DRIFT CALIBRATION TECHNIQUES FOR FUTURE FELS

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Abstract

Future FELs (Free-Electron-Lasers) requires a precise detection of the cavity field in the injector section with a resolution of much less than 0.01^o in phase and 0.01% in amplitude for a cavity operation frequency at 1.3GHz. Long-term stable SASE (Self Amplified Spontaneous Emission) at FLASH (Free-electron LASer in Hamburg) operation mainly suffers from injector accelerator components and the stability of the reference distribution. Especially thermal instabilities of the distributed cavity field detectors, probe pickup cables and their mechanical vibrations influence the energy stability dramatically on a scale of 0.1%, a scale which is 10 times worse than required. To eliminate the long-term amplitude and phase changes of the field detectors of the order of $0.2\%/^o$C and $0.2^o/^o$C, we made an out-of-loop measurement of the field detector performance by injecting a reference signal prior to the arrival of the cavity field signal. This enabled pulse-to-pulse calibration which compensated for the drifts of the field detectors. By applying the injected calibration method, we demonstrated a dramatic phase and amplitude stability improvement from the ps-range to the 0.008^o (peak-to-peak) range in phase and 0.02% (peak-to-peak) in amplitude; this represents an improvement in drifts by a factor of about 100. The injected calibration was successfully employed during FLASH operation.

INTRODUCTION

Future FELs (Free-Electron-Lasers) require a precise detection of the cavity field in the injector section with a resolution of much less than 0.01^o in phase and 0.01% in amplitude for a cavity operation at 1.3GHz.

Long-term stable and robust SASE operation mainly suffers from the instability of the reference distribution and accelerator components of the injector section.

Field detectors before the first bunch compressor are especially critical. When a high-gain cavity field regulation is used, the field detector drifts are pushed directly onto the beam. Consequently a reduction of the drifts of the cavity field detection is indispensable for robust and stable SASE operation.

Thermal instabilities of the distributed cavity field detectors, probe pickup cables and their mechanical vibrations influence the energy stability on a scale of 0.1%, which is 10 times worse than desired. To reduce the cavity field detector amplitude and phase drifts we tested calibration schemes, which involved injecting the reference prior to the arrival to the cavity pickup signals and using that reference to calibrate the field detectors. These methods are known as reference injection and reference tracking.

ROBUST MACHINE OPERATION

For having a long-term stable and robust SASE operation of the future FELs, we propose, as depicted in Fig. 1 several active and passive stabilization mechanism.

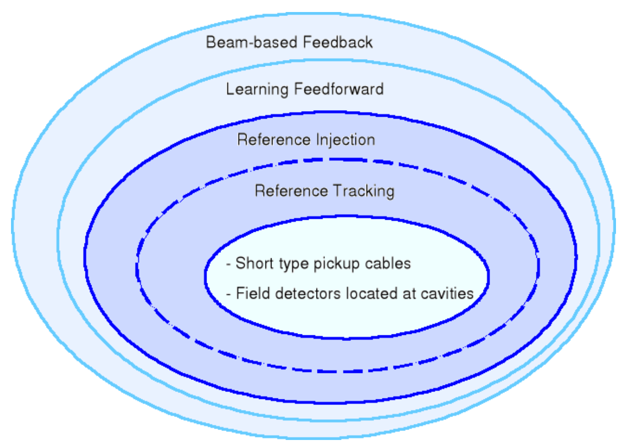

Figure 1: Active and passive stabilization mechanism for a long-term stable SASE operation.

First of all, to reduce the long-term instability of the cavity field detection, the detectors have to be located near to the cavity pickup using short low drift cables. To prevent mechanical vibrations, cables have to be fixed properly and N-type connectors are recommended for high frequency signals. Furthermore, to suppress correlated amplitude and phase noise sources of the field detectors, the so called reference tracking has to be applied. The reference injection, effectively suppresses long-term drifts of the field detectors.

Another important stabilization mechanism is the adaptive feedforward or learning feedforward, which compensates iteratively all deterministic imperfections of the actuator chain of the field regulation [2]. To reduce the fast bunch arrival-time jitter within the beam pulse a beam-based, intra-bunch-train feedback has to be applied. In addition, remaining long-term arrival-time changes caused by several accelerator components can be finally compensated [4].

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THERMAL STABILIZATION

Extensive tests in accelerators and laboratories showed typical drifts of the field detectors of about $0.2^{\circ}/^{\circ}\mathrm{C}$ in phase and $0.2\%/^{\circ}\mathrm{C}$ in amplitude for active and passive analog front-ends [3]. Even using the non-IQ sampling scheme, a spatial distributed field detector consists of several temperature dependent components (mixers, cables, board substrat material, filters, dividers, amplifiers and a complex local signal-generation), which requires a temperature stability of $0.05^{\circ}\mathrm{C}$ (peak-to-peak) for the injector sections, respectively $0.5^{\circ}\mathrm{C}$ (peak-to-peak) for main linac sections. This would require a cost-intensive, sophisticated climatisation and temperature stabilization.

REFERENCE TRACKING

The idea of the reference tracking method is to track the phase of the accelerator reference by using an additional field detector channel, which measures correlated phase drifts of the local frequency generation. This can be used to correct the measured phases of the other field detector channels. Reference tracking requires nearly identical field detector channels. Measurements in the accelerator environment showed a wide amplitude and phase spread for different detector channels. In addition, the phase and amplitude drift of the field detector is temperature and a strong humidity dependent.

REFERENCE INJECTION

The method of reference injection injects the accelerator's reference signal during the beam pause, providing a calibration phase for the complete field detector chain.

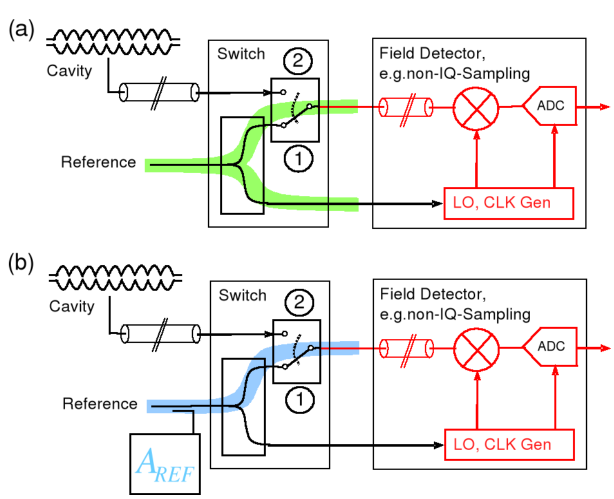

Figure 2: (a) The reference injection eliminates the complete field detector phase drifts by subtrating the phase during the beam pause (state 1) and the measured phase (state 2). (b) The field detector amplitude drift is reduced by tracking the amplitude reference with a long-term stable amplitude detector.

As depicted in Fig. 2a, after subtracting the measured phase (state 2) during the beam pulse from the previously calibrated phase (state 1), long-term drifts from the field detection can be efficiently eliminated. According to Fig. 2b, the field amplitude is tracked and compensated similarly by a specialized long-term stable high frequency amplitude detector ($\mathrm{A_{REF}}$). Contrary to reference tracking, this method supports non-identical receiver channels and relax the drift requirements for the field detectors dramatically.

MEASUREMENT RESULTS

Performance in Laboratory

Fig. 3 shows the laboratory performance of the reference injection for a measurement time of 60 hours.

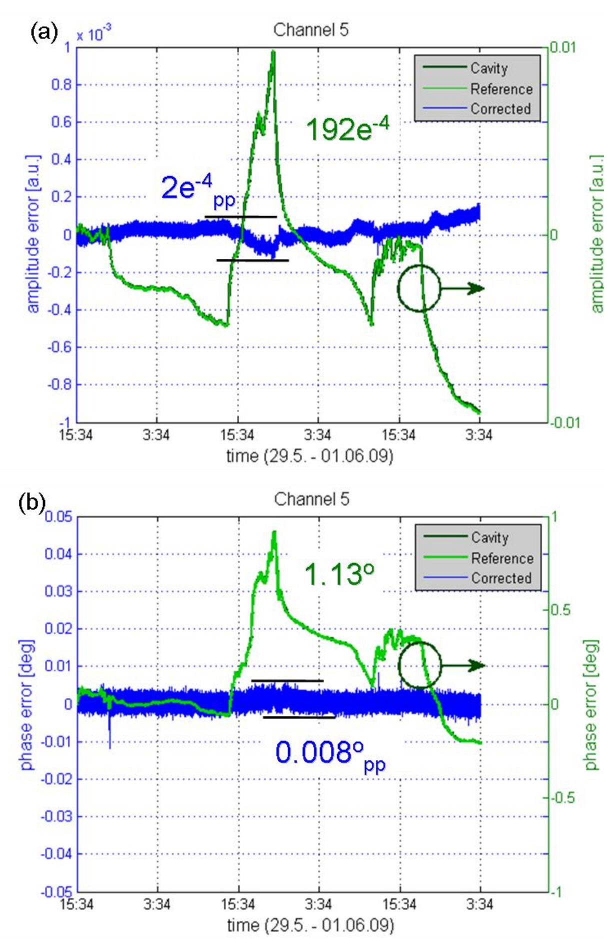

Figure 3: Measured (a) amplitude and (b) phase deviation for the injected corrected signal (blue marked) and uncorrected (green marked) over 60 hours.

Instead of biasing the setup with a cavity signal, as shown in Fig. 2, for the performance evaluation in laboratory the reference signal itself is used. During the measuring time of 60 hours, the uncorrected measured phase drift of the detection was 1.92% in amplitude and 1.13° in phase (peak to peak), while the reference injected corrected amplitude and phase drift are effciently reduced to 0.02% and 0.008° (peak-to-peak) by a factor of about 100 from the ps-range to the 3.5fs (rms) range.

Performance at FLASH

The results of the drift calibration tests at FLASH are shown in Fig. 5. According to measurement principle of the reference injection, Fig. 4 shows the field detector input combining the reference signal during state 1 and the cavity field during the measuring state 2.

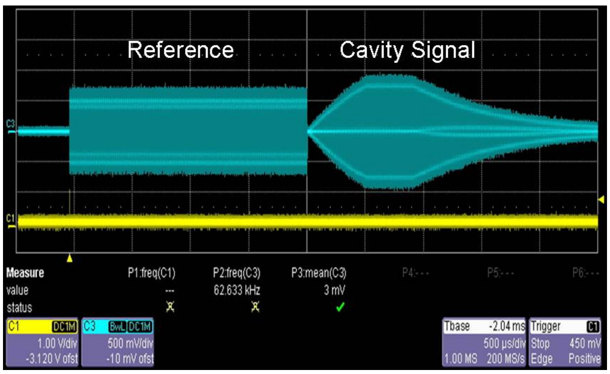

Figure 4: Screen shot of the field detector input combining the reference and cavity signal.

The performance test of the reference injection in the accelerator is performed by using a vector sum control with eight cavity signals at the acceleration module (ACC1) located in the injector section.

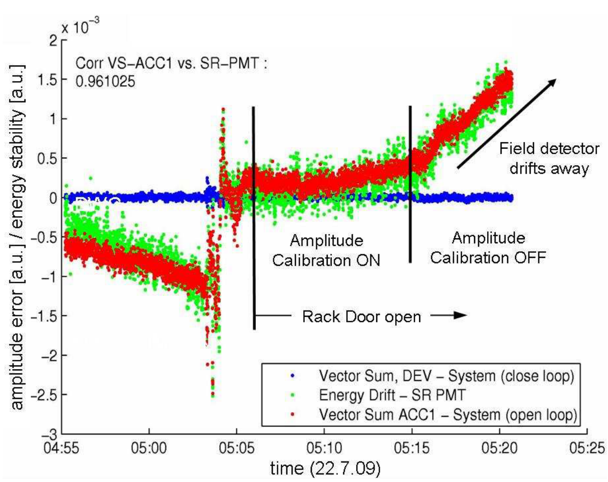

Figure 5: Measured beam energy and cavity field amplitude drift. The reference injection improves the long-term beam energy stability.

To verify the improvements of the drift compensation the energy drift of the beam is measured using a synchrotron radiation camera at the first bunch compressor (BC2). To elimiate actuator noise, one field regulation operates in close loop for an optimal pulse-to-pulse beam stability. A second field regulation serves as drift watchdog to monitor the field stability outside the loop [1].

According to Fig. 5, the measured beam energy drift is 96% correlated to the measured amplitude drift of the cavity field vector sum, which is in accordance with the noise correlation presented elsewhere [1]. This clearly demonstrates that the field detectors are the main source of long-term and short-term beam arrival time fluctuations.

As shown in Fig. 5, the temperature of the field detectors are perturbated by simply opening the door of a thermally stabilized rack. As long as the amplitude calibration of the reference injection method is on the measured field amplitude and the beam energy is constant. As expected, when switching the compensation off, both signals drift by 0.15%. Due to some practical limitations, namely uncompensated components like attenuators, inner rack cables and the fact, that the amplitude reference detection was not optimized, the stability improvements are not expected to be good as the laboratory tests.

SUMMARY AND OUTLOOK

The method of reference injection for phase and amplitude calibration to eliminate long-term drifts of the field detector has been successfully tested for the first time at FLASH. By using the two device under test method, we determine the amplitude drift of the field detector as the main source of the beam energy, respectively SASE long-term instability. By applying the method of reference injection, the field detector long-term stability is improved by a factor of about 100 from the ps-range to the 3.5fs (rms) range and 0.02% for the amplitude. To avoid imperfections of the setup, an integrated microwave design of the calibration unit has to be realized for future FELs.

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