European X-Ray FEL

Transverse Intra Bunch Train Feedback System

Conceptual and Technical Design Report

Work Package 16

Editor

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Contents

1 Revision History

Date	Author	Comment
May 26, 2015	B. Keil	1st draft
July 10, 2015	B. Keil	2nd draft. Wrote parts of chapter 5.
July 21, 2015	B. Keil	3rd draft, minor corrections.
November 19, 2015	B. Keil	First internally released version.
February 17, 2016	B. Keil	First externally released version. IBFB electronics topology & cabling updated. Various minor changes.

2 Overview and Requirements

This document describes the conceptual and technical design as well as non-technical aspects ("Conceptual and Technical Design Report") of the E-XFEL transverse intra bunch train feedback (IBFB). The IBFB is a contribution of the Paul Scherrer Institute (PSI) / Switzerland to work package WP16 ("Lattice"), described in the Technical Annex 16-2 to the Accelerator Construction Agreement (ACA).

Chapter 2 gives an overview of the IBFB system, its purpose and general requirements.

Chapter 3 contains technical descriptions of the IBFB and its various subsystems, showing that the chosen solutions are adequate and meet the technical requirements.

Chapter 4 provides an overview of the interfaces of the IBFB to other work packages, showing that these interfaces are compatible to these work packages and meet their requirements.

Chapter 5 discusses all relevant formal and administrative aspects of the IBFB, including quality assurance methods, risk assessment, and schedule.

2.1 Introduction

In order to achieve sufficient and reproducible intensity and pointing stability of the X-ray photon pulses generated in the E-XFEL SASE undulators, the electron beam should deviate less than ~σ/10 from its nominal (ideally straight) trajectory in the undulators, with typical beam sizes of σ=30µm or less depending on beam charge and resulting emittance. However, due to a number of transverse perturbations sources, deviations of more than ~σ/10 from this trajectory are expected to occur without operational feedback system. Perturbations that are random, i.e. not reproducible, will therefore be corrected by a fast intra bunch train feedback (IBFB) system that can measure and correct the trajectory individually for each bunch. In addition, for perturbations that are reproducible from bunch train to bunch train (or change sufficiently slow) the IBFB will apply a static (or adaptive) feed-forward correction.

2.2 IBFB System Topology

Figure 1 shows the schematic topology of the IBFB. The core of the IBFB is located just upstream of the beam distribution kickers. The IBFB core consists of BPMs measuring the position of each bunch with low latency ("upstream and downstream BPMs"), an IBFB electronics that computes the necessary correction kicks, and of a kicker system that is able to apply these kicks individually to each bunch via two horizontal and two vertical stripline kicker magnets driven by RF power amplifiers.

In each transverse plane, the IBFB uses two BPMs downstream of the respective kickers for an ultra-fast feedback loop that corrects the beam position at these BPMs towards a desired position in each plane. Two more BPMs upstream of the IBFB kickers are used to compare the expected position at the downstream BPMs with the real position, thus allowing to detect and correct kick angle errors, e.g. due to deviations of expected and real beam energy.

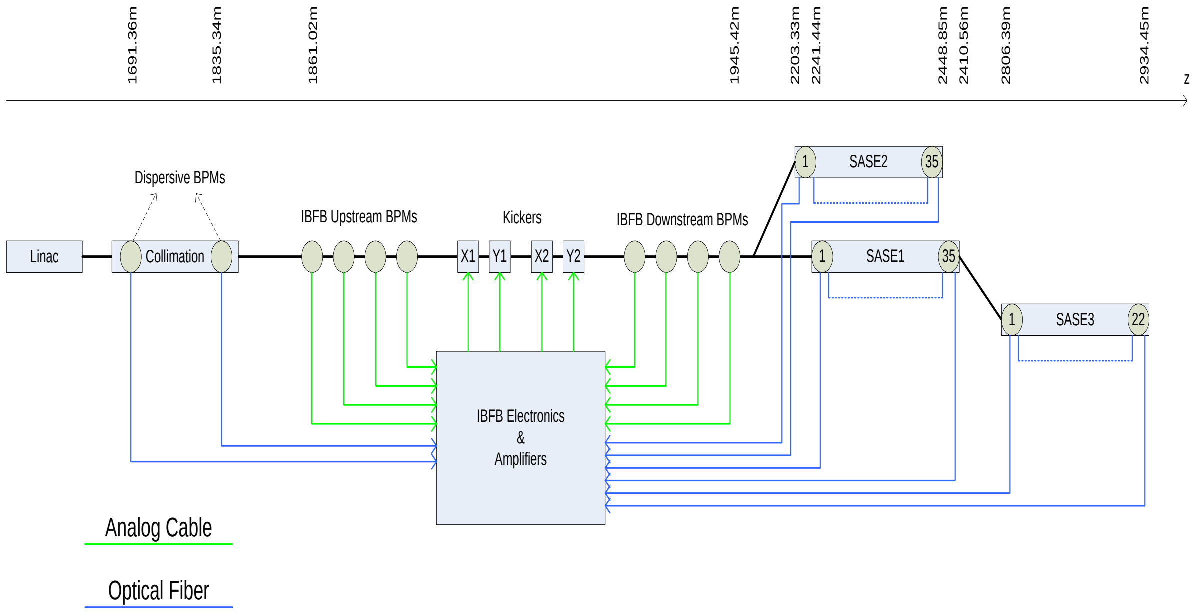

Figure 1: IBFB system topology.

In order to be able to detect and correct beam trajectory perturbations that may occur between the IBFB core system and the undulators (e.g. due to quadrupole magnet vibrations), the BPM electronics in the undulators are connected to the IBFB via fast multi-gigabit fiber optic links (blue lines in Figure 1), in contrast to the BPMs of the IBFB core and the kickers that are connected to the IBFB electronics and power amps via coaxial cables for lowest latency (green lines in Figure 1). Please note that Figure 1 is simplified to illustrate the general IBFB concept, while the exact component locations and their order are shown in Table 3 on page 8.

By transferring beam position readings from undulators to the IBFB core system, the latter can fine-tune the beam trajectory in the undulators, thus optimizing the electron-photon beam overlap and FEL performance. In order to minimize the cabling effort and number of fiber optic interfaces, the undulator BPM electronics will be connected in a bi-directional daisy chain, where the first and last BPM electronics in each undulator is connected to the IBFB core system. This redundant cabling makes the system more robust, where the data transfer still works (with somewhat higher latency) when the daisy chain is broken, e.g. due to a broken fiber optic cable or a power failure of a BPM electronics unit.

The IBFB also receives the readings of at least one cavity BPM at a location with non-zero dispersion in the collimator section. This allows the IBFB to detect beam energy variations and correct the kicker scaling factors accordingly. Since beam position changes at dispersive BPMs may result both from energy variations and from transverse trajectory perturbations (e.g. quadrupole magnet vibrations), the non-dispersive IBFB upstream BPMs are used to subtract transverse trajectory jitter from the dispersive BPMs via an optics model.

2.3 Transverse Beam Trajectory Perturbations

Table 1 shows the presently expected main horizontal (X) and vertical (Y) beam trajectory perturbation sources, their estimated worst-case peak amplitudes and necessary correction kicks, normalized to 30m beta function both at the location of position measurement and of the kicker. Since no significant random perturbations with very high frequencies are expected, a feedback loop latency of <1.5µs was specified for the IBFB [1], allowing to correct non-reproducible perturbations up to a maximum (0dB) frequency of ~70kHz. Although a lower latency is possible, the choice of a target latency that is somewhat larger that the technically feasible minimum value allows to use e.g. ADCs with higher resolution (having higher latency) for the BPMs, or more advanced FPGA algorithms to correct BPM RF front-end IQ imbalance and X/Y-coupling, thus reducing BPM-noise dominated perturbations that the IBFB adds to the beam. Since the IBFB kickers can apply arbitrary individual kicks for each bunch, the additional feed-forward corrections applied by the IBFB allow to correct reproducible perturbations of any frequency from several MHz down to DC within the available kick range.

Table 1: Expected transverse beam trajectory perturbations in the E-XFEL undulators. The perturbations and kicks are worst-case peak values [2][3] , normalized to 30m beta function at the location of the BPMs and kickers.

	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**

2.3.1 Quadrupole Magnet Vibrations

One source of random perturbations where the expected beam movement is significant is the vibration of quadrupole magnets in the cryostats of the superconducting linac RF accelerating structures, where the comparatively complex mechanical supports are naturally not as stable as for normally conducting linacs where quadrupoles have simpler massive supports. Since the typical oscillation period of magnet vibrations is relatively long (~10-100ms) compared to a bunch train length of max. 0.6ms, the vibrations cause an overall trajectory perturbation that varies very slowly along the bunch train, with nearly the same perturbation amplitude and angle for adjacent bunches. Vibrations are therefore – despite their low perturbation frequency – one reason why a low-latency IBFB is required: When the IBFB detects the perturbation at the beginning of the bunch train, it starts applying corrections such that the following bunches converge towards their nominal orbit, where the convergence time (in the order of typ. 10µs, depending on perturbation amplitude and bunch spacing) scales with the IBFB latency.

2.3.2 Dumping of Not Corrected Bunches

The IBFB as well as other beam based feedback systems in E-XFEL like the longitudinal/LLRF feedback may need a number of bunches at the head of the bunch train before their corrections become fully effective and reach the desired stability level. The unstable bunches at the head of the train can be dumped by the beam distribution system that is located downstream of the IBFB (and upstream of the SASE undulators), where only the following stabilized bunches reach the undulators. Due to a maximum bunch train length of ~600µs, dumping bunches at the head of the train for a duration of ~10µs has little impact on the maximum number of X-ray photons that can be generated per bunch train.

2.3.3 Beam Distribution System

The E-XFEL beam distribution system has a fast dump kicker that can generate arbitrary bunch patterns for the undulators. This kicker also dumps the beam while a slower but stronger kicker (based on a Lambertson septum and a flat top pulser kicker) changes its field to redirect part of a bunch train to another undulator line. Due to this concept, the high-frequent trajectory perturbations generated by the distribution system should be negligible. Its low-frequent perturbations, e.g. due to capacitor bank droop, are minimized by suitable design techniques, and are expected to be mainly reproducible, thus allowing the IBFB to apply a feed-forward correction if necessary.

2.3.4 Perturbations between IBFB and Undulators

The only expected source of significant non-reproducible perturbations between IBFB and undulators are mechanical magnet vibrations that have low frequencies (typ. 10-100Hz), with a perturbation amplitude that should be low compared to main linac quadrupole vibrations. Thus, the higher latency of the undulator BPM data received by the IBFB core system is uncritical: For the first bunches in a train, the IBFB will only use the downstream (and/or upstream) BPM data to correct the trajectory, in addition to the previously mentioned feed-forward corrections. As soon as the IBFB receives the first readings from the undulator BPMs, it performs additional fine tuning of the beam trajectory in the undulators.

2.4 Requirements to the IBFB

2.4.1 Overview and Deliverables

The deliverables of the PSI contribution to WP16, i.e. the IBFB, consist of the following components:

- BPM electronics for 9 BPMs of type BPMI (“IBFB BPMs”) as defined in the European XFEL component list [4].
- Four stripline kicker magnets, with 2.2m flange-to-flange length and about 2m effective strip length.
- RF power amplifiers to generate suitable electromagnetic fields in these kicker magnets.
- Electronics (called “IBFB core electronics”), including its internal firmware and software, that:
    - Receives the BPM data,
    - calculates corrective kicks from the BPM data via feedback and/or feed-forward algorithms, both for the horizontal and for the vertical plane,
    - allows to apply these kicks to the beam in both planes by driving the above mentioned RF power amplifiers accordingly, with the possibility to apply individual kicks to each bunch in a bunch train (i.e. macro pulse), and

- provides the required interfaces to the control, timing and machine protection system.

Table 2: List of IBFB deliverables [1].

No.	IBFB Component Name	Quantity
1	IBFB BPM electronics	Electronics for 9 BPMs
2	IBFB core electronics	1
3	RF power amplifiers	8
4	Kicker magnets	4

2.4.2 BPMs

The performance requirements to the IBFB BPM electronics are identical to the requirements of the undulator BPM electronics [5], with the exception that the latency of the BPM electronics is so small that an overall feedback loop latency of <1.5 μs can be achieved. It should be noted that the electronics of the undulator cavity BPMs (PSI contribution to WP17) will also have the same low latency (far below the maximum latency of 1ms allowed by the specification [5]), thus allowing to use the undulator BPMs also for intra bunch train corrections.

2.4.3 Kickers

In Table 1 the maximum kick angle at the bottom of the table has been calculated simply by adding the peak-to-peak values of the different perturbations, where the value for each perturbation is a worst case estimate. Moreover, not all perturbations occur at the same time in the bunch train, and some perturbations are only present for advanced operation modes that are not mandatory for first beam operation. Furthermore, Table 1 assumes 30m beta function at the location of the kicker and BPMs, while the actual values are different (see [6] and Table 3). Therefore, the maximum required kick angle of the baseline IBFB system has been estimated and specified as ±2.4 μrad in the IKCA [1] for each of the four kicker magnets (two for horizontal, two for the vertical plane).

2.4.4 Interfaces

The IBFB system has technical interfaces to other subsystems and work packages, including:

- The control system.
- The timing system.
- The vacuum system.
- The supports on the girders.
- The alignment system.
- The standard BPM system.

The interfaces of the IBFB are discussed in more detail in chapter 4.

2.5 Magnet Lattice and IBFB Component Locations

Table 3 shows the longitudinal (Z) coordinates of the different IBFB system beam line components, as well as the beta functions, betatron phases, and vertical dispersion at their locations. The IBFB component locations, magnet lattice and beam optics have been optimized according to different criteria (see [6]):

- Large horizontal (vertical) beta functions and optimal horizontal (vertical) betatron phase advance (close to an odd integer multiple of 90°) between the horizontal (vertical) kickers, to reduce the required kick angles and thus the costs of the kicker system.
- Large horizontal (vertical) beta functions and optimal horizontal (vertical) betatron phase advance (close to an odd integer multiple of 90°) between the two downstream BPMs (and between the two upstream BPMs) used by the IBFB to correct the horizontal (vertical) trajectory, to reduce the noise that the IBFB modulates onto the beam (dominated by BPM noise).
- Placement of all IBFB core system BPM pickups and kickers downstream of the collimators at locations with no dispersion (except one dedicated BPM in the collimator for beam energy measurement), but still upstream of the fast dump kicker, thus allowing IBFB tests and beam-based IBFB tuning and calibration while the beam is being dumped.
- Avoiding an increase of the number of quadrupoles (and related costs) in the IBFB area to achieve the above goals.

For the chosen IBFB kicker locations and beam optics, the kick strength required for the IBFB kickers and the required kicker magnet length and RF amplifier power is reasonably low (see section 3.5 and ref [6]). Although the available kick strength should be sufficient, space for four more IBFB kickers (identical design, 2.2m flange-to-flange each) has been reserved, thus allowing to (nearly) double the kick angle if needed by connecting two kickers (located very close to each other) in series to the same RF power amplifiers and thus nearly doubling the effective kicker length. An increase of the RF amplifier power is also feasible, but the amplifier costs scale approximately with the power and thus with the square of the maximum kick angle, therefore increasing the effective kicker length (that scales linearly with the kick angle) is usually more cost effective than increasing the amplifier power.

Table 3: List of IBFB BPM pickups and kickers, with the values of optical functions at their locations [4]. Z is the longitudinal coordinate in the tunnel, E is the beam energy, β_x and β_y are the beta functions, ϕ_x and ϕ_y are the betatron phases (in units of rad/(2π)), D_y is the vertical dispersion.

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

It should be noted that β_x at the last X downstream BPM (BPMI.1939.TL) is only 11.6m, and the X betatron phase advance to the other X downstream BPM (BPMI.1925.TL) is only $\Delta\phi_x$=0.14, while β_y

for both Y downstream BPMs (BPMI.1910.TL and BPMI.1930.TL) is >30m and their Y betatron phase advance is $\Delta\phi_y$=0.2, which is closer to the optimal value of 0.25. Therefore, when using the downstream BPMs in a fast feedback loop, the X feedback loop will modulate more BPM noise onto the beam than the Y feedback loop for similar beam positions and measurement ranges. However, the resulting beam trajectory perturbations caused by the BPM noise are still expected to be uncritical [6], and changes of the lattice e.g. by adding and moving quadrupole magnets to improve the values of the optical functions would cause significant costs. Therefore the above locations and optics have been agreed on as a reasonable compromise between performance and costs.

3 IBFB Subsystems

3.1 BPM System

The high-resolution BPMs in E-XFEL have two types of 3.3GHz dual-resonator cavity BPM pickups: One type with 10mm aperture used in the undulator intersections, and one with 40.5mm aperture used in the warm beam transfer lines, including the BPMs of the IBFB core system. All these BPMs have the same electronics, firmware and software, and both pickup types also have a similar position cavity sensitivity for a given beam offset. For the 40.5mm aperture IBFB and 10mm aperture undulator BPMs, the single-bunch position resolution is <1µm as required for the stabilization of the undulator orbit. For the remaining 40.5mm cavity BPMs (not used by the IBFB), the electronics will be equipped with additional input attenuators at the RF front-end inputs, thus providing a larger position measurement range at the expense of somewhat less resolution (that is however still better than the moderate <10µm single-bunch position RMS noise specified for these BPMs).

Figure 2: E-XFEL cavity BPM electronics for two BPMs (front side), consisting of a customized crate where boards are plugged in from the front and rear side [7]. The two boards shown at the top are the RF front-ends (RFFEs). The board at the bottom is the FPGA carrier board (GPAC) with two ADC mezzanines (one per RFFE) that digitize and process the RFFE output signals, using differential coaxial cables between RFFEs and ADCs to minimize interference noise.

The IBFB BPM design also determines the bunch charge range where the IBFB can be used. At very low bunch charge, the noise of the BPMs scales inversely with the bunch charge, and so does the noise modulated by the IBFB onto the beam (for fixed settings of the feedback parameters). Although the E-XFEL IBFB and undulator cavity BPMs have been specified to reach <1µm RMS noise only between 100pC and 1000pC, PSI designed the BPM electronics to reach this performance also for much lower charge down to about 20pC (see Figure 3). Moreover, the noise modulated by the IBFB onto the beam can be reduced if necessary by changing the feedback algorithm parameters to reduce the feedback loop bandwidth. However, this will of course also lower the frequency up to which random perturbations can be corrected, and reduce the correction efficiency at lower frequencies. Therefore the IBFB will allow to adjust the feedback algorithm settings to the bunch charge, either manually or automatically, by measuring the bunch charge with the IBFB BPMs and adjusting the feedback algorithm parameters accordingly.

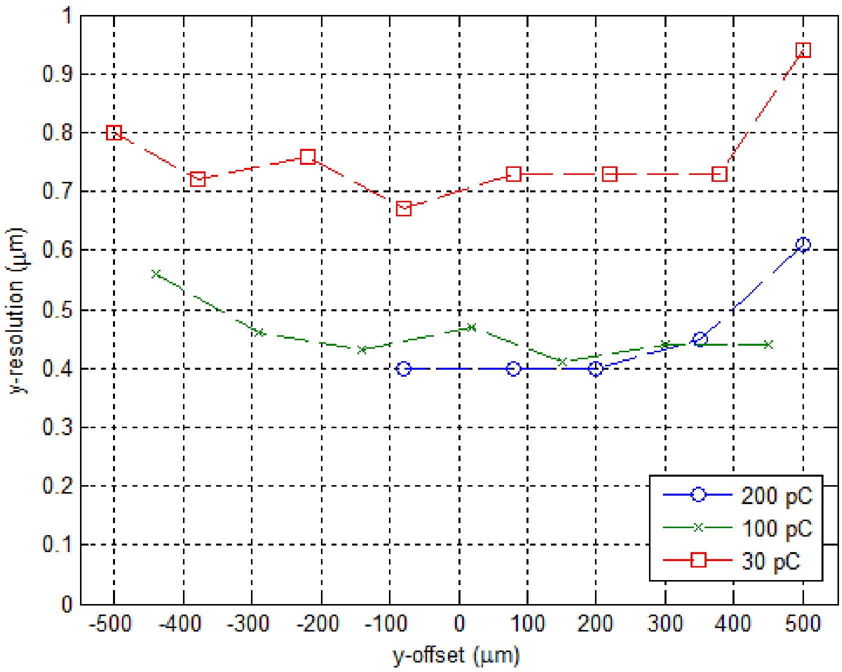

Figure 3: Position resolution (RMS noise) of E-XFEL undulator BPM, measured by correlating data of several BPMs for different bunch charges [7].

Except for their input protection circuit, the IBFB BPMs are otherwise identical to the normal E-XFEL 3.3GHz cavity BPMs, therefore they will not be further discussed here. More details can be found in the CDR of the E-XFEL BPM system [8] and publications [7][9][10].

3.2 Feedback network

The lowest feedback loop latency is achieved by using upstream/downstream BPMs directly connected to the IBFB system. In addition, fine-tuning of the undulator beam trajectory is done by transmitting undulator BPM data to the IBFB via fiber optics. Due to the rather large distance between IBFB core system and undulators, the latency of the undulator BPM data transmitted to the IBFB is significant. There are 35 BPMs each in SASE1 and SASE2, and 22 in SASE3. The fiber optic network that connects these BPMs to the IBFB consists of three independent subnets (one per undulator), using a bi-directional daisy chain for each undulator, where both ends of each chain are connected to the IBFB. In order to minimize the latency for the undulator BPM data transmission, only four of the BPMs in the chain are normally allowed to transmit their data to the IBFB controller, while the network interface of all other BPMs is set to bypass mode, thus avoiding that data from

BPMs used by the IBFB is delayed by network traffic of unused BPMs. Since each subnet is bi-directional, the same data is transmitted in both directions of the chain. The resulting latency for the data transfer to the IBFB is different for each direction, and depends on the location of the BPM electronics in the chain. The IBFB controller uses the data which comes first the rejects the second data frame that arrives later, thus automatically optimizing the network latency. With this topology, the undulator position can be delivered to the IBFB controller even if one node in the chain is down and the chain is broken at one point, although the latency for the data transfer may increase. If two or more nodes are down and break the chain at two points, only the BPMs before the first and after the last broken node can be selected for the feedback. If necessary, the BPMs to be used by the IBFB can be selected (and changed) dynamically during operation by the control room operators in order to optimize X-ray beam stability and intensity, where the electron beam position and angle in the undulators is usually most critical in the area where the X-ray beam reaches saturation.

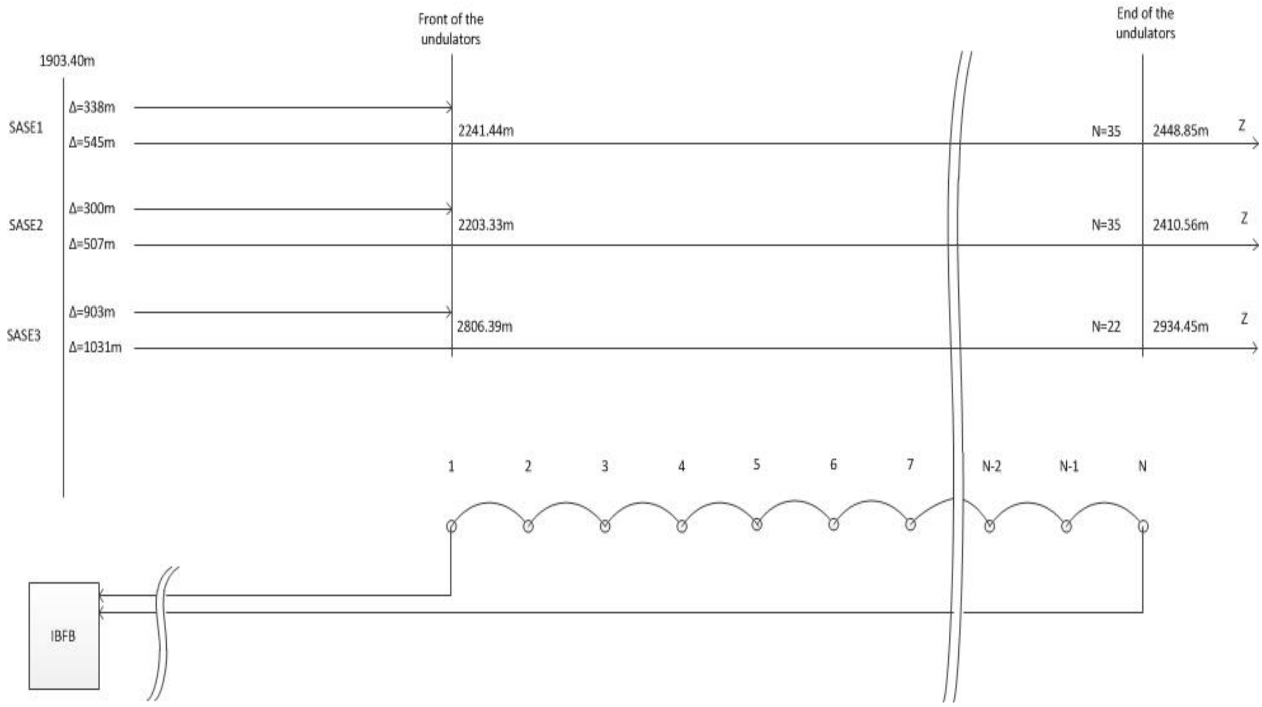

Figure 4: Distance of undulators to IBFB electronics and number of BPMs per undulator.

3.3 Feedback Electronics

Figure 5 illustrates the different interconnections of the IBFB core system electronics:

- It receives BPM data from upstream, downstream, collimator and SASE undulator BPMs via multi-gigabit fiber optic links (red lines in the figure, where just one collimator BPM will be initially connected to the IBFB, but a connector for an optional 2nd BPM is foreseen),
- drives the RF power amplifiers via coaxial cables (top right, green lines)
- monitors the signals of the RF power amplifiers (green lines at the bottom: Directly at the power amplifier, and at the output ports of the kicker magnets), and
- controls and monitors the RF power amplifier health status and enables/disables the amplifier with a gate signal via multi-pin digital cables (top left, blue lines).

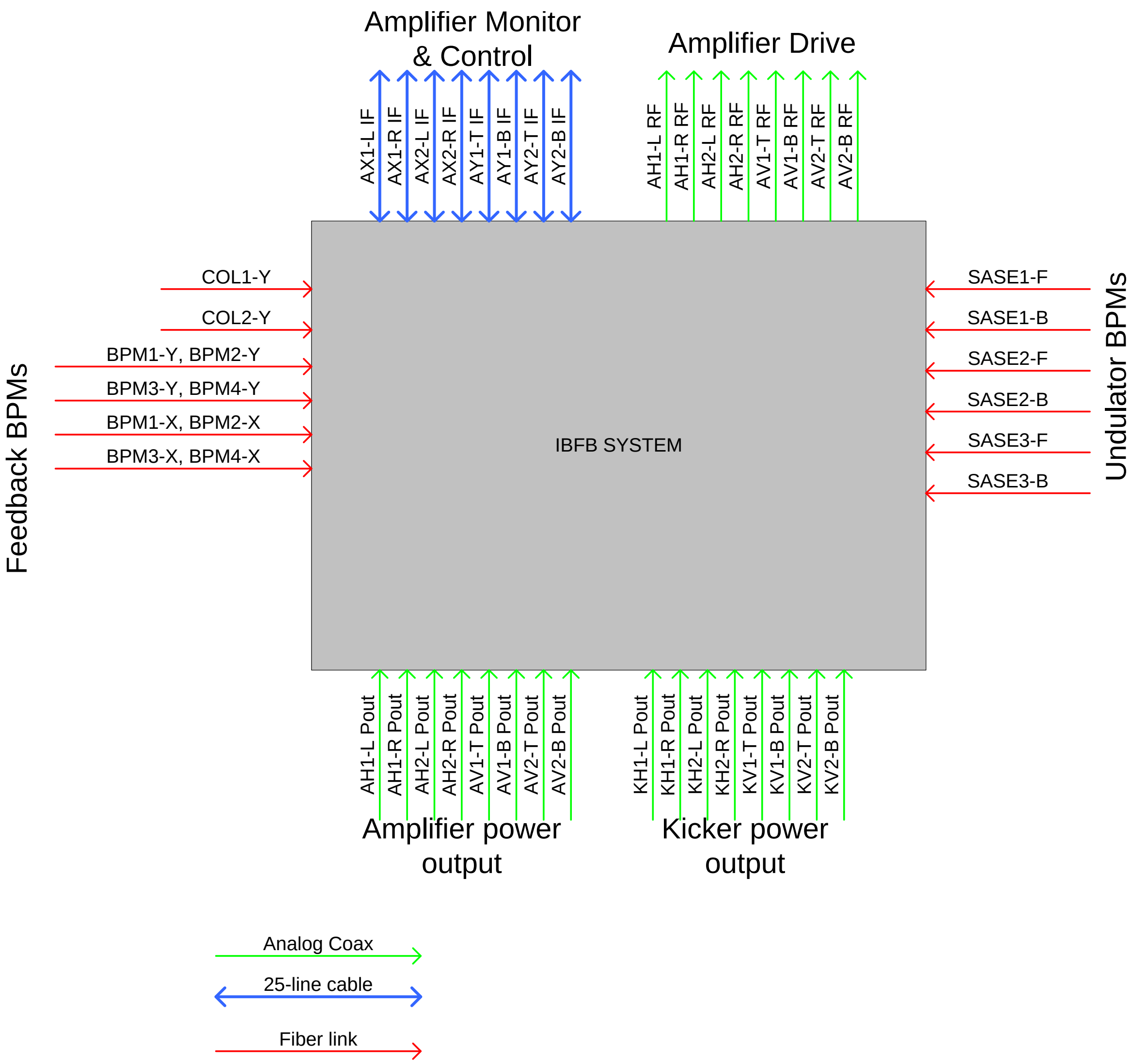

Figure 5: Interfaces of the IBFB core system electronics.

Figure 6 shows the technical implementation of the IBFB electronics. It consists of three FPGA boards that communicate via multi-gigabit links. The board on the left side of the figure, called “Controller”, performs the IBFB algorithm. It has direct fiber optic connections to upstream and downstream BPMs that are needed for the low-latency feedback loop. The undulator BPMs and dispersive collimator BPM are received indirectly from a 2nd FPGA (“Feedback Network Switch” in the middle of Figure 6) that collects this data via mezzanine modules with four SFP+ fiber optic transceivers each (“quad SFP” modules). Monitoring of the kickers and power amplifiers is done by a third FPGA board (‘Amplifier & Kicker Monitor’ on the rights side of Figure 6), and the respective data exchange with the controller board is done via another optical link.

The Controller FPGA board (on the left side of Figure 6) also drives the power amplifiers of the kicker system via two DAC mezzanines with four DAC channels each (one DAC per amplifier, see section 3.5). 16-bit DACs with max. 500MSamples/s are synchronized to the accelerator bunch repetition rate and allow to generate suitable waveforms that drive the power amplifiers of the kicker magnets (within the bandwidth limits of the amplifiers, see section 3.5). The controller board also has a digital interface to the kicker amplifiers (via its rear transition module, blue arrow in Figure 6) that allows e.g. to monitor their health status (e.g. over temperature flags, see section 3.5), enable/disable the complete amplifier ("gate input") as well as individual (redundant) internal amplifier power modules, including the possibility to switch over to a redundant spare amplifier module if one of the two operational power modules fails. The amplifier is enabled beam-synchronously (using an external trigger received from the E-XFEL timing system) via its gate input well before the beam arrives, and disabled after the full bunch train has passed the IBFB.

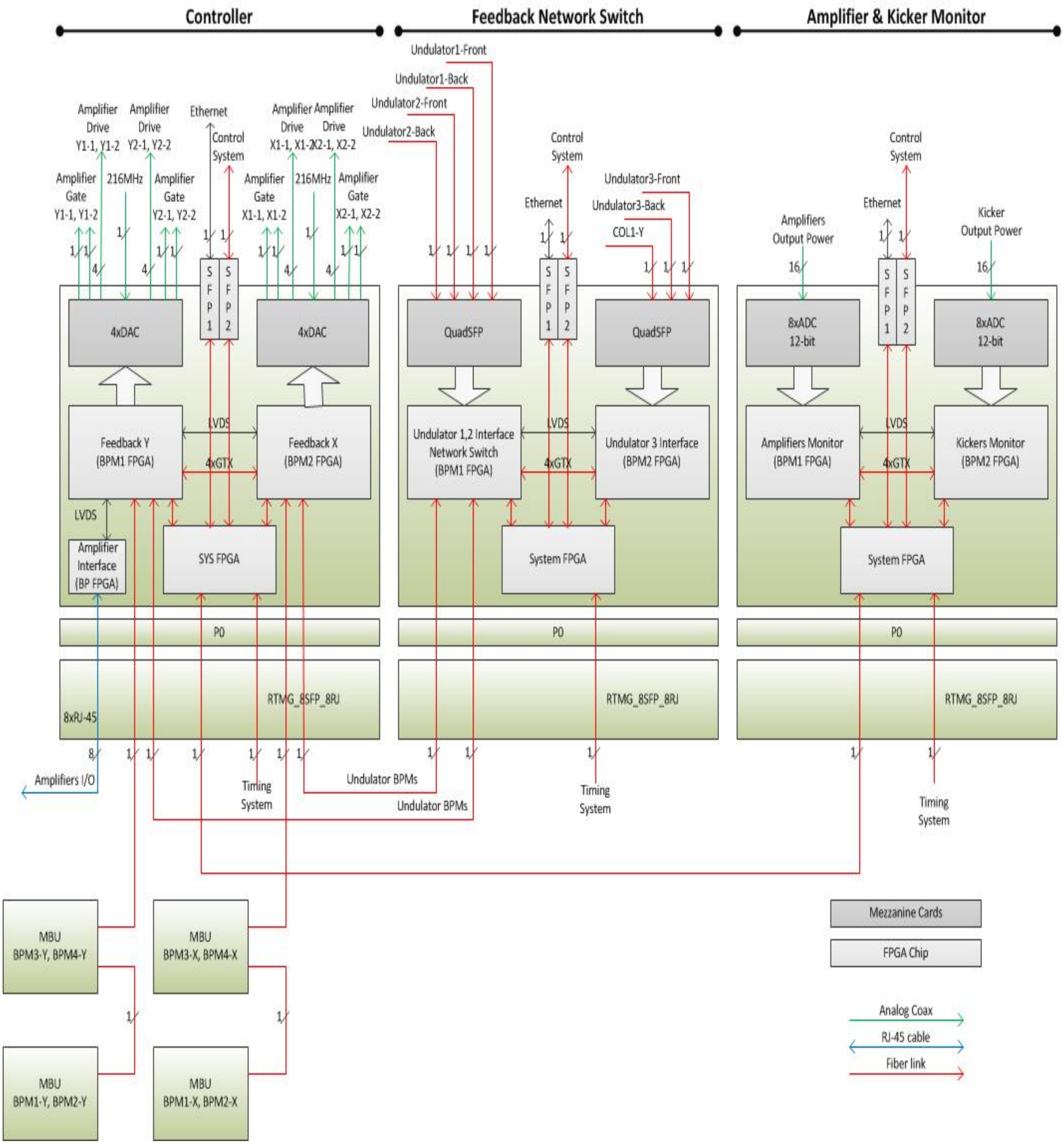

Figure 6: Layout and connections of the IBFB electronics FPGA boards that receive the BPM data, monitor the power amplifiers, perform the IBFB algorithm, and correct the orbit by driving the RF power amplifiers of the kickers with suitable waveforms.

The feedback network switch board interconnects the undulator feedback subnets and the BPM from collimation section with the IBFB controller board. This board is equipped with two quad SFP mezzanine cards and an RTM with eight SFPs. The task of the switch is to receive position data from undulator BPMs, filter out the redundant BPM data frames, and only send the relevant BPM data to the controller. The switch also checks the health of each subnet periodically by injecting special test frames from one side and receiving them on the other side of the chain while the network is idle.

The FPGA board on the right side of Figure 6 monitors the output signals of the kickers and of the RF power amplifiers via two 8-channel 12-bit 500MSample/s ADC mezzanines with bunch-synchronous clocks, thus allowing to detect drifts and malfunctions (e.g. the failure of one of the two operational RF power amplifier modules in the amplifier).

Every GPAC board is synchronized to the accelerator by a direct optical (SFP+) interface to the E-XFEL timing system, where the link allows to retrieve triggers, bunch synchronous clock, and other information from the timing system. In addition, each board has an optical (SFP+) interface to the E-XFEL DOOCS control system, where protocol and physical layer are compatible to the BPM system where a larger number of BPMs are already in operation.

3.4 Software and Firmware

Figure 7 shows the different functional blocks of the IBFB core system firmware. The central block called “Feedback Algorithms” (shown in more detail in Figure 9) retrieves the BPM data from a reflective memory (implemented in the FPGA via internal block RAM and multi-gigabit fiber optic links), calculates corrective kicks using beam optics transport matrices that can be configured via the control system, and generates suitable waveforms for the DACs that drive the RF power amplifiers of the IBFB kicker system. The amplifier output signals and status flags are monitored, thus allowing the system to detect failures or adjust the timing and gains.

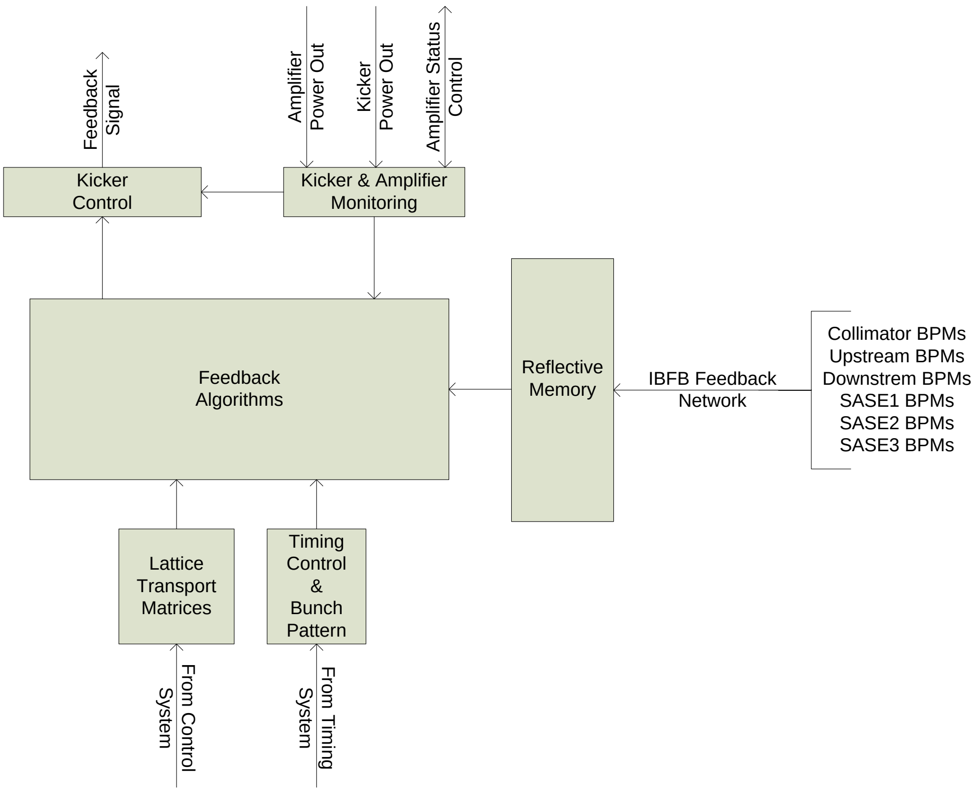

Figure 7: Block schematics of IBFB system firmware. The internal structure of the functional block “Feedback Algorithms” is shown in Figure 9.

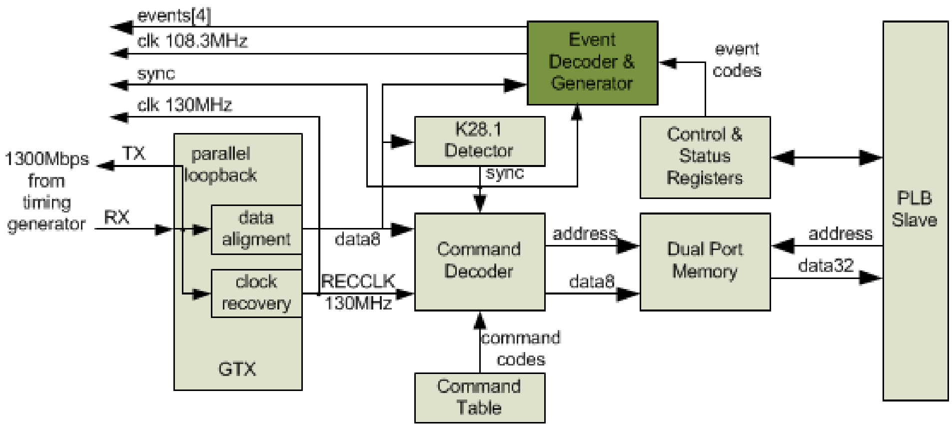

Figure 8: E-XFEL timing interface (only lowest layer shown) implemented by PSI on an FPGA of the IBFB electronics. The interface receives the 1300Mbps data stream from the optical timing system interface, generates clocks and triggers from this data stream, and stores relevant information e.g. about the expected bunch pattern, bunch charge etc. for access via an on-chip bus system.

The IBFB receives information like the expected bunch arrival time, bunch pattern and charge from the interface to the E-XFEL timing system, thus allowing the BPM system and IBFB to pre-adjust the RFFE settings to the expected bunch charge. The IBFB timing system interface is implemented in firmware (see Figure 8) on the IBFB FPGA boards that have a direct connection to the timing system via an optical fiber optic transceiver.

As shown in Figure 9, the IBFB can calculate the corrective kicks using both the upstream and downstream BPM information, with additional data from SASE BPMs and a dispersive BPM. For the baseline system, only the downstream BPMs will be part of a fast feedback loop (“downstream feedback”) that corrects the beam position at these BPM to a desired value. This feedback loop is intended for non-reproducible perturbations, while reproducible perturbations are preferably corrected by an adaptive feed-forward algorithm using suitable lookup tables.

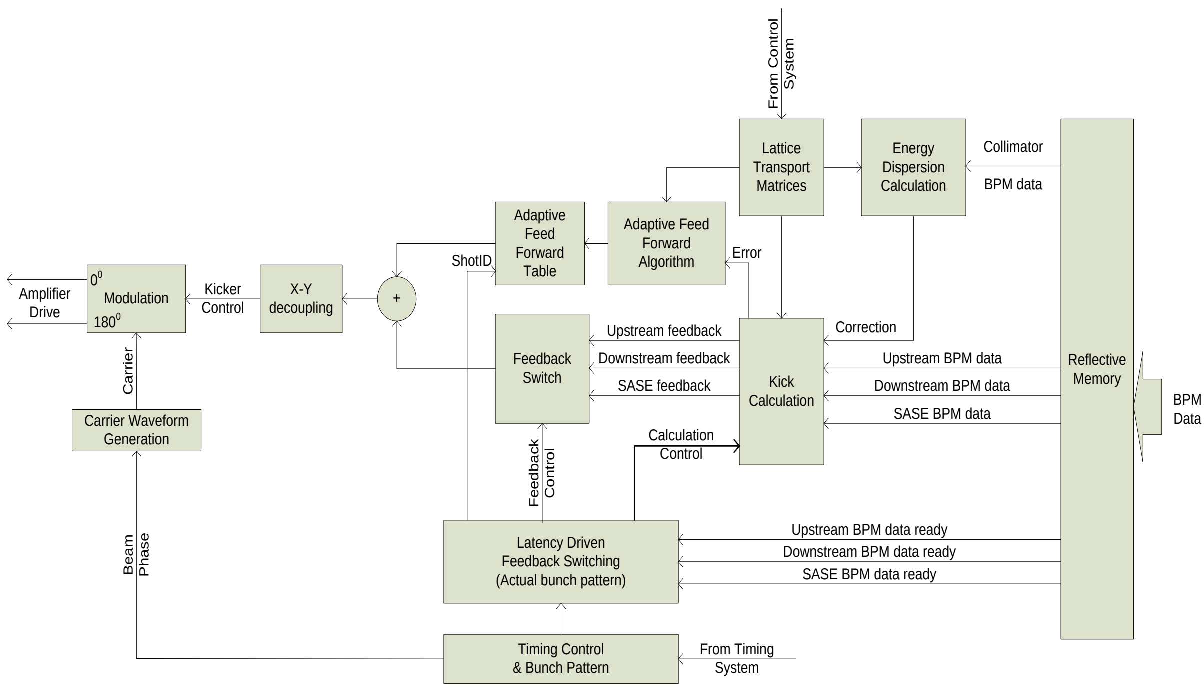

Figure 9: Block schematics of feedback/feed-forward algorithm.

The IBFB allows the use of different feed-forward lookup tables and feedback parameter settings for different accelerator operating modes (e.g. different bunch patterns and bunch charges), such that the accelerator can be switched between different modes and the IBFB can already correct the first bunch train after switching the mode without having to wait until tables and parameters have been optimized for the mode. However, the IBFB can still automatically optimize the feed-forward lookup tables and relevant feedback settings, e.g. for perturbations that are not perfectly reproducible but have slow variations over time. The IBFB also monitors the beam energy using one or several dispersive BPMs, which allows minimizing the influence of beam energy variations on the quality of the corrections applied by the IBFB.

Due to the large distance from IBFB core system to undulators, the BPM data from the SASE undulators arrives only after a few microseconds at the IBFB core system (e.g. ~5µs for SASE1 and SASE2, ~7µs for SASE3 when using 5GBaud fiber optic transmission baud rate [11]). Therefore the first bunches of each bunch train are only corrected using the low-latency downstream BPMs close to the IBFB. As soon as the SASE BPM data of a bunch train is received by the IBFB core system, the IBFB applies suitable corrective kicks in order to optimize the beam trajectory in the undulators, using lattice transport matrices that predict the undulator orbit as a function of the IBFB kicks. Energy dependencies of this matrix can be corrected by measuring the beam energy via one or several collimator BPMs and adjusting the matrix accordingly. If necessary, the IBFB also allows to measure the required lattice transport matrices and their energy dependence once or periodically, using e.g. one or several pilot bunches. For long bunch trains, high-frequency perturbations will be corrected by the fast feedback loop using only the downstream BPMs, while low-frequency trajectory perturbations of SASE BPMs will also be corrected by adjusting the reference orbit of the low-latency feedback (i.e. desired beam position) at the downstream BPMs accordingly.

Since IBFB BPMs and kickers may be tilted relative to each other, a correction of horizontal (X) and vertical (Y) coupling is foreseen in the BPM electronics (for the BPM coupling) and in the IBFB core system (for the IBFB kicker coupling). The IBFB kicker system is able to apply an arbitrary kick to each individual bunch (see section 3.5). However, in order to apply a kick at the right time, the arrival time of the bunch and the bunch spacing must be known to the IBFB. This information is received from the timing system, with an optional override and fine-tuning by the control system, e.g. in case the timing system is temporarily not available during first beam commissioning. Since the IBFB BPMs are able to measure the beam arrival time beam-based with respect to an external timing system trigger, it is possible to correct the IBFB kicker timing accordingly. The IBFB kicker system allows to generate short pulses that have a flat top when the bunch arrives. By tuning the timing such that the bunch is centered in the middle of the kicker pulse flat top, the kick angle of each bunch becomes insensitive against beam arrival time and kicker system phase drifts. Due to known system delays, an initial adjustment of the kicker timing can be made already during pre-beam commissioning of the IBFB system, and only needs to be checked and if necessary fine-tuned with beam.

As shown in Figure 9, the IBFB firmware includes a waveform generator with a carrier waveform, where the IBFB feedback and feed-forward algorithms modulate the amplitude of the carrier waveform to determine the kick angle for each bunch. As shown in section 3.5, this carrier waveform will not be a sine wave. Instead, the DAC will generate a carrier waveform that results in nearly rectangular kicker output pulses with a flat top and minimal ringing and undershoot/overshoot (see page 23, Figure 21). The pulse length is fixed, and the pulse spacing depends on the bunch spacing.

The correction of nonlinearities of the kicker system is foreseen via a lookup table that translates the desired kick into the modulation amplitude of the carrier waveform.

3.5 Kicker System

The IBFB kicker system uses stripline kickers with 50 ohms impedance, where the two opposite strips of the kicker are driven by two RF power amplifiers operated in push-pull mode, i.e. with signals of opposite polarity.

3.5.1 Stripline Kicker Magnet

Figure 10 shows a longitudinal cut through an IBFB kicker prototype that was designed by PSI for the IBFB. Only about 30% of the overall length (that is 2.2m flange-to-flange) is visible in the figure. The RF power amplifier signals enter the kicker at the left side via two HN-type connectors that are connected to the strips via flexible bellows (shown in Figure 11, right photo) to allow relative movement of strips and outer vessel due to thermal expansion and contraction. Each of the two conductive strips inside the vessel is held in place via five ceramic spacers with equal distance (only two visible in Figure 10), where the center spacer has a fixed position, while the other four can slide longitudinally (see Figure 11, middle photo). This leads to a significant reduction of thermal stress and risk of cracks of the ceramics during assembly and vacuum bake-out.

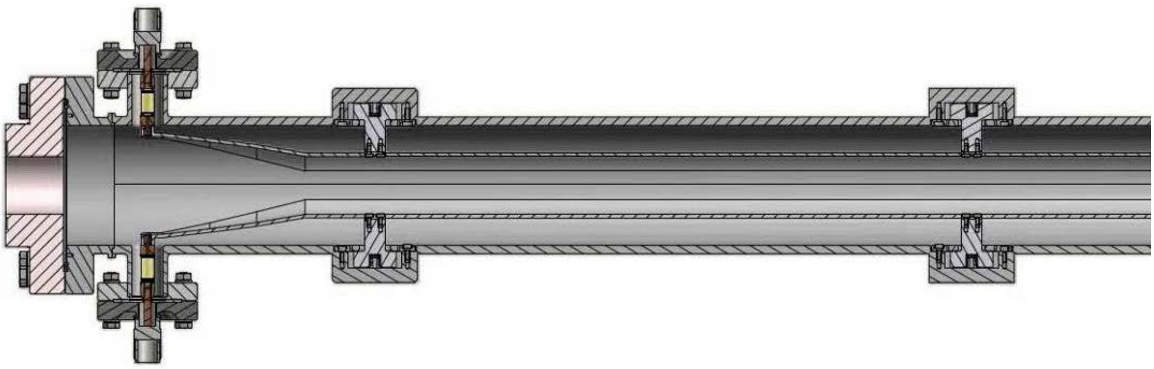

Figure 10: IBFB kicker magnet (only left end shown). High-power RF signals enter the kicker via HN-type connectors and RF feed-throughs that are connected to the two conductive strips via flexible bellows (brown/yellow). The strips are held in place via five ceramic spacers per strip (only two shown in the picture), where four of them can slide with respect to the outer vessel, thus avoiding mechanical stress of the ceramics and allowing vacuum bake-out.

The kicker vessel and strips are made from aluminum, which reduces the weight and allows easier and more cost-efficient machining. The vacuum flanges at both ends are made from stainless steel. Rather than using the expensive explosion-bonding technique to connect steel to aluminum, a special second gasket between the aluminum kicker body and steel end flange pieces is used. This cost-efficient solution has already been employed successfully for UHV beam pipes at other accelerator labs. Figure 11 shows the kicker prototype during production at the company that did the detailed mechanical design and production in collaboration with PSI.

Figure 12 shows the reflection at the kicker input in dB as a function of the drive signal frequency. The blue and pink curves are measurements of the first kicker prototype, the red curve is a simulation. The measured values meet the requirements, therefore no change of the RF design of the prototype kicker was necessary for the series version. Nevertheless, the mechanical design for the series version still has some minor improvements, e.g. to simplify the production and assembly.

Figure 11: IBFB kicker magnet during assembly. Left: Kicker magnet without end flanges. Middle: Sliding ceramic spacer (white) allows relative movement of strip and outer vessel. Right: Flexible RF feed-through at end of strip.

The quality of the vacuum in the first kicker prototype did not meet the E-XFEL requirements, where an RGA scan performed by PSI revealed a contamination with hydrocarbons. The contamination was caused by an accidental exposure of the kicker to grease at the end of the production process at the manufacturer COMEB. The kicker was then shipped back to COMEB who applied a bake-out procedure to clean the kicker. After bake-out, the pressure was close to E-XFEL requirements, but did still not quite meet them (see Figure 14) due to spikes in the mass spectrum above the mass 50 that should have been about 10 times smaller. Therefore COMEB agreed to fabricate a new kicker for PSI.

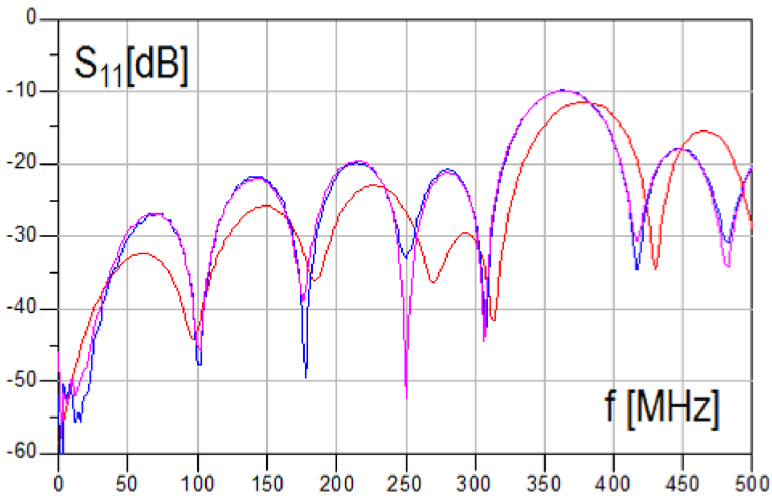

Figure 12: Measured reflection S_{11}[dB] (blue: port 1, pink: port 2) and simulated reflection (red) of IBFB prototype kicker vs. frequency.

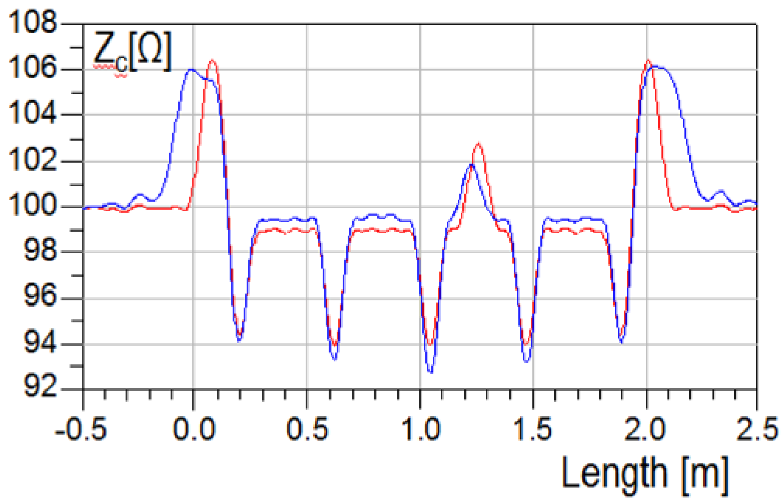

Figure 13: Differential impedance of the stripline kicker as function of the longitudinal coordinate (blue: measurement, red: simulation). The two positive peaks at the very left and right are caused by an impedance mismatch of the input and output port at both ends of the kicker. The five negative peaks in between are caused by the five ceramic pieces that hold the strips in position. One peak at 1.25m is caused by a flange for a vacuum pump in the kicker vessel.

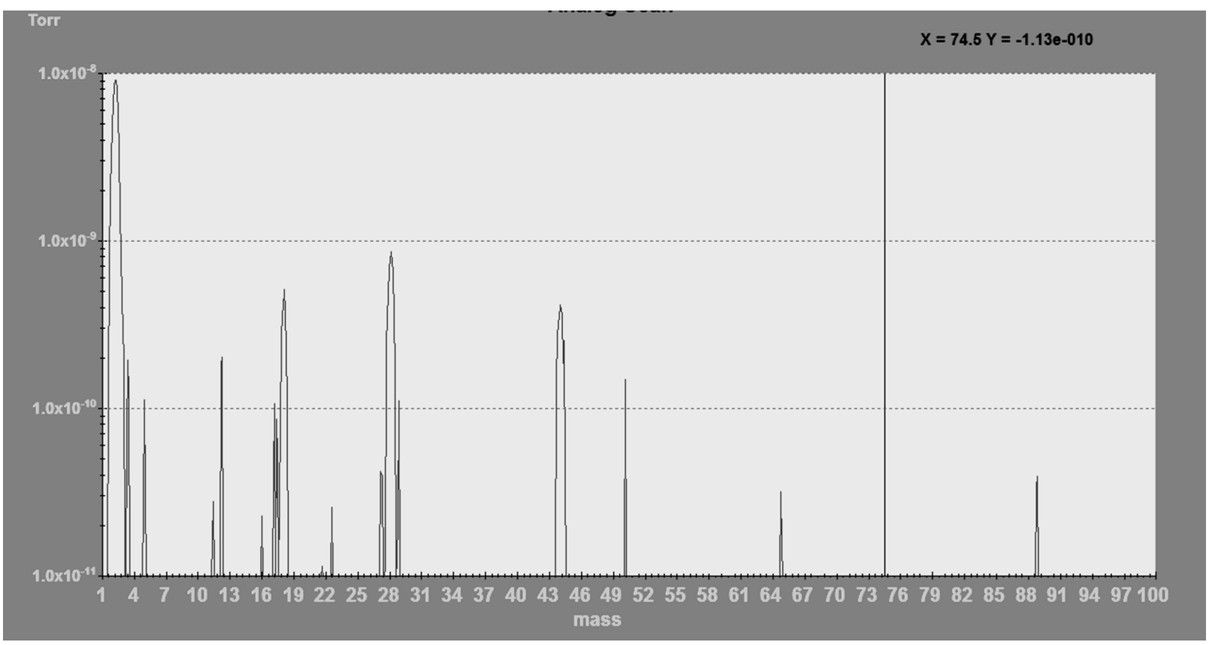

Figure 14: Residual gas spectrum of the IBFB kicker prototype, measured at COMEB after bake-out.

Although COMEB could easily have met the E-XFEL vacuum requirements for the series production of the IBFB kickers (the production step that caused the prototype vacuum contamination was eliminated for the series version anyway by simplifying the mechanical design and production steps), the series version was not produced by COMEB, but by the company CINEL, due to a slightly lower price, shorter delivery time, and better quality control procedures and related equipment. The construction drawing and specification according to which the kicker is being fabricated can be found in ref. [12] and [13].

3.5.2 RF Power Amplifiers

Since E-XFEL has bunch trains with up to ~600µs length and typically 10Hz (max. 25Hz) repetition rate, the IBFB kicker system may use pulsed amplifiers with ~1ms maximum pulse length, 25Hz max. repetition rate, and <3% duty cycle. Suitable commercially available kW-range solid-state power amplifiers that meet IBFB requirements are commonly used e.g. for MRI systems. After an extensive market study, PSI purchased two prototypes from the company TOMCO in 2012.

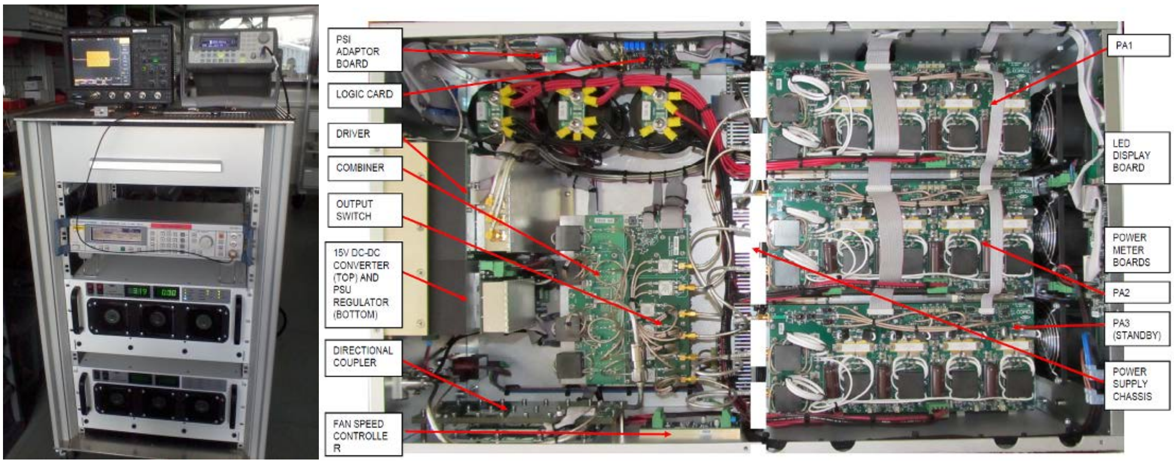

Figure 15: Left: Test rack with two IBFB prototype amplifiers (bottom) with test/measurement equipment (top). Right: Components inside the amplifier housing, with power amplifiers (right) and output combiner (left).

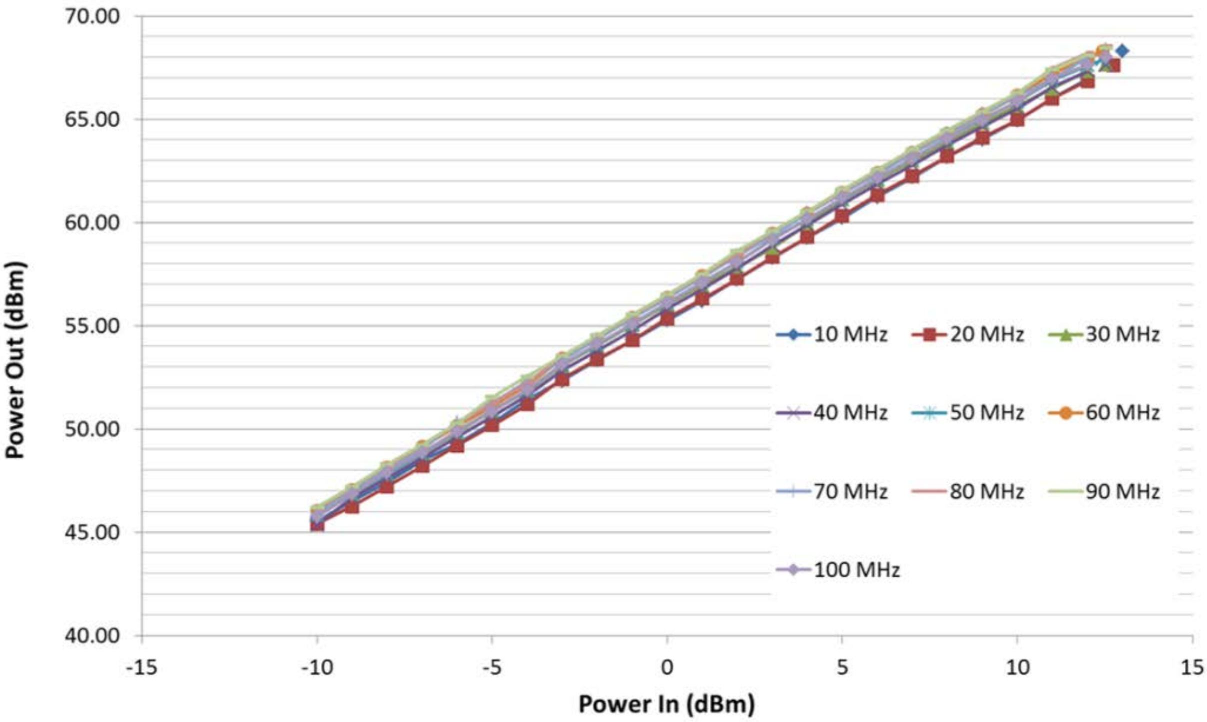

Figure 16: Output power vs. input power of the IBFB RF power amplifier, for different frequencies, showing very good linearity even above the specified maximum power of 3kW (=64.8dB).

Figure 15 shows the lab test setup at PSI as well as the components inside the housing of the amplifier. The prototypes purchased by PSI are based on an already existing commercially available amplifier model, but the PSI prototypes were modified in order to improve the MTBF. Modifications include a redundant main power supply as well as redundant amplifier sub-modules, where the amplifier can continue to operate even if one of the redundant components fails. PSI also signed an NDA with TOMCO in order to get the full documentation of the amplifier circuits and used components, thus allowing long-term maintenance and repair of the amplifiers by PSI or DESY personnel if necessary.

Figure 16 is a plot of output power vs. input power of the amplifier, measured at PSI for one of the purchased prototypes. Both the linearity and the maximum power are better than specified by PSI (see ref. [14]), as well as the droop (i.e. deviation of the power from an ideal flat top for constant input power) as shown in Figure 17.

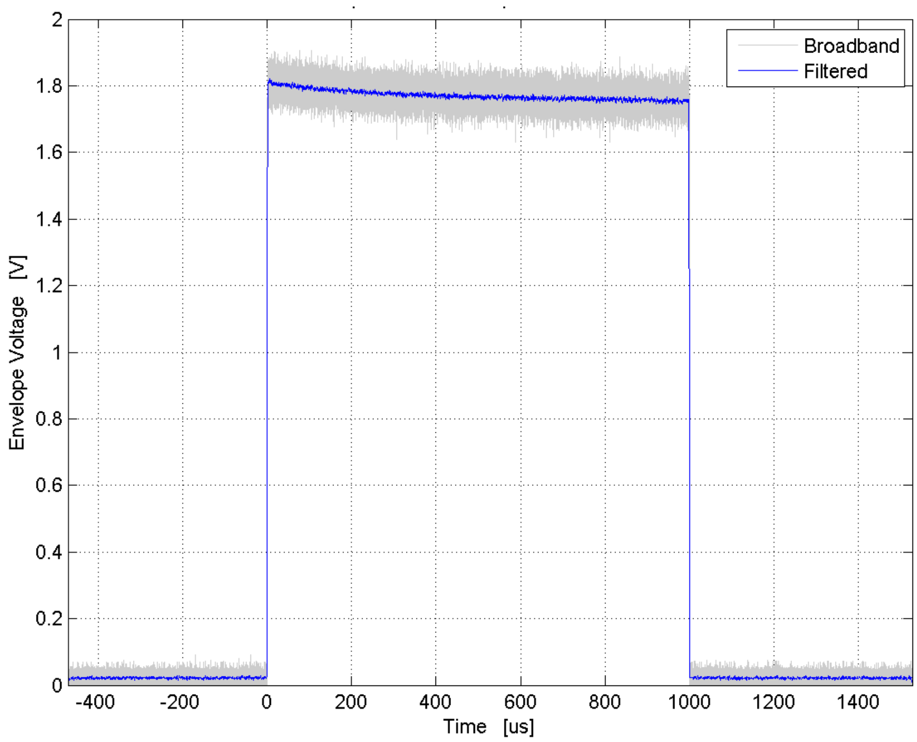

Figure 17: Output power of the IBFB power amplifier vs. time for an 1ms long drive pulse with constant amplitude. The droop (i.e. decrease of power during the pulse) is 2x better than specified (0.26 vs. 0.5dB).

Figure 18 shows the frequency response of the RF power amplifier measured by PSI, Figure 19 the output signal response to a rectangular input signal pulse. Obviously, such an output signal shape is not well suited for the IBFB, since significant ringing of the output signal causes undesired kicks of the following bunches (with 222ns minimal bunch spacing in E-XFEL).

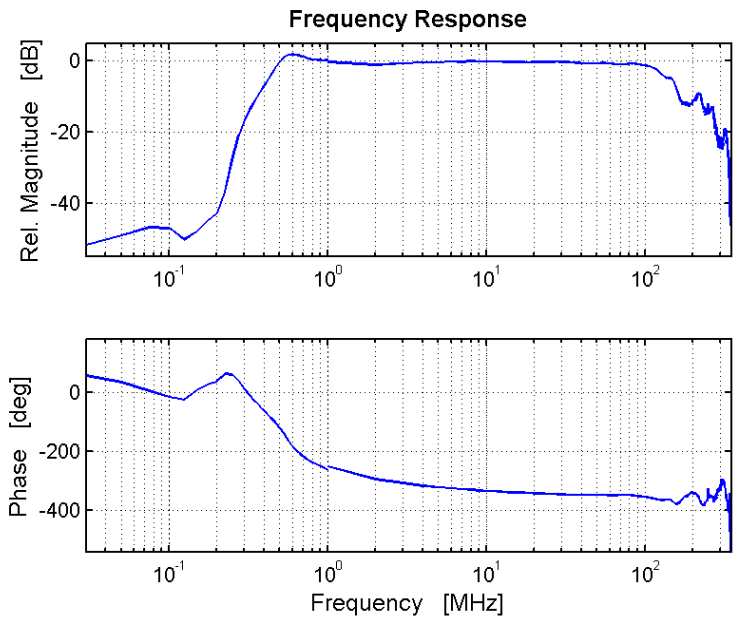

Figure 18: Frequency response of the IBFB power amplifier.

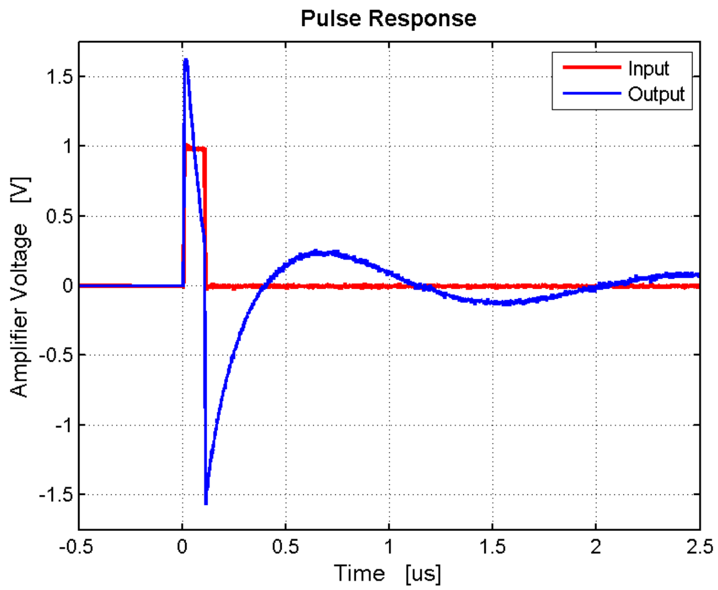

Figure 19: Output signal (blue) of the IBFB power amplifier for a rectangular input signal pulse (red), with undesired ringing after the pulse.

In Figure 20 a symmetric DC-free rectangular output pulse was generated by using a suitable input pulse. The output pulse form is already much better since the symmetry and lack of a DC component in the pulse avoids the long ringing that is caused by the frequency response roll-off at low frequencies shown in Figure 18. However, the resulting output pulse shown in Figure 20 still has a significant droop, thus causing an undesired beam arrival and DAC clock phase dependence of the kick angle.

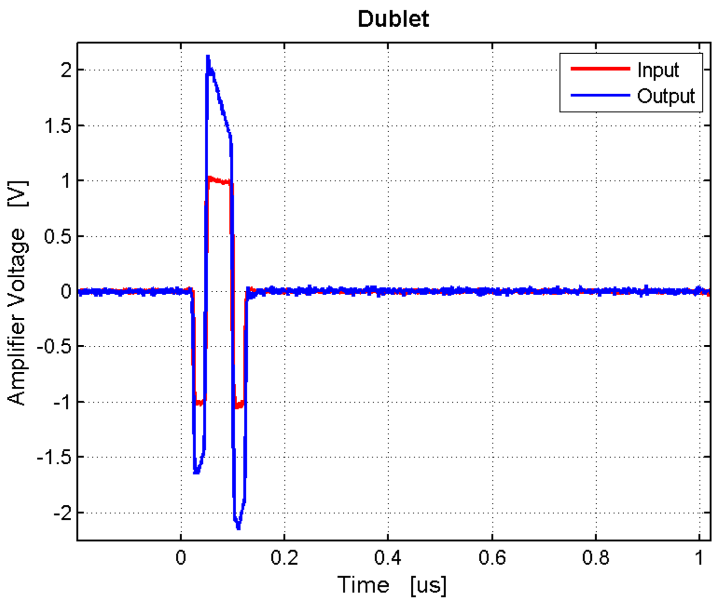

Figure 20: Output signal of the IBFB RF power amplifier for a rectangular DC-free symmetric input signal pulse ("doublet"). No more undesired ringing, but undesired slope ("droop") of output signal.

In Figure 21, we managed to generate an optimized output waveform with a nearly flat top, by introducing suitable slopes to the amplifier input waveform. By using such waveforms, the IBFB will be able to apply well-defined arbitrary kicks to each electron bunch which are insensitive against arrival time and phase drift, with minimal disturbances for the following bunches.

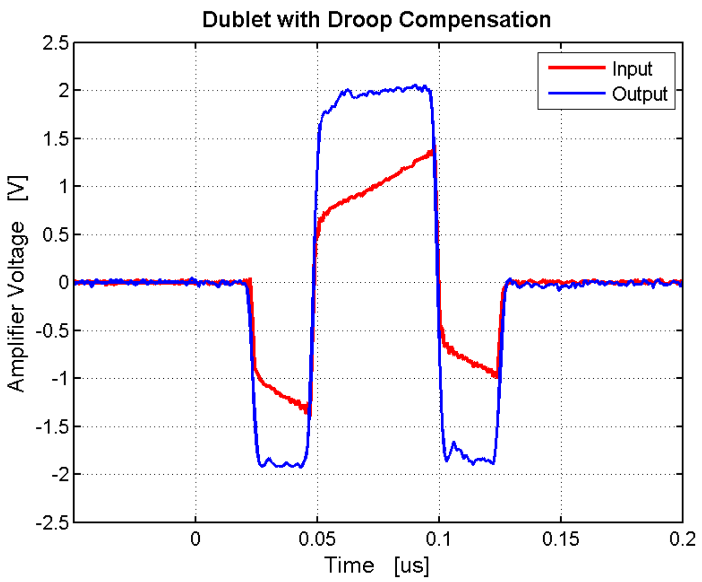

Figure 21: Optimization of output signal (nearly ideal flat top, no post-pulse ringing), by optimized input signal shape.

In order to achieve low latency, the IBFB uses two 4-channel DAC mezzanine board plugged onto an FPGA carrier board that performs the IBFB algorithm (left "Controller" board in Figure 6). The 4-channel DAC board uses 16-bit 500MSPS DACs that are able to generate the required drive waveforms for the IBFB RF power amplifiers with the necessary resolution, with a clock synthesis chip that can generate the sampling clock for each DAC from the machine reference clock, with individually programmable phase delay for each DAC to compensate asymmetries in cable delays, amplifier phase delays etc. The IBFB electronics (including FPGA boards, DAC mezzanines, kicker interface boards) has been produced and successfully tested with the IBFB power amplifiers in the lab. Since the control/status interface of the amplifier is a multi-pin connector with a larger number of single-ended IO signals that are not well suited for transmission over long cables in potentially noisy environments like particle accelerators, we designed an interface board that is attached to the amplifier and that allows to set and read the status IOs via a robust differential serial protocol, using shielded differential CAT6 cables for the connection to the IBFB core electronics that monitors and controls the amplifiers. This serial interface is also used to enable and disable the amplifier via its gate input with low and deterministic latency.

4 Interfaces to Other Work Packages

In order to be able to reach the nominal performance of the IBFB system, the tunnel infrastructure and other accelerator subsystems must fulfil the requirements defined in EDMS document D00000001767781, and the BPM pickups used by the IBFB must fulfill the requirements specified in EDMS document D00000002604261 table 5-3 and 5-4 (requirements to beam transfer line pickup) and table 5-6 (mechanical requirements for pickup type “IBFB cavity”).

The following sections summarize requirements from the IBFB to specific work packages and vice versa.

4.1 WP02 Low-Level RF (LLRF) and WP-18 Special Beam Diagnostics

Although there is no direct interface between IBFB and LLRF / Special Beam Diagnostics systems, some BPMs of WP17 (also delivered by PSI) will allow to transfer low-latency beam position and/or charge information to LLRF and special beam diagnostics systems. The protocol for the data transfer has been defined and implemented, and was successfully tested by common tests of PSI and DESY.

4.2 WP16 Lattice

The WP 16 leader has specified the requirements to the IBFB system in ref. [1]. As described in the previous sections, the chosen IBFB system architecture and technology is able to meet these requirements.

In order to optimize IBFB system costs and performance, PSI and DESY agreed on magnet lattice and beam optics modifications as described in section 2.5.

4.3 WP17 Standard Beam Diagnostics

The IBFB has interfaces to the BPM system that is part of WP17. The respective BPM electronics components of WP17 are also designed by PSI and thus naturally meet the interface requirements of the IBFB. Specifically, the standard BPM system and the IBFB use the same type of FPGA board and interface protocols to transfer BPM data to the IBFB core system.

4.4 WP-19 Warm Vacuum

All vacuum components of the IBFB are compliant to the European XFEL vacuum specifications (EDMS No D00000001425601,D,1,2 and D00000001975641).

WP19 (MVS Group) is responsible for the timely verification of this conformance and for timely reporting of any detected non-conformances to PSI. IBFB kickers have been produced, tested at PSI, and the design, vacuum quality and test protocols have been approved by WP19.

4.5 WP-28 Accelerator Control Systems

The IBFB electronics uses the same type of FPGA board like the BPM system, and the IBFB cavity BPM electronics is identical to the non-IBFB cavity BPM electronics (with the exception of additional input attenuators that allow to choose the position measurement range of each BPM). Thus, the control and timing system interface protocol for the IBFB will be identical to the BPM system. The necessary information has already been exchanged between PSI and WP-28/DESY, and the timing system and DOOCS control system interfaces for the BPM system have already been successfully implemented and tested by PSI and WP-28/DESY. For the IBFB core electronics, the only difference to the BPM system will be a different memory map layout, where a suitable DOOCS server can easily be developed by WP-28/DESY, based on the BPM system server.

4.6 WP-35 Radiation Safety

The European XFEL facility must provide sufficiently shielded installation locations for the IBFB and BPM electronics that allow the use of standard electronics components in order to reach the desired electronics lifetime of at least 20 years without radiation damage and with a negligible number of radiation-induced single event upsets or other radiation induced failures. The expected dose is expected not to exceed 0.5 Gy/a for gammas and 0.5 Gy/a for neutrons.

Like all E-XFEL BPMs, also the IBFB BPM electronics allows to monitor the radiation levels at the location of the BPM electronics, by plugging the standard radiation monitor FMC module (designed by DESY) onto a suitable interface connector of the IBFB BPM electronics. Readout of the data will be provided via the DOOCS interface of the BPM electronics. The IBFB core system electronics is located directly next to the BPM electronics and thus requires no additional radiation monitor FMC.

4.7 WP-32 Survey and Alignment

The IBFB kicker vacuum vessel has fiducial marks that have been reviewed and approved by WP-32.

5 Administrative Topics

5.1 Quality Management

Before developing the E-XFEL IBFB systems (including the BPM electronics for the IBFB), PSI has already collected extensive experience with the production of similar systems for various accelerators. For the IBFB, PSI did a pre-selection of manufacturers based on their technical capabilities and experience with the production of comparable systems in the past. Before choosing the companies for the series production of the different system components, prototype and pre-series versions are produced, and their quality is analyzed with suitable methods, including thermal stress tests of printed circuit boards, optical and X-ray inspection of soldering joints and components, as well as short- and long-term electrical and functional tests. Detailed specifications and production instructions have been elaborated together with the companies in order to ensure a reliable and reproducible production process, where potential problems are analyzed and solved as early as possible in the development and production process to ensure easy manufacturability of all systems with high production yields. After assembling the respective systems, functional and burn-in tests of complete systems are performed and adequately documented at PSI before shipment to DESY/E-XFEL. Furthermore, long-term tests of prototypes and pre-series versions at PSI and DESY accelerators are performed where possible in order to ensure the required quality and functionality of hardware, embedded firmware and software, as well as the documentation needed to integrate the PSI in-kind contribution into the other accelerator subsystems. The various properties of mechanical components like kicker magnets are specified in detail and then measured during and after production to ensure compliance with all specifications.

5.2 Component Tracking

All relevant IBFB system components, including PCBs, have serial numbers that allow to identify each component. Serial numbers are optically visible on the components, but can also be read out digitally from the electronics systems via the DOOCS control system, thus allowing remote tracking of component locations and movements in the tunnel (e.g. in case of replacement of faulty components by spares). The status of the different subsystem components is contained in a dedicated database that allows to get an overview of the location and status of all components. The database also has the capability of automatic updates based on information retrieved remotely from the operational systems in the accelerator.

5.3 Risk Management

Regular collaboration meetings of the relevant experts from PSI and DESY/E-XFEL are organized to discuss the elaborated solutions and make sure the design meets the requirements and specifications that are also elaborated and discussed during these meetings. By applying suitable quality management methods as described above, the risk of components that do not meet the specifications and requirements is minimized as far as reasonably possible. The risk of schedule delays during production is also minimized by choosing manufacturers not just according to their quality, but also their ability to guarantee timely production with minimal risk of unexpected delays. Moreover, by qualifying more than one potential manufacturer, the risk of delays due to a manufacturer is minimized.

Within the development team, the risk of delays is mitigated by choosing the staff competences and by distributing the work and review processes such that an unexpected long-term absence or leave of a person can be mitigated as far as possible by redistributing the work within the team until a successor has been hired or the work force has otherwise been compensated.

5.4 Safety Analysis

The vacuum components of the IBFB are vessels with flanged, braised or soldered connections. All materials used are compatible with E-XFEL UHV requirements. The IBFB kickers use ceramics as insulator for feedthroughs and stripline holders and thus are ROHS compliant. The vessels are from aluminum, the outer vacuum flanges to the beam pipe from stainless steel. The IBFB kickers have no movable parts, except of manual alignment possibilities and very small thermal expansion during vacuum bake-out. Therefore, there is no resulting danger for maintenance personnel. All cables will be halogen free. Heavy and stiff long distance cables will end on patch panels on both sides. Therefore, stress relief is provided minimizing the risk of damaging UHV feedthroughs and electronics boards.

The electronics is compliant to standards defined in the IKCA. The IBFB BPM and feedback electronics uses a CE certified commercially available main power supply to convert the 230V AC mains to 12V and 5V DC voltages that are used by the different electronics modules. The 230V main power supply is installed inside the BPM electronics unit in a way that eliminates any risk of electrical shock. Fans inside the BPM electronics will be protected against accidental touching. The IBFB BPM and feedback electronics designed by PSI are ROHS compliant. The IBFB power amplifiers are commercial systems compliant to standard safety requirements (IEC 61010:2001).

5.5 Project Schedule

The schedule for the IBFB components is as follows:

- 20.11.2015: IBFB kicker magnets tested and delivered to DESY.
- 15.04.2016: All other IBFB system hardware delivered to DESY.
- 30.04.2016: All IBFB systems installed and commissioned without beam.
- 01.06.2016: Swiss In-kind contribution to E-XFEL IBFB accepted and accredited by E-XFEL/DESY.

6 References

[1] Technical Annex 16-2 to the E-XFEL Accelerator Construction Agreement: “Transverse Intra Bunch Train Feedback”.

[2] B. Keil et al., “Design Status of the European XFEL Transverse Intra Bunch Train Feedback”, Proc. IBIC’12, Tsukuba, Japan, 2012.

[3] W. Decking, “IBFB Requirements, Part 1”, Talk at E-XFEL BPM and IBFB Collaboration Meeting, PSI, Villigen, Switzerland, 14.-15.1.2013.

[4] E-XFEL component list version 8.4.5, January 26, 2015.

[5] “Performance Specifications for the European XFEL BPM System”, EDMS document D00000002604261.

[6] V. Balandin, W. Decking, N. Golubeva , “XFEL: TLD beam line KS kickers and IBFB BPMI location”, Internal DESY report, July 5, 2013.

[7] M. Stadler et al., “Low-Q Cavity BPM Electronics for E-XFEL, FLASH-II and SwissFEL”, Proc. IBIC’14, Monterey, CA, USA, 2014.

[8] E-XFEL BPM System Conceptual Design Report, EDMS no. ...

[9] B. Keil et al., “Beam-Based Calibration and Performance Optimization of Cavity BPMs for SwissFEL, E-XFEL and FLASH2”, Proc. IBIC’14, Monterey, CA, USA, 2014.

[10] D. Lipka et al., “FLASH Undulator BPM Commissioning and Beam Characterization Results”, Proc. IBIC’14, Monterey, CA, USA, 2014.

[11] W. Koprek, “Feedback Network Concept and Protocol”, Talk at E-XFEL BPM and IBFB collaboration workshop, Villigen, PSI, January 14-15, 2013, slide 12.

[12] F. Marcellini et al., “E-XFEL IBFB Kicker Requirements”, EDMS document ...

[13] IBFB kicker construction drawing. EDMS no. ...

[14] F. Marcellini et al., “Specification of the E-XFEL IBFB RF Power Amplifier”, EDMS document ...