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STABLE BEAM OPERATION AT 33 MV/m IN STF-2 CRYOMODULES AT KEK

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Abstract

In STF at KEK, as the operational demonstration of the SRF accelerator for ILC, the STF-2 cryomodules (CM1+CM2a: one and half size CM with 12 cavities) have achieved 33 MV/m as average accelerating gradient with 7 cavities in Mar/2019. After that, one cavity with the lowest performance installed in CM2a was replaced with one N-infused cavity developed for High-Q/High-G R&D between Japan and US. From Apr/2021, the beam operation started again and those CMs achieved 33 MV/m as average accelerating gradient with 9 cavities including one N-infused cavity again. This is remarkably important milestone for the ILC project. In this report, the detailed results will be presented.

INTRODUCTION

In the Superconducting RF Test Facility (STF) of the High Energy Accelerator Research Organization (KEK), research and development of superconducting cavities and cryomodules (CMs), which are the core technologies for the International Linear Collider (ILC) project [1, 2], has been promoted since 2006. There are four experimental projects that have been implemented so far, as shown in Table 1. In STF-2, a total of 6 cooldown tests have been conducted, and only the low power test was carried out in the 1st and 5th cooldown tests.

Table 1: Four Projects Performed in STF

Project	Experimental period
STF Phase-1 (STF-1) [3]	F.Y. 2008~2009
S1-Global [4]	F.Y. 2010~2011
Quantum Beam [5]	F.Y. 2012~2013
STF Phase-2 (STF-2, 1st) [6]	F.Y. 2014
STF-2, 2nd	F.Y. 2015
STF-2, 3rd [7]	F.Y. 2016
STF-2, 4th [8]	F.Y. 2018
STF-2, 5th	F.Y. 2020
STF-2, 6th [9]	F.Y.2020~2021

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Since the ILC is an energy frontier machine, it is required to operate at the highest accelerating gradient possible, and STF has been developing superconducting cavities that can reach the higher accelerating gradient. Nine 9-cell cavities that reached the ILC spec of 35 MV/m or higher in vertical test (VT) were installed in the STF-2 CMs, which started experiments in 2014 (12 cavities for the entire cryomodule), and from February to March 2019. In the 4th cooldown test conducted, beam operation was performed with a high accelerating gradient exceeding the ILC specifications. Table 2 shows the ILC specifications for beam operation. In the Quantum Beam project shown in Table 1, one small CM with two cavities was developed and operated for beam acceleration. This CM is used as Capture CM (CCM) in the STF-2 accelerator.

Table 2: ILC Specification in Beam Operation [9]

Item	Specification
Accelerating gradient	31.5 MV/m
Q_0	1.0×10^{10}
Drive Frequency, Mode	1.3 GHz, TM_{010}, π-mode
Cavity fill time	924 μsec
Beam pulse length	727 μsec
Total RF pulse length	1650 μsec
Pulse repetition rate	5 Hz
Beam current	5.8 mA
Operational temperature	2 K

CAVITY REPLACEMENT

After the 4th cooldown test, CAV#9 with the lowest performance in the STF-2 CMs was replaced with a new cavity. This new cavity experienced nitrogen infusion (N-infusion) process as a new surface treatment recipe for the higher performance. This is the plan being promoted by Japan-US collaboration since 2017. This cavity replacement work was the first time in STF (not ever done in the past projects). From mid. of Aug/2019, the disassembly work of CM2a started, pulled out of the tunnel, and cavity string

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was installed in the clean room at the end of Jan/2020. Around mid. of Feb/2020, cavity replacement work was done, and CM2a was installed in the beamline again at the end of Mar/2020. On Jun/2020, the completion inspection of CM2a was done by local government in Ibaraki-ken prefecture to carry out cooldown test again. On Sep/2020, 5th cooldown test was done to carry out the tuner drive test by low power. As a result, it turned out that there was no problem in driving the tuner system including piezo for every cavity. Figure 1 shows the cavity replacement work. Table 3 is the summary of this work.

Figure 1: State of CAV#9 replacement work.

Figure 2 shows the schematic view of the STF-2 accelerator. The RF Gun system, which cathode deposition chamber was replaced with a new one in 2020, is operated at 4 MW. There are two bending magnets at downstream of each CM (CCM and STF-2 CMs) where beam energy can be measured. Totally, 14 9-cell cavities (2 for CCM, 8 for CM1 and 4 for CM2a) are used for the cooldown test.

Table 3: Summary of CAV#9 Replacement Work

Date	Content
Aug/2019	Disassembly of CM2a
Nov/2019	Pulling CM2a out of tunnel
Jan/2020	Installing cavity string in clean room
Feb/2020	Replacing CAV#9 with n-infused cavity
Mar/2020	Installing CM2a in beamline
	Work was stopped due to COVID-19
Jun/2020	Completion inspection by local government
Sep/2020	5th cooldown test

PERFORMANCE OF CAVITY AND CM

In the 4th cooldown test, the waveguide system was connected to only 8 cavities, however, in the 6th cooldown test, that was connected to all 12 cavities installed in the STF-2 CMs. At room temperature, RF conditioning for all power couplers including two ones in Capture CM were done as the following RF condition:

- 400 kW up to 900 µsec/5 Hz
- 100 kW at 1.65 msec/5 Hz

From 8/Feb, the cooldown for all CMs started, and reached 2K on 15/Feb. After checking the measurement system, which is the consistency check (done around 3 MV/m) in the accelerating gradient obtained from each of P_{for} and P_{tra}, RF conditioning for all cavities was done and the highest accelerating gradient was checked for them.

Accelerating Gradient

The accelerating gradient is the most important parameter for the ILC, and has been measured in several cooldown tests in the STF-2 project. Figure 3 shows the comparison of accelerating gradient between last VT and 6th cooldown test of CMs. CAV#9 is the cavity that was replaced in F.Y.2020 after N-infusion process. This cavity had heavy field emission (F.E.) in the last VT, however, no degradation in the accelerating gradient occurred in this cooldown test. In the 2nd cooldown test done in 2015, significant performance degradation was observed in the three cavities (CAV#5-CAV#7) in CM1, however, in this cooldown test, the performance of CAV#5 improved drastically. This is the first case in STF. The performance of the remaining two cavities (CAV#6, #7) remained low as before. The performance degradation was observed in CAV#1 and CAV#2 in CM1, even though they were under vacuum with the both sides closed by gate valves for the past two years after the 4th cooldown test done in 2019. The cause of this is not well understood, yet.

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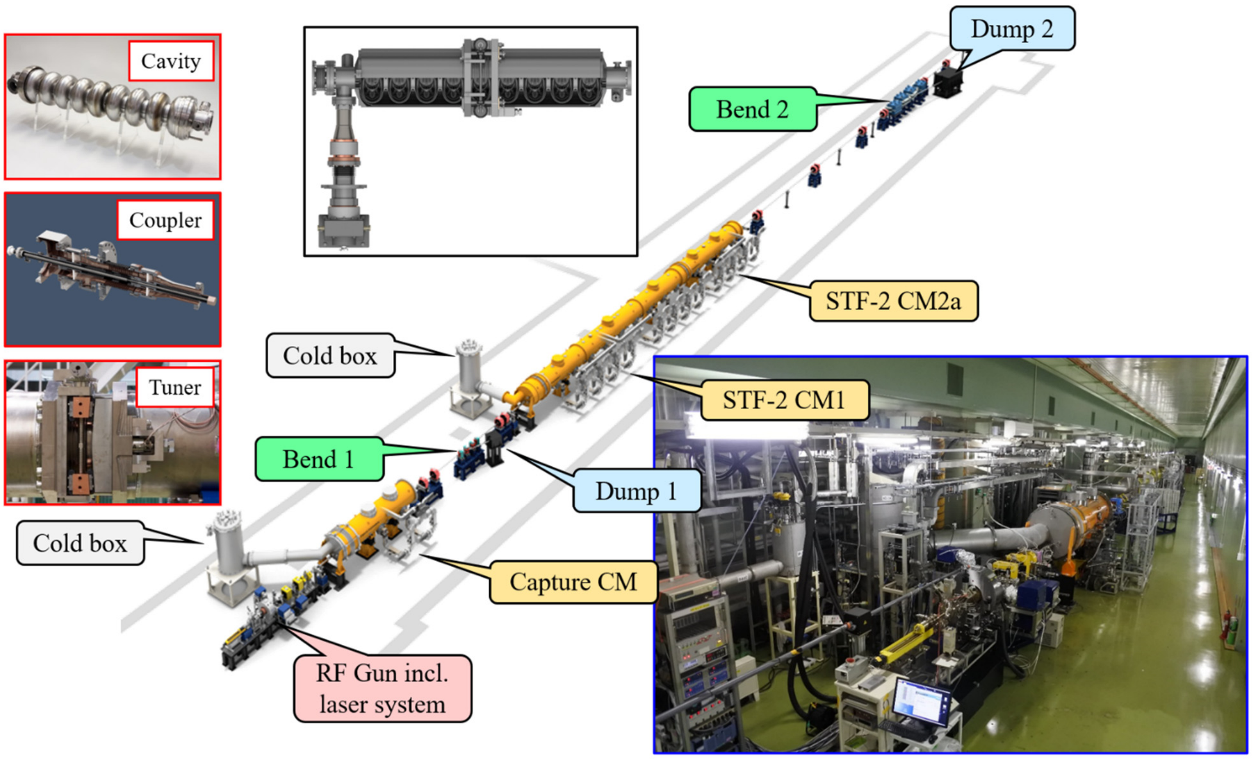

Figure 2: Schematic view of the STF-2 accelerator.

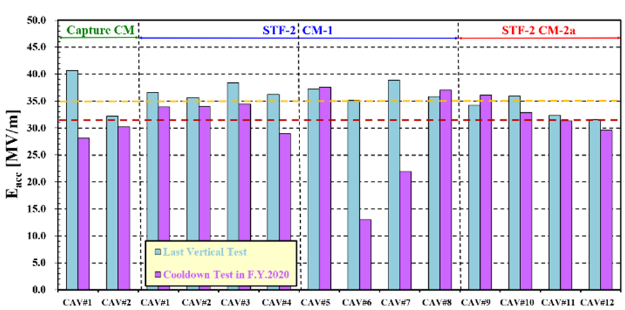

Figure 3: Comparison of accelerating gradient between last VT and 6th cooldown test of CMs. Two dotted lines show the specifications for VT and CM test.

Radiation Dose and Onset Gradient

The measurement of the radiation level is the best method to monitor changes in cavity conditions. Generally, after the long-term operation of SRF accelerator, cavity performance tends to degrade due to the influence of dust coming from the outside of gate valves or themselves, or the other causes. At STF, to check cavity conditions, the radiation level for every cavity at some locations (upstream, downstream, and middle of CM, and below the cavity being measured) has been measured several times. When measuring the radiation level, only one cavity is tuned, and the rest are detuned. Figure 4 shows the result for the radiation level below CAV#1 in CM1. Until 2019, there was no change in that, however, the higher level was observed in this cooldown test, even though this cavity was under vacuum after the 4th cooldown test as described in the previous section. As with the accelerating gradient above, the cause is not well understood.

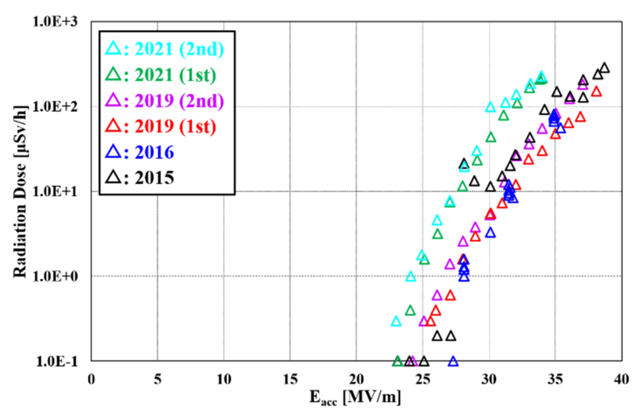

Figure 4: History of the radiation level for CAV#1.

Figure 5 shows the radiation level for CAV#9, newly installed into CM2a. During the RF conditioning on Feb/2021, heavy field emission was observed in all directions. However, after the beam operation for one month, the radiation level measured at the upstream of CM1, and CCM, has dropped drastically on Apr/2021. Similar results were observed in some other cavities.

It is also important to observe the radiation onset gradient for every cavity. Figure 6 shows the onset gradient for CAV#1 measured at four locations. There is no change in the onset gradient observed in the three directions (upstream, below cavity, and downstream) since the 2nd

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cooldown test in 2015, however, the onset gradient measured at the middle of CM, not below CAV#1, shows the trend of the degradation.

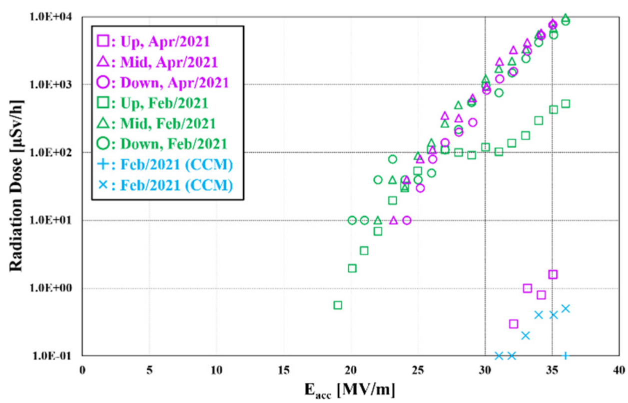

Figure 5: Radiation level for CAV#9.

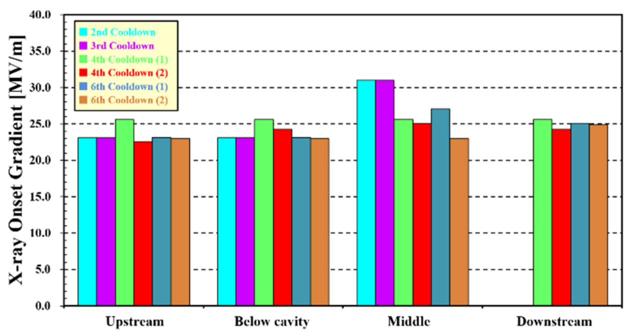

Figure 6: Onset gradient for CAV#1 measured at four locations.

Checking Q_{tra} as Evaluation of Systematic Error

The measurement of Q_{tra} is effective in evaluating the systematic error in the measurement of accelerating gradient. At STF, this has been done by low power test using network analyser. Figure 7 shows the result. The systematic error between the three measurements since 2014 was within a few percent. In 2021, only five cavities were measured due to the schedule. CAV#9 is a different cavity between 2014 and 2020 and beyond, as described before. This result means that the RF measurement system including the RF signal cables in STF-2 CMs has been remarkably stable.

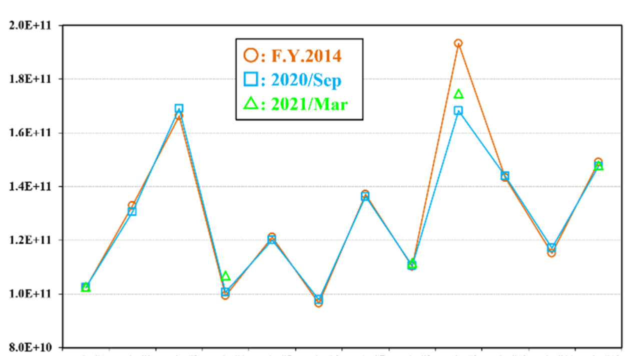

Figure 7: History of Q_{tra} from F.Y.2014.

BEAM OPERATION

From the end of Mar/2021, the beam operation started in injection mode, and the beam reached the beam dump #1. On Day2, the beam reached the beam dump #2 in linac mode. As shown in Fig. 2, since there are two bending magnets (Bend1 and Bend2) installed at upstream and downstream of CM1/2a, the energy difference measured at them is the energy gain in CM1/2a. Table 4 shows the beam parameters in STF-2 accelerator. From the viewpoint of radiation safety, only the allowable values are shown for the first three parameters.

After opening all gate valves installed at the upstream and downstream of all CMs, the condition of some cavities became unstable temporarily. This phenomenon was also observed during the 4th cooldown test, and some cavities had quench when shifting to the closed-loop operation. After the additional RF conditioning, all cavities have recovered to a stable state.

Table 4: Beam Parameters in STF-2 Accelerator

Parameters	Value
Max. allowable beam energy	500 MeV
Max. allowable beam intensity	3.0 μA
Max. allowable beam power	1.35 kW
Max. number of bunches per train	1000
Bunch spacing	6.15 nsec
Max. train length	6.15 μsec
RF repetition rate	5 Hz
Bunch charge	600 pC
Bunch current	97.5 mA

After checking the radiation safety and tuning the beam quality, the maximum beam energy reached 384 MeV with 14 cavities. After that, the beam operation was limited to 9 cavities with higher performance in CM1/2a, and the average accelerating gradient obtained from the difference of beam energy measured at Bend1 and Bend2 reached 32.9 MV/m. This is remarkably important milestone for the ILC project. Table 5 shows the summary including the previous beam operation performed in FY2018.

Table 5: Summary of Parameters Achieved in the Beam Operation of STF-2 Accelerator

Parameters	Mar/2019	Apr/2021
Number of cavities incl. CCM used for operation	7 + 2	12 + 2
Beam energy	280 MeV	384 MeV
Beam intensity	0.28 μA	1.8 μA
Beam power	78 W	677 W
Total charge per pulse	56 nC	360 nC
E_{acc} from beam energy	33.1 MV/m (7 cavities)	32.9 MV/m (9 cavities)
E_{acc} from RF power (P_{tra})	33.8 MV/m (7 cavities)	33.0 MV/m (9 cavities)

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During the highest beam current operation with 1000 bunches, beam loading was observed for all cavities as shown in Figure 8. In the left-down figure, around the middle part of flat-top of all RF signals, there is a small dent due to beam loading. At this time, compensation of beam loading was not done perfectly by the LLRF system. Since this may have caused beam loss in the downstream section of the beamline (actually, some components around there were activated temporarily after beam operation), therefore, it is planned to compensate for beam loading perfectly with lower bunch current in next beam operation. If the beam loss is reduced, the next goal of the STF-2 project is to increase the beam power by 5 times. In this case, the beam intensity, the length of bunch train, and the bunch current are equivalent to the ILC specifications as shown in Table 2. This is another milestone in the STF-2 project.

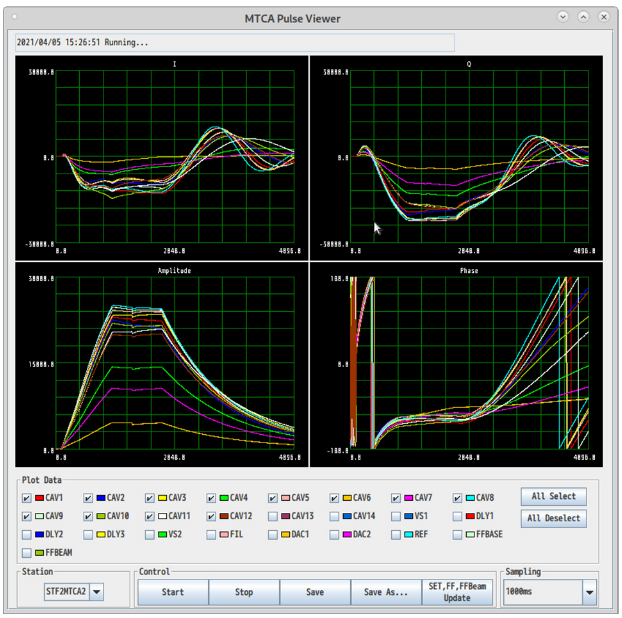

Figure 8: RF signals of all cavities in CM1/2a. In-phase, Quadrature, Amplitude, and Phase are shown.

CONCLUSION

The cavity replacement work for CAV#9 in CM2a was successfully done. In the 5th cooldown test of the STF-2 cryomodules, it was confirmed that there was no problem in driving all tuner systems. In the 6th cooldown test, beam acceleration test with 14 cavities including CCM was carried out, and it was confirmed that the average accelerating gradient obtained from the beam energy reached 32.9 MV/m, and the maximum beam energy reached 384 MeV. This is remarkably important milestone for the ILC project. The next goal is the beam operation with long bunch train as ILC. In this beam operation, the beam power will increase by 5 times.

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