

RESULTS ACHIEVED BY THE S1-GLOBAL COLLABORATION FOR ILC

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Abstract

The S1-Global cryomodule experiment [1] by ILC-GDE (International Linear Collider, Global Design Effort) was planned to achieve “S1” goal, which is to operate at least one of cryomodule with 31.5MV/m ILC average gradient. The design, fabrication, assembly, experiment, and disassembly were done by the international collaboration based on ILC-GDE. The experiment hosted by KEK STF (Superconducting RF Test Facility at KEK) was performed from June 2010 to February 2011. The achieved gradient performance of the contributed cavities was average 30.0MV/m before installation, 27.7MV/m for single cavity operation after installation, and 26.0MV/m for 7 cavities simultaneous operation [2, 3].

The other goal of the S1-Global is to perform plug-compatibility concept by building one set of cryomodule from brought-in cavities and couplers of each laboratories. The half-size cryomodule-C was its demonstration built from INFN cryostat, two set of DESY cavities and couplers, and two set of FNAL cavities and couplers. The connection of cryomodule-C and KEK cryomodule-A was also another aspect of plug-compatibility.

The S1-Global program was the truly international cryomodule experiment by the effort of GDE members and GDE participation laboratories. The program has demonstrated to realize the international cryomodule and their performance close to ILC specification. The issues of the current cryomodule technologies and what we need to solve in the next were identified.

INTRODUCTION

The S1 is one of the identified tasks by the GDE R&D board, where an RF operation of a cryomodule with an average accelerating gradient of 31.5MV/m is to be demonstrated. The S1-global experiment was the world’s first program of building a segment of a superconducting linac system and testing a string of superconducting RF

cavities by a global collaboration in the Technical Design phase of the ILC project. The proposal was to bring eight 9-cell superconducting cavities and associate hardware components from institutions in the world, install them in common cryomodules, and demonstrate their operation by a global collaboration. The participating institutions contributed their hardware and human resources on an equal footing. The picture of the cryomodules is shown in Fig.1. While the S1-Global program lacked beam operation, it involved all the essential steps that are required prior to beam acceleration. The program successfully addressed numerous critical issues such as the plug-compatibility (i.e. compatible but not identical) of hardware components, as well as single- and multiple-cavity operation with pulsed microwave power and associated LLRF controls. While the tests were all completed by the end of February 2011, disassembly of the S1-Global cryomodules was started on May 2011 toward the end of the year 2011, practically all of the contributed cavity components were brought back to their home institutions for post-mortem diagnosis studies.

CAVITY PACKAGE

A new half-length cryomodule (Cryomodule-C) was designed and prepared by INFN, while the other half cryomodule (Cryomodule-A) was built by modifying an existing 6-m STF cryomodule at KEK.

The upstream module, Cryomodule-C, has 2 FNAL cavities, TB9AES004 for slot C1 and TB9ACC0112 for slot C2, and two DESY cavities; Z108 for slot C3 and Z109 for slot C4. Four cavities are equipped with TTF3 type main input couplers. In Fig.2, the illustrations of their cavity packages are shown. TB9AES004 was last tested in the horizontal test stand at FNAL before shipment, while TB9ACC011 was last tested in the vertical test stand. They are processed and tested at JLAB, ANL and FNAL. DESY cavities were processed with the DESY EP treatment and had been previously installed in the module 8 and tested on the CMTB at DESY. Before shipment to KEK, Z108 and Z109 underwent 6 HPR cycles and were tested in the DESY vertical cryostat.

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Figure 1: The S1-Global cryomodule from the view of the input coupler side. Right cryomodule is from INFN.

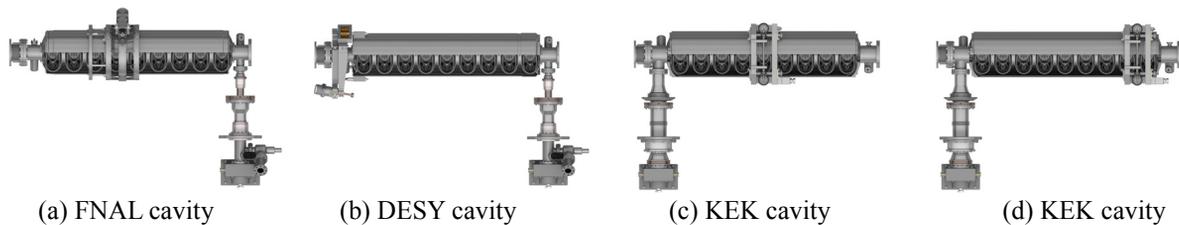


Figure 2: Cavity package contribution from each laboratory. There are two cavities in each type. (a) FNAL cavity with blade tuner and TTF3 coupler, (b) DESY cavity with Saclay/DESY tuner and TTF3 coupler, (c) KEK cavity with slide-jack tuner in centre and STF2 coupler, (d) KEK cavity with slide-jack tuner in the end and STF2 coupler.

These cavities were sent to KEK with input coupler cold section mounted in a vertically upward position, and the cavity under vacuum.

The downstream module, Cryomodule-A, has four KEK supplied cavities, in slots A1 – A4. The cavities were TESLA-like cavities, named MHI05, MHI06, MHI07, and MHI09. Each cavity was processed and tested at KEK. There are two types of tuners utilized, central slide-jack tuner on MHI05 and MHI06, and lateral slide-jack tuner on MHI07 and MHI09. STF2 Couplers for each cavity were produced by Toshiba, and pre-conditioned at KEK up to 1.0MW in pulsed operation, with a 1.5 msec pulse width at 5 Hz.

CRYOMODULES

The design of the Cryomodule-C cross section is almost the same as the TTF-type III cryomodule. The cryomodule mainly consists of the cavity-packages, input couplers, the gas return pipe (GRP), magnetic shields, two sets of thermal shields, cooling pipes and the vacuum vessel. The distance of 1383.6 mm between the input couplers, same as the TTF-type III and XFEL design, was used for four cavities although the cavity-packages of FNAL and DESY have different lengths, 1247.4 mm and 1283.4 mm, respectively. This mismatch was resolved with the bellow pipes between the cavities. The designs of these two cavity jackets are different because of the different type of frequency tuner, the blade tuner and the Saclay-type tuner, as shown in Fig. 2. However, the cavity support lugs have the same distance

of 750 mm between two lugs along their axis, and the fixed distance 197.5 mm from the input coupler axis, independent of the type of cavity package design and as a result, the cavity package supports to the GRP, are identical, i.e. ‘plug compatible’. The frequency tuners of these cavities were driven by the cold motor and the Piezo element. The cold motors were installed inside the 5 K shield. The DESY and FNAL cavities were designed to be enclosed with the magnetic shields.

The Cryomodule-A was used in STF phase-1. The thermal and mechanical designs of Cryomodule-A were based on the TTF-type III cryomodule. However the components in the Cryomodule-A have different dimensions from those in the Cryomodule-C. The KEK cavities for Cryomodule-A have two designs with different locations of the frequency tuner as shown in Fig. 2. Upstream two cavity-packages have the tuner located at the centre of the helium jacket. The distance between the support lugs along the cavity axis is designed to be 750mm, i.e. the same distance as the FNAL and DESY cavities. The downstream two cavity packages have the tuner placed at the opposite end of the jacket with respect to the input coupler. The distance of the support lugs is changed to 650 mm and the tuning action does not require sliding of cavity at the support pads in this case. Since the KEK tuners have the driving motor outside the vacuum vessel, they were driven by the warm motor, while the Piezo element is in the cold side.

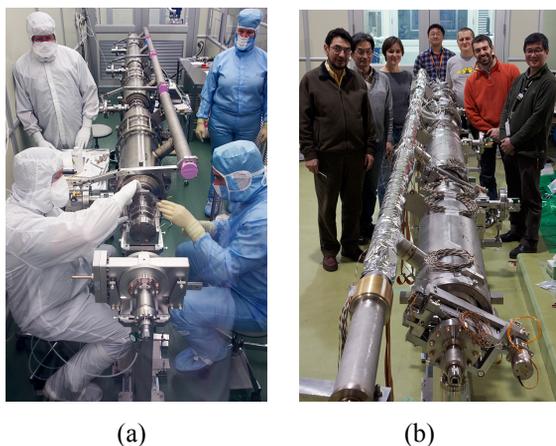


Figure 3: (a) Cold mass assembly of Module-C in clean-room by DESY-FNAL-KEK team (b) Cavity package assembly of Module-C by INFN-FNAL-KEK team.

Assembly of both Cryomodule-C and Cryomodule-A is mainly divided into two processes: the cavity string assembly in the class-10 clean room (CR), and the cold mass assembly outside of the CR. Fig. 3 pictures shows the STF assembly work done by international cooperation. For the cavity assembly in the clean room, two weeks were scheduled for each module. For the cold mass assembly, two months for Cryomodule-C and one month for Cryomodule-A were scheduled. The Cryomodule-C assembly was scheduled first to ease final assembly of the two modules in the STF tunnel. After moving the cavity-string out of the clean room, the cold mass was assembled from January 25 to March 19, 2010. Transportation of the two cryomodules down to the STF tunnel was completed on April 28th.

The operation of the cryogenic system was done a day-by-day basis. The operation started in the mornings and stopped in the evenings. No operation on Saturdays and Sundays. It took almost 2 weeks (10 workdays) to complete cooling-down of the 8 cavities from room temperature to 2 K. During the experiment weeks, the study was possible to start at noon from Tuesday to Friday.

HLRF AND LLRF

Two HLRF systems were used for the S1-global. They are the No. 1 station and the No.2 station. TH2104C was for the No.1 station and the other was newly procured TH2104A for the No.2 station. Both were capable to output 5-MW power at the frequency of 1.3 GHz with the pulse width of 1.5ms and repetition rate of 5Hz. In power distribution system (PDS) in RDR, there are two types of PDS proposed, that is, the linear PDS and the tree type PDS using 3dB power dividers. Both systems were evaluated in the S1-global test [3], as shown in Fig. 4. A tree type power-dividing scheme (3-dB Hybrid PDS) using variable 3-dB hybrids was employed to cryomodule-C. In this system variable power divider of the variable tap-off (VTO) supplied by SLAC was

introduced. The linear distribution system (TESLA type PDS) was used in cryomodule-A. The variable QL system using a reflector and a phase shifter was introduced in each coupler port.

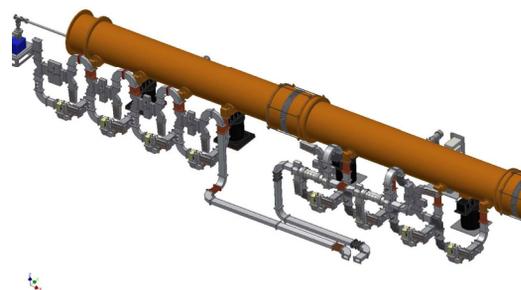


Figure 4: Power distribution system used in S1-global test. Linear PDS in the left, and tree-type PDS in the right. SLAC VTO are installed in the right PDS.

To examine each cavity performance efficiently, two RF power sources were used. A conventional digital low-level RF (LLRF) system was adopted in this evaluation. An FPGA board on a commercial digital signal processing (DSP) board (Barcelona) was used to control the RF output from each klystron. The FPGA board has 10 of 16-bit ADCs and 2 of 14-bit DACs with an FPGA and installed to cPCI [7]. In the vector-sum performance evaluation, to maximize each cavity's gradient, the ratios of the RF input powers to the cavities are optimized using tuneable hybrids and variable tap-offs. One cPCI became the FB controller and operated a vector-sum control.

SINGLE CAVITY PERFORMANCE TEST

The cryomodules were cooled down three times during the test. The first cool-down test was carried out from June to July 2010 for measurement of the thermal and mechanical performance of the cryomodules, together with RF tests of all cavities with low power. The second test was done from September to December 2010 for check-up of the cavity performance, the LFD measurement, its compensation by piezo tuners, a long-term operation, and the dynamic loss measurement by high RF power. The DRFS power system [8,9] was tested in the third cold test from January to February 2011 by using two 800 kW klystrons that were placed in the tunnel.

In the low power RF tests [4] done by INFN/FNAL/KEK team, it was found that tuners attached in TB9ACC011 and MHI-09 were not controllable, and it was not possible to set the frequency of these cavities to 1300.000 MHz. Therefore, simultaneous operation of multiple cavities was limited to 7 cavities rather than 8. Results of low power tuner tests are shown in Fig. 5.

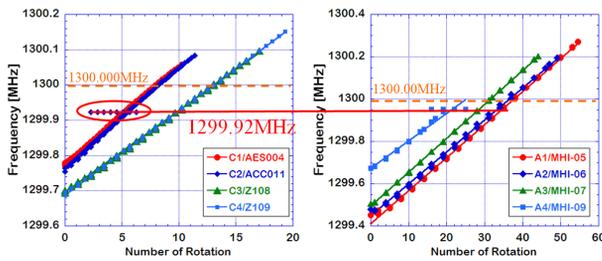


Figure 5: The result of the drive test for the motor tuner at low power. The tuner of TB9ACC011 did not work at 2K, and MHI-09 could not be set to 1300.000 MHz.

The slow tuner of TB9ACC011 failed after only a single tuning cycle (Fig. 5). In addition, one of the two-piezo actuators installed on the same cavity discharged at approximately half the nominal maximum operating voltage of 200V and the fast tuning range was smaller than expected. After disassembly, the reason of this slow tuner fail was found that the two M3 set screws in the shaft connecting the motor and the harmonic drive had worked loose presumably due to vibration during operation. One of the two screws had worked completely loose. The second was unable to transmit the full torque of the motor and was allowing the shaft to slip.

A visual inspection of the TB9ACC011 piezo actuators during disassembly showed that the two brass end caps holding the actuator stack were not well aligned. Misalignment of the caps can result in the transmission of excessive shear forces to the actuator stack. Further inspection revealed the actuator installed on the coupler side of the cavity had fractured on one edge. The physical damage to the stack can account for the both the discharges observed during operation and for the reduced tuning range.

The slow tuner of MHI-09 failed during the first excursion test (Fig. 5). The rotation of the motor became slow and finally stopped in the point of 1299.95MHz. After the several trial of the motor rotation, the frequency finally did not change even the motor was rotating. After the disassembly, the tuner was carefully checked. When the fixed bolts of the slide-jack were loosen from the thick flange, the tuner mechanism became smooth and no stuck. In that case there were 0.55mm to 0.6mm gap space between flange and the slide-jack. This was caused by the flange bending deformation, which came from the welding heat.

After the second cool-down, the conditioning of each cavity with high power was carried out. The achieved gradient values in vertical and cryomodule tests are summarized in Fig. 6. The maximum average gradient was 30.0 MV/m at vertical test, however, went down to 27.7 MV/m for single cavity operation and 26.0 MV/m for simultaneous operation of seven cavities at the cryomodule test. In this conditioning, the performance of MHI-06 was drastically improved from 28MV/m in vertical test to 38MV/m. On the other hand, the gradient of the two cavities (TB9ACC011 and Z108) were

significantly reduced by 27% and 38% each. Issues during the assembly processes or transportation to KEK are suspected. This problem should be certainly addressed by the post-mortem diagnosis studies. MHI-05 performance (actually, performance of the input coupler) also degraded to 16MV/m during the adjustment for the feedback control due to the abnormally excess of the input power.

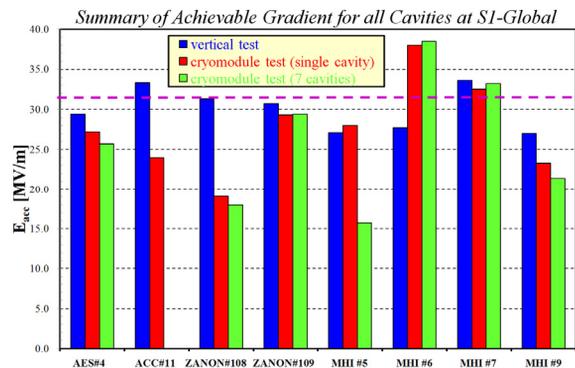


Figure 6: The achieved gradient values for eight cavities in vertical and cryomodule tests. The purple dotted line shows 31.5 MV/m of the ILC average operation gradient.

The LFD measurement for each cavity was carried out by using ‘pulse shortening’ method. The detuning frequency for three periods -- rise-up, flattop, and full-pulse -- was evaluated for the comparison of the stiffness of all the cavities. The slopes of linear fitting between the detuning frequency for the three periods and the square of the gradient shows the cavity stiffness, as shown in Fig. 7. The MHI cavities are found to be stiffer than others. The effect is remarkable in the flattop period, while the difference is smaller in the rise-up period.

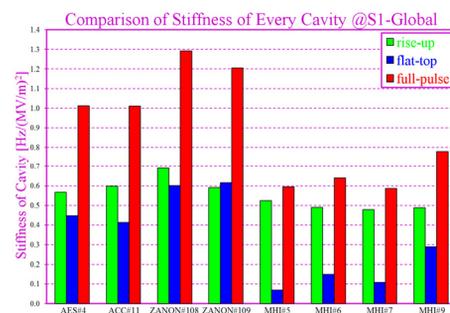


Figure 7: Comparison of the slopes from rise-up, flattop and full-pulse

Two kind of the LFD compensation were tried. The ‘single pulse compensation’ by a half sine waveform, which was used at STF Phase-1 [4] and the ‘adaptive compensation’, a new method presented in [5], were tried. Both methods turned out to be successful. As the compensation of LFD, a pulse corresponding to half period of a sine waveform is applied to piezo before the

start of the RF pulse. Four adjustable parameters for the piezo drive exist, that is, drive frequency, delay time, pulse height, and pulse offset. The excursion peak-to-peak of the detuning frequency at the flattop of the pulse was introduced as a measure of the compensation. After the compensation, MHI cavity still has a smaller peak-to-peak of the detuning frequency at the flattop period. In addition to the standard method of LFD compensation, an adaptive feed-forward method developed at FNAL for CM1 was employed to compensate detuning in six of the eight S1-G cavities. This compensation method also successfully suppressed LFD in each of the S1-G cavities tested to the point where residual detuning should have no significant impact on the design, the cost, or operation of a machine such as the ILC.

The static heat loads of the cryomodules at 2 K, 5 K, and 80 K were measured by calorimetric methods [6]. The total heat load at 2 K for eight cavities was evaluated to 7.2W. The 5K heat load was evaluated to 7.3W for module-A and 5.3W for module-C. The 80K heat load was also evaluated to 48.7W for module-A and 34.4W for module-C. They are good agreement with calculated values. The dynamic losses of several cavities were evaluated by the cavity-tuned operation and the cavity-detuned operation for cavity loss and coupler loss. Q_0 value by this calorimetric method shows 4 to 9×10^9 . For the heat loss estimation of the input couplers, four cavities in each module were detuned and operated at a power level of 32 MV/m. The four couplers losses of Module-C and A were 0.5 W and 4.6 W, respectively. The loss of the TTF-III coupler is consistent with this estimation. The loss of the STF-2 couplers was found to be one order bigger than the TTF-III. The temperature rises were found at the connection flanges between the STF-2 couplers and the cavity beam pipes. This temperature rise is considered to be due to heat generation at the 3 μ m Cu layer on the inner surface of the outer conductor.

OPERATION OF SEVEN CAVITIES WITH VECTOR-SUM FEEDBACK CONTROL

In the final stage of the experiment, one 5-MW klystron feeds its power to all eight cavities. The performance of operation with vector-sum feedback control was evaluated [7]. During this operation, one cavity (C-2) could not be used for the vector-sum control because its mechanical tuner failure. The input powers to the cavities were adjusted by the tuneable hybrids and the variable tap-offs to yield the maximum gradient for each cavity. The detuning of each cavity during the RF pulse flat-top (1 ms) was set near 0 Hz by using the Piezo tuners. The result of vector-sum feedback control operation for seven cavities is shown in Fig. 8. The average gradient of seven cavities after input power optimization for each cavity was 26 MV/m. Since the average of each cavity's quench limit was 26.7 MV/m, the operation near quench limit of each cavity was

achieved. The amplitude and phase stabilities were 0.005%rms and 0.015°rms, respectively, which satisfy the ILC requirements of 0.07%rms in amplitude and 0.24°rms in phase.

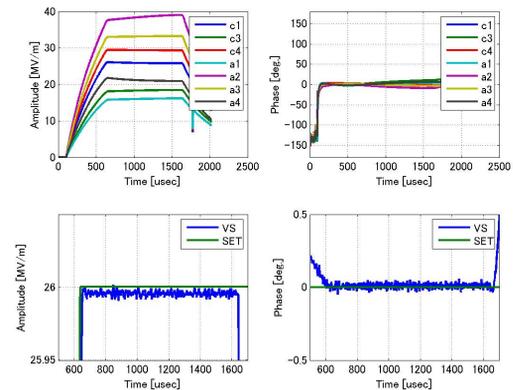


Figure 8: Vector-sum operation. Left: each cavity's gradient and vector-sum gradient, right: each cavity's phase and vector-sum phase.

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