INTRA BUNCH TRAIN FEEDBACK FOR THE EUROPEAN X-FEL

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Abstract

After joining the preparatory phase of the European X-FEL project, the Paul Scherrer Institut agreed in taking over responsibility for electron beam stabilization by developing a fast intra bunch train feedback (IBFB) system, which will be tested in its prototype version at the FLASH facility at DESY. The IBFB will make use of the long bunch trains provided by the superconducting drive accelerators of FLASH as well as the European X-FEL allowing to damp beam motions in a frequency range of a few kHz up to several hundreds of kHz applying modern control algorithms in a feedback loop. The FPGA-based, digital data processing and the low latency time (preferably < 200 ns) permit the elimination of long range (from bunch train to bunch train) and ultra fast (bunch by bunch) repetitive beam movements by adaptive feed forwards. In this paper, we will introduce the IBFB design concept and report on first test measurements with newly designed stripline beam position monitors for the FLASH facility.

BEAM STABILITY REQUIREMENTS

First start-to-end simulations of the European X-FEL [1] indicate that transverse beam stability in the order of one tenth of the rms beam sizes ($\sigma/10$) is required to permit stable SASE operation at the target wavelength of 1 Å and to allow scientific experiments at the various user end stations. This range of beam stability is regularly achieved in today's 3rd generation synchrotron light sources within a frequency band of 10^{-4} Hz up to several hundreds of Hz using global or local beam feedback systems, which actively stabilize the cw-like bunch patterns of the storage rings [2]. Considering transverse rms beam sizes of < 30 µm at the location of the undulators, the same micron-level beam stability needs to be achieved for a SASE-based user facility like the European X-FEL for the specific time structure of the superconducting drive accelerator, which delivers up to 650 µs long bunch trains with bunch distances of 200 ns at a 10 Hz repetition rate. Under these conditions, the frequency range from a few Hz up to some kHz, where most of the beam position disturbances are generated by noise sources like e.g. ground motions, cooling water and Helium flow, power supply jitter, switching magnets, RF transients and jitter, photo-cathode laser jitter and related beam current variations as well as long range wakefields, remains inaccessible for regular closed orbit feedback systems. Their range of application will be limited to the stabilization of drifts and low frequency beam motions up to a few Hz. A fast feedback system like the IBFB, however, with a low latency time (preferably < 200 ns), can make use of the long macro pulses of the European X-FEL with up to 3250 consecutive bunches to damp beam motions in a frequency range from a few Hz to several hundreds of kHz by applying modern control algorithms in a feedback loop. Furthermore, both long range (from bunch train to bunch train) and ultra fast (bunch-by-bunch) repetitive beam movements can be eliminated by additional adaptive feed forwards. Table 1 summarizes the specifications for the transverse prototype IBFB system, which will be tested at the FLASH facility at DESY and for the final version, which will be implemented behind the main accelerator of the European X-FEL.

Table 1: Transverse IBFB Specifications

Trans. IBFB Specifications	**VUV-FEL**	**X-FEL**
bunch-by-bunch stability - at location of IBFB - along undulators	< σ/10 5 - 15 µm < 5µm	< σ/10 3 - 10 µm < 3µm
max. beam position offset * - at location of the pick-ups	< 10 · σ < 1.5 mm	10 · σ < 1 mm
bunch-by-bunch resolution	≤ 2 µm	≤ 1 µm
system latency	< 1000 ns	< 200 ns

* this defines the maximum range of beam offset from bunch train to bunch train, where the IBFB will still be able to apply corrections to the specified values

TOPOLOGY AND DESIGN CONCEPT

One of the most challenging requirements for the intra bunch train feedback system is the achievement of an ultra fast response time of < 200 ns for bunch-by-bunch corrections at the European X-FEL. By placing two pick-ups (BPM-1 and BPM-2) for horizontal and vertical beam position measurements upstream of the electromagnetic correction kickers, the IBFB topology (see Fig. 1) uses the circumstance that the pick-up signals in the cables and the electron bunches in the beam pipe travel in parallel, thus reducing the system latency time. In addition, the noise of the system may also be reduced, since the upstream BPMs will only measure the uncorrected beam.

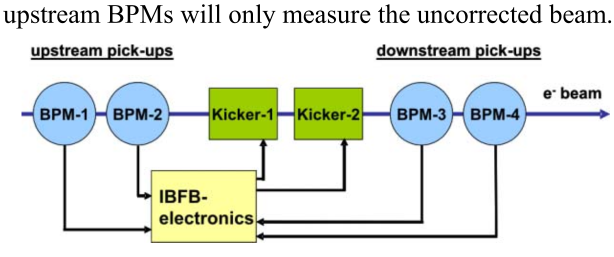

Figure 1: Topology of the IBFB for the European X-FEL

Instant verification of the corrected beam positions can be achieved by the two downstream BPMs (BPM-3 and BPM-4). Thus, static and dynamic effects like kicker scaling errors or inaccuracies of the optics model can be detected and eliminated by dynamic adaptation of the applied feedback model. Moreover, it will be possible to predict long range beam movements from bunch train to bunch train and correct repetitive disturbances through slow adaptive feed forwards using look-up tables. While the BPM pick-up design will be optimized for highest resolution with well matched input signals for the RF front end, the digital part of the system (see Fig. 2) will follow a highly flexible and modular approach by using FPGA-based technology for calculating fast corrections and a set of DSPs for model-based adaptive feed forwards. In this way, it will be possible to constantly adapt the feedback model in the data processing part of the IBFB to the actual operating conditions of the real accelerator. Interconnections with other complementary feedbacks and accelerator components can be achieved through multi Giga-bit fiber optic links based on the Rocket I/O standard providing the possibility of sharing all relevant information for beam stabilization on a real-time basis.

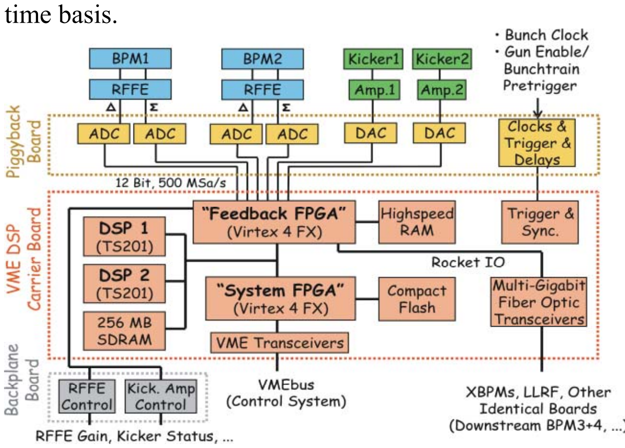

Figure 2: IBFB digital hardware concept

Beam-based information from the IBFB system could thus be used to improve e.g. low level RF stability, gun laser and bunch compressor settings. Likewise, real time data exchange between different electron beam and photon beam position diagnostics may allow efficient cascading of feedbacks and permit the adaptation of feedback parameters for stable SASE operation.

STATUS OF IBFB SUB-COMPONENTS

The signal level of matched striplines will not be sufficient for the anticipated micron resolution of the IBFB. A resonant stripline [3] uses a shifted coupler position near the shorted end of the stripline, resulting in a resonance effect and a corresponding decrease of the device's bandwidth. Simultaneously the maximum transfer impedance is increased leading to a higher output signal level. The resonance frequency of 1.625 GHz (20 times the FLASH clock frequency of 81.25 MHz) provides a rather compact mechanical design, taking the limited space available for installation at the FLASH facility into account. The quality factor of the resonator is approximately 30, providing a good compromise between the increase of output signal and the rms pulse length (ringing time) of 7 ns for a single bunch. This is long enough to allow simplified processing in the RF front end, but also short enough to achieve a low IBFB system latency and to avoid signal cross talk of adjacent bunches. The figure below shows the calculated time domain response as well as a 3-D mechanical model of the resonant strip-line for the VUV-FEL.

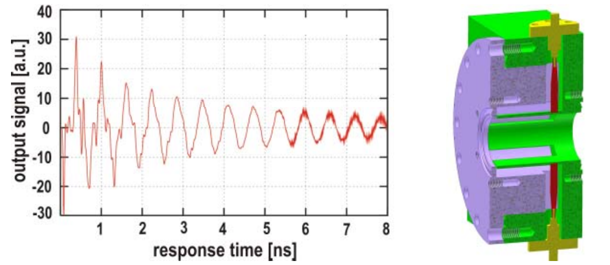

Figure 3: Left: time domain response function of the resonant stripline for the FLASH facility. Right: 3D mechanical drawing of the BPM pick-up.

Cavity BPM

In view of the more stringent requirements for the final IBFB system at the European X-FEL, a cavity BPM is presently under design as well. At an operating frequency of 4.3875 GHz (54 times the FLASH clock frequency) and with a loaded quality factor of 240, this kind of pick-up provides an ultra high beam position sensitivity of 100 µV/µm and can thus achieve an ultimate bunch-by-bunch position resolution of < 1 µm for the nominal European X-FEL bunch charge of 1 nC. Moreover, its immediate signal response and its relatively fast signal decay time of 100 ns is well suited for a low latency feedback system like the IBFB. This specific pick-up design incorporates new concepts for cavity tuning, coupling, quality factor control and matching. Fig. 4 shows an electromagnetic simulation of the cavity BPM indicating the optimized coupling of the beam position sensitive TM_{11} dipole mode to the out-coupling waveguides, while the coupling of the bunch charge sensitive TM_{01} monopole mode to the waveguides is well suppressed by the design.

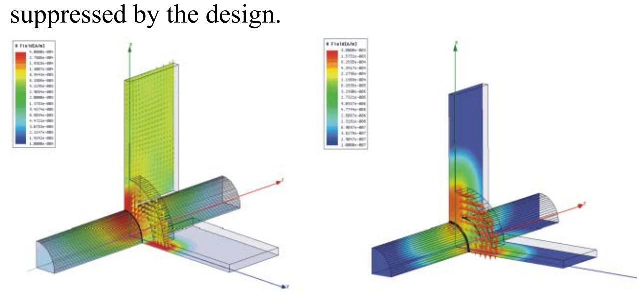

Figure 4: Left: magnetic coupling of the position sensitive TM_{11} dipole mode for the European X-FEL cavity BPM. Right: suppressed coupling of charge sensitive TM_{01} monopole mode.

RF Front End for Stripline BPM

The RF front end is the analog input stage of the IBFB electronics, in which the exponentially decaying signals from the resonant stripline pickup (see Fig. 3) are preconditioned, down-converted to the base band, and filtered for subsequent digitization. The magnitude of the stripline pickup monopole mode signal (1.610 GHz) is proportional to the bunch charge, while the pickup dipole mode signal (1.647 GHz) is proportional to the beam position times the bunch charge. The dipole mode signal may be obtained by taking the difference (Δ) of the signals from two opposing electrodes, whereas the monopole mode signal may be obtained by taking the sum over all electrode signals. The monopole mode signal can be approximated by taking the sum (Σ) of the signals from two opposing electrodes only, thereby neglecting the quadrupole mode. The transverse beam positions are contained in the ratio of difference to sum (Δ/Σ) signals. The main difficulty for the RF front end is to accurately detect the very weak Δ-signal in the presence of the strong Σ-signal (-75 dBc for 1 µm). The presently designed RF front end generates the Δ and Σ signals from the pickup electrode signals by using 3dB 180° hybrids independently for the horizontal and the vertical planes. Signal scaling to adapt for varying beam currents is performed by variable gain amplifiers. The conversion of the Δ and Σ RF signals to the base band is accomplished by mixing with a local oscillator signal, which is derived from the accelerator reference clock of 81.25 MHz. Large beam offsets can be eliminated by a programmable offset stage at the Δ output of the RF front end. This ensures that a high position resolution can be maintained even if the beam is far off from the centre. To satisfy the low latency requirement and to enable single bunch measurements, the base band Δ and Σ signals are flat-top pulses of roughly 15 ns duration. The pulse shape is formed by the pickup envelope response and the ringing filters in front of the 180° hybrids. The topology of the RF front end is shown in Fig. 5.

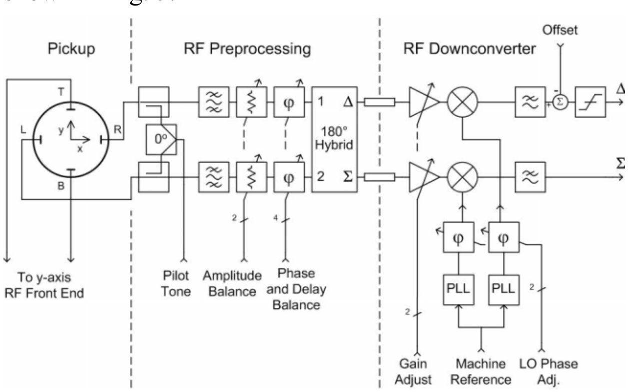

Figure 5: Proposed BPM RF front end (x-axis only).

The pickup's sensitivity to the beam position, or the difference between signals from opposing pickup electrodes, is only 0.002 dB / µm. Amplitude, phase, and delay imbalances of the pickup signal cables, the ringing filters, and the 180° hybrids lead to heavy distortion of the desired flat-top pulses, and to signal errors that are comparable in magnitude to several tens of micrometers of beam offset. Therefore, to achieve the aspired position resolution of 1 µm, the above mentioned imbalances as well as temperature, aging, and radiation induced component variations must be continuously compensated. This is done by means of amplitude, phase, and delay tuning elements in the RF paths preceding the 180° hybrids, and an automatic tuning mechanism employing a sinusoidal RF pilot. Tuning is performed during the idle times between bunch trains. The effect of signal degradation due to imbalances in the pickup cables, ringing filter, and 180° hybrid is illustrated in Fig 6. In the more realistic non-ideal case, the imbalances considered are −0.01 dB in amplitude, 0.02° in phase, and a delay imbalance corresponding to a cable length difference of 0.5 mm. The resulting flat-top RF and IF pulses are heavily distorted due to the strong monopole mode signal leaking into the Δ channel.

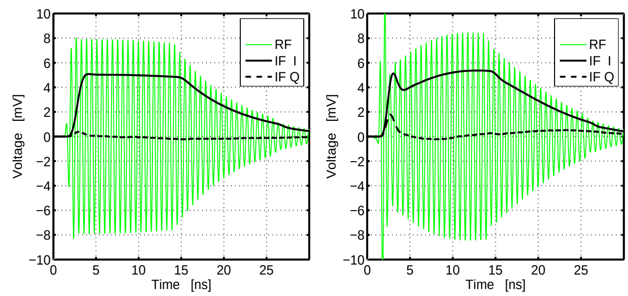

Figure 6: Simulated RF and IF signals of the Δ channel for a beam offset of 10 µm. Left: Ideal case without mismatches. Right: Non-ideal case with mismatches.

It needs to be noted that the imbalances listed for the non-ideal case are already extremely small, and cannot be achieved by precise manufacturing alone. Continuous control of the amplitude and phase tuners is therefore necessary.

OUTLOOK

After freezing the design of the digital hardware concept (see Fig. 2), the ADC / DAC part and the IBFB carrier board are presently under design. A pre-series of the stripline pick-ups has been manufactured at DESY and will be characterized in combination with the RF front end on a laboratory test-bench at PSI. Three IBFB measurement systems will be installed during the September shut down in SLS booster synchrotron, which provides in its single bunch mode similar beam parameters as the FLASH facility (1 nC bunches with 1 µs booster revolution time). A first complete IBFB prototype system is expected for testing in spring 2007.

REFERENCES

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