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BEAM-TRANSIENT-BASED LLRF VOLTAGE SIGNAL CALIBRATION FOR THE EUROPEAN XFEL

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Abstract

The European XFEL linac consists of 25 superconducting RF (SRF) stations. With the exception of the first station which is part of the injector, each station comprises 32 1.3-GHz SRF TESLA cavities, driven by a single 10-MW klystron. A sophisticated state-of-the-art low-level RF (LLRF) system maintains the complex vector sum of each RF station. Monitoring and maintaining the calibration of the cavity electric field (gradient) probe signals has proven critical in achieving the maximum energy performance and availability of the SRF linac. Since there are no dedicated diagnostics for cross-checking calibration of the LLRF system, a procedure has been implemented based on simultaneously measuring the beam transient in open-loop operation of all cavities. Based on methods originally developed at FLASH, the European XFEL procedure makes use of automation and the XFEL LLRF DAQ system to provide a robust and relatively fast (minutes) way of extracting the transient data, and is now routinely scheduled once per week. In this paper, we will report on the background, implementation, analysis methods, typical results, and their subsequent application for machine operation.

BEAM TRANSIENT

The beam transient voltage V_t as a function of beam-on time t for an on-resonance cavity can be expressed as

$$V_t(t) = -\frac{Q_b}{\Delta t_b} R_L\left(1 - e^{-t/\tau}\right)$$
$$\approx -\tfrac{1}{2} Q_b \left(\frac{r}{Q}\right) \omega_0 \frac{t}{\Delta t_b} \quad \text{for } t \ll \tau, \qquad (1)$$

were Q_b is the single bunch charge; Δt_b is the bunch spacing; R_L is the loaded shunt impedance; and ω_0 and τ are the cavity frequency and time constant respectively. The basic assumption is that all cavities generate the identical transient response (for the same beam pulse). For short beam pulses of ~50 μs (<< τ = 1130 μs) the only variations arise from differences in (r/Q) (=1030 Ω) or cavity frequency (f_0 = 1.3 GHz) which are considered negligible. Taking typical beam values of Q_b = 250 pC and Δt_b = 0.45 μs (2.25 MHz repetition rate), equation (1) gives ~1 kV transient amplitude per bunch, or ~100 kV for a one-hundred-bunch beam pulse, which represents a ~0.5% of the typical accelerating gradient in a cavity (~20 MV). Although the RF stability is in general better than this at XFEL [1-3], resolving the transient generally requires averaging over many pulses.

ALGORITHM

The approach dates back to a similar method developed for FLASH [4]. The beam transient is measured with the nominal accelerating RF field present, which provides a calibration point at the typical working values. Furthermore, since no changes are need to the operational state of the accelerator taking the measurements becomes very quick and can be done within a few minutes during nominal operations. The transient itself is measured using the difference between beam-on and beam-off measurements. Figure 1 shows an example of the typical raw data.

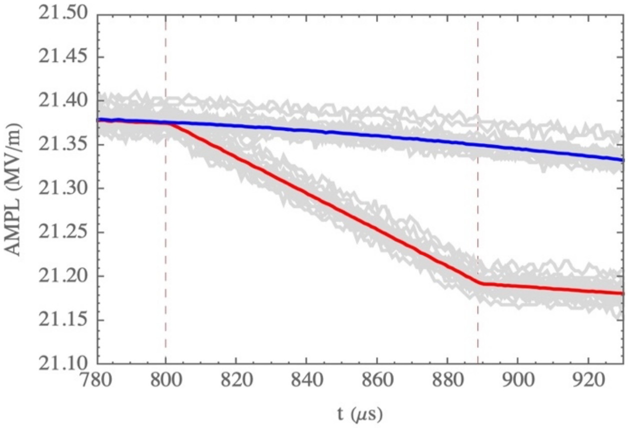

Figure 1: Example of cavity voltage amplitude data used to calculate the transient. Blue: averaged beam off. Red: averaged beam on. Grey: individual single-pulse measurements. The dashed lines indicate the period of the beam pulse, which in XFEL starts at t = 800 μs.

All the measurements are taken open-loop (i.e. no feedback control). The beam is turned on and off with a period of ~5 seconds (50 pulses) for total time of approximately one minute (see Fig. 2). The on and off data are interleaved to reduce the influence of slow drifts in the applied RF which could influence the difference calculation. During the beam-on data, the beam energy at the end of the accelerator is also recorded; this additional data can be used for absolute calibration. The RF signals are automatically record by the XFEL DAQ system, which runs continuously.

The analysis of the data is performed entirely in the complex plane. The raw cavity voltage waveforms are extracted from the DAQ system as amplitude and phase and converted into complex numbers. The beam-on and beam-off data are first averaged and then subtracted to provide the required beam transient. The transient is reported after 100 bunches (t = 845 μs). Despite the care taken to avoid the influence of drifts in the RF, experience has shown that some offset between the on and off datasets is inevitable. Hence a small correction is applied to the transient measurement based on the difference between the signals at the start of the beam pulse (t = 800 μs, see Fig. 3). Care has been taken to make sure that the correlation between the real and imaginary parts is taken into account in propagating the (statistical) errors (the complex errors are dealt with in a non-standard way, with real and imaginary parts treated as independent variables).

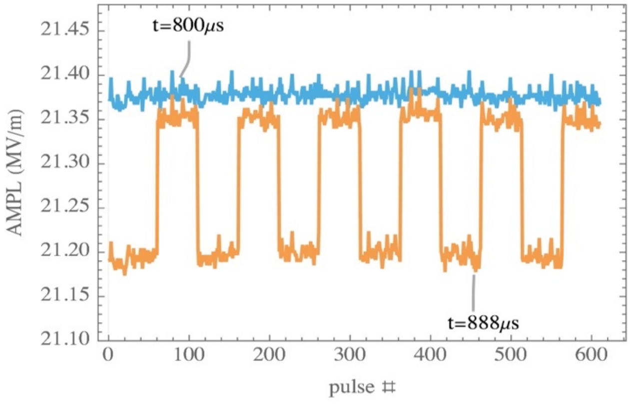

Figure 2: Cavity voltage sample points (amplitude) measured during data acquisition. (blue) t = 800 µs, showing the stability of the RF; (orange) t = 880 µs (after 200 bunches) showing the impact of the beam transient during beam-on.

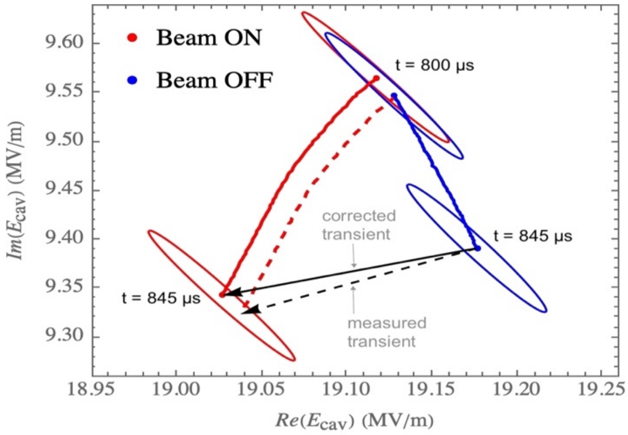

Figure 3: Estimation of beam transient from measured (complex) voltages. The ellipses indicated the statistical uncertainty from the averaging (1 std. err.). The small difference (drift) at the t = 800 µs point is used to correct the transient difference between the t = 845 µs points.

AUTOMATION

In order to reduce the invasive time required by the procedure, both the data acquisition and subsequent analysis have been completely automated. The prerequisite for data acquisition is a stable beam with at least 100 bunches (typically 200), with good loss-free transmission to the high-energy beam dumps. A MATLAB© [5] script supported by a user interface then: (1) opens the LLRF loop of all stations; (2) Turns the beam ON for approximately 5 seconds and for each pulse records the beam energy profiles from the downstream spectrometer; (3) turns the beam off and waits ~5 seconds; (4) repeats (2) and (3) a further five times; (5) closes the loop on all the LLRF systems and re-establishes normal operations. The entire process takes approximately 2 minutes and can be run any time by the operators.

A second MATLAB© script then extracts the cavity voltage waveforms for the time period for each of the 24 RF stations (768 cavities) as well as the beam charge information from a single beam toroid at the end of the linac. The analysis and reporting tool (written using Mathematica© [6]) then analyses the raw LLRF signals. The analysis tool generates a comprehensive report which is then available for inspection. The data extraction and analysis require approximately 25 minutes, but is entirely in parallel with operations.

EXAMPLE RESULTS

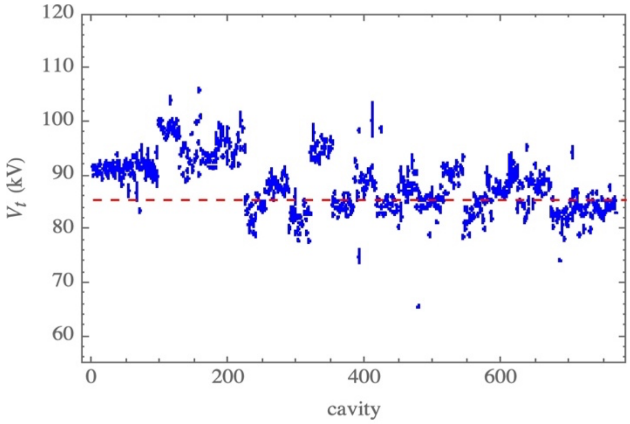

Figure 4: Example transient amplitude measurements for all cavities in the XFEL linac. The dashed line is the mean. Error bars represent ±1 std. err. (statistical).

The beam transient amplitudes for a typical dataset is shown in Fig. 4, and the corresponding transient phase is shown in Fig. 5. Table 1 gives the relevant parameters for the dataset.

Table 1: Parameters for Example Dataset

Beam energy	17.77	GeV
Bunch charge	253±1	pC
Number of bunches	100	
Beam pulse length	44.4	µs
ON / OFF pulses	211/300	

Assuming identical and on resonance cavities, the transient amplitude induced by the beam should be equal, assuming the cavity voltage probes are all correctly calibrated (or at least correctly cross-calibrated). Figure 4 shows an average amplitude of 88 kV with a ±10 kV RMS spread, which is significantly larger than the typical statistical error on the individual amplitudes (±0.6 kV std. err.) Some fraction of this spread is almost certainly calibration errors. However, systematic errors which account for ~5% of the error. In general, these values are monitored for stability over time but are not corrected, unless very large errors are reported.

Large excursions in transient phase are however acted upon. All phases should ideally be zero. The typical statistical error on the transient is approximately ±2° (std. err.) but can be as large as ±5°. Figure 5 shows two interesting features, one around cavity number 210 and another at 550. These correspond to RF stations A9 and A19 respectively. Closer examination of A9 indicated a phase offset between the LLRF manager and subordinate systems of 45°. A19 was later shown to have an overall phase rotation error of 18°. Both were corrected.

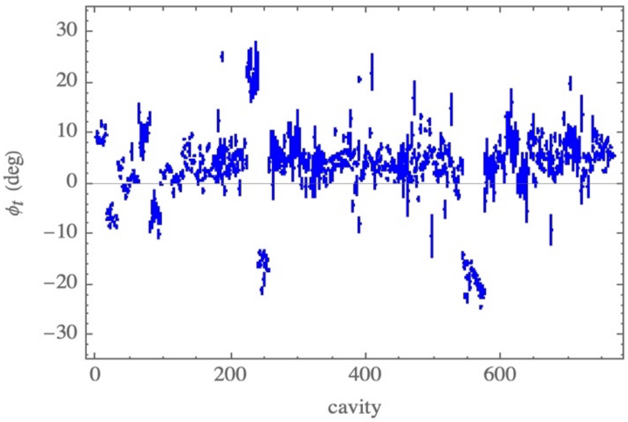

Figure 5: Beam transient phase for all cavities in the XFEL linac. Error bars are ±1 std. err. (statistical).

Looking at Fig. 5, there is a hint of a systematic offset of about +4°, which is under investigation, although it plays no significant role in operations. In general, with the observed stability and the number of pulses averaged, the accuracy of the technique is almost certainly dominated by systematics.

ABSOLUTE CALIBRATION

During beam-on data acquisition, the beam energy at the end of the linac is also recorded. The spectrometer is quoted as having an absolute accuracy better than 100 MeV (<1% relative). This data can be used to provide an absolute calibration for the probe signals. Again, the starting point is the assumption that the beam transient in every cavity is equal in amplitude and at zero phase. The transient measurements (Fig. 4) are then used to calculate cavity probe complex scale factors, which, when applied, result in the theoretical transient amplitude given by Eq. (1). The same scale factors are then applied to the measured RF cavity voltage, and the total beam voltage is calculated by summing the real parts. A final single (real) energy scale factor is then calculated and applied, using the measured beam energy.

In principle the absolute probe calibration can be obtained directly from Eq. (1). However, the fact that this needs to be scaled to agree with the beam energy measurement leads to an interesting observation. Figure 6 shows the scale factors for all the datasets recorded for the past twelve months. The data show that the observed transient in consistently ~12.3% lower than the theoretically predicted value from Eq (1). This factor has been historically observed in Tesla cavities for many years, starting with original measurements in FLASH. The reason for this apparent difference is still under investigation.

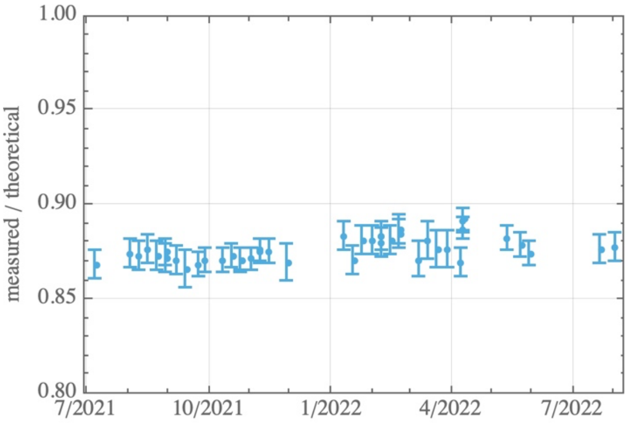

Figure 6: Beam energy scale factors for all datasets recorded in the last twelve months. The factor can be interpreted as the ratio of "measured" to theoretical transient amplitude. Error bars are ±1 std. err. (statistical).

CONCLUSIONS

A fast quasi-non-invasive method of cavity probe calibration has been developed by using the measured beam transient simultaneously in all 768 cavities in the XFEL L2 and L3 linacs. This procedure is routinely used to monitor the LLRF calibration, and in particular any large phase misalignments with single RF stations (32 cavities). Typical statistical errors are at the few per cent level. Systematic errors are still be evaluated by there is evidence these are at the 4—5% level. An absolute calibration is also available which uses the measured beam energy at the exit of the linac, which results in energy scale factor indicating that the transient amplitude is consistently 12.3 ±0.1 % less than the expected theoretical value. This anomaly is under investigation.

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