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SwissFEL RF BPMs: Status & Plans

SwissFEL Performance Workshop, 27.1.2021

Contents

BPM Pickup Quantities Today

Pickups installed, BPM electronics in production, to be installed 2-3/2021

BPM Type	Aper-ture [mm]	Quality Factor Q_L	Freq. [GHz]	ADCs per BPM	# Gun - Aramis	# Athos Branch Used	Athos Branch Unused
BPM-C38	38	28	3.3	6	6	0	0
BPM-C16	16				89	27	0
BPM-C8	8	1000	4.9	3	24	6	4
BPM-C5	5				0	22	0
Overall	-	-	-	-	119	55	4

93% of Athos Branch BPMs available & commissioned

BPM-C5/-C8 (high-Q, 4.9 GHz) in/near undulators

- Higher resolution, but can only measure **1 bunch**
- Electronics: "MBU" (similar to E-XFEL) or "DBPM3" (=SLS2 platform)

BPM-C16/-C38 (low-Q 3.3 GHz) in transfer line, collimators & dump

- **28ns dual-bunch** operation
- Electronics: "MBU" (similar to E-XFEL)

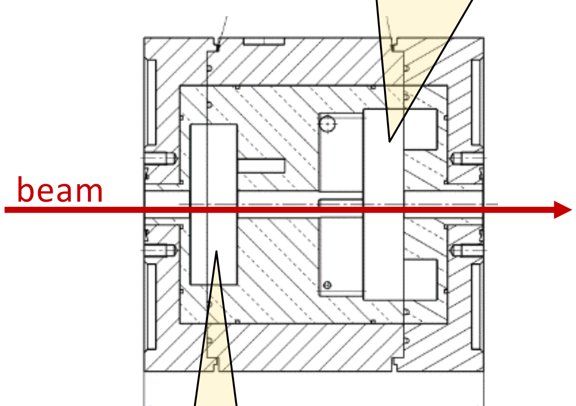
DBPM3 maybe for PORTHOS? Would need new RFFE/ADC design

DBPM5 Pickup: Hybrid Copper/Steel Body

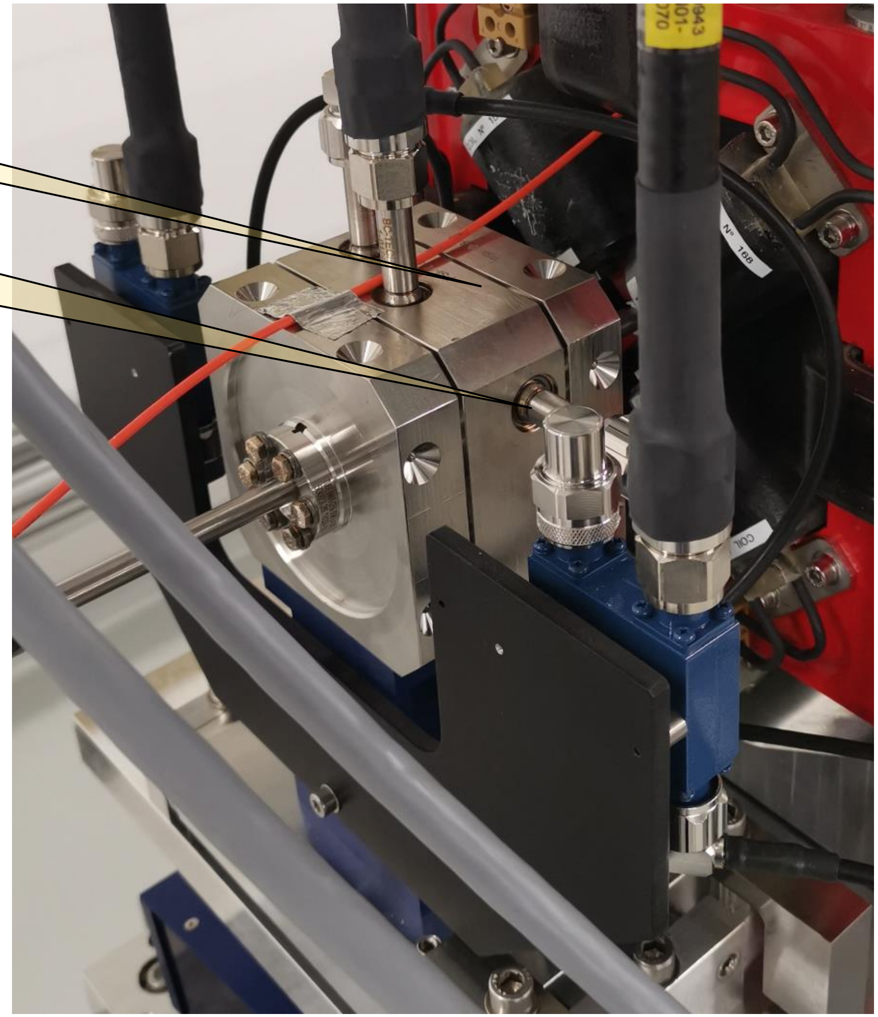
DBPM5: 1 reference resonator port (**signal ~ charge**)

1 of 4 position resonator ports (**signal ~ beam_position * charge**)

DBPM8: position resonator (similar to CBPM5 ...)



reference resonator



SwissFEL BPM Electronics Types

GFA/AEK in-house designs

"MBU": Old BPM electronics platform developed for E-XFEL/SwissFEL ~10 years ago (VME-based, complex HW production)

"DBPM3": New PSI BPM electronics platform (SLS2, HIPA BPM upgrade, ...)

- **Athos undulator BPMs**: ~2.5x cheaper than MBU (by using newer technologies)
- Much easier production & testing
- Similar analog but much better digital performance
- **EPICS IOC & timing interface integrated** into BPM electronics (FPGA, 2-core & 4-core CPU on same chip: **Xilinx Zynq UltraScale+**)

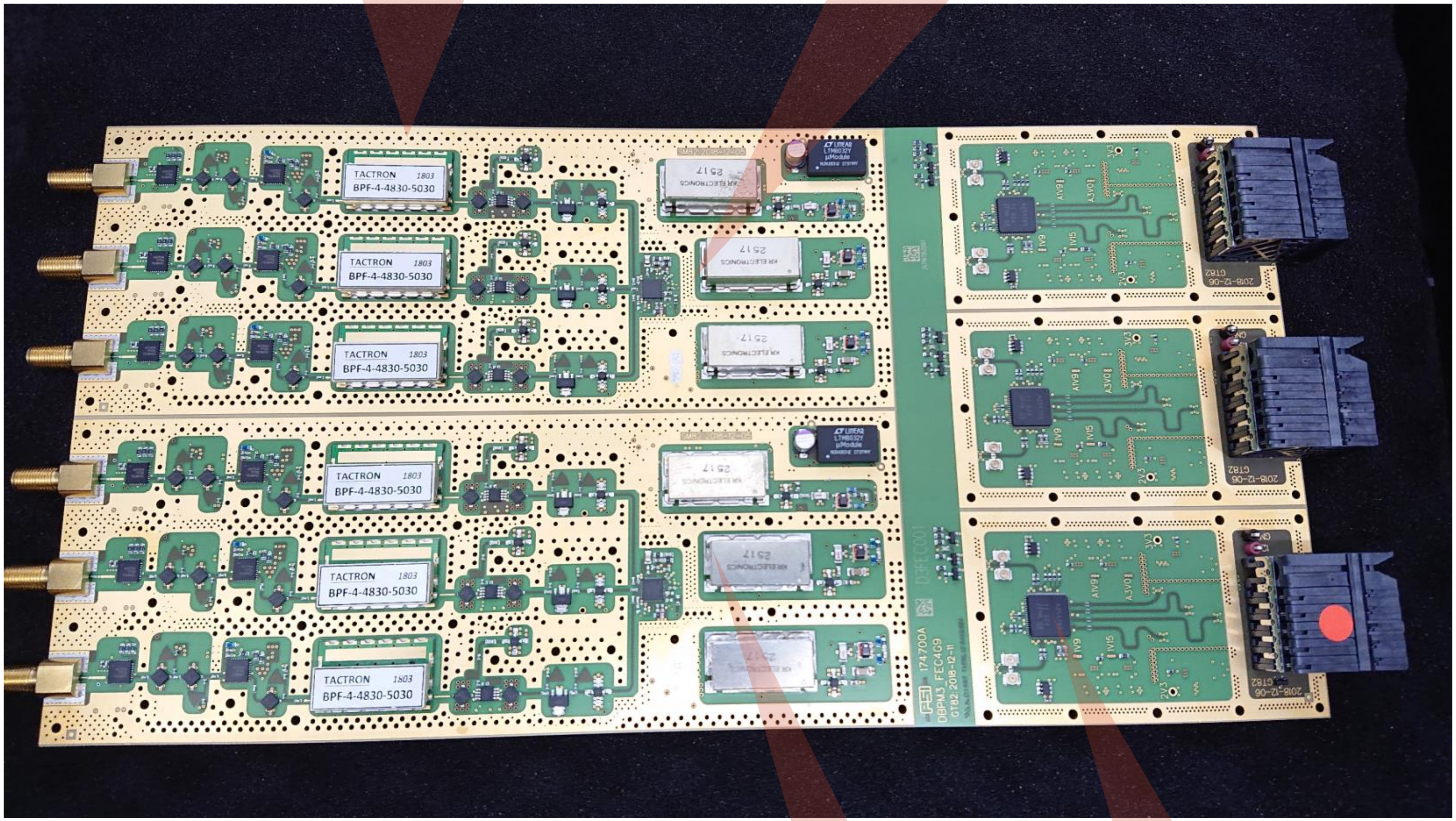
New SwissFEL 4.9 GHz DBPM3 Electronics

- Four 4.9 GHz High-Q Cavity BPMs per 3 HE Unit
- 500 MSample/s 16-Bit ADCs, 10Gbps serial data (old BPMs: 160 MSample/s, parallel data)
- Back-end same as SLS2 BPMs

New SwissFEL 4.9 GHz DBPM3 Electronics

Top side: RF shields not yet mounted

3-Channel RF front-end, 1st cavity BPM



3-Channel RF front-end, 2nd cavity BPM

2-channel 16-bit 500MSPS ADC (JESD204B)

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SwissFEL BPM Electronics Status & Schedule

Today:

- Aramis:
  - MBUs
- Athos:
  - High-Q BPMs: 13 DBPM3, 15 MBU (= Aramis spares)
  - Low-Q BPMs: MBU

4-5/2021:

- Athos High-Q BPMs use only DBPM3

End 2021:

- Aramis high-Q BPMs also upgraded to DBPM3 (-> old high-Q BPM electronics used/needed as long-term spares for low-Q BPMs, except RFFEs)
- **Replace VME-based BPM IOCs (IFC1210) with** more performant integrated IOCs for all BPMs (**Zynq Ultrascale+**) -> enable **100 Hz plus easier maintenance & necessary future upgrades** of EPICS database (2-bunch calibration, automatic alarms, PORTHOS, ...)

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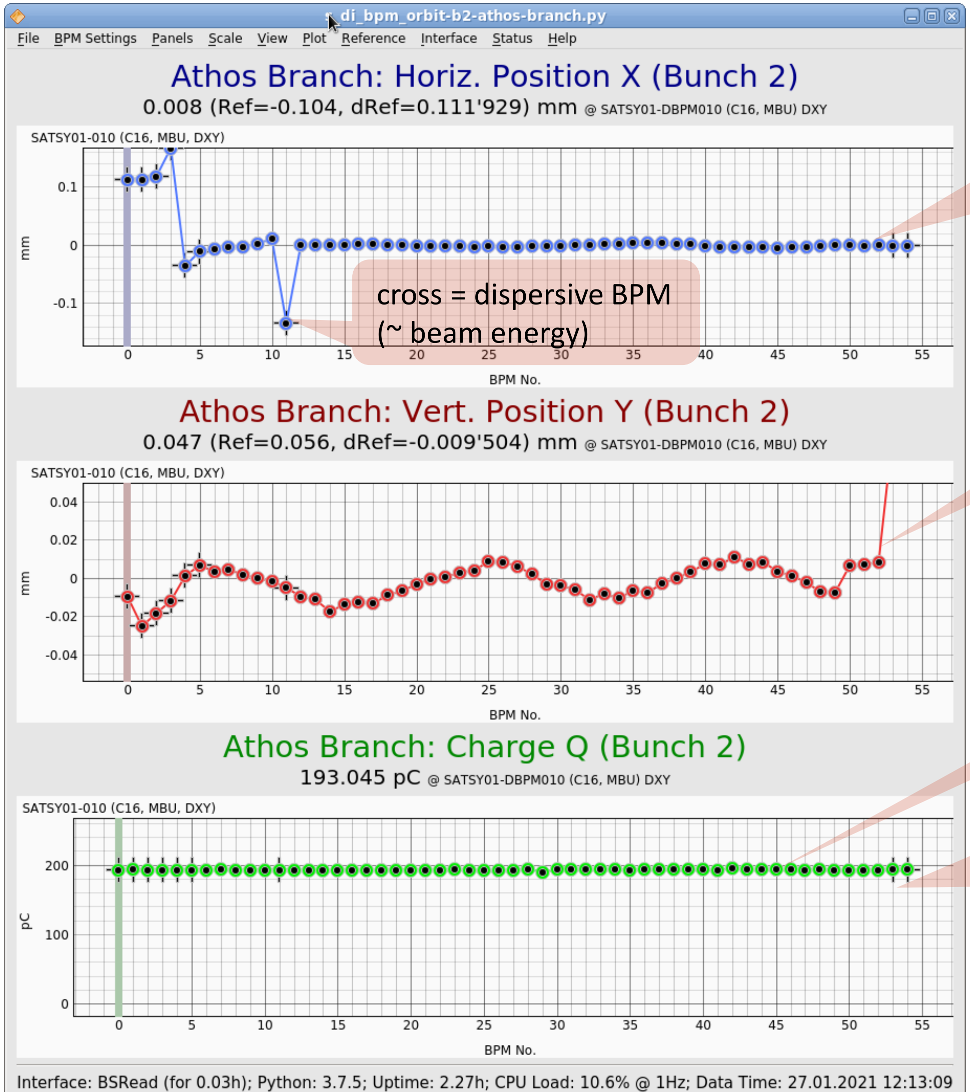
BPM Noise and Crosstalk



DBPM3 **electronics position noise ~0.4µm RMS @ 100-200µm beam offset** (value may include real beam motion -> may be even better) @ 170pC.

Real beam motion typically (much) larger than BPM noise

DBPM3 **charge noise <0.04% (<70fC) @ 170pC**

Low-Q BPMs: Bunch-to-bunch crosstalk (measurement error of 2nd bunch due to presence/absence of 1st bunch) of charge measurement typ. < 1% @170pC (measured at SINEG01-DBPM340)

(Some) BPM Activities & Improvements 2020

EPICS IFC1210 IOCs for BPMs now work at 100 Hz (incl. BSRead):

- Temporary solution: Standard EPICS controls software replaced by BPM specific optimized software, more performant but hard(er) to maintain.
- Final solution (WIP): IFC1210 VME IOCs will be replaced with ZynqU+ IOCs (new SLS2 standard) -> ~10x more IOC performance per BPM.

X/Y position scaling factors calibrated with beam (conversion of ADC units to mm):

- Calibrated for all Aramis & Athos BPMs on motorized movers (for Athos fully automated, including check if results are reasonable)
- Reproducibility over several weeks/months typ. ~1% (resolution of calibration limited by beam motion/noise, using 100x averaging & several measurement steps per BPM)

Calibration script should only be used by BPM experts (or in agreement with them ...)

```
sf-lc7a ~/git/sf_diagnostics_scripts > s_di_bpm_cmd.py "cal_xy_scaling_satun_auto SATUN01-DBPM070 SATUN02-DBPM070 SATUN03-DBPM070"
# Executing command cal_xy_scaling_satun_auto SATUN01-DBPM070 SATUN02-DBPM070 SATUN03-DBPM070 for accelerator all ...
Calibration X/Y position scaling factors for BPMs ['SATUN01-DBPM070', 'SATUN02-DBPM070', 'SATUN03-DBPM070']
# SATUN01-DBPM070:X-SCALE-CORR 0.811
# SATUN01-DBPM070:X-SCALE-CORR 0.816
# SATUN01-DBPM070:X-SCALE-CORR 0.808
# SATUN01-DBPM070:X-SCALE-CORR 0.822
# SATUN01-DBPM070:X-SCALE-CORR [0.8106, 0.8158, 0.8081, 0.8215]
#   Average   = 0.814
#   Peak-Peak = 0.0134
#   Median    = 0.8132
#   RMS       = 0.0059
#  -> Scaling factor is **NOT** O.K. (outside 2 signma of this measurement).
Changed SATUN01-DBPM070:X-SCALE from 6.300 to 5.128 (factor = 0.814 +- 0.003406, values = [0.8106, 0.8158, 0.8081, 0.8215])

# SATUN01-DBPM070:Y-SCALE-CORR 0.954
# SATUN01-DBPM070:Y-SCALE-CORR 0.934
# SATUN01-DBPM070:Y-SCALE-CORR 0.946
Warning: Permanently added 'sf-lca,172.26.120.57' (RSA) to the list of known hosts.
# SATUN01-DBPM070:Y-SCALE-CORR 0.931
# SATUN01-DBPM070:Y-SCALE-CORR [0.9536, 0.9337, 0.9457, 0.931]
#   Average   = 0.941
#   Peak-Peak = 0.0226
#   Median    = 0.9397
#   RMS       = 0.0106
#  -> Scaling factor is **NOT** O.K. (outside 2 signma of this measurement).
Changed SATUN01-DBPM070:Y-SCALE from 6.300 to 5.928 (factor = 0.941 +- 0.006120, values = [0.9536, 0.9337, 0.9457, 0.931])
```

0.34% error

0.61% error

X/Y Scaling Factor Calibration

December 2020, SATUN08-DBPM070: **X position scaling factor changed by ~5%** because beam offset was 0.8mm -> **RFFE attenuator had non-standard value**.

5% scaling factor change means:
- **50µm orbit offset change for 1mm beam offset (!)**
- **5µm for 0.1mm beam offset**

```
# SATUN08-DBPM070:X-SCALE-CORR 1.008
# SATUN08-DBPM070:X-SCALE-CORR 1.093
# SATUN08-DBPM070:X-SCALE-CORR 1.061
# SATUN08-DBPM070:X-SCALE-CORR 1.049
# SATUN08-DBPM070:X-SCALE-CORR [1.0078, 1.0927, 1.0614, 1.0486]
#   Average   = 1.0526
#   Peak-Peak = 0.0849
#   Median    = 1.055
#   RMS       = 0.0352
#  -> Scaling factor is **NOT** O.K. (outside 2 sigma of this measurement).
Changed SATUN08-DBPM070:X-SCALE from 7.100 to 7.473 (factor = 1.053 +- 0.020323, values = [1.0078, 1.0927, 1.0614, 1.0486])

# SATUN08-DBPM070:Y-SCALE-CORR 0.983
# SATUN08-DBPM070:Y-SCALE-CORR 0.992
# SATUN08-DBPM070:Y-SCALE-CORR 0.989
# SATUN08-DBPM070:Y-SCALE-CORR 1.003
# SATUN08-DBPM070:Y-SCALE-CORR [0.9834, 0.992, 0.9894, 1.0032]
#   Average   = 0.992
#   Peak-Peak = 0.0198
#   Median    = 0.9907
#   RMS       = 0.0083
#  -> Scaling factor is O.K. (within 2 sigma of this measurement).
Not changing SATUN08-DBPM070:Y-SCALE from 6.967 to 6.911 (factor = 0.992 +- 0.004792, values = [0.9834, 0.992, 0.9894, 1.0032])

# SATUN09-DBPM070:X-SCALE-CORR 1.004
# SATUN09-DBPM070:X-SCALE-CORR 1.012
```

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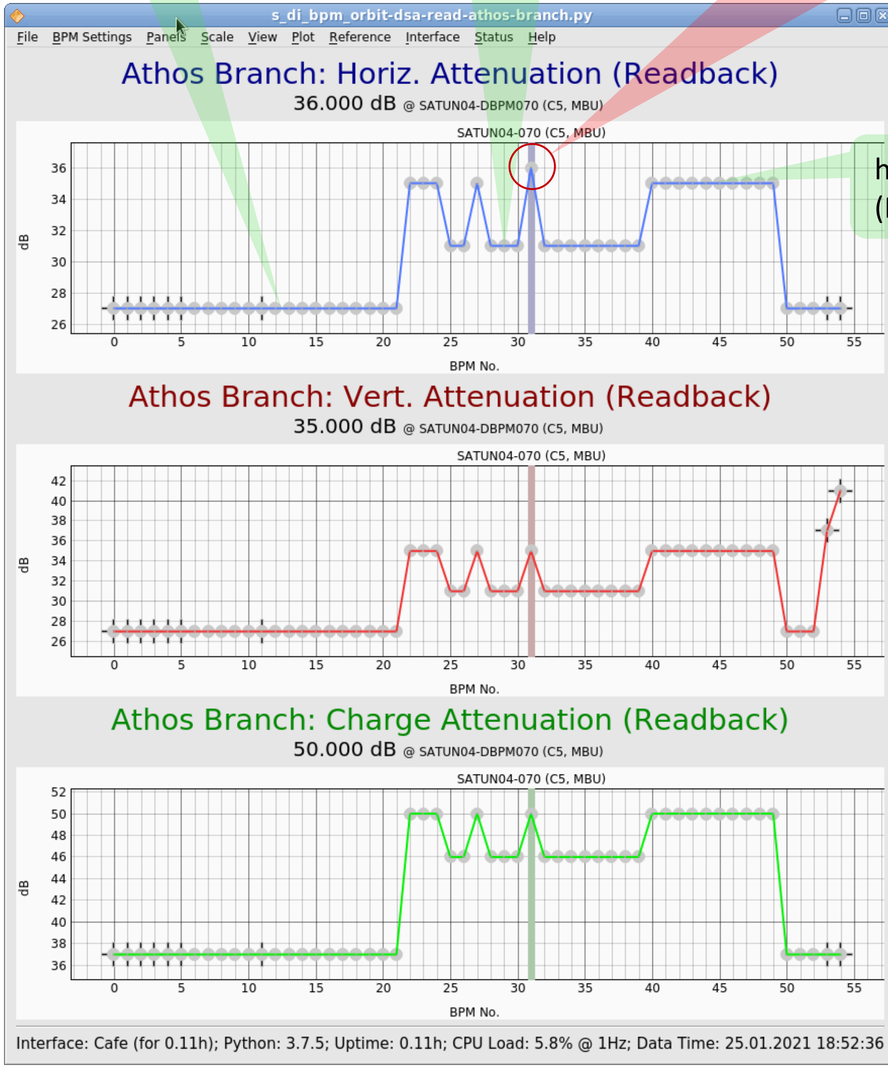
BPM Attenuator Settings

low-Q BPMs: 27dB

high-Q BPMs (DBPM3): 31dB

One high-Q BPM (MBU): 36dB = non-standard (X beam position "too large")

high-Q BPMs (MBU): 35dB



At ~170pC, each BPM type has a **reproducible standard RFFE attenuator** setting (and thus position and charge scaling factor) **as long as beam offset is <0.4mm**.

If beam offsets gets much larger, **automatic gain control of BPM FPGAs increases attenuation to avoid ADC saturation**.

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BPM Performance Depends on Orbit

- BPMs have digital step attenuators, 63dB range, 1dB steps. Reality: Steps not exactly 1 dB, vary from BPM to BPM & from step to step.
- **Lab: All 63 attenuator settings per channel (X,Y,Q) (pre-)calibrated**, but calibration not perfect (cannot reproduce beam conditions in lab perfectly).
- **Beam: So far only one "standard" attenuator setting calibrated with beam** (Athos: ~15 min/BPM @ 10 Hz, automated)
- Automatic attenuation control on FPGA level: Non-standard attenuation when beam offset gets >> 0.4mm to avoid ADC saturation.
  - **Short term solution: Keep undulator beam positions <0.4mm**. **Center the orbit symmetrically around 0mm (+-0.4mm is better than 0....+0.8mm)**
  - **Medium/long-term solution: Calibrate more attenuator settings with beam**, speed up calibration procedure (and Athos rep rate ...), improve lab-based calibration.
- Noise and drift of BPMs also increase (~linearly) with beam offsets -> +-0.4mm standard measurement range in undulators seems reasonable, could be increased at expense of more noise.

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- Hardware & Quantities
- Performance & Beam Measurements
- Summary

Summary & Outlook

Special thanks to AEK for making this possible (despite loss of key personnel), and for delivering first SLS2 DBPM3 prototype (based on Athos DBPM3).

Status:

- New DBPM3 electronics: Performance O.K. (analog + digital). Number of software/firmware errors found and fixed so far comparably low, considering the system is complex & many components/technologies are very new.
- In a few weeks, all Athos BPMs will have BPM electronics (presently only four *least critical* BPMs still have no electronics - installation order agreed on with R. Ganter et al.)

Plans 2021+

- Finish DBPM3 series production (last HW expected 3/2021)
- Replace all high-Q BPM electronics with DBPM3 until end 2021 (incl. Aramis)
- Replace IFC1210 BPM IOCs with Zynq UltraScale+ IOCs (prototype 2021, series 2022)
- Calibration of position scaling factors for BPMs without movers & for non-standard attenuation (AEK-BD collaboration)
- Digital suppression of:
    - Bunch-bunch crosstalk (so far ~1%, except few pre-series RFFEs, to be replaced with series)
    - Nonlinearities of cavity resonators etc. (causing systematic measurement errors at large beam offsets)
- Long-term drift studies, better/automated lab & beam calibration & fault detection software

Thank you for your attention!

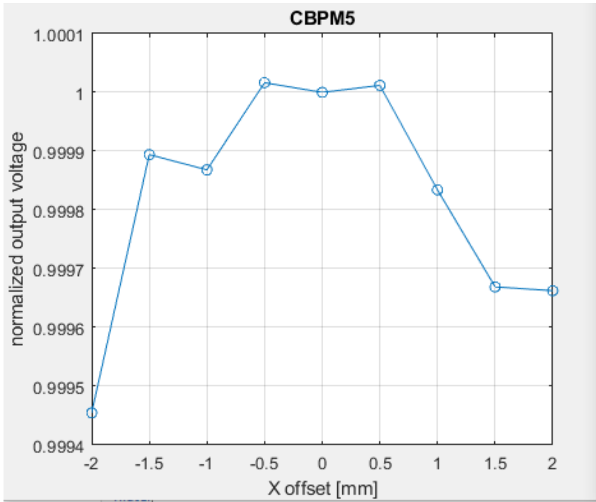
Thanks to all PSI groups contributing to the BPM system!

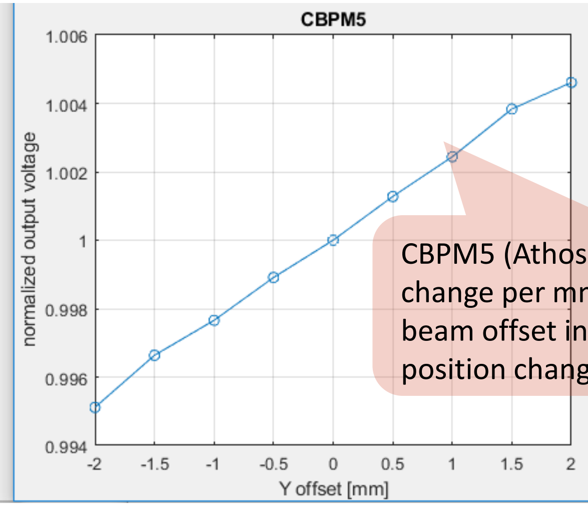
Questions?

Backup Slides

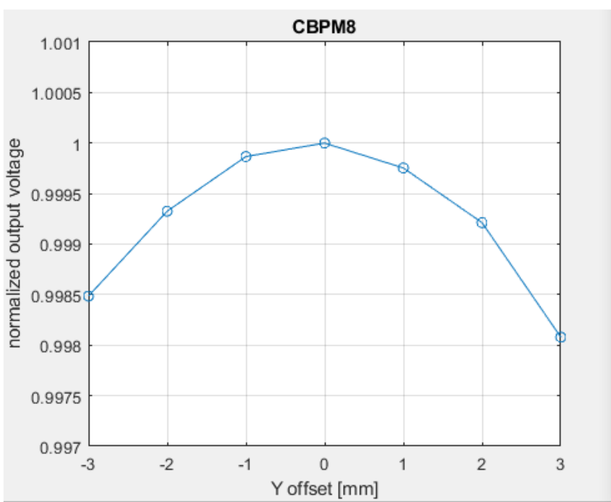
Position Dependence of Charge Reading

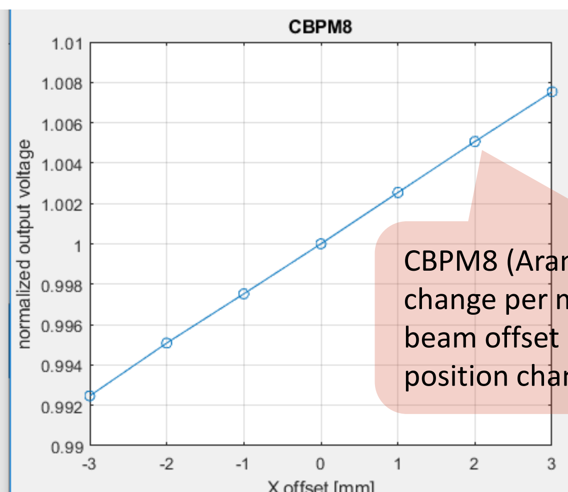
Reason: Cavity resonator that measures charge has only one RF coupler (CBPM5: at top, CBPM8: at side) -> asymmetric RF field.





CBPM5 (Athos): 0.24% charge signal change per mm (only in **Y**) -> +-1mm beam offset in Y+X causes +-2.4µm position change in **X**



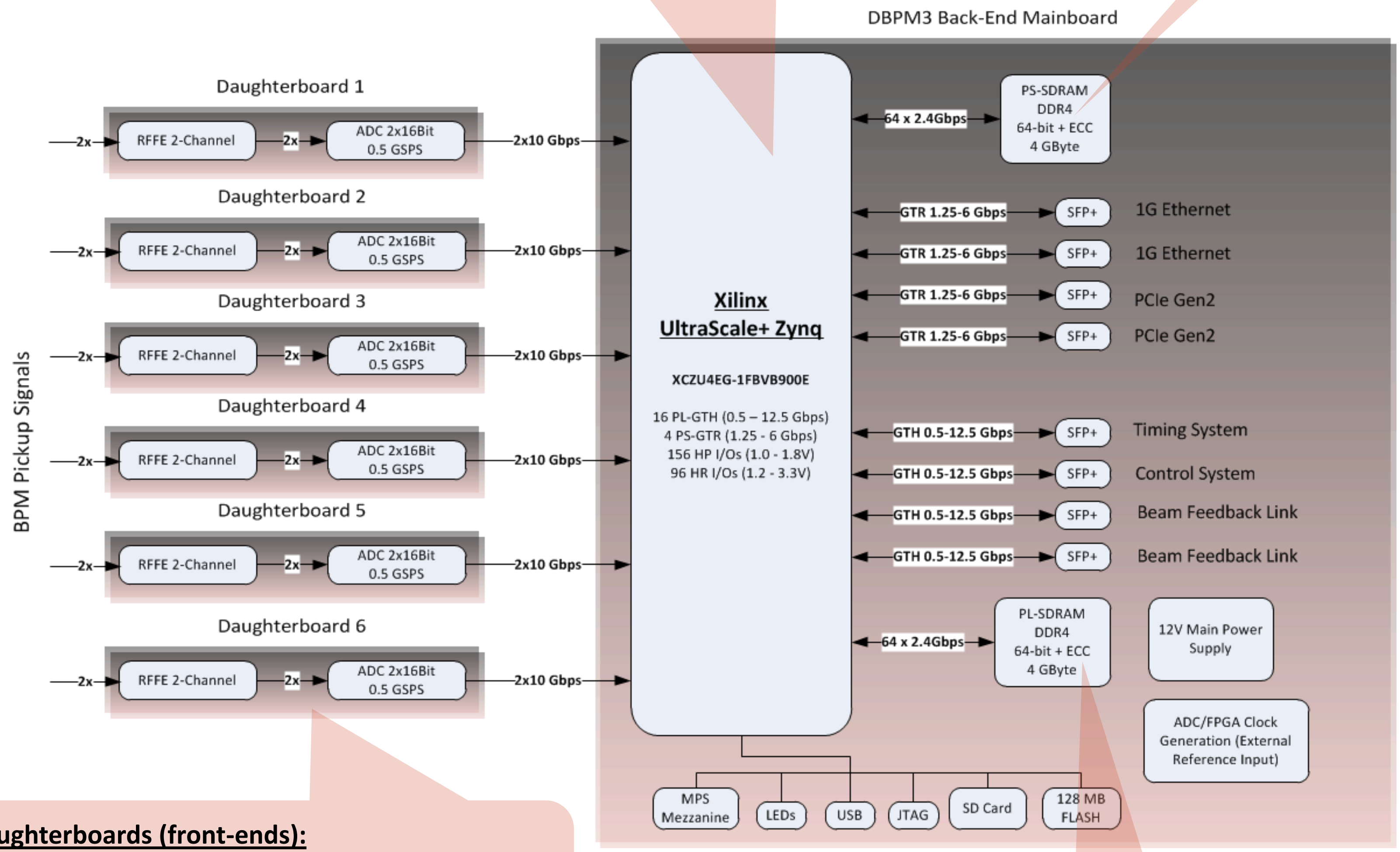


CBPM8 (Aramis): 0.25% charge signal change per mm (only in **X**) -> +-1mm beam offset in Y+X causes +-2.5µm position change in **Y**

DBPM3

System-on-Chip (SoC): BPM/feedback data processing (FPGA + real-time CPU), EPICS/Linux (2nd CPU), timing system interface.

RAM for Linux/ EPICS



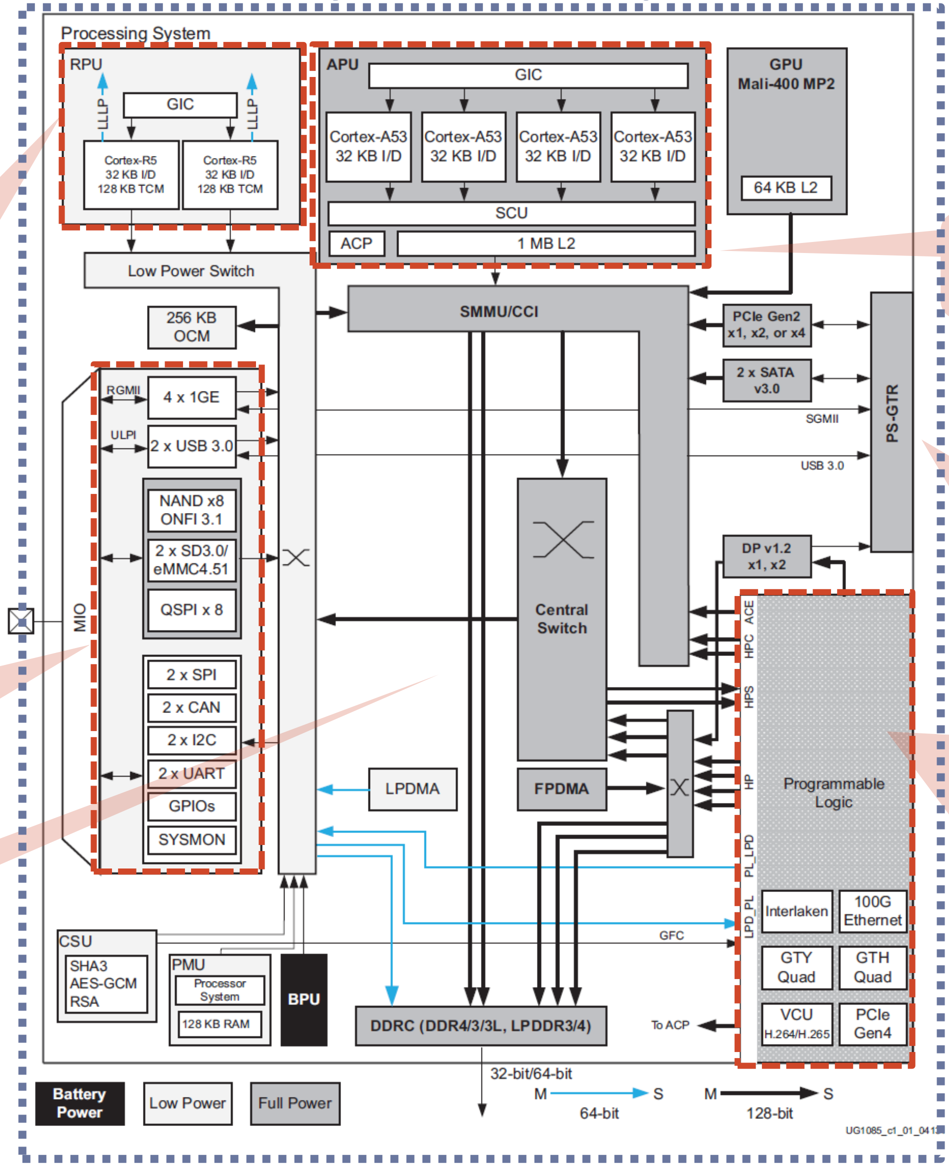
Daughterboards (front-ends):

- 6x single-width (feedback network switch)
- or 3x double width (SLS button BPM)
- or **2x triple-width (SwissFEL cavity BPM)**

RAM for measurement / ADC raw data

DBPM3: Xilinx Zynq UltraScale+ SoC

System-on-a-Chip



APU: Processor for Linux with EPICS IOC

RPU: Realtime processor for FOFB algorithm, BPM control & data processing, ...

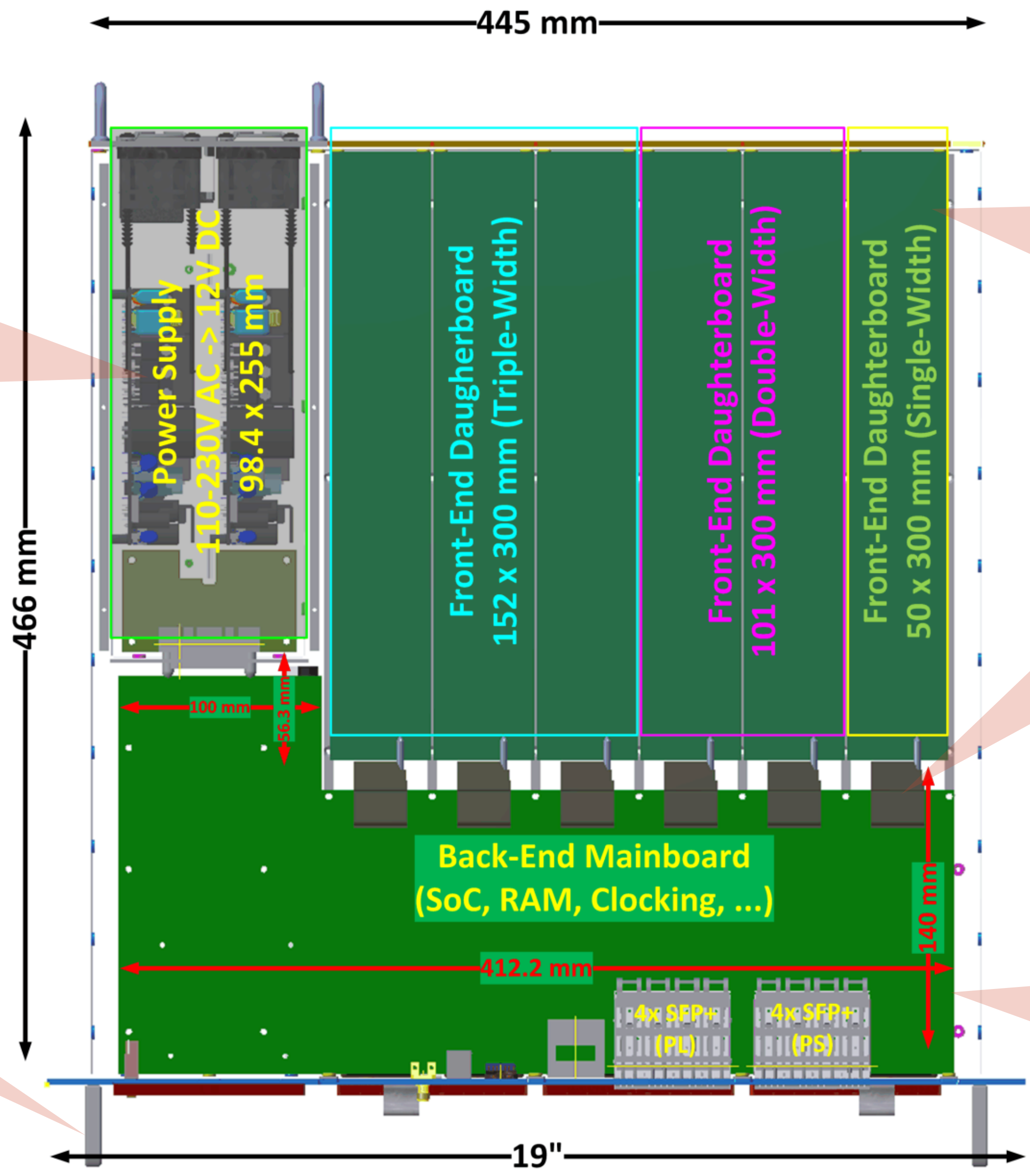
Multi-gigabit interfaces (PCIe, Ethernet, ...)

Standard Interfaces (USB, EEPROM, FLASH memory, ...)

FPGA (logic elements with programmable interconnect, ...) for digital downconversion of ADC raw data, timing system interface, feedback interface, ...

Flexible on-chip data/address "bus" (switch) system

DBPM3 System: 19" Unit



Commercial power supply (optional redundancy)

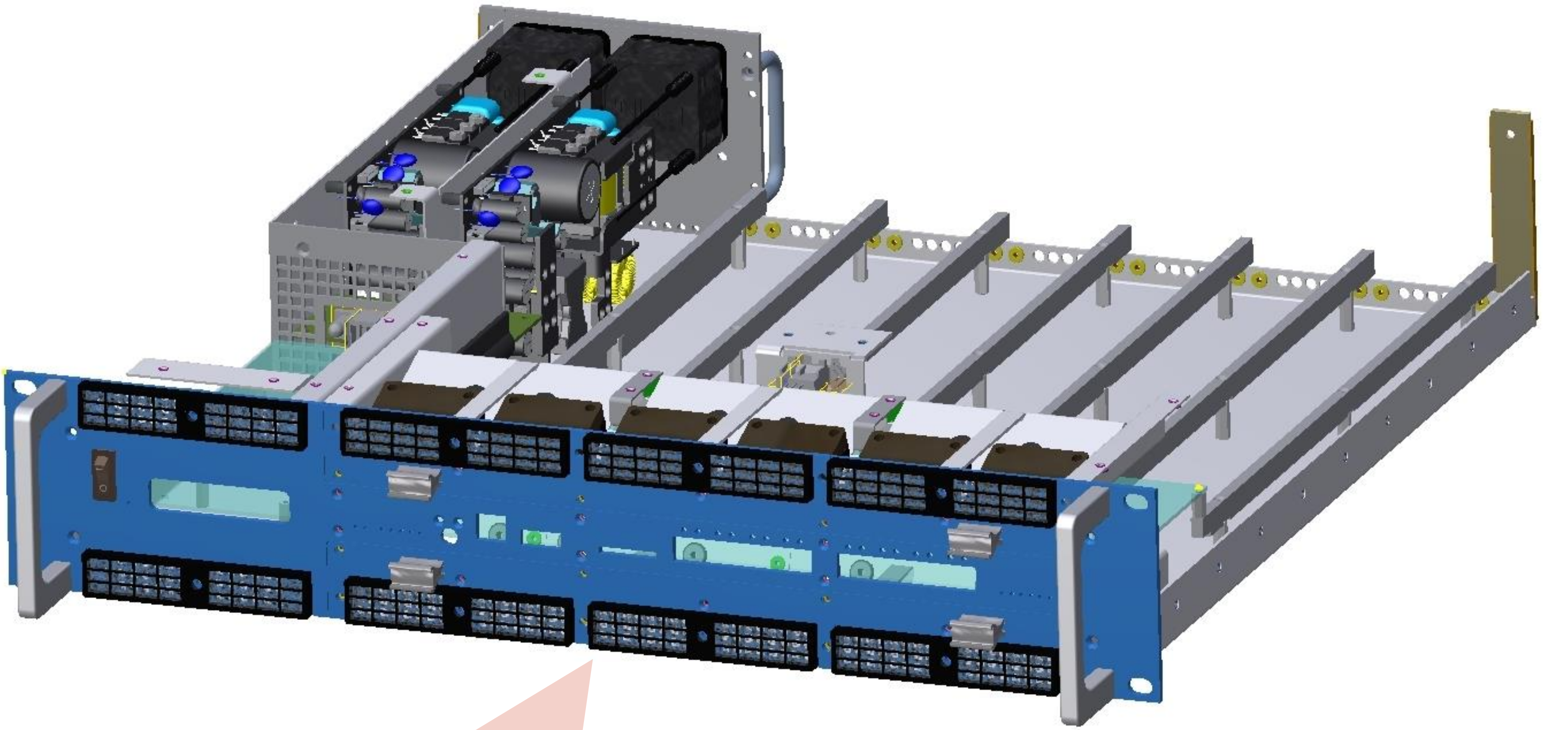
Front-ends ("daughter-boards") plugged in from rear side (live insertion possible)

Guided coplanar daughterboard connector (multi-gigabit data links, clocks, user IOs, ...). Dual-source.

Back-end mainboard (with SoC, external interfaces, ...)

Front side

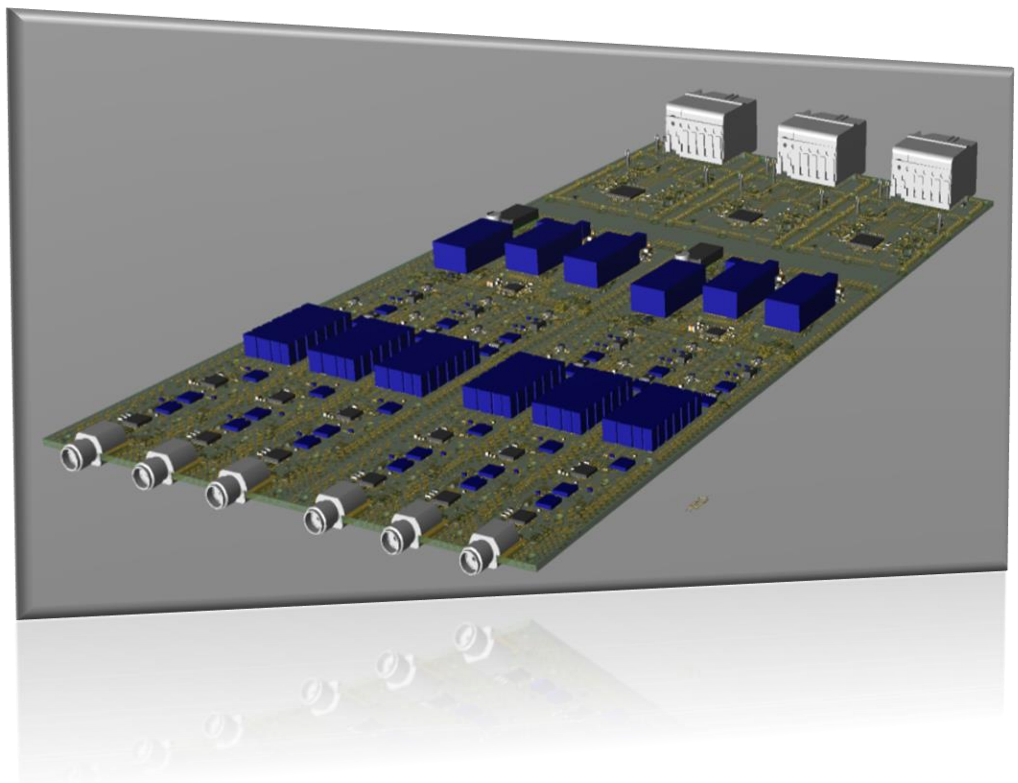
DBPM3 System



Air flow/ventilation optimized for high temperature stability & low BPM drift (suboptimal in VME-based solutions).

DBPM3: Athos High-Q RFFE/ADC

- One DBPM3 unit handles 4 SwissFEL high-Q cavity BPMs (2 RFFEs per unit, 2 BPMs / 6 channels per RFFE).
- 500 MSPS 16-Bit ADCs (JESD204B, 10Gsps per link)
- Multi-gigabit connectors to DBPM3 FPGA board
- Design (M. Stadler / M. Gloor)



DBPM3 Quantities & Applications

Application	#DBPM3 Units*	BPMs or SFPs per Unit**	Needed in Year	Develop-ment Status
SwissFEL High-Q BPMs	24	4	2019	Advanced
SLS1 RF BPM	76	3	2020+	WIP
SLS1 Fast Orbit Feedb.	18	16	2020+	WIP
SLS2 RF BPM	31	3	2024	WIP
SLS2 Fast Orbit Feedb.	27	16	2024	Concept
HIPA RF BPM	20	3	2025+	Concept
SLS2 Beam Loss Mon	...	...	2024	Idea
SLS2 Photon BPM	...	...	2024	Idea
HIPA Diagnostics	...	...	...	Idea
Overall ****	**196**			

* Incl. spares & prototypes
** Fast Orbit Feedback (FOFB) uses fiber optic tree network with SFP+ transceiver daughterboards.
*** Price incl. front-end electronics. Back-end price 4.45 kCHF / unit incl. VAT
**** Excluding applications with status "Idea"

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DBPM3 Technology

Proposed DBPM3 platform saves overall costs (personnel + material), reduces hardware complexity, improves performance and maintainability by using newer/different technology (compared to previous generations):

- Xilinx Zynq UltraScale+ System-on-Chip (SoC)
  - First SoC generation that combines BPM/feedback data processing (FPGA + real-time CPU) and *performant* EPICS/Linux CPU on a single chip.
  - Same SoC also proposed for other SLS2 systems -> high synergies.
  - Pin-compatible SoCs available with same CPU but different FPGA sizes -> minimize effort for control system integration & firmware/software tools
- Single 12V power supply (optional redundancy)
- Only gigabit serial data transfer (for ADCs, communication/interfaces, ...)
- Housing/fans optimized for low temperature drift (needed for extremely challenging SLS BPMs)
- Design driven by most challenging application (SLS BPM), but also took other possible applications into account (as far as possible without unreasonable increase of cost, effort, project delays, ...).

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DBPM3 Complexity

DBPM3: Reduced hardware complexity

- Lower costs
- Lower design & maintenance effort (hardware, firmware, software/controls)
- Higher MTBF
- Production & test can be fully outsourced (not possible for previous BPM electronics), attractive for licensing/industrialization.

BPM System	Extra Timing System VME Card Needed	Extra VME CPU card & crate for EPICS IOC Needed	# Printed Circuit Boards per Button BPM	# FPGAs per Button BPM
Old SLS 1.0	yes	yes (1 per 6 BPMs)	10	2 + ASICs
SwissFEL Platform	no	yes (1 per 16 BPMs)	3.25	1.75
DBPM3 Platform	no	no	1.33	0.33