CRYOMODULE TESTS OF THE STF PHASE-1 AT KEK

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Abstract

A 6-m cryomodule including four Tesla-like cavities was assembled, and was tested as the STF phase-1.0 at KEK. The performance as a total superconducting cavity system was checked in the cryomodule test at 2 K with high rf power. One of four cavities achieved a stable pulsed operation at 32 MV/m higher than an operating accelerating gradient in ILC. The maximum accelerating gradient, Eacc,max, obtained in the vertical cw tests was maintained or slightly improved in the cryomodule tests operating in a pulse mode. Compensation of Lorentz force detuning at 31 MV/m was successfully demonstrated by a piezo tuner and pre-detuning.

INTRODUCTION

Construction of Superconducting RF Test Facility (STF) has been carried out at KEK for the future International Linear Collider (ILC) project, since 2005. The main purpose of the STF is to develop cryomodules containing high gradient cavities, which can be stably operated at an average accelerating gradient of 31.5 MV/m. A superconducting cavity system, which includes four Tesla-like 9-cell cavities, input couplers and frequency tuners, was designed and fabricated, [1]. The component tests of the 9-cell cavities [2] and the input couplers [3] were carried out in order to qualify their performances. In the first step called the STF phase-0.5, a 6-m cryomodule containing one Tesla-like cavity had been tested in 2007. Overall superconducting cavity system had worked well without any big troubles in the initial test, [4 and 5].

In the second step called the STF phase-1.0, assembly of the cryomodule containing four Tesla-like cavities was started in Jan. 2008. After installation in the tunnel and cooling-down of the cryomodule, high power tests at 2 K were carried out in July-Dec. 2008. The purposes of the cryomodule test in the STF phase-1.0 are as follows:

- To check the performance as a total superconducting cavity system, and to find out the improvement points for the future project.
- To confirm a stable pulsed operation at higher fields, and to compare the achieved Eacc,max in the cryomodule tests with the results in the vertical tests.
- To demonstrate a compensation of Lorentz force detuning by a piezo tuner, and to establish the effectiveness of an improved stiffness in a cavity support structure.

In this paper, high gradient performance of four Tesla-like cavities in the cryomodule tests is mainly described.

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ASSEMBLY OF CRYOMODULE

Assembly procedure of the STF cryomodule is summarised as follows:

- In a class-10 clean room, string assembly of four cavities were performed. Attachment of input couplers with a cold rf window and HOM pick-up antennas, connection with a bellow duct between two cavities and installation of a gate-valve in each end beam-tube were carried out, (Figure 1, left).
- In a class-1000 clean room, after vacuum leak-check of the string cavities, argon gas was introduced very slowly for ~40 hours up to an atmospheric pressure, (Figure 1, right).
- At an outside area of a clean room, attachment of frequency tuning system and alignment of four cavities were carried out, (Figure 2, left).

Figure 1: String assembly in a class-10 clean room (left) and vacuum leak-check in a class-1000 clean room (right).

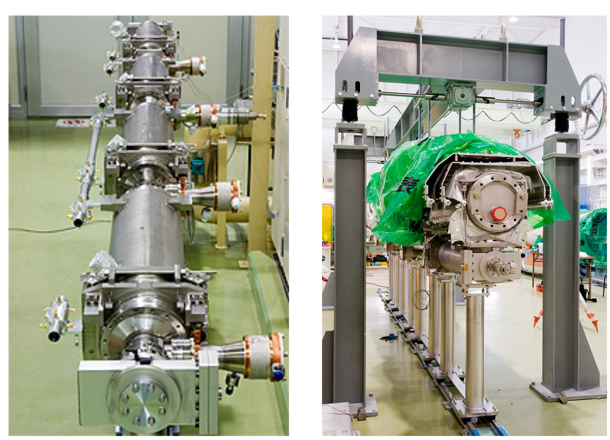

Figure 2: Alignment of four cavities (left) and hanging the string cavities on a GRP (right).

- At a cryomodule assembly area, the string cavities were hung on a helium gas return pipe (GRP), and the cavities were covered with 5 K and 80 K thermal shields, (Figure 2, right).
- An assembled cold mass including four Tesla-like 9-cell cavities was inserted into a vacuum vessel, as shown in Figure 3.
- The completed STF cryomodule was installed in the tunnel. The cryomodule was connected with a cold box for supplying liquid helium and liquid nitrogen. Input couplers of four cavities were connected with a high power rf source through an rf power distribution system [6] consisting of waveguides, circulators, power dividers and directional couplers, as shown in Figure 4.

Figure 3: Insertion of an assembled cold mass into a vacuum vessel.

Figure 4: Installation of the cryomodule in the STF tunnel.

PROCESSING OF INPUT COUPLERS

Prior to combine with the 9-cell cavities (see, Figure 1), processing of the input couplers were carried out at a high power test stand with a pulsed klystron of 5 MW. RF processing was initially started in a short pulse operation of 10 or 100 μsec, and rf power level was increased very carefully. Finally, rf processing up to 1.0 MW in a pulsed operation with 1.5 msec and 5 Hz was successfully performed in four input couplers. The processing time at the test stand was about 50 hours, as shown in Figure 5.

After installation of the cryomodule in the STF tunnel, connection of a warm coupler with a cold coupler was carried out in a working area covered with a special clean booth to keep a clean environment. In-situ baking of cold rf windows inside the cryomodule was carried out at 85°C for 15 hours. Baking of the cold rf windows prior to rf processing is very effective to reduce the processing time. Rf processing of the input couplers at room temperature before cool-down was carried out up to 240-330 kW under the total reflection condition. The processing time was 11-17 hours, as shown in Figure 6. Processing of the No.3 coupler (C/#2 cavity) was carried out twice, and the processing time in the second was remarkably short. It is considered that a memory of the previous processing has been preserved.

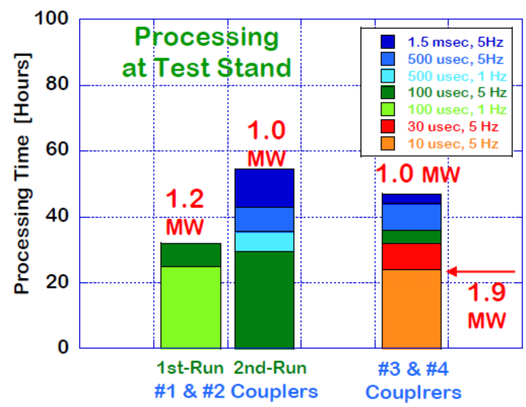

Figure 5: Processing time of two pairs of input couplers at the test stand under the matching condition.

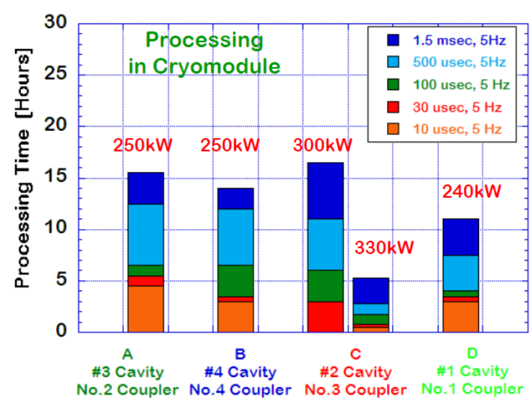

Figure 6: Processing time of four input couplers in the cryomodule under the total reflection condition.

TUNER PERFORMANCE

Slide-Jack Tuner

Tuning characteristics of four cavities in low power rf measurements at 2 K is shown in Figure 7. The dynamic range of the frequency change was 600~800 kHz, and the frequency sensitivity was about 300 kHz per mm, as expected. However, one cavity (A/#3) showed the strange performance, and the reason might be due to a mistake of adjusting a true frequency in the pre-tuning at room temperature. Therefore, an operating rf frequency was changed from 1300.000 MHz to 1300.500 MHz in order to drive simultaneously four cavities, as shown in the orange lines in the figure.

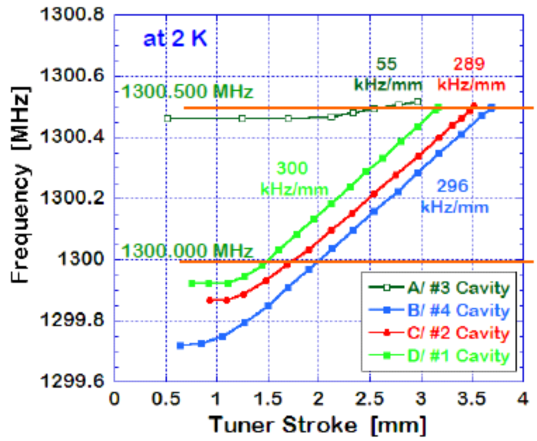

Figure 7: Frequency shift vs. a tuner stroke, equivalent to change of a total cavity length by a slide-jack tuner.

Piezo Tuner

Optimization of timing, frequency, amplitude and waveform of the drive pulse signal to a piezo tuner is important for an effective compensation of Lorentz force detuning. The maximum load of 5 kN and the stroke at a low temperature of about 4 µm are required. Three low voltage type (max. +150V) and one high voltage type (max. +1000V) piezo elements were set in the piezo tuner of four cavities, in order to compare their performances. Measurement of pulse response signals driven by the piezo tuner and the results of the frequency change, Δf, are shown in Figure 8. The frequency change of more than 300 Hz was obtained in the high voltage type (+500V). On the other hand, the frequency change in the low voltage type (+100V) was considerably lower than an expected Lorenz detuning frequency (-350 Hz) at 31.5 MV/m. Improvement of the piezo tuner system with the low voltage type is needed for the next step.

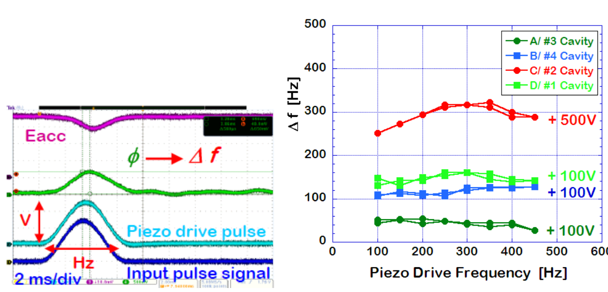

Figure 8: Pulse response signals driven by a piezo tuner with a single pulse (left) and the frequency change (Δf) as a function of a drive frequency with a piezo tuner (right).

HIGH FIELD PERFORMANCE

One of four cavities achieved a stable pulsed operation at 32 MV/m higher than an operating accelerating gradient in ILC. The typical pulse signals without and with an rf feedback control are shown in Figure 9. The input rf power of 340 kW was reduced to 240 kW (70%) after 0.5 msec by a step pulse. Although change of the cavity phase and decrease of the accelerating gradient were seen in the left figure, they were precisely kept to be constant by the rf feedback control in the right figure, [7]. Comparison of the maximum acceleration gradient, Eacc,max, obtained in the cryomodule test with that in the vertical test is shown in Figure 10. The average Eacc,max in the vertical tests and the cryomodule test (1.5 msec) were 22.7 MV/m and 23.7 MV/m, respectively. Therefore, it is concluded that the cavity performance have been maintained in the cryomodule with no severe degradation. Since the average Eacc,max in the shorter pulse-width of 0.6 msec (0.1 msec at flat-top) was 28.3 MV/m, it is considered that the achievable Eacc,max might be limited by a total amount of the heat loss at the hot spot.

The observation of x-rays radiation in each cavity is shown in Figure 11. Heavy x-ray radiation due to field emission higher than 100 µSv/h was detected by a sensor located just under the cryomodule. Contamination by dust particles during connecting with a beam-tube in the STF tunnel might be considered as one of the potential causes.

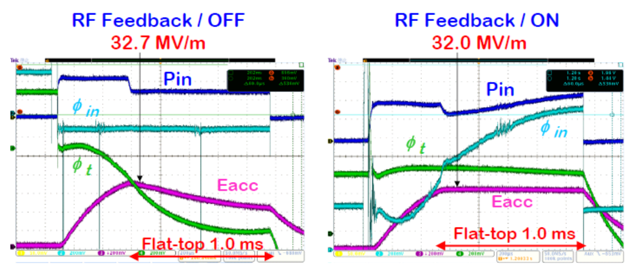

Figure 9: Pulsed signals at high field operation without an rf feedback control (left) and with rf feedback control (right). The light blue line is an input phase (ϕ_{in}) between an input rf power and a reference. The green line is a cavity phase (ϕ_t) between a transmitted rf power through a cavity and a reference. The dark blue line is an input rf power, and the pink line is an accelerating gradient.

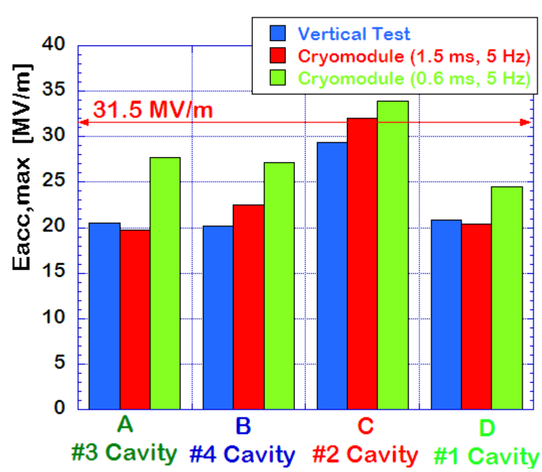

Figure 10: Comparison of Eacc,max between in the vertical cw tests and in cryomodule tests in the pulsed operation with 1.5 msec / 0.6 msec and 5 Hz.

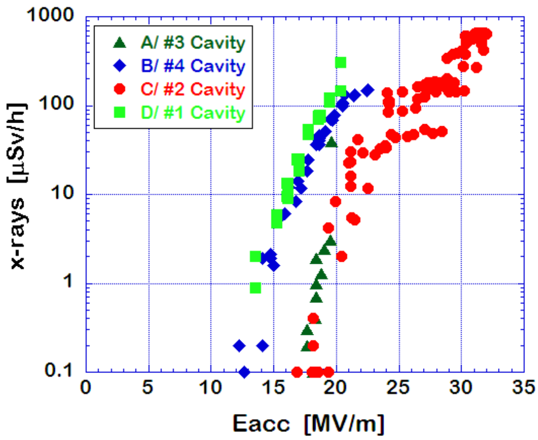

Figure 11: Relation between x-ray radiation levels and accelerating gradients in four cavities in the pulsed operation with 1.5 ms and 5 Hz.

LORENTZ FORCE DETUNING

A resonant frequency of a cavity gradually lowers due to deformation of a cell-shape by Lorentz force during an rf pulse. Figure 12 shows an example of Lorentz force detuning at 30 MV/m in a stable pulsed operation with 1.5 msec and 5 Hz. The observed detuning frequency, Δf,

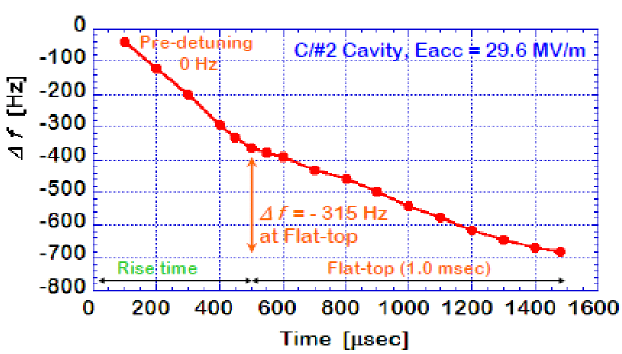

Figure 12: Observation of Lorentz-detuning frequency (Δf) at 30 MV/m measured by a pulse-cut method, [7]; rf feedback control/ON, pre-detuning/0 Hz, piezo tuner/OFF.

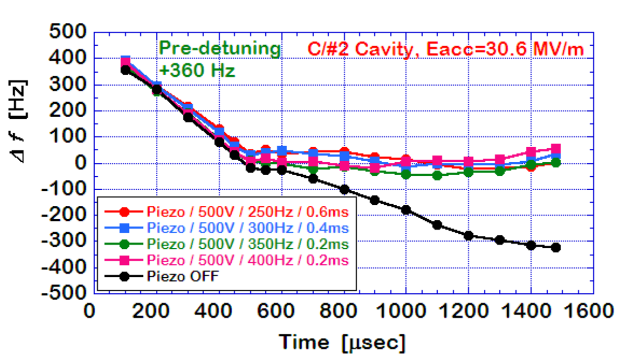

Figure 13: Successful compensation of Lorentz force detuning by pre-detuning and a piezo tuner. The data in a case of no piezo drive (black dots) is added for the comparison. (The detailed result is reported in ref. [8].)

during the rise time of 0.5 msec and the flat-top of 1.0 msec was -360 Hz and -315 Hz, respectively. The detuning frequency in the rise time can be compensated by pre-detuning or off-set detuning, which is to set a resonant frequency of a cavity higher than a drive frequency of an rf power source in advance, (see, Figure 13). The detuning frequency at the flat-top is necessary to compensate by using a piezo tuner. The detuning frequency of -315 Hz at 30 MV/m was relatively much lower than that in the Tesla cavity tested at DESY, and this was resultant in the improved stronger stiffness in the Tesla-like cavity. This effect is helpful to reduce the required piezo stroke and to minimise the tuning error at flat-top by compensation.

Successful compensation of Lorentz force detuning at 31 MV/m by pre-detuning and a piezo tuner is shown in Figure 13. The pre-detuning was adjusted to +360 Hz, and the parameters of the piezo drive pulse were optimised to the drive frequency of 250, 300, 350, 400 Hz with the suitable delay time between a piezo drive pulse and an rf pulse in the fixed applied voltage of +500V. The tuning error less than +/- 50 Hz at the flat-top, which is a target value in ILC, was achieved in the wide parameter range to drive the piezo.

DYNAMIC LOSS MEASUREMENT

Dynamic rf loss was measured at 2 K by a flow rate of the evaporated helium gas in the cryomodule, [4]. Total rf loss of four cavities being operated with the vector-sum control [7] on resonance is shown as a function of the average input power to four cavities in Figure 14, together with the total heat load at four input couplers (off resonance). Difference of these two values means the net rf loss in the cavity inner surface. The measured heat load at 2 K at the input couplers was much higher than a calculated value of 0.03 W per one coupler at an input power of 350 kW.

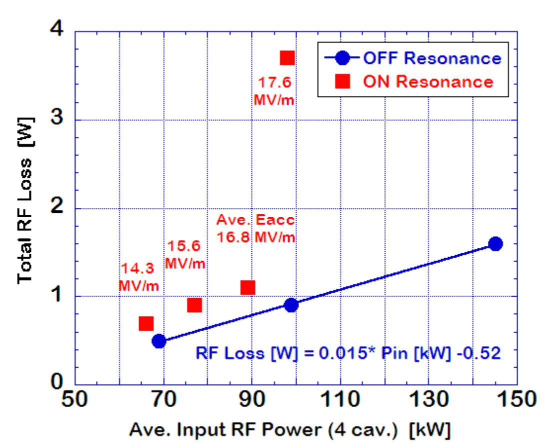

Figure 14: Measurement of the dynamic rf losses at 2 K in the four-cavity simultaneous operation with off-resonance (blue) and on-resonance (red). Measured static loss of 9 W has been already subtracted in this figure.

The rf loss in the cavity inner surface gives a Qo value, as shown in Figure 15. Although the Qo values drops due to field emission as seen in Figure 11, the Qo values of higher than 10^{10} at the lower fields are shown in the figure. This result indicates a good shielding effect of the magnetic shield inserted in the helium vessel.

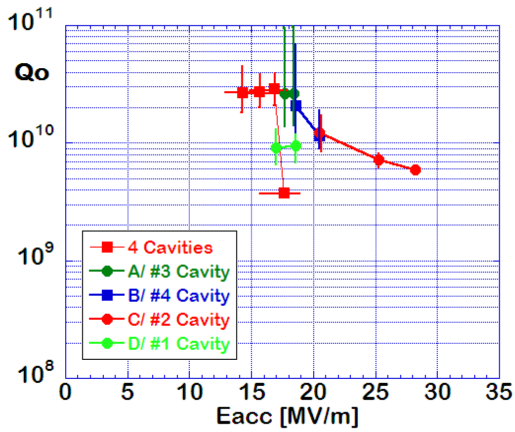

Figure 15: Unloaded Q values (Qo) calculated from the results of the dynamic rf loss measurement at 2 K.

SUMMARY

Two notable progresses were made in this cryomodule tests containing four Tesla-like 9-cell cavities:

- A stable pulsed operation at 32 MV/m was confirmed in one cavity with no severe degradation from the vertical test results.
- Successful compensation of Lorentz force detuning at 31 MV/m was demonstrated by pre-detuning and a piezo tuner.

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