PAUL SCHERRER INSTITUT

PSI

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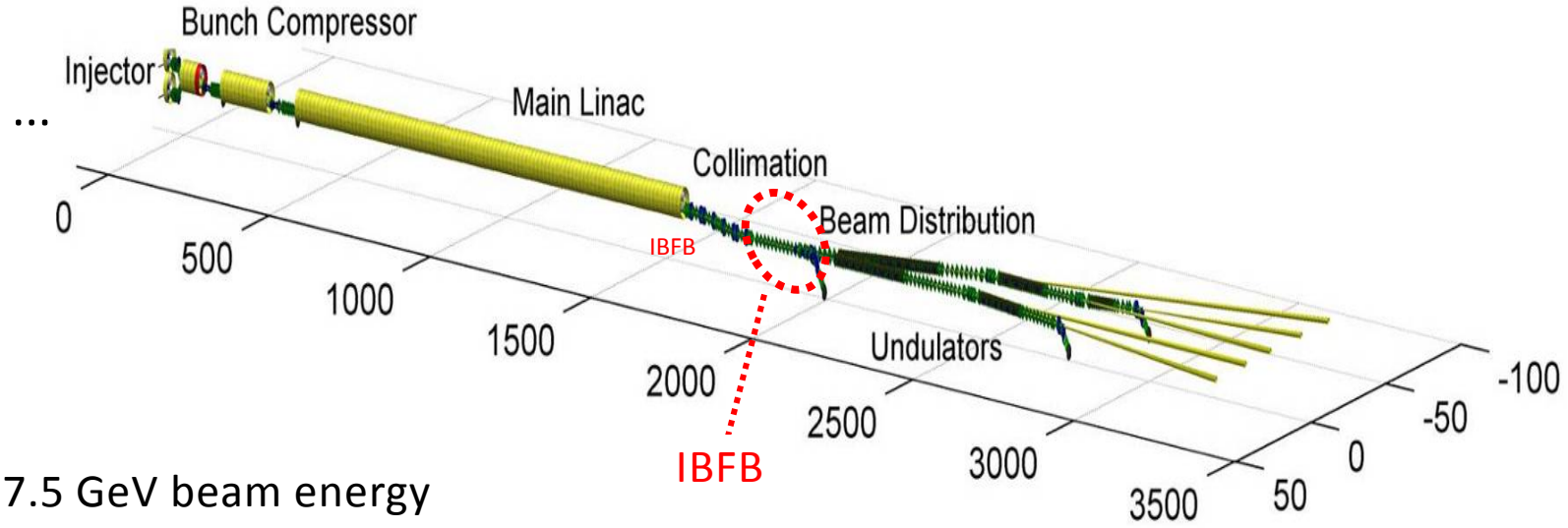
Status of the Transverse Intra Bunch Train Feedback of the European XFEL

IBIC 2017

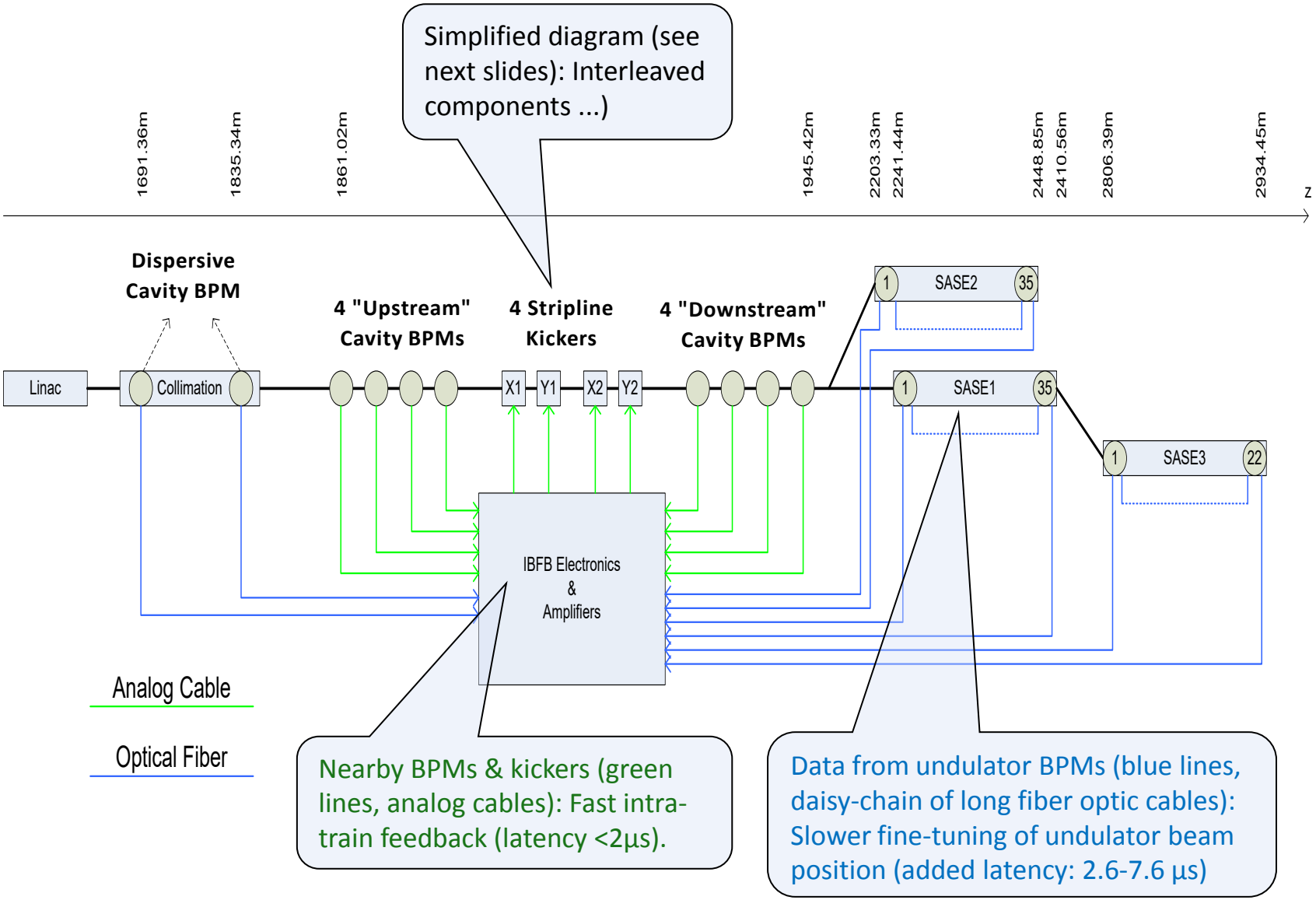
Contents

Overview



- 17.5 GeV beam energy
- Max. 600µs bunch train length
- Max. 2700 bunches (minimal spacing: 222ns)
  - Gun: Periodic bunch spacing N*111ns, N>1
  - Dump kicker (downstream of IBFB) can generate arbitrary bunch patterns for undulators & can dump first (uncorrected) bunches of a bunch train
- Transverse IBFB: Swiss in-kind contribution to E-XFEL
  - Correct each bunch individually (feed-forward & intra-train feedback)
  - Single IBFB serves several undulators

Overview: IBFB Topology



Overview: Beam Trajectory Perturbations

Magnet vibrations are "slow" (f<100Hz), but resulting random position offset of bunch train needs fast correction by IBFB.

- Table shows worst-case estimate (by DESY) of peak trajectory perturbations, normalized to 30m beta function.
- Latency <2µs expected to be sufficient to stabilize beam.

	X [µm]	Y [µm]	Frequency [kHz]	Plane	Perturbation Type	Kick(X) [µrad]	Kick(Y) [µrad]
Magnet Vibrations	±28	±28	<1	X/Y	Random	±1.0	±1.0
Power Supply Noise	±12.6	±12.6	<1	X/Y	Random	±0.5	±0.5
Vibration-Induced Dispersion Jitter	±2.5	±2.5	<1	X/Y	Random	±0.1	±0.1
Beam Distribution Kicker Drift	±0	±1	<1	Y	Repetitive	±0	±0.04
Beam Distribution Kicker Noise	±0	±1	<5000	Y	Random	±0	±0.04
Spurious Dispersion (3% Energy Chirp)	±15	±15	<1	X/Y	Repetitive	±0.5	±0.5
Nonlinear Dispersion (3% Energy Chirp)	±15	±0	<1	X	Repetitive	±0.5	±0
Spurious Dispersion (1E-4 Energy Jitter)	±0.5	±0.5	<5000	X/Y	Random	±0.02	±0.02
Nonlinear Dispersion (1E-4 Energy Jitter)	±0.15	±0	<5000	X	Random	±0.005	±0
Wakefields	±25	±25	<5000	X/Y	Repetitive	±0.9	±0.9
Sum Of Peak Values	**±98.8**	**±85.6**				**±3.5**	**±3.1**

In-Kind contract: ±2.4urad @ 17.5 GeV (optimized optics, not all perturbations occur at same time, ...)

Overview: IBFB Components In Beam Pipe

IBFB measures beam energy

Longitudinal position

Name	Comment	Z [m]	E[GeV]	β_x[m]	φ_x	β_y [m]	φ_y	D_y [m]
BPMI.1837.CL	Dispersive IBFB BPM	1837.27	17.63	187.76	16.04	309.09	17.71	-0.103
BPMI.1860.TL	Y Upstream BPM	1860.92	17.63	18.36	16.57	40.61	18.14	0.000
BPMI.1863.TL	X Upstream BPM	1863.70	17.63	31.09	16.59	24.31	18.15	0.000
BPMI.1878.TL	Y Upstream BPM	1878.88	17.63	21.55	16.66	27.72	18.27	0.000
KFBY.1883.TL	Y Kicker	1883.36	17.63	21.86	16.71	26.10	18.30	0.000
BPMI.1889.TL	X Upstream BPM	1889.08	17.63	36.78	16.74	12.46	18.34	0.000
KFBX.1893.TL	X Kicker	1893.56	17.63	37.85	16.76	9.53	18.44	0.000
KFBY.1908.TL	Y Kicker	1908.56	17.63	11.16	16.93	34.85	18.55	0.000
BPMI.1910.TL	Y Downstream BPM	1910.03	17.63	11.97	16.94	33.29	18.55	0.000
KFBX.1923.TL	X Kicker	1923.56	17.63	43.08	17.02	14.35	18.70	0.000
BPMI.1925.TL	X Downstream BPM	1925.03	17.63	41.03	17.02	15.35	18.71	0.000
BPMI.1930.TL	Y Downstream BPM	1930.33	17.63	22.40	17.05	30.84	18.75	0.000
BPMI.1939.TL	X Downstream BPM	1939.08	17.63	11.62	17.16	50.22	18.78	0.000

Downstream BPMs used in fast feedback loop, upstream BPMs to check/verify system operation

Beta functions (optimized for IBFB): Acceptable compromise between costs & performance

Horizontal and vertical components are interleaved.

Overview: IBFB Rack Locations

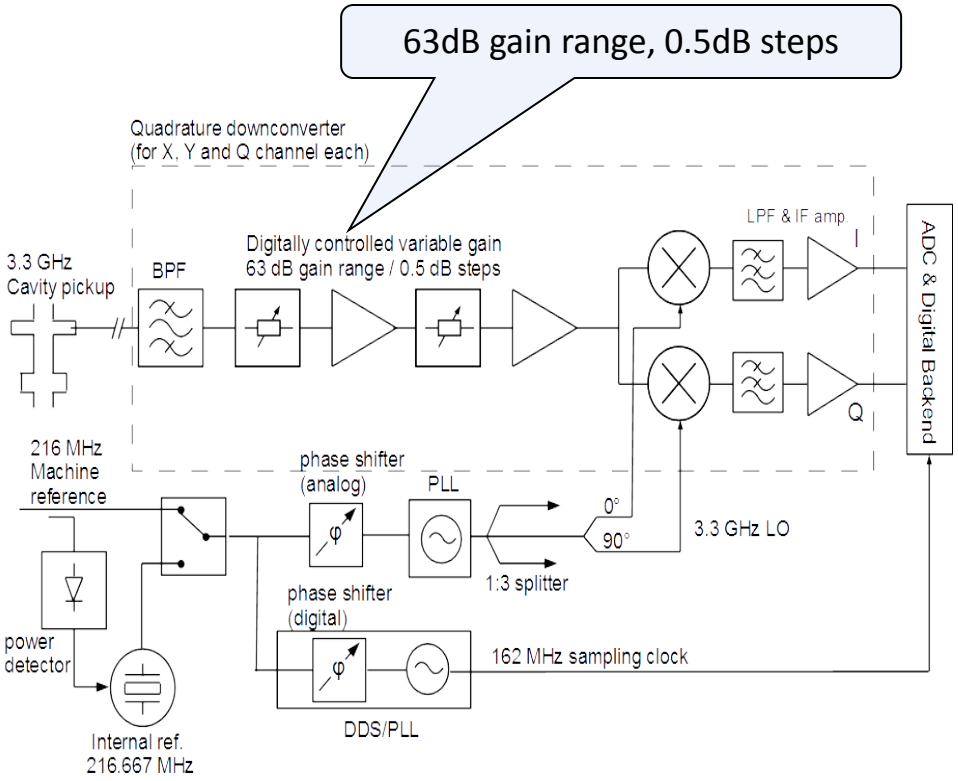
- IBFB core electronics distributed over six 19'' racks (16m distance) near IBFB BPM pickups & kicker magnets:
  - 4 power amplifier racks (4 stripline kickers, 8 amplifiers: push/pull mode)
  - 1 BPM electronics rack
  - 1 digital electronics rack

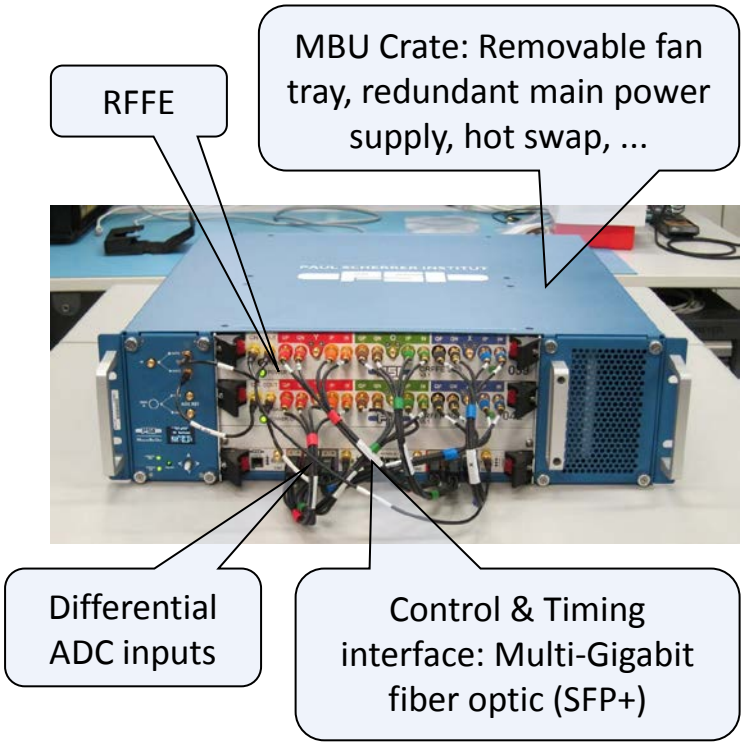
No.	*Rack Contents*	*Longitudinal Position z[m]*
1	IBFB Kicker V1-1 Amplifier IBFB Kicker V1-2 Amplifier	1894.5
2	IBFB Kicker V2-1 Amplifier IBFB Kicker V2-2 Amplifier	1895.5
3	Analog IBFB Electronics	1900.7
4	Digital IBFB Electronics	1901.7
5	IBFB Kicker H1-1 Amplifier IBFB Kicker H1-2 Amplifier	1909.5
6	IBFB Kicker H2-1 Amplifier IBFB Kicker H2-2 Amplifier	1910.5

Contents

IBFB Cavity BPMs

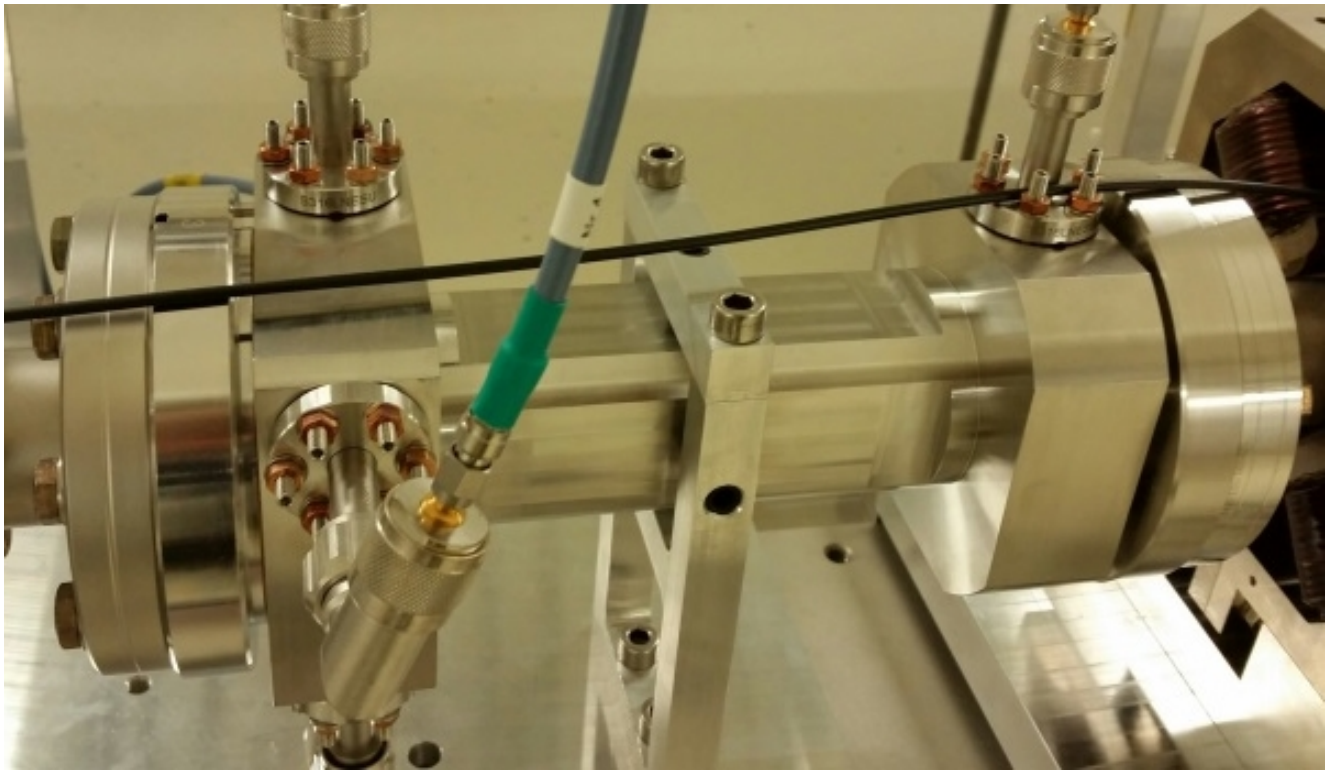
- E-XFEL BPMs: 304 buttons, 129 dual-resonator cavities, 21 re-entrant
- IBFB: Standard E-XFEL cavity BPMs (pickup: DESY, electronics: PSI):
  - 3.3 GHz, low-Q (~70), IQ downconversion to baseband
  - Sub-µs latency (multi-gigabit fiber links).



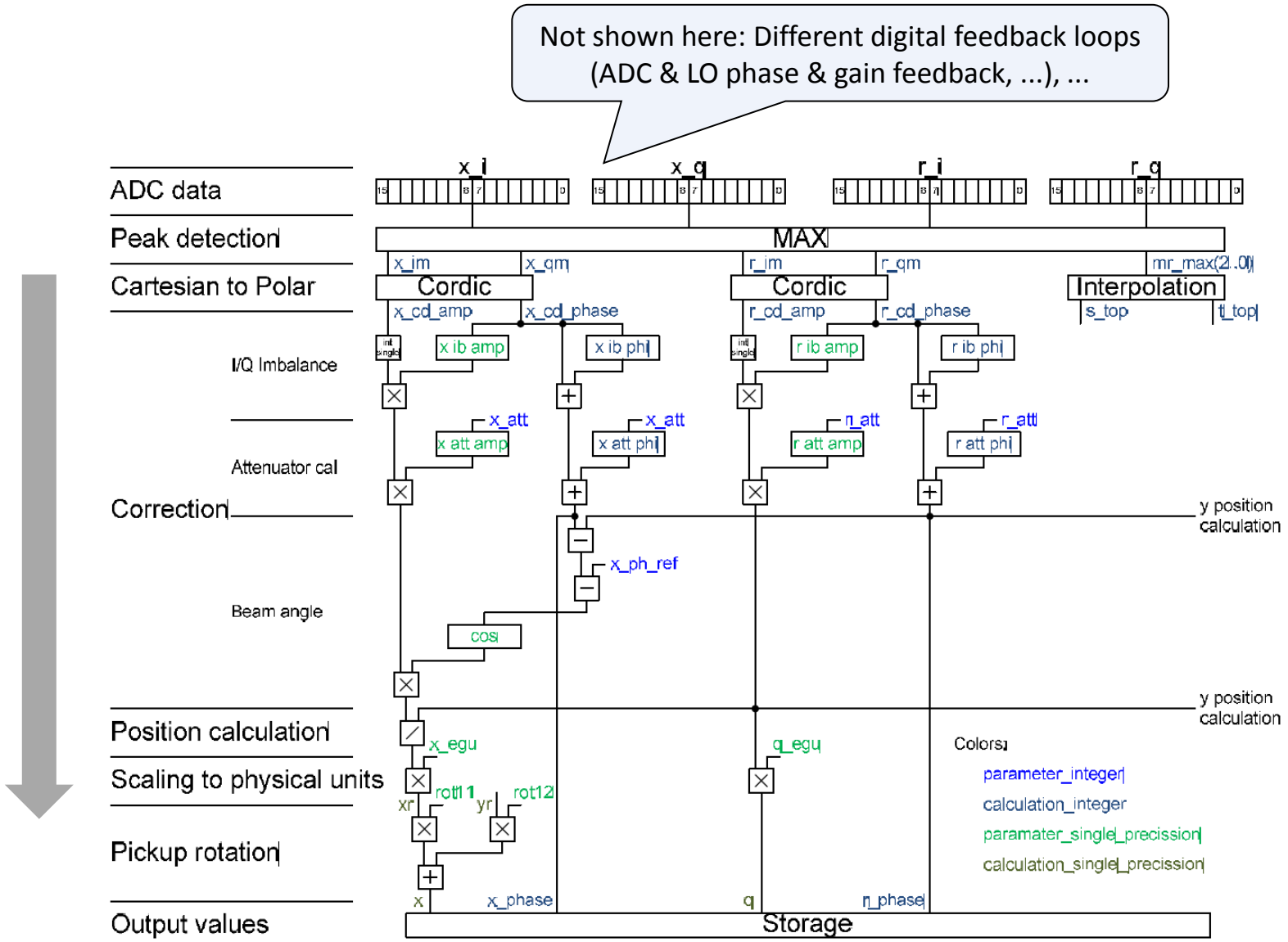


IBFB Cavity BPM Pickup

- Design: DESY (D. Lipka, S. Vilcins et al.) based on SACLA design
- 3.3 GHz, Q_L~70, L=255mm, Ø=40.5mm
- <1µm resolution @ 50-1000 pC (in ±1 mm range)
- Used also in transfer lines (energy measurement, ...)



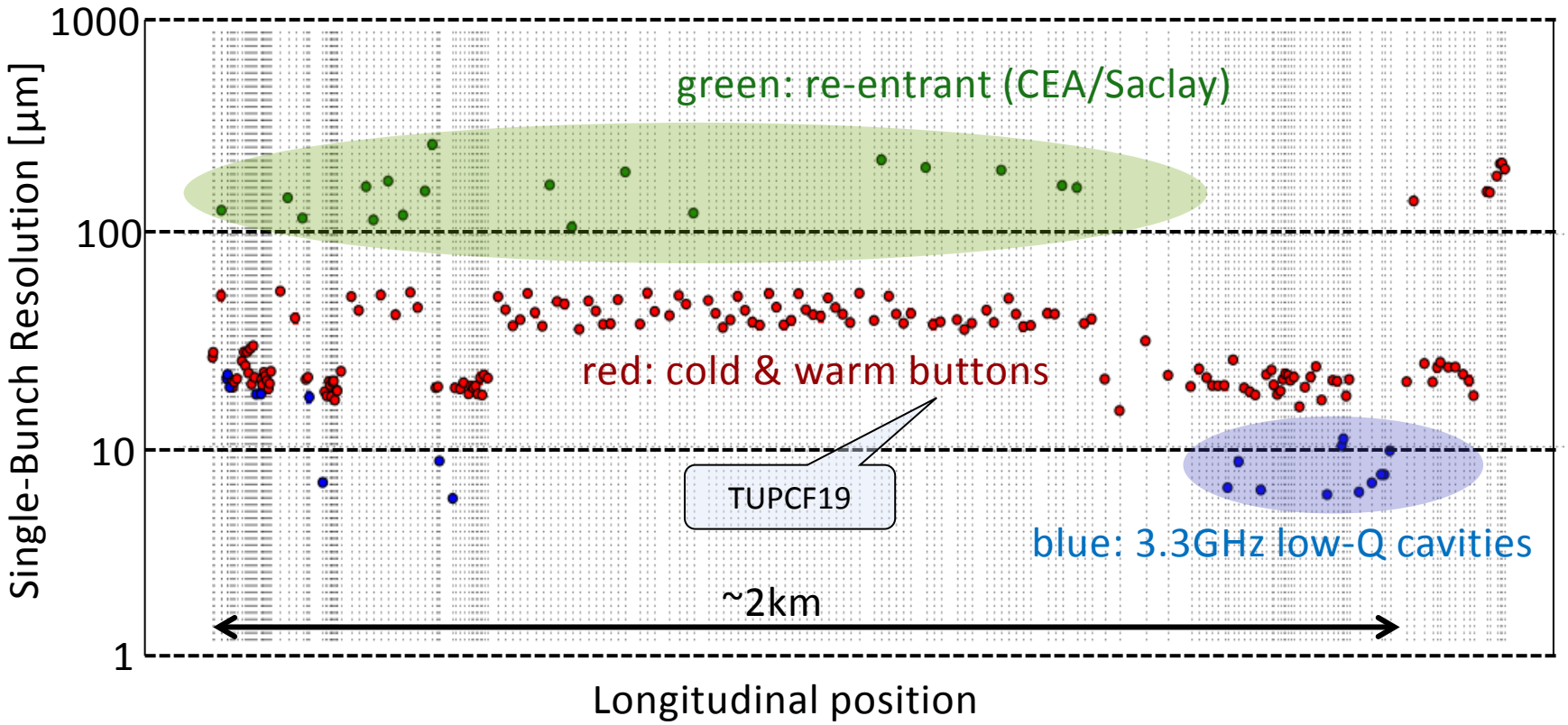
IBFB BPM: Digital (FPGA) Signal Processing



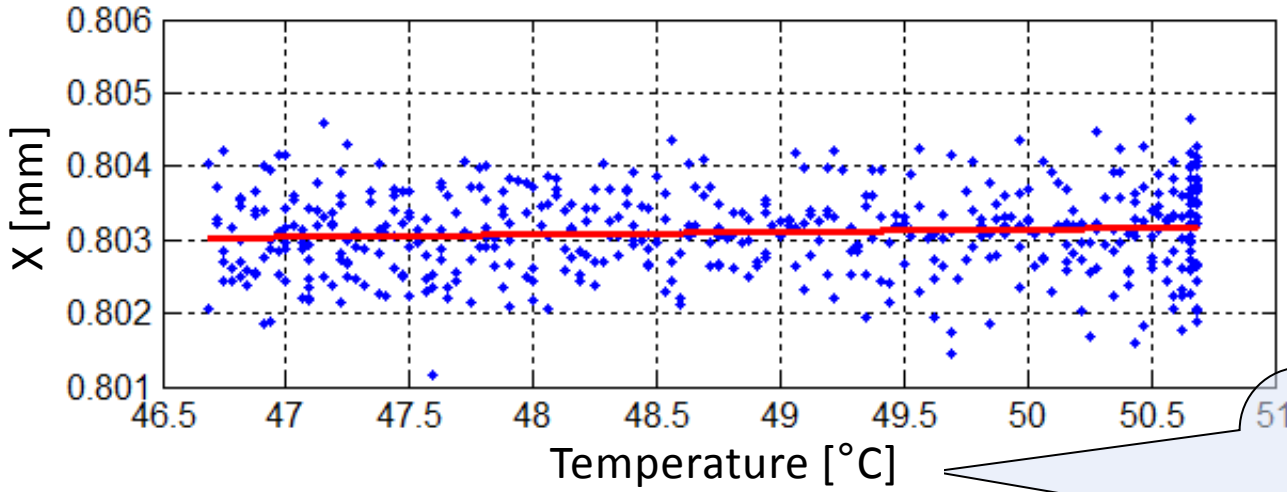
E-XFEL: Resolution of all BPMs @ **6pC**

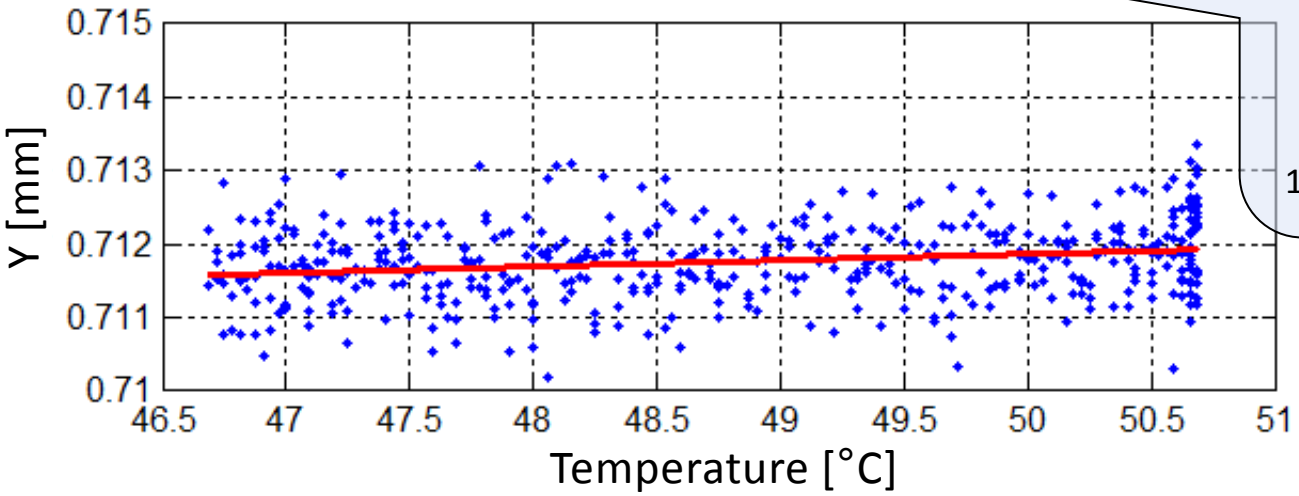
- Measurement: DESY script (D. Lipka, N. Baboi) based on SLAC method.
- E-XFEL (low-Q) cavity BPMs: Resolution · charge ~ 50 µm·pC
- SwissFEL: < 8 µm·pC (low-Q), < 4 µm·pC (high-Q)

TUPCF17 & 18



IBFB BPM Electronics: Temperature Drift

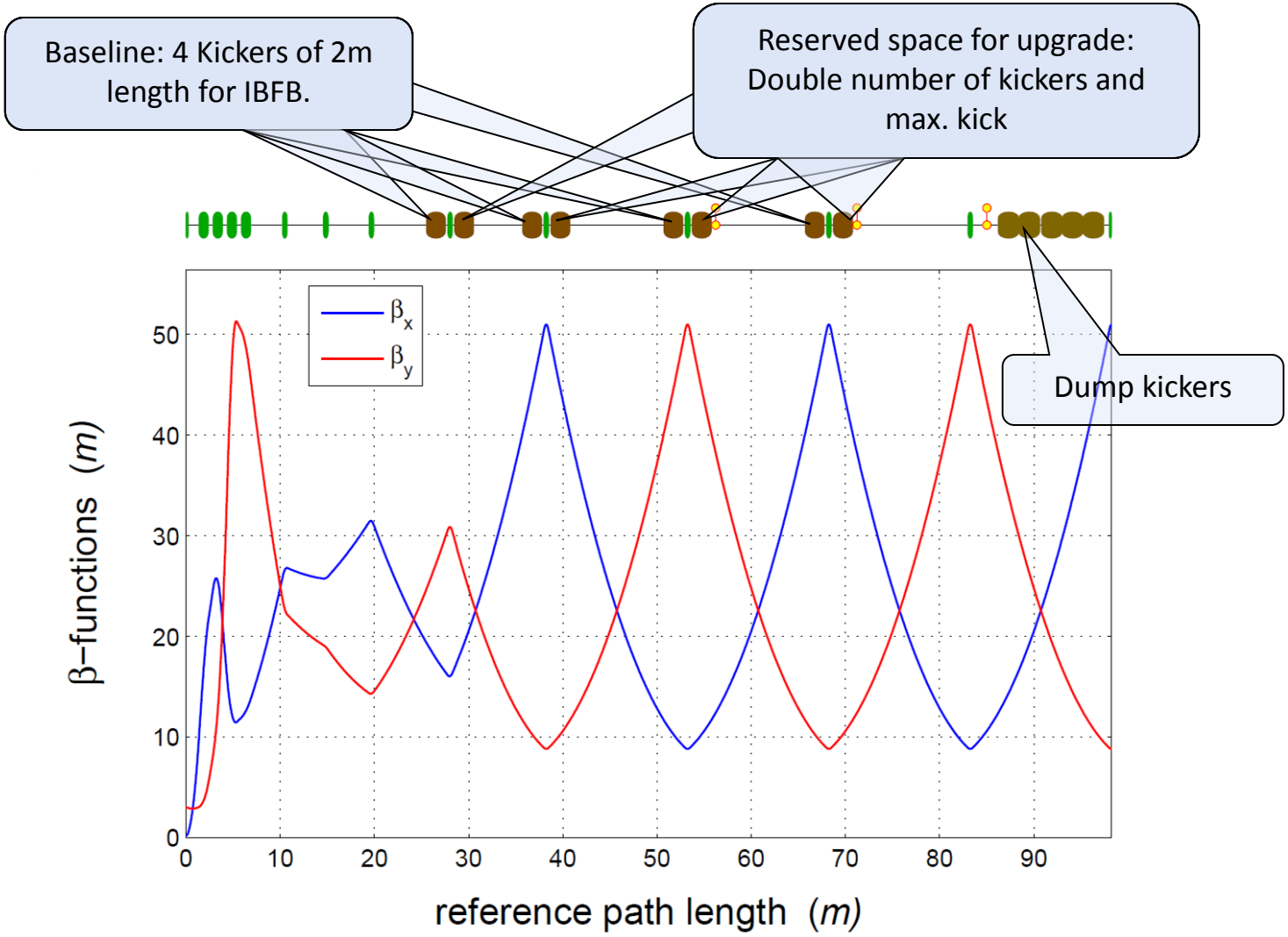




Temperature drift scales with beam offset. Active temperature stabilization: <100nm/°C drift at 1mm offset (0.01%/°C)

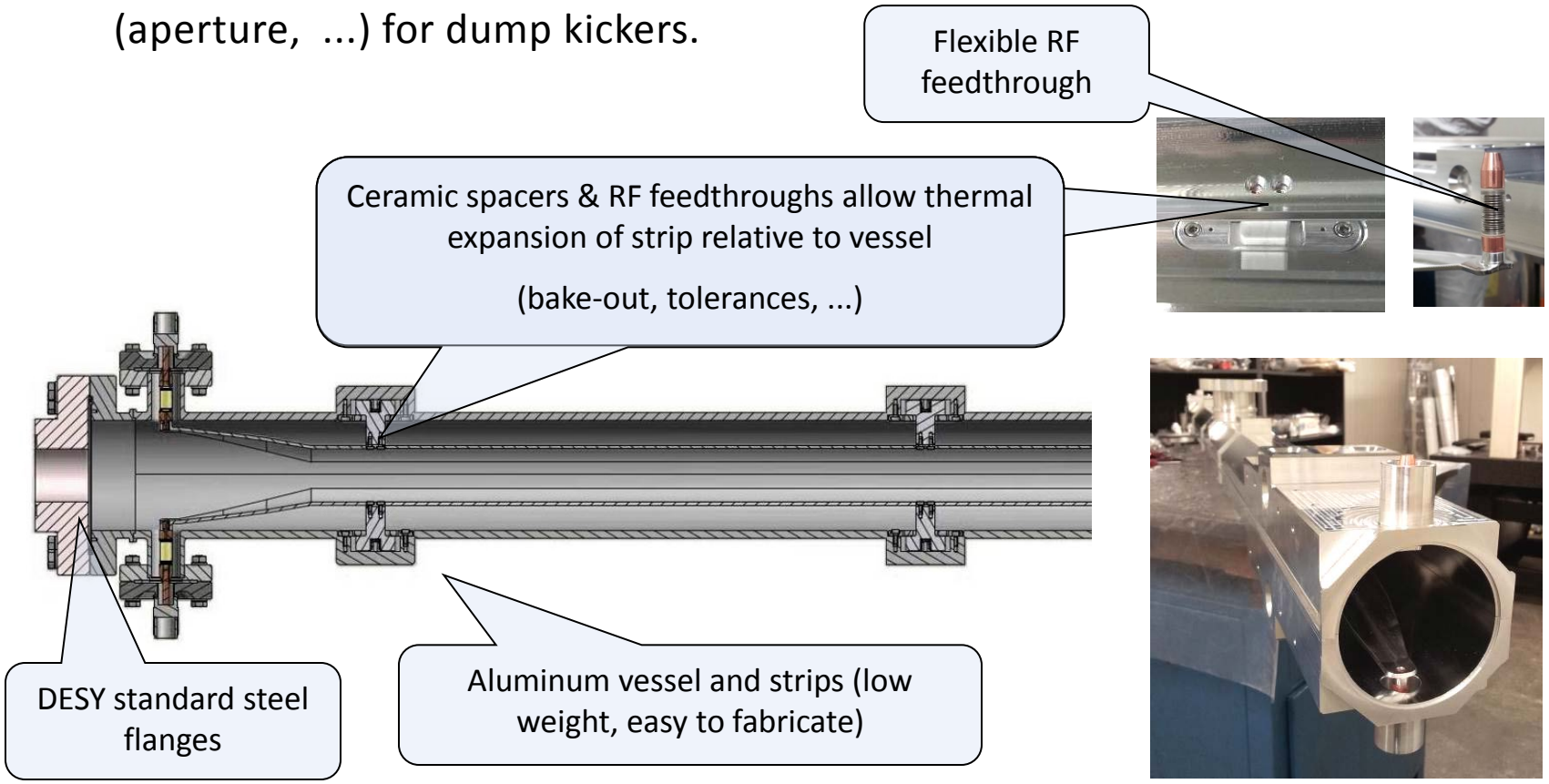
Contents

IBFB: Beam Optics and Magnet Lattice

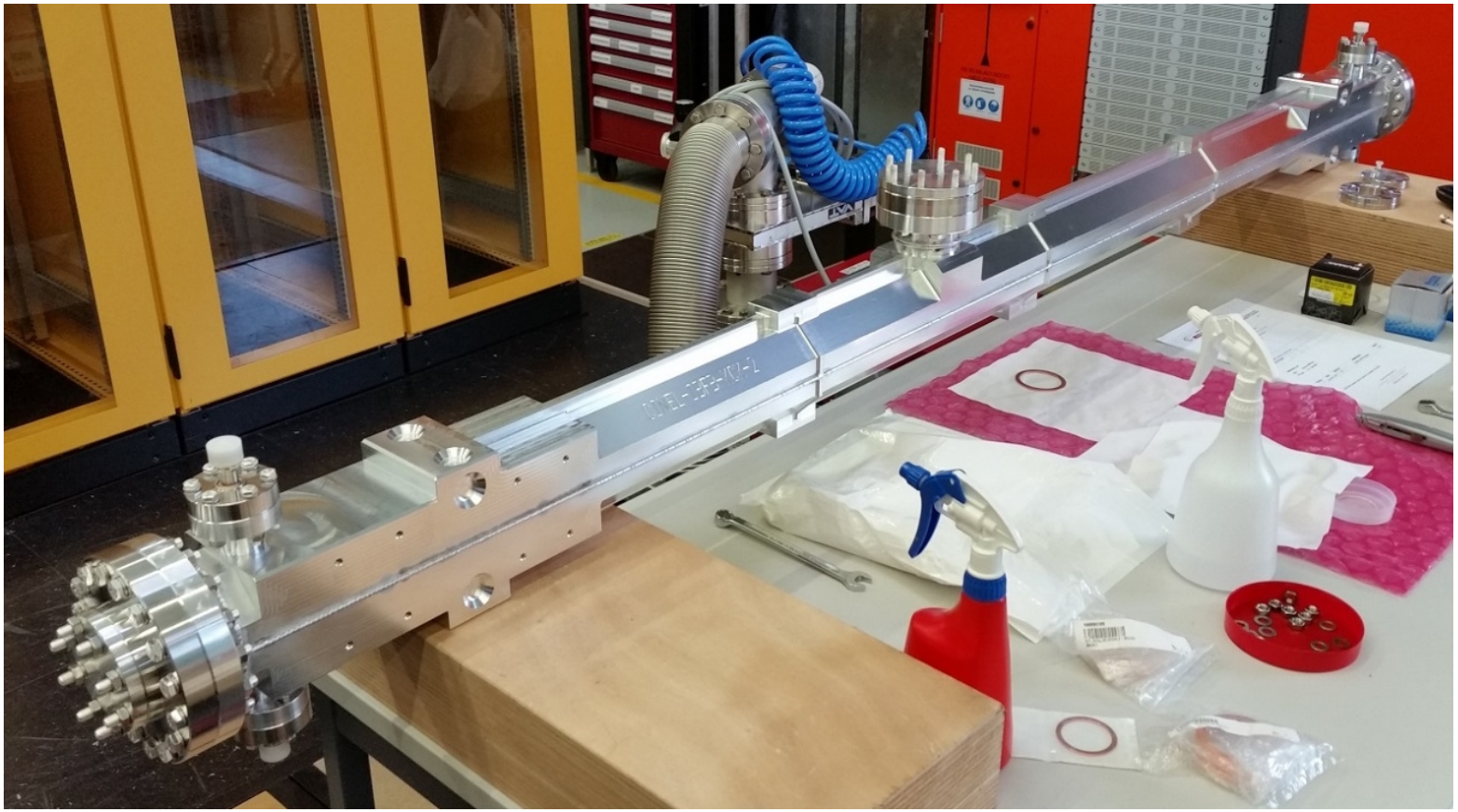


IBFB Kicker Magnets

- 2m long stripline kickers, 50 Ohms (PSI design, based on CTF3/Daphne design by F. Marcellini et al., INFN Frascati), supported by DESY (M. Dohlus et al.).
- DESY uses modified version (aperture, ...) for dump kickers.

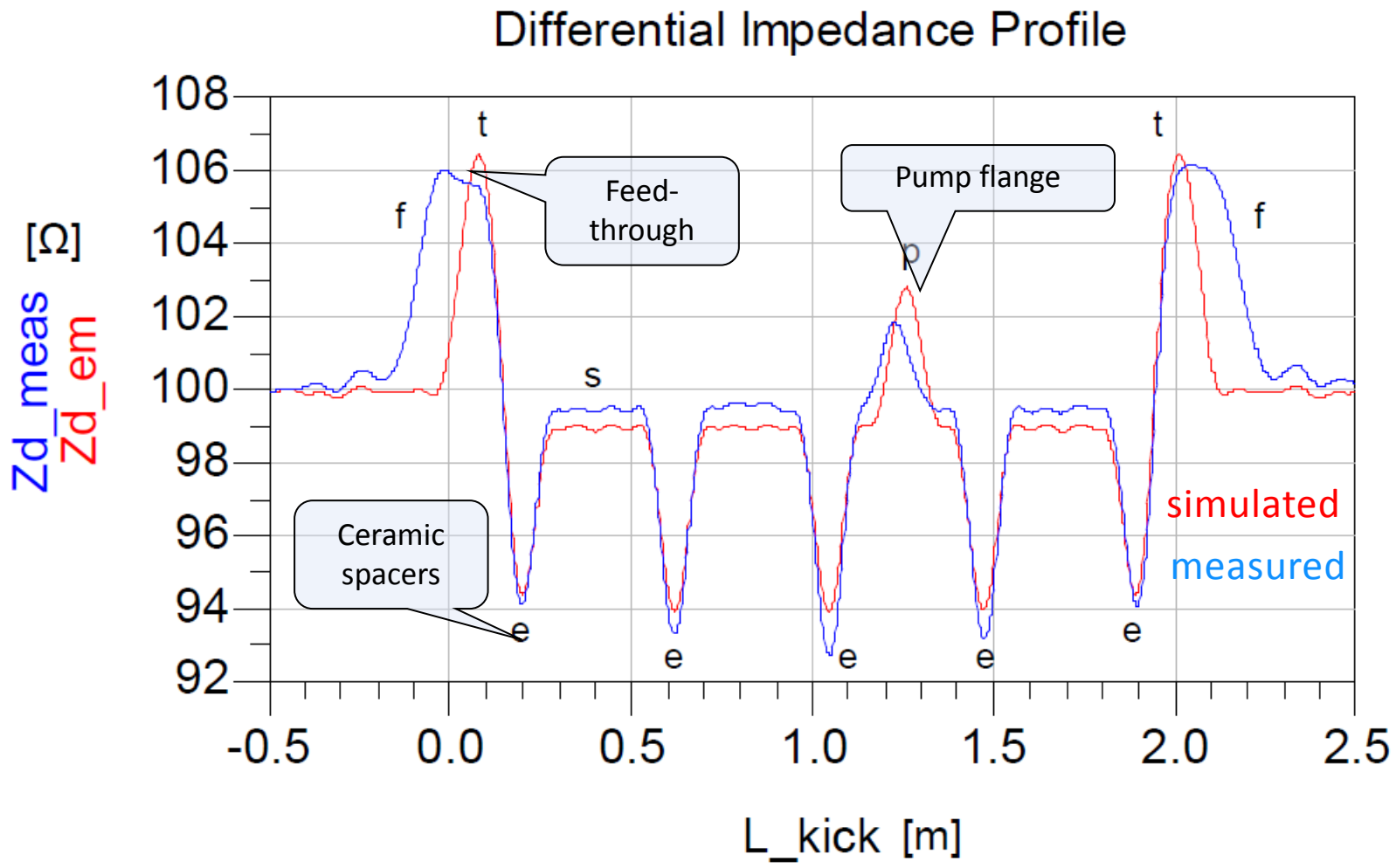


IBFB Kicker Magnets



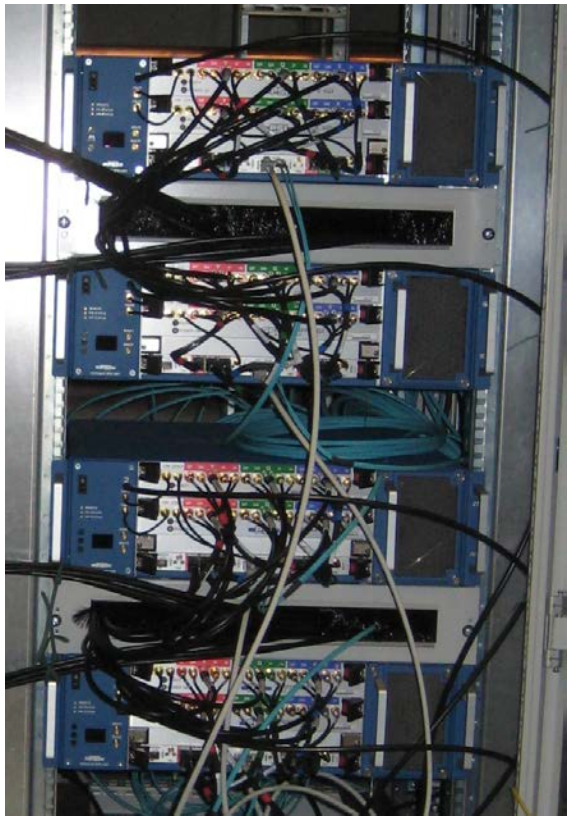
IBFB Kicker in E-XFEL Tunnel

IBFB Kicker Magnet: Impedance



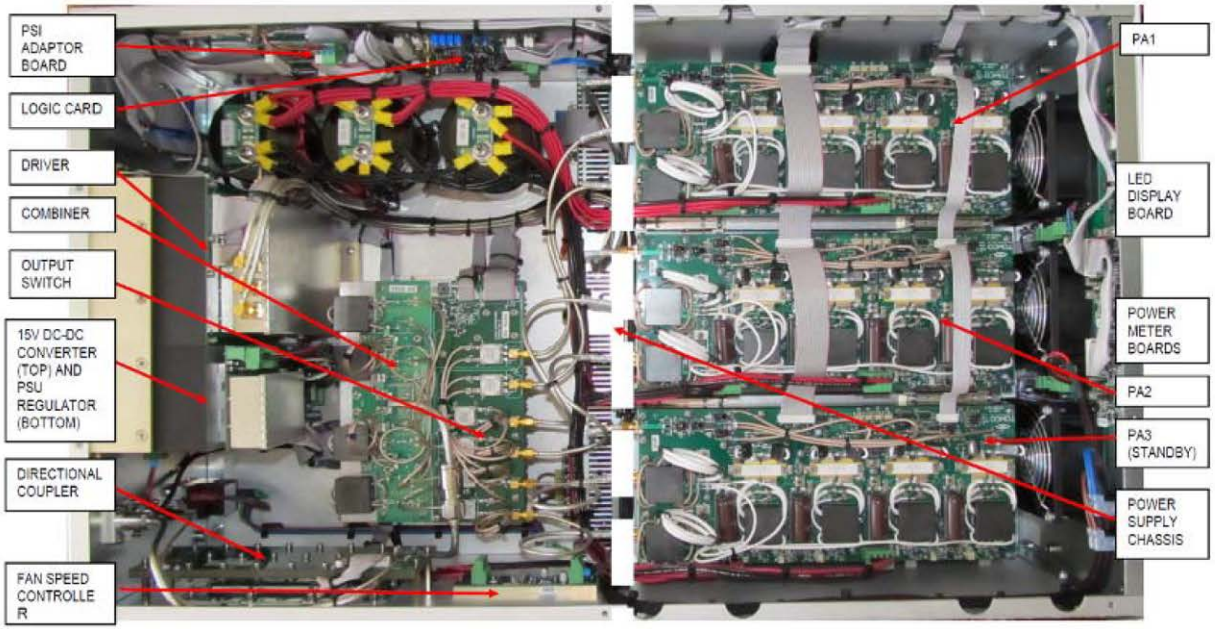
BPM Electronics & Kicker Amp Racks

Last pre-beam test in E-XFEL tunnel before our first IBFB beam shift (June 2017)

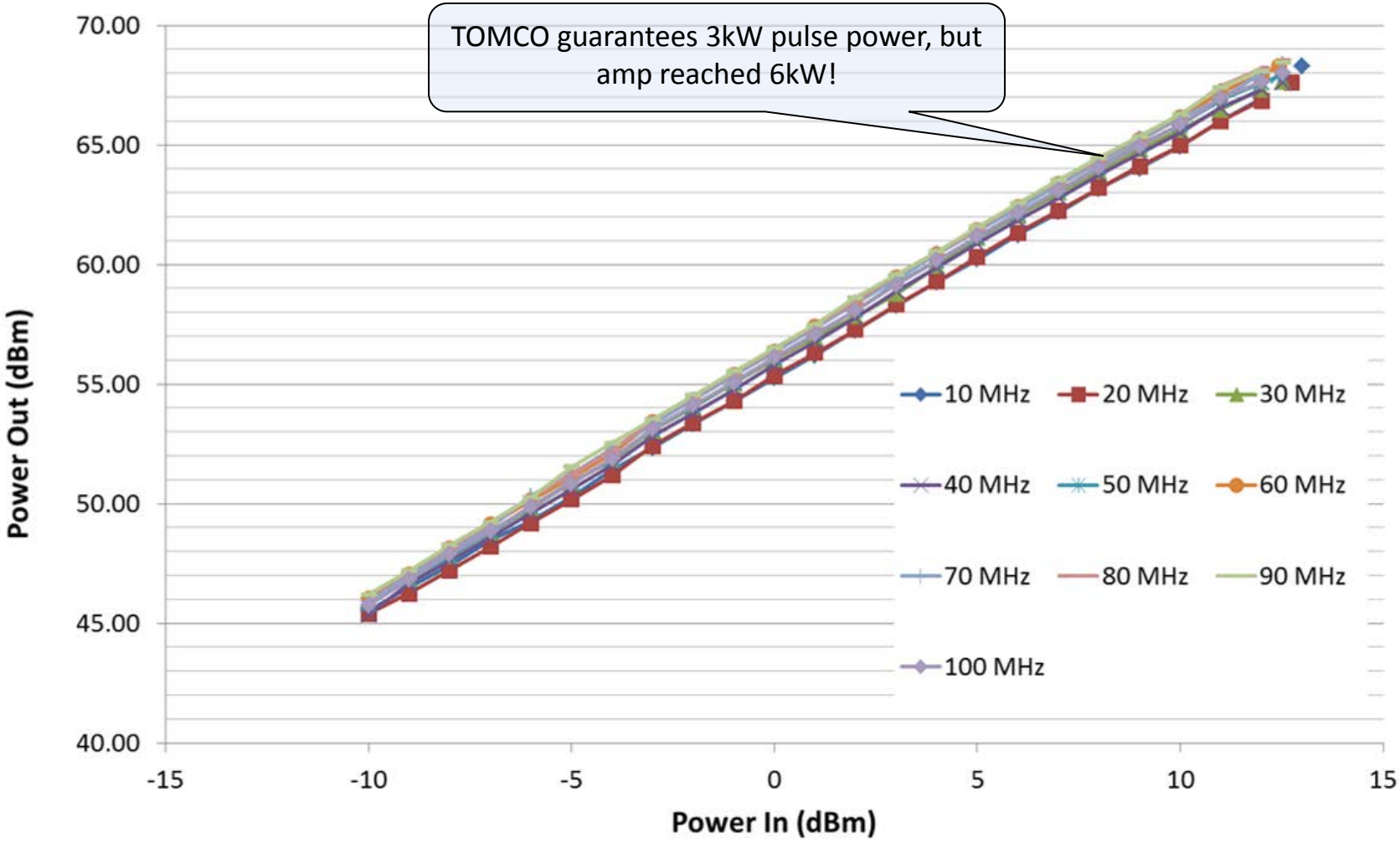


IBFB Kicker: RF Power Amplifiers

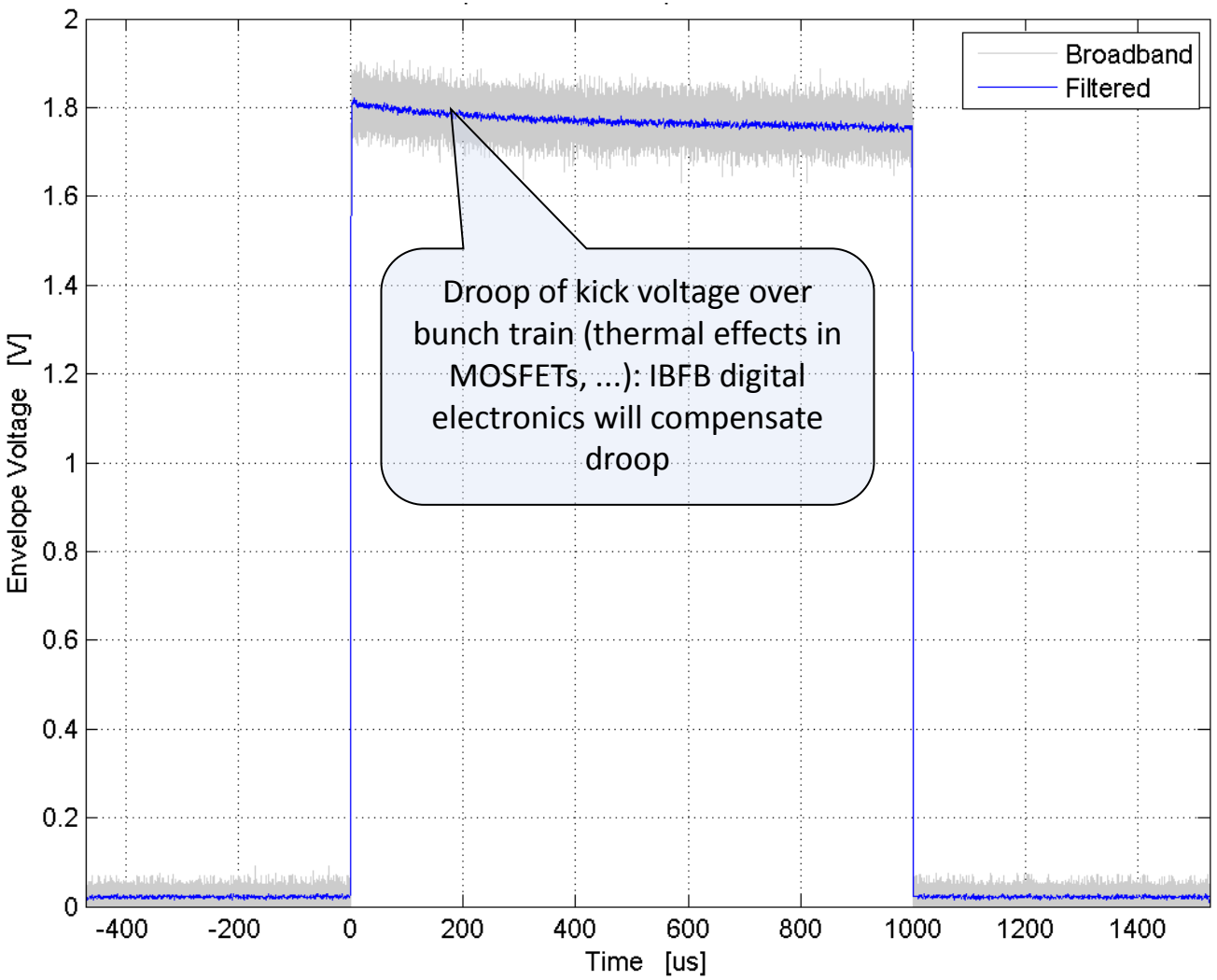
- Commercial solution (company TOMCO), modified/improved for PSI (redundant mains power supply & amplifier modules, ...).
- Class AB, solid state. Spec: 2kW pulsed (-1dB), 3kW saturated.
  Test: ~6kW saturated (company wanted to improve linearity ...)
- ±4 µrad kick angle



IBFB Kickers: Power Amplifier Linearity



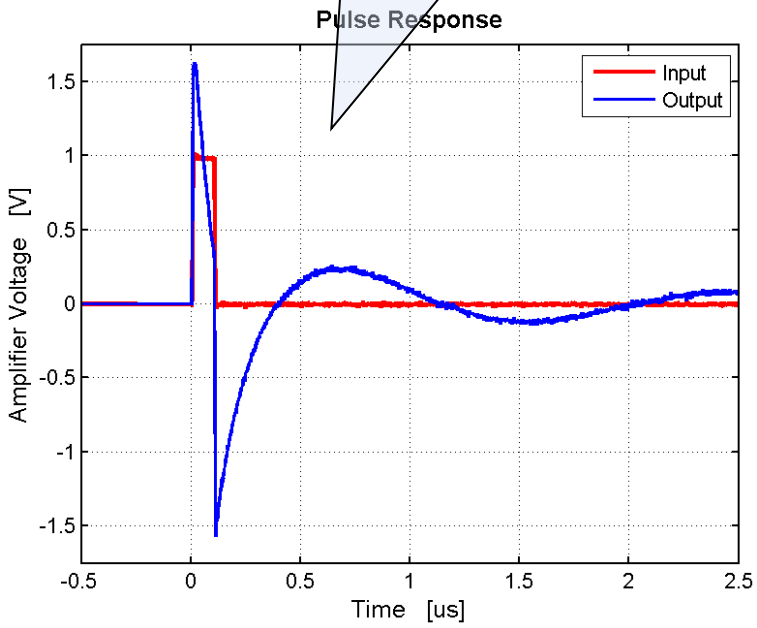
IBFB Kickers: Power Amplifier Droop



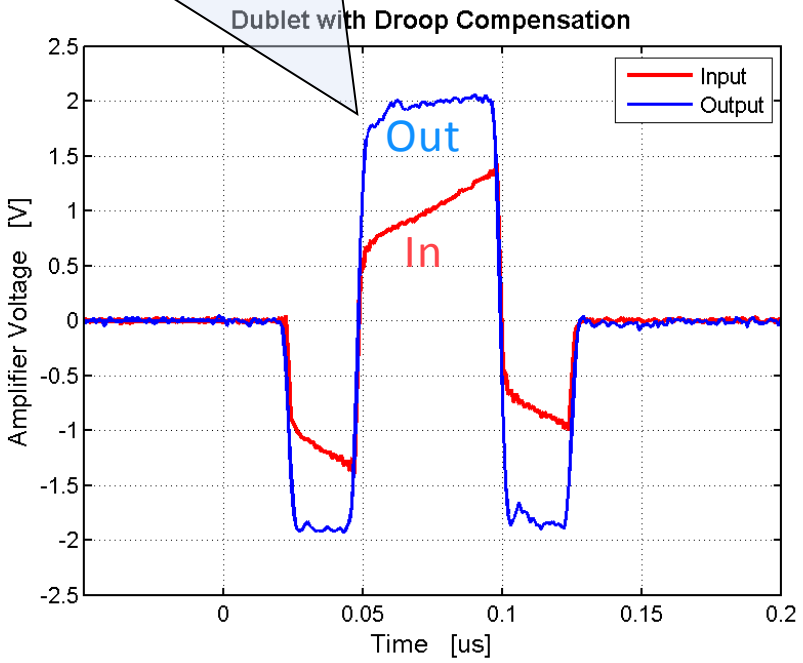
IBFB Kickers: Power Amp Drive Pulse

- IBFB kicker amps driven by fast low-latency 16-bit DAC: Arbitrary waveform
- Special amplifier input waveform: Kick each bunch individually with minimal crosstalk to next bunch & minimal arrival time dependence of kick angle.

Unipolar kicker amp input pulse: Kicker amp output pulse not nice ...

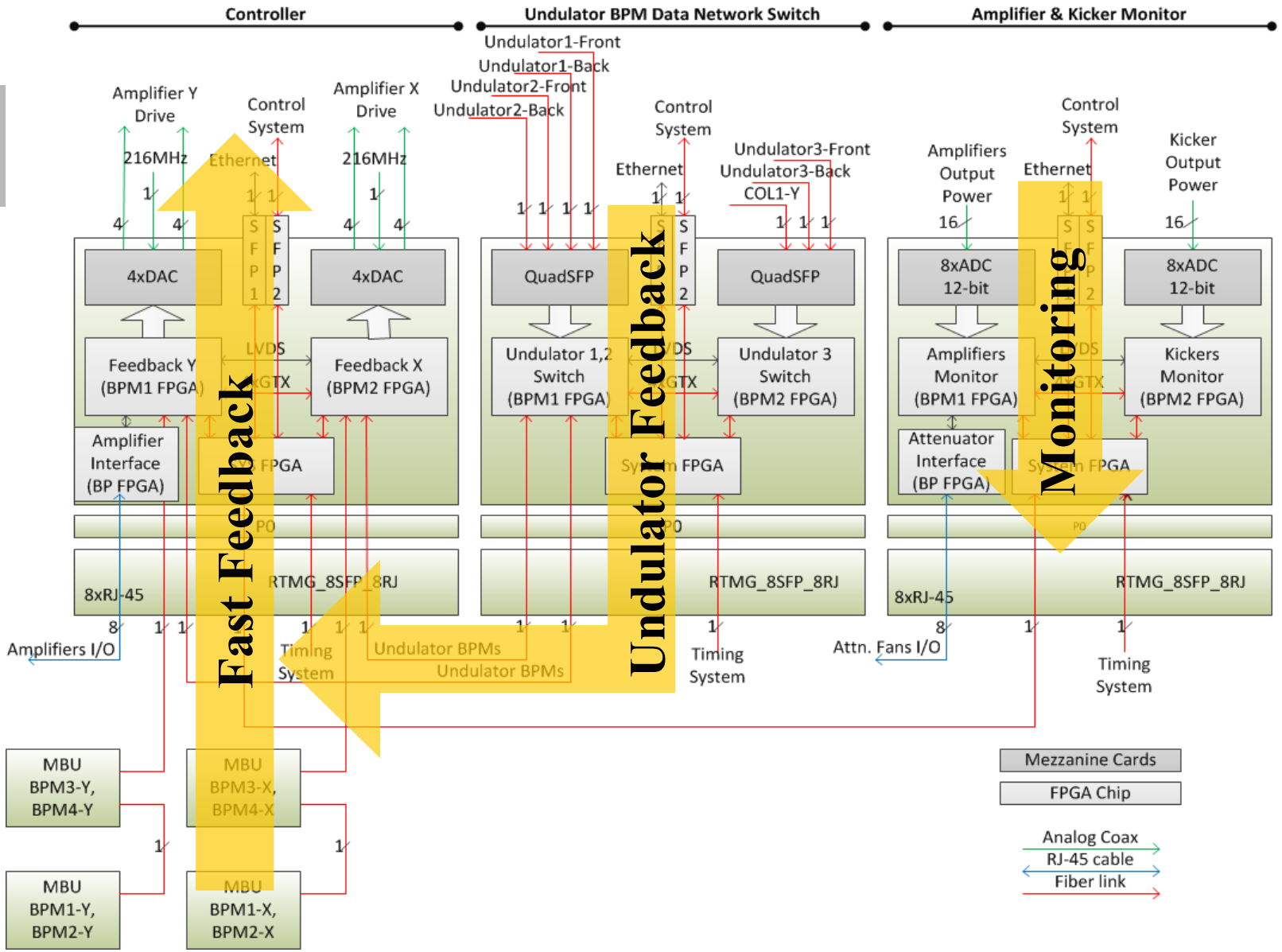


IBFB uses optimized pulse forms: Electron bunch sees ~14ns window of this pulse -> scan trigger delay to put beam on top of pulse.

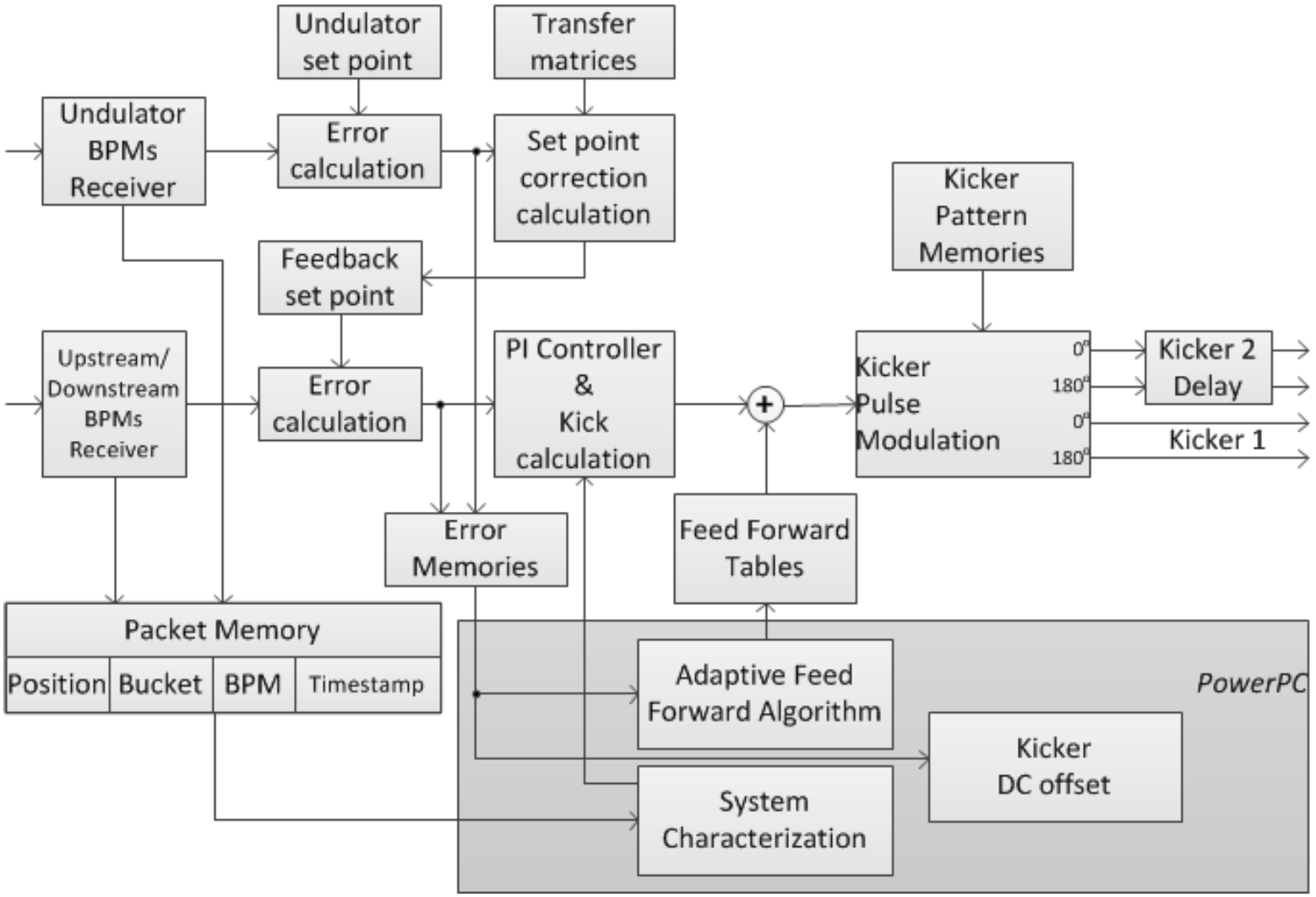


Contents

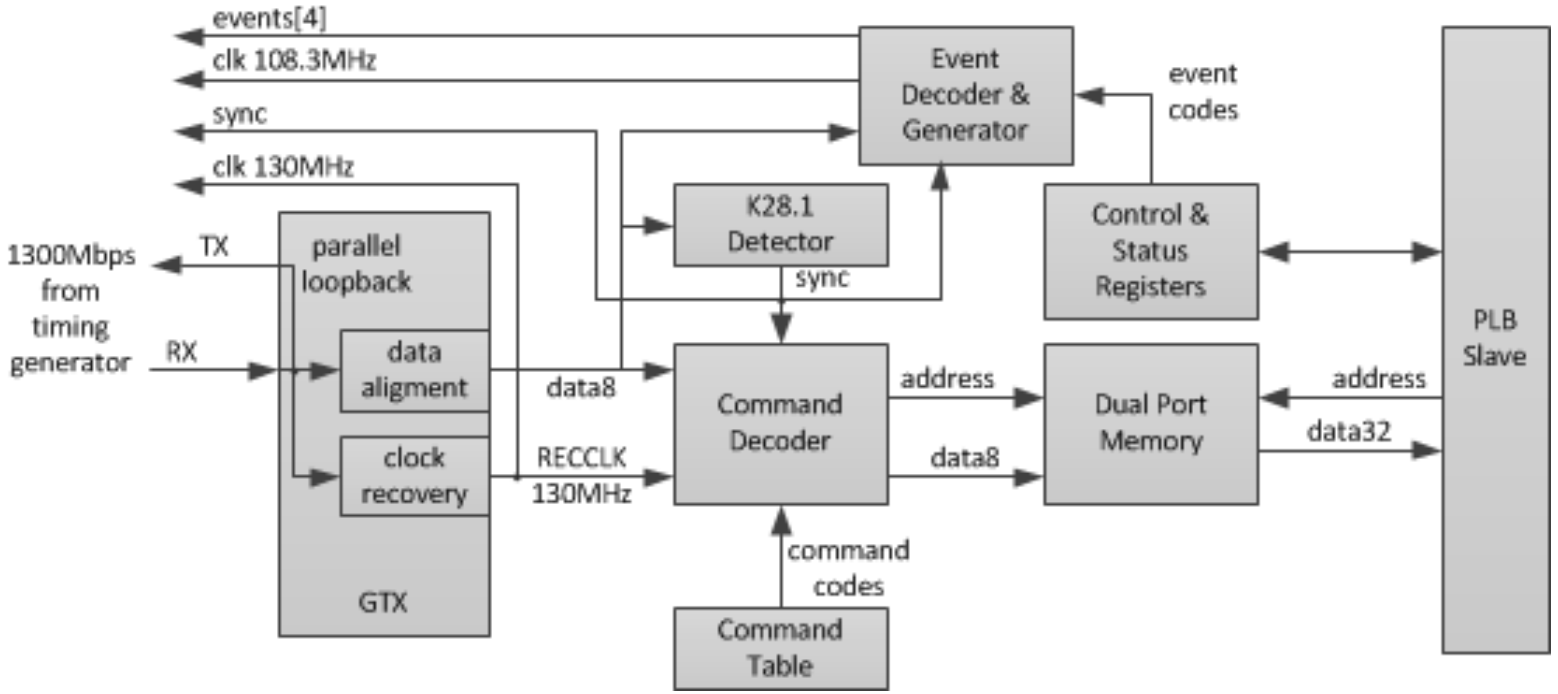
IBFB Feedback Engine: Three FPGA Boards



IBFB Controller – Firmware Block Diagram

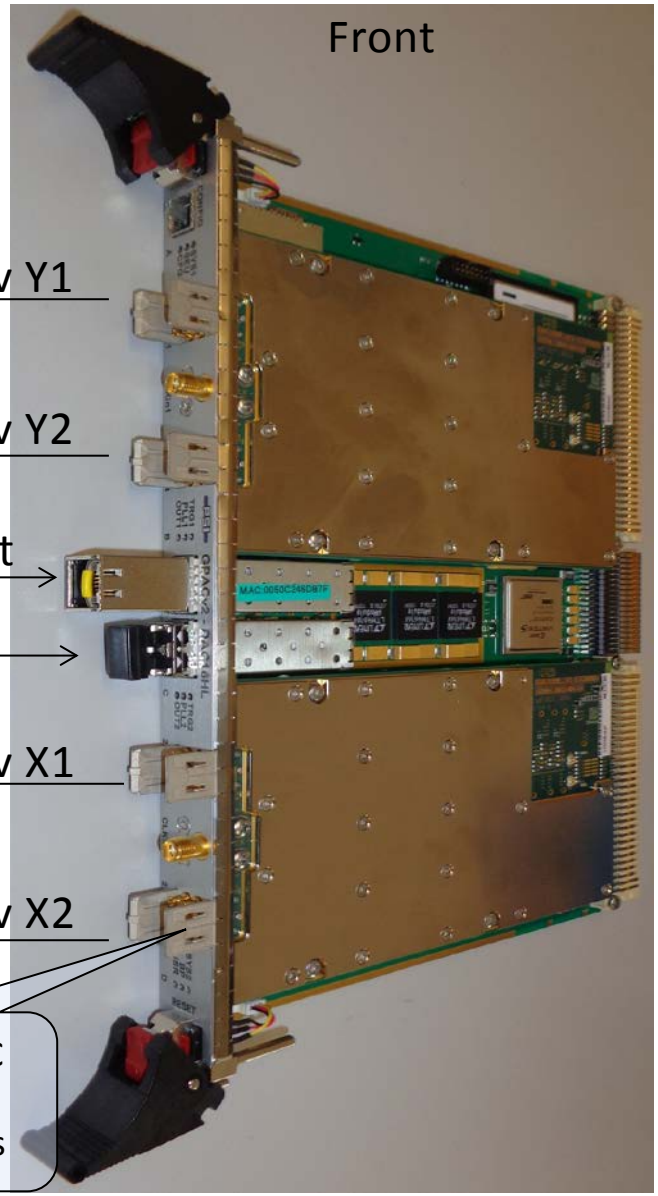


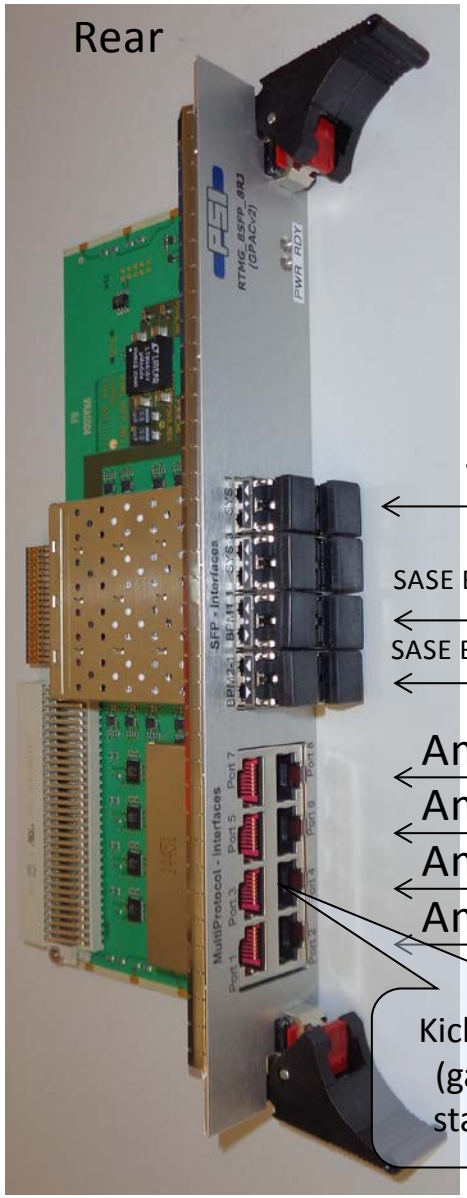
IBFB timing receiver



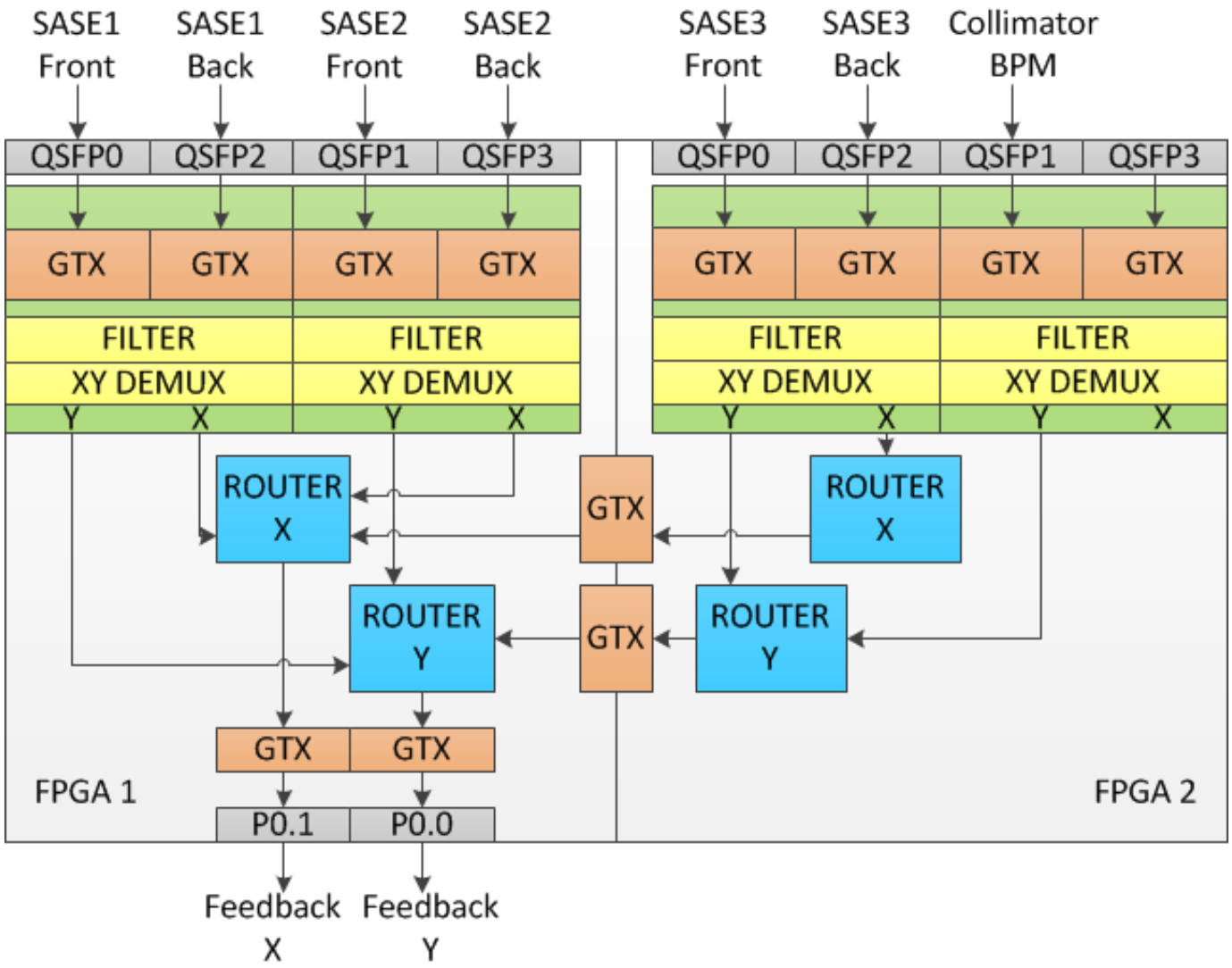
- IBFB: Direct interface to E-XFEL timing/event system (multi-gigabit fiber link):
  - Receives events/triggers (start of bunch train, ...).
  - Reconstructs bunch clock etc. from fiber link for FPGA firmware sync.
  - Receives information about bunch train (pattern, # bunches, spacing, ...) needed by IBFB FPGA algorithm & IBFB network switch.

Feedback Controller (16-bit 500MSPS DAC)

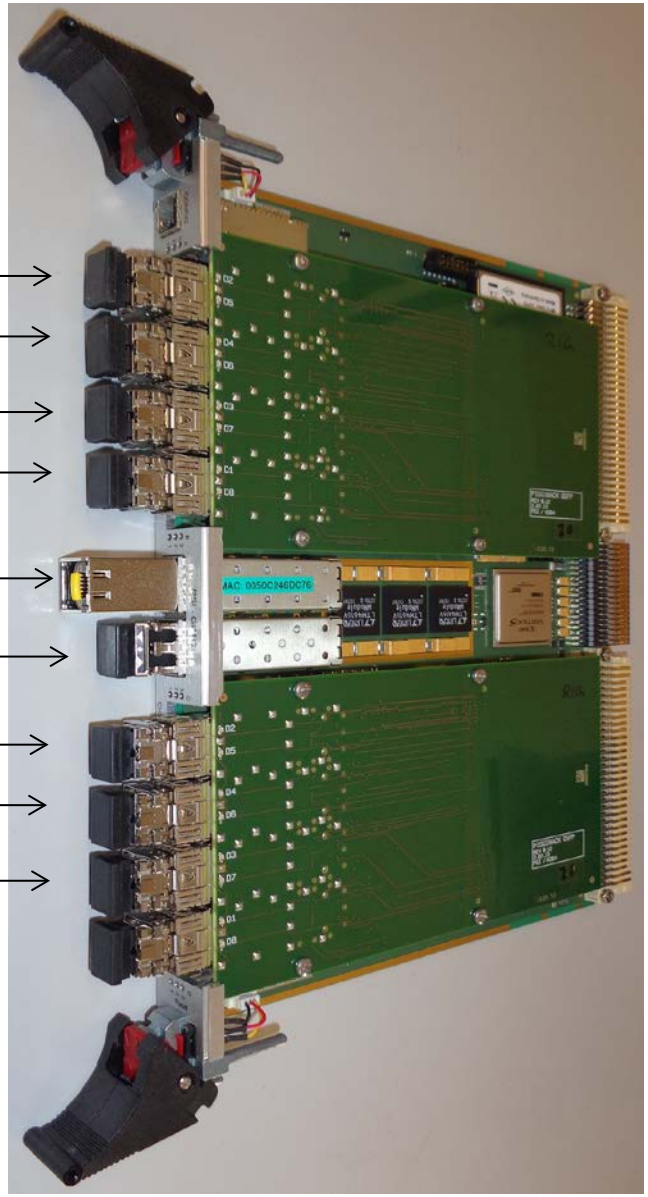


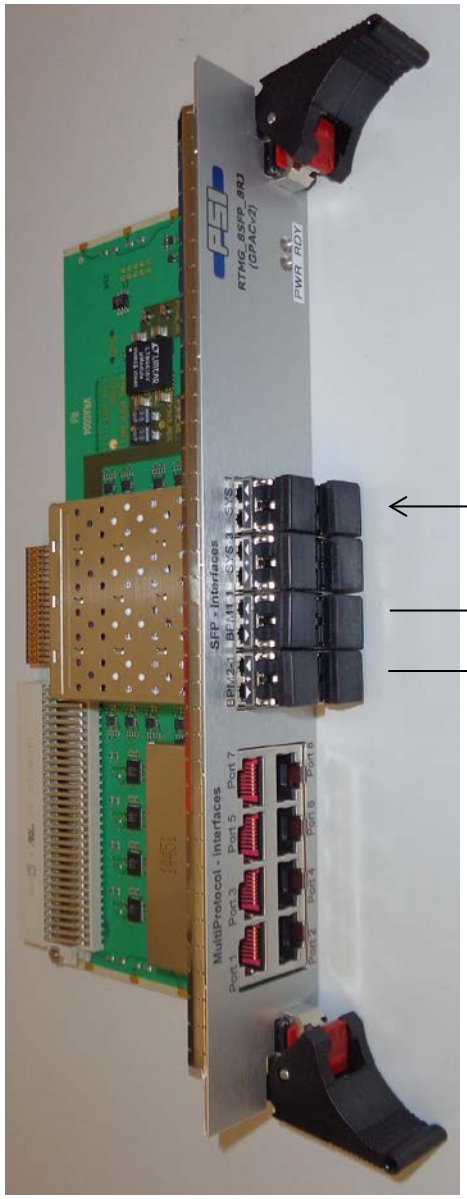


Undulator BPM Network Switch Architecture

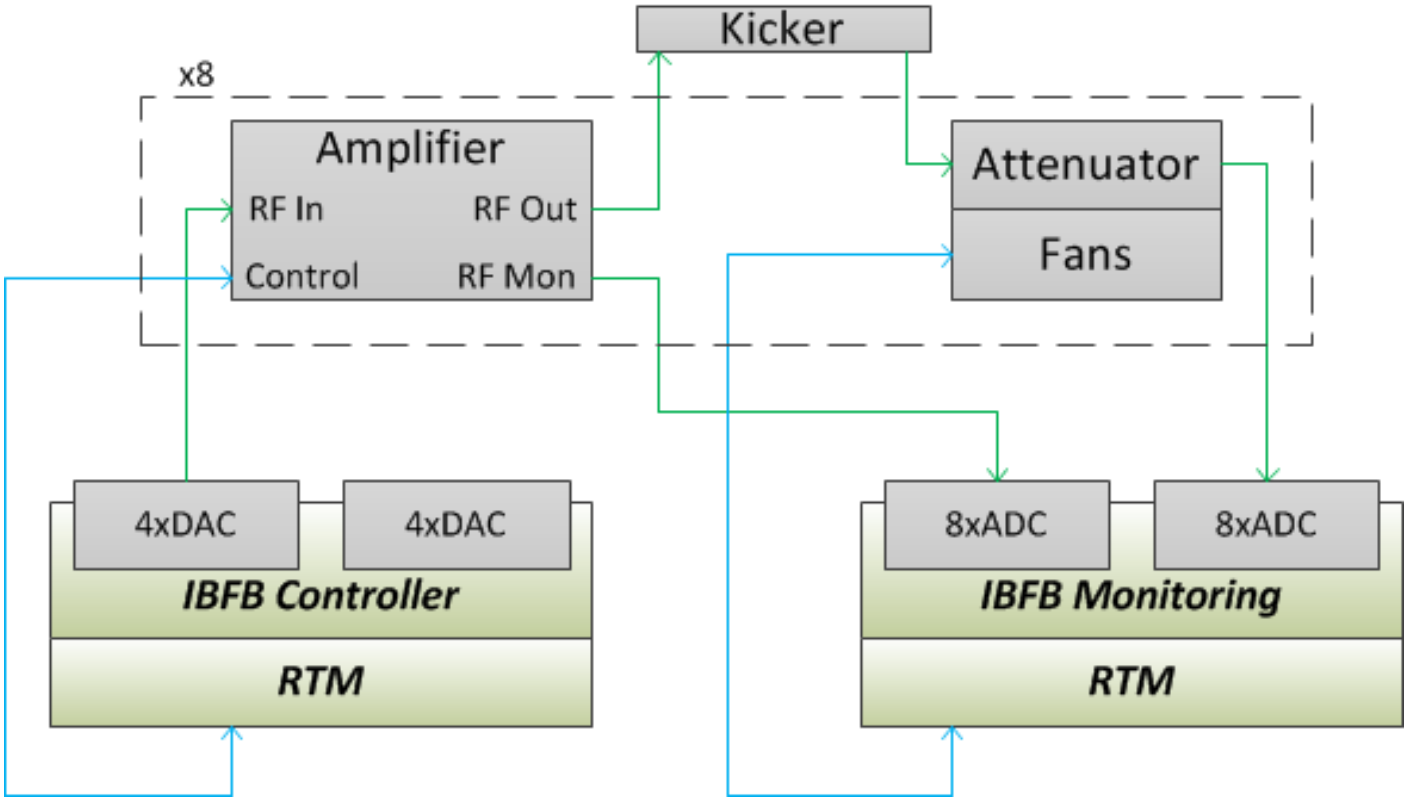


Undulator BPM Data "Network" Switch (SFP+)



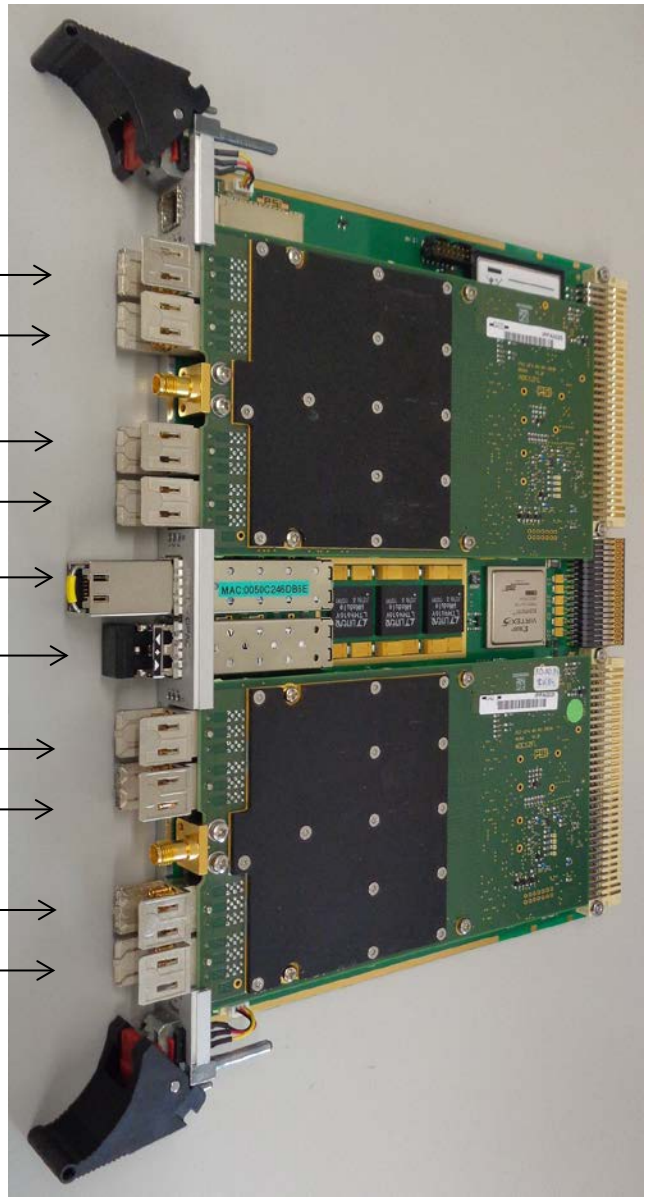


IBFB Monitoring

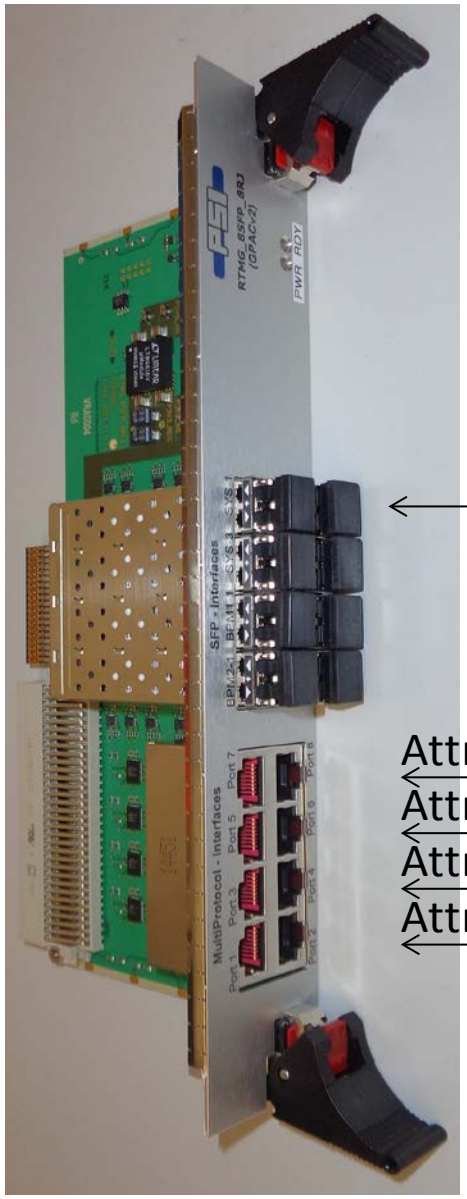


- Digitizes kicker & amplifier output waveforms (after attenuation: 6kW ...) @ 216MSPS (remote monitoring of amplifier gain/drift, pulse shape optimization, ...).
- Power amplifier control (gate enable) & health monitoring.

Amp/Kicker Monitor (12-bit 500MSPS ADCs)



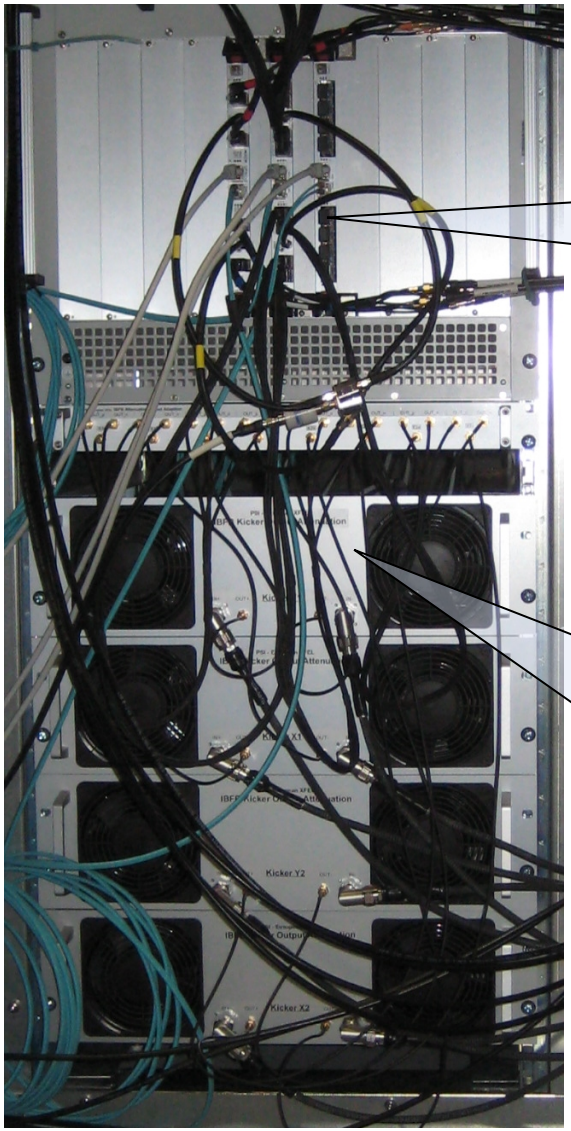
Kicker X1
Kicker X2
Kicker Y1
Kicker Y2
Ethernet
DOOCS
Amp X1
Amp X2
Amp Y1
Amp Y2



Timing
Attn. Fans Y1
Attn. Fans Y2
Attn. Fans X1
Attn. Fans X2

IBFB Electronics Rack

front



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FPGA Boards with DACs & ADCs

Power attenuators for kicker output signal monitoring by ADCs

Contents

E-XFEL Setup for IBFB Beam Tests

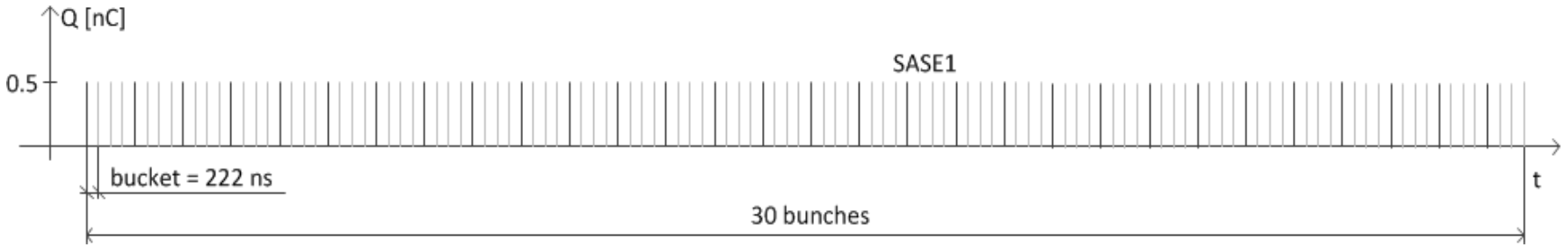
So far: Only two (dedicated) beam shifts @ E-XFEL to test IBFB & kick beam.

1st shift (June '17): Test of kickers (feed-forward table, trigger delay scan, bunch crosstalk, beam response matrix, ...). Setup:

- 0.5 nC bunch charge, 13.5 GeV
- 30 bunches per train (=max. we could get, no SASE)
- 0.222 µs bunch spacing
- 10 Hz rep rate

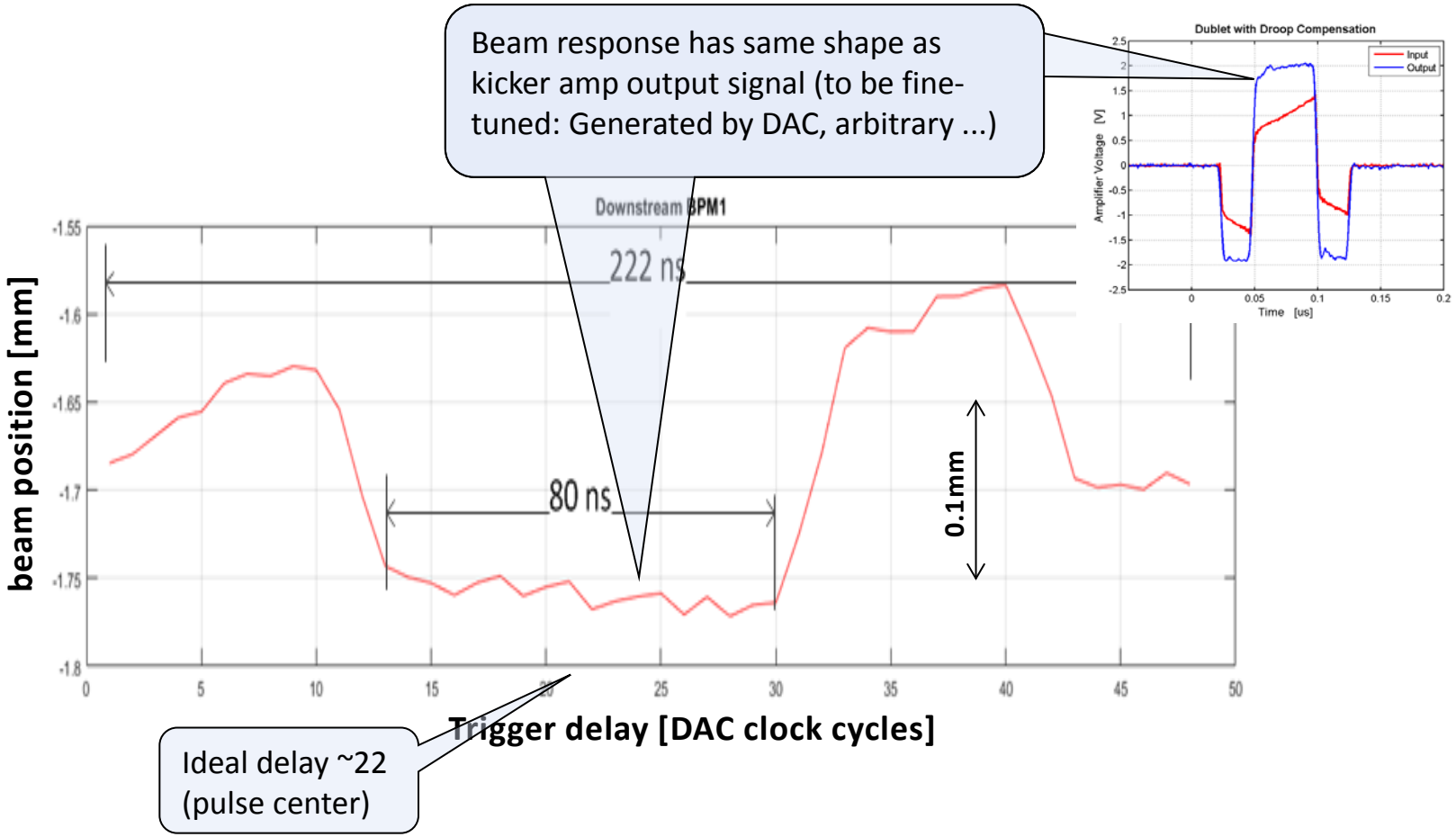
2nd shift (August '17): Loop closed for the 1st time. Machine Setup:

- 30 bunches per train (generating FEL radiation in SASE1)
- 1.1 µs bunch spacing (want long train)
- Closing feedback loop for the 1st time



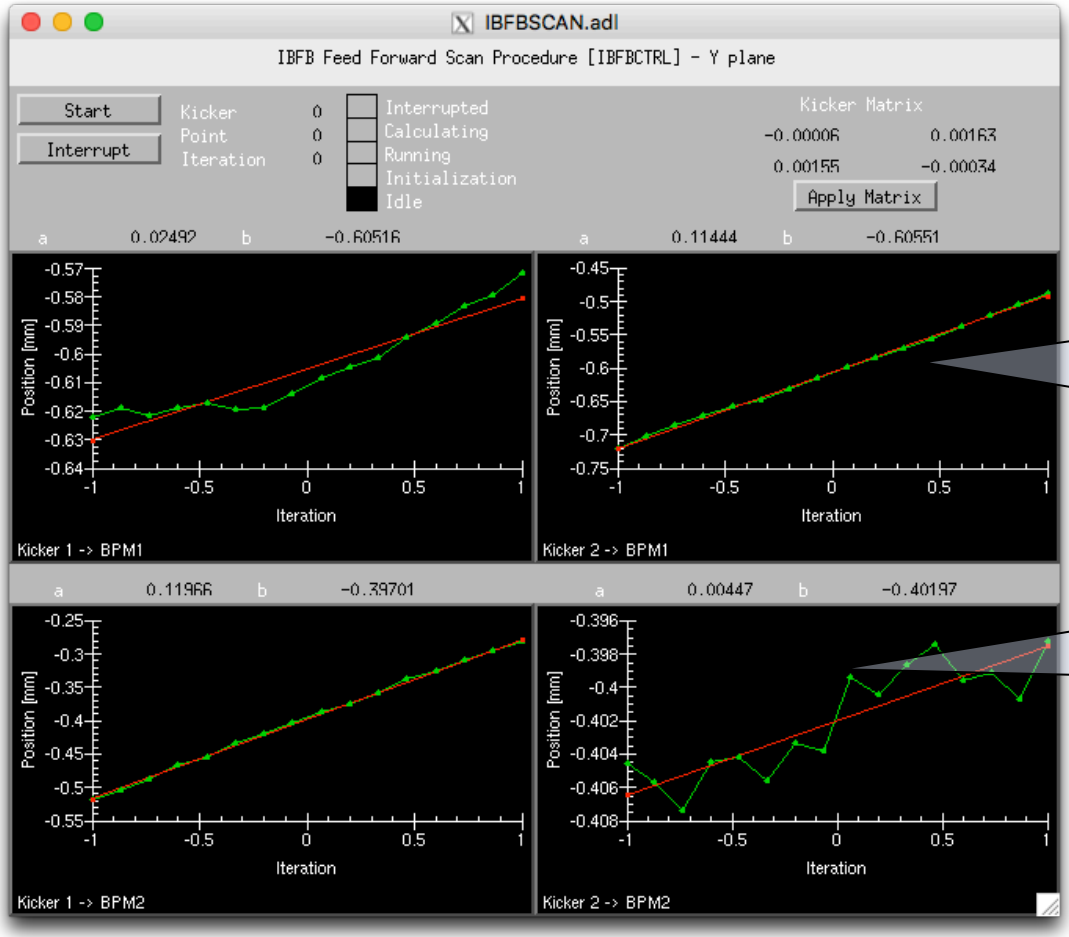
IBFB Kicker Delay Scan

- IBFB uses short DC-free "doublet" pulses to kick each bunch individually
- Pulse timing automatically adjusted/optimized by high-level software (future: implement low-level)
- Measurement of pulse trigger delay vs. beam position



Beam Response Measurement

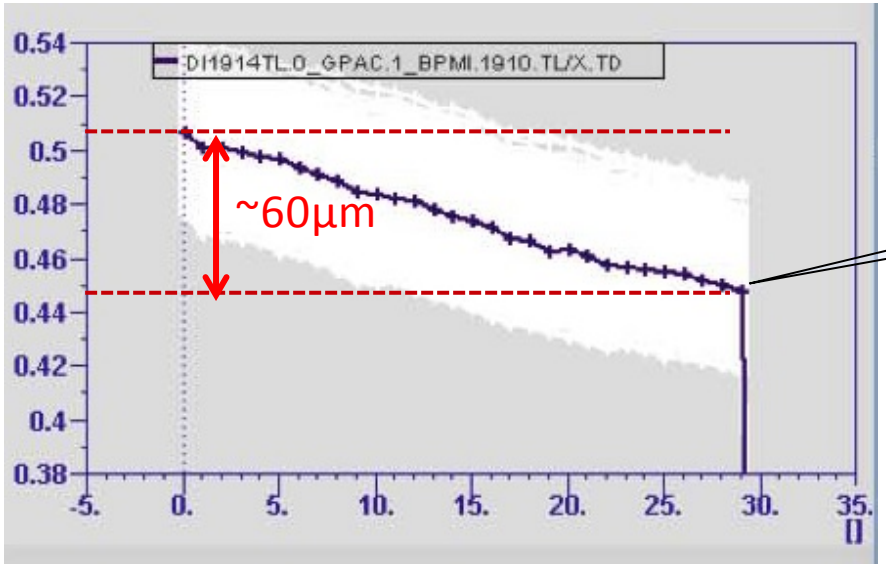
- IBFB software automatically measures beam response matrix (beam position change as function of IBFB kick) for all IBFB BPMs & kickers (multi-point fit)
- Inverted matrix then used by feedback to calculate kicks from BPM data



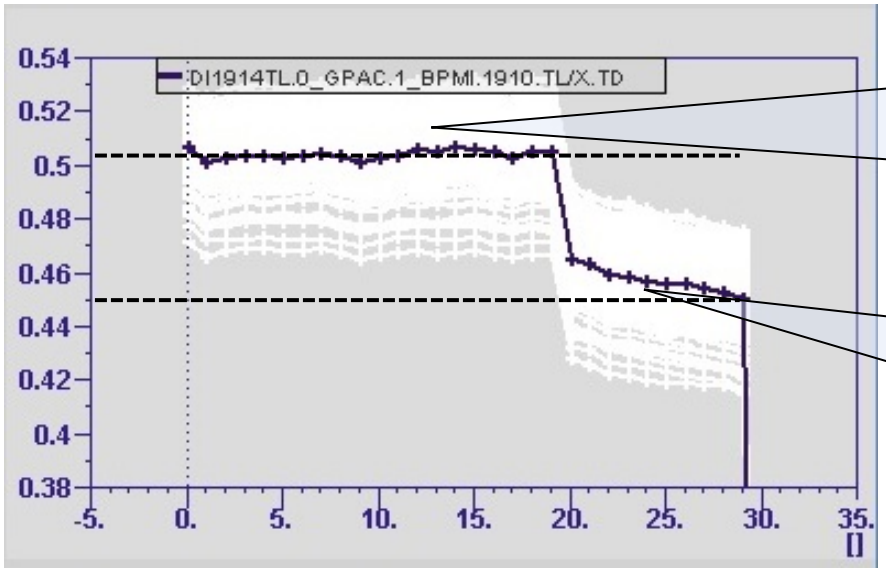
Beam position @ downstream BPMs as function of kick angle (green: measured, red: fit).

Orbit jitter could be removed using upstream BPMs (to be implemented).

Feed-Forward Tests



IBFB kickers off

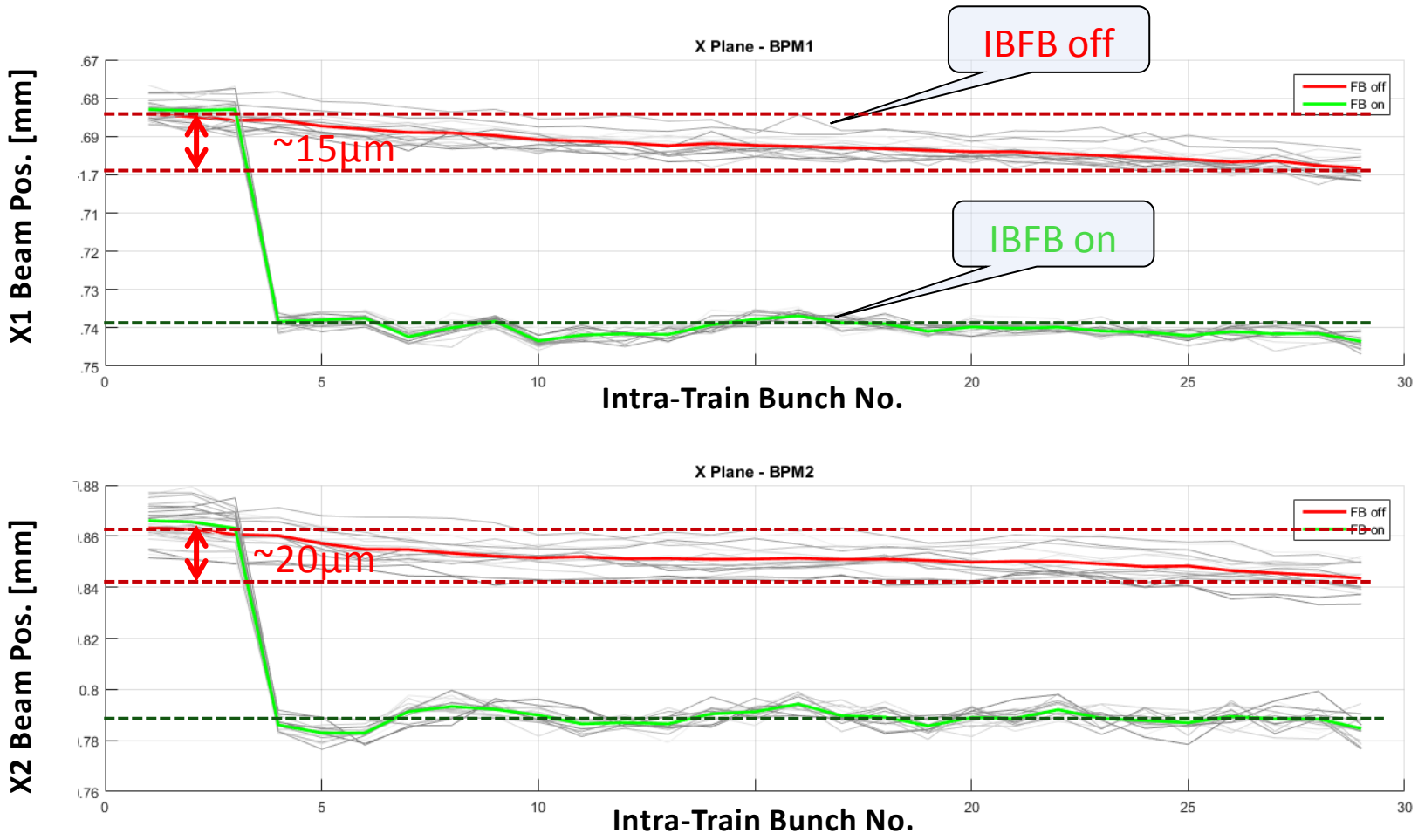


IBFB kickers on: Linearly increasing kick for first 20 bunches. Last 10 bunches intentionally not kicked to visualize kicker impact)

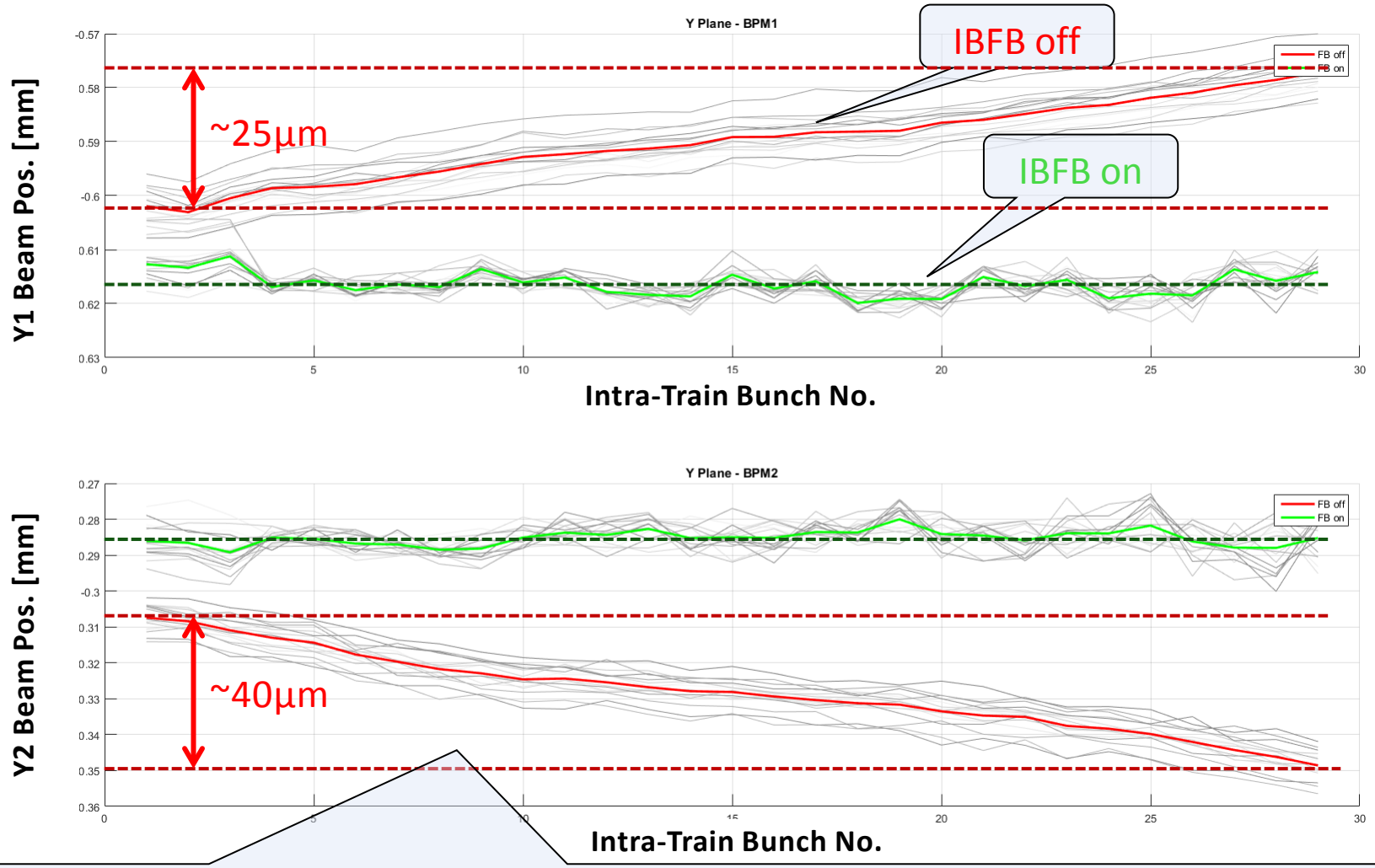
~5% crosstalk on next 2 bunches, can be removed by tuning kicker pulse shape

Intra-Train Bunch No.

Feedback Loop Tests (Horizontal)



Feedback Loop Tests (Vertical)



Tests done with simplistic preliminary FB controller & suboptimal settings (& beam positions too large, ...) to check if system works. Final controller (FB+FF, ...) & settings will have better performance.

Summary & Outlook

IBFB beam commissioning just started:

- Feed-forward & basic functionality test.
- Feedback loop closed for 1st time.

Next Steps:

- Combine adaptive feed-forward with feedback.
- Optimize settings (beam pos. near zero, ...).
- More complex FB controller algorithms:
  - PID controller, using data of all previous bunches.
  - Reduce PID controller gain over the bunch train:
    - Start with high gain (-> fast convergence).
    - Then reduce gain (-> IBFB puts less noise on beam).
- Try longer bunch trains & shorter spacing.
- Optimize kick pulse shape (minimize bunch-bunch crosstalk).
- Make system robust: Automatic adaptation to different accelerator settings (bunch spacing, train length, charge, ...).
- Use data of dispersive BPM & undulator BPMs for fine-tuning.
- Tune/optimize IBFB system parameters with SASE.

Team & Credits

PSI:

- Waldemar Koprek
- Raphael Baldinger
- Robin Ditter
- Mathias Gloor
- Alessandro Malatesta
- Fabio Marcellini
- Goran Marinkovic
- Markus Roggli
- Markus Stadler
- Daniel Treyer

DESY:

- Winfried Decking (WPL, ...)
- Vladimir Balandin (Optics)
- Martin Dohlus (RF Sim)
- Nina Golubeva (Optics)
- Jens Klute (Installation)
- Dirk Lipka (BPM Pickup)
- Dirk Nölle (BPM Pickup)
- Silke Vilcins (BPM Pickup)

... and many other supporters at PSI, DESY & SBFI