OPERATION TEST OF DISTRIBUTED RF SYSTEM WITH CIRCULATOR-LESS WAVEGUIDE DISTRIBUTION IN S1-GLOBAL PROJECT AT STF/KEK

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Abstract

The distributed RF dystem (DRFS) is one of the candidate designs for a single main linac tunnel in the international linear collider (ILC). In the S1-Global project, one DRFS unit, consisting of four superconducting cavities, two klystrons, and a modulator, was constructed at STF/KEK. In a demonstration of this DRFS, a power distribution system from the RF source to the cavities was constructed without circulators and the performance of the RF system was evaluated. The results of the DRFS operation with this circulator-less waveguide distribution system are reported here.

INTRODUCTION

The S1-Global project is a collaborative work by INFN, DESY, FNAL, SLAC and KEK as part of the global design effort (GDE) for the ILC. The goal of the project is to operate a string of superconducting cavities developed for the ILC using a single common cryogenic system and to achieve an average accelerating gradient of 31.5 MV/m, required for the ILC. For this project, a total of eight cavities (two from DESY, two from FNAL, and four from KEK) were installed into two half-size cryomodules, and a demonstration of the system was carried out from September 2010 to February 2011 at STF in KEK [1].

During the S1-Global test period, two different RF systems were operated and their performances were evaluated. First, one RF unit, consisting of one 5-MW klystron and the power distribution system was constructed and used to feed power to the eight cavities; this was similar to the RF unit in the reference design report (RDR). After evaluating the performances of each cavity, such as the quench limit and the effect of the Lorentz force detuning, a vector sum feedback operation with seven cavities was carried out and the stability of the accelerating field was evaluated [2].

In the latter half of the test period, the distributed RF System (DRFS) [3] was demonstrated. The DRFS is one of the candidate designs for a single main linac tunnel design of the ILC. In the basic DRFS plan, thirteen 800-kW klystrons, having a modulating anode (MA), are connected to a single DC power supply and an MA modulator and feed power to twenty-six superconducting cavities, which correspond to one RDR RF unit. All this equipment for generating RF power is placed inside the underground tunnel.

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In this demonstration, the RF system consisted of four superconducting cavities, two MA klystrons, one MA modulator, and a DC power supply (Fig. 1). This is a minimal composition of a DRFS unit from the viewpoint of operating more than one klystron. The entire low-level RF system, including the feedback system, was placed near the RF source in the tunnel. The feedback system was constructed using FPGA boards based on micro-TCA [4].

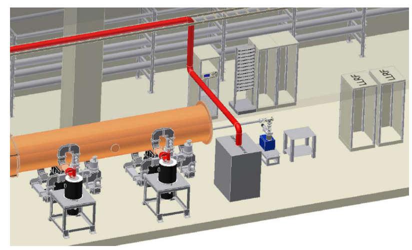

Figure 1: Layout of the DRFS in the S1-Global.

Because a superconducting cavity has a standing-wave –type structure, RF power is reflected from the cavity at the pulse rising time and pulse falling time when the power is pulsed. If two cavities with the same parameters (loaded Q (Ql), cavity detuning, and so on) are configured with the correct phase difference, it is possible to cancel the reflected power to the RF source and to eliminate the circulators from the power distribution system. The removal of the circulators is also expected to contribute to a cost reduction for the construction. In this demonstration of the DRFS, the power distribution system from the RF source to the cavities was constructed without circulators and the performance of the RF system was evaluated.

CIRCULATOR-LESS WAVEGUIDE DISTRIBUTION SYSTEM

The role of the circulators in an RF power distribution system is to prevent the unstable operation of the RF source caused by the reflected power and to protect the klystron's ceramic window from high voltage of the standing wave formed by the forward and reflected power. The circulators also decrease the crosstalk between cavities from the reflected power. These functions make it possible to operate an RF source using feedback control and to measure the cavity parameters (Ql, detuning) for diagnosis. In the case of the circulator-less waveguide system, the reflected power cancellation is achieved by use of two cavities with the correct phase difference. However, if the cancellation is not perfect, the reflected power returns to the klystron and crosstalk appears between cavities. This made it necessary to demonstrate the stable feedback operation of the RF source and the cavity diagnosis for the DRFS with a circulator-less waveguide distribution system.

Circulator-Less Waveguide Distribution of DRFS in S1-Global

Figure 2 shows the power distribution system from the klystron to two cavities constructed for the DRFS demonstration at the S1-Global. The RF output power from the klystron was split into two equal RF cavity inputs using a single magic-tee. In order to cancel the reflected power from each cavity at the magic-tee, one straight waveguide (80-mm long), which corresponded to an operating frequency of about 90°, was inserted into one side of the waveguide between the magic-tee and the cavity.

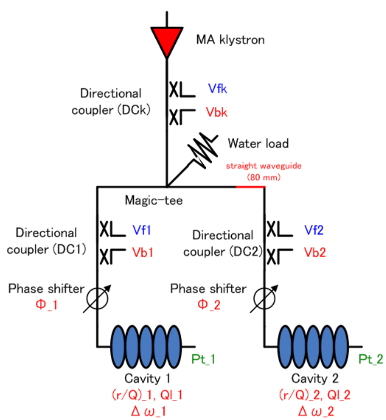

Figure 2: Schematic of RF system with circulator-less waveguide distribution system.

Three directional couplers were used in the power distribution system, as shown in Fig. 2. The directional coupler located near the klystron (DCk) monitored the forward and backward signals of the klystron (Vfk and Vbk). The other two were placed in front of the cavities (DC1 and DC2) to measure their signals (Vf1, Vb1, Vf2, and Vb2).

Two phase shifters were installed in the waveguides between the magic-tee and the cavities to estimate the influence of the reflected RF power caused by the setting error of the waveguide and cavities.

KLYSTRON PERFORMANCE

In order to estimate the influence of the reflected power on the klystron's performance, both of the cavity waveguides were shorted by end plates instead of cavities. The reflected power to the klystron was adjusted by changing the phase length of the phase shifter. The VSWR measured at directional coupler DCk was under 2.0 within ±20° of the phase length from the position of minimal reflection, as shown in Fig. 3. This was consistent with the estimation from the simulation. This tolerance was sufficiently wide in comparison with the expected phase difference caused by the configuration error (about 5°).

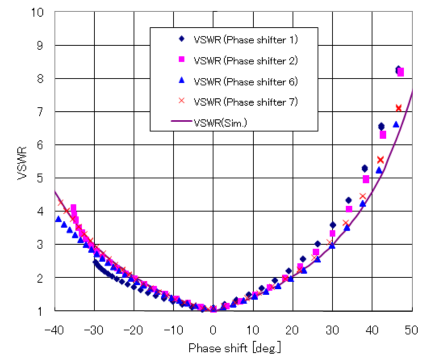

Figure 3: VSWR results caused by phase length difference.

RELATION BETWEEN VSWR AND CAVITY DETUNING

The phase of the cavity voltage signal (Vt) and the reflection signal from the cavity (Vb) are affected by the cavity detuning. In the case of operation without the beam, the phase difference between the cavity voltage signal (Vt) and the forward signal to the cavity (Vf) is half that of the phase difference between the reflected signal (Vb) and the input signal (Vf). If the detuning values for the two cavities are not equal, the cancellation of the reflected power from the cavities is insufficient and the reflected power to the RF source would take place.

The detuning of the cavity during an RF pulse is estimated using Vf and Vt:

$$r\dot{\varphi} - r\Delta\omega = \omega_{1/2}\rho\sin(\theta - \varphi) \quad (1)$$

where r and ρ denote the cavity and cavity input amplitude; φ and θ, are the cavity phase and cavity input phase; and $\Delta\omega$ and $\omega_{1/2}$, are the cavity detuning and half-bandwidth of the cavity, respectively. The observed Vf signal is a mixture of the forward and backward signals of the cavity caused by the finite directivity (20–30 dB) of the directional coupler. To calculate the cavity detuning, Vf and Vb are corrected using the measured directivity [2].

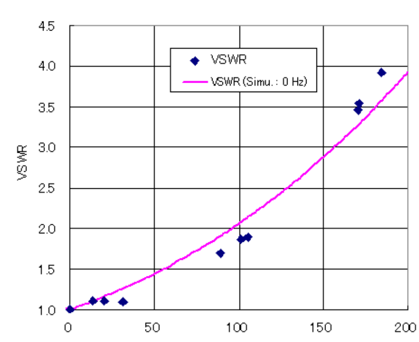

Figure 4: Effect of cavity detuning difference on VSWR results.

Figure 4 shows the correlation between the detuning differences between the cavities at the pulse flattop and its VSWR. The detuning of the cavity was calculated using eq. (1). The VSWR calculated by the simulation, including the cavity detuning difference, is shown by a purple line in Fig. 4 and agrees well with the VSWR observed at DCk. From this agreement, it is concluded that the calculation of the cavity detuning based on eq. (1) is effective even in the circulator-less waveguide distribution system.

For stable operation of the DRFS, the VSWR should be suppressed to less than 2. This is achieved by controlling the cavity detuning difference within 100 Hz in a case where the Ql of each cavity is equal to 2.4×10^6. The ILC requires suppressing the cavity detuning at the pulse flattop to within 50 Hz to guarantee the power margin of the RF source. If the requirement for regulating the cavity detuning is met, a stable operation of the RF system will be carried out.

FIELD STABILITY UNDER FEEDBACK OPERATION

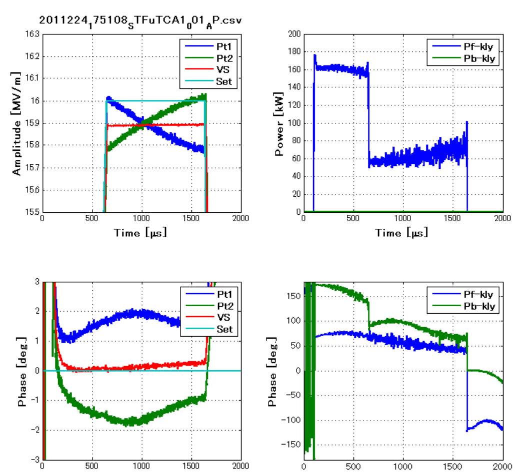

Figure 5: Amplitude and phase of each cavity and the vector sum (left), klystron output power, reflected power, and their phases (right).

Figure 5 shows the results of the vector sum feedback operation at 16 MV/m accelerating field with a proportional gain of 145. In order to evaluate the stable feedback operation range, the cavity detuning and the phase length were changed using the piezo tuner and the phase shifter under the feedback operation.

Figure 6 shows the correlation between the cavity detuning difference and stability of the amplitude and phase of the accelerating field at the flattop. When the cavity detuning difference reached ±200 Hz, an amplitude stability of 1.3×10^{-4} (rms) and phase stability of 0.04° (rms) were achieved with the feedback operation. Moreover, after changing the phase length by ±20° using the phase shifter, the amplitude and phase stability were estimated, and an amplitude stability of 1.3×10^{-4} (rms) and phase stability of 0.04° (rms) were verified with the feedback operation. These evaluated amplitude and phase stabilities satisfy the ILC requirements of 0.07% for the amplitude and 0.24° for the phase.

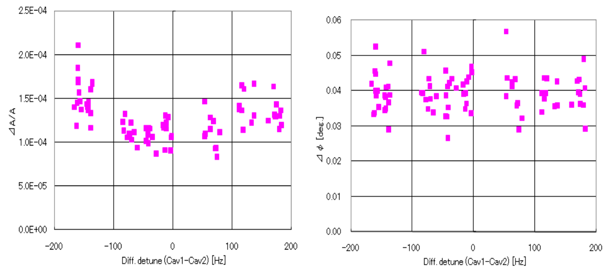

Figure 6: Correlation of cavity detuning difference with stability of amplitude (left) and with phase (right) at RF flattop under feedback operation.

FUTURE PLAN

At STF/KEK, the construction for the Quantum Beam experiment has been progressing and operation will begin in the spring of 2012. In this experiment, the electron beam (an average DC current of 10 mA, 62 pC per bunch, 6.15-ns bunch spacing, 1-ms pulse width) emitted from an RF gun will be accelerated up to 40 MeV using two superconducting cavities [5]. The DRFS is planned to as the RF system for the cavities. In the Quantum Beam experiment, the demonstration of the DRFS under the beam operation required for the ILC will be carried out because the average DC beam current of the Quantum Beam experiment will be almost the same as that of the ILC (9-mA average DC beam current).

SUMMARY

The demonstration of a DRFS with circulator-less waveguide distribution was carried out. The VSWR calculated using the phase length and cavity detuning difference was consistent with the measured VSWR, and the range of stable RF operation was evaluated. Feedback operation was carried out under various conditions and it is concluded that the stabilities of the amplitude and phase satisfied the ILC requirements.

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