# PERFORMANCE OF LLRF SYSTEM AT S1-GLOBAL IN KEK*

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*Abstract*

Total eight cavities were installed for S1-Global in preparation for the International Linear Collider. Vector-sum operation and the distributed RF system (DRFS) were evaluated. On-line cavity diagnostics (such as quench detection and dynamic detuning monitoring) was used for efficient operation. The performance is summarized and the quench phenomena observed in high-gradient operation are analyzed in terms of loaded Q and cavity detuning.

## INTRODUCTION

S1-Global is a worldwide effort to examine cavity performance in preparation for the International Linear Collider (ILC) [1]. Eight cavities were installed (two at FNAL (cavities C-1 and C-2), two at DESY (C-3 and C-4) and four at KEK (A-1, A-2, A-3 and A-4). Although these cavities have different types of input-coupler, tuner and structure, all were installed into one cryogenic system [2], which is similar to the planned setup at ILC.

S1-Global was conducted from September, 2010 to February, 2011; it can be divided into three periods. In Stage 1, the performance of each cavity, such as the quench limit and Lorentz force detuning, was examined. To examine the cavity efficiently, two RF sources were used. Each 5-MW klystron (1.3 GHz, 5 Hz, 1.6 msec.) could drive four cavities.

In Stage 2, the vector-sum performance was evaluated. Figure 1 shows a schematic of the RF configuration in Stage 2. To maximize each cavity's gradient, the ratios of the RF input powers to the cavities are optimized using tuneable hybrids and variable tap-offs [3].

A conventional digital low-level RF (LLRF) system was adopted during these two stages. An FPGA board on a commercial DSP board (Barcelona) was used to control the rf output from each klystron. The FPGA board has 10 16-bit ADCs and 2 14-bit DACs with an FPGA [4]. An additional RF monitor using an intermediate frequency (IF) mixture was employed to perform cavity diagnostics [5]. Three IFs are mixed by an RF combiner and the mixture is input to each ADC. The signal is separated into three IQ components (cavity pick-up, cavity input and RF reflection from the cavity) by digital signal processing. This enables the use of a maximum of 30 RF signals by 10 ADCs.

In Stage 3 of S1-Global, a distributed RF system (DRFS) [6] was evaluated. Two 800-kW klystrons were connected to one RF modulator; each klystron drove two cavities. The digital feedback system based on μTCA [7] was located near the cryomodule tunnel in Stage 3.

A special feature of the DRFS is that it was operated without circulators [8]. If the cavities are paired, the RF reflection can be cancelled when the paired cavities are operated with exactly the same parameters (dynamic detuning , Ql and so on). If the cancellation is not perfect (for example, during commissioning of the cavities), reflection to the klystron occurs, and cross-talk between the cavities subsequently appears. The former may results in the damage of the klystron and the latter makes cavity diagnostics difficult. Correct on-line cavity diagnostics are essential for DRFS operation. Therefore, we have developed these diagnostics, as described below.

## LLRF INTERLOCK SYSTEM

Quench, which is the transition from superconducting to normal conducting on the cavity surface due to excess RF fields, introduces a serious cryogenic heat load. If quench occurs, the RF input to the cavity should be shut down as soon as possible; otherwise, the system cannot operate until recovery of the cryogenic system. Thus we developed a rapid quench detection and interlock system. The loaded Q (Ql) of each cavity (~2.4e6) is calculated using the RF decay time at the end of the RF pulse; if the value is lower than the threshold for Ql (e.g., 2e6), RF operation stops at the next pulse as shown in Fig.2. This quench-interlock system works well and helps lower the heat load to the cryogeincs.

DRFS operation makes it difficult to detect quench with this procedure because of the cross-talk between cavities. However, we continued to use the Ql value obtained from simple RF decay. Quench detection sometimes requires an additional pulse, but the cryogenic heat load is reduced even in this case.

Arc detectors attached near the cavity couplers and RF power interlocks are also introduced to protect the couplers and klystrons, respectively, from breakdown.

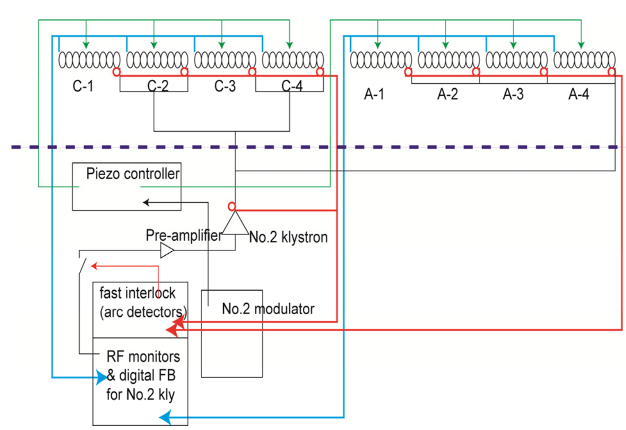


Figure 1: Schematic of the RF configuration in Stage 2.

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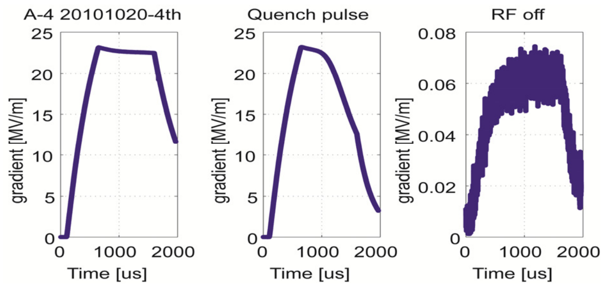


Figure 2: Quench interlock using Ql.

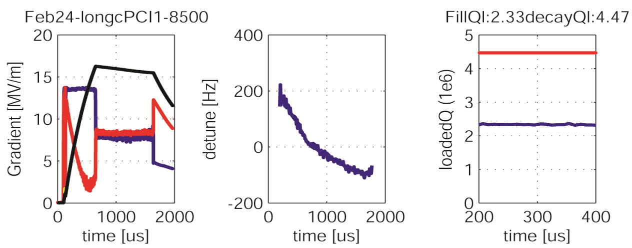


Figure 3: Example of cavity diagnostics. Left: waveforms (black: cavity pickup, blue: cavity input, red: reflection), center: dynamic detuning, right: Ql values (blue: from eq.(2), red: from RF decay).

## CAVITY DIAGNOSTICS

Dynamic detuning caused by the Lorentz force in the cavity affects the RF performance at operation above 20 MV/m. Piezo-actuators are installed in all the cavities, so the cavity tuning can be controlled dynamically. Cavity detuning should be maintained below 50 Hz during the RF flat top. Optimization of the piezo requires a precise detuning monitor (e.g., < 5 Hz). Dynamic detuning is typically measured by the pulse-shortening method [9], in which the RF pulse length is changed and the detuning at the end of the pulse is calculated from the phase change. These values appear reliable but microphonics (fluctuation in the pulse-to-pulse detuning) is not considered. In addition, this method is not suitable for circulator-less systems such as the DRFS because the release of stored energy in one cavity becomes the RF input to the other cavity (and vice versa). Thus, we cannot define a clear "RF-off" status, which is essential for the pulse-shortening method. To solve these problems, we developed a real-time detuning monitor based on the cavity differential equation. The cavity voltage ($V_{cav}$) and cavity input voltage ($V_{for}$) satisfy the following cavity equation,

$$\frac{d}{dt}V_{cav} = -\left(\omega_{1/2} - j\Delta\omega(t)\right)V_{cav} + 2\omega_{1/2}V_{for} \quad (1)$$

where $\omega_{1/2}$ $(= 2\pi f_0/2Q_l)$ and $\Delta\omega(t)$ are the bandwidth and dynamic detuning of the cavity, respectively. By using eq. (1), we can obtain Ql and detuning.

Eq.(1) can be modified as

$$\frac{1}{2}\frac{d}{dt}|V_{cav}|^2 = \omega_{\frac{1}{2}}(t)\left(|V_{for}|^2 - |V_{ref}|^2\right) \quad (2)$$

where $V_{ref}$ is the reflection voltage from the cavity and satisfies $V_{cav}=V_{for}+V_{ref}$.

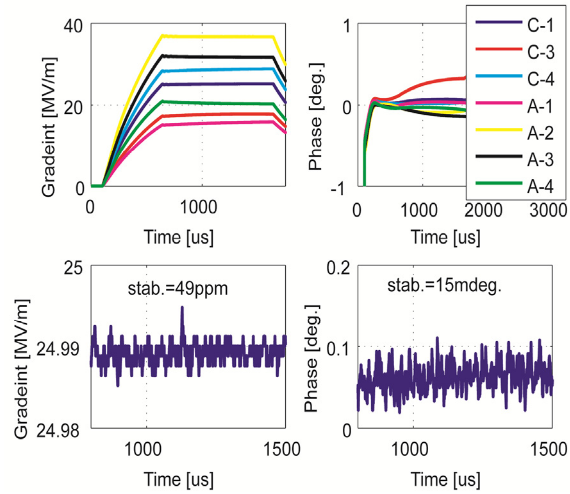


Figure 4: Vector-sum (VS) operation. Left: each cavity's gradient and vector sum gradient, right: each cavity's phase and vector sum phase.

We can calculate the time-dependent Ql by using eq.(2) except in the RF flat-top region where the cavity voltage ($V_{cav}$) is constant.

The precise cavity input power is needed for the detuning calculation. Because the directional RF couplers have a directivity of 20~30 dB, cross-talk occurs between $V_{for}$ and $V_{ref}$, so it is difficult to determine the precise cavity input power. To obtain better resolution for detuning and Ql, both $V_{for}$ and $V_{ref}$ are corrected by using the measured directivities. Figure 3 shows the results of the cavity diagnostics (dynamic detuning and Ql values) during DRFS operation. Although Ql values obtained from a simple decay constant depended on the detuning condition (right panel, red line), those calculated from eq. (2) (blue line) were constant under various detuning condition. The cavity diagnostics works well for detuning control, especially for optimization of piezo control.

## RF STABILITY

The result of vector sum operation for seven cavities is shown in Fig.4. One cavity (C-2) could not be used for vector-sum control because its tuner failed. The amplitude and phase stabilities were 0.005%rms and 0.015°, respectively, which satisfy the ILC requirements of 0.07% in amplitude and 0.24° in phase [1]. The RF dividing ratio was adjusted to yield the maximum gradient for each cavity. Piezo tuners were used to obtain ~0 Hz detuning during the RF flat-top (1 ms).

The detuning variation of each cavity at RF-flat-top during 6,000 s of operation is shown in Fig.5. An abrupt change in the detuning (~2,800 s) occurred in some cavities. The trend of the detuning changes agrees well with the change in He pressure in the cryomodule. The sensitivity to cavity detuning depends on the cavity type, rather than the gradient. High gradient cavities (A-2, A-3) show smaller detuning owing to their stiff structure.

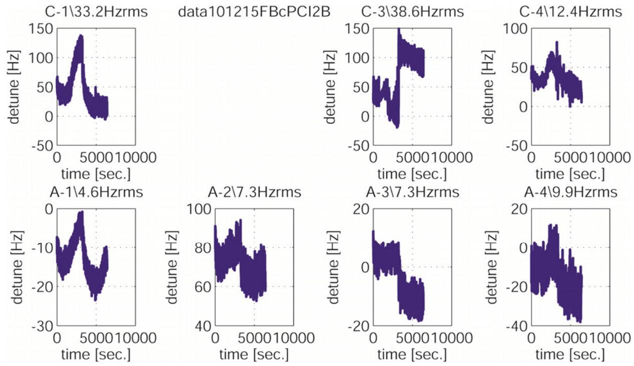


Figure 5: Detuning fluctuation of each cavity during 6,000 s of operation.

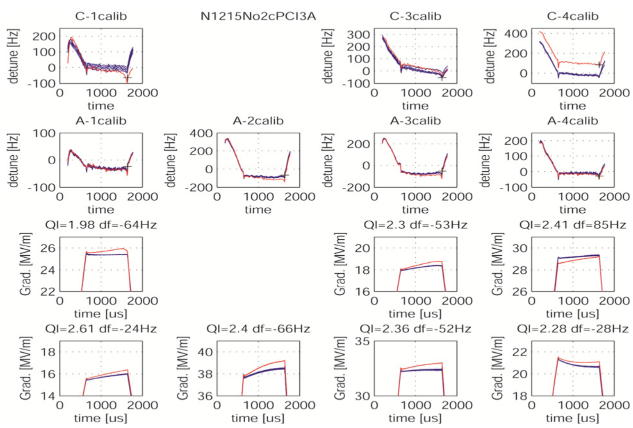


Figure 6: Cavity detuning (upper eight panels) and amplitude (bottom eight panels) for each cavity. Red line: quench pulse, blue lines: previous pulses.

## QUENCH PHENOMENA

The digital LLRF system can store the RF waveforms of the last 150 pulses. These data can be used to examine the interesting phenomenon of quench during vector-sum operation. Figure 6 shows the cavity gradient of each cavity in a typical quench event. The red line corresponds to the quench pulse, and the blue lines correspond to the previous pulses. The upper eight plots show the detuning of each cavity during RF operation. The bottom eight plots show the cavity gradient. An abrupt detuning change (~100 Hz) occurred in C-4. As a result, all the other cavities' gradients increased so that a constant vector-sum was maintained. The gradient of C-1 increased by about 3%, which exceeds the quench limit. The margin between the operational gradient and the quench limit should be carefully considered.

## MICROPHONICS COMPENSATION

A slow drift in detuning was observed, as shown in Fig.6. Since the time-range of the drift is ~1,000 s or more, we tried to compensate for it by controlling the DC bias of the piezo actuators. This correction was made at the upper level controller (via EPICS). Figure 7 shows the detuning of the cavities using micropnics correction.

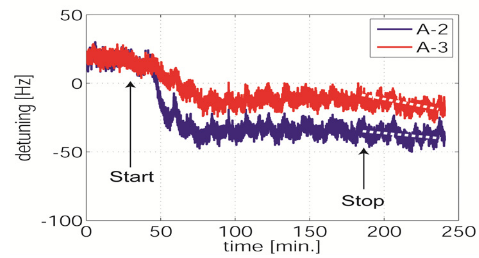


Figure 7: Microphonics compensation by using DC piezo-offset control.

Detuning control was applied starting at 45 min. Since the set values for the detuning are 50 Hz below equilibrium, it takes 30 min to reach equilibrium. We stopped the control stopped on 170 min, after which a gradual decrease in detuning was observed. The results confirm that static detuning compensation using piezo is effective.

## SUMMARY

S1-Global successfully completed operation in February, 2011. The vector-sum performance satisfied the ILC requirements. The quench detector effectively prevented excess heating of the cryogenics. The on-line detuning monitor helped optimize the piezo used to compensate dynamic Lorentz force detuning. The drift in the static detuning (microphonics) was corrected using DC offset control of the piezo.

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