LLRF System Performance at S1-Global in KEK

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S1-Global: International collaboration to examine cavity performance for ILC. Sep, 2010 ~ Feb, 2011 @KEK-STF.

Total 8 SC cavities are installed into two half-size cryomodules, which are similar to the planned setup at ILC.
**HLRF schemes for ILC**

- **RDR**: Reference Design Report of ILC
  - One klystron drives 26-cavities

- **DRFS**: Distributed RF Scheme
  - Each klystron drives 2-cavities in circulator-less PDS

**Demonstration**

- 5MW klystron drives 8 cavities
- Each 800kW klystron drives 2 cavities

**Minimum DRFS units**

- 1 klystron feeds power to 2 cavities.
- 1 DC power supply and MA modulator drive 13 klystrons.

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LLRF Studies in S1-Global

Contents

**S1-Global (RDR)**
- Diagnostics
  - Fast quench protection
  - Real time detuning monitor
- Vector-sum performance for 8 cavities

**S1-Global (DRFS)**
- Diagnostics
  - $Q_L$ calculation
- Vector-sum performance (without circulators)
Photos of S1-Global (RDR-type)

5 MW klystron
(1.3GHz, 5 Hz, 1.6ms)

LLRF digital FB system & Interlock modules

Tunner controllers & monitors (vac., power)

Klystron Hall

Cryomodule & WG in the tunnel

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FPGA board is a daughter card of a commercial DSP board.

- **ADC-inputs** (Multi-connector)
- **I,Q DAC outputs**

**cPCI digital FB board**

- 10ch 16-bit ADC (LTC2208)
- 2ch 14-bit DACs (AD9764)

**cPCI crate**

- CPU board
- Digital I/O board
- FPGA digital FB board

**FB calc.** → **FPGA**

- Complex calc. like derivation of \( Q_L \)
- Data communication

**DSP**
Loaded Q (Q_L) interlock system was installed to quit RF quickly in quench occurrence.

\[ V_{cav} \propto e^{-t/\tau}, \quad Q_L = \frac{\tau \omega_0}{2} \]

QL of each cavity is calculated in DSP on the cPCI FB board.

When quench event is detected, RF operation stops at the next pulse.

QL interlock worked well and contributed to the stable cryogenic operation.
Real time detuning monitor

Correction of the dynamic detuning in real time is effective to good RF performance.

<Examples of detune curves>

Without correction by Piezo tuner

![Graph showing dynamic detuning without correction]

With correction by Piezo tuner

![Graph showing dynamic detuning with correction]

Dynamic detuning is well corrected.

Real time detuning monitor is quite helpful to adjust the Piezo tuners.

Derivation of dynamic detuning

\[ V_{cav} = V_{for} + V_{ref}, \]

\[ \frac{d}{dt}V_{cav} = -(\omega_1/2 - j\Delta\omega(t))V_{cav} + 2\omega_1/2 V_{for} \]

Detuning is derived by using these 3 signals:

- \( V_{cav} \): Cavity voltage
- \( V_{for} \): Cavity input voltage
- \( V_{ref} \): Reflection voltage from cavity

For 8 cavities, total 8cav x 3 = 24 signals are required.
Data taking by IF-MIX

 advantageous: 24 signals required for detuning monitor were taken with only 8 ADCs by using IF-MIX

IF-MIX: method to input different IF-signals into one ADC

\[ f_{IF} = \sum_{N} \left( \frac{N}{M} \right) \cdot f_{SR} \] (Sampling rate of ADC : \( f_{SR} = 40.625 \text{ MHz} \))

\( f_{IF1} = 4.514 \text{ MHz} \) \( (N=1, M=9) \)
\( f_{IF2} = 9.028 \text{ MHz} \) \( (N=2, M=9) \)
\( f_{IF3} = 13.542 \text{ MHz} \) \( (N=3, M=9) \)

Each signal is derived by Fourier expansion

\[ I = \frac{2}{M} \sum_{n=1}^{M} x_i(n) \cdot \cos\left(\frac{2\pi \cdot N}{M} \cdot n\right) \]
\[ Q = \frac{2}{M} \sum_{n=1}^{M} x_i(n) \cdot \sin\left(\frac{2\pi \cdot N}{M} \cdot n\right) \]

Results of 3 waveforms taken in one ADC by IF-MIX
Result of vector sum operation

Average acceleration field = 25 MV/m

These results satisfy the requirement of ILC, 0.07% and 0.24°.
The first test of DRFS for ILC was conducted at the end of S1-Global.

Two klystrons with modulation anodes (MA) were connected to a DC power supply and an MA-modulator.

Each klystron drove 2 cavities. (KLY#1→C1+C2, KLY#2→A2+A3)
Circulator-less operation using Magic-T

In DRFS, reflections from 2 similar cav. are canceled by magic-T. Therefore circulator is possible to be omitted.

In the case of un-balanced reflection (amp., phase), reflection power go to the klystron. Therefore performance should be checked.

S1-Global examined this situation as described later.

Phase-shifters are introduced to evaluate the system. (not to be used at ILC-DRFS)
LLRF rack layout in the tunnel

- LLRF rack is located near the cryomodule.
- μTCA FB system
- μTCA digital feedback system are used for DRFS.
The board has been developed for cERL-project (CW operation) at KEK.

For DRFS, the logic was changed for pulse operation.

EPICS was installed in the digital board for communication control.

EPICS: Experimental Physics and Industrial Control System
Schematic diagram of LLRF system

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<Latency of FB board>
ADC : 7.5 clock, DAC :15 clock @ 81.25MHz
IQ separation & Correction : 5 clock@40.625MHz
Calculation in FPGA : 23 clock @ 81.25MHz
Total  55.5 clock @ 81.25MHz   (0.68 \mu s)

IIR filter : 35kHz~150kHz LPF in normal operation

8/9\pi  mode  rejected
noise in ADC-input
Sag-compensation

Since bouncer circuit was not installed due to budget shortage, there are 8% droop in HV.

\[ A(t) \begin{pmatrix} \cos \varphi(t) \\ -\sin \varphi(t) \end{pmatrix} \begin{pmatrix} \sin \varphi(t) \\ \cos \varphi(t) \end{pmatrix} \]

Especially, phase rotation is too large to suppress by feedback only.

Correction Table

HV: ~8% droop

Sag compensation was performed at before the DAC-output
Result for circulator-less operation

(When reflection is not canceled or large, circulator-less system should be checked.)

Typical Operation

- Low reflection: VSWR~1.1

Operation under different detuning

- Large reflection: max VSWR~3

\[ \Delta f_1 > \Delta f_2 \sim 130\text{Hz} \]

Stability
0.015% rms, 0.06deg.rms

Vector sum is still regulated stably. (0.04%rms, 0.06deg.rms)

\[ Q_L = \frac{\omega_0 (v_{for}^2 - v_{ref}^2)}{\frac{d}{dt} |V|^2} \]

Q\_L by cavity eq.

Both are same results.

Therefore, under circulator-less operation, vector sum operation and \( Q_L \) diagnostics using cavity eq. worked well.

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Feedback Performance in DRFS

μTCA2: HV=67kV, IIR=35kHz, Vector-sum Operation for Cav1, cav2
FB + FF Operation

Stability: 0.017% rms in Amplitude
0.03 deg. rms in Phase

These results satisfy the requirement of ILC, 0.07% and 0.24°.

LLRF system worked well without trouble in this machine-time despite placed in the tunnel.
Summary

S1-Global successfully completed operation in February, 2011.

Various diagnostics such as on-line quench pulse detector, dynamic detuning monitor were also implemented.

The digital FB system using cPCI or μTCA are adopted for vector-sum field regulation.

The vector-sum performance satisfied the ILC requirements.

Circulator-less system operated in good stability and $Q_L$ diagnostics worked well even in the large reflection condition.

Following operations are planned in future

Beam Operation will start at STF in KEK.
- Quantum beam project will start from Jan.2012. (10 mA, 40 MeV)
- STF-2 project will start from April 2013. (8.7mA, 273 MeV)
Thank you for your attention.
Cavity equation

- The cavity should satisfy the differential equation.
- In addition directivity (~20dB) of rf monitor-coupler should be concerned.
  -> The directivity can be corrected using this formula.

\[
\dot{V} = -\left(\frac{\omega_1}{2} - j\Delta\omega\right)V + 2\frac{\omega_1}{2}V_{\text{for}}
\]

\[
V_{\text{cav}} - j\Delta\omega V_{\text{cav}} = \omega_1/2 V_{\text{dif}}
\]

\[
V_{\text{dif}} = V_{\text{for}} - V_{\text{ref}}
\]

\[
V_{\text{cav}} - j\Delta\omega V_{\text{cav}} = \omega_1/2 V_{\text{dif}}
\]

\[
V_{\text{cavR}} + \Delta\omega V_{\text{cavl}} = \omega_1/2 V_{\text{difR}}
\]

\[
V_{\text{cavl}} - \Delta\omega V_{\text{cavR}} = \omega_1/2 V_{\text{difl}}
\]

\[
\frac{1}{2} \frac{d}{dt} |V|^2 = \frac{1}{\omega_1} \frac{d}{dt} |V|^2
\]

\[
Q_i = \frac{\omega_0 \left( V_{\text{for}}^2 - V_{\text{ref}}^2 \right)}{\frac{d}{dt} |V|^2}
\]