FLASH BEAM-OFF RF MEASUREMENTS AND ANALYSES*

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Abstract

The FLASH L-Band superconducting (SC) accelerator facility at DESY has a LLRF system that is similar to that envisioned for ILC. This system has extensive monitoring capability and was used to gather performance data relevant to ILC. In particular, waveform data were recorded with beam off for three, 8-cavity cryomodules to evaluate the input rf stability, perturbations to the SC cavity frequencies and the rf overhead required to achieve constant gradient during the 800 µs pulses. In this paper, we discuss the measurements made in September 2008 and the data analysis procedures, and present key findings on the pulse-to-pulse input rf and cavity field stability.

INTRODUCTION

The FLASH facility at DESY is the world's only FEL for VUV and soft X-ray production. Presently it has six accelerator modules each containing eight, L-Band (1.3 GHz), 1-m long, 9-cell, SC cavities. The three modules, ACC4-ACC6, are the focus of this study as they are very similar to an ILC rf unit. These 24 cavities are powered by a single klystron and the LLRF system monitors the input (forward) and reflected rf at each cavity as well as the cavity fields using probe couplers. The probe signals for the 24 cavities are summed vectorally and used in Feedback (FB) and Adaptive Feed Forward (AFF) algorithms to keep the net gradient from the 24 cavities constant during the 800 µs beam period that follows a 500 µs cavity fill period. These algorithms control the drive rf to the klystron in this process. The AFF corrections incorporate the repetitive pulse-to-pulse corrections made by the FB system.

LLRF waveform data were collected on 09/18/08 with the beam off and without cavity piezo actuator compensation for Lorentz force (LF) detuning. Three sets of the data were taken in which: 1) FB and AFF were off; 2) FB was on and AFF was off; and 3) FB and AFF were on. For each set, the phase and amplitude waveforms for the rf input, reflected and probe signals of all 24 cavities were recorded simultaneously for 100 pulses using the DOOCS system. The pulses could only be measured at ~1/3 Hz because the time to acquire one data set was about 3 seconds [1]. In the future, we plan to use data from the FLASH DAQ archiver system [2], which acquires pulse-synchronous waveforms at the 5 Hz machine repetition rate.

The main purpose of this study was to measure the input and cavity rf stability. The latter is affected by LF detuning and microphonic induced cavity frequency changes. Here the FB and AFF off data are mainly relevant. We also wanted to determine the rf overhead required when piezo actuators are used to compensate LF detuning, as would be the case in the ILC. However, the piezo system is not yet fully automated at FLASH, and the data were taken without this compensation. Thus, the rf overhead inferred from the FB and AFF on results are larger than would be with such compensation. Only beam-off data were recorded as the FLASH beam differs significantly from ILC.

DATA ANALYSIS

For SC cavities operated without beam, the input rf pulse has two levels (i.e., two flattop regions) which correspond to the cavity fill period and the nominal constant gradient period. During the latter period, the input rf is about a factor smaller as there is no beam loading.

For the Vector Sum (VS) signals (i.e., the vector sum of the 24 calibrated cavity probe signals) and the cavity input and reflected signals, a Time Domain (TD) analysis was done where the mean and standard deviation of the 100 pulses were computed versus time during the pulse. For the individual cavity probe signals, this analysis was also performed, and in addition, a Frequency Domain (FD) study was done for the 100 pulses at a selected time at the beginning and at the end of the probe signal flattop period.

The TD analysis for the cavity input signals consisted of five basic steps: 1) the input signals during the first flattop period were calibrated in units of MV/m using the cavity probe flattop signals as a reference (the probe signals had been calibrated prior to the data taking); 2) each set of four data points were averaged to eliminate any 250 kHz LLRF reference signal leakage [3]; 3) the standard deviation and mean value at each data sample time for the 100 pulses were computed for each set of measurements; 4) the electronic noise contribution was subtracted from the standard deviation values in quadrature based on the rf-off baseline values; and 5) since relative effects are of most interest, the ratio of the jitter (standard deviation) to the mean amplitudes were computed, which we call Percentage Standard Deviation (PSD) [4].

For the TD analysis of the VS signals, both the PSD of the amplitude and the ASD (Absolute Standard Deviation) of phase were computed, but the relatively small electronic noise contribution was not subtracted. For the cavity reflected and probe signals, the mean value and PSD were computed, also without subtracting the noise.

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KEY FINDINGS

We find that the FB and AFF algorithms work well to reduce the VS jitter and flatten the VS amplitude and phase. Also, the input rf signals are very stable (~0.1% amplitude jitter) with both FB and AFF off, indicating that the klystron modulator and rf drive systems have very small pulse-to-pulse variations. The cavity probe signal jitter is dominated by variations in the pulse-to-pulse cavity detuning; the jitter is essentially random pulse-to-pulse with large cavity-to-cavity variations that are not significantly correlated among cavities. In addition, the cavity field jitter doesn't scale with the square of cavity gradient in 14-24 MV/m range as would be expected for LF detuning. This suggests there may be large variations in the mechanical stiffness among the 24 cavities (a factor of two might be expected) and/or there are local sources driving the cavity vibrations. More details on these findings are given in the following sections.

Vector Sum Signals

Figure 1 and 2 show the VS amplitude and phase results with FB and AFF on. The flattop PSD decreases from 0.1-0.4% with FB and AFF off to 0.05-0.08% with FB and AFF on. The phase ASD decreases from 0.25-0.45 degrees with FB and AFF off to 0.06-0.075 degrees with FB and AFF on. The FB alone works well to reduce the amplitude PSD and phase ASD, but it does not fully flatten the pulse. Fortunately, AFF can flatten the pulse to the resolution limit.

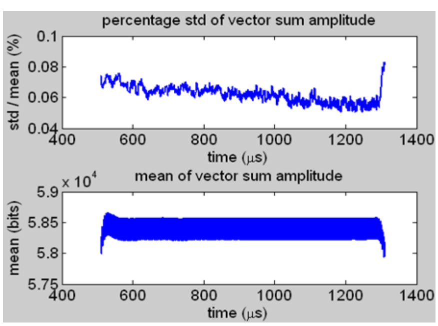

Figure 1: PSD and mean VS amplitude for the flattop.

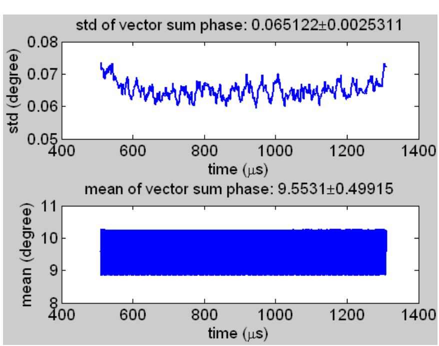

Figure 2: ASD and mean VS phase for the flattop.

Cavity Input and Reflected Signals

There is significant cross-talk between the input and reflected signals because the directional couplers used in measure these signals have only ~20dB isolation. That is, the input rf signals as measured are proportional to a vector sum of actual input rf plus some fraction of the reflected rf, which is large during the fill period. This cross-talk causes slight differences in the input rf flattop shapes for the different cavities. The jitter on the input signal is also strongly affected by this cross-talk in some cases.

Ideally, the reflected rf at the end of the first flattop period should be zero. That is, given the cavity Q_{ext}, the fill time is set so the reflected power goes to zero at the end of fill period when the cavity is running on-frequency. Instead, the measured reflected rf amplitudes at the end of the first flattop period are around 50% of initial reflection during that period (the initial reflection roughly equals the input rf amplitude). This large ratio suggests that the cavities were significantly detuned during the fill period. This is not too surprising as LF detuning during the fill period for 20 MV/m operation is expected to be roughly half of the cavity bandwidth [3].

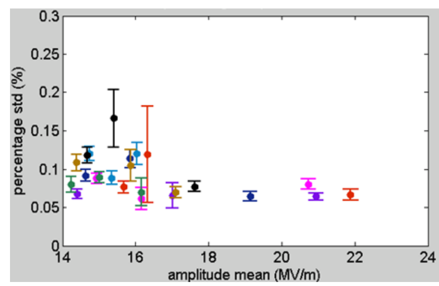

Figure 3: Input signal PSD averaged over the first flattop period for all cavities as a function of mean amplitude.

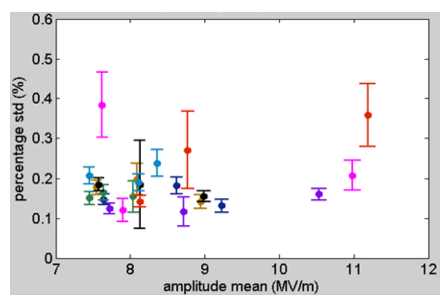

Figure 4: Input signal PSD averaged over the second flattop period for all cavities as a function of mean amplitude.

Figure 3 and 4 show the input rf PSDs with FB and AFF off for all cavities averaged over the two flattop regions, respectively, with the noise contribution subtracted in quadrature. The error bars on the points encompass the range of jitter during the flattop periods. With FB and AFF off, the flattop amplitude is very stable pulse to pulse; the fractional jitter is ~ 0.07% for first flattop and 0.15% for the second. This factor of two increase suggests the jitter originates from noise in the rf drive as the absolute rf jitter is independent of amplitude. This differs from usual case in which modulator voltage variations generate proportional rf jitter. The cavities with high PSD are ones where there is a large jitter in the reflected signals and the cross-talk contribution dominates the actual input rf jitter.

Cavity Probe Signals

The cavity probe signal waveforms vary smoothly pulse-to-pulse suggesting that the changes are due to integrated effects as opposed to fast transients such as those caused by dark currents and multipacting. The PSD of the cavity probe signals at each sample point during the flattop period are plotted for all cavities in Figure 5 for the FB and AFF off case. The jitter is typically a few tenths of percent at the beginning of flattop and grows up to 4% by the end of flattop.

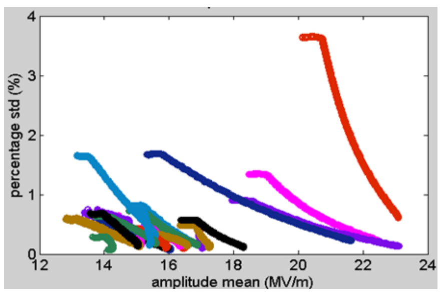

Figure 5: PSD of all cavity probe signals at each sample point during the flattop period as a function of gradient.

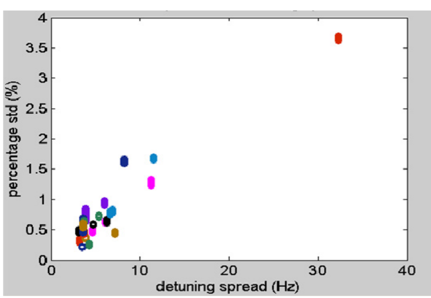

Figure 6: Correlation between cavity probe PSD and detuning ASD at the end of the flattop.

Figure 6 shows that there is a strong correlation between the cavity probe PSD and the pulse-to-pulse detuning jitter at the end of the flattop (measured by computing the cavity phase derivative with respect to time just after the input rf goes to zero). Thus, variations in the pulse-to-pulse cavity detuning are likely driving the probe signal jitter.

Figure 7 shows one example of the FD analysis of the probe signals at the beginning and end of the flattop. Although there are some peaks in the FFT spectra, they do not contribute significantly to the integrated spectra (corresponding to the jitter ASD values in TD). This indicates that the jitter is essentially random pulse-to-pulse. Also, the computed jitter correlation coefficients between cavities show that the cavity-to-cavity jitter is essentially uncorrelated.

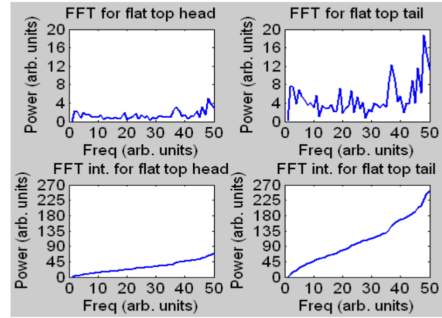

Figure 7: FFT and integrated FFT of for ACC6-CAV1.

In general, higher gradient cavities have higher jitter, but the jitter does not scale with the square of cavity gradient as would be expected in a simple LF detuning interpretation. As noted above, either the mechanical stiffness varies significantly among the cavities and/or some are vibrating more than others due to local external forces.

CONCLUSIONS AND FUTURE PLANS

Overall, the LLRF system at the FLASH facility performs well in reducing the VS amplitude jitter to less than 0.1% and the phase jitter to less than 0.1°. The fractional jitter of the input rf is at the 0.1% level, which is excellent. The cavity probe signals are particularly interesting as their jitter is much larger (up to 4%) and grows along the pulse. The source of this jitter needs to be better understood as it may have important implications for XFEL and ILC.

There are number of effects that still need be evaluated, in particular, the reduction in the rf overhead afforded by piezo compensation, and the jitter that such compensation may introduce. Also, it would useful to measure how the probe signal jitter varies with gradient as higher gradients than those in this study are required for ILC. The plan is to continue to take more data for these cavities with/without piezo compensation and with beam on/off at different gradients and feedback gain levels.

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REFERENCES

[1] J. Carwardine, private communication.
[2] M. Davidsaver, 'Experience with FLASH DAQ / Archiver,' LCWS/ILC 08, November, 2008.
[3] T. Schilcher, 'Vector Sum Control of Pulsed Accelerating Fields in LF Detuned SC Cavities,' Ph.D. Thesis, TESLA 1998-20, DESY.
[4] S. Pei, 'FLASH RF Measurements and Analysis,' LCWS/ILC 08, November, 2008.