REVIEW OF SRF CAVITIES FOR ILC, XFEL, AND ERL APPLICATIONS

Hitoshi Hayano
High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Abstract

Well-balanced performance cavity is required for ILC, XFEL and ERL applications such as for high gradient, strong HOM damping, high beam loading operation, and alignment. The basement is the TESLA technology which has been developed from early 90's by the TESLA collaboration. By the advance of the fabrication quality control and the surface treatment quality control made great improvement in their performance. This paper reviews mainly TESLA cavity technologies for above-mentioned performance.

INTRODUCTION

1.3GHz multi-cell structure is used for the superconducting RF cavity for ILC, XFEL and ERL applications. High performance is required for these applications such as high gradient, high HOM damping, high beam loading operation, and reasonable alignment tolerance. The basement is the TESLA technology which has been developed from early 90's by the TESLA collaboration. The TESLA 9-cell cavity (Fig.1) is designed to have high performance for TESLA linear collider, later for XFEL and ILC. The acceleration module which is named as cryomodule includes 8 or 9 cavities with dense manner in the 12m cryomodule. The total number of cavity used will be ~17000 for ILC and ~800 for XFEL. An 1ms rf pulse flat-top width with 5 or 10Hz repetition are applied into the cavities. The required operational accelerating gradient is 31.5MV/m for ILC and 24MV/m for XFEL.

Figure 1: 1.3GHz TESLA 9-cell cavity.

ERL cavity which is operated in the superconducting state uses the similar technologies of TESLA cavity. The main features of ERL cavity (Fig. 2) compared with TESLA cavity are CW operation, high average current, energy recovery mechanism in its beam operation. The main difference is the HOM damping scheme. Wide diameter beam pipes and HOM absorber in the beam pipe are used to get order two smaller HOM impedance.

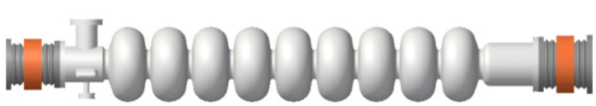


Figure 2: KEK Design of 1.3GHz 9-cell cavity for ERL application, as an example.

The paper reviews the technical development and recent performance results for the common and basic cavity technology between these applications [1][2][3].

SUPERCONDUCTING MULTI-CELL CAVITIES

Design

The shape of TESLA cavity is the results of optimization for high gradient long linac; such as, choice of frequency, number of cells which is related to effective length of active acceleration length, field homogeneity and absence of trapped mode, cell-to-cell coupling, iris diameter, E_{peak}/E_{acc}, B_{peak}/E_{acc}.[1] XFEL and ILC adopt TESLA design. The basement ERL cavity design is TESLA design, however, strong HOM damping is the first priority, so that further optimization was done for the HOM couplers and HOM damping.

Fabrication and Tuning

The cavity is fabricated mainly by pure niobium (Nb) sheet which has RRR greater than 300. Nb-Ti alloy is used for flange materials and the end plate. Ti is used for helium jacket and helium supply pipe. The most experienced fabrication for the advanced performance is that the Nb sheets are pressed to a half cup, beam pipes are made from Nb pipe material, and then welded by electron beam welder (EBW). The smooth and flat finish of EBW seams without any defects and contaminations are essential for the high gradient performance. Since the fabrication method is press and weld, the precise frequency tuning and precise cell-to-cell alignment are done by 6 jaws push and pull action for each cell with automated way (Fig.3).

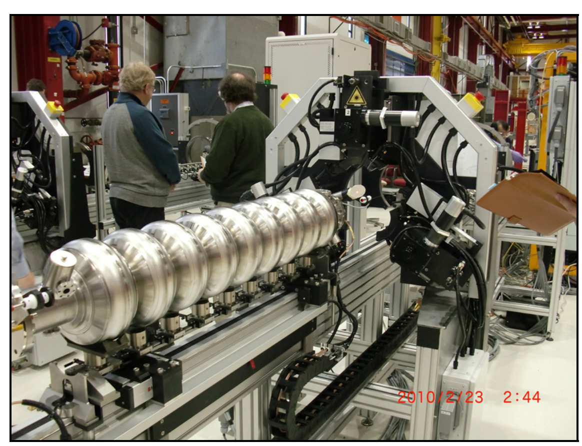


Figure 3: Automated tuning machine of frequency and alignment for TESLA cavity.

Surface Treatment

The surface treatment after fabrication is the combination of electro-chemical polishing (EP, see Fig. 4), buffered chemical polishing (BCP) and mechanical grinding (Centrifugal Barrel Polishing; CBP). EP is the most high performance treatment, because of its smooth and bright finish even at the grain boundary steps. The EP facilities are now introduced in many laboratories or under planning of installation in the world. The optimization of EP operation parameter, such as voltage, temperature, fluorine concentration, and agitation, and rinse parameter such as initial water rinse optimization, ultrasonic and degreaser rinse optimization are now underway to get more smoother surface and to reduce field emission residual source from the surface.

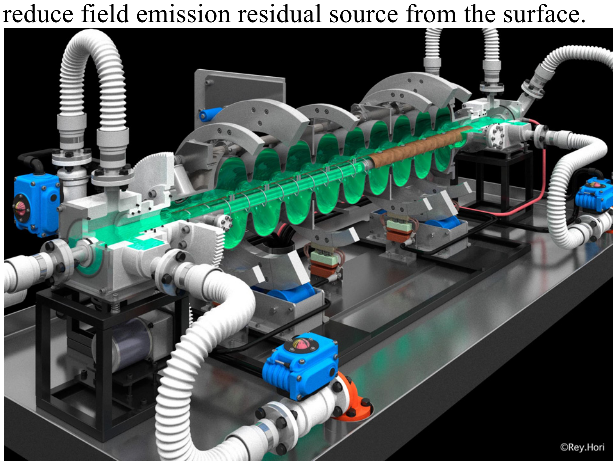


Figure 4: Conceptual illustration of EP machine for cavity surface treatment.

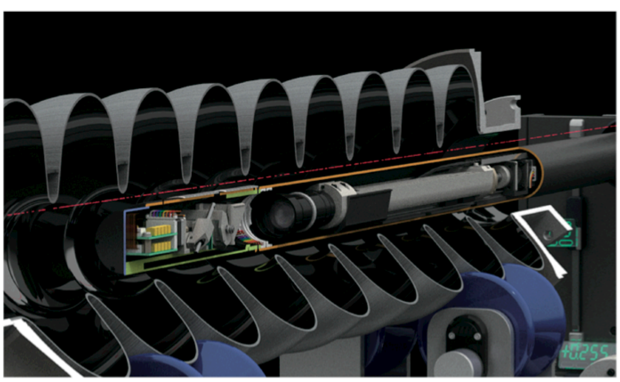


Figure 5: Conceptual illustration of inner surface inspection camera with special illumination.

Testing and Jacketing

Testing the cavity performance is done at a vertical Dewar test by cooling the cavity to below 2K and applying CW rf of about 100 - 200W. Temperature mapping and X-ray mapping on the cavity are used to identify the location of quench and thermal heating. When the performance is limited by the quench or heating, optical inspection is applied after the vertical test. The compact high magnification C-MOS camera together with special illumination by LED light and plastic light guide give a good contrast defect image inside of the cavity (Fig. 5). Only the reasonable performance cavity goes to the jacketing process. Ti jacket vessel with bellows is welded to the cavity endplates. The bellows are for the tuner of frequency tuning action, such as longitudinal extension and compression.

Gradient Performance and Issues

The high gradient performance with high production yield is required. By the recent advance in the quench position locater, such as T-mapping device, X-ray-mapping device, second sound sensor[4], inspection camera[5], and pass-band mode measurement, the statistics of the relation between quench and defect became increased. The molding method to catch up detailed defect shape is recently pursued. Small tip of foreign materials on the Nb surface and welding seam defects were identified as the source of low field quench in the early stage of the development. By the advance of material purity, quality control (QC) of material production, QC of EBW, and QC of surface treatment and assembly, gradient performance has been improved greatly. In Figure 6, the gradient yield statistics edited by GDE gradient database team for the recent fabricated and tested cavity by qualified vender are shown. The issues which are not yet solved completely are; defects appeared after several EP treatment, field emission source and its removal method, optimization of EP treatment parameter, best rinse method after EP treatment.

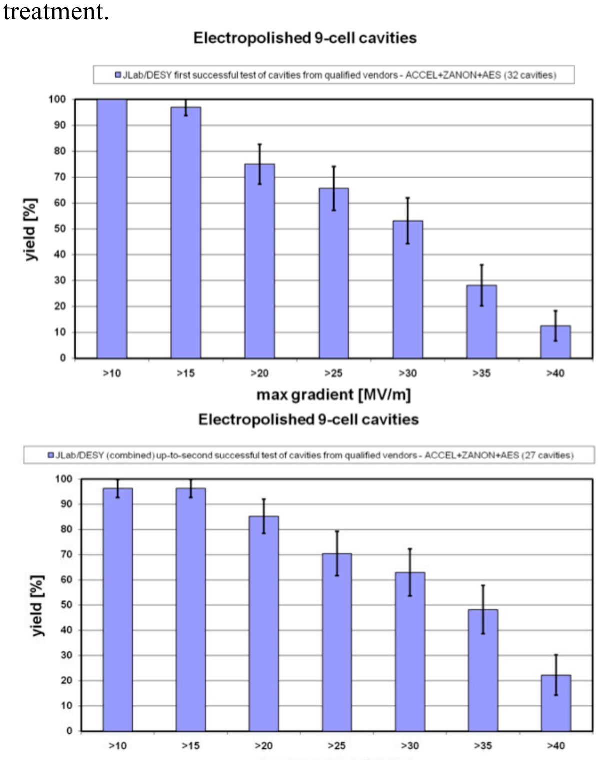


Figure 6: Gradient yield statics of the recent 32 cavities of the first test (upper) and 27 cavities of the second test (lower).

ADVANCED TECHNOLOGY FOR HIGH QUALITY BEAM

HOM Damping

TESLA design cavity has two coaxial-type HOM couplers on both sides of beam pipes (Fig.7). The couplers couples TM110, TE111, TM011, and so on, however do not couple to TM010 accelerating mode. This type of coaxial coupler design has an advantage of compactness for more efficient acceleration. Required HOM impedance $(R/Q)Q_{ext}/f$ for XFEL and ILC is around less than 1×10^6, on the other hands, ERL design is 2 order lower. The ERL cavity uses other damping design in order to damp more efficiently, that is, beam pipe HOM absorber. Other aspect, coaxial coupler uses coupling antenna and feed-through. The feed-through are the source of heating problem in the CW operation.

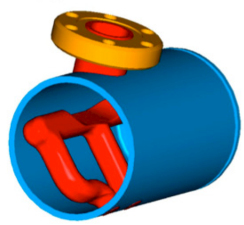


Figure 7: Illustration of HOM coupler antenna which is placed at the both of beam pipe in TESLA cavity.

HOM antenna optimization and improvement

In order to minimize the trapped mode in the TESLA cavity design, the end cells half-cell-shape were modified to its asymmetry shape. The antenna twisted angles on both side of HOM coupler were also optimized to the mirror symmetry angles. The pick-up electrode was also modified to expand its area, in order to make more distance space between HOM antenna inner conductor and pick-up electrode to avoid touching by the fabrication error. On other aspect, pickup antenna uses feed-through connector. The feed-through ceramics is the source of heating problem in the CW operation. The improvement of this ceramics to have more thermal conductivity, and thermal anchor attachment are under development. For XFEL cavity qualification in vertical Dewar test, pulsed operation instead CW to avoid this heating problem is also under testing.

Beam-pipe HOM Absorber

In Figure 8, illustration of beam pipe HOM absorber which is designed and demonstrated in Cornell ERL injector accelerator is shown. The HOM absorber which is done by ferrite plates at around beam pipe bellows wall are placed in the cavity to cavity connection bellows. Gas helium cooling channels are placed in the outside of the ferrite plates. The diameter of this absorber is relatively wider than TESLA cavity beam pipe to get enough HOM damping. The KEK 9-cell cavity design has another feature on the beam pipe HOM damper. It has a polarization mixture structure for quadrupole mode to effectively extract out to HOM absorber.

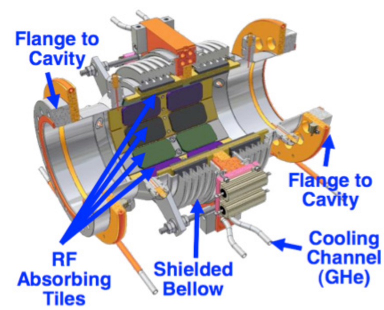


Figure 8: Illustration of beam pipe HOM absorber which is designed and installed at Cornell ERL injector.

Pulsed Operation with Lorentz Detuning Compensation

In the pulsed rf input into the superconducting cavity, detuning is happened at the rf filling transient, because of cavity shape deformation by Lorentz force. The mechanical tuner which controls the cavity resonant frequency should have fast response piezo actuator to compensate the Lorentz force detuning. There are three kind of mechanical tuner; that is, the lever-arm tuner designed by Saclay, the blade tuner designed by INFN, and the slide-jack tuner designed by KEK. The compensation demonstrations were done for these tuners. However, GDE S1-Global project will give the same condition for the performance comparison. The S1-Global experiment will be performed until December 2010. An example of the compensation is shown in Fig.9 for the case of the lever-arm tuner.

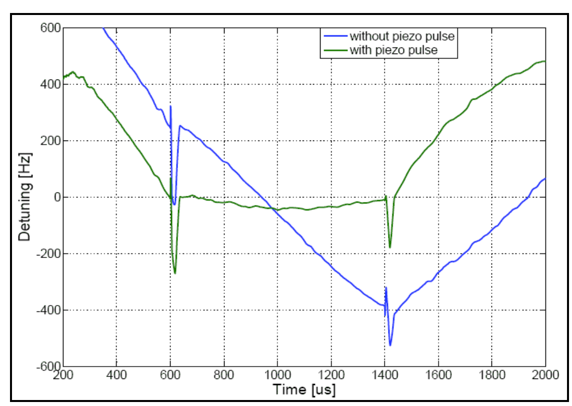


Figure 9: Lorentz detuning compensation test of piezo-actuator in lever-arm tuner by DESY at 33MV/m.

Precise Digital Feedback Control with Feed Forward

To make flat energy beam acceleration over the 1ms bunch train, flat-top rf amplitude and phase control is essential. A small latency digital feedback loop by FPGA (Field Programmable Gate Array) chip brought us the precise feedback control with freedom of the control logics. An example of this control for the 4 cavity feedback at STF cryomodule are shown in Fig. 10. However, as the rf control is done for the vector sum signal of each cavity pickup, so that, when each cavity has different loaded Q-values, the rf amplitude of smaller Q-values cavity than an average will increase at flat-top and that of larger Q-values cavity will decrease. The Q-value variation will bring rf amplitude variation at the flat-top. It will cause a risk of quench for the cavity which will operate at very close to its performance limitation. To reduce its quench risk, Q-value adjustment for each cavity by adjusting coupling of the input coupler insertion is required.

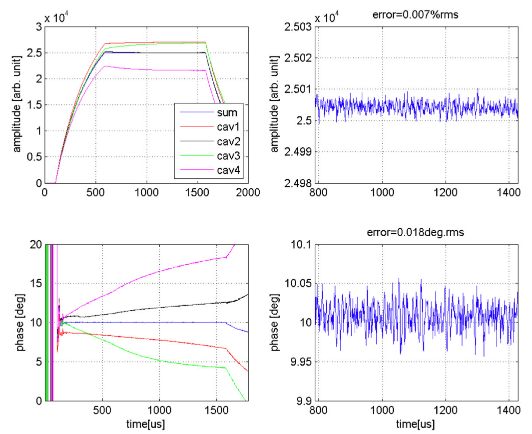


Figure 10: Stabilized rf field amplitude and phase of STF 4 cavity vector sum digital feedback control.

Antenna Kick Issue

The asymmetry of coupler antenna around beam axis is illustrated in Fig.11, together with rf field asymmetry on the beam axis. This asymmetry was a discussion for wake field effect on the emittance growth and rf kick effect on the beam. So that, new antenna configuration was proposed such as Fig.12 upper right. Careful research and precise calculations were performed by several researchers. The red line on the Fig.12 emittance plot is the growth by the new HOM antenna setup. The black line is the growth after dispersion corrected. The old setup growth is shown by the blue line, and is negligible small. The conclusion of the study was followings;

(1) Only wake field effect for the new setup was considerably reduced compared with old setup.

(2) rf kick effect on the beam emittance was getting worth for the new setup, even after the dispersion corrected.

(3) Old setup (original TESLA design) gives smaller emittance growth in ILC linac for considering both effect, such as wake field and rf kick.

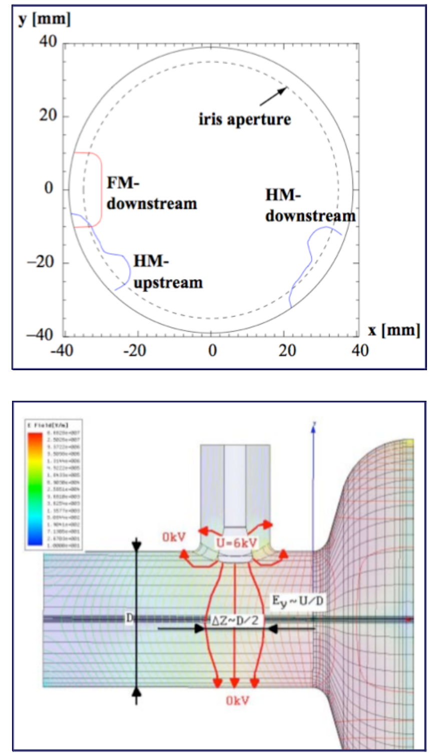


Figure 11: existing HOM layout from the beam view (upper). The beam kick contribution of rf field asymmetry by couplers at beam pipe (lower).

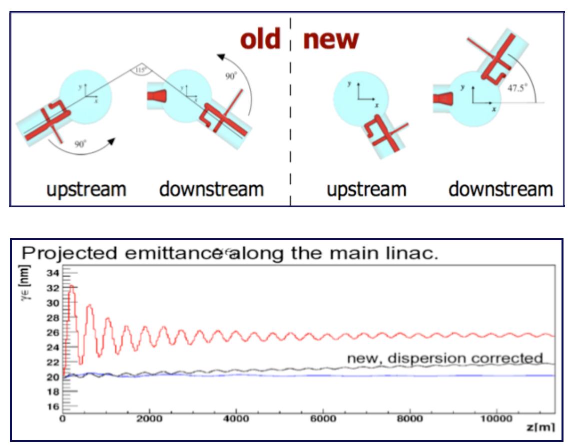


Figure 12: existing old HOM layout design and newly proposed layout (upper). The calculated emittance growth in the ILC main linac for both layout(lower).

Alignment Tolerance for Long Linac

The standard alignment errors are assumed in ILC main linac case (Fig.13) and emittance growth are estimated for 11km length linac. The assumed errors seem to be reasonable and attainable by cryomodules in ILC. The growth by cavity offset is about 7% growth contribution out of 32% growth, and it is not so tight tolerance, however, it is important to realize in the cryomodules.

	Vertical	Horizontal
Quad Offset (µm)	360	1080
Quad Roll (µrad)	300	
Cavity Offset (µm)	640	1920
Cavity Pitch and Yaw (µrad)	300 (pitch)	900 (yaw)
BPM Offset (µm)	360	1080
BPM Roll (µrad)	0	
BPM resolution (µm)	1	1
BPM scale error	0	0

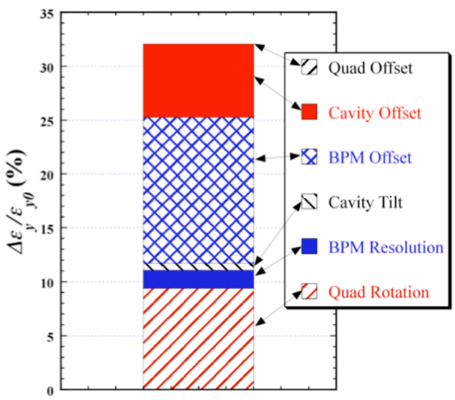
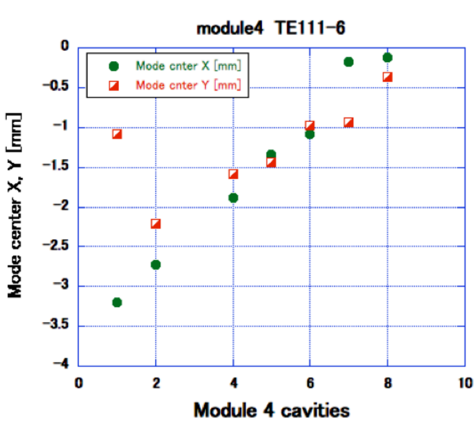
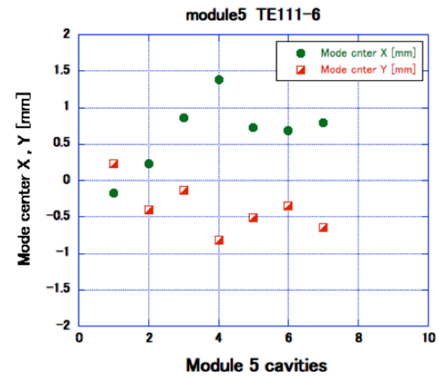


Figure 13: Assumed error of component alignment (upper), and contribution of emittance growth of each error (lower), done by code SLEPT.

HOM-BPM for Alignment Confirmation

To know about cavity offset in the actual cryomodule, HOM pickup by the beam passing is used to estimate. The experiment of the electrical centre estimation at FLASH accelerator was done by pick up HOM signal digitized by the fast oscilloscope, and used TE111 the 6th mode. Fig.14 shows the results of cavity offset relative to the BPM axis in the neighbourhood. The average offsets are; X=-0.21+/-1.23mm, Y=-0.51+/-0.78mm. The vertical spread is little bit larger than the standard error in the simulation. The care for the actual cavity alignment should be paid in the future.





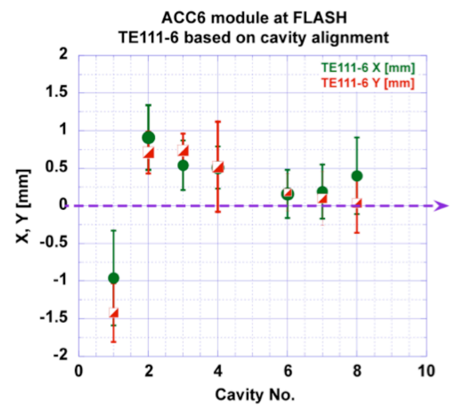


Figure 14: Electrical center offset of the cavities in the DESY FLASH module 4, 5 and 6, relative to BPM axis.

SUMMARY

The advance of TESLA cavity performance for the gradient yield, acceleration field control, HOM damping and alignment tolerance are well progress in these years by the effort of XFEL development and ILC development. HOM damping effort for the ERL cavities is also progressed by using beam pipe HOM absorber technology. The HOM detection beam experiment suggests that cavity alignment inside of cryomodule is an issue to be solved in the next.

ACKNOWLEDGEMENT

The author would like to thank all the members of TESLA technology collaborators, XFEL collaborators and ILC collaborators. The figures, pictures and experiment data shown here are referred from workshops, conferences, GDE website and DESY website, and the author is gratefully appreciated.

REFERENCE

[1] TESLA Technical Design Report, part II accelerator, March (2001); http://flash.desy.de/tesla/tesla_documentation/

[2] ILC Reference Design Report, ILC-Report-2007-001 (2007); http://www.linearcollider.org/cms/?pid=1000437

[3] Proceedings and presentations of EPAC2006, EPAC2008, SRF2009, GDE meeting 2008, 2009, 2010.