CHALLENGES IN ILC SCRF TECHNOLOGY*

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Abstract

With a baseline operating gradient of 31,5 MV/m at a Q-value of 10^{10} the superconducting nine-cell cavities of the ILC are a challenging milestone for SRF technology. Worldwide intensive ILC R&D programs are underway or in the planning stage in all three regions of America, Asia and Europe. This paper will give an overview of the main activities in the field of superconducting RF (SCRF) technology.

INTRODUCTION

In 2004 the International Technology Recommendation Panel (ITRP) recommended the choice of superconducting rf technology for a future linear collider. This choice was accepted by ICFA [1], and the first workshop on the International Linear Collider (ILC) was held at KEK in November 2004. During the 2nd ILC Workshop at Snowmass in August 2005 the goal was set to define a baseline configuration, which was published after intense discussions at the GDE (Global Design Effort) meeting at Frascati end of 2005. The Baseline Configuration Document (BCD) is a living document and will evolve following developments in design, costing and successful R&D improvements [2, 3]. In addition to the BCD the Alternative Configuration Document (ACD) describes a number of promising future options in order to gain in performance, cost or risk reduction.

Table 1: Main ILC cavity parameters

ILC parameters:		**BCD (baseline)**	**ACD (alternative)**
Cavity shape		TESLA	Low Loss or Reentrant
Cavity Acceptance Performance	Eacc [MV/m]	35	40
	Q_0	$0,8 \cdot 10^{10}$	$0,8 \cdot 10^{10}$
Cavity Operation Performance	Eacc [MV/m]	31,5	36
	Q_0	$1,0 \cdot 10^{10}$	$1,0 \cdot 10^{10}$
Coupler		„TTF type III“	
Cryomodule		„Type IV”	
		8(9) cav. /module	8(9) cav. /module

The ILC is based on 1.3 GHz nine-cell structures of ultrapure Niobium (Fig.1). Table 1 shows some important parameters related to cavity and cryomodule design.

Figure 1: 1.3 GHz 9-cell Niobium cavity of TESLA shape.

CAVITY FUNDAMENTALS

The Q-value of a superconducting cavity is related to the surface resistance R_s by $Q_0 = G / R_s$ with the geometry factor G given only by the geometry of the cavity. For accelerator cavities G is about 270 Ω. As explained in detail in [4], the experimentally observed surface resistance can be described by the BCS-component $R_{BCS}(T, \omega)$, the residual resistance R_{res} determined by preparation and experimental conditions as well as a gradient dependant component R_s (H). One example of the latter is the so-called “Q-slope without field emission”, which appears in electropolished cavities. In order to cure this effect a special bake procedure is applied [5].

At an operating temperature of 2K a well prepared cavity shows a typical Q-value of $2 \cdot 10^{10}$ at low gradient. The Q-value of 10^{10} at the baseline operating gradient requires excellent preparation and experimental conditions resulting in cavities free of additional loss mechanisms like enhanced field emission (see below).

An intensively discussed topic of the last years is the rf critical magnetic field [4] of Niobium. Experimental results indicate a maximum magnetic surface field of (180 – 190) mT at 2 K.

Cavity shape

The shape of the cavity cells determines important characteristics of the accelerator structure as well as fundamental properties of the accelerator (Figure 2, 3) [6]. Here only some cavity related aspects will be discussed. The well-proven TESLA shape used in more than 120 nine-cell structures is the baseline ILC design. It is optimised with respect to cell-to-cell coupling k_{cc} and a low ratio of surface electric field to gradient E_{peak}/E_{acc}. The cell-to cell-coupling of 1.9 % ensures robust tuning properties, good HOM-damping and avoids trapped modes. E_{peak}/E_{acc} of 2.0 is favourable in order to reduce field emission loading. The tilted iris areas allow good wet cleaning and rinsing. The Low-Loss (LL) shape is optimized with respect to a comparable low magnetic surface field to gradient ratio H_p/E_{acc}. This allows about 15% higher gradient for the same magnetic field value.

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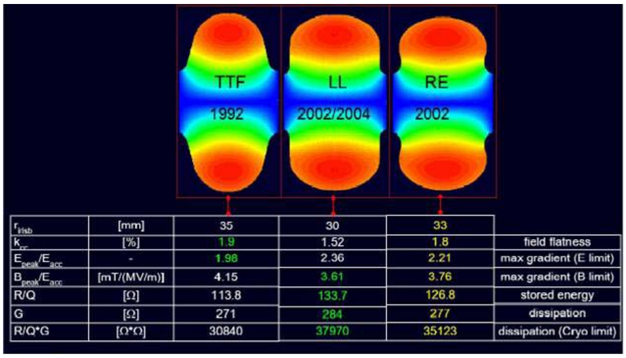
Drawbacks are the reduced iris diameter, lower cell-to-cell coupling and an 18% higher E_{peak}/E_{acc}. The re-entrant shape (RE) is a compromise with respect to the rf parameters, but the wet cleaning is more difficult. Up to now no nine-cell cavity of this shape exists.



r_{iris}	[mm]	35	30	33	
k_{cc}	[%]	1.9	1.52	1.8	field flatness
E_{peak}/E_{acc}	-	1.98	2.36	2.21	max gradient (E limit)
B_{peak}/E_{acc}	[mT/(MV/m)]	4.15	3.61	3.76	max gradient (B limit)
R/Q	[Ω]	113.8	133.7	126.8	stored energy
G	[Ω]	271	284	277	dissipation
R/Q*G	[Ω*Ω]	30840	37970	35123	dissipation (Cryo limit)

Figure 2: Comparison of cavity shapes.

Figure 3: Reentrant (upper left) and Large Grain TESLA (lower left) single cell cavities; Low-Loss single- and nine-cell cavities (left).

Anomalous loss mechanisms

A detailed description of anomalous loss mechanisms in scrf cavities can be found in [4, 9].

Anomalous loss mechanisms like local thermal breakdown ("quench") or enhanced field emission (responsible for dark currents) often limit the performance of accelerator structures far below their maximum magnetic field limit.

A local thermal breakdown takes place, if the heat load produced by a lossy defect (e.g. a normalconducting particle) cannot be transported to the Helium bath any more. Depending on the heat production and the thermal conductivity at a certain field the surrounding Nb material will exceed the critical temperature T_c and a large surface area becomes normalconducting. As all stored energy is dissipated within about a millisecond, the field breaks together and the cavity quenches.

In order to avoid a quench the Nb material of the cavity needs to be free of lossy defects, and a high thermal conductivity is requested. For the ILC a large amount of such high quality Niobium is necessary with a high reproducibility. Though a number of excellent cavity results (see below) have shown that the required Nb purity is at hand, the industrialization and quality control for app. 20000 cavities still keeps a challenge.

Particles, chemical contaminations like hydrocarbons and surface irregularities have been identified to create field emission [7]. With today's standard preparation procedures, typically field emission loading in well-prepared cavities at 1.3 GHz starts at gradients of (20 – 25) MV/m. No systematic degradation between vertical tests and horizontal system performances is found. Single-cell cavities with their relaxed complexity of necessary components and assembly often achieve gradients far beyond 30 MV/m without field emission. In the last years several 1.3 GHz nine-cell cavities achieved gradients above 35 MV/m both in vertical and horizontal operation. At TTF/FLASH one nine-cell cavity was operated at 35 MV/m with beam [8].

The experience of cavity treatment and handling of the last 20 years leads to the summary, that the quality of surface preparation, final cleaning and dustfree assembly is crucial for field emission free cavities (Figure 4).

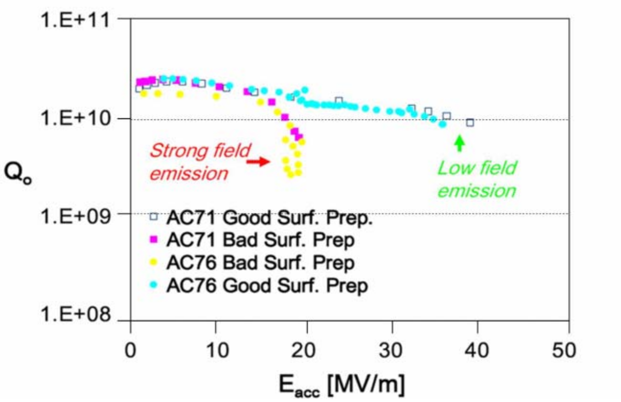


Figure 4: Examples of cavity performance after good and bad preparation procedures.

Preparation techniques

The BCD cavity preparation scheme contains:

- Cleaning after fabrication, mechanical + electrical entrance-check and first tuning
- First electropolishing (EP) (Figure 5) of (120-150) µm in order to remove the damage layer caused

by mechanical stress and deformation. The standard EP mixture contains HF and H_2SO_4 with a volume ratio of 1 : 9 [10].

- 800C firing under defined vacuum conditions in order to release mechanical stress and degas hydrogen
- Final electropolishing of (20 - 50) µm followed by ultra pure water rinsing.
- High Pressure Rinse (HPR) (Figure 6), assembly, HPR for the vertical acceptance test

Details of state-of-the-art cavity preparation is described in [4, 9, 10]

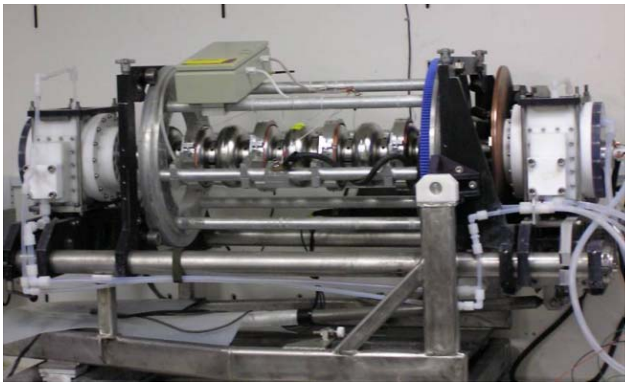


Figure 5: Horizontal EP setup at JLAB.

Figure 6: High Pressure Rinsing stand at DESY and Saclay.

R&D ON CAVITIES: S0 TASK FORCE

The mission of the task forces S0 on cavities and S1 on cryomodule (see next chapter) is to provide the information needed for final choice on gradient and exact procedures. It was decided to apply a phased approach to match both, design requirements and cost effort.

The situation before us is:

- The proof-of-principle for (35 – 40) MV/m in nine-cell cavities exists (Figure 7)
- Excellent single cell results of (40 – 50) MV/m show that the baseline preparation techniques are at hand (Figure 7)
- The yield for gradient > 35 MV/m in nine-cell cavities is low

As described above many tests are limited by field emission, some by quench and few by hydrogen Q-disease. The main goal of S0 is to **improve the yield for high gradients.**

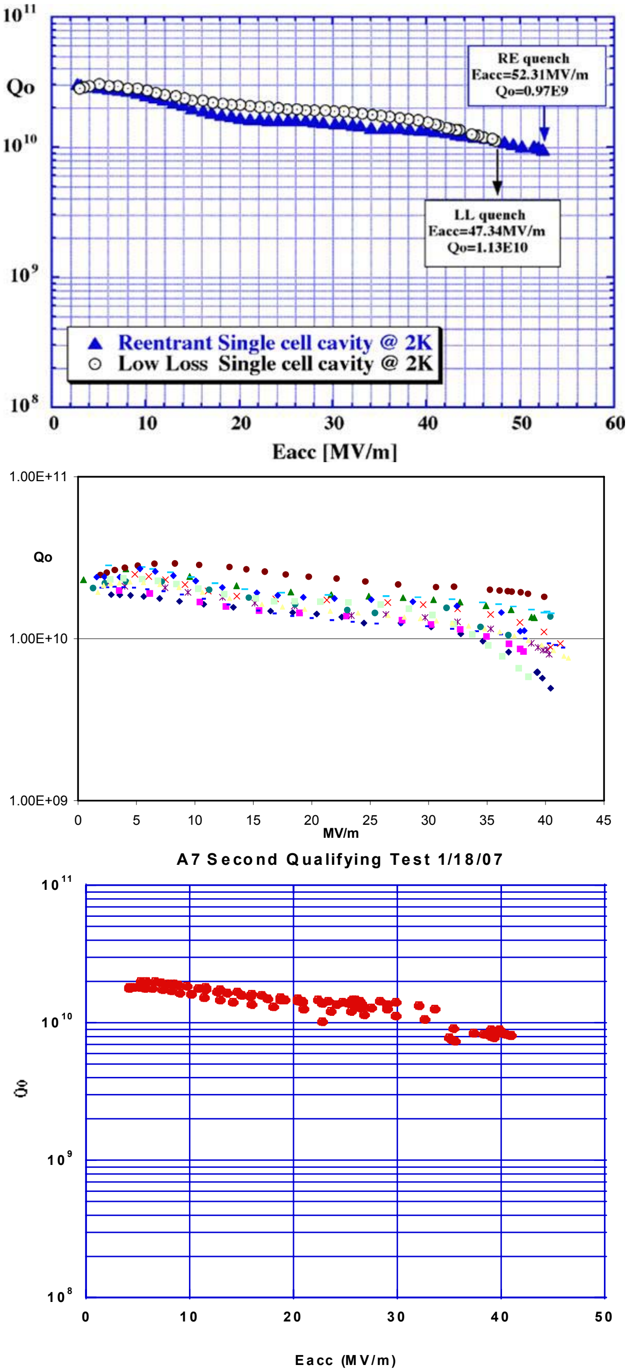


Figure 7: Q(E) performance of RE- and LL-single cells at Cornell/KEK (top); collection of nine- and single-cell results at TTF and CERN/DESY/Saclay collaboration (middle), recent nine-cell result at JLab.

The way to this goal requires the improvement of reproducibility of cavity processing. A yield of 80% in the first test is aimed at. Several R&D programs are launched or participated in parallel to improve fabrication and preparation processes. General topics of investigation are:

i) program on EP and rinsing parameters on single-cell cavities

ii) interregional "tight-loop" experiments on qualified nine-cell cavities in order to define a baseline yield in all regions.
iii) improved quality control by process monitoring (acids, process parameters, water, etc.) and comparison of HPR systems [10]
iv) process monitoring of the assembly procedures
v) improved quality control of the Nb material and during cavity fabrication

The process improvements will be transferred to nine-cell cavities as fast as possible with the goal of a final best recipe. The order of staged batches of 50 nine-cell cavities each are foreseen with aiming for a "final" production and preparation batch with a reproducible gradient of > 35 MV/m in the first or second test.

Valuable input is available from the work of the Tesla Technology Collaboration (TTC). A formal request for collaboration with the TTC is launched. Furthermore the R & D work of the European CARE project, the American SMTF project and of several individual labs is highly valued. Significant benefit is available by synergy effects with the European XFEL project.

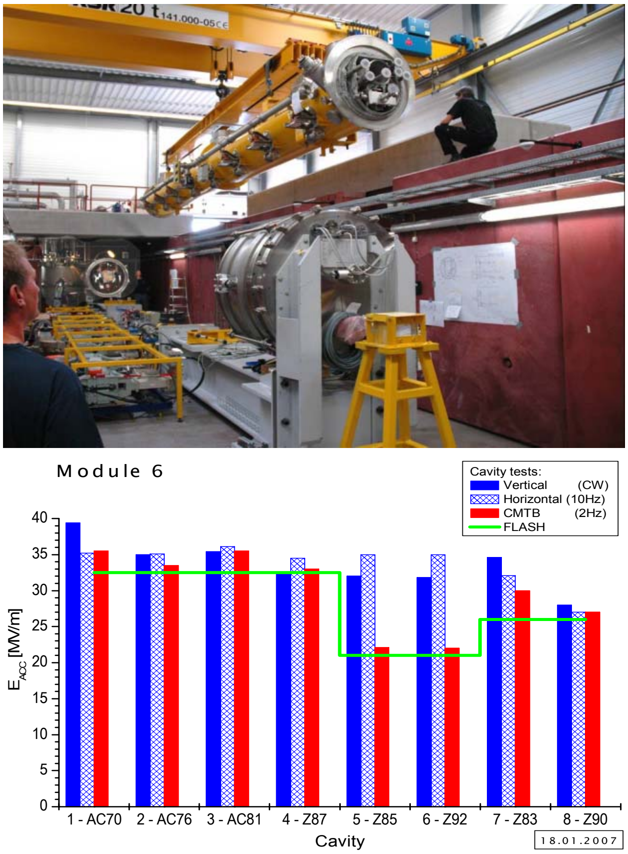


Figure 8: Assembly of the first module to CMTB at DESY (top); gradients of all 8 cavities of module 6 for TTF/FLASH (bottom).

CRYOMODULES: S1 TASK FORCE

An important milestone on the way to the ILC will be the successful test of at least three modules with 31.5 MV/m at $Q_0 = 10^{10}$ operational gradient. These modules shall be fully equipped including fast tuners and other features that could affect gradient performance. Each module should be operated a few weeks under realistic rf and cryo conditions. It is not necessary, that the modules have the final design. Depending on the cavity situation an exchange and re-assembly of cavities is an option.

As an intermediate step a module test with 31.5 MV/m average gradient with accordingly adapted rf distribution may act as a proof-of-existence.

Recently at DESY the Cryo Module Test Bench (CMTB) started its operation with the test of TTF/FLASH module 6 (Figure 8). Though two cavities significantly degraded compared to their fully equipped horizontal test, module 6 was tested successfully including several modes of rf and cryo operation with an average gradient of about 28 MV/m (Figure 8). The reason for the degradation is still unknown. With an adapted rf distribution 4 of 8 cavities will be operated at about 32 MV/m in FLASH.

At KEK as well as at FNAL cryomodule test facilities are close to operation. KEK will test modules with 4 cavities each. Both the BCD TESLA-shape and the ACD Low-Loss shape will be used. The first module assembled and tested at FNAL will be a kit of dressed cavities provided by DESY.

A GLANCE TO ACD

The Alternative Configuration Document is a natural part of the BCD [2]. In most cavity and cryomodule related topics alternatives and long range R&D items are investigated. Examples are listed below:

- Alternative cavity shapes (see above)
- Cavities fabricated of large grain niobium (Figure 3)
- Simplified power coupler designs
- In-situ processing of field emitter by High Peak Power Processing [4]
- Aggressive cost reduction ideas

OUTLOOK

The next near term milestone will be the presentation of the Reference Design Report including a detailed cost estimate in Beijing in Feb 07. It is expected that the European XFEL project with its 1,6 km of superconducting accelerator modules will get its official go ahead in summer 07. In addition to the above mentioned coincident R & D topics, the industrialization of the XFEL will be a reliable technical and cost baseline for the ILC.

In 2007 cryomodule tests will start at KEK and FNAL. The work on nine-cell cavities at DESY, FNAL, JLAB and KEK will be continued. In addition important R & D programs on single-cells, material properties and processing will be continued.

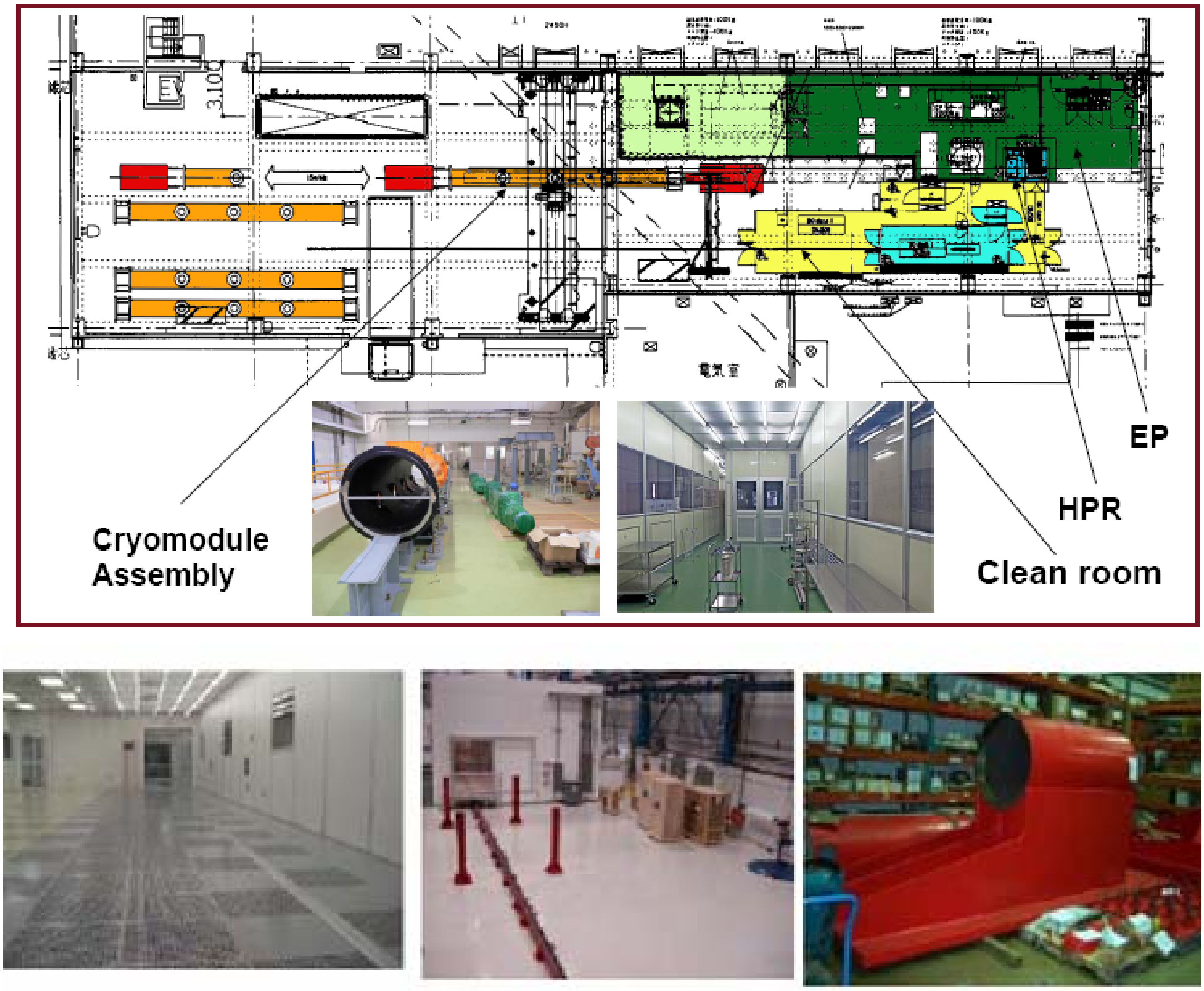


Figure 9: Cryomodule and cleanroom infrastructure at KEK (top) and FNAL (bottom).

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