TEST RESULTS OF THE INTERNATIONAL S1-GLOBAL CRYOMODULE

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Abstract

The S1-Global experiment is a collaborative project [1, 2] by INFN, DESY, FNAL, SLAC and KEK as part of the Global Design Effort (GDE) for the ILC. Eight superconducting RF cavities (two from DESY, two from FNAL and four from KEK) were installed into a cryostat. Three different types of frequency tuning systems (Blade tuner from INFN/FNAL, Saclay tuner from DESY/CEA-Saclay and Slide-Jack tuner from KEK) and two types of input couplers (TTF-III from DESY and STF-II from KEK) were implemented. In 2010-2011, operational tests were performed three times in the 2K environment, and many aspects of high-power pulsed operation of the cavities and associated hardware elements were studied, including: high power, cavity performance, Lorentz force detuning (LDF) and its compensation by Piezo actuators, simultaneous operation of cavities, static and dynamic heating loss, an RF system based on the Distributed RF Scheme (DRFS) [3] with LLRF (Low Level RF) feedback system. In this talk, results of the S1-Global cryomodule test are reported, discussed and summarized.

INTRODUCTION

The main motivation for the S1-Global project is to demonstrate an average accelerating gradient of 31.5 MV/m in a string of superconducting cavities in a common cryostat, as envisaged for the ILC whose design is under development by the GDE (Global Design Effort) [4], and the project was launched at the ILC GDE meeting in Mar/2008 [2]. For this work, eight cavities were contributed from DESY, FNAL and KEK, and installed into two ‘half cryomodules’, each 6-m long. One module (Cryomodule-C) is designed and newly built by INFN [5]. The other (Cryomodule-A) is a modification of an existing 6-m STF cryomodule [6], which was used in 2008 at the STF Phase-1 of KEK. Contributions of collaborating institutes are:

- DESY: Two TESLA type cavities [7] with Saclay-type tuners, and TTF-III power couplers.
- FNAL: Two TESLA type cavities, TTF-III power couplers, and integration of the INFN Blade tuners in the cavity packages.
- INFN: Design and construction of Cryomodule-C, and production and setting of the Blade tuners for the FNAL cavities.
- KEK: Four TESLA-like cavities including STF-II power couplers and Slide-jack tuners with two different set positions (centre or end) [8], modification of Cryomodule-A, power distribution, and infrastructure for the cryomodule tests including the software development.
- SLAC: Two sets of VTO power distribution for Cryomodule-C, and conditioning of FNAL power couplers at the test bench.

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S1-GLOBAL CRYOMODULE

The S1-Global project aims to operate 8 cavities with the average accelerating gradient of 31.5 MV/m in a way similar to what the ILC design envisages. It also serves an excellent platform for comparing the performance of the cavities, power couplers, tuners built by collaborating institutions in the world. Studies on the effect of the LFD and the compensation by piezo actuator in the high power operational conditions are particularly useful. Table 1 summarizes the hardware components that are implemented in Cryomodule-A and -C.

Table 1: Comparison of S1-Global cryomodules.

	Cryomodule-A	Cryomodule-C
Cavity type	TELSA-like	TESLA-type
Power coupler	Disk window	Cylindrical window
Coupling	Variable	Variable
Tuner type	Slide-jack	Blade/Saclay
Cavity package	KEK-a/KEK-b	DESY/FNAL
Magnetic shield	Inside jacket	Outside jacket
Package length	1247.6 mm	1247.4/1283.4 mm

Cavities

The eight cavities were fabricated by four cavity vendors: AES, ACCEL (RI), ZANON and MHI, and are names as: AES004 (C-1), ACC011 (C-2), Z108 (C-3), Z109 (C-4), MHI-05 (A-1), MHI-06 (A-2), MHI-07 (A-3) and MHI-09 (A-4). The cavity design of AES, ACCEL and ZANON is the TESLA-type, and that of MHI is the TESLA-like type, as shown in Figure 1. Their most notable difference is the mechanical stiffness of the end group. The TESLA-like cavity has a stiffer structure for the end plate of the helium jacket.

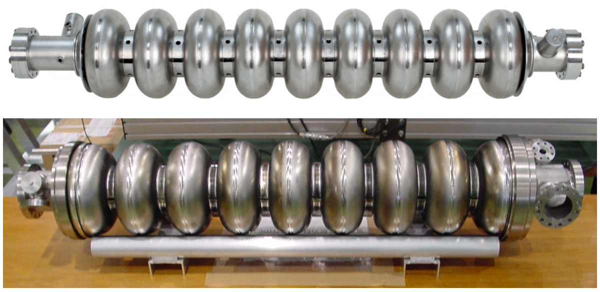


Figure 1: TESLA-type (top) and TESLA-like (bottom) cavities.

The average accelerating gradient of the eight cavities in the vertical test (V.T.) was 30.0 MV/m. The result is shown with that of the cryomodule test in Figure 8.

Power Couplers

Two types of power couplers, TTF-III and STF-II, were used in the S1-Global cryomodules. The most notable difference is in the designs of RF windows: TTF-III has a cylindrical window and STF-II has a disk type window. Both couplers have two windows on the warm and cold sides, and the coupling can be varied. Figure 2 shows the power couplers.

Figure 2: TTF-III (left) and STF-II (right) couplers.

Tuners

Three types of frequency tuners are used: Blade-type, Saclay-type and Slide-jack-type. Furthermore, the Slide-jack tuner has two different implementations for study: MHI-05 and -06 have the tuner located in the middle part of cavity along its length direction (KEK-a), and MHI-07 and -09 have the tuner located near the end (KEK-b). These tuners are shown in Figure 3. One of the critical study items at the S1-Global is to compare the performance of these tuners.

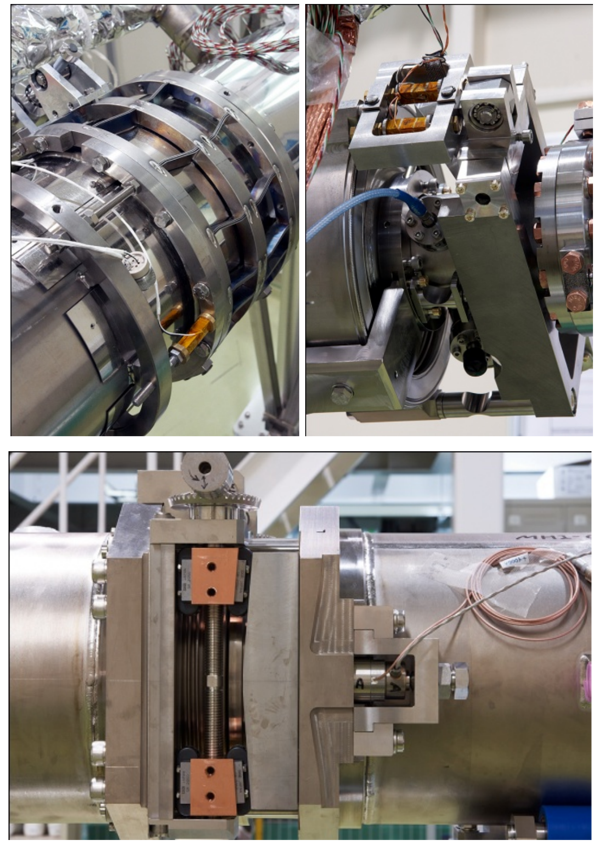


Figure 3: Blade (top-left), Saclay (top-right) and Slide-jack (bottom) tuners.

Cryomodules

The S1-Global cryomodule is separated into two half cryomodules, the Cryomodule-A designed by KEK and the Cryomodule-C by INFN. They were connected with each other with the flow lines of helium and nitrogen. The details of the S1-Global cryomodule are reported in [9]. Figure 4 shows their installation into the STF tunnel.

Figure 4: Status of installation into STF tunnel.

Assembly

Assembly work of the hardware systems for the S1-Global involves that of cavity strings, power couplers, tuners and cryomodules. The cavity string assembly was carried out in a class 10 clean room at STF by members from FNAL/DESY and KEK. The cold parts of power couplers, for four TESLA-like cavities and four TESLA-type cavities were assembled. Tuner systems were attached outside the clean room by members from

INFN/FNAL and KEK. In a cryomodule assembly area, the cavity string was hung underneath a helium gas return pipe, then they are covered with 5K and 80K thermal shields, and installed into vacuum vessels. After installation into the tunnel, the warm parts of the power coupler were attached by members from DESY and KEK. Figure 5 shows pictures of the assembly work in progress. More details are reported in [9].

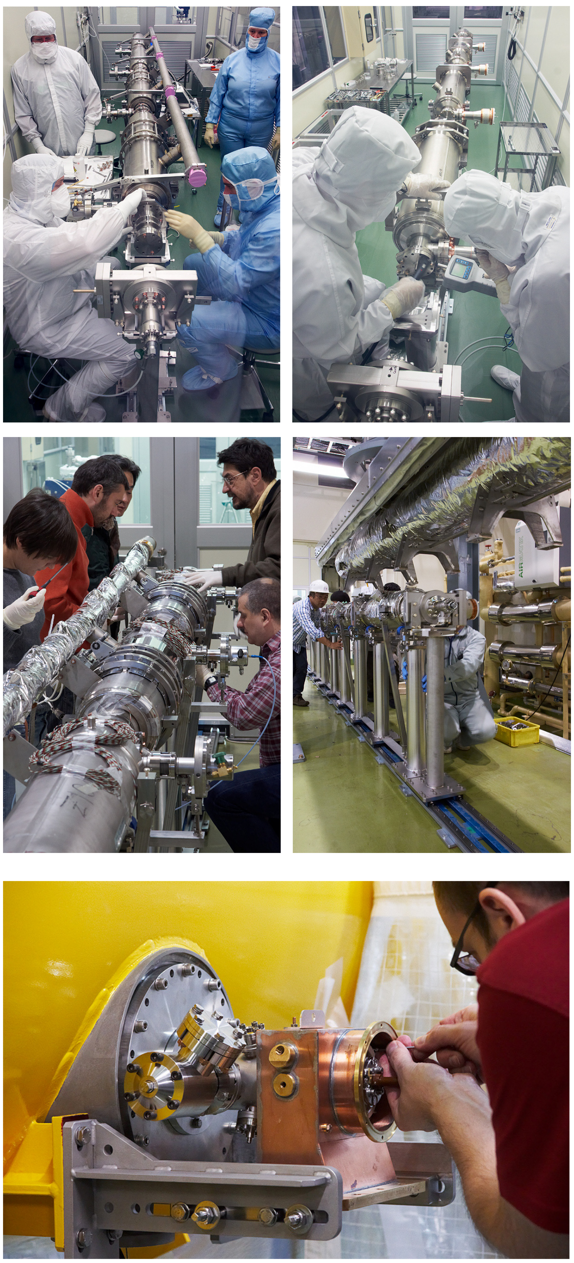


Figure 5: Assembly work of the cryomodules in progress.

COLD TESTS OF THE CRYOMODULES

Cold testing was performed from Jun/2010 to Feb/2011, interspersed by scheduled downtime and additional hardware work. The cryomodules were cooled down three times in total. The first cool-down test was carried out from June to July, 2011 for measurement of the thermal and mechanical performance of the cryomodules, together with RF tests of all cavities with low power [8, 9]. The second test was done from September to December, 2011 for check-up of the cavity performance, the LFD measurement, its compensation by piezo tuners, a long term operation, and the dynamic loss measurement with high power. The DRFS was tested in the third cold test [10] from Jan to Feb, 2011 by using two 800 kW klystrons that were placed in the tunnel.

Low Power RF Tests

In the low power RF tests [8] by INFN/FNAL/KEK team in the first cool-down, it was found that tuners attached in ACC011 and MHI-09 were not controllable, and it was not possible to set the frequency of these cavities to 1300.000 MHz, the canonical operation frequency. The trouble is presumed to cause by tension due to mechanical misalignment of tuner components (fuller analyses are to be performed soon). Therefore, simultaneous operation of multiple cavities is limited with 7 cavities rather than 8. Results of low power RF tests are shown in Figure 6.

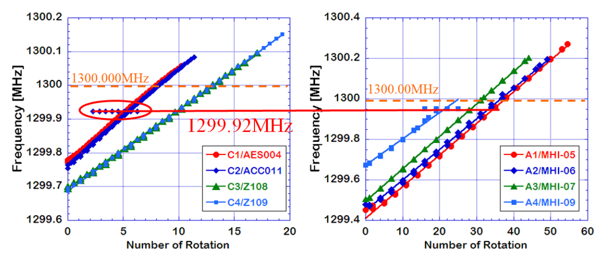


Figure 6: The result of the drive test for the motor tuner at low power. The tuner of ACC011 did not work at 2K, and MHI-09 could not be set to 1300.000 MHz.

On the other hand, adjustment of the variable coupling could be performed for all power couplers, and they were set to the optimum coupling of 2.4 x 10^6, giving to the pulse rise-up time of 540 μs, as shown in Figure 7.

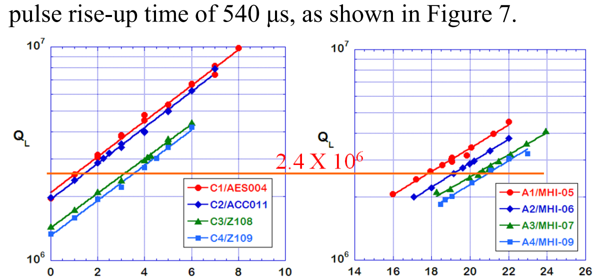


Figure 7: The results of the drive test for the variable coupling of the power couplers.

Cavity Conditioning

After the second cool-down, the cavity conditioning with high power was carried out by members from DESY and KEK. The achieved gradient values in vertical and cryomodule tests are shown in Figure 8. The maximum average gradient is 30.0 MV/m at vertical test, 27.7 MV/m for single cavity operation and 26.0 MV/m for simultaneous operation of seven cavities (presented later) at cryomodule test. The gradient of the two cavities (ACC011 and Z108) was significantly reduced in the cryomodule. Issues during the assembly processes are suspected. This problem should be certainly addressed in the real ILC.

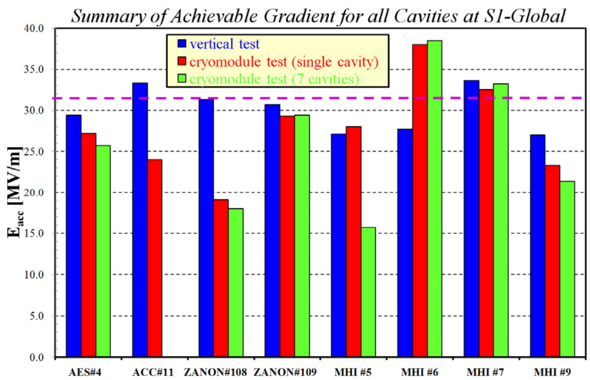


Figure 8: The achieved gradient values for eight cavities in vertical and cryomodule tests. The maximum average gradient is 30.0 MV/m at vertical test, 27.7 MV/m for single cavity operation and 26.0 MV/m for simultaneous operation of seven cavities at cryomodule test. The purple dotted line shows 31.5 MV/m of the ILC specification.

Power Coupler Conditioning

RF conditioning was done for all power couplers at a room temperature. The standing wave remains in the power coupler due to total reflection. The achievable power was 500 kW for pulse width of 500 μs and 200 kW for 1500 μs at a repetition rate of 5 Hz. The average conditioning time was 21 hours for TTF-III-type couplers and 13 hours for STF-II-type, respectively. The difference between them is probably due to the structure of the RF window. All RF windows did not have any vacuum leaks during the S1-Global experiments.

Measurement of Mechanical Vibration with Piezo

Mechanical vibration modes were measured in the low power condition for all cavities. In addition, for MHI cavities, measurements were done by using a piezo response in the high power condition. The observed dominant mechanical modes exhibited considerable variations, as shown in Figure 9. This is presumably due to different mechanical constraint conditions. The dominant mode found are as follows: 540 Hz for MHI-05, 220 Hz for MHI-06, 325 Hz for MHI-07, 210 Hz for MHI-09, 179 Hz for AES004, 204 Hz for ACC011, 260 Hz for Z108 and 245, 252 Hz for Z109. The first order mechanical vibration mode is known to have a frequency of around 200 Hz.

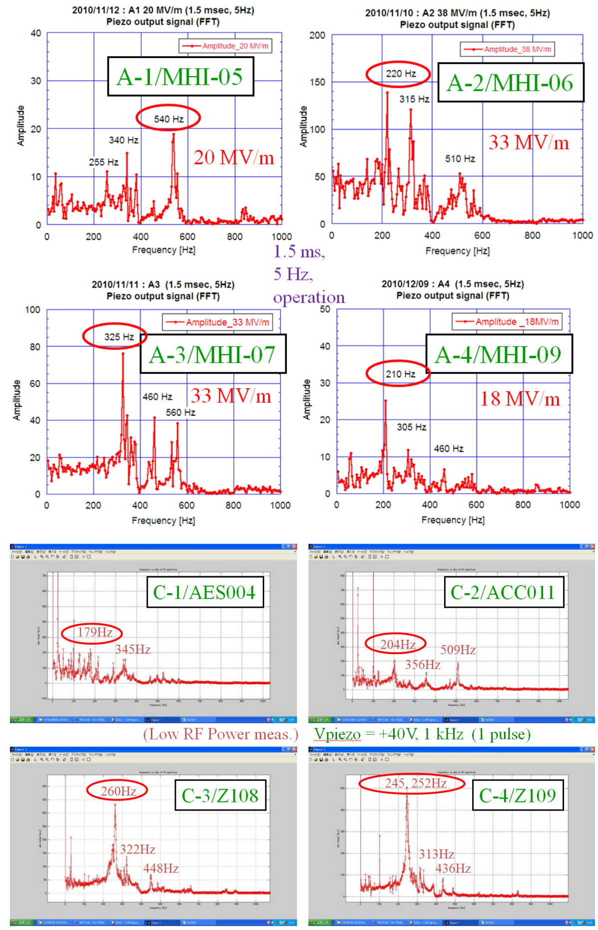


Figure 9: The result of the mechanical vibration modes measured at high power for Cryomodule-A, and at low power for Cryomodule-C.

LFD Measurement

After conditioning, the LFD measurement for each cavity was carried out by members from FNAL and KEK. The KEK team used the 'pulse shortening' as a measurement method, which is the standard method at KEK. The Figure 10 shows an example of the pulse shortening method for MHI-06 with each step of 50 μs. The Figure 11 shows the examples of the linear fitting range at the pulse end for the evaluation of Q_L and the detuning frequency (Δf) with the pulse width of 1,500 μs and 450 μs. The fitting range is about 40 μs from the pulse end for the both pulses. Figure 12 shows the results of the LFD measurement at the maximum gradient for every cavity. The points at the pulse width of 0.0 μs are the extrapolation values by the quadratic curve fitting for the measured points in the rise-up period.

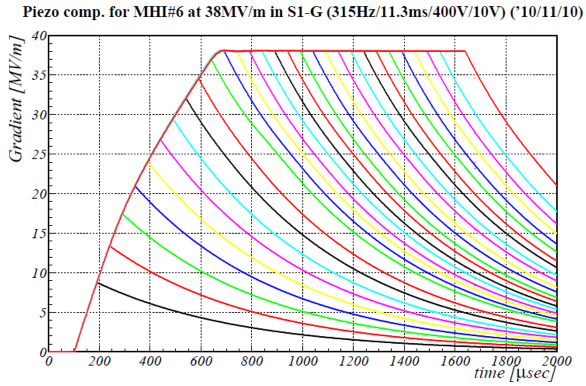


Figure 10: The example of the pulse shortening method. Each step is 50 μs.

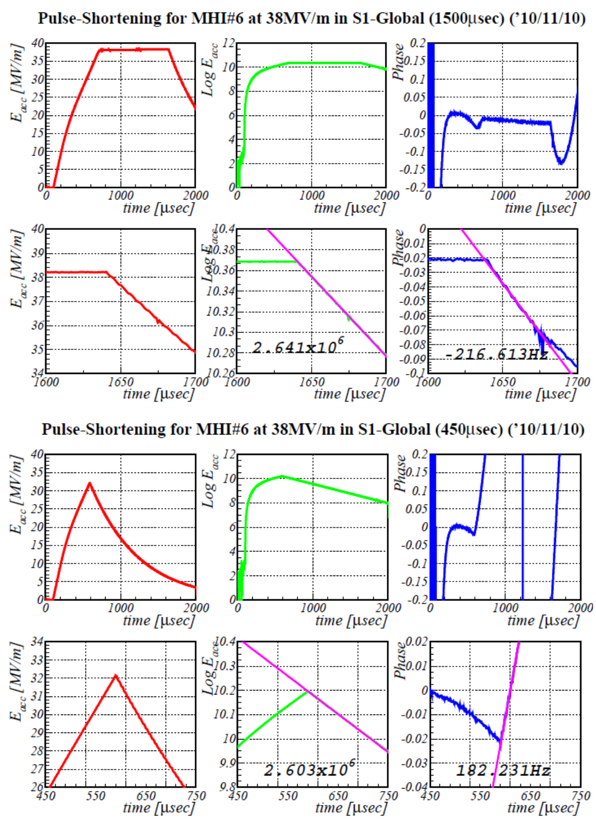


Figure 11: The examples of the linear fitting range for the pulse width of 1500 μs (top) and 450 μs (bottom). The red graph shows the accelerating gradient, green shows the logarithmic gradient, blue shows the phase for MHI-06, and purple line shows the fitting line.

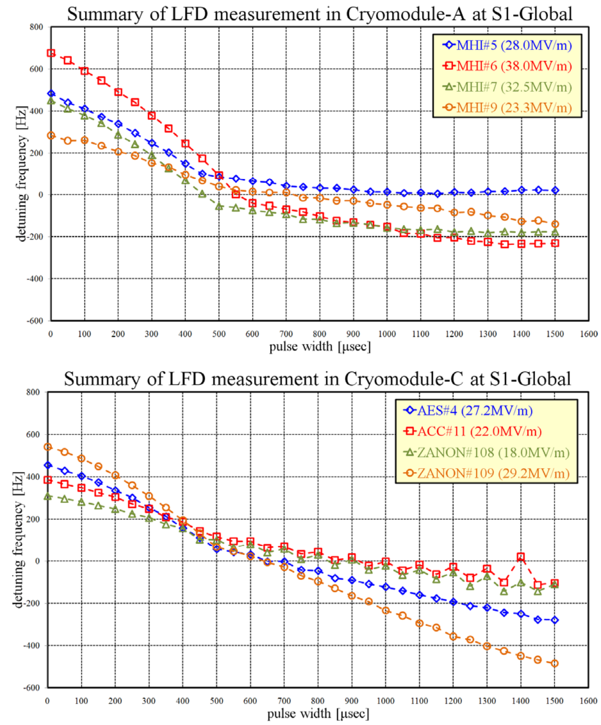
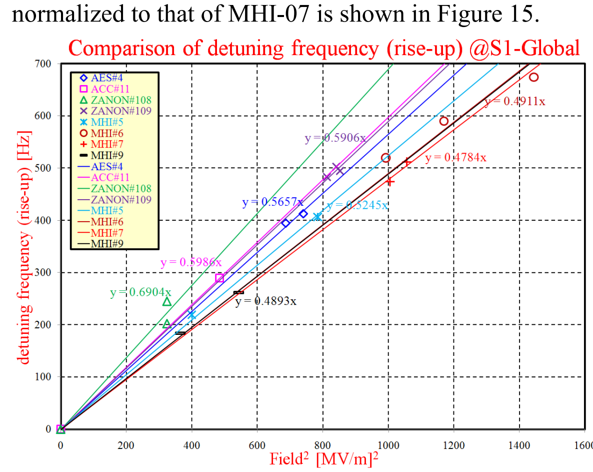


Figure 12: The result of LFD measurement at the maximum gradient for every cavity.

The detuning frequency for three periods -- rise-up, flat-top, and full-pulse -- was evaluated for the comparison of the stiffness of all the cavities. Figure 13 shows the correlation between the detuning frequency for the three periods and the square of the gradient. From the slopes of linear fitting on these data, it is possible to evaluate the cavity stiffness, as shown in Figure 14. The MHI cavities are found to be stiffer than others. The effect is remarkable in the flat-top period, while the difference is smaller in the rise-up period. According to the analogy of the 'Two Modes Model' [11], high stiffness of the end plate of a helium jacket is much more effective in the slow mode (several hundred Hz). The comparison of the ratio of the stiffness which is normalized to that of MHI-07 is shown in Figure 15.



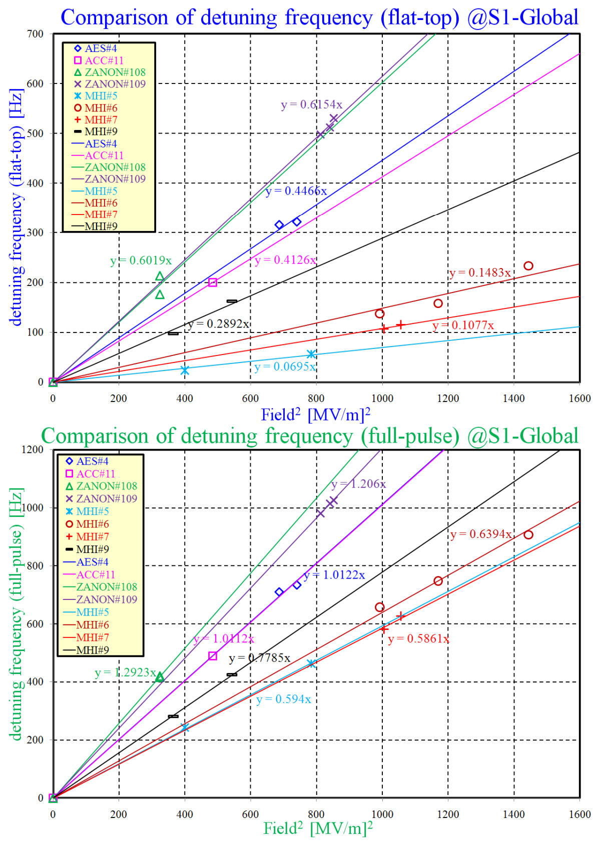


Figure 13: Correlation between the detuning frequency and the square of the field for rise-up, flat-top and full-pulse including the linear fitting.

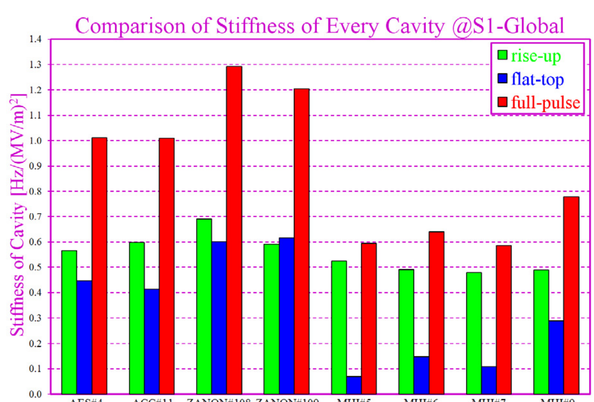


Figure 14: Comparison of the slopes from rise-up, flat-top and full-pulse.

Cavity	AES004	ACC011	Z108	Z109	MHI-05	MHI-06	MHI-07	MHI-09
rise-up	1.16	1.18	1.34	1.21	1.09	0.97	1.00	0.98
flat-top	3.99	3.90	5.66	5.44	0.71	1.59	1.00	2.72
full-pulse	1.73	1.73	2.20	2.06	1.01	1.09	1.00	1.33

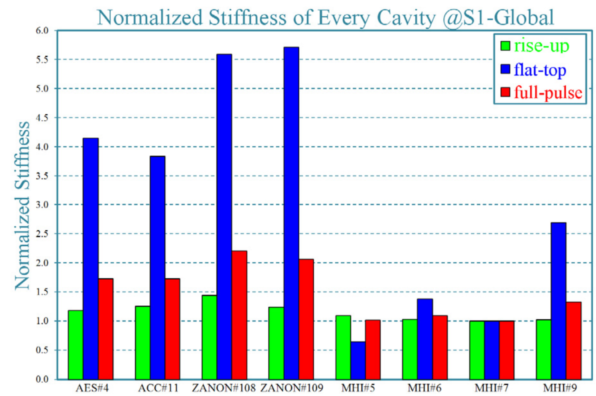


Figure 15: Comparison of the ratio of the slopes normalized to that of MHI-07.

Compensation of LFD by Piezo

The compensation of LFD by piezo for all cavities was also carried out by members from FNAL and KEK. The KEK team used the 'single pulse compensation' by a sine curve, which was used at STF Phase-1 [11]. The FNAL team introduced the 'adaptive compensation', a new method presented in [12]. Both methods turned out to be successful.

In the compensation of LFD by the KEK team, for the pre-detuned cavity, a pulse corresponding to one period of a sine curve is applied to piezo before the RF pulse, as shown in Figure 16. Four adjustable parameters for the piezo drive exist, that is, drive frequency, delay time, pulse height, and pulse offset. The Figure 17 shows the results of the compensation by the pulse shortening method for 6 cavities. The excursion peak-to-peak of the detuning frequency at the flat-top of the pulse was introduced as a measure of the compensation similar to STF Phase-1 [11]. Figure 18 shows the correlation between the peak-to-peak of the detuning frequency and the gradient for the best three results of the compensation by the pulse shortening method. After the compensation, MHI cavity still has a smaller peak-to-peak of the detuning frequency at the flat-top period. This means the MHI cavity package has stiffer structure than the other ones.

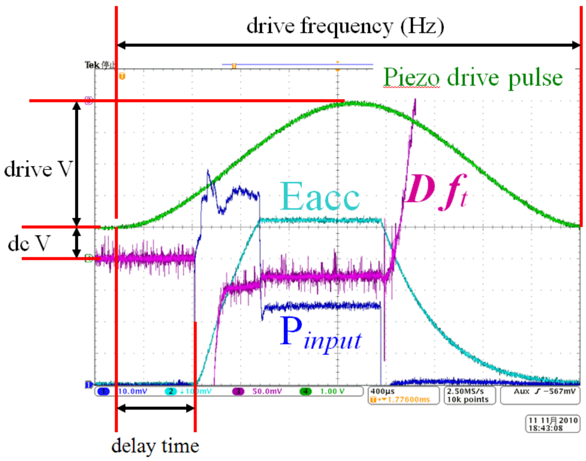
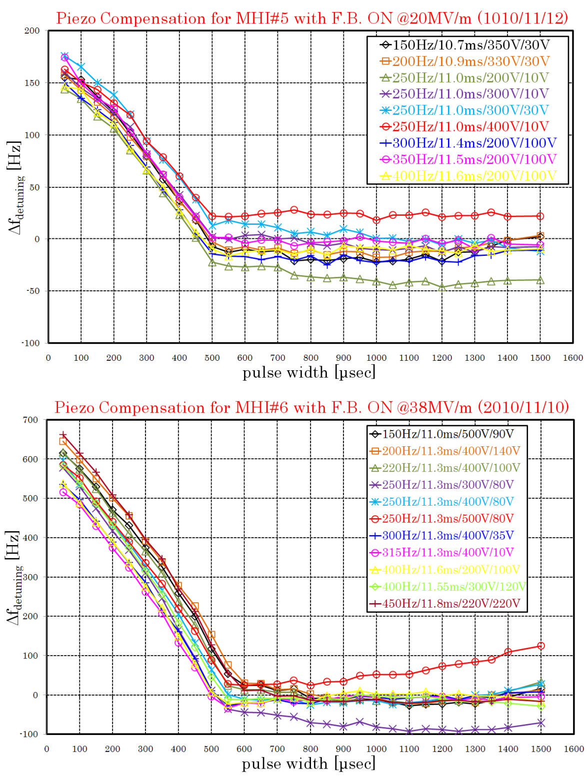


Figure 16: One pulse of sine curve added to piezo for the compensation of LFD. The blue shows the input power, light blue shows the accelerating gradient, purple shows the cavity phase and green shows the drive pulse to a piezo. Four adjustable parameters exist, that is, drive frequency, pulse height, pulse offset and delay time for the piezo drive.



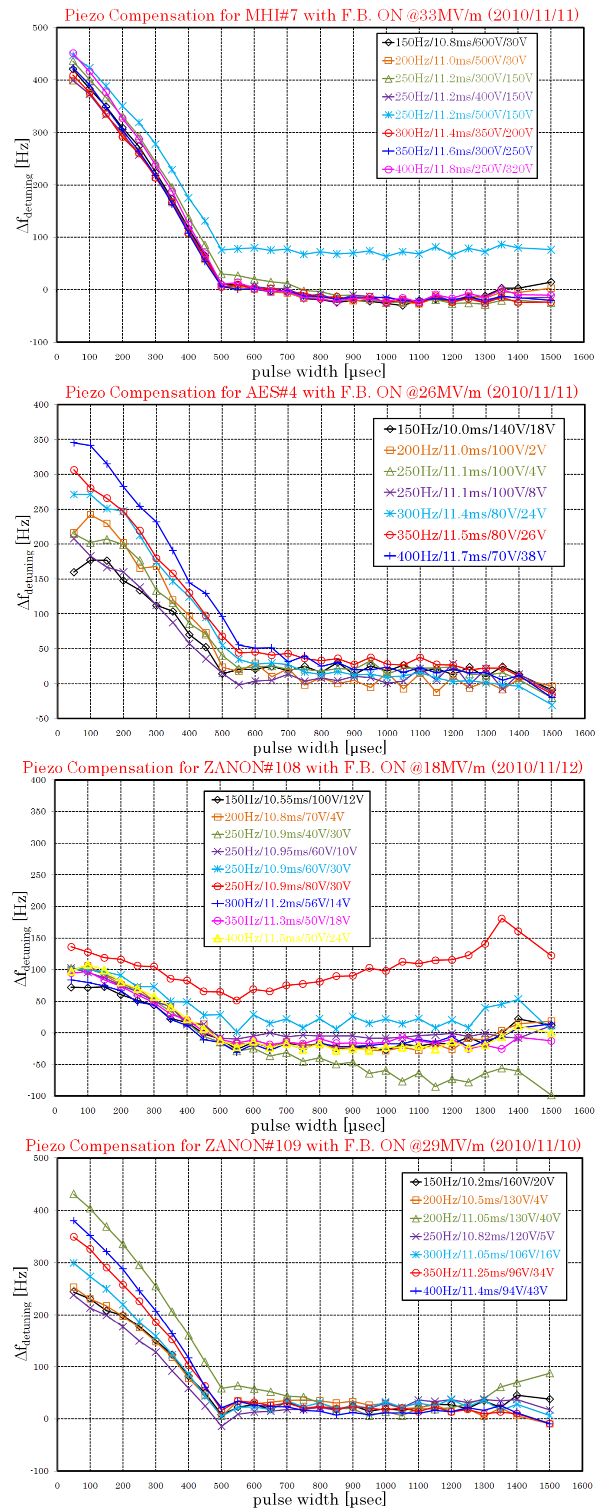


Figure 17: Results of the compensation by piezo for 6 cavities. Adjustable parameters in black framework show drive frequency, delay time, pulse height and pulse offset for sine curve pulse (from left to right).

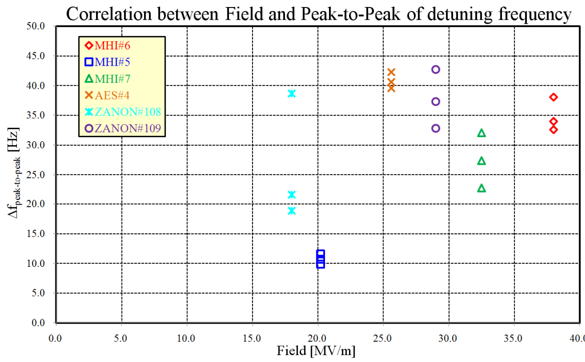


Figure 18: The correlation between the excursion peak-to-peak of the detuning frequency at flat-top and field. The best three results are shown here.

Long Term Operation of Single Cavities

Long term operation for single cavities was carried out many times in the S1-Global cryomodule test. The longest operation was over 4 hours for MHI-06 at 38.0 MV/m with the feed-back ON and piezo ON, as shown in Figure 19. The decrease of Q_L was observed clearly, and at the end of the run, it was decreased by 8.3% from the initial value. However, the decrease was stopped during the last 10,000 pulses with piezo ON. This cause is probably due to the heating of the inner conductor, presented in the next section 'Long term operation of 7 cavities'.

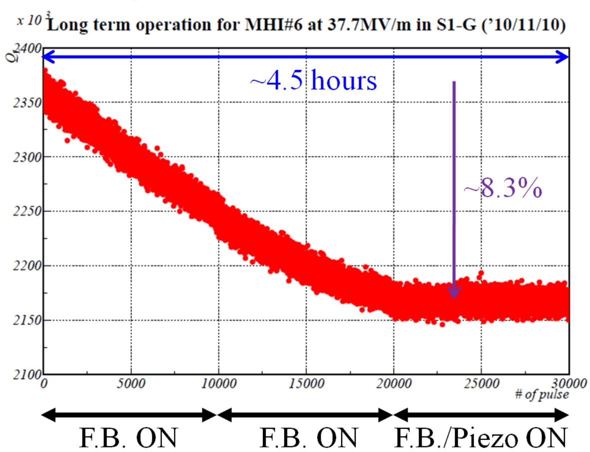


Figure 19: The trend of Q_L during the long term operation for MHI-06.

Long Term Operation of 7 Cavities

Simultaneous operation of seven cavities at the average gradient of 25.0 MV/m was carried out at the end of the second cold test. ACC011 was excluded from this exercise due to the problem with its tuner as discussed earlier. During this operation of about 2 hours, the LLRF feed-back system and piezo drive (feed-forward) worked stably. Figure 20 shows the trend of Q_L and the detuning frequency for the 7 cavities. Figure 21 shows the distributions of Q_L and the detuning frequencies. Since AES004 and ACC011 had the large change in the detuning frequency, the distribution was wider. The superimposed RF pulses at the flat-top for three periods are shown in Figure 22. Something happened at around pulse #3,000, and the detuning frequency changed for all cavities. Especially, the detuning frequency and Q_L for ACC011 show large changes. Figure 23 shows the trend of the various monitors about RF, helium and vacuum. From these figures, it is clear that the helium pressure and flow were gradually increasing from the beginning to the middle during this operation. A correlation seems to exist between the helium pressure and the changes of the detuning frequency for AES004 and Z109. The detuning frequency of the MHI cavities also changed slightly.

The decrease of the Q_L was observed for every cavity, and especially the changes between the initial and end value for MHI-06 and -07 were large, that is, -3.9% and -3.5%. These cavities ran at 38 and 33MV/m, and more input power was required for the power coupler. The cause of the drop of the Q_L may be due to the heating of the inner conductor of the power coupler. The increase of the vacuum level of the inner conductor, as shown in Figure 23, suggests the heating during this operation.

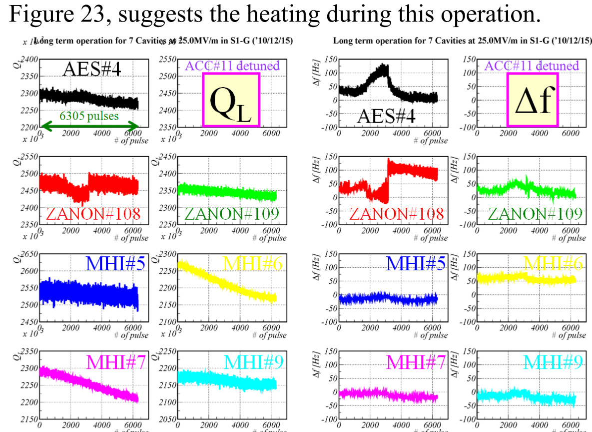


Figure 20: The trend of Q_L and the detuning frequency during the long term operation for 7 cavities.

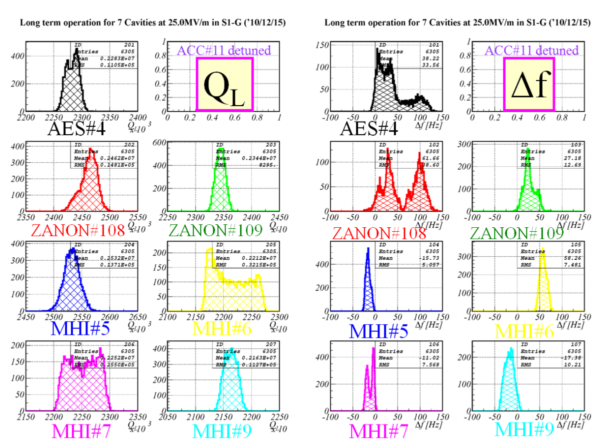


Figure 21: The distributions of Q_L and the detuning frequency during the long term operation for 7 cavities.

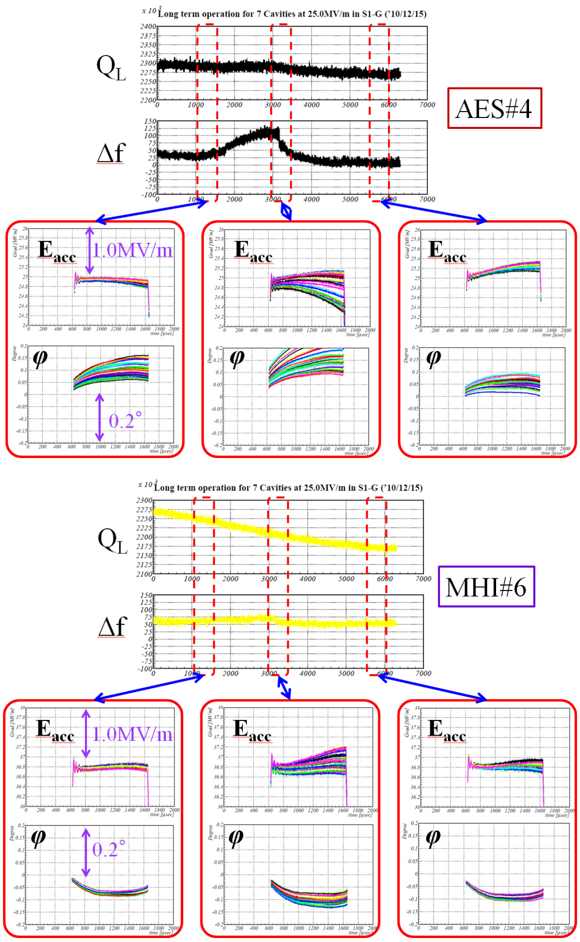
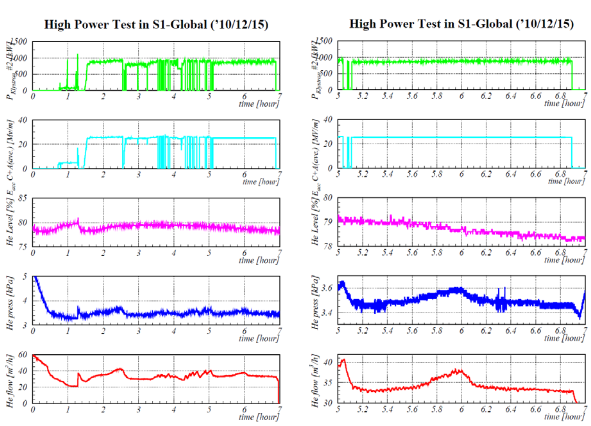


Figure 22: The superimposed RF pulses at the flat-top for three periods during the long term operation.



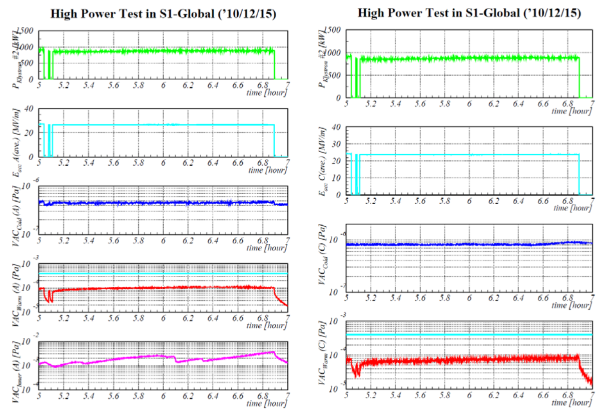


Figure 23: The trend of helium level, helium pressure, helium flow and vacuum during the long term operation (17:00-19:00). 12:00-19:00 (top-left) and 17:00-19:00 (others). The vacuum level at three locations for Cryomodule-A (left) and two locations for Cryomodule-C (right) are shown in the bottom figures.

Dynamic Loss Measurement

The dynamic loss measurement was carried out by members from FNAL and KEK in three steps, that is, for one cavity, four cavities and seven cavities in the tuned and detuned conditions [13]. The heat loss was estimated from the helium flow rate. In the meanwhile, the liquid helium supply was temporarily stopped. The results are shown with the numerical values in Figure 24. It is clear that STF-II coupler has more heat loss from the results of the detuned four cavities. The difference between them was almost 9 times.

It is conceivable that the Q_0 values below 10^{10} were caused by field emission. It is also clear from the result of the three radiation monitors attached nearby the cryomodule, which typical measured values were above several 10 μSv/h at their maximum gradient.

Summary of dynamic loss measurements

	C-4 Z109	C-1 AES004	A-3 MHI07	A-2 MHI06	A-2 MHI06	4 C Cavities	4 A Cavities	4 C Cavities	4 A Cavities	7 Cavities	7 Cavities
Date	Nov. 17	Nov. 19	Nov. 23	Nov. 24	Nov. 25	Nov. 26	Nov. 30	Dec. 2	Dec. 3	Dec. 9	Dec. 10
Gradient [MV/m]	28	25.2	32.3	38	32	32 Detune	32 Detune	20 .0 Average	26.9 Average	25.4 Average	20.4 Average
Q_D, W	0.84	1.4	2.8	4.8	2.6			2.7	6.9	9.6	4.8
$Q_{D\text{-det}}$, W	0.09	0.18	0.7	1.8	1.2	0.5	4.6	0.2	2.5	2.6	1.6
$Q_{D\text{-cav}}$, W	0.8	1.3	2.0	2.9	1.3			2.5	4.4	7.0	3.2
Q_0	8.8E9	4.3E9	4.3E9	4.2E9	6.5E9						
								C1=22.2 C2=18.9 C3=14.9 C4=24.3	A1=15.8 A2=37.6 A3=32.9 A4=21.4	C1=25.2 C2=NA C3=17.6 C4=28.8 A1=15.3 A2=37.4 A3=32.4 A4=20.9	C1=20.1 C2=NA C3=14.1 C4=23.0 A1=12.3 A2=30.4 A3=26.0 A4=16.7

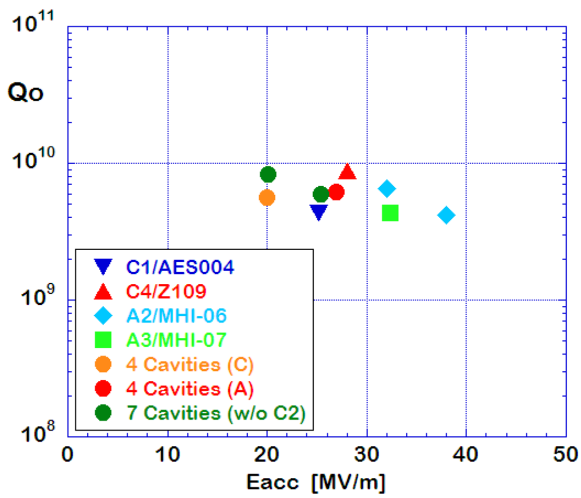


Figure 24: The results of the dynamic loss measurement. The measurements on 26/Nov. and 30/Nov. were carried out with the detuned cavities. Every Q_0 value was below 10^{10}.

ISSUES & FUTURE PLANS

There were two significant issues in this S1-Global cryomodule test, to be addressed in development of real-life ILC cryomodules:

- Performance degradation of cavities after the assembly into the cryomodule (two cavities exhibited this problem).
- Uncontrollable tuners after cooling-down (two tuner units exhibited this problem).

An investigation of the tuner trouble for AES004 and the disassembly of the power couplers from the Cryomodule-C will be carried out by members from DESY/INFN in December, 2011. All cavities of Cryomodule-C will be sent back to DESY and FNAL, and the cause of the gradient drop will be investigated there. Such work is expected to offer important knowledge in the next stage of development.

SUMMARY

The S1-Global project was completed successfully in February, 2011. Simultaneous operation of all eight cavities at 31.5 MV/m in an integrated cryostat was not achieved. However, many useful experiences and results were obtained, as follows:

- Assembly work by the S1-Global team was successful.
- 6 of 8 cavities reached the almost same gradient at the cryomodule test as the vertical test.
- Mechanical vibration modes were found to vary from cavity to cavity.
- LFD measurement was successful. MHI cavity turned out to be stiffer.
- Compensation by piezo was successful. All types of the tuners tested have demonstrated good effectiveness.
- Simultaneous operation of seven cavities was comparatively stable. The Q_L decreased gradually during the operation for every power coupler.
- From the results of the dynamic loss measurement, it was observed the STF-II coupler has a larger heat loss.
- Communication among the international members of the S1-Global team worked well.

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