ADVANCES IN SRF DEVELOPMENT FOR ILC*

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Abstract

The International Linear Collider (ILC) is planned as a next energy-frontier electron-positron collider accelerator, and research and development for the ILC SRF cavity technology has progressed in the Technical Design (TD) phase since 2007. This paper reports advances in the SRF research and development, and discusses preparation for the SRC cavity industrialization.

INTRODUCTION

The International Linear Collider (ILC) is planned as a next energy-frontier electron-positron collider accelerator. The main linac design is based on 1.3 GHz SRF cavity technology, and to accelerate electron and positron beams up to 250 GeV in each positron and electron linac. Based on the ILC Reference Design Report published in 2007, the ILC Global Design Effort (IC-GDE) has progressed the technical design work and R&D programs during the Technical Design (TD) phase to be completed in 2012 [1-4]. The ILC accelerator design has been updated since 2009, so called 'SB2009', with a motivation of 'cost containment'. It contains four major updates: (1) cavity field gradient spread of +/-20% with keeping the averaged gradient at 31.5 MV/m in operation, (2) single tunnel for Main Linac (ML) accelerator, (3) relocation of undulator-based positron source to high-energy end of the electron linac, and (4) a reduced beam-power parameter set with 3.2 km circumference Damping Ring (DR) [5]. Figure 1 shows the SB2009 accelerator layout. Figure 2 shows the SRF R&D plan time-chart in the TD phase with four categories: (1) cavity gradient R&D, (2) cavity-string performance in cryomodules, (3) cryomodule performance with accelerator beam operation, and (4) preparation for industrialization. The following sections describe advances in the R&D efforts.

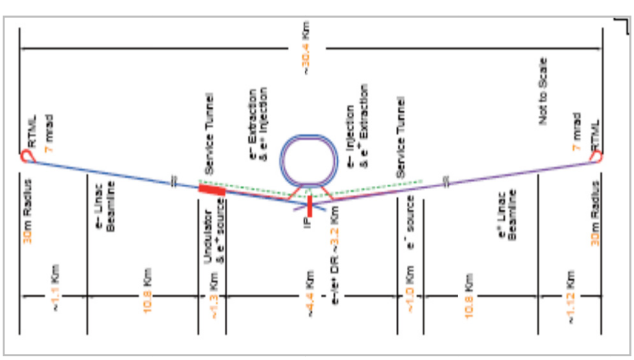

Figure 1: ILC layout updated from RDR to SB2009.

#Work coordinated and supported by ILC Global Design Effort

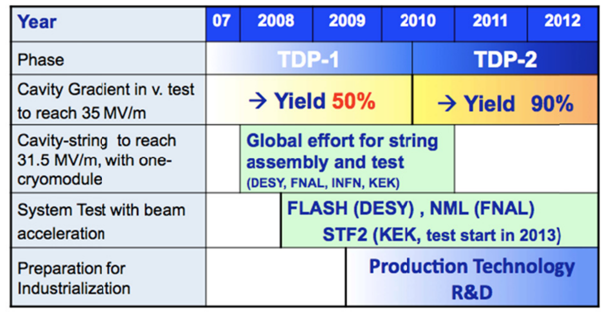

Figure 2: Global SRF R&D plan for the ILC.

GRADIENT R&D WITH 9-CELL CAVITY

The current ILC SRF cavity design is based on the TESLA-type, 1.3-GHz, 9-cell cavity [6] as the photo shown in Figure 3. The design gradient has been set at 35 MV/m on average with $Q_0 \geq 8x10^9$ to realize the stable, long-term operation at 31.5 MV/m with Q_0 of $\geq 1x10^{10}$. The SRF R&D plan is scoping to realize a successful cavity production yield of ≥ 50% as an interim milestone, and to reach a successful production yield of ≥ 90 % by the end of TD phase. To evaluate the progress from a viewpoint of industrialization readiness, a standard process for the cavity fabrication and surface preparation has been settled, as summarized in Table 1, following to a technical assessment given by the Tesla Technology Collaboration [7].

Table 1: Fabrication and surface preparation process for the ILC SRF 9-cell cavity.

Fabrication	- Material purchasing - Sub-component fabrication - Cavity assembly using EBW technology - Acceptance inspection
Surface preparation process (1st & 2nd pass allowed)	- Electro-Polishing: EP1 (~150µm) - Cleaning with ethanol or detergent - High-pressure pure-water rinsing - Hydrogen degassing at > 600 C - (Field flatness tuning) - Electro-Polishing: EP- 2 (~20µm) - Cleaning with ethanol or detergent - High-pressure pure-water rinsing - Antenna assembly - Baking at 120 C
Cold Test	Performance test with temperature and radiation monitoring, and RF mode test

Figure 3: A 1.3 GHz Tesla-type 9-cell cavity [6].

In the TD phase, we have established a clear definition of the production yield for a global database. It has adopted the yield after the first-pass and second-pass in the surface preparation process as a rules for the cavity qualification. The ILC cavity global-database team has been formed [8], and the team is consisting of members from Cornell, DESY, Fermilab, JLab and KEK. It is taking on the task of not only creating the database, but also defining the rules for how the data should be included and how the data would be presented. Figure 4 shows a cavity gradient performance progress with production yield for the second pass as of March 2011 [9].

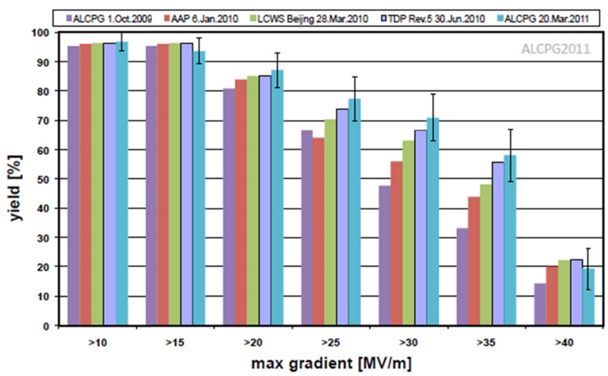

Figure 4: Cavity gradient performance progress with production yield for the second pass as of March 2011.

The improved understanding of reasons for gradient limit has been important to improve the cavity gradient yield [5]. Field emission has been much reduced due to the application of post-EP cleaning procedures such as ethanol rinsing and ultrasonic cleaning with detergent. A further reduction of the field emission has been achieved by applying the procedure of continued acid circulation during the EP process with a lower current density resulting in the cavity surface temperature kept lower. This procedure reduces sulphur-bearing niobium oxide granules, and hence reduces inherent contaminants on the as-polished surface. The optimized electro-polishing and following streamlined cleanroom assembly resulted in reproducible cavity processing and hence reproducible cavity gradient results. As a result from the continued improvement of the cavity processing and better understanding of the gradient limit, the interim gradient goal of the 50% yield at 35 MV/m and $Q_0 \geq 8x10^9$ has been achieved. Table 2 summarizes general status in the production yield evaluation and Table 3 summarizes further topical progress and highlights in the cavity gradient R&D in 2010 – 2011.

Table 2: Progress in the production yield evaluation of 9-cell cavities for the ILC SCRF cavity gradient R&D.

Year	# cavity applied	Manufactured by:	Processed & tested by:
Dec., 2007	4	ACC, Zanon	DESY, JLab
October, 2009	28	ACC, Zanon	DESY, JLab
March, 2011	41	ACC/RI, Zanon, , AES, MHI,	DESY, JLab, KEK

Table 3: Global highlights in gradient R&D, 2010-2011.

Joint effort	Achievement / Progress
RI-JLab [10]	90 % yield achieved at ≥35 MV/m and Q_0 ≥8e9
RI-Fermilab–ANL-JLab [11].	≥ 35MV/m and $Q_0 \geq 8x10^9$
RI-Fermilab-ANL [12]	34.5MV/m with a tumbled cavity
NW-Fermilab-ANL [13]	28.8MV/m with the first NW cavity
KEK-Fermilab-ANL [14,15]	G improvement from 11 to 30 MV/m with local-repairing
IHEP-KEK [16]	20MV/m w. the first IHEP cavity (LL/LG, with no end-group)
PKU-JLab [17]	28MV/m with the PKU cavity (TESLA/FG, with end group)
Hitachi-KEK [18]	35 MV/m with the first Hitachi cavity (TESLA-like, FG, no-end)
MHI-KEK [19]	40 MV/m and Q_0 ≥ 8e9
KEK-JLab [20]	40 MV/m and Q_0 ≥ 8e9 at 35 MV/m (LL, FG with end group)
RI-DESY [21]	45 MV/m @ Q_0 >1e10, with LG with BCP and EP

CAVITY-STRING ASSEMBLY AND TEST IN CRYOMODULE

The cavity/cryomodule string integration and cold tests have progressed at three facilities of TTF/FLASH at DESY, New Muon Laboratory (NML) at Fermilab, and Superconducting Test Facility (STF) at KEK. FLASH has progressed cryomodule tests with XFEL prototype modules [22]. NML construction started at Fermilab in 2007. The first cryomodule (CM1) and the associated facility have been in operation since 2010, and the CM1 test is in progress [23]. STF construction started at KEK in 2005, and the first cryomodule test was performed in 2007. The S1-Global cryomodule program started, in 2009, with a global collaboration among DESY, INFN, Fermilab, SLAC, and KEK [24]. Two TESLA-type cavities [6] were contributed by DESY and Fermilab, and four TELSA-like cavities [25] were contributed by KEK. A set of cryomodules (vacuum vessel and cold-mass) were provided in cooperation of INFN and KEK [26]. The assembly and test have been successfully carried out in 2010. Table 4 summarizes the progress and status in these facilities and Figures 5, 6, and 7 show cavity performances in the field gradient achieved in their cryomodule tests in comparison with individual 9-cell cavity performance tests [22-24, 27, 28]. Thermal performance of the S1-Global cryomodule has been evaluated as reported in the reference [29].

Table 4: Progress in cavity-string tests in cryomodules.

Facility	Year: Subjects studied and progress
FLASH/TTF (DESY)	2005: String test start, 2008: First accelerator beam at 3 mA, 2009: Beam operation at 22 kW av. , 2010: String gradient reach <32MV/m> , 2011: Long beam pulse & G-margin.
NML/SRF-BTF (Fermilab)	2007: First cryomodule (CM1) assembly, 2010: CM1 installation, and cold test start, 2011: String gradient in progress, 2011: CM2 installation (planed).
STF (KEK)	2007: STF1 installation, cavity-string test, 2010: String gradient <26MV/m>, 2011: Distributed RF system test, 2011: ST2/QB installation (planned).

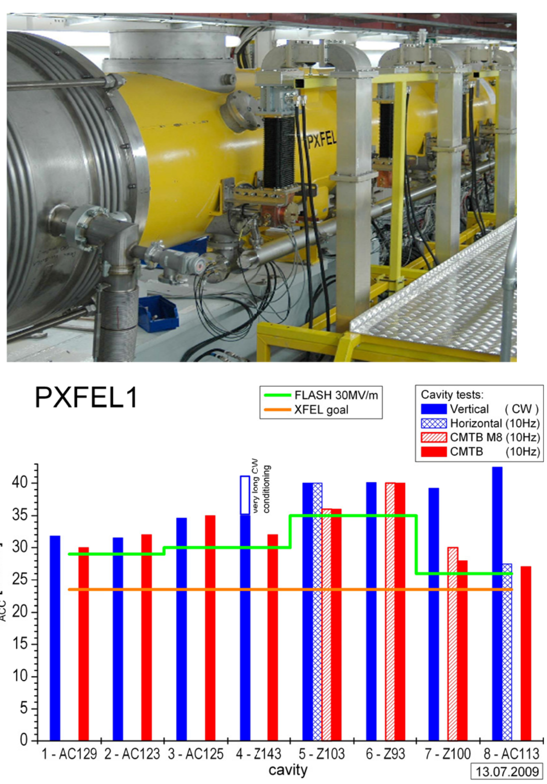

Figure 5: (top) Prototype XFEL cryomodule at FLASH, and (bottom) field gradient distribution [22].

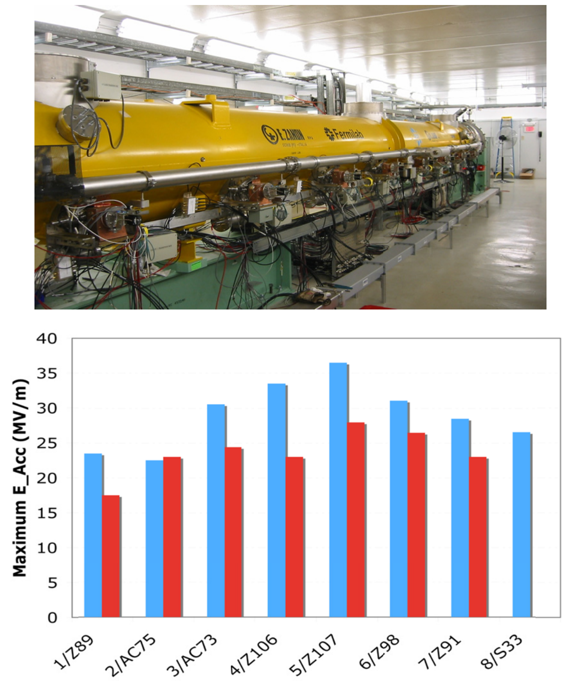

Figure 6: (top) Cromodule-1 at NML, and (bottom) the field gradient distribution (right) compared with individual test in horizontal position (left) [23].

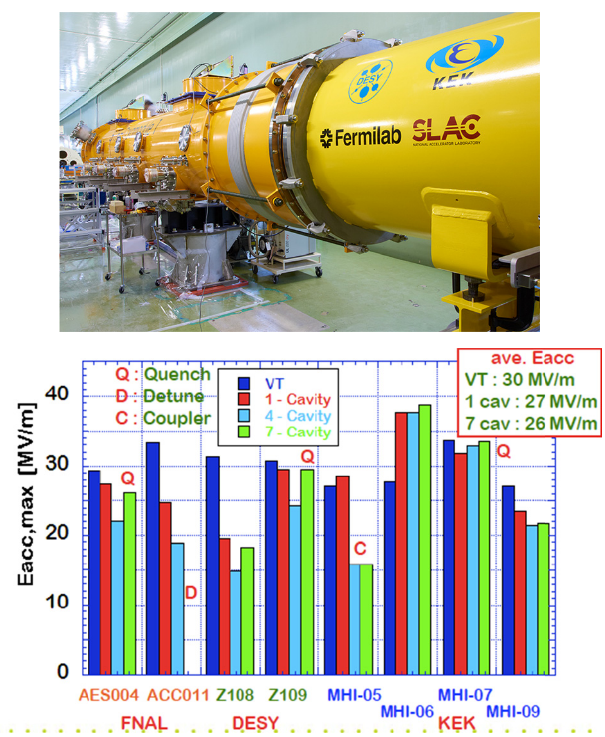

Figure 7: (top) S1-global cryomodule installed at STF, and (bottom) the gradient distribution in cavity-string operation (right three) compared with the result from their individual vertical test (most left) [24, 27, 28].

The S1-Global cryomodule contained three kinds of tuners: Blade-tuner developed by INFN [30], Saclay-type tuner by Saclay [31], and Jack-type tuner by KEK [32]. The tune-ability and stability of cavity-string gradient were examined by using two low level RF control systems: one developed at Fermilab [33] and one at KEK [34]. Figure 8 shows a vector sum stability demonstrated by using the KEK low-level control system, during a one RF cycle with a flat top period of ~ 1 ms [34].

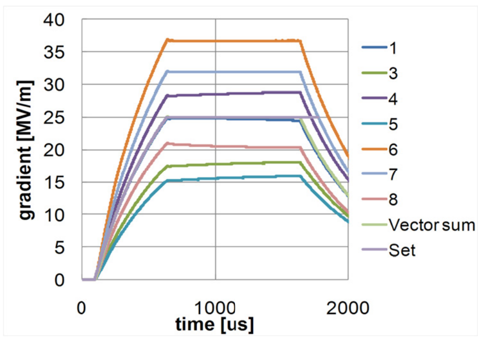

Figure 8: LLRF control to compensate the Lorentz force detuning, and the vector sum stability in S1-Global cavity-string test.

The distributed RF system operation proposed by KEK was demonstrated in the end of the cold S1-Global performance test [35], [36].

CRYOMODULE PERFORMANCE WITH BEAM ACCELERATION AT FLASH

TTF/FLASH has successfully extended the crryomodule string with adding the first prototype EXFEL cryomodule as the accelerator cryomodule ACC7, and Figure 9 shows the layout [37-39].

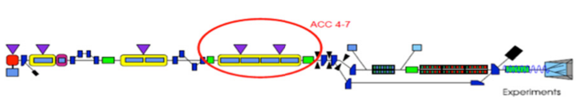

Figure 9: TTF/FLASH accelerator layout at DESY. Yellow boxes indicate 7 SRF cryomodules containing 8 cavity string each.

The primary goals of the FLASH accelerator beam test for demonstrating the ILC operational conditions were defined as (1) to establish operation of FLASH with heavy beam loading and long pulses (800μs pulses at 9mA), and as (2) to characterize operation at the limits of gradient and RF power in the presence of heavy beam loading. The first objective was achieved in 2009 as major progress summarized in Table 5 [34]. Note that 6mA is a baseline current for the low power option.

In early 2011, long-bunch train operation were examined for the present ILC baseline design assuming all cavity operation within 3% of their quench limits at full beam loading. The progress in this test is summarized in Table 6 [39].

Table 5: High beam power and long bunch-trains realized at the FLASH accelerator experiment, in 2009.

Metric	ILC goal	FLASH progress
Macro-pulse beam current	6 mA / 9 mA	9 mA
Bunches / pulse	2400 x 3nC (3 MHz)	1800 x 3nC 2400 x 2nC
Pulse length	970 μs	800 μs
Cavity operating close to quench	31.5 MV/m +/-20%	> 30 MV/m, at 4 cavities in ACC1-6

Table 6: Cavity gradient operating conditions in 2011.

Metric	ILC goal	FLASH progress
Cavity operating G spread	+/-20% spread	+/- 25 % spread in ACC6-7
Gradient flatness (in vector sum)	2%ΔV/V (800 μs, 9 mA)	2.5%ΔV/V (400 μs, 4.5 mA)
Gradient operating margin	within 3% of quench limit	To be focused in test plan, in 2012
Energy stability	0.1 % at 250 GeV	<0.15% p-p (0.4ms) <0.02% rms (5Hz)

FLASH has successfully demonstrated proof-of-principle technologies for the ILC SCRF operation, in terms of accelerator beam current, beam pulse length, cavity gradient spread, gradient flatness, and operational margin as well as the beam energy stability.

PREPARATION FOR SRF CAVITY INDUSTRIALIZATION

The ILC project and the scale of the construction inevitably require industrial effort and cooperation to realize cost-effective production of large numbers of accelerator components. The primary challenge is the construction of the SRF main linac, a significant cost driver, and it requires manufacture of ~16,000 9-cell cavities and ~1,700 cryomodule assemblies. The SRF cavity production represents a high-tech state-of-the-art component, and requires careful mechanical assembly of the subcomponents (such as deep-drawn half cells) using electron-beam welding, and carefully controlled chemical polishing, cleaning, high-pressure rinsing, baking, and all work in clean or semi-clean room environments. The assembly of the complete cavity string into the cryomodules also requires clean-room environments and well-defined procedures.

The industrialization models need to be flexible and adaptable to any possible management scenario, and any possible impact on the costs needs to be quantified. Several key points have emerged to manage cost-effective manufacture:

- The risk to the manufacturers must be reduced to an acceptable minimum. It is realized by carefully specifying the production process, so-called "build-to-print", and requiring sufficient documentation and sign-off on each step of the process,
- The ILC partner laboratories must assume responsibility for managing the risk associated with achieving expected performance. Testing of the cavities and cryomodules must be responsible with laboratories those who need to host the necessary test infrastructure.

Figure 10 shows the concept of a possible globally coordinated cavity and cryomodule production, based on a concept with 'regional hub-laboratory' contribution [40].

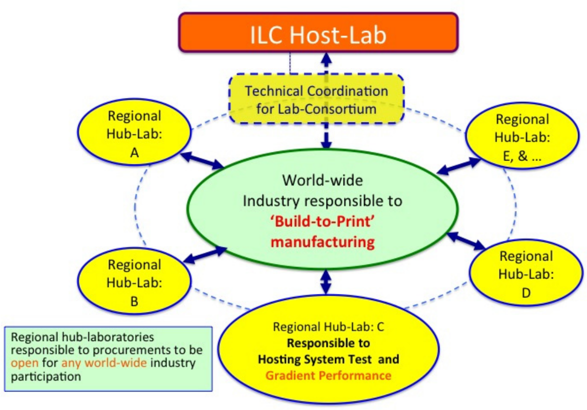

Figure 10: A possible model for ILC cavity/cryomodule production in cooperation of laboratories and industry.

As its name suggests, the hub-laboratory is a central coordinating laboratory for regional cryomodule production. A consortium of hub-laboratories forms close cooperation to the ILC host-laboratory via the adopted governance mechanism. The hub laboratory's key responsibilities are to:

- responsible to the performance of the cryomodules to be delivered to the ILC host-laboratory,
- provide the cold testing infrastructure (for both cavities and cryomodules assembly);
- manage and supervise the industrial contracts, and
- provide quality control and assurance.

It is quite likely that the hub-laboratory will procure and qualify the niobium material, and will host the cavity-string and cryomodule assembly facility to be run under contract with industry.

SUMMARY

The International Linear Collider (ILC) is planned as a next energy-frontier electron-positron collider. The SRF cavity development for the ILC has progressed in the Technical Design phase since 2007. The cavity field gradient has achieved the interim milestone of the 50 % production yield at 35 MV/m with $Q_0 \geq 8 \times 10^9$. The field gradient improvement has been realized with various R&D efforts and better understanding. The best field gradient of $\geq$ 45 MV/m has been realized with a large-grain, Tesla-style cavity with the final surface chemical process using electro-polishing.

The cavity-string performance in the cryomodule has been demonstrated in three major facilities: FLASH at DESY, NML at Fermilab, and STF at KEK. The first prototype cryomodule for the EXFEL installed into FLASH has demonstrated an average field gradient of 32 MV/m, and the S1-Global cryomodule test at STF has demonstrated a cryomodule assembled and tested with an international collaboration. The CM1 test at NLM is in progress. The cromodule-string test with beam acceleration has progressed at DESY with also international cooperation, and the ILC accelerator operational condition of 9mA and long bunch-train have been successfully demonstrated.

The preparation for the SRF cavity industrialization is in progress with multiple communications with industry and laboratories. An industrialization model based on a consortium of regional hub-laboratories to support the ILC host laboratory is under discussion.

The Technical Design phase is to be completed by the end of 2012 with publishing the ILC Technical Design Report.

ACKNOWLEDGMENTS

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REFERENCES

[1] ILC Reference Design Report (RDR), 2007: http://www.linearcollider.org/about/Publications/Reference-Design-Report
[2] ILC-GDE Technical Design Phase R&D Plan, ILC-Report-2008-13: http://ilcdoc.linearcollider.org/record/15442
[3] A. Yamamoto for the ILC-GDE SCRF collaboration, "Global R&D effort for the ILC SCRF LINAC Technology," Proc. EPAC-08, Genova, (2008).
[4] A. Yamamoto for the ILC-GDE SCRF collaboration, "Superconducting RF cavity development for the International Linear Collider," IEEE Trans. *Appl. Superconductivity,* 19 No. 3, p. 138 (2009).
[5] The international Linear Collider – A Technical Progress report (2011); http://www.linearcollider.org/about/Publications/interim-report

[6] B. Aune, et al., "Superconducting TESLA cavities," Phys. Rev. ST-AB, 3 (9) 092001 (2000).
[7] H. Weise et al., TTC Report 2008-2, 2008.
[8] See: ILC Newsline020091029; http://www.linearcollider.org/newsline/readmore_20091029_ftr1.html
[9] C. Ginsburg *et al.*, presented in ALCPG, Oregon, 2011.; http://physics.uoregon.edu/~lc/alcpg11/wgs.html
[10] R. Geng, "Overview of ILC High Gradient Cavity R&D at Jefferson Lab," SRF'11 (this conferfence), Chicago, July 2011, MOPO012, (2011); http://www.JACoW.org.
[11] C. Ginsburg, private communication.
[12] C.A. Cooper *et al.*, "Centrifugal Barrel Polishing (CBP) of SRF Cavities Worldwide," SRF'11 (this conference), Chicago, July 2011, WEIOA02, (2011).
[13] C. Ginsburg, private communication
[14] K. Watanabe *et al.*, "Cavity Inspection and Repair Techniques," SRF'11 (this conferene), Chicago, July 2011, WEIOB012, (2011).
[15] G. Wu *et al.*, "Guided Cavity Repair with Laser, E-Beam, and Grinding," SRF'11 (this conference), Chicago, July 2011, WEIOB01, (2011).
[16] J.Y. Zhai *et al.*, "IHEP 1.3 GHz Low-Low Large Grain 9-cell cavity R&D for ILC," SRF'11 (this conference), Chicago, July 2011, WEIOB06, (2011).
[17] R.L. Geng and K.X. Liu, "Q0 improvement of Large-Grain Multi-Cell Cavities by Using JLab's Standard ILC EP Processing," SRF'11 (this conference), Chicago, July 2011, TUPO049, (2011).
[18] T. Watanuki *et al.*, "Status of the 9-cell Superconducting Cavity R&D for ILC at Hitachi," SRF'11 (this conference), Chicago, July 2011, TUPO030 (2011).
[19] E. Kako, private communication.
[20] F. Furuta *et al.*, "High Gradient Results of ICHIRO 9-cell Cavity in Collaboration with KEK and JLab," SRF'11 (this conference), Chicago, July 2011, TUPO014, (2011).
[21] D. Reschke et al., "Update on Large Grain Cavities with 45 MV/m in a Nine-Cell Cavity at DESY," SRF'11 (this conference), Chicago, July 2011, TUPO046, (2011).
[22] D. Kostin *et al.*, "Update on Module Measurements for the XFEL Prototype Modules," SRF'11 (this conference), Chicago, July 2011, MOPO010, (2011).
[23] E.R. Harms *et al.*, "RF Test Results from Cryomoduule-1 at the Fermilab SRF Beam Test Facility," SRF'11 (this conference), Chicago, July 2011, MOPO013, (2011).
[24] N. Ohuchi *et al.*, "S1-Global collaborative efforts – 8 -Cavity-Cryomodule: 2 FNAL, 2 DESY, and 4 KEK," LINAC'10, Tsukuba (2010).
[25] E. Kako *et al.*, "Cryomodule test of four Tesla-like cavities in the Superconducting Test Facility at KEK," Phys. Rev. ST-AB, 13, 041002 (2010).
[26] N. Ohuchi et al., PAC'09, Vancouver, 2009: http://www.JACoW.org.
[27] Y. Yamamoto *et al.*, "Test Results of the International S1-Global Cryomodule," SRF'11 (this conference), Chicago, July 2011, THOA01, (2011).
[28] E. Kako *et al.*, "S1-global module tests at STF/KEK", to be published in Proc. IPAC11, San Sebastian (2011).
[29] N. Ohuchi, *et al.*, "Thermal performance of the S1-Global cryomodule for ILC," to be published in Proc. IPAC11, San Sebastian (2011).
[30] C. Pagani et al., "Piezo-assisted Brade-tuner: Cold Test Results", SRF'07, Beijing, p/318 (2007): http://www.JACoW.org.
[31] M. Liepe et al., "Dynamic Lorentz Force Compensation with a Fast Piezoelectric Tuner", SRF'01, Tsukuba, p.243 (2001). http://www.JACoW.org.
[32] S. Noguch, "New tuners for ILC Cavity Application", SRF'07, Beijing, WE303 (2007); http://www.JACoW.org.
[33] W. Schappert *et al.*, "Adaptive Lorentz Force Detuning Compensation in the ILC S1-G Cryomodule at KEK," SRF'11 (this conference), Chicago, July 2011, MOPO064, (2011).
[34] S. Michizono *et al.*, "Performance of the LLRF system at S1-Global in KEK", to be published in Proc. IPAC'11, Spain (2011).
[35] S. Fukuda *et al.*, "Distributed RF scheme (DRFS) – Newly proposed HLRF scheme for ILC," LINAC'10, Tsukuba, Japan, MOPO027, p112 (2010); http://www.JACoW.org.
[36] T. Matsumoto *et al.*, "Operation test of distributed RF system with circulator-less waveguide distribution in S1-Global project at STF/KEK", to be published in Proc. IPAC'11, Spain (2011).
[37] N. Walker, *et al.*, "Operation of the FLASH Linac with Long Bunch Trains and High Average Current," PAC'09, WE6F109, p. 2766, PAC'09 (2009); http://accelconf.web.cern.ch/AccelConf/PAC2009/papers/we6pfp109.pdf.
[38] S. Peri, J. Carwardine, N. J. Walker *et al.*, "Latest results on Cavity Gradient and Input RF Stability FLASH/TTF Facility," LINAC'10, TUPEA059, p470 (2010); http://www.JACoW.org.
[39] J. Carwardine, S. Schreiber, and N. Walker, presented at The 2nd workshop on Linac Operation with Long Bunch Train held at DESY, February, 2011; http://indico.desy.de/conferenceDisplay.py?confId=3007.
[40] A. Yamamoto presented at The 2nd workshop on SCRF Technology and Industrialization, held as a satellite workshop of SRF'11, Chicago, July 2011; http://ilcagenda.linearcollider.org/conferenceDisplay.py?confId=5182.