Superconducting RF Cavity Development for the International Linear Collider

A. Yamamoto for the ILC Global Design Effort,

Abstract—**The International Linear Collider is planned as the next energy-frontier electron-positron accelerator. The main linacs of the collider are based on superconducting radio-frequency cavity technology, and to accelerate electron and positron beams up to 250 + 250 GeV at the center-of-mass energy. Based on the Reference Design Report issued in 2007, the ILC Global Design Effort has moved into the Technical Design phase. This paper describes the status of the design, R&D efforts, and future plans of the superconducting RF cavity for the ILC.**

Index Terms—**ILC, Linear accelerator, linear collider, particle accelerator, superconducting RF cavity,**

I. INTRODUCTION

THE International Linear Collider (ILC) is proposed as the next energy-frontier electron-positron machine, and would be built as a global effort [1]. The main linacs of the ILC are based on superconducting radio-frequency (SCRF) accelerator technology, as recommended by the International Technology Recommendation Panel [2] and endorsed by the International Committee for Future Accelerators. The ILC Global Design Effort (ILC-GDE) was launched to advance the accelerator design and R&D efforts and produced the Reference Design Report (RDR) in 2007 [3]. The ILC design assumes a field gradient of 31.5 MV/m in the SCRF accelerator cavity to achieve a center-of-mass energy of 250 + 250 GeV with two 11-km long main linacs. Figure 1 shows a schematic layout, and Table 1 summarizes the main parameters of the main linac. Figure 2 shows a 9-cell superconducting cavity developed the ILC R&D at DESY. With the choice of 1.3 GHz SCRF, the beam aperture is relatively large (70 mm), which makes the transverse wakefields generated by off-axis beams fairly small. The very low power loss in the cavity walls allows the use of long RF pulses, which reduces the required peak RF power and produces a high wall-plug to beam efficiency. Cavity performance is key to the design as the linac lengths are determined by the average field gradient in the cavities, and the required cryogenics cooling power depends on the cavity quality factor (Q_0). A major goal of the global ILC R&D effort is to achieve a field gradient of 35 MV/m with quality factors of 10^{10} or higher in 9-cell cavities with a yield of 90 % during acceptance testing. This should ensure reliable operation at 31.5 MV/m during the machine running. Current R&D efforts have resulted in more than ten 9-cell cavities with a field gradient higher than 35 MV/m in vertical performance tests [4]. The yield is, however, much lower than 50% due to field emission and quenching.

TABLE I DESIGN PARAMETERS FOR THE ILC MAIN LINAC.

Parameter	Value
Center-of-mass energy	500 GeV
Peak luminosity	2×10^{34} cm^{-2}s^{-1}
Beam repetition rate and pulse time-duration	5 Hz and 1 ms
Average beam current in pulse	9 mA
Average field gradient in cavity	31.5 MV/m
Number of 9-cell cavities (cryomodule)	14,560 (1,680)

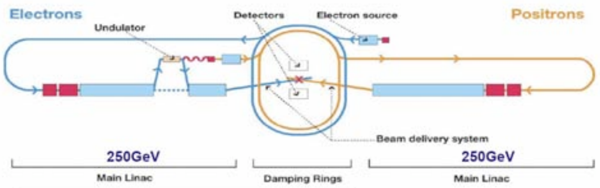

Fig. 1. A schematic layout of the ILC .

Following the RDR, the ILC Technical Design Phase (TDP) started in 2008. It is to be carried out in two stages: TDP-1 to demonstrate the technical feasibility by mid-2010, and TDP-2 to verify the technical credibility with accelerator system engineering by the end of 2012. The major R&D goals have been identified as follows [5,6]:

- Cavity field gradient:
  - Reach a field gradient of 35 MV/m for 9-cell cavities in vertical tests with a yield of 50 % at a quality factor of $>10^{10}$ for cavity preparation processes in TDP-1, and 90 % for cavity production in TDP-2,
  - Demonstrate an average field gradient of 31.5 MV/m in a string test of 9-cell-cavities in one cryomodule in early TDP-2,
- Cavity and cryomodule integration

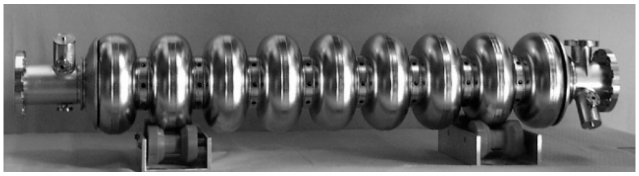

Fig. 2. A 9-cell superconducting cavity developed at DESY.

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  - Establish a "plug-compatible" design and interfaces,
  - Make further improvement to components,
  - Encourage practical "project implementation" in global effort and balance.
- <u>Accelerator system engineering:</u>
  - Demonstrate system performance with beam acceleration in an accelerator unit consisting of three cryomodules powered by one RF system.

The field gradient studies are made at the various stages of accelerator build-up, including i) single-cell cavities, ii) 9-cell 'bare' cavities in vertical test facilities, iii) 'dressed' cavity string in cryomodules as shown in Fig. 2, and iv) three cryomodule string tests with ILC-like RF system and beams.

II. STATUS OF CAVITY R&D

Superconducting cavity technology for large-scale accelerators has been advanced significantly by the TESLA Technology Collaboration (TTC) [7] centered at DESY in the past ten years. It has culminated in approval of the European X-ray Laser Project (EuroXFEL) [8], which is based on a ~ 20 GeV linac with the similar technology to the ILC. This progress has been achieved through efforts and experiences accumulated at DESY, Cornell University, CERN, KEK, JLab, CEA, and many other institutions.

A. Cavity Shape

Searched for optimum cavity shapes to improve the field gradient have benefited by studies using single-cell cavities. Table 2 lists characteristics of three cavity shapes currently being investigated and Fig. 3 shows their cross sections [9-11].

TABLE II. CAVITY SHAPES STUDIED FOR THE ILC.

Parameter	**TESLA**	**LL/IS**	**RE**
Iris aperture (mm)	70	60/61	66
E_{peak}/E_{acc}	1.98	2.36/2.02	2.21
B_{peak}/E_{acc} (mT/(MV/m))	4.15	3.61/3.56	3.76
Char. shunt impedance: R/Q (Ω)	114	134/138	127
Geometric factor: G (Ω)	271	284/285	277
$G \times R/Q$ $(\Omega \times \Omega \times 10^5)$	3.08	3.80/3.93	3.51

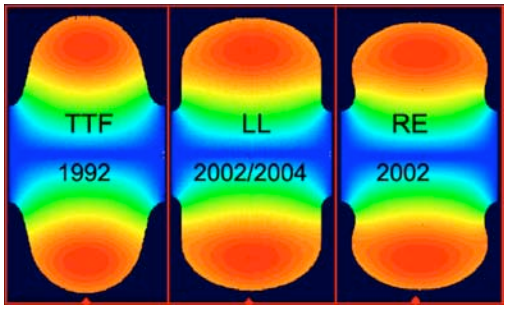


Fig. 3. Various RF cavity design for TESLA and ILC.

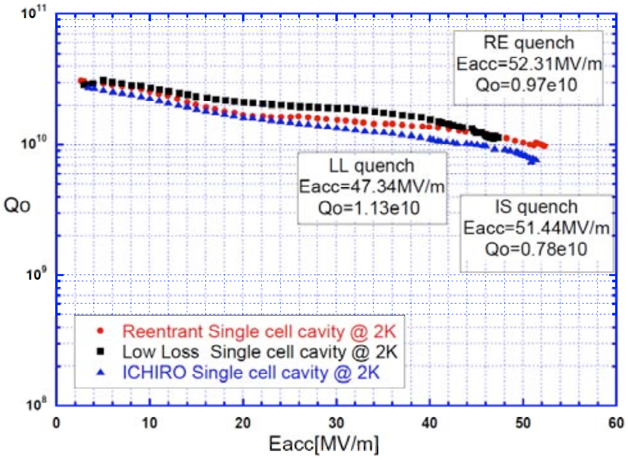


Fig. 4. Field gradient recordd for RE, LL and IS (modified LL) cavities.

The TESLA shape has a favourable low E_{peak}/E_{acc}, ratio, acceptable cell-to-cell coupling, and a small wake-field loss factor [12]. It has lower risk of field emission and dark current, and its higher order mode (HOM) behaviour is well studied. Two alternate shapes, low-loss/Ichiro-shape (LL/IS) [10], and the re-entrant (RE) [11] and, have advantages of a lower B_{peak}/E_{acc}, a higher G×R/Q, and a lower cryogenics loss. They can potentially reach high gradients, since B-peak ultimately limits superconducting operation. Both shapes, however, have a higher risk of field emission since E_{peak}/E_{acc} is 10 ~ 20 % higher than that in the TESLA shape. Tests of those single-cell cavities have reported a maximum field gradient of > 52 MV/m as shown in Fig. 4 [13,14]. A new RE cavity shape with the same aperture as the LL shape has reached 59 MV/m in a Cornell/KEK collaboration [11,15].

B. Cavities with large-grain/single-crystal Nb sheet

Fabricating cavities from large-grain or single-crystal Nb sheets is being investigated to improve performance (due to fewer grain boundaries) and lower cost (eliminates the sheet rolling process which can introduce contamination) [16]. Figure 5 shows inner surface of a half-cell cavity with the large grain niobium. Pioneering work has been carried out at JLab, and various efforts are in progress at Cornell University, DESY, Peking University, KEK, and other laboratories. This material may allow elimination of the EP process, and require only an easier buffered chemical polishing (BCP) process. At JLab, large-grain single-cell cavities have reached 30-35 MV/m with BCP treatments only. In collaboration of DESYwith JLab, a single-grain single-cell cavity reached 37.5 MV/m, also with a BCP treatment [17]. Studies of large grain, single cell cavityies fabricated at IHEP and chemically treated at KEK has reached 40.3 MV/m [18].

Fig. 5. Inner surface of a large grain cavity at JLab.

C. Cavity fabrication and surface preparation process

Extensive efforts have been made to establish standard cavity fabrication and surface preparation processes [19]. As a consequence a global process guideline is being formulate as summarized in Table III [20].

TABLE III. CAVITY FABRICATION AND PREPARATION.

Step	Contents
Fabrication process	- Nb-sheet preparation and forming of half-cell, - Assembly with electron-beam welding (EBW)
Surface preparation process	- 1st Electro-polishing (Bulk-EP) - Ultrasonic degreasing/Ethanol rising /Fresh EP, - High-pressure, pure-water rinsing - Hydrogen degassing (Heating in vac.) - Tuning of field flatness, - 2nd EP - High-pressure, pure-water rinsing, or Fresh-EP - Assembling with inut-coupler and antenna - Baking
Vertical test	- Testing at 2K - Thermometry and mode measurement

The most promising surface preparation technique is electro-polishing (EP) as developed for TRISTAN at KEK [21]. Sharp edges or tips are smoothed out, resulting in a very glossy surface. Cleaning of the surface after the EP process is also crucial for avoiding field emission. Ultrasonic degreasing by using detergent has been attempted with good results at JLab, and ethanol rinsing achieved good results at DESY as it is discussed below. High-pressure rinsing with ultra-high purity water is crucial as the final process. Further R&D on the EP process continues at JLab, CEA, and other laboratories. As a summary of fundamental research and development based on the single cell cavity, Fig. 6 shows progress of the field gradient with the single cell niobium cavity, according to advances of surface preparation process as well as the cavity shape [10].

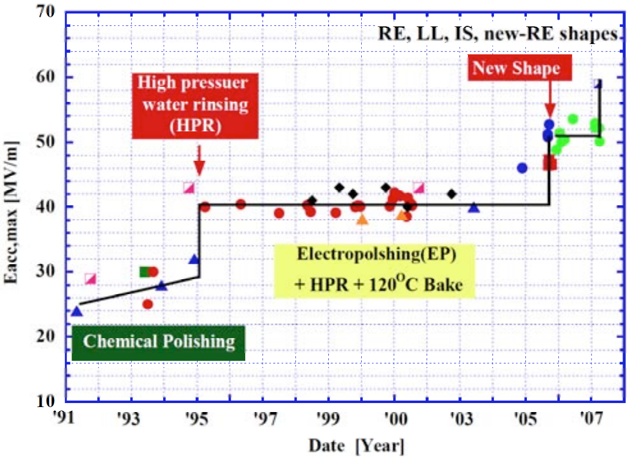


Fig. 6. Progress of field gradient with single cell cavities [18a].

D. Progress with 9-cell cavities

Substantial R&D progress has been made, especially on the surface preparation process, with the TESLA 9-cell cavities at DESY [22]. At DESY, ethanol rinsing has been shown to be effective to improve the field gradient limit due to field emission. Figure 6 shows a comparison of the cavity field gradient performance with and without ethanol rinsing [23]. Significant improvement of the maximum field gradient is seen with ethanol rinsing. On the other hand, unidentified surface defects are suspected for two lowest gradient cavities even with the ethanol rinsing.

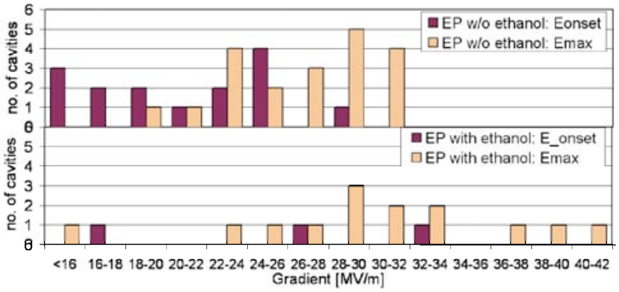


Fig. 6. Ethanol rinse effect on the onset (E-onset of field emission and maximum gradient (E-max) for the 9-cell cavities at DESY.

Figure 7 shows a summary of cavity performances achieved by an American collaboration of Fermilab, JLab, Cornell University with contributions from KEK [24-26]. Multiple surface preparation processes and vertical test results are summarized for various cavities. The best field gradient result of 41 MV/m was obtained with the cavity fabricated by ACCEL (A7) and processed/tested by the Fermilab-JLab collaboration. JLab has explored a surface cleaning using "ultrasonic degreasing" (USD) with detergent. Using this process, less than 15% of tests show the maximum field

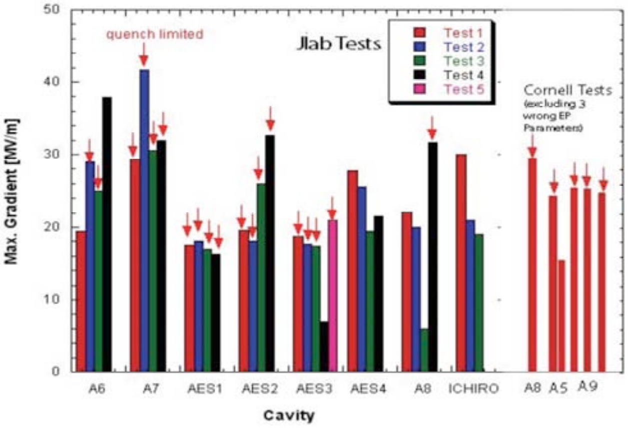


Fig. 7. Performance of 9-cell cavities by the American collaboration, (with KEK contribution).

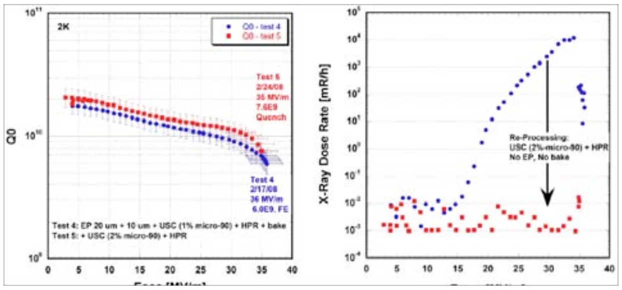


Fig. 8. Effect of ultrasonic degreasing with detergent on field emission observed with a LL cavity processed at JLab.

gradient limited by field emission. Figure 8 shows an example of USD applied to an LL cavity (Ichiro-5) built by KEK. After the second USD with 2% detergent a significant reduction of field emission (right) is seen with a maximum field gradient (left) of > 35 MV/m [27]. Cornell has developed a vertical EP method to simplify the EP process with good results. Fermilab and ANL have been collaborating to completed new infrastructure to process cavities [28]. Fermilab and JLab are making their efforts to establish cooperative programs with Indian Institutions on the SCRF R&D.

In an Asian effort, KEK has been advancing the R&D work for TESLA-type and LL-type cavities in cooperation with Chinese, Korean, and Indian institutions. Recently, four 9-cell cavities similar to the TESLA-type were developed and vertically tested at KEK. One of four cavities has reached a maximum field gradient of 29 MV/m after improving the smoothness of the EBW region by additional barrel polishing [29,30]. The LL type 9-cell cavities have been evaluated in collaboration with JLab as discussed above. A new infrastructure for vertical testing and cavity preparation including the EP process has been completed at KEK.

E. Progress with cavity-string in a cryomodule

Achieving ILC level performance of 9-cell cavities in a cryomodule is an important milestone. In the XFEL and ILC linacs, eight or nine 9-cell cavities will be assembled as a string in one cryomodule. Figure 9 shows the average field gradient achieved with 9-cell cavity string (right) in cryomodule at TTF/FLASH, DESY, compared with the average gradient of individual 9-cell cavities (left) measured in vertical test [4, 31]. The average field gradient of a 9-cell cavity string in a cryomodule has recently reached >28 MV/m.

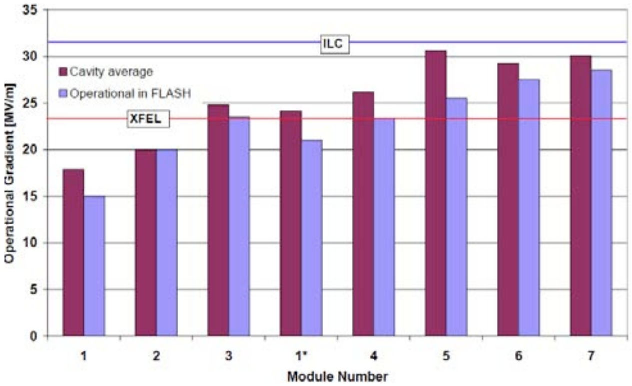


Fig. 9. Progress in the average field gradient of eight cavity string in cryomodule at TTF/FLASH.

III. FURTHER R&D PLAN

Based on the recent progress world-wide, another 15 ~ 20 % improvement in the field gradient is still needed to reliably satisfy the ILC SCRF requirements. R&D will continue with the goal of i) finding the causes of the field gradient limitation, ii) developing countermeasures to remove them, and iii) verifying the countermeasures worked in a statistically meaningful way.

A. Cavity surface inspection and improvement of yield

The electric field gradient is fundamentally limited either by i) field emission, mainly around the "iris" area, or ii) by a quench that is caused by heating from surface defects or dark current, mainly in or near the "equator" area [18]. The field gradient limit can also be caused by particle contamination during the cavity assembly and integration into the cryomodule. An optical inspection system using a high resolution CCD camera has been recently developed by collaboration between Kyoto-University and KEK [32]. The system has been used to identify local defects in 'hot' area seen with thermometry measurements during vertical testing [33]. Figure 10 shows the high-resolution camera and an inside surface showing defects identified with this camera. Further investigation using this camera system is underway. As this technique matures, it may allow a fast way to identify and correct problems encountered during quality control in the fabrication and preparation process of the cavities. A new long-range microscope system is also being developed at JLab and it offers comparable surface view via mirrors.

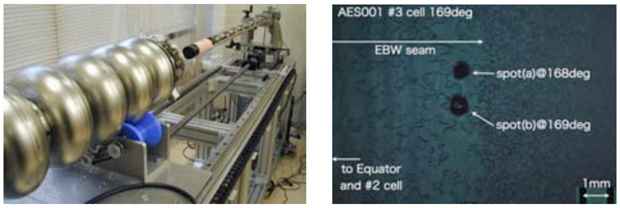


Fig.10. Observation of inner surface of a cavity using a high-resolution optical camera system.

B. Cavity integration with plug-compatibility

Since the SCRF technology and the cavity system construction in the ILC project may need to be shared by multiple regions and institutions, plug-compatible designs and interfaces are desired. The cavity shape and some components such as tuners may be optimized with plug-compatible designs within a prescribed cavity envelope, interfaced with common beam pipe flanges, input-coupler flanges, and functional parameters as shown in Fig. 11. The coupler configuration for

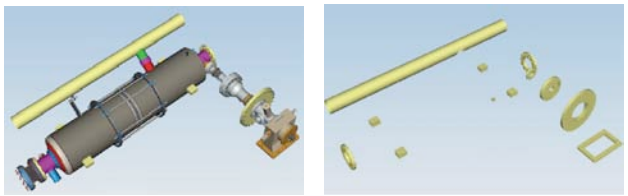


Fig. 11. Cavity integration with plug-compatible interfaces

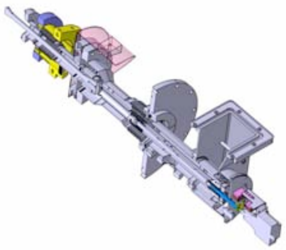


Fig. 12. Input RF power coupler (XFEL type).

the case of TESLA/XFEL type are illustrated in Fig. 12 [34]. Either cold or warm plug-compatible condition is to be settled. The plug-comatibility is an important guiding concept that benefits both the accelerator complex construction and the present R&D efforts.

C. Cryomodule design and engineering

The cryomodule design for the ILC is proceeding under the plug-compatibility philosophy. The system engineering is being carried out based on experience with the TESLA cryomodule in the DESY-INFN-Fermilab-KEK collaboration [35-37]. Figure 13 shows the cross section under design study. A means of simplifying the 5-K radiation shield is also investigated to reduce cost.

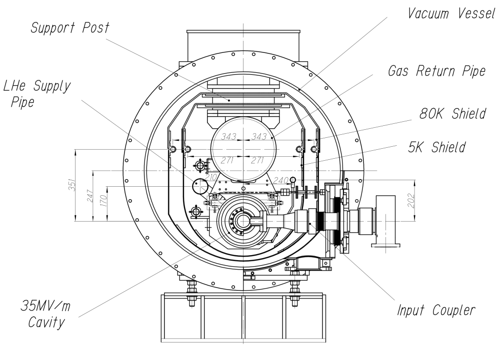


Fig. 13. Cross section of the Cryomodule being designed.

D. Cavity-string test in a cryomodule unit

A global collaborative effort for 9-cell cavity-string tests in a cryomodule is in progress [6]. Two units each of dressed cavities are to be provided by DESY and Fermilab, and four cavities are to be provided by KEK for this work. A cryomodule enclosure and associated components is to be prepared by the KEK-INFN collaboration. This will allow the examination of the plug-compatibility concept, and help to demonstrate that the ILC can be designed and built as global effort. Figure 14 shows the cross section of the cavity string assembly in this global cryomodule.

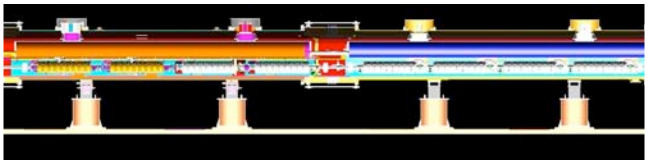


Fig. 14. Layout of the global cryomodule for an eight-cavity string test.

E. Cryomodule-string test with one RF-power unit

Cryomodule-string tests with one RF-power unit are to be carried out eventually at three sites, DESY, Fermilab and KEK, as demonstrations of technical credibility, including overall system engineering with beam acceleration [38]. DESY is well along in preparing for this test using existing infrastructure at TTF. Fermilab and KEK have started to prepare the infrastructure, including cryogenics and RF systems. SLAC is developing a Marx generator for the modulator to be used at Fermilab. Figure 15 show the schematic layout planned at KEK.

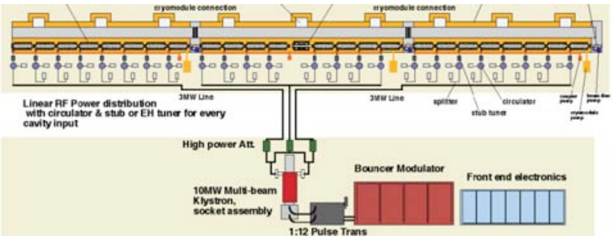


Fig. 15. Schematic layout for the cryomodule string tests with one RF-power unit.

F. Cryogenics system

The scale and features of the cryogenics system for the ILC are expected to be similar to the LHC accelerator cryogenics system, which also operates at 2 K. Figure 16 shows the conceptual diagram for the ILC cryogenis. The conceptual design for this system is in progress [39], and a design pressure of 2 bar was adapted recently for the cavity and cryomodule cryogenic system. Further system engineering will be carried out to determine the most cost effective design in view of both construction and long-term operation, in reference to the extensive experience at CERN-LHC.

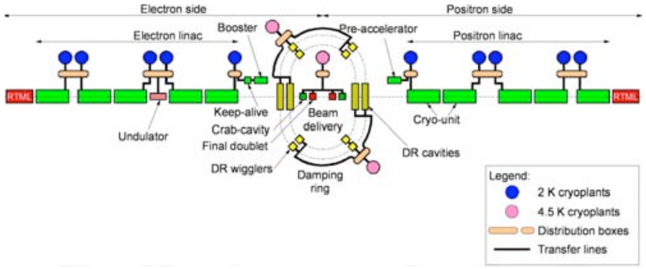


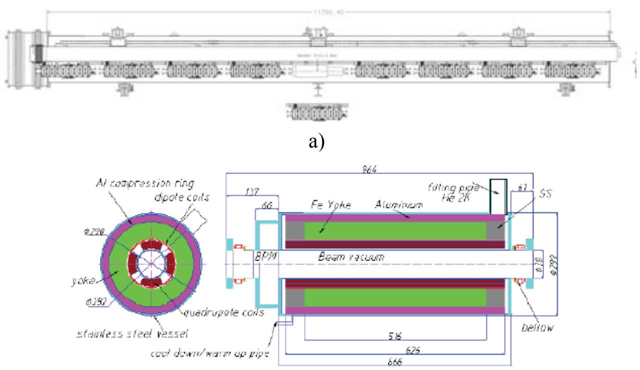
Fig. 16. Conceptual diagram for the ILC cryogenics.

G. High level RF system and R&D

A cost effective RF power source is a major focus of ILC R&D. The current existing klystron/modulator technology is likely to be updated by using Marx generator technology [40]. Figure 13 shows the Marx generator currently under development. A cost effective RF power distribution (wave guide) system is also a major topic for ILC engineering and R&D [41].

H. Superconducting Quadrupole Magnets

Studies are underway on several fronts to optimize the overall linac design. Control of the power level to individual cavities is being considered to maximize the average gradient as the sustainable cavity gradients are likely to vary significantly in each RF unit of 26 cavities [42]. Also, studies are being carried out to ensure that the small beam emittances are preserved along the linacs, which will require micron-level beam position resolution and stability of the quadrupole magnet centers over time and with field strength changes. A prototype superconducting quadrupole magnet, shown in Fig. 17, for the main linac was recently tested with



a)

b)

Fig. 17. Crosssections of a) a cryomodule and b) a superconducting quadrupole magnet placed at the axial center in the cryomodule.

encouraging results in terms of the magnetic axis stability with varying field strength.

IV. SUMMARY

A The Technical Design Phase (TDP) for the ILC started in 2008, and is being carried out in two stages: TDP-1 to demonstrate the technical feasibility, by mid-2010, and TDP-2 to verify technical credibility by the end of 2012. The R&D goals are to:

- Reach a 9-cell cavity field gradient of 35 MV/m at Q_0 $>10^{10}$ with a production yield of 90% for TDP-2,
- Demonstrate an average field gradient of at least 31.5 MV/m in one cryomodule in early TDP-2, and in three cryomodule with an ILC-like RF system for TDP-2.
- Establish "plug-compatible" cavity and cryomodule design,
- Demonstrate cryomodule string test with beam acceleration.

The design and R&D are being carried out globally, which bodes well for building a truly international linear collider.

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