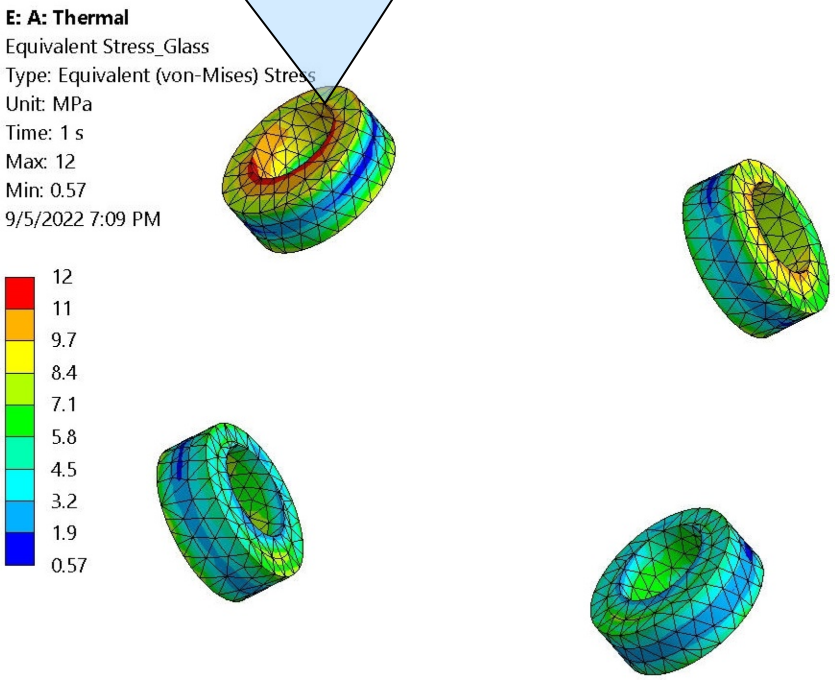


BPM: Thermal Stress of Borosilicate Glass

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

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





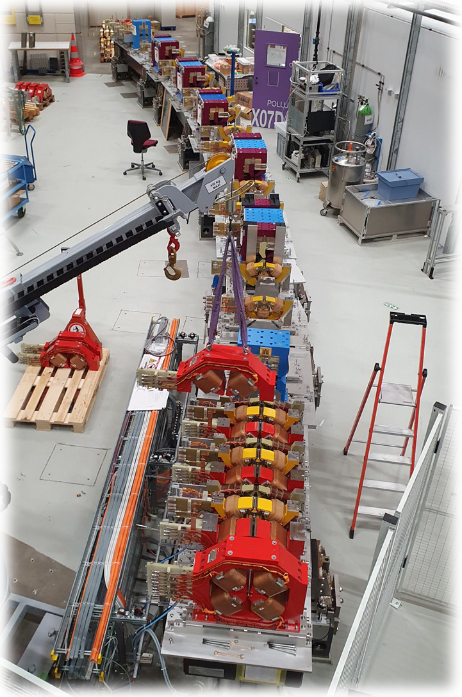
BPM Mechanics: Performance

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.

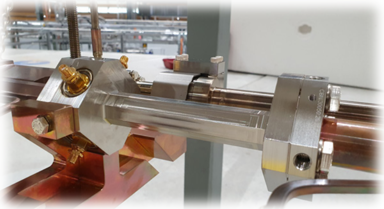
Simulated beam-induced BPM pickup *center* motion	**ΔX [µm]**	**ΔY [µm]**
Motion from **0 mA to 400mA** beam current	-11.3	4.7
Motion @ **Top-up (400...404mA)**	< 0.1	<0.05

- 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

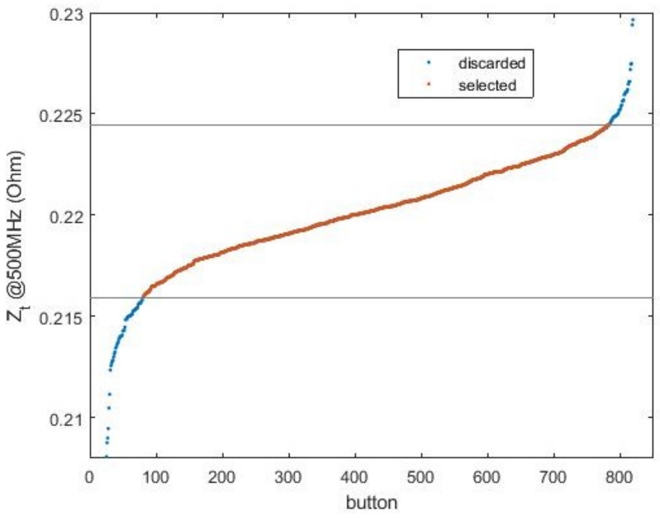


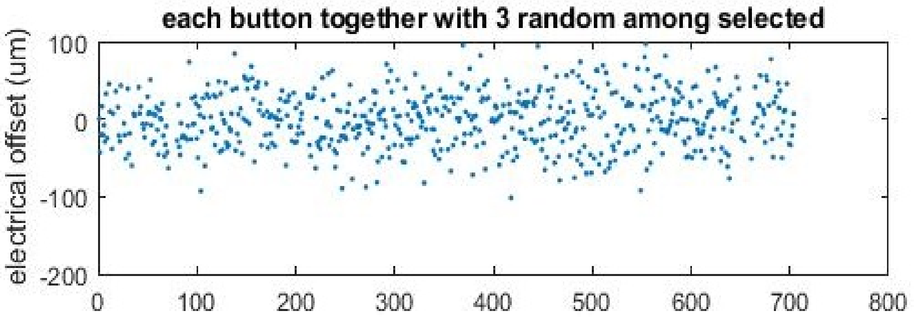
- All BPM electrodes produced
- >25% of BPM blocks produced
- 1/12 of beam pipe assembled
- No vacuum problems so far

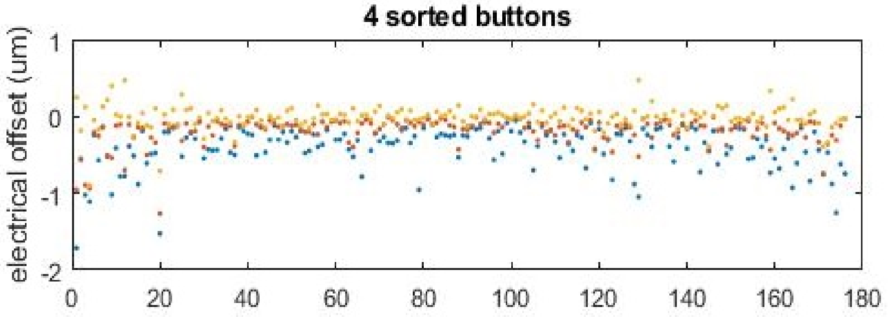


BPM Button Electrode Sorting

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







Contents

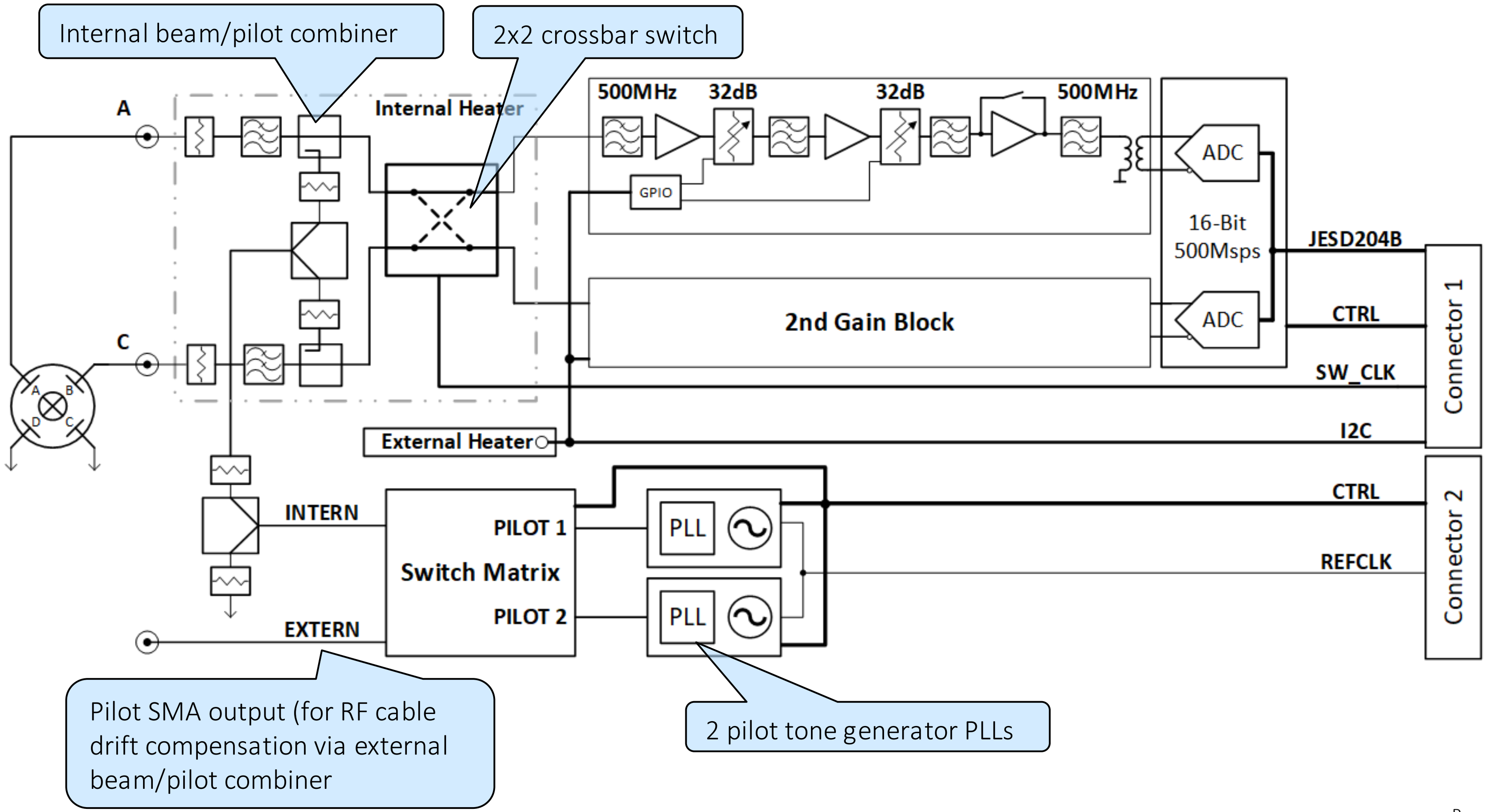
SLS2 BPM Electronics: "DBPM3" (PSI Design)

<u>Generic 19'' back-end</u> (AMD/Xilinx **<u>Zynq UltrasCSCale+ MPSoC</u>**), also used in SwissFEL (-> IBIC'22 TUP12)

SLS 2.0: **<u>3 RF Front-End</u>** (RFFE) modules per unit, **<u>integrated ADC</u>** (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):

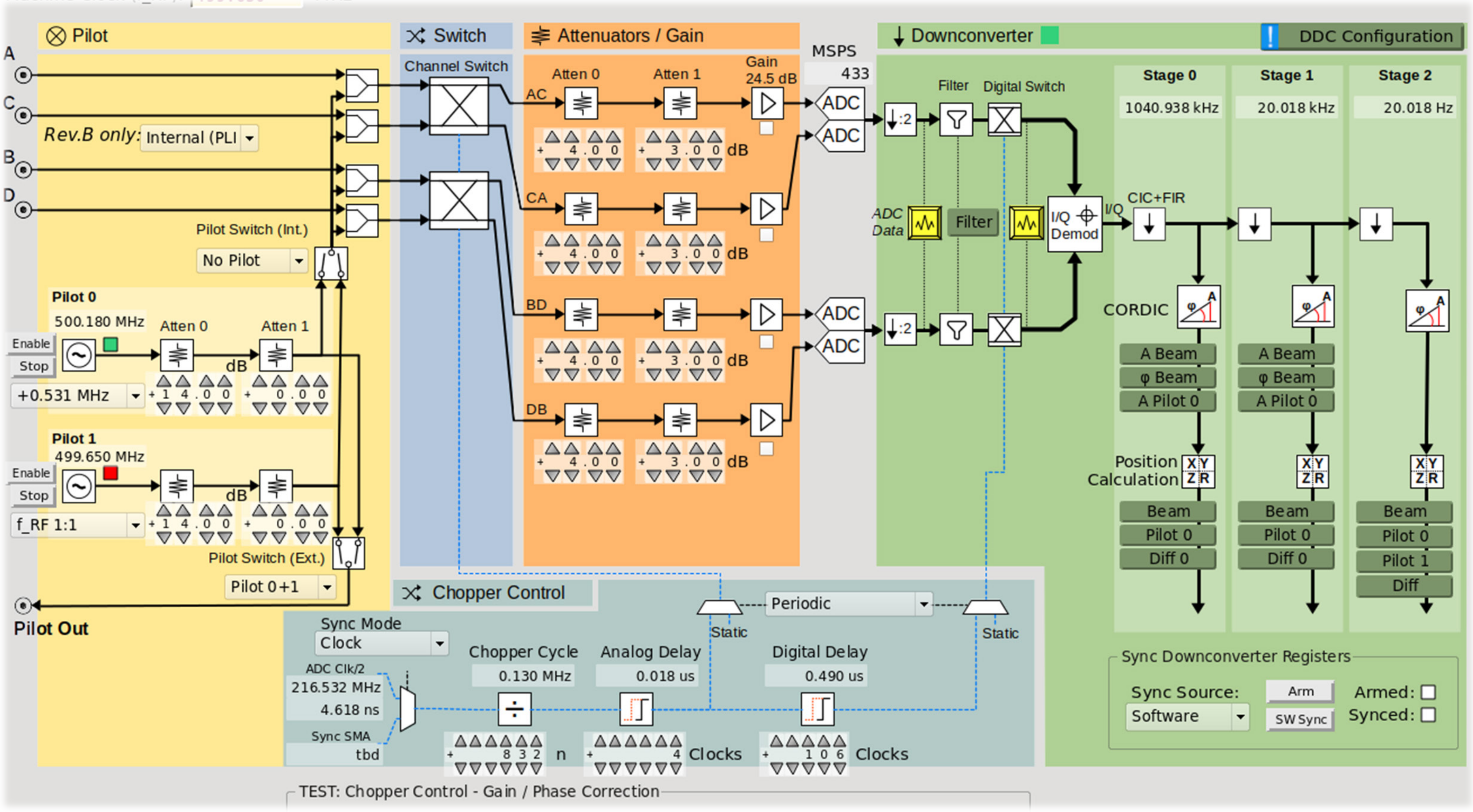
- Passive methods:
  - Equalize cable properties (measure & sort by TOF/attenuation)
  - Thermal cable bundle isolation
  - Cable trays below floor (lower temp. variation)
- Active methods (so far):
  - Pilot tone

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

GUI: Settings for DBPM3 Test @ SLS 1.0 Ring



Python GUI: DBPM3 DDC Filters

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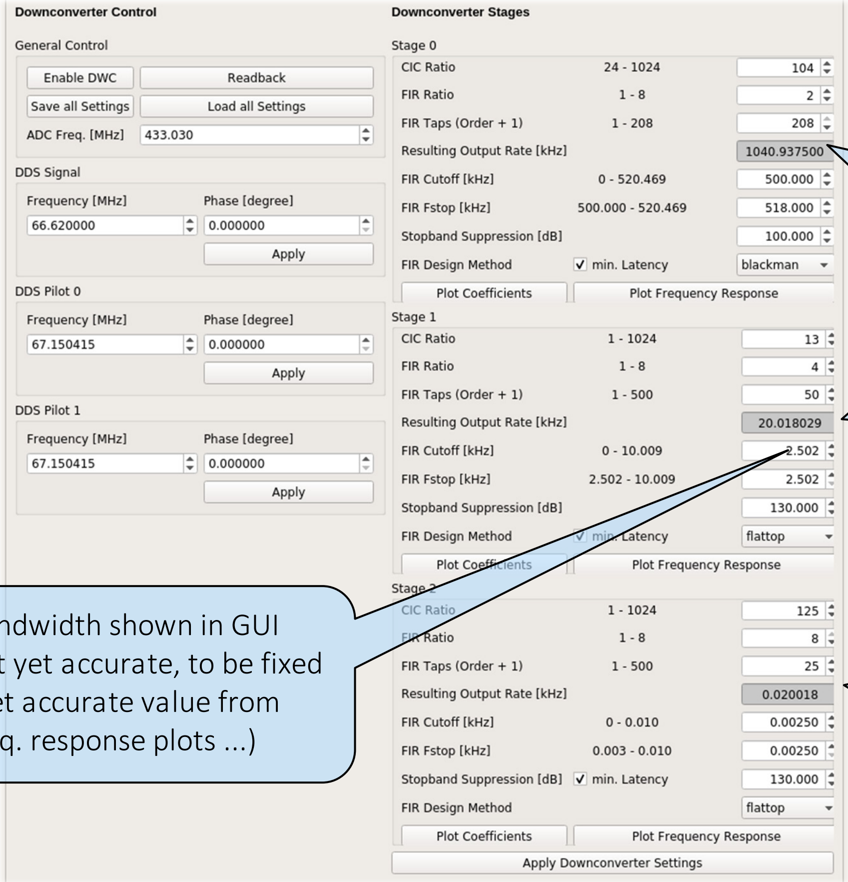
Programmable during operation via EPICS ...

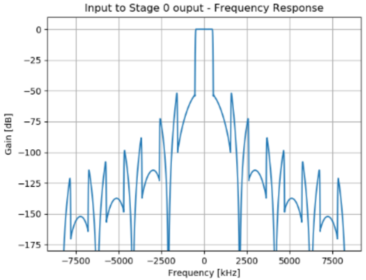


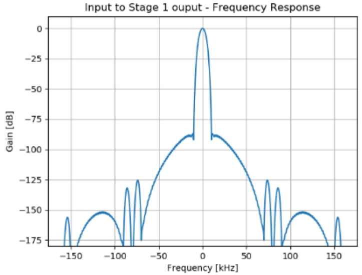
DDC **Stage 0**: 1.04 MSPS (= turn-by-turn), **0.5 MHz BW**

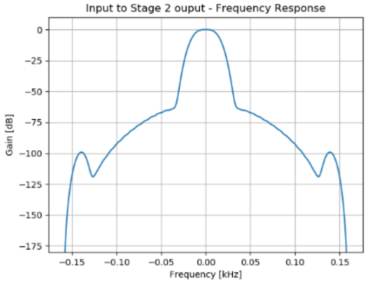
DDC **Stage 1**: 20 kSPS, **3.3 kHz BW** ("fast orbit feedback data").

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

bandwidth shown in GUI not yet accurate, to be fixed (get accurate value from freq. response plots ...)







DBPM3 Electronics Test @ SLS Storage Ring

Test Setup:

- DBPM3 RFFE Rev. C (received mid August): First with pilot output
- 400 mA SLS 1.0 ring BPMs beam signal
  - 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

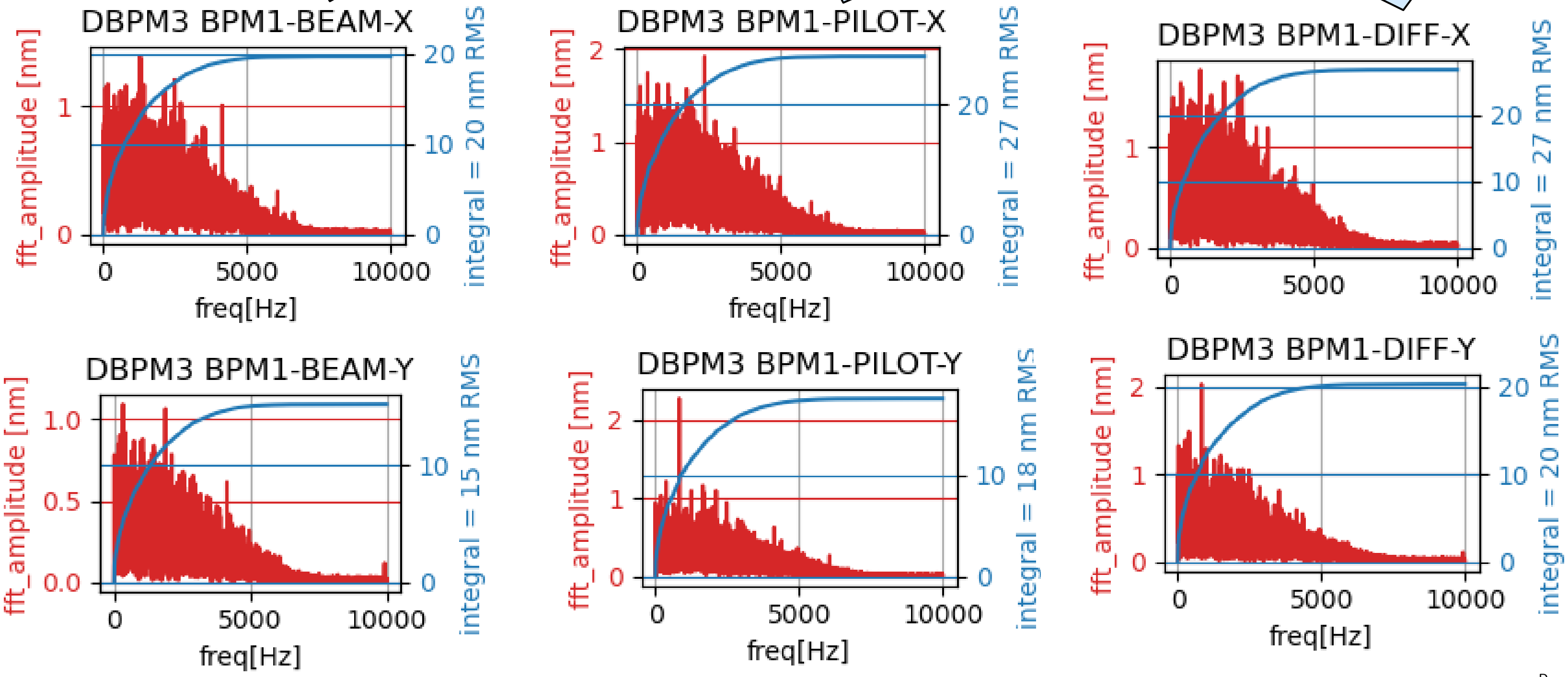
DBPM3 Electronics: RMS Position Noise

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)



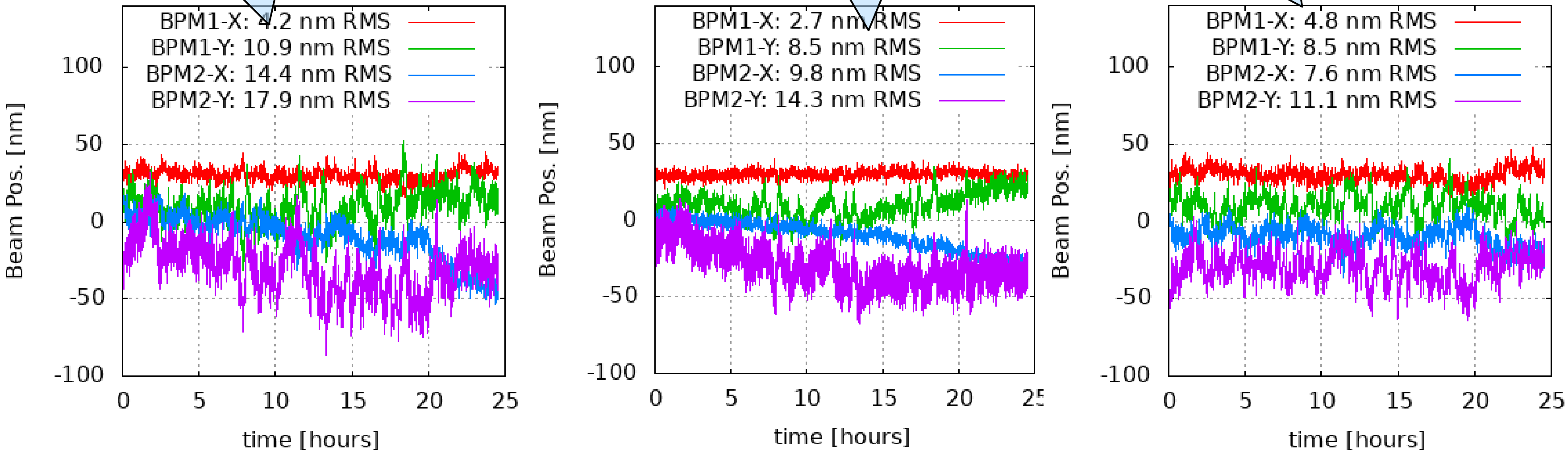
DBPM3 Electronics: 24 Hour Position Drift

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

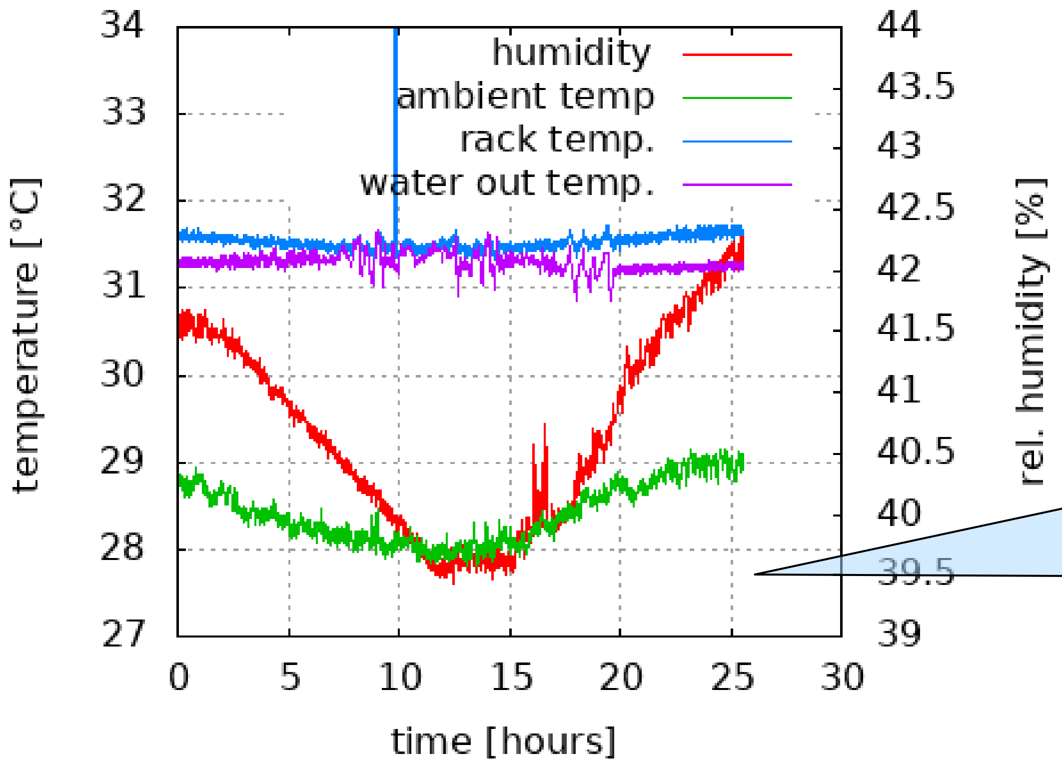
Beam signal only: < 17.9 nm RMS

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

Summary & Outlook

BPM Status:

- Mechanics: Production ongoing (>25% done).
- Electronics: Latest results promising, now long-term test with more units. Strategy:
  - 1st beam 1/2025: Upgrade only ring BPMs with present DBPM3 design ("gen. 1")
    - Series production soon, ~2 months left for minor changes
  - Q1/2026 = 2nd (shorter) dark time: Move DBPM3 gen. 1 from ring to linac/booster/TL (finally replacing old SLS1 systems there), install improved DBPM3 "gen. 2" in ring.

Outlook & To Do:

- Test pilot-based drift compensation with long RF cables (20-36m)
  - Build "passive" beam-pilot combiner box, install near beam (copy from present RFFE)
  - Test 1 vs. 2 pilot tones, drift/noise dependence on pilot & ADC clock frequencies, ...
- Firmware/software upgrades (temperature regulation, ...)
- Develop DBPM3 "gen. 2". Ideas: Newer ADC, generate pilot tone with fast DAC (DDS), ...

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Wir schaffen Wissen – heute für morgen

Thanks to:

F. Marcellini (Pickup/RF)
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J. Purtschert (Firmware/Software)
G. Marinkovic (SW/FW/HW)
X. Wang (Mechanics/Simulations)
D. Stephan (Vacuum/Mechanics)
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