GLOBAL R&D EFFORT FOR THE ILC LINAC TECHNOLOGY

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Abstract

The International Linear Collider is being 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 GeV each. After completion of the Reference Design Report in 2007, the Global Design Effort is currently in the Technical Design phase. This paper describes the status of the design, R&D efforts, and future plans.

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. It produced the Baseline Configuration Document (BCD) in 2005, and published the Reference Design Report (RDR) in 2007 [3]. The ILC design assumes a cavity field gradient of 31.5 MV/m to achieve a center-of-mass energy of 500 GeV with two 11-km long main linacs. Figure 1 shows a schematic layout, and Table 1 summarizes the main parameters. 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 at least 35 MV/m with quality factors of 10^{10} or higher in 9-cell cavities during initial 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.

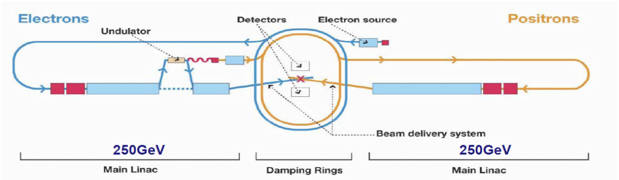

Fig. 1. Schematic layout of the ILC for 500 GeV CM.

Table 1: Design parameters for the ILC main linac.

Parameter	**Value**	**[Unit]**
Center-of-mass energy	500	GeV
Peak luminosity	2×10^{34}	$cm^{-2}s^{-1}$
Repetition rate	5	Hz
Avg. cavity accelerating gradient	31.5	MV/m
Beam pulse time-duration	1	ms
Average beam current in pulse	9	mA

R&D IN THE TECHNICAL DESIGN PHASE

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

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

Fig. 2. A view of a cryomodule with cavity-string installed.

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.

STATUS OF CAVITY R&D

Superconducting cavity technology for large-scale accelerators has been advanced significantly in the past ten years by the TESLA Technology Collaboration (TTC) [6], which is centered at DESY. It has culminated in approval of the XFEL light source [7], which is based on a ~ 20 GeV linac similar to that proposed for ILC. This progress was achieved through efforts and experiences accumulated at DESY, Cornell University, CERN, KEK, JLab, CEA, and many other institutions.

Cavity shapes

Searches 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 [8, 9].

Table 2. Cavity shapes investigated for ILC.

Parameter	**TESLA**	**RE**	**LL**
Iris aperture (mm)	70	70	60
E_{peak}/E_{acc}	1.98	2.40	2.36
B_{peak}/E_{acc} (mT/(MV/m))	4.15	3.78	3.61
Characteristic shunt impedance: R/Q (Ω)	114	121	134
Geometric factor: G (Ω)	271	280	284
G × R/Q ($\Omega \times \Omega \times 10^5$)	3.08	3.38	3.80

The TESLA shape has a favourable low E_{peak}/E_{acc}, ratio, acceptable cell-to-cell coupling, and a small wake-field loss factor [10]. It has lower risk of field emission and dark current, and its higher order mode (HOM) behaviour is well studied. Two alternate shapes, the re-entrant (RE) [9] and low-loss (LL) [11], 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 [9, 12, 13]. A new RE cavity shape with the same aperture as the LL shape has reached 59 MV/m in a KEK/Cornell collaboration [13].

Fabrication and Surface Preparation

Extensive efforts have been made to establish standard cavity fabrication and surface preparation processes [14]. As a consequence a global process guideline is being formulate, and it covers:

- Cavity fabrication:
  - Nb-sheet preparation, forming of half-cells, assembly with electron beam welding (EBW)
- Surface preparation:
  - Electro-polishing (Bulk-EP: > 100 μm removal)
  - Ultrasonic degreasing / Ethanol rinsing / Fresh-EP
  - High-pressure, pure-water rinsing
  - Hydrogen degassing (heating in vacuum: > 600 C)
  - Tuning of field flatness
  - 2^{nd} electro-polishing (~ 20 μm)
  - Ultrasonic degreasing / ethanol rinsing /fresh-EP
  - High-pressure, pure-water rinsing
  - Assembly with couplers or antennas
  - Baking (> 100 C)
- Cold, vertical test
  - Testing with thermometry and mode measurement.

The most promising surface preparation technique is electro-polishing (EP) as developed at KEK. 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. High-pressure rinsing with ultra-high purity water is also crucial as the final process.

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 [16, 17]. Figure 3 shows the TESLA 9-cell cavity. At DESY, ethanol rinsing has been shown to be effective to improve the field gradient limit due to field emission. Figure 4 shows a comparison of the cavity field gradient performance with and without ethanol rinsing [17]. 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.

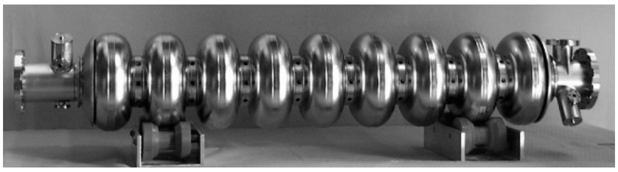

Fig. 3. A TESLA 9-cell cavity.

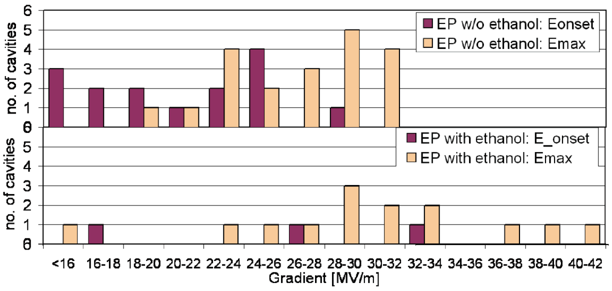

Fig. 4. Ethanol rinse effect on the onset (E-onset) of field emission and maximum gradient (E-max).

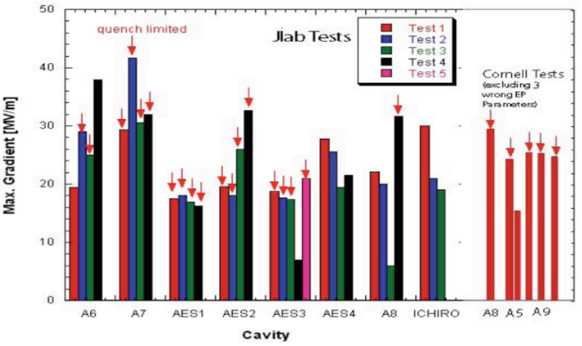

Fig. 5. Performance of 9-cell cavities by American collaboration, (with KEK contributions).

Figure 5 shows a summary of cavity performances achieved by a n American collaboration of Fermilab, JLab, Cornell University with contributions from KEK [18-20]. 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 gradient limited by field emission. Figure 6 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 [21]. Cornell has developed a vertical EP method to simplify the EP process [20] with good results. Fermilab and ANL have recently completed new infrastructure to process cavities. Fermilab is also leading a program of SCRF R&D in collaboration with Indian institutions.

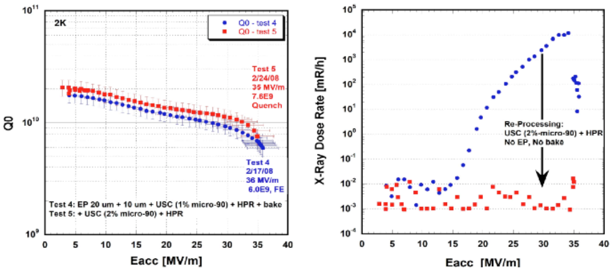

Fig. 6. Effect of ultrasonic degreasing with detergent on field emission.

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 TESLA-type 9-cell cavities have been 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 [22]. 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.

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 7 shows the average field gradient achieved with 9-cell cavity string (right) in cryomodule at TTF (FLASH) compared with the average gradient of individual 9-cell cavities (left) measured in vertical test at DESY [23]. The average field gradient of a 9-cell-cavity string in a cryomodule has recently reached > 28 MV/m.

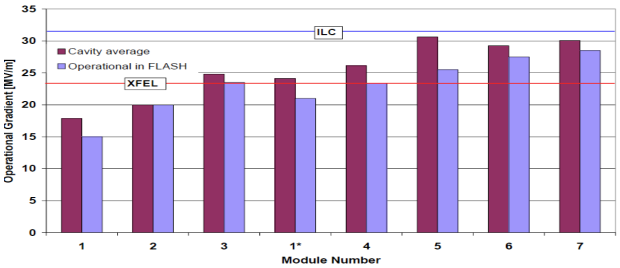

Figure 7: Progress in the average field gradient of eight cavity string in cryomodule at TTF (FLASH).

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.

Cavity surface observation and feedback

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 [14]. 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 [24]. The system has been used to identify local defects in 'hot' area seen with thermometry measurements during vertical testing. Figure 8 shows the high-resolution camera and an inside view 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.

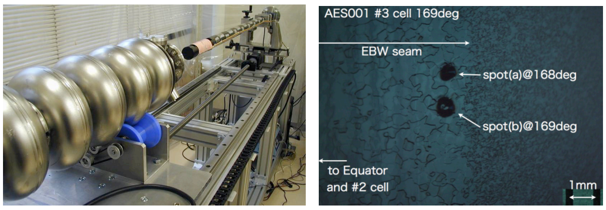

Fig.8. Observation of inner surface of a cavity using a high-resolution optical camera system.

Cavities with large-grain/single-crystal sheets

Fabricating cavities from large-grain or single-crystal Nb sheets is being developed to improve performance (due to fewer grain boundaries) and lower cost (eliminates the sheet rolling process which can introduce contamination). Pioneering work has been carried out at JLab, and various efforts are in progress at Cornell University, DESY, Peking University, KEK, and other laboratories [25]. This material may allow elimination of the EP process, and require only an easier chemical polishing (CP) process. At JLab, large-grain single-cell cavities have reached 30 - 35 MV/m with CP treatments only. A single-grain single-cell cavity reached 37 MV/m, also with a CP treatment [13, 26].

Cavity integration and 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. This is an important guiding concept that benefits both the accelerator complex construction and the present R&D efforts.

Cryomodule design and system 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 [27, 28]. Figure 9 shows the cross section under design study. A means of simplifying the 5-K radiation shield is also investigated to reduce cost.

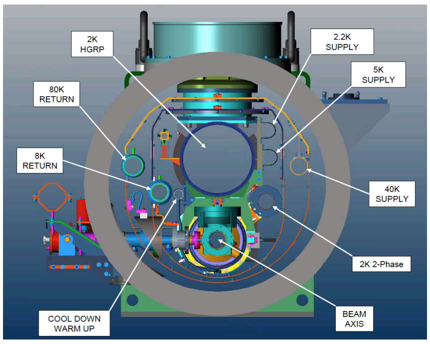

Fig. 9. Cryomodule cross section under design study.

Global cavity-string test in cryomodule

A global collaborative effort for 9-cell-cavity-string tests in a cryomodule is in progress. Two units each of dressed cavities are to be provided by DESY and Fermilab, and 4 cavities are to be provided by KEK for this work. A cryomodule enclosure and associated components is to be prepared by a KEK-INFN collaboration. This will allow the examination of the plug-compatibility concept, and help to demonstrate that the ILC can be designed as global effort. Figure 10 shows the cross section of the cavity string assembly in this global cryomodule.

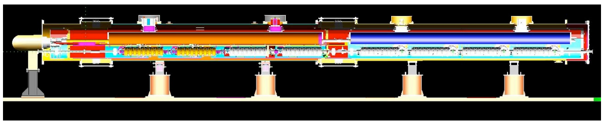

Fig.10. Conceptual layout of the global cryomodule to test an eight cavity string..

Cryomodule-string test with one RF-power unit

A cryomodule-string test with one RF-power unit is planned to be carried out eventually at three sites (DESY, Fermilab and KEK) as a demonstration technical credibility, including overall system engineering and beam acceleration [29]. 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 11 show the schematic layout planned at KEK.

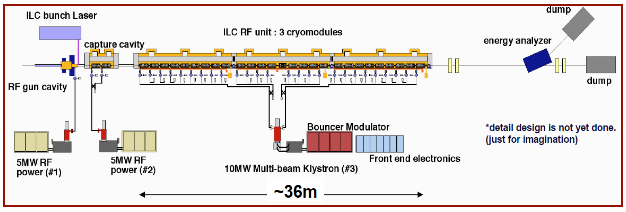

Fig. 11. Layout of the KEK cryomodule string test with beam acceleration.

Cryogenics engineering design

The scale and features of the cryogenics system for the ILC are expected to be similar to the LHC accelerator cryogenics, which also operates at 2K. The conceptual design for this system is in progress [30], 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.

High level RF system design 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 [31]. Figure 12 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 [32].

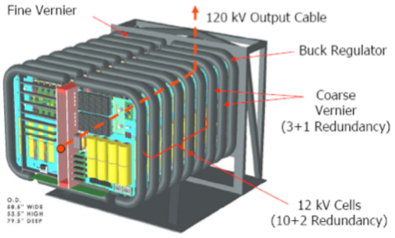

Fig. 12. Marx Generator expected as an alternate, advanced HV power source for the ILC.

Main linac integration

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 [33]. 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 for the main linac was recently tested with encouraging results in terms of the magnetic axis stability with varying field strength.

SUMMARY

The Technical Design Phase (TDP) for the ILC has started (in 2008) and will be completed 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 a "plug-compatible" cavity and cryomodule design,
- Demonstrate beam acceleration through a string of cryomodules.

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

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REFERENCES

[1] International Linear Collider; http://www.linearcollider.org.
[2] ITRP Recommendation, (2004); http://www.fnal.gov/directorate/icfa/ITRP_Report_Final:pdf.
[3] ILC Reference Design Report, ILC-Report-2007-001 (2007); http://www.linearcollider.org/cms/?pid=1000437.
[4] L. Lilje, "High-gradient superconducting RF cavities for particle acceleration", PAC'07, Albuquerque, p. 2754 (2007).
[5] ILC Research and Development Plan for the Technical Design Phase, Release 2, ILC-EDMS Doc. #813385 (2008).
[6] TESLA Technology Collaboration; http://tesla-new.desy.de/.
[7] XFEL project; http://www.xfel.net, http://xfel.desy.de.
[8] J. Sekutowicz, "Design of a low loss SRF cavity for the ILC", PAC'05, Knoxville, p.3342 (2005),
[9] R. Geng, "Review for new shapes for high gradients", Physica C, 441 p.145 (2006).
[10]A. Aune et al., "Superconducting TESLA cavities", Phys. Rev. ST– Accelerators and Beams, **3**, 092001 (2000).
[11] F. Furuta et al., "Experimental comparison at KEK of high gradient performance of different single cell superconducting cavity designs", EPAC'06, MOPLS084 (2006).
[12] L. Lilje, "High-gradient superconducting RF cavities for particle acceleration", EPAC'06, THPPA02 (2006).
[13] R.L. Geng et al., "High gradient studies for ILC with single-cell re-entrant shape & elliptical shape cavities made of fine-grain & large-grain Nb", PAC-2007, p.2337 (2007).
[14] H. Padamsee, J. Knobloch, T. Hays, "RF superconducitivity for accelerators", John Wiley & Son, Inc. (1998)..
[15] K. Saito et al., 4th WS, RF Superc., Tsukuba, p. 635 (1990).
[16]L. Lilje, P. Schmuser et al., "Achievement of 35 MV/m in the Superconducting Nine-Cell Cavities for TESLA", Nucl. Inst. Meth., **A524** (1-3), 1-12 (2004).
[17] D. Reschke and L. Lilje, "Recent experience with nine-cell cavity performance at DESY",
[18] M. Champion, presented at ILC-SCRF, Fermilab (2008).
[19] R.L. Geng et al., Proc. SRF-2007, WEP28 (2007).
[20] W.J. Ashmanskas et al., Proc. SRG-2007, WEP39 (2007).
[21] R.L. Geng, ILC-SCRF meeting at Fermilab (2008)
[22] K. Sennyuu et al., "Status of the superconducting cavity development for the MHI", EPAC-2008, MOPD009 (2008).
[23] L .Lilje, XFEL: "Plan for 101 cryomodules" PAC'07(2008)
[24] Y. Iwashita et al., "Development of a high resolution camera and observation of superconducting cavities", EPAC'08, MOPP103 (2008).
[25] P. Kneisel et al., "Performance of Single Crystal Niobium Cavities, EPAC-02, MOPP 136 (2008).
[26] W. Singer et al., "Advances in large grain/single crystal SC resonators at DESY", PAC 2007, Albuquerque, (2007).
[27] C. Pagani, et al., "The Tesla cryogenic accelerator module", Tesla report 2001-36.
[28] K. Tsuchiya et al., "Cryomodule development for superconducting RF test facility (STF) at KEK", EPAC'06, p. 505 (2006).
[29] H. Hayano et al.,LINAC'06, Knoxville (2006).
[30] T. Peterson et al., "ILC Cryogenic System Reference Design", Proc. ICEC-2007, to be published in Adv. Cryog. Eng. (2008).
[31] C. Adolphsen, "ILC RF system R&D", PAC'07, p.3813 (2008).
[32] C. Nantista et al., "An RF waveguide distribution system for the ILC test accelerator at NML", PAC'07, p.2442 (2008).
[33] K Bane, C Adolphsen and C Nantista, "RF distribution optimization in the main linacs of the ILC", SLAC-PUB-12628 (2007).