Paul Scherrer Institut

BPM Electronics for European XFEL and SwissFEL

Boris Keil

Paul Scherrer Institut

Contents

Introduction

PSI Electron BPM Systems & Design Activities

Accelerator	***1st Beam***	***# BPMs***	***Status / Activity***
SLS	2000	~140 (button, reson. stripline)	Digital BPM system since 2000. 2011: Start design of new BPM electronics. SLS Linac: FEL BPM test area.
SwissFEL Test Injector	2010	~25 (reson. stripline, …)	19 resonant stripline BPMs in operation. Test area for cavity & button BPMs.
E-XFEL	2014/15	~410 (button, cavity)	PSI provides BPM electronics for ~290 buttons & ~120 dual-resonator cavities.
SwissFEL	2016	~150 (cavity, stripline)	Adaptation of E-XFEL cavity pickups & electronics to lower charge & shorter bunch spacing.

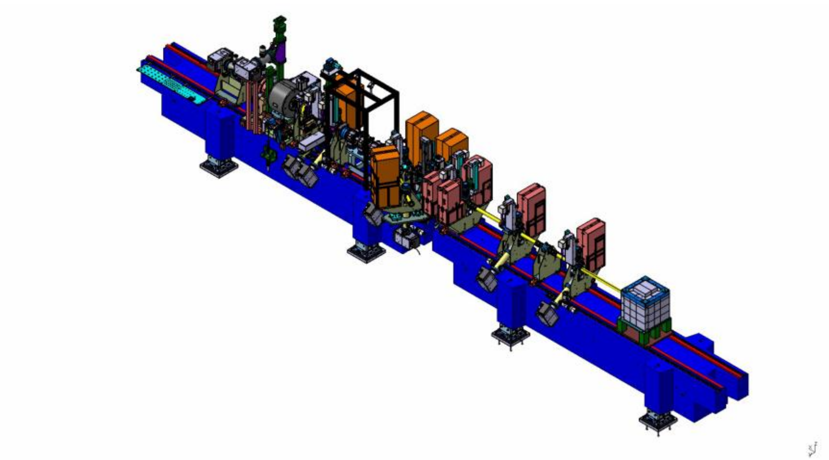
BPM electronics PSI in–house designs, except ~30 re-entrant cavity BPM RFFE in E-XFEL (C. Simon, CEA/Saclay).

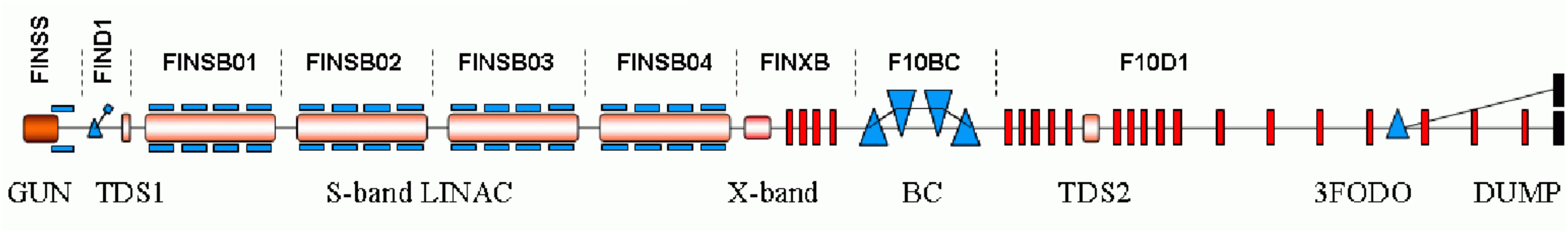
Contents

SwissFEL Test Injector BPMs

SwissFEL Test Injector

- Goal: R&D for SwissFEL.
- Beam since 2010.
- E_{max}~250MeV, 1 bunch, 10Hz.
- 10-200pC.





SwissFEL Test Injector BPMs

Choice of BPM & Electronics Type

Goal: Want "robust" standard BPM.

- Moderate resolution: ~10μm.
- Large position & charge range: ±10mm, 10-200pC.
- Needed ~20 BPM working 9/2010 (too early to use E-XFEL designs …).

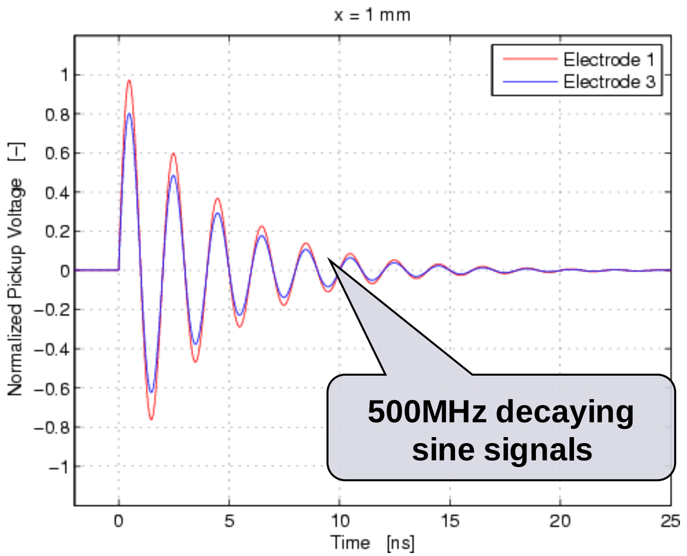
Solution: Re-use/modify existing PSI pickup & electronics

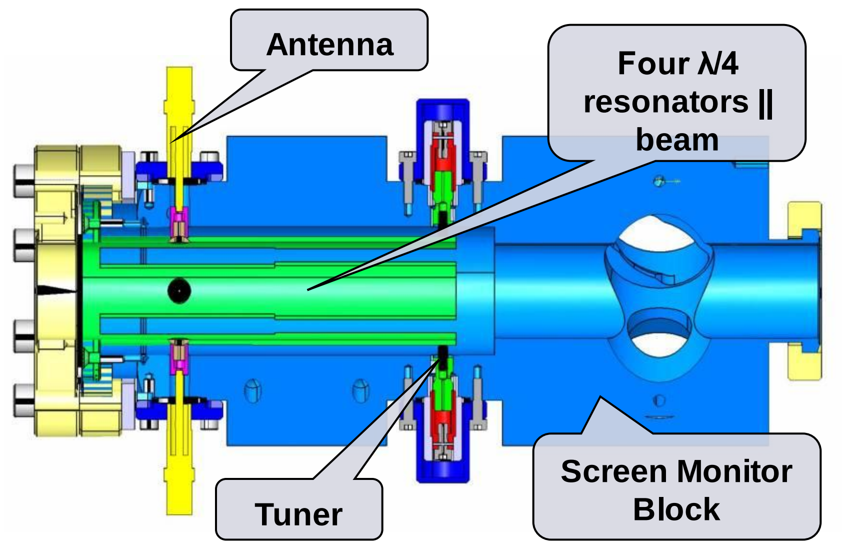
- Pickup = 500MHz resonant stripline (used in SLS linac).
- Electronics = 5GSPS digitizer mezzanine + generic "VPC" FPGA carrier board (modified PSI muon detector digitizer).

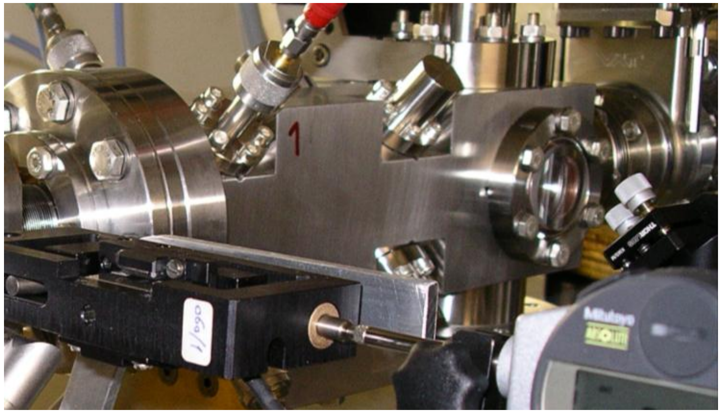
SwissFEL Test Injector BPMs

Resonant Stripline Pickup

- Already used in SLS linac & transfer lines.
- Optimized for SwissFEL test injector: frequencies, tuners, tolerances, ...

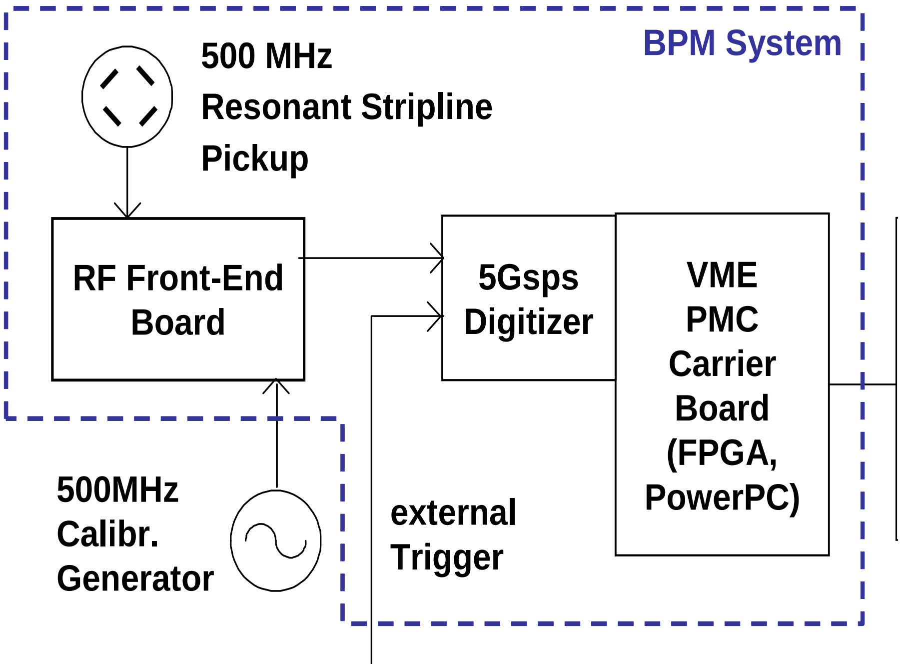






SwissFEL Test Injector BPMs

Resonant Stripline BPM System

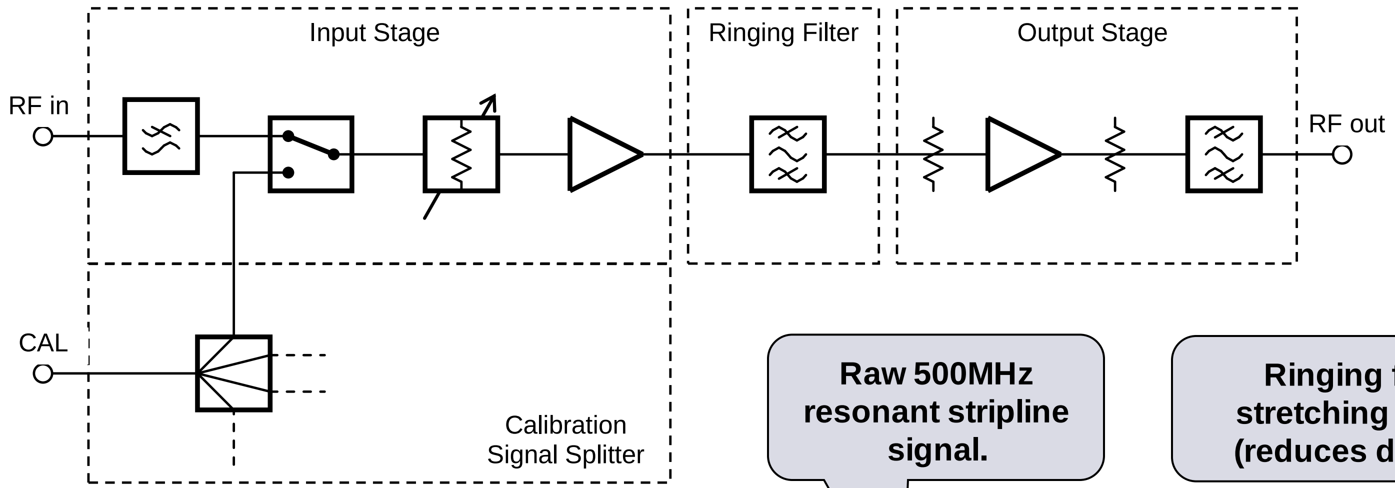


VME Crate with 4 BPM electronics (see FEL2010, WEPB15).

- RFFE filters, stretches & amplifies 500MHz ringing signal from pickup.
- Digitizer: Direct sampling with 5GSPS, no mixer.
- FPGA on VME carrier: Amplitude & position calculation.

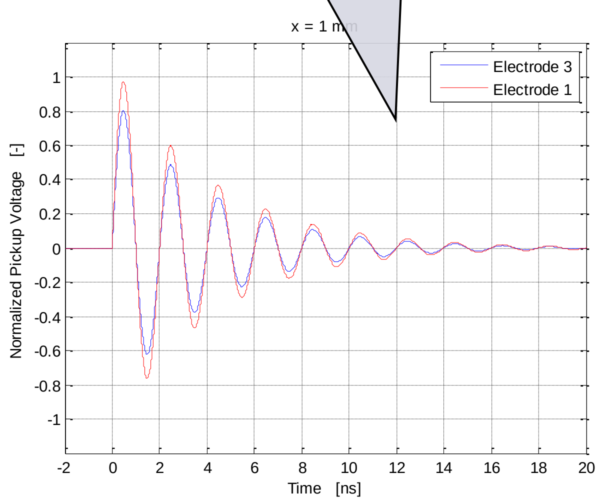
SwissFEL Test Injector BPMs

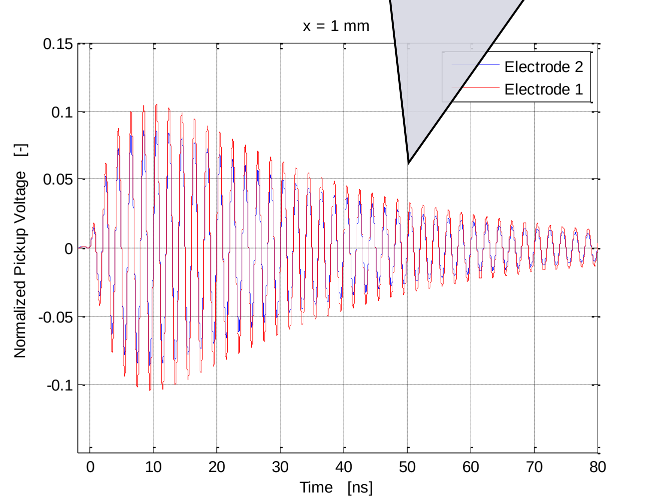
Resonant Stripline BPM: RFFE



Raw 500MHz resonant stripline signal.

Ringing filter output: Pulse stretching improves resolution (reduces digitizer jitter impact).



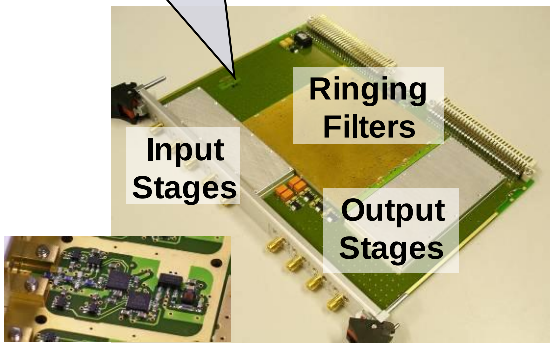


SwissFEL Test Injector BPMs

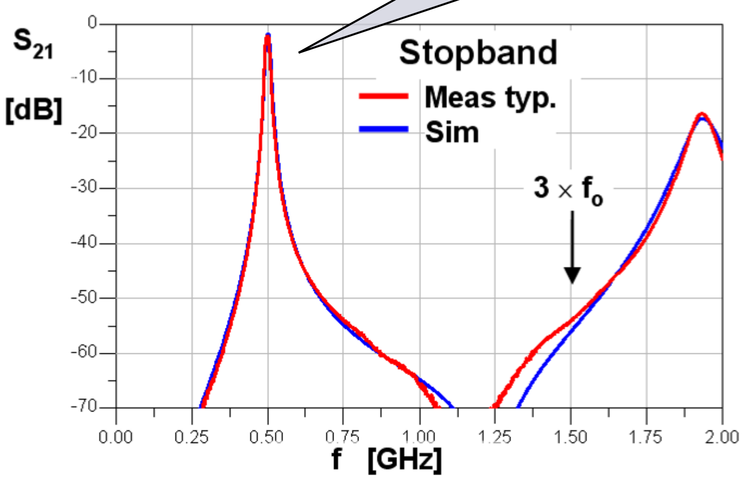
Resonant Stripline BPM: Electronics Modules

- PSI in-house design, incl. 5GSPS analog waveform sampling chip (originally designed for low-cost sampling of some 1000 photomultiplier signals at MuGamma experiment).

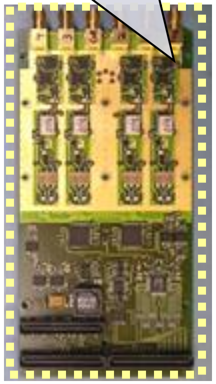
RF Front-End



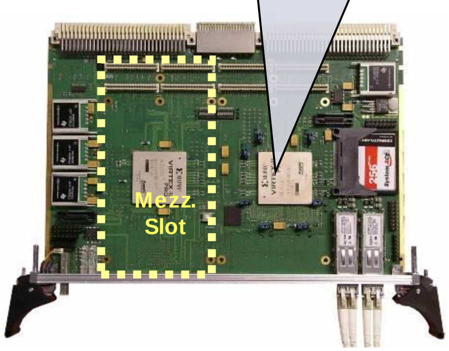
500MHz Ringing Filter Response



5 GSample/s Digitizer Mezzanine

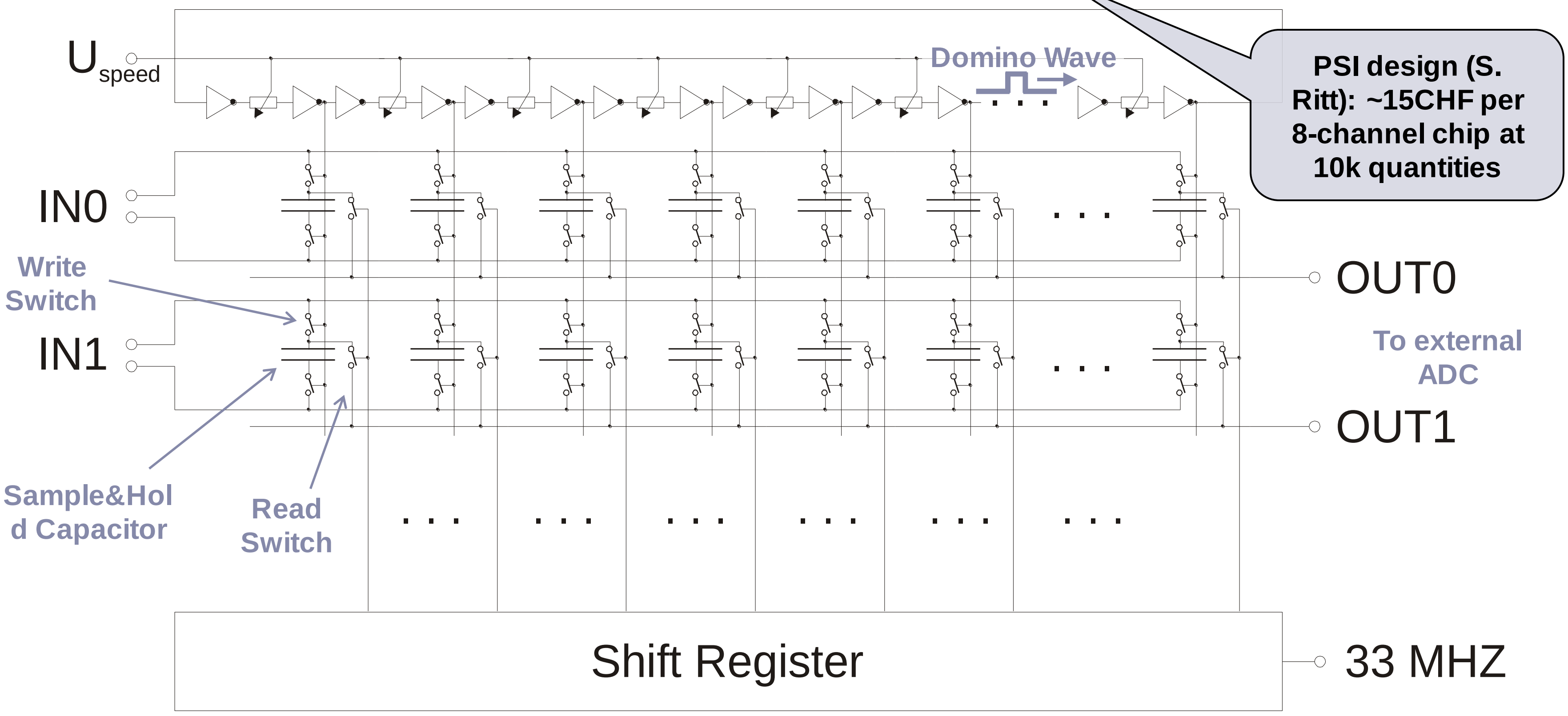


General-Purpose “VPC” FPGA VME Board (Design 2004)



Analog Waveform Sampling Chip

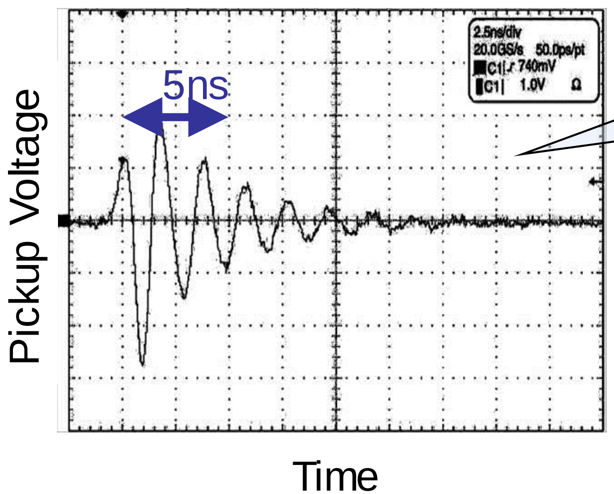
Low-cost 5 GSample/s Domino Ring Sampler (DRS) Chip - Principle



[S. Ritt, "Design and Performance of the 5 GHz Waveform Digitizing Chip DRS3", *IEEE Nucl. Sc. Symp. Conf.,* Honolulu, 26. Oct - 3. Nov. 2007]

SwissFEL Test Injector BPMs

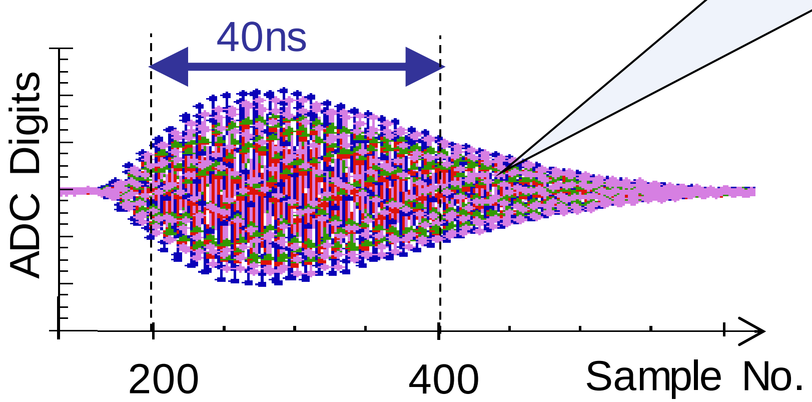
Signal Waveforms

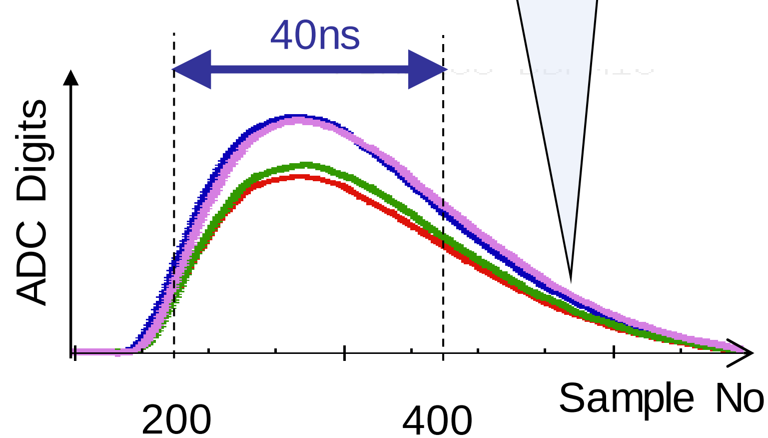


Low-passed pickup signal (scope measurement).

RFFE output, digitized by BPM electronics (5Gsps), after gain/offset/jitter correction & FIR filtering in FPGA.

FPGA calculates envelopes of RFFE signals. Beam position calculated from integrals.

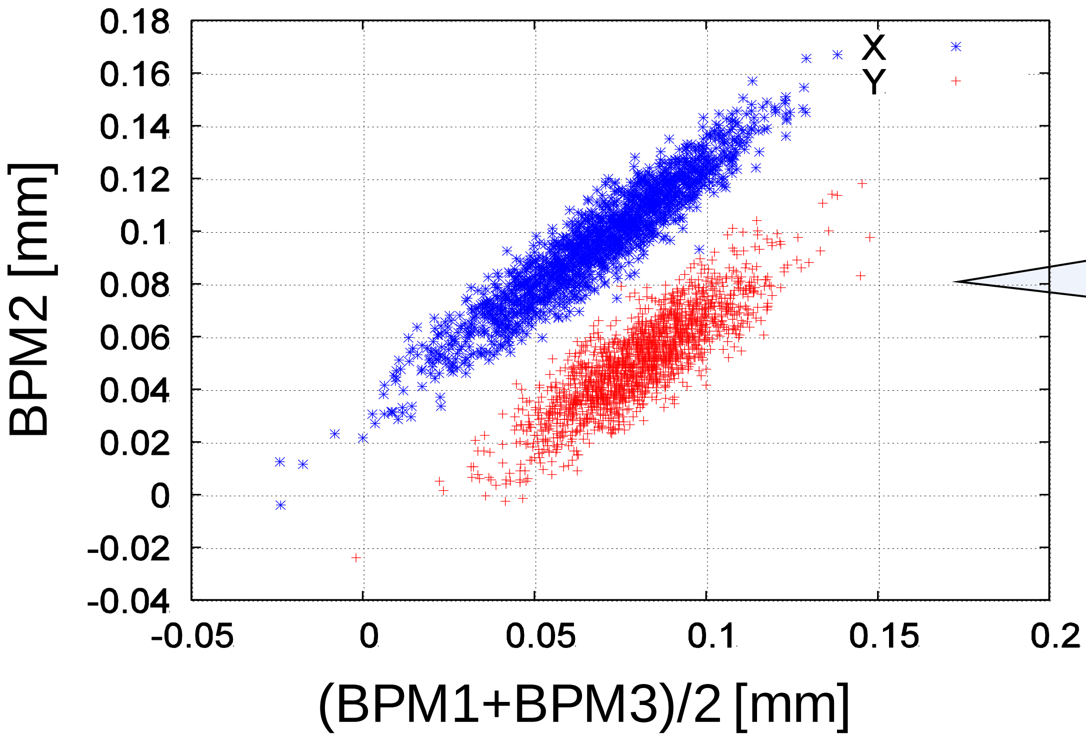




SwissFEL Test Injector BPMs

Position Resolution

- 7um RMS noise from 5-500pC (dominated by DRS chip sampling jitter).
- 30um RMS noise at 1pC (thermal noise ~1/Q).
- For 16.2mm geometry factor (45° strip angles), >20mm pp-range.

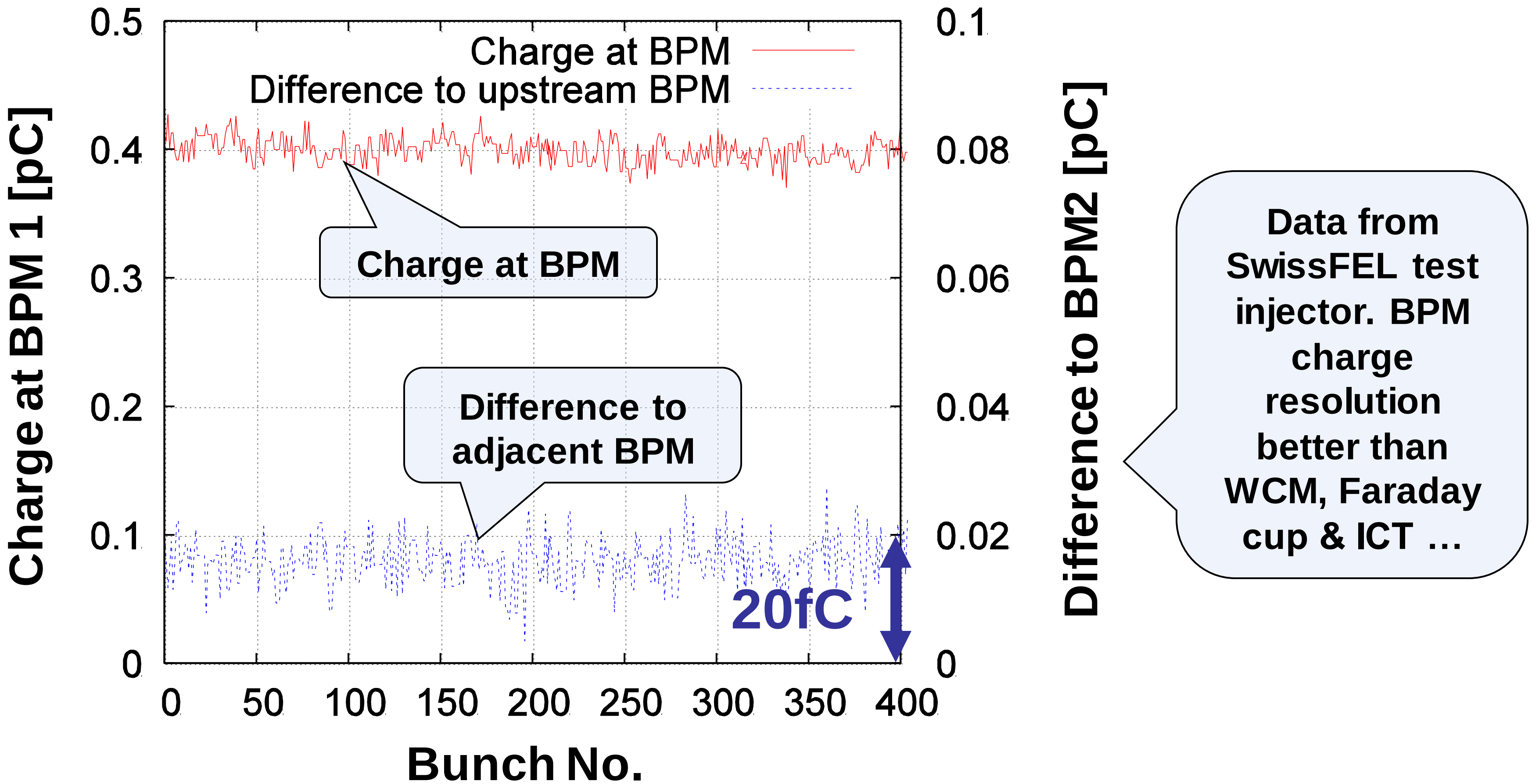


Correlation of 3 adjacent BPMs: 1800 position measurements (over 3 minutes).

SwissFEL Test Injector BPMs

Charge Resolution

- Correlation of adjacent BPMs: ~4fC RMS noise @ 400fC bunch charge



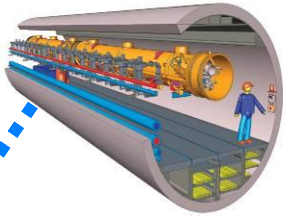
Contents

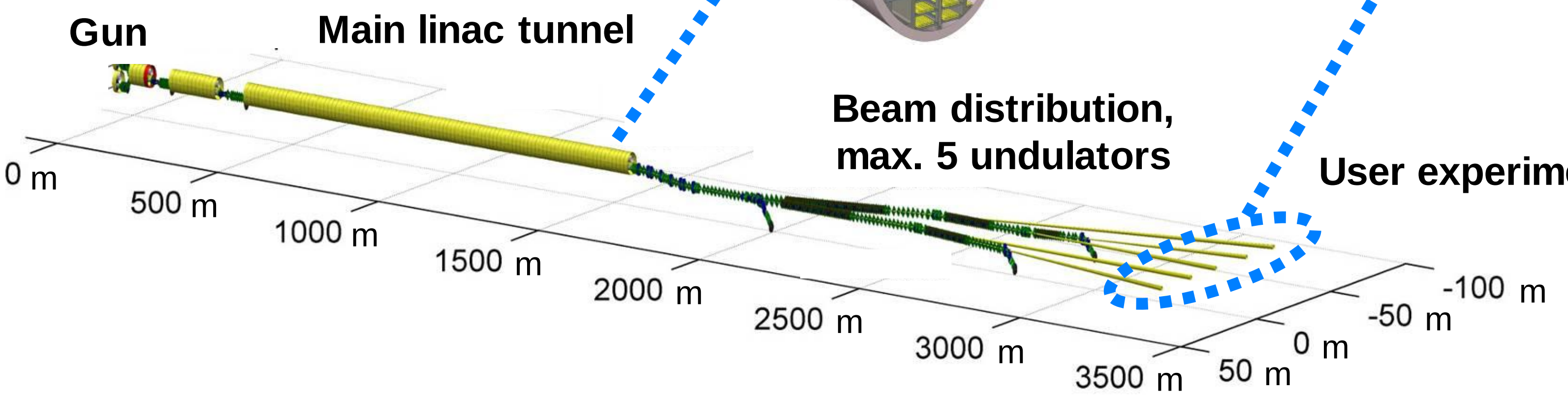
E-XFEL BPMs

E-XFEL

- L ~ 3400m. 17.5GeV. SASE <0.1nm.
- Trains of ~2800 bunches @ 10Hz.
- ~222ns min. bunch spacing.
- 20-1000pC / bunch.

Originally 100-1000pC...





E-XFEL BPMs

E-XFEL BPMs: Collaboration Team and Deliverables

Preliminary

BPM Type	Count	Pickup / Mechanics	RF Front-End Electronics	ADC, Digital Back-End Electronics	FPGA Firmware/ Software
Cold Button	56	DESY**	PSI	PSI	PSI
Re-Entrant Cavity	26	CEA/Saclay**	CEA/Saclay**	PSI	PSI
Warm Button *	237	DESY**	PSI	PSI	PSI
Transfer Line Cavity	24	DESY**	PSI	PSI	PSI
Undulator Cavity	98	DESY**	PSI	PSI	PSI

-- cold -- ---- warm ----

* Different types / pipe apertures needed (beam dump: 100mm, transfer lines: 40.5mm, …)

** See talks from D. Lipka & C. Simon

- Modular electronics, common “generic” digital back-end.
- Pickup-specific RF front-ends.
- Common hardware & firmware: Less work & costs.

E-XFEL BPMs

BPM Performance Requirements

- Table from BPM CDR 2010. Preliminary (length, quantities, …).
- Most values from beam dynamics work package (Decking et al.).

	Type	Quantity	Beam Pipe Diameter	Vacuum length	Single Bunch RMS Resolution	Averaged RMS Resolution over 1000 bunches of identical trains	Drift per 1 deg C, min 0.1 µm	Operation range for maximum resolution	Operation range providing reasonable signal	Linearity	x/y Crosstalk	Charge Dependence (dQ=10%)	Bunch to Bunch Crosstalk	Transverse Alignment Tolerance (RMS)	Pipeline Latency
			mm	mm	µm	µm	µm	mm	mm	%	%	µm	µm	µm	ms
Cold BPM	Button/Re-entrant	102	78	170	50	10	10	± 3.0	± 10	10	1	50	10	300	10
Gun BPM	Button	3	40.5	100	100	10	10	± 3.0	± 10	5	1	100	10	200	10
Standard BPM	Button	219	40.5	200/ 100[1]	50	10	10	± 3.0	± 10	5	1	50	10	200	10
Standard BPM	Button	6	100	200	100	10	10	± 5.0	± 20	10	1	100	10	200	10
Cavity BPM Beam Transfer Line	Cavity	12	40.5	255	10	1	1	± 1.0	± 2	2	1	10	1	200	10
Cavity BPM Undulator	Cavity	117	10	100	1	0.1	1	± 0.5	± 2	2	1	1	0.1	50	10

[1] **Warm button: Flanged version & welded version (where flanged is too long)**

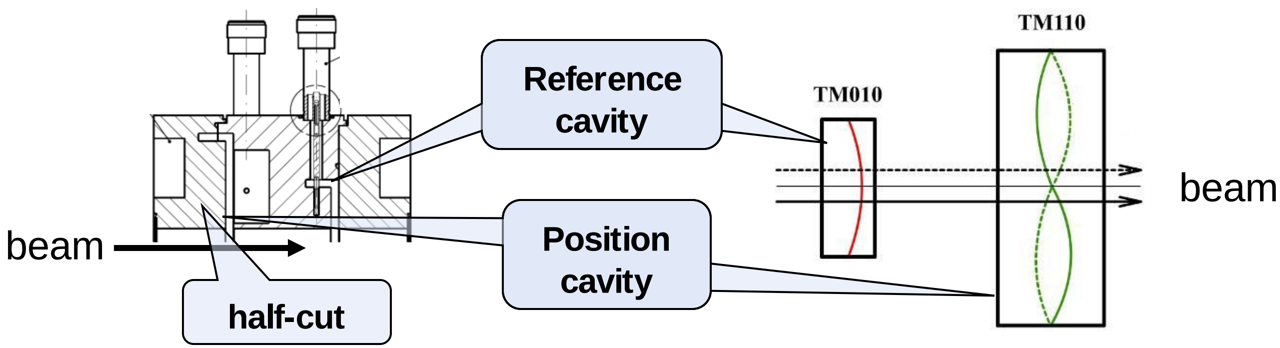
E-XFEL BPMs

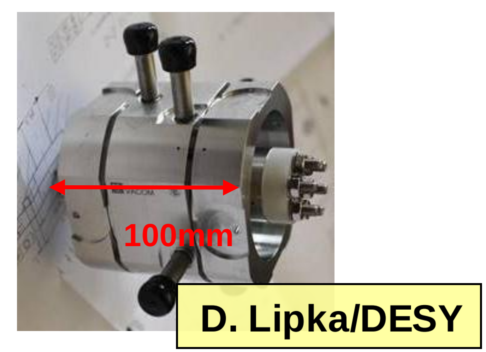
Undulator Cavity BPM: Design

- Based on 4.8GHz SPring8/SCSS design.
- Adapted to E-XFEL (3.3GHz, …).

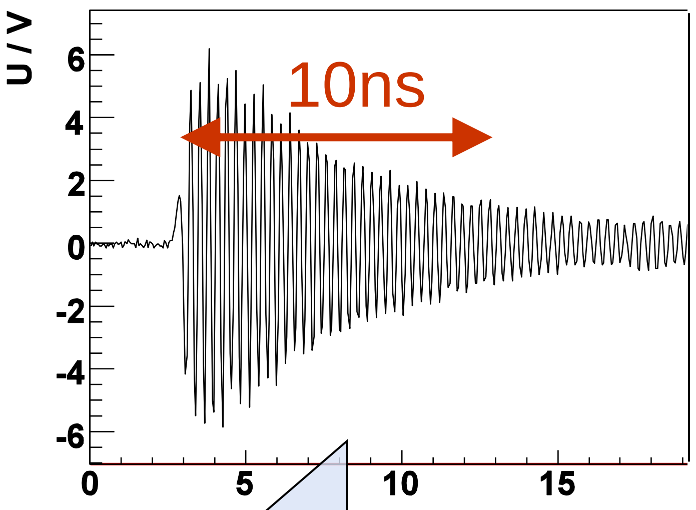
Same BPM electronics for 10mm and 40.5mm aperture: <$f_{cut-off}$

Frequency (both resonators)	3.3GHz
Loaded Q (both resonators, desired mode)	~70
Q (uncoupled modes)	typ. 200-300
Sensitivity	2.9V/(nC*mm)
Thermal noise (lossless cables & electronics, …)	55nm @ 20pC
Angle signal (90° to position signal)	1mm * dx/dz



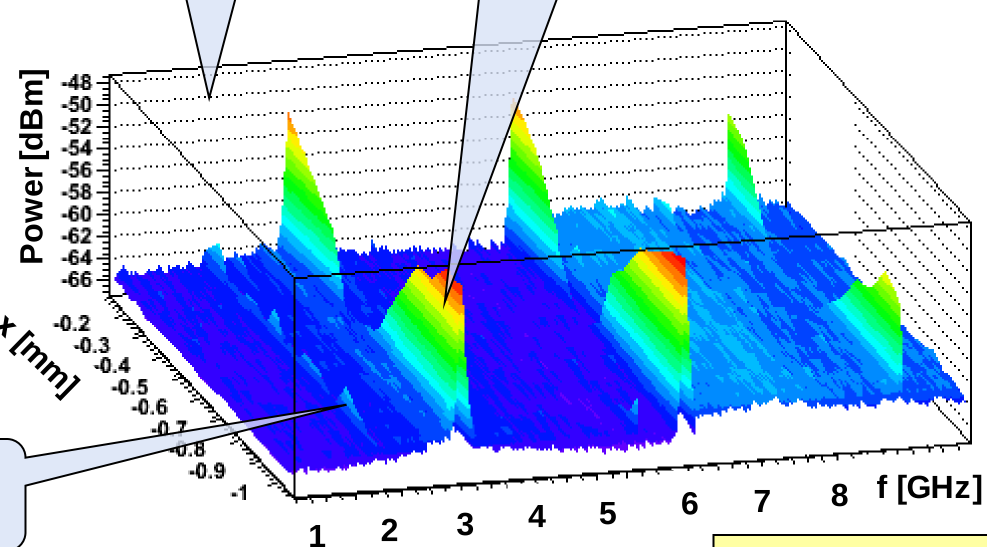


Undulator Cavity BPMs (Cont'd)



Flash beam test: 3.3GHz Position resonator signal (~2.7 V/(nC*mm))

Flash beam test: Position resonator spectrum vs. cavity position (motorized 2D mover)



3.3GHz Dipole mode

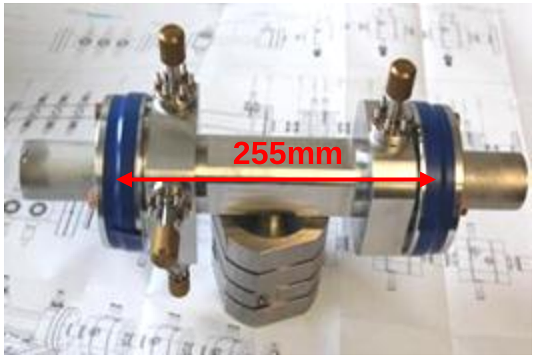
Monopole mode (suppressed by coupler)

D. Lipka/DESY

E-XFEL BPMs

Transfer Line Cavity BPM

- 3.3GHz, 40.5mm aperture.
- Used for: Transverse intra-train feedback, energy measurements, launch jitter control & correction (energy, BAM, linac entry, …), optics measurements, …



Similar to undulator type, slightly less resolution (~20%). Main differences: ~16x more angle signal (→ align 16x better), cavity spacing (→ crosstalk).

Frequency (both resonators)	3.3GHz
Loaded Q (both resonators, desired mode)	~70
Q (uncoupled modes)	typ. 200-300
Sensitivity	2.5V/(nC*mm)
Thermal noise (lossless cables & electronics, …)	65nm @ 20pC
Angle signal (90° to position signal. Cause: Misalignment)	~16mm * dx/dz

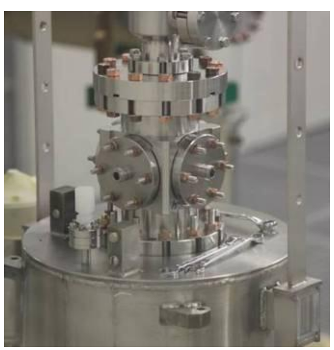
D. Lipka DESY

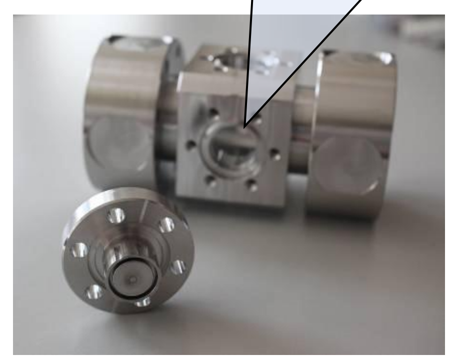
E-XFEL BPMs

Cold & Warm Button BPM

- Cold Button : Aperture 78mm.
- Warm Button: Aperture 40.5mm (transfer line), 100mm (beam dump).
- Version with and without flange (space requirements …).
- Warm Button: ~3x better position resolution @ low charge than cold button (aperture: 2x, button size: 1.5x).

Prototype installed at FLASH, test with beam (April/May 2011)





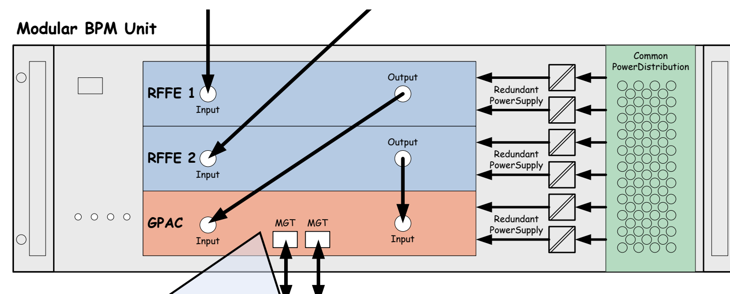
D. Lipka et al.

E-XFEL BPMs

Modular BPM Unit ("MBU")

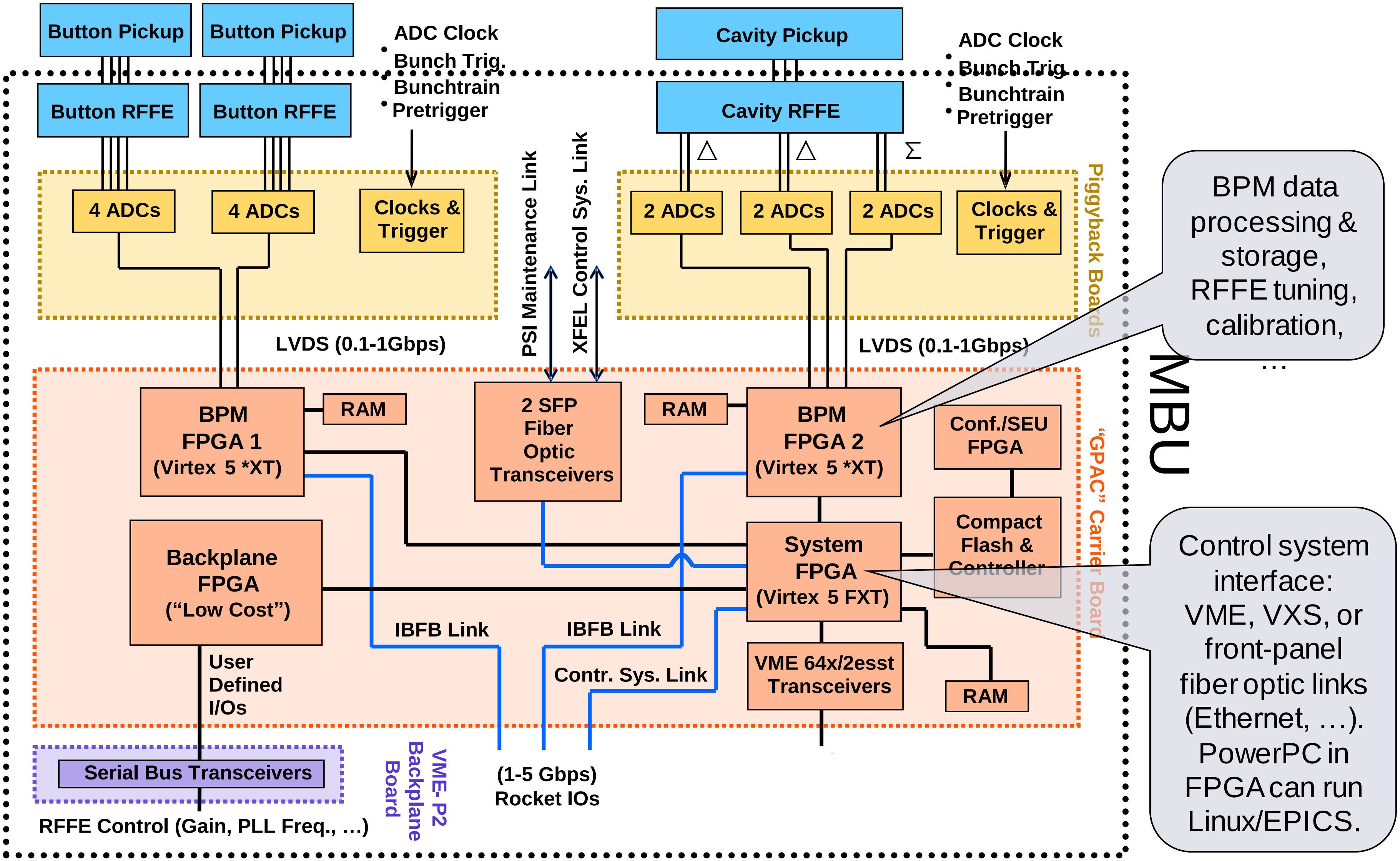
- 19" housing, power supply, fans, …
- Contains 4 button RF front-ends (RFFEs), or 2 cavity RFFEs, or combination.
- Common digital-back-end FPGA board (GPAC = Generic PSI ADC carrier) + two ADC mezzanines.

MBU for two undulator BPMs



Control, timing & feedback interfaces: Multi-gigabit fiber optic links. Multi-protocol & baud rate support (PCI-e, Ethernet, …)

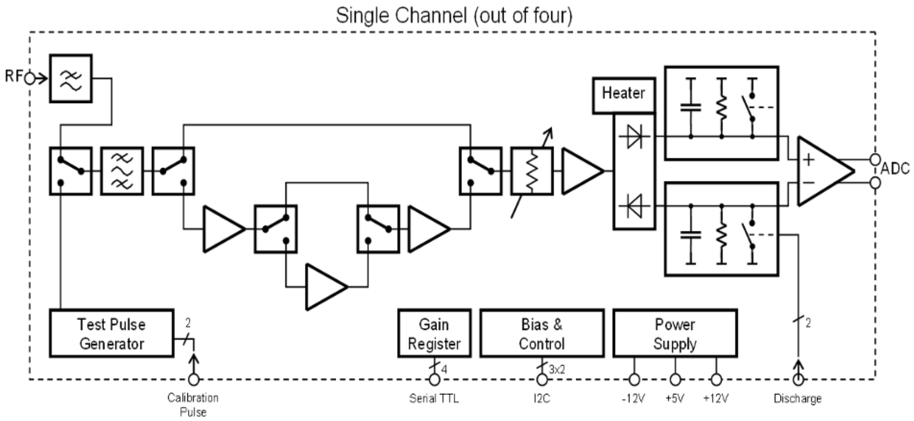
E-XFEL BPMs

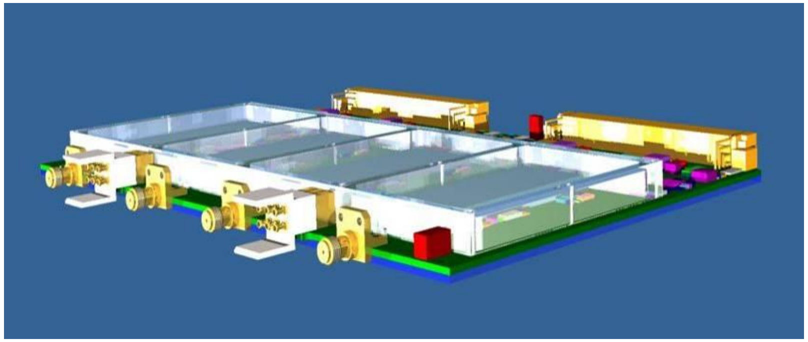

Button Pickup
Button Pickup
Button RFFE
Button RFFE
ADC Clock
Bunch Trig.
Bunchtrain
Pretrigger
4 ADCs
4 ADCs
Clocks & Trigger
Cavity Pickup
Cavity RFFE
Δ
Δ
Σ
ADC Clock
Bunch Trig.
Bunchtrain
Pretrigger
2 ADCs
2 ADCs
2 ADCs
Clocks & Trigger
Piggyback Boards
PSI Maintenance Link
XFEL Control Sys. Link
LVDS (0.1-1Gbps)
LVDS (0.1-1Gbps)
BPM FPGA 1 (Virtex 5 *XT)
RAM
2 SFP Fiber Optic Transceivers
RAM
BPM FPGA 2 (Virtex 5 *XT)
Conf./SEU FPGA
Compact Flash & Controller
Backplane FPGA ("Low Cost")
System FPGA (Virtex 5 FXT)
IBFB Link
IBFB Link
Contr. Sys. Link
VME 64x/2esst Transceivers
RAM
User Defined I/Os
"GPAC" Carrier Board
MBU
Serial Bus Transceivers
VME-P2 Backplane Board
(1-5 Gbps) Rocket IOs
RFFE Control (Gain, PLL Freq., …)
BPM data processing & storage, RFFE tuning, calibration, …
Control system interface: VME, VXS, or front-panel fiber optic links (Ethernet, …). PowerPC in FPGA can run Linux/EPICS.

E-XFEL BPMs

Button BPM RFFE

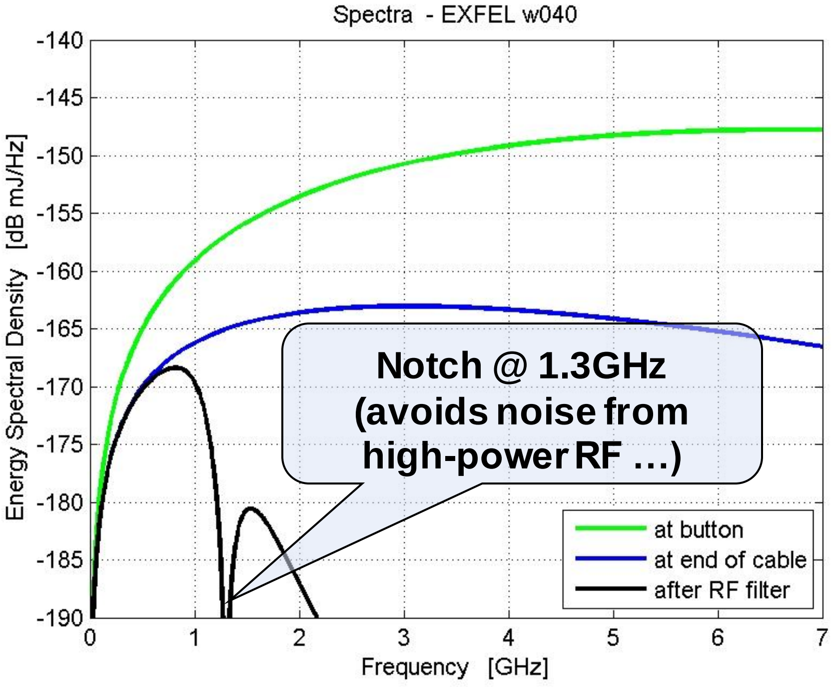
- Input filter (bandpass, 1.3GHz notch, …).
- Variable gain stage (>40dB), calibration pulser.
- Peak detector with hold capacitor. Discharge: Automatic (resistor) or triggered (GPAC FPGA).
- Status: PCB being soldered, lab & beam test Q1-2/2012. Modular design: Fast design iterations (if needed).

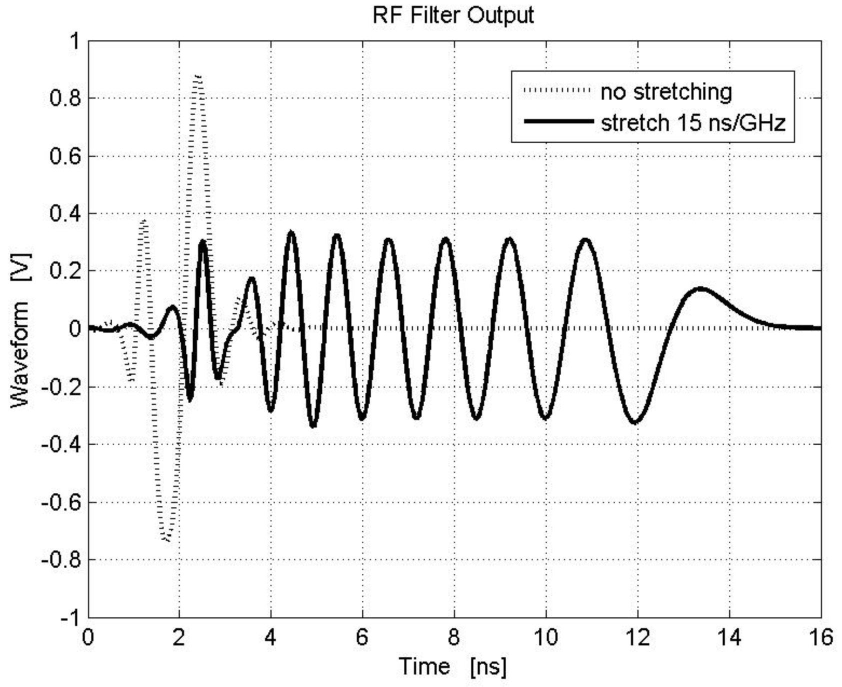




Button BPM RFFE (Cont'd): Input filter

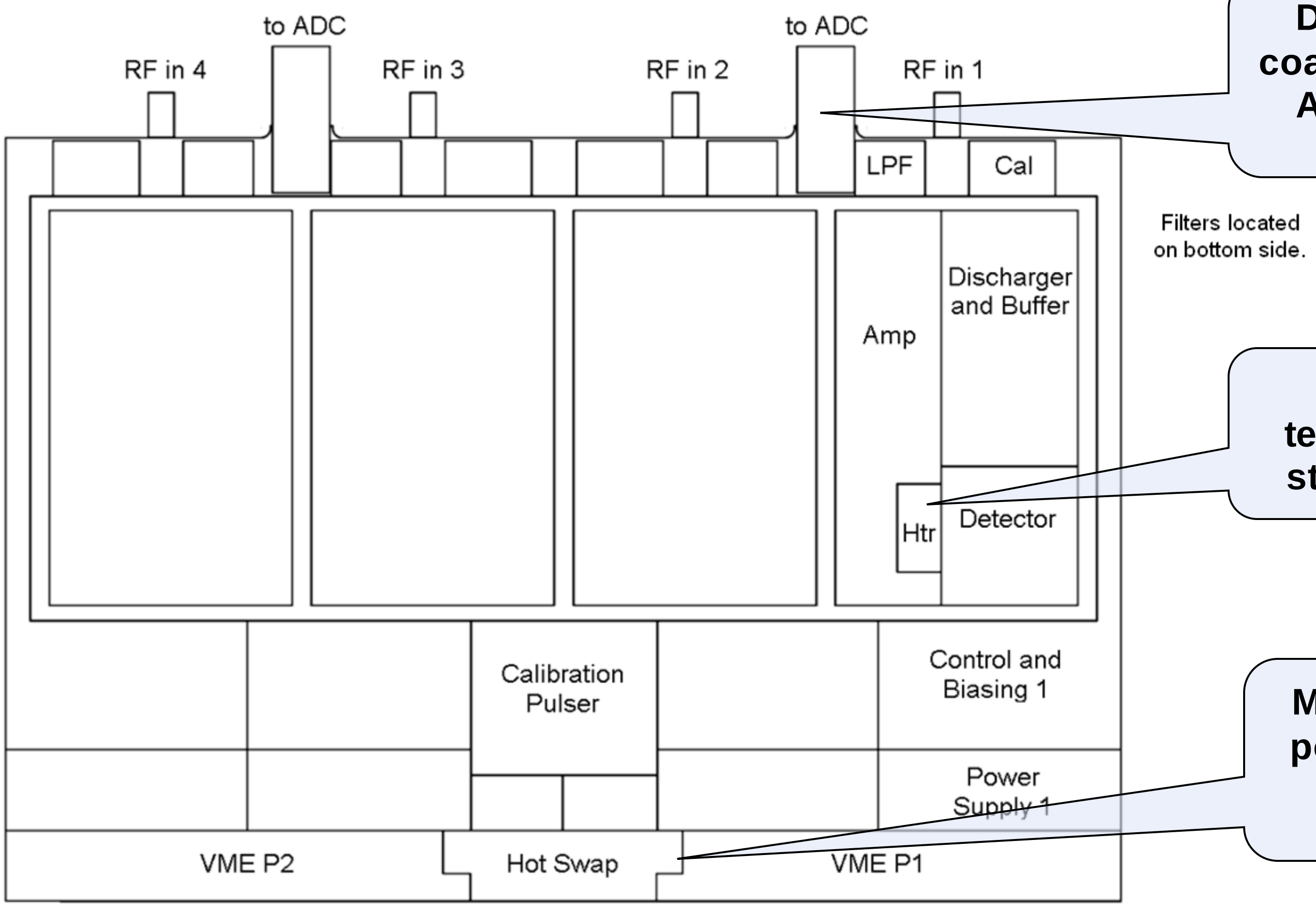
- Dispersive input filter stretches button pickup pulse.
- Eases signal handling (linearity/saturation, …).
- Bandwidth >1GHz: More energy, better low-charge resolution.





E-XFEL BPMs

Button BPM RFFE : PCB Floor Plan

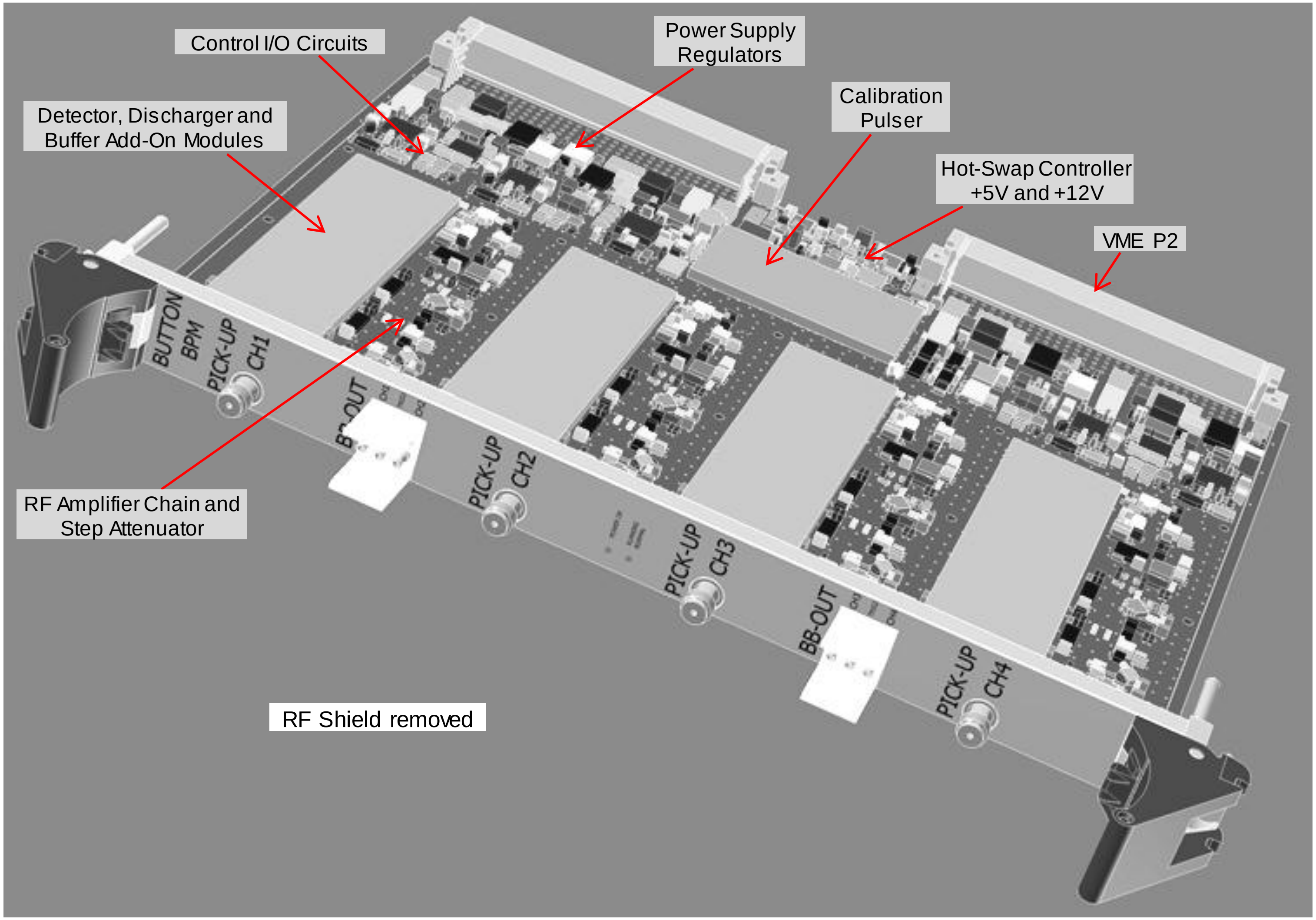


Differential coax outputs to ADCs: Low noise.

Active temperature stabilization

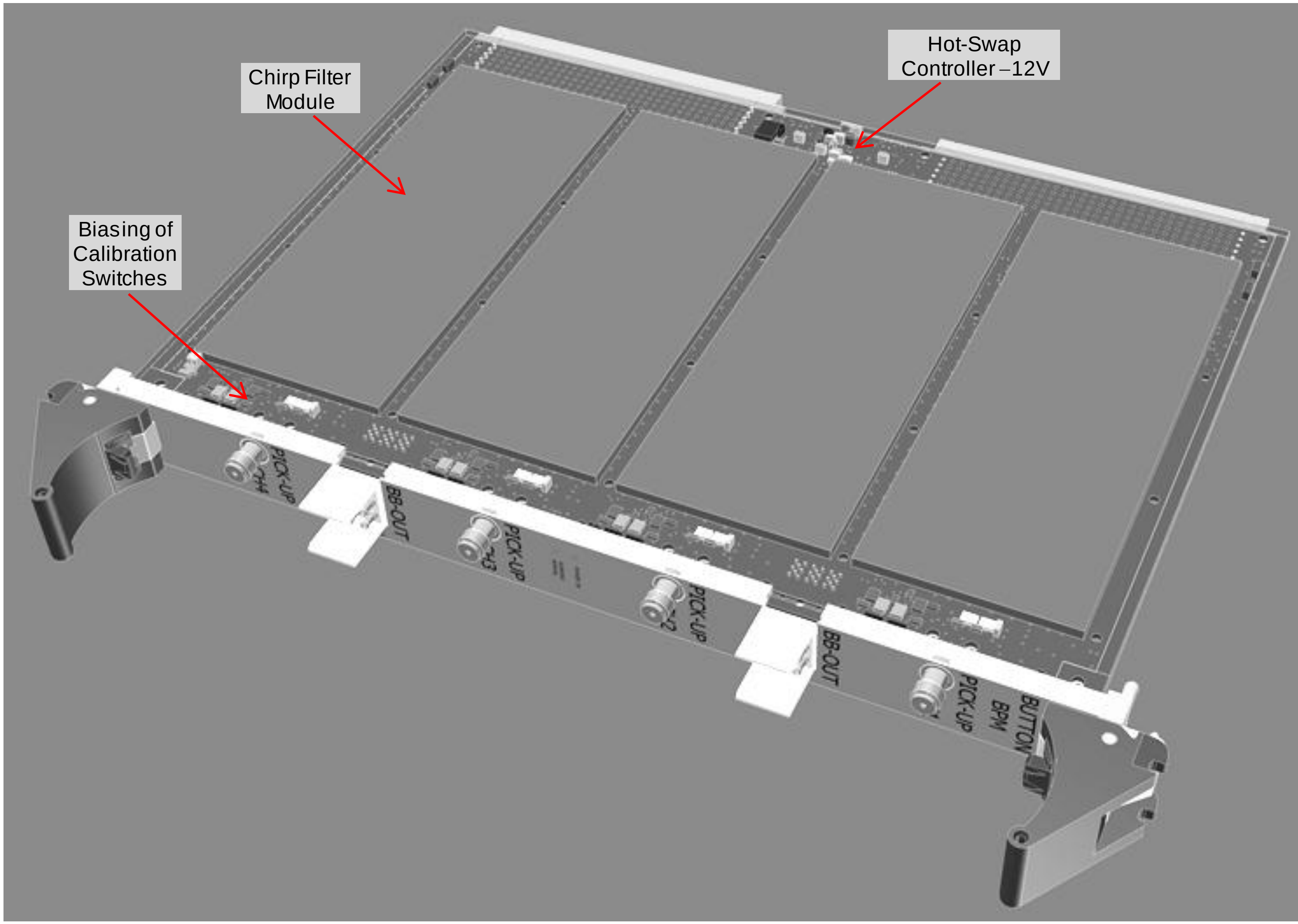
Monitoring of power supply voltage & current

E-XFEL BPMs

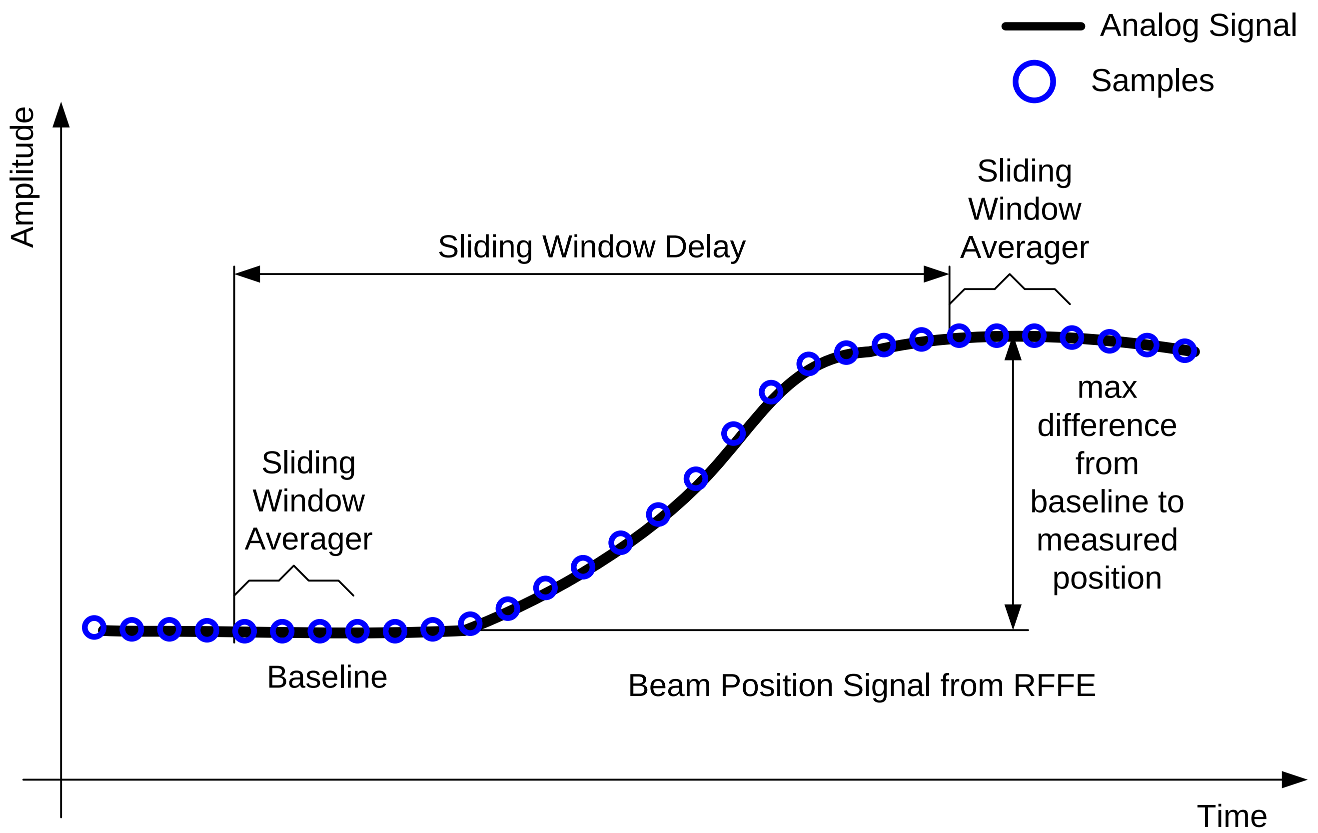


Control I/O Circuits
Power Supply Regulators
Detector, Discharger and Buffer Add-On Modules
Calibration Pulser
Hot-Swap Controller +5V and +12V
VME P2
BUTTON BPM PICK-UP CH1
PICK-UP CH2
PICK-UP CH3
BB-OUT
PICK-UP CH4
RF Amplifier Chain and Step Attenuator
RF Shield removed

E-XFEL BPMs

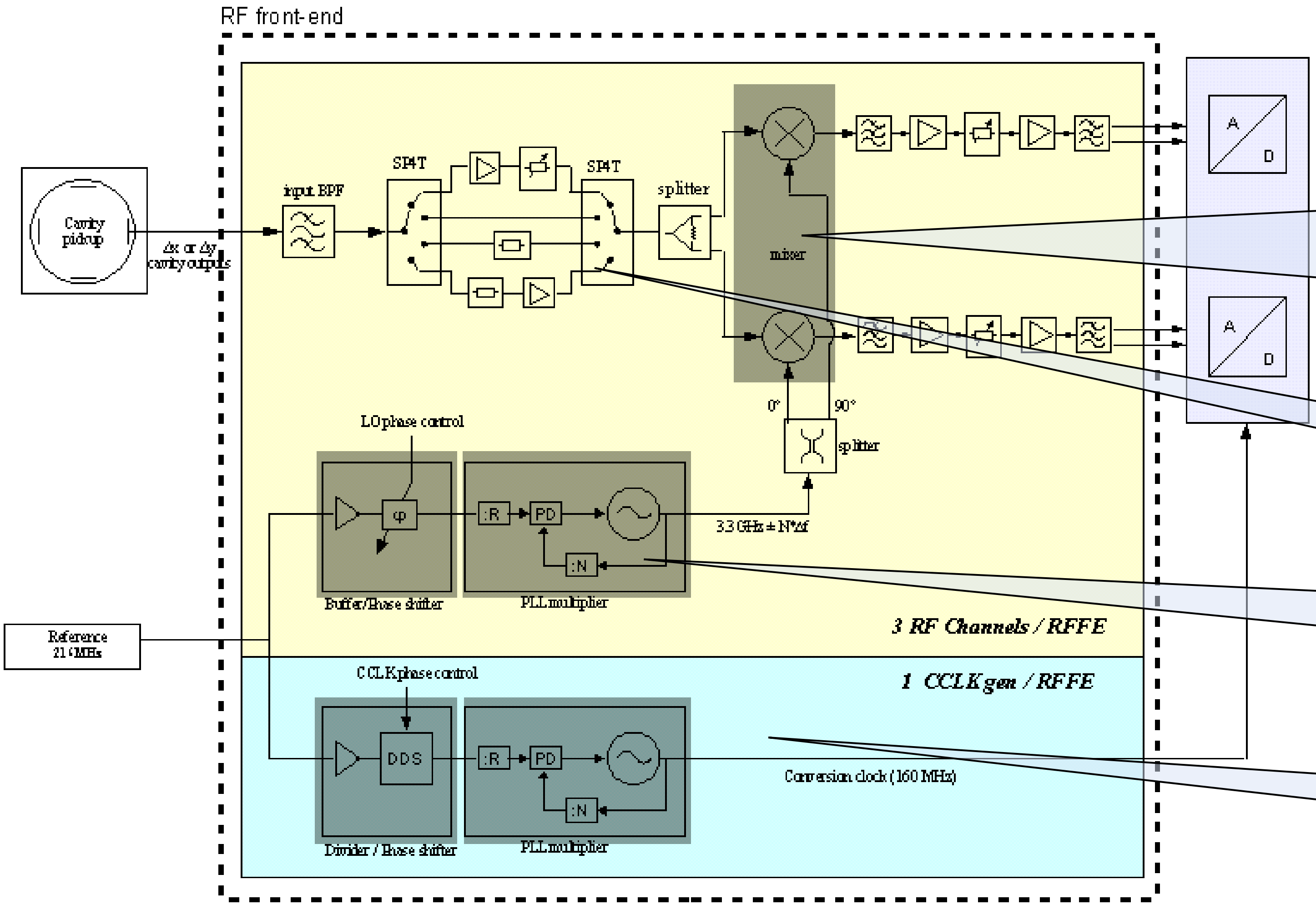

Hot-Swap Controller –12V
Chirp Filter Module
Biasing of Calibration Switches
BB-OUT
BB-OUT
BUTTON BPM PICK-UP

Button BPM Algorithm Concept



E-XFEL BPMs

Undulator Cavity BPM RFFE



IQ demodulation of 3.3GHz cavity RFFE signal to baseband

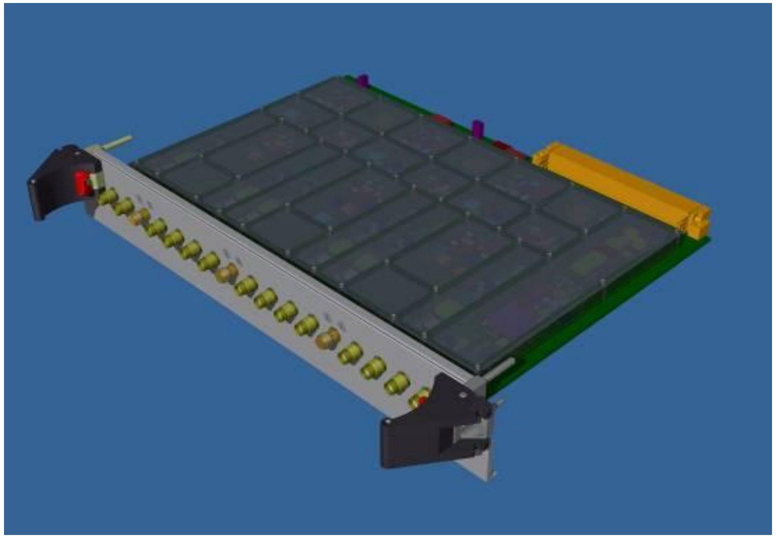
4 gain ranges (>20dB)

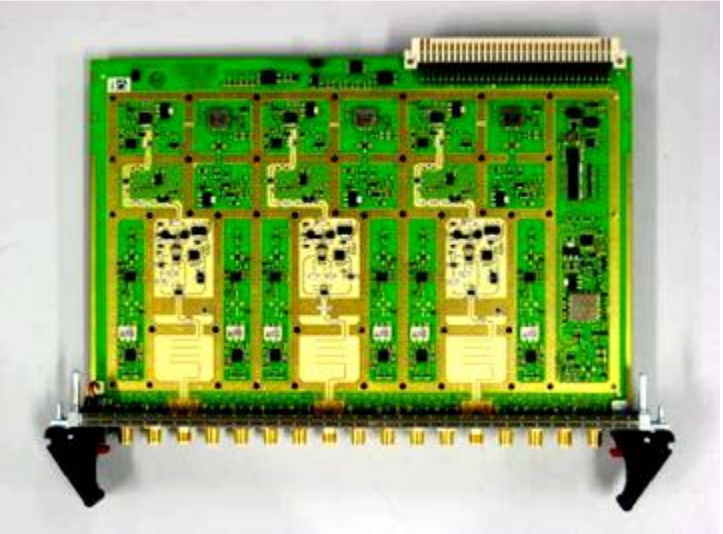
3 LOs. Phase & frequency programmable.

ADC clock synthesis

E-XFEL BPMs

Undulator Cavity BPM RFFE



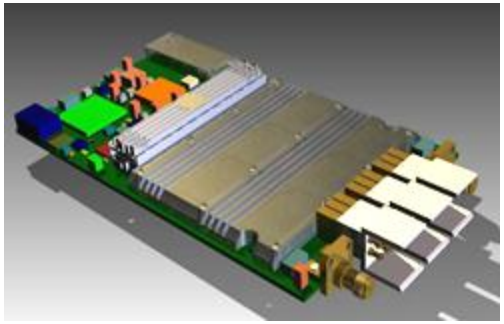


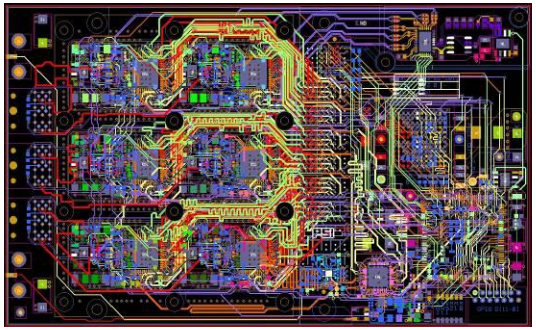
- 2nd version (2011): Active temperature stabilization, solid shielding, ADC clock synthesis, more gain ranges, …
- Beam tests: 1-2µm RMS noise @ FLASH without adjusting gain, delays, LO, … (1 shift, lack of time …) → expect < 1µm if adjusted.
- Lab & beam test with properly adjusted/calibrated RFFE ongoing.

E-XFEL BPMs

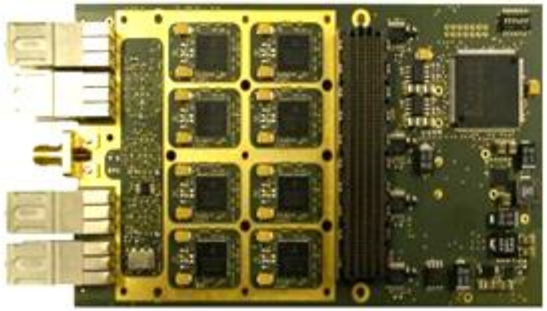
Undulator & Button BPM ADC Mezzanines

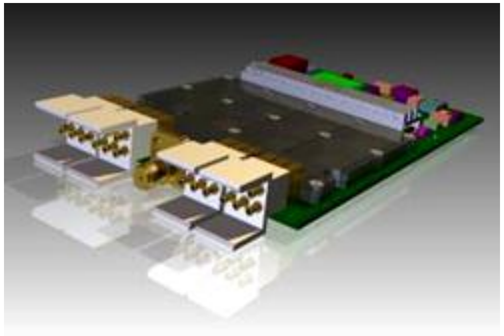
Cavity BPMs: 6-channel, 16-bit, 160MSamples/s.

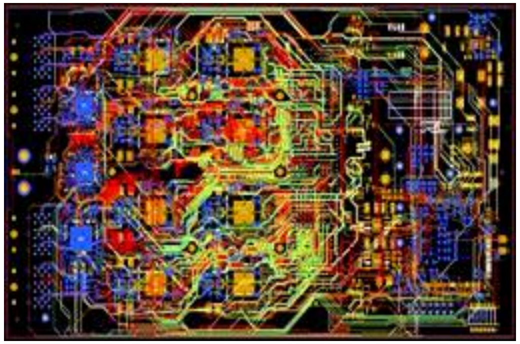




Button BPMs: 8-channel, 12-bit, 500MSamples/s.







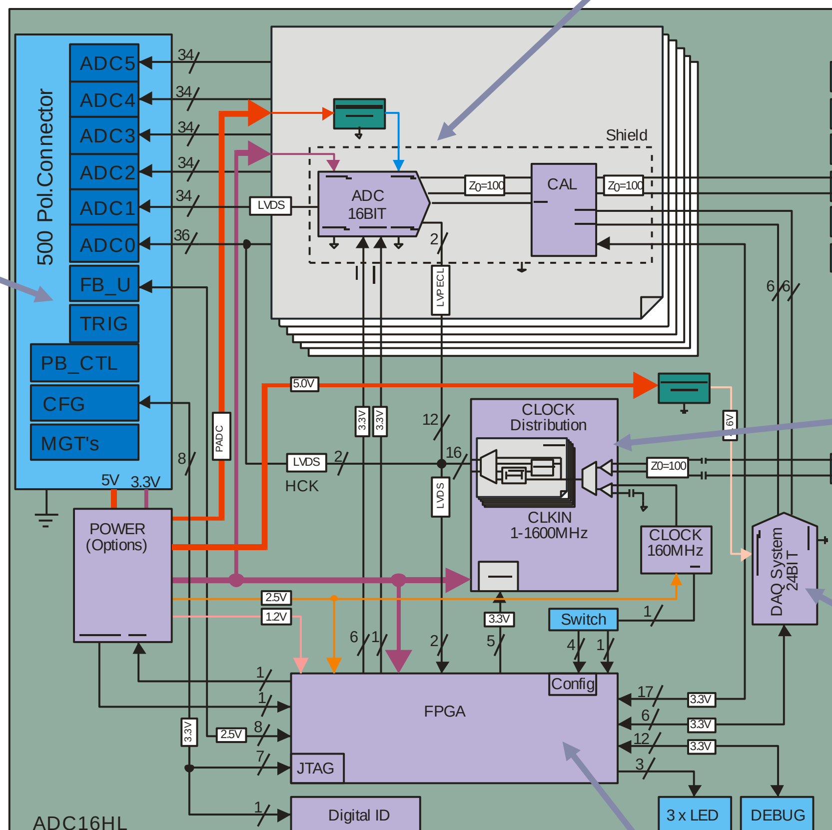
Both types: Differential coax inputs, 150ps step clock phase adjust per ADC.

E-XFEL BPMs

Cavity BPM Electronics: ADC Mezzanine Board

Six 16-bit 160Msps ADCs

500pol. High Speed Connector (Carrier Board FPGA Interface)



Differential Inputs

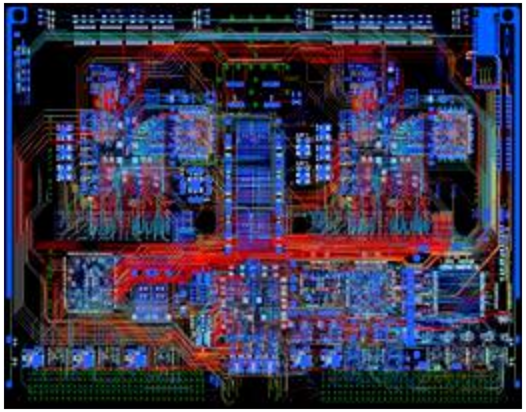
Low Jitter Clock Distribution (80fs)

On-Board Gain and Offset Calibration

Control Unit

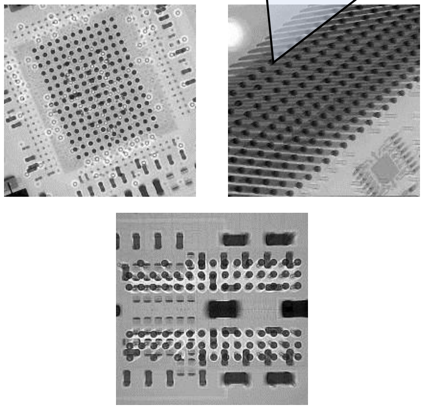
E-XFEL BPMs

Digital Back-End (GPAC) FPGA Board: Hardware



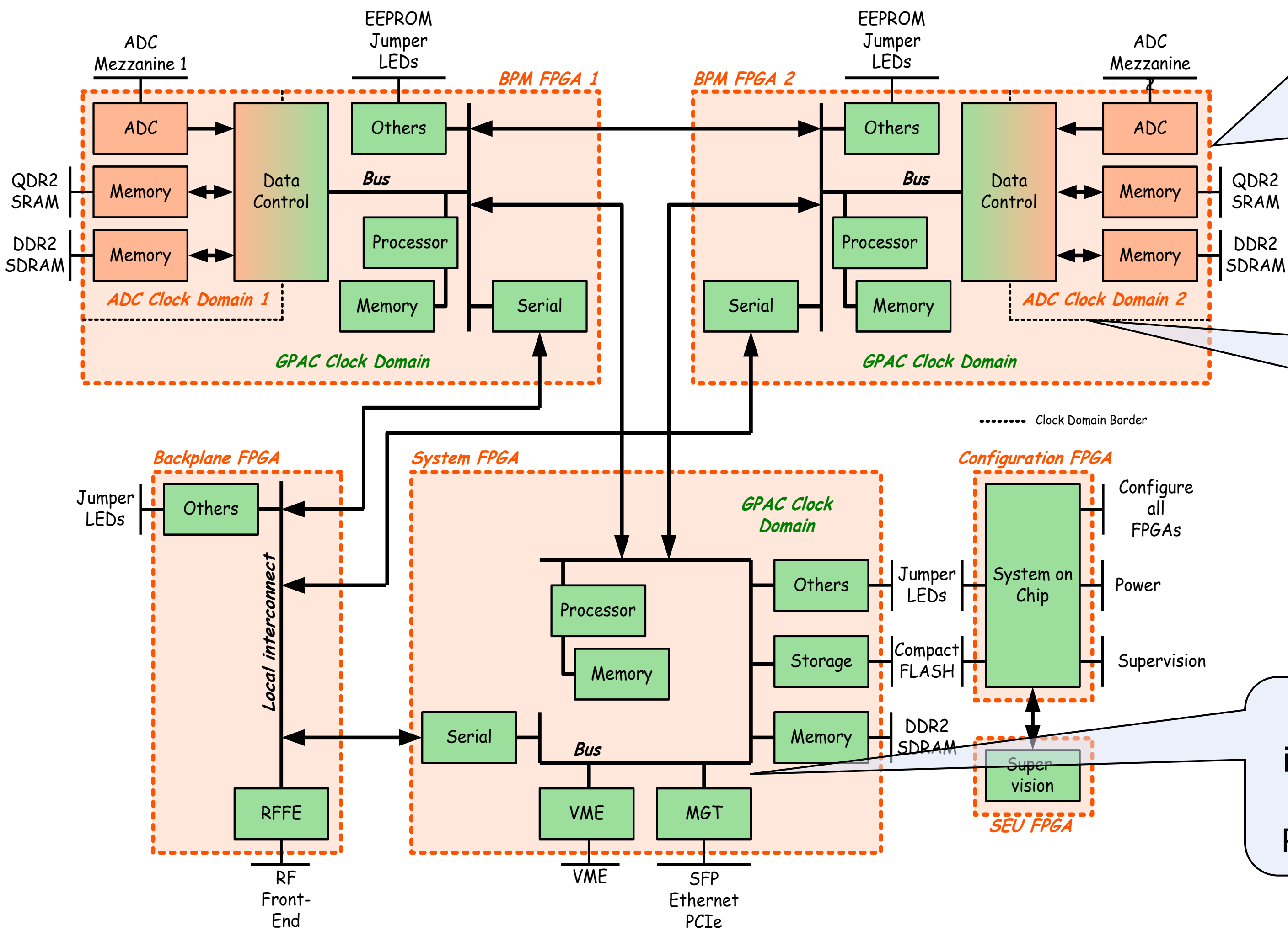
- Mid 2010: First prototype delivered to PSI.
- Only faults found & fixed: Few capacitor values (time constant for power-up) changed, EEPROM replaced (was too small).
- Working fine, extensive tests done. Now: Focus on firmware/software & long-term beam tests.

X-ray quality control (RAMs, connector)



E-XFEL BPMs

GPAC: FPGA Firmware/Software



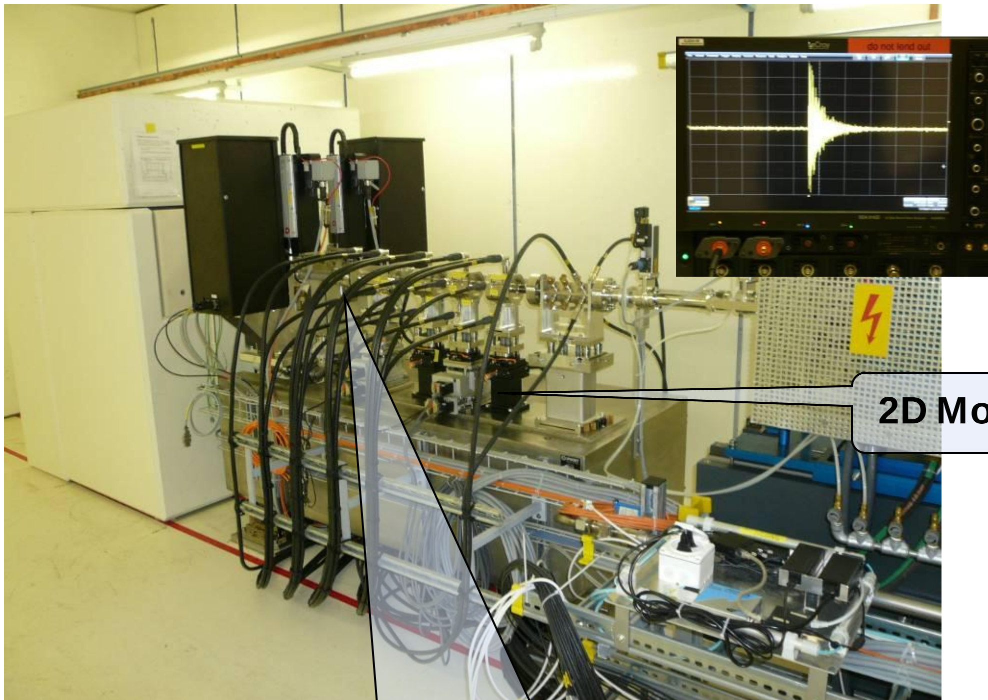
Cavity BPM: Storage of ADC waveform in RAM working (2GByte/s, complete bunch train)

Position calculation in FPGA

Control system interface for long-term beam tests (PSI, FLASH) implemented.

E-XFEL BPMs

E-XFEL Cavity BPM: Test @ SwissFEL Test Injector



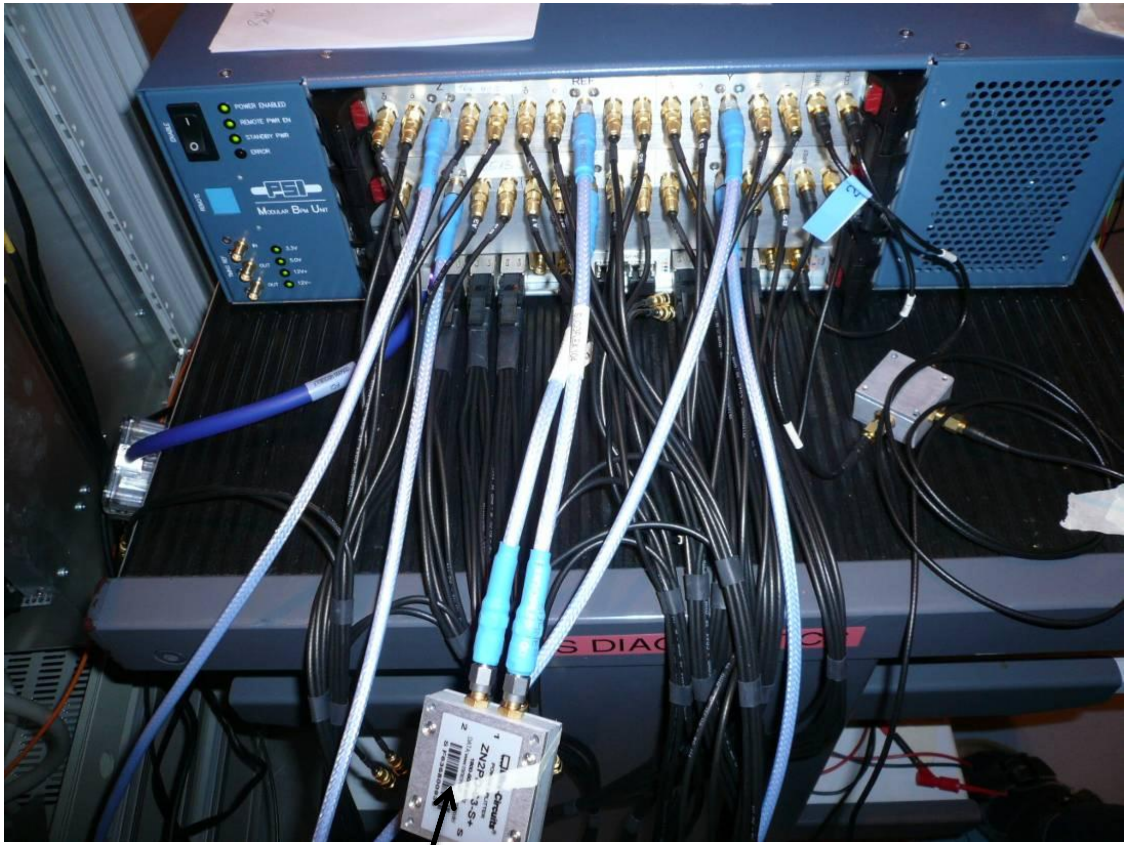
2D Mover

Three E-XFEL undulator cavity PU & one beamline cavity PU

E-XFEL cavity BPM electronics for 2 BPMs (works in MBU and standard VME crates)

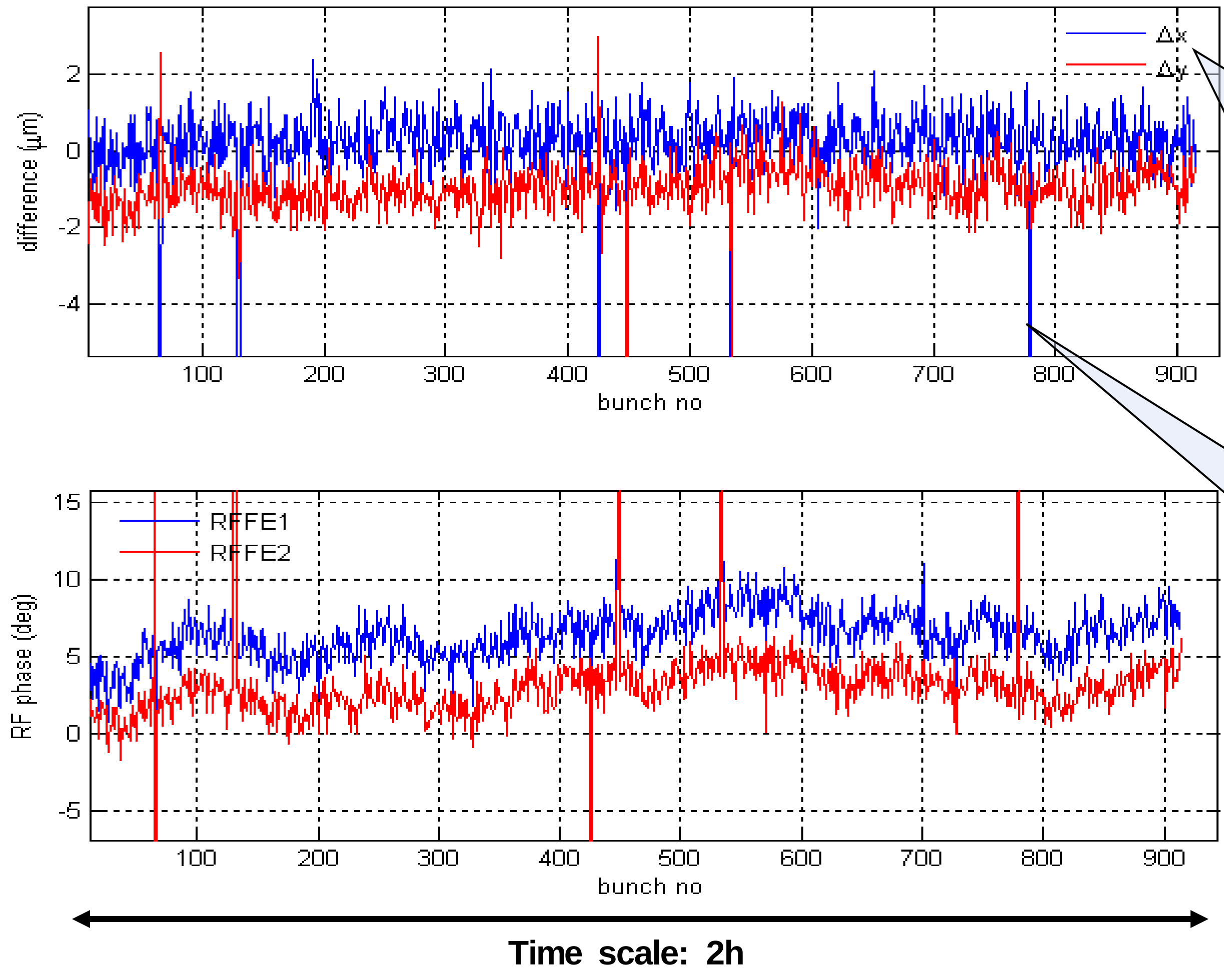
- Status: Waiting for beam for multi-BPM noise correlation (after shutdown).

MBU For Two Cavity BPMs: Beam Test @ SLS Linac



Reference cavity signal splitter

E-XFEL Cavity BPM: Latest Beam Test @ SLS Linac



Signal of one cavity BPM pickup split to two electronics:
~300nm noise
~500nm drift.
Drift will be reduced (phase feedback, I/Q imbalance calibration, ...)

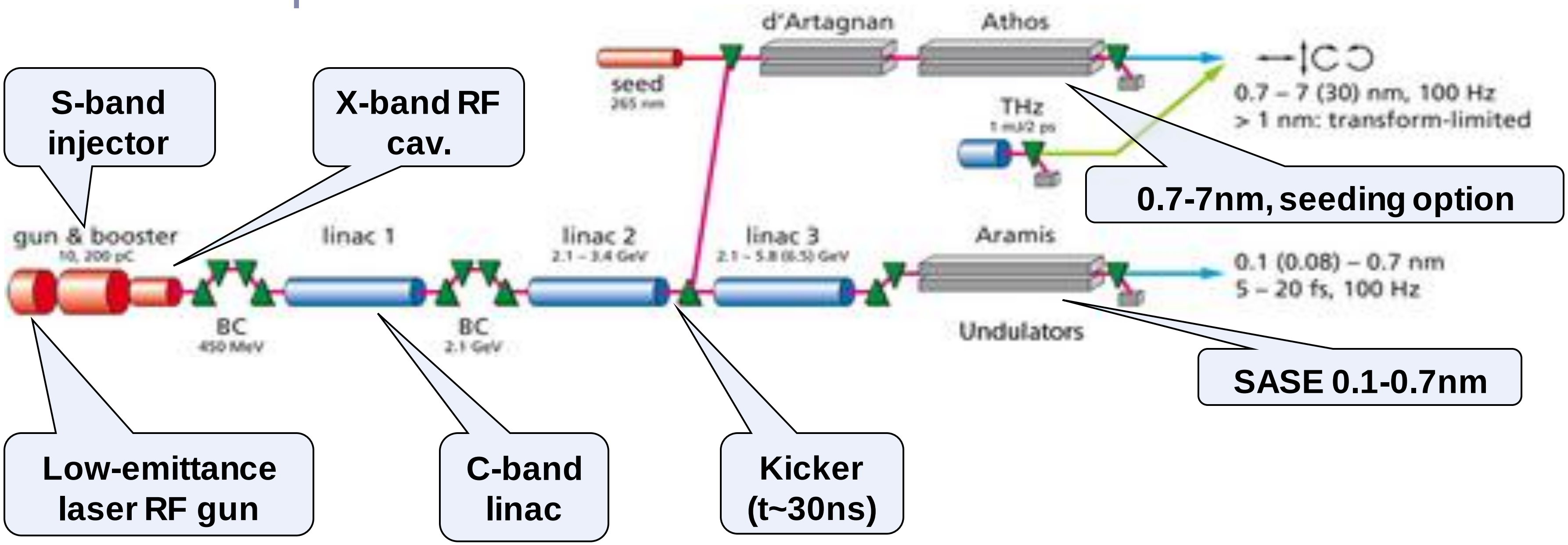
Parasitic test during SLS operation: SLS top-up injection caused spikes (arrival time switched by N*2ns)

Contents

SwissFEL BPMs

SwissFEL

- L~700m. 5.8GeV. SASE, λ_{min}=0.1nm.
- Trains of 2 bunches (1 per undulator).
- ~28ns bunch spacing, 100Hz.
- 10-200pC.



SwissFEL BPMs

Quantities

	Inner Pipe Diameter			
Machine Section	***38mm***	***16mm***	***8mm***	***Sum***
Gun	1			1
Injector	15	6		21
BC1	2			2
Linac1		22		22
BC2	2			2
Linac2		12		12
Linac3		14		14
Aramis Collimator & Matching		10		10
Aramis Undulator			21	21
Aramis Beam Dump		2		2
Athos Switchyard / Transfer Line		36		36
Athos Undulator			14	14
Athos Dump		2		2
Overall	**20**	**104**	**35**	**159**

Machine Section	***BPM Type***	***Inner Pipe Diameter***	***#***	***Length***	***Noise & Drift 10-200pC***	***Comment***
Injector + Bunch Compr.	Dual-Resonator Cavity	38mm	20	255mm	<10um	Alternative: resonant stripline
Linac + Transfer Lines	Dual-Resonator Cavity	16mm	104	150mm	<3-5um	Alternative: resonant stripline
Undulators	Dual-Resonator Cavity	8mm	35	100mm	<1um	

SwissFEL BPMs

Differences to E-XFEL

- Official charge range: 10-200pC. But: Trend to shorter bunches & lower charge. Be prepared for ~2pC ...
- Linac: 2 bunches, 28ns spacing, 100Hz.
- Officially: 1 Bunch in undulators (distribution kicker).

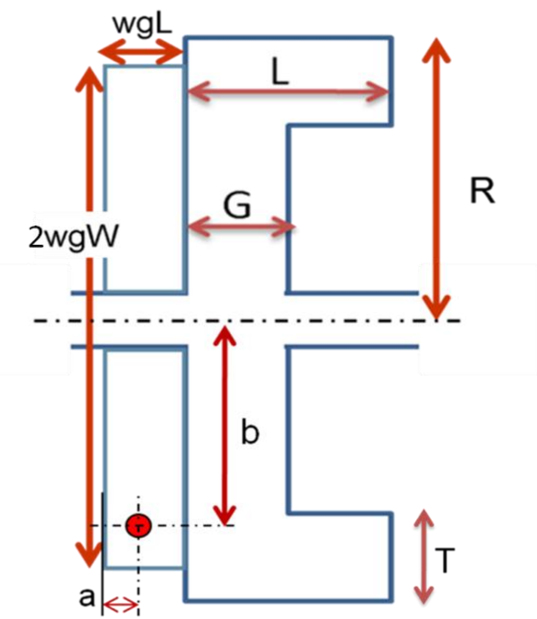
BPM System

- Injector: Keep resonant striplines (+ E-XFEL button elec.), or use 2-resonator 3.3GHz cavity (budget-dependent ...).
- Undulators + Linac: Baseline = 2-resonator cavity BPM.
- Based on E-XFEL systems, but adapted to low charge, shorter bunch spacing, different timing/control system, ...

SwissFEL Undulator Pickup: Position Cavity

- Option 1: Use optimized 3.3GHz version. RF design finished (Fabio Marcellini, HFSS). Now production in PSI workshop, then beam test.
- Option 2: Use higher frequency (e.g. 4.8GHz). Being investigated.

Electrical Parameters	Stainless Steel	Copper coated
Frequency [GHz]	3.301	3.305
Q_L	69	79
S_{11}	0.1369	0.0190
R_s /x [Ω/m]	44.9	51.4
R/Q/x [Ω/m]	0.65	0.65
Q_e	160	162
Sensitivity [V/nC/mm]	9.35	9.30

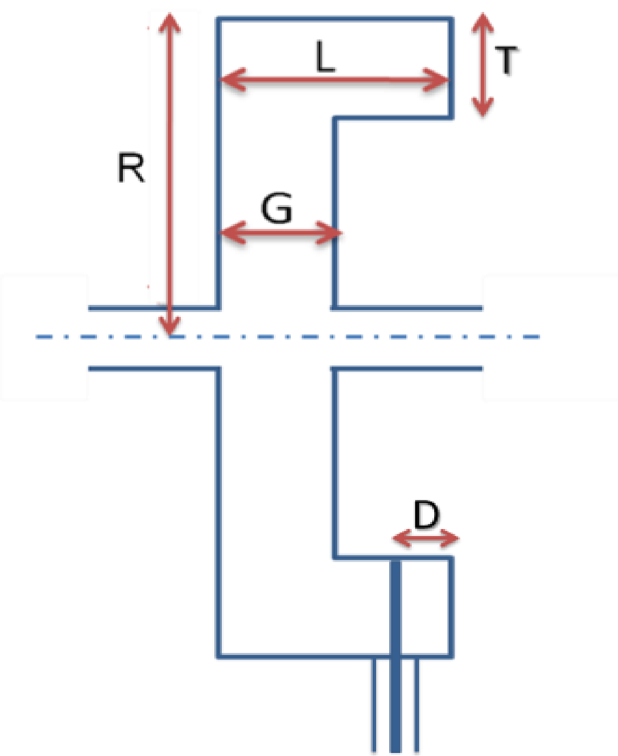


Geometrical Parameters	[mm]
R	37
L	15
G	7
T	7
wgW	34
wg H	4
wg L	25
a	6.5
b	25

~3x higher than E-XFEL: 340nm RMS @ 10pC with 20dB margin for cable/noise. Penalty: More angle sensitivity ...

Fabio Marcellini

SwissFEL Undulator Pickup: Reference Cavity



Geometrical Parameters	[mm]
R	23.5
L	13
G	3
T	3
D	4.5

Additional goal: Cost / tolerance optimization

Electrical Parameters	Copper
Frequency [GHz]	3.307
Q_L	80
S_{11}	0.9283
β	26.9
R_s [Ω]	1195
R/Q [Ω]	14.9
Q_e	83
Sensitivity [V/nC]	62.2

Uncritical

Fabio Marcellini

Contents

Summary & Outlook

- SwissFEL Test Injector BPMs: Goal achieved – using robust "proven" (non-final) electronics allows to work on E-XFEL & final SwissFEL designs without being bothered by operators ☺

- E-XFEL button electronics: Test start Q1/2012. Could also be used for SwissFEL injector resonant striplines (to be tested).

- E-XFEL 3.3GHz cavity BPMs: Lab & single-pickup beam tests promising. Next steps: Multi-pickup correlation, long-term test with beam (SwissFEL test injector, then FLASH), user-friendly operation & automation.

- Final SwissFEL cavity BPMs: Sub-µm resolution <10pC feasible keeping 3.3GHz E-XFEL frequency. Higher frequency, impact & removal of angle signal (digitally/mechanically) to be investigated.

PSI Team & Credits

<u>E-XFEL/SwissFEL BPM Electronics:</u>
Raphael Baldinger (Electronics Tech.)
Robin Ditter (Electronics Tech.)
Waldemar Koprek (Firmware/Software Engineer)
Reinhold Kramert (Electronics Eng., MBU)
Goran Marinkovic (Firmware/Software Engineer)
Markus Roggli (Electronics Eng., ADCs)
Markus Stadler (RF Engineer, Cavity Electronics)
Daniel Treyer (RF Engineer, Button & Stripline Electronics)

<u>SwissFEL BPM Pickups:</u>
Fabio Marcellini (RF Engineer, INFN / PSI guest scientist, Cavity BPMs)
Martin Rohrer (Mech. Engineer)
Micha Dehler (RF Engineer, Resonant Stripline)
Alessandro Citterio (RF Group, Resonant Stripline)

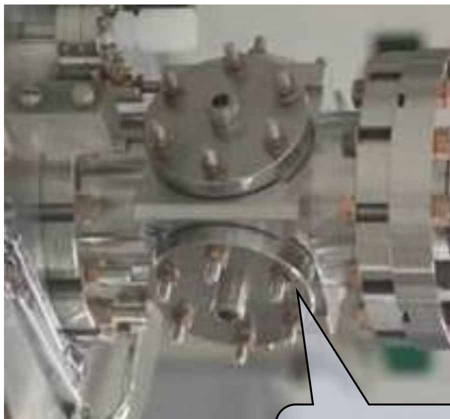
<u>And:</u>
Thanks also to Volker Schlott & SER, support from other PSI/GFA groups, DESY E-XFEL diagnostics team (E-XFEL pickups) & Claire Simon/CEA (re-entrant E-XFEL BPM pickup & RFFE).

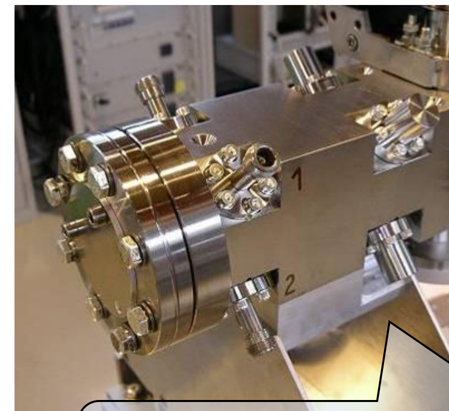
Paul Scherrer Institut

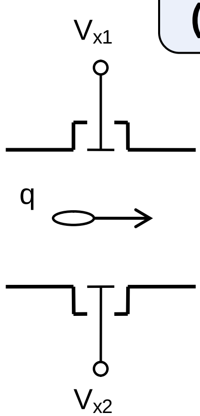
Thank you for your attention!

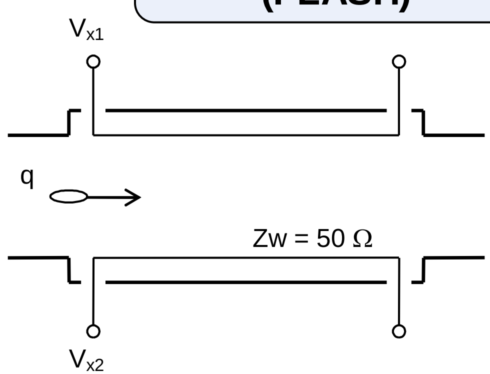
Supplementary Slides …

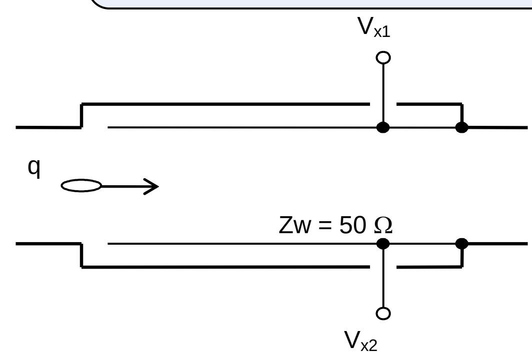
RF BPMs: Pickup Types







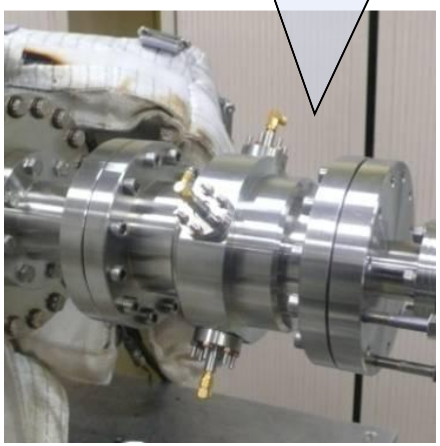




Beam Position = k * $(V_{x1}-V_{x2})/(V_{x1}+V_{x2})$. Factor k (~10mm) determined by geometry.

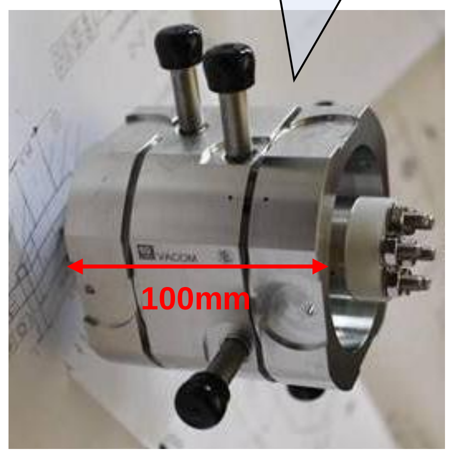
RF BPMs: Pickup Types (Cont'd)

Single-resonator cavity (E-XFEL, cold linac, "re-entrant")



f_{Pos} = 1.7GHz
f_{Ref} = 1.2GHz

Dual-resonator cavity (E-XFEL undulators)

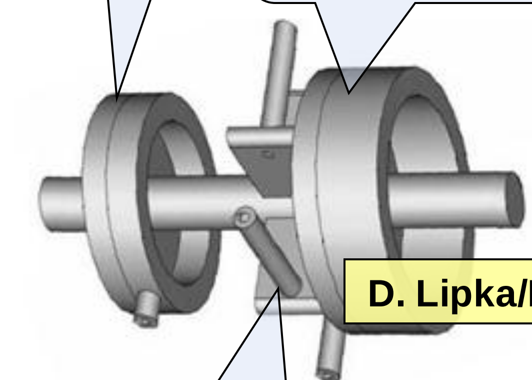


f_{Pos} = f_{Ref} = 3.3GHz

Lower electronics drift

Reference cavity: signal ~ bunch charge

Position cavity: signal ~ position * charge



D. Lipka/DESY

Visible: Vacuum, couplers

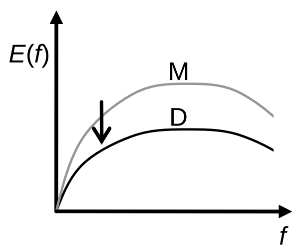
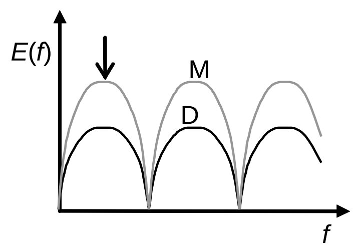
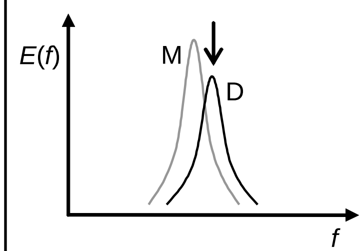
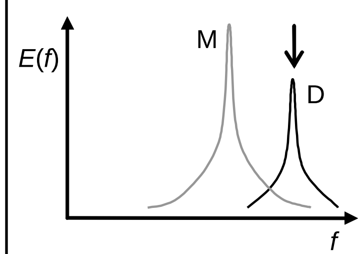
High resolution: Mode-selective couplers suppress undesired other modes

Beam Position = k * (V_{Pos_Mode} / V_{Ref_Mode}). Factor k: Not fixed, variable via attenuator: Zoom!

RF BPMs: Pickup Types (Cont'd)

Low cost: Standard BPM

Best resolution, lowest drift: Undulator BPM

Pickup	Button	Matched Stripline	Resonant Stripline	Cavity
Spectrum				
Monopole Mode Suppression	Modal (hybrid) / electronics	Modal (hybrid) / electronics	Modal (hybrid) / electronics	Modal (coupler), frequency, phase (sync. det.)
Typical RMS Noise, 10pC, *20mm pipe*	~200µm	<80µm	<4µm	~1µm
Typical Electronics Frequency	300…800MHz	300…800MHz	500-1500MHz	3-6GHz

"Typical" noise: Examples & estimates (scaling, …) based on existing systems, not theoretical limit …

RF BPMs: Pickup Types (Cont'd)

- Buttons: Moderate resolution @ low charge. O.K. with long bunch trains (E-XFEL): Averaging.
- Striplines (matched + resonant): Better low-charge SNR that buttons (resonant: >10x). O.K. for low-charge single-bunch injector/linac/transfer lines.
- Single-resonator cavity + normal couplers: Common-mode suppression limits performance.
- Dual-resonator cavity + mode-suppressing couplers: Optimal performance (common mode suppression, drift, …), highest SNR.

Undulator BPM for LCLS, SACLA, E-XFEL, SwissFEL, …

SwissFEL Test Injector BPMs

Systematic & Random Sampling Jitter

DRS Chip: Features and Characteristics

- **8 channels, 1024 samples/channel.**
- **Max. sample rate 5 GSa/s, on-chip PLL.**
- **Usable input bandwidth > 500 MHz.**
- **Random jitter (2 - 4 ps rms) limits SNR.**
- **Deterministic jitter (50 ps rms) removed by calibration and real-time spline interpolation via FPGA FW/SW.**