# STATUS OF THE EUROPEAN XFEL TRANSVERSE INTRA BUNCH TRAIN FEEDBACK SYSTEM

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*Abstract*

The European XFEL (E-XFEL) will have a transverse intra bunch train feedback system (IBFB) that is capable of correcting the beam position of individual bunches in the ~650us long bunch train, with a minimal bunch spacing of 222ns. The IBFB measures the beam positions with high-resolution cavity BPMs, and corrects the position of each bunch via stripline kicker magnets driven by class AB solid-state RF power amplifiers. The production of the IBFB BPM pickups is finished, and a pre-series version of the low-latency BPM electronics, including firmware and software, has been successfully tested with beam. After successful production and tests of prototypes, the series production of IBFB kicker magnets and RF power amplifiers is in progress. The IBFB feedback electronics hardware development is mainly finished, while firmware and software development is still ongoing. This report summarizes the latest design status and test results of the different IBFB system components.

## IBFB SYSTEM OVERVIEW

Figure 1 shows the layout of the IBFB. The core of the system is located just upstream of the E-XFEL beam distribution kicker system and downstream of the collimation area. Four cavity BPMs (CBPMs) downstream of the IBFB ("downstream BPMs") are used to implement a fast feedback loop, where two vertical and two horizontal stripline kickers can apply individual kicks to each bunch in order to correct the beam trajectory at the downstream BPMs to the desired position. A feedback loop latency of ~1µs is expected to be sufficient to damp all relevant perturbations.

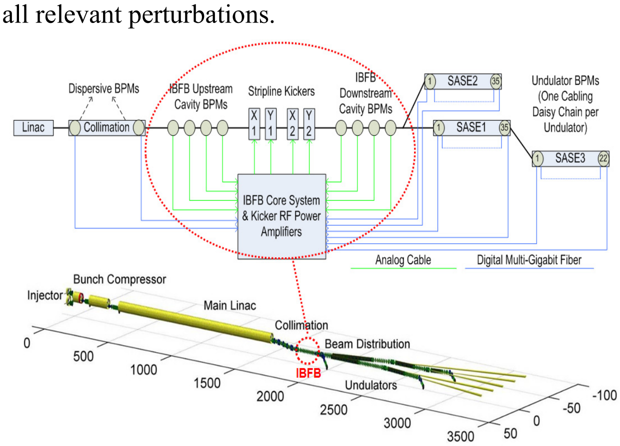


Figure 1: IBFB System.

The necessary kick amplitudes are calculated by an FPGA board that receives the beam position data from the CBPM electronics via fast fiber optic links. The FPGA board applies the kicks via two digital-to-analog converter (DAC) mezzanines with four 16-bit 500MSPS DACs each. In order to apply corrective kicks to each bunch, the DAC mezzanines generate suitable output waveforms that are amplified by pulsed solid-state RF power amplifiers driving the stripline kicker magnets. Each stripline kicker has two amplifiers for driving its two opposite strips in push-pull mode, i.e. with opposite voltages.

Four CBPMs upstream of the kickers ("upstream BPMs") are used by the IBFB to predict the beam position at the downstream BPMs from the upstream BPM readings and DAC set values. This enables the IBFB e.g. to detect failures or drifts of the RF power amplifiers, variations of the beam energy, or to check and adjust the IBFB timing.

The IBFB also receives the data of a dispersive CBPM in the collimator section (for beam energy measurement and kicker scaling factor adjustment) as well as data from all undulator CBPMs via digital multi-gigabit fiber optic links. In order to reduce the amount of cables, the undulator CBPMs of each of the three initial undulators (SASE1, SASE2, SASE3) are connected in a daisy chain, where only the first and last CBPM electronics of each chain is connected to the IBFB core system via single-mode fiber optic cables up to 1km length. When the first bunches of the E-XFEL bunch train (with up to 650µs train length and down to 222ns bunch spacing) arrive at the IBFB, it first corrects the trajectory using only downstream BPM data. As soon as the first undulator CBPM data is received by the IBFB, it fine-tunes the beam trajectory (if necessary), such that the following bunches reach the desired beam position in the undulators. Due to the long distance from IBFB to undulator CBPMs, the resulting latency of this correction is 4 to 10µs, depending on undulator and BPM location. However, the beam trajectory perturbations that occur between IBFB and undulators are expected to be either low-frequent (e.g. quadrupole magnet vibrations) or predictable, therefore it is sufficient to do this fine-tuning of the undulator beam trajectory once at the beginning of the bunch train, and then with a low correction bandwidth for the remaining part of the bunch train, in combination with the above mentioned fast (low-latency) feedback loop based on BPMs near the IBFB. In addition to this feedback-based correction, the IBFB will also perform an

* This work was partially funded by the Swiss State Secretariat for Education, Research and Innovation SERI.



ISBN 978-3-95450-176-2

adaptive feed-forward correction of the beam positions, by predicting perturbations that are reproducible or varying slowly from bunch train to bunch train, such that the feedback loop only has to correct the unpredictable perturbations.

## BEAM POSITION MONITORS

The performance requirements to the IBFB BPMs are identical to the requirements of the undulator BPMs [2], i.e. <1µm resolution and weekly drift at 100-1000pC and ±0.5mm range, with the exception that the latency of the BPM electronics must be so small that an overall feedback loop latency of ~1µs can be achieved. It should be noted that the electronics of all E-XFEL cavity BPMs will have the required low latency, thus allowing to use also cavity BPMs in undulators and transfer lines for intra bunch train corrections.

Figure 2: E-XFEL cavity BPM electronics (MBU = Modular BPM electronics), with two cavity BPM RF front-ends (RFFEs, top) and FPGA carrier board with two ADC mezzanines (bottom) [2].

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 CBPMs of the IBFB core system. All these CBPMs have basically the same electronics, firmware and software. However, since the 40.5mm CBPMs have a position cavity sensitivity (in units of V/mm/nC) and Q factor comparable to the 10mm CBPMs, their position cavity signal may be up to four times higher for the same beam charge when the beam is close to the aperture limit. Therefore the non-IBFB CBPMs have additional attenuators at their RF front-end (RFFE) inputs, where the necessary attenuation to protect the RFFE from overvoltage is still low enough to reach their specified single-bunch position RMS noise of <10µm RMS for a measurement range of ±10mm. The 40.5mm BPMs used by the IBFB core system for the ultra-fast feedback loop require a resolution <1µm RMS for a desired range of ±1mm. Therefore their RFFEs do not have additional attenuators, but a special input protection circuit that clips the input signals when they reach a certain voltage. The IBFB CBPMs also determine 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.

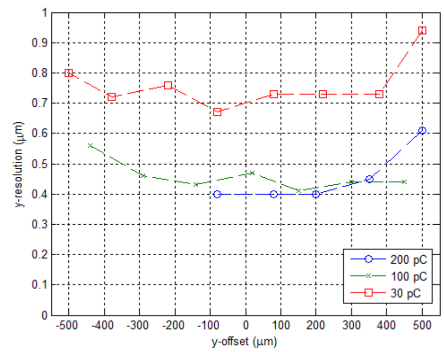


Figure 3: Position resolution (RMS noise) of E-XFEL cavity BPM, measured by correlating data of several BPMs, for different bunch charges [3].

## KICKERS

E-XFEL has a variety of random and reproducible beam trajectory perturbation sources, where a conservative estimate predicts worse-case beam trajectory perturbations of about ±100µm (assuming 20m beta function) [1]. For 17.5GeV beam energy, this corresponds to kick angles of ±3.5µrad (for the same beta function at the kickers). Although the beta functions and betatron phase advance at the locations of the kickers have been optimized to reduce the required kick strength, we still decided to install a baseline kicker system that provides about ±4µrad kick angle at 17.5GeV. In order to reach this value, we designed 2.2m long (flange-to-flange) stripline kickers with 2m effective strip length (for a 40.5mm aperture beam pipe), driven by pulsed RF power amplifiers with a specified linear power of >2kW.

### *Stripline Kickers*

Figure 4 shows a longitudinal cut through an IBFB kicker. 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 N-type connectors that are attached to the opposing strips via flexible bellows (shown in Figure 5, right photo) to allow relative movement of strips and outer vessel due to thermal expansion and contraction.

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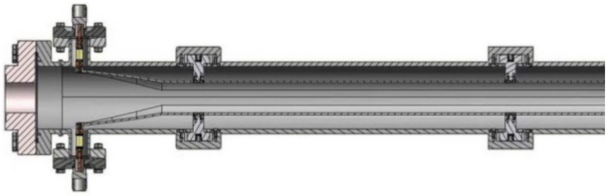

Figure 4: IBFB stripline kicker cross section (only 1/3rd of the kicker shown).

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 4), where the center spacer has a fixed position, while the other four can slide longitudinally (see Figure 5, middle photo). This avoids mechanical stress and risk of cracks of the ceramics during assembly and 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 had already been employed successfully for UHV beam pipes at other accelerator labs. Figure 5 shows a kicker prototype during production at the company.

Figure 5: 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.

Figure 6 shows the reflection at the kicker input in dB as a function of the drive signal frequency. Figure 7 shows the impedance of the stripline kicker as a function of the longitudinal coordinate (blue: measurement, red: simulation). The positive peaks at the very left and right are caused by a small 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. The positive peak at 1.25m is caused by a flange for a vacuum pump in the kicker vessel. Figure 8 shows one of the four IBFB series version kickers during the vacuum acceptance test at PSI. The produced kickers passed all acceptance tests and are now ready for installation in the E-XFEL tunnel.

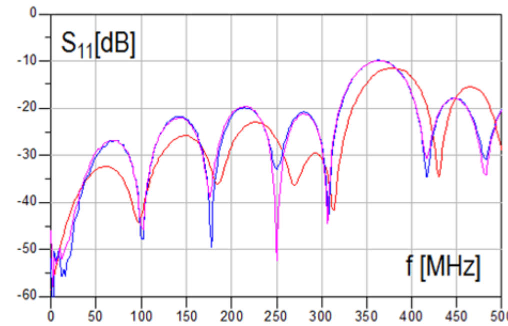


Figure 6: Measured reflection S11[dB] (blue: port 1, pink: port 2) and simulated reflection (red) of IBFB prototype kicker vs. frequency.

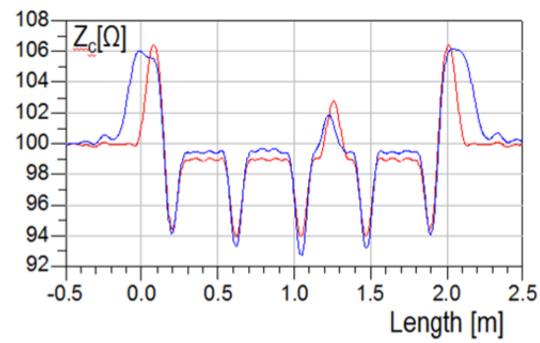


Figure 7: Kicker impedance as function of longitudinal position (red: simulation, blue: measurement).

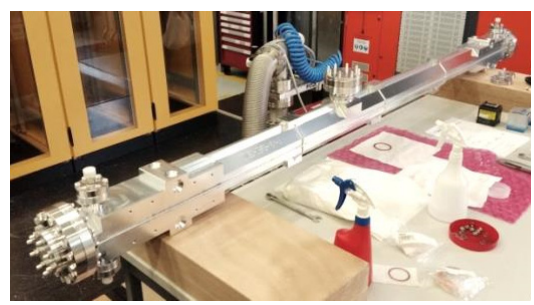

Figure 8: IBFB kicker magnet during vacuum acceptance test at PSI.

## RF POWER AMPLIFIERS

Since E-XFEL has bunch trains with up to ~650µs length and typically 10Hz (max. 25Hz) repetition rate, the IBFB kicker system uses 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 the IBFB requirements are commonly used e.g. for radar and MRI systems. After an extensive market study, PSI purchased two prototypes from the company TOMCO in 2012. These prototypes are based on an already existing commercially available amplifier model, but were modified by the manufacturer 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.



ISBN 978-3-95450-176-2

Figure 9: Two IBFB RF Power Amplifiers.

Figure 10 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 (we measured 6kW, compared to a specification of 2kW linear and 3kW saturated), as well as the droop (i.e. deviation of the power from an ideal flat top for constant input power) shown in Figure 11. The measured amplifier latency is <35ns, compared to a specification of <50ns. Figure 12 shows the frequency response of the amplifier measured at PSI, Figure 13 the output signal response to a rectangular input signal pulse. Obviously, such an output signal 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).

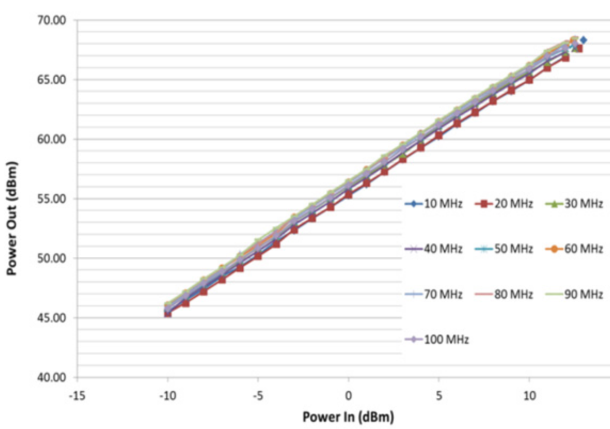


Figure 10: Output power vs. input power of the IBFB RF power amplifier, for different frequencies.

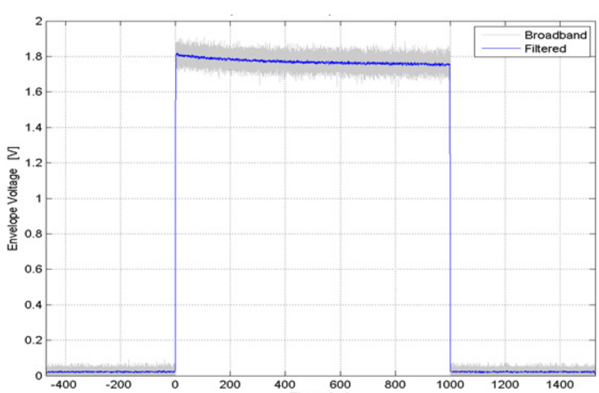


Figure 11: Output voltage of the IBFB power amplifier vs. time for constant input power.

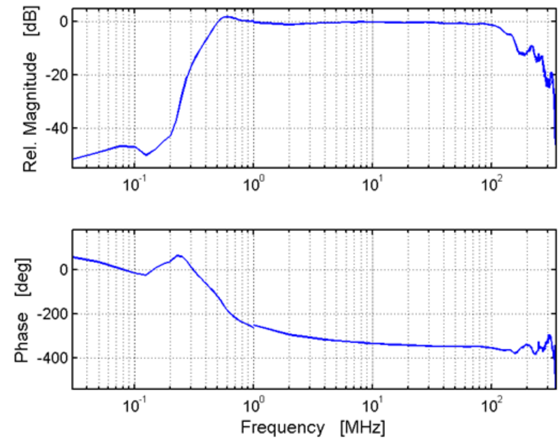


Figure 12: Frequency response of the IBFB power amplifier.

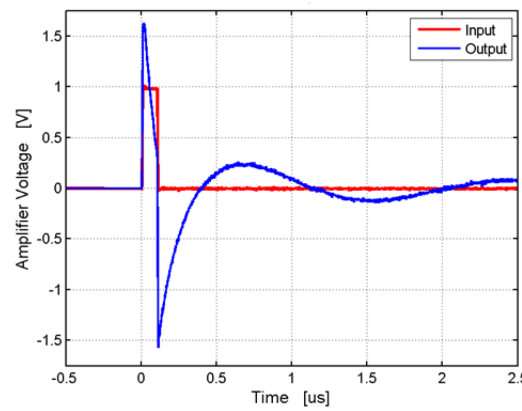


Figure 13: Output signal (blue) of the IBFB power amplifier for a rectangular input signal pulse (red), with undesired ringing after the pulse.

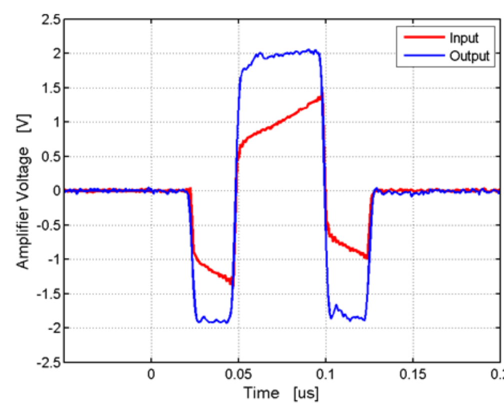


Figure 14: Optimization of output signal (nearly ideal flat top, no post-pulse ringing), by optimized input signal shape.

As shown in Figure 14, we managed to generate a practically optimal output waveform with a nearly flat top, by introducing suitable slopes a DC-free symmetric amplifier input waveform. By using such waveforms, the IBFB will be able to apply well-defined arbitrary kicks to each electron bunch, where the kick angle is insensitive against arrival time and phase drift, with minimal disturbances for the following bunches.

ISBN 978-3-95450-176-2

## FEEDBACK ELECTRONICS

Figure 15 shows the IBFB system core electronics, consisting of two FPGA boards ("GPAC" = Generic PSI ADC Carrier) also used by the E-XFEL BPM system. The FPGA board on the left side of Figure 15 performs the actual feedback and feed-forward algorithm (using a combination of FPGA firmware and software in the embedded processor of the FPGA). The board applies the calculated corrective kicks via two DAC mezzanines with four 16-bit 500MSPS DAC channels each. The DACs 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). The power amplifiers also have a fast gate input that is controlled by dedicated (coaxial) output signals of the DAC mezzanine boards, thus allowing the IBFB core electronics to enable and disable the amplifiers beam-synchronously. The FPGA board on the right side of Figure 15 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. The FPGA board also has a digital interface to the kicker amplifiers that allows e.g. to monitor their health status or enable/disable 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.

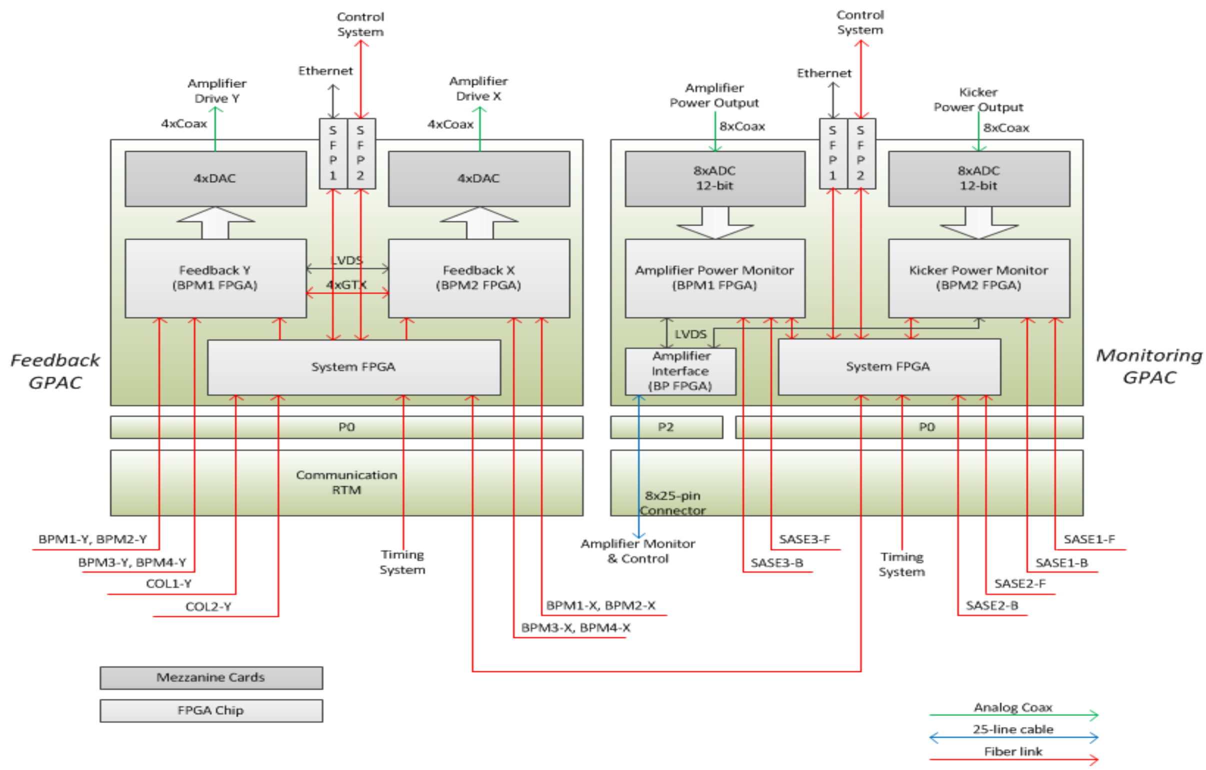


Figure 15: IBFB Feedback Electronics.

## SUMMARY AND OUTLOOK

The production of the IBFB kickers and other hardware components is nearly finished, with installation in the E-XFEL tunnel in Q1/2016. The IBFB will be ready for beam operation mid-2016, including software/firmware where the implementation is still ongoing. First beam at the IBFB is expected in the 2nd half of 2016. Although the IBFB kicker system allows to correct the presently expected maximum trajectory perturbations, space for additional four kicker magnets is reserved, thus allowing to double the kick angle if necessary. In addition to beam trajectory correction, the IBFB can also be used for other purposes, e.g. 2-color FEL operation, where the IBFB applies a controlled kick to each bunch, such that it lases only in the first or only in the 2nd half of the undulator line (using a suitable DC kicker in the middle of the line), where both halves are tuned to different wavelengths.

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ISBN 978-3-95450-176-2