R&D IN RF SUPERCONDUCTIVITY TO SUPPORT THE INTERNATIONAL LINEAR COLLIDER

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Abstract

The R&D in on superconducting radiofrequency technology for the International Linear Collider (ILC) spans a broad range of topics, ranging from the search for high gradients through improved processes, new cavity geometries as well as the use of new materials (large-grain and single-crystal niobium metal). Besides these alternatives R&D paths, a large part of the baseline design for the ILC baseline is being going through an industrialisation effort in the framework of the European XFEL project. This paper talk will review the status of the global ILC SRF R&D program and discuss plans for the future.

THE ILC PROJECT

The International Linear Collider (ILC) extensively uses superconducting radiofrequency (SRF) accelerating structures for particle acceleration. This allows for an efficient transfer of power to the particles while maintaining a comparatively low frequency of 1.3 GHz and low peak power requirements. To achieve a center-of-mass energy of 500 GeV 16088 SRF accelerating structures - also called cavities - are needed in the two 11 km long main linacs. The overall footprint of the accelerator is about 31 km.

THE ILC R&D OPTIONS

The advantages of SRF technology have been discussed extensively in other publications [1, 2]. This paper focuses on the ongoing international R&D efforts to ensure the ILC's performance goals and at the same time to develop a cost conscious design.

With the publication of the Baseline Configuration Document (BCD) [3] and the Reference Design Report (RDR) [4] the R&D topics have been made available to the community at large. Whereas the RDR concentrates on the baseline choices for the technology e.g. the cavity shape to allow a consistent costing exercise, alternative choices are being discussed mainly in the BCD.

R&D FOR THE BASELINE DESIGN

The baseline choices for the accelerating structures and the cryostat design for the ILC are based largely on the technology developed for the TeV-Energy-Superconducting Linear Accelerator (TESLA) which will be used for the European X-ray free-electron laser (XFEL) which is currently being constructed at DESY [5].

Cavity Shape

The baseline cavities for the ILC use the TESLA shape which has been tested and optimised since many years (Fig. 1). The main advantage of this shape is the relatively low ratio between electrical surface field E_{peak} and accelerating gradient E_{acc}. The accelerating gradient in the cavities is 31.5 MV/m. More parameters are summarized in table 1.

Cavity treatment

For superconducting cavities at very high electric and magnetic surface fields great care has to be taken during manufacturing and preparation for beam acceleration. Normalconducting inclusions in the material and contaminations on the surface need to be avoided. For example, the niobium bulk material used for cavity fabrication needs to have good thermal conductivity as the heat produced on the inner side of the cavity needs to be conducted to the coolant (liquid helium) on the outside.

In addition, the preparation and assembly in clean rooms and ultra-pure water supplies for rinsing the surfaces are a must. Electropolishing (EP) is the most promising surface preparation technique for superconducting cavities to remove the damage layer and to obtain the final surface finish. The niobium material is removed in an acid mixture under the flow of an electric current. Sharp edges or tips are smoothed out and a very glossy surface can be obtained. It has been chosen to be the baseline cavity preparation for the ILC as several nine-cell cavities exceeded the gradient specified for the ILC both in low-power (Fig.2) and high-power tests.

Fig. 1: A TESLA 9-cell cavity with a length of about 1m.

Table 1: Parameters for the baseline ILC accelerating structures.

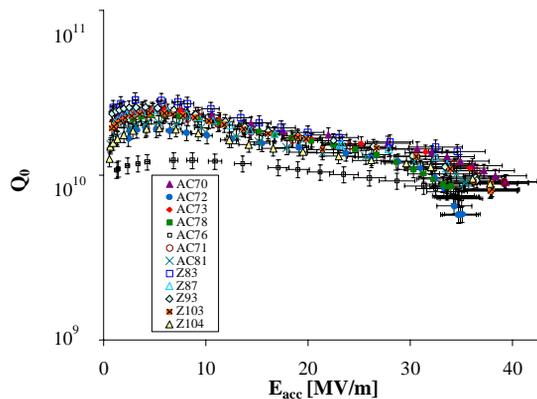| Parameter	Value	Units
Type	Standing wave	
Number of cells	9	
Accelerating mode	TM010, π-mode	
Active length	1.038	m
R/Q of fundamental mode	1036	Ω
Iris diameter	70	mm
Cell-to-cell coupling	1.9	%
Operating gradient	31.5	MV/m
Average Q_0	1.0×10^{10}	
Average Q_{ext}	3.5×10^{6}	
Fill time	596	μs
Cavity resonance width	370	Hz
E_{peak}/E_{acc}	2	
B_{peak}/E_{acc}	4.26	mT/(MV/m)

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Figure 2: Several electropolished cavities yield gradients of more than 35 MV/m in low-power continuous wave acceptance tests.

R&D on Cavity Preparation

While the gradients needed for the ILC have been demonstrated, more focused R&D is underway to increase the yield of the cavities at these high gradients. One surface contaminant identified from the cavity preparation process is sulphurus produced in the EP setups. Currently, cleaning processes specifically reducing sulphurus contamination are being investigated on both single- and nine-cell cavities e.g. EP with uncontaminated 'fresh' electrolyte [6], ultrasound degrease [7] and alcohol rinse [8].

This is done in an internationally coordinated effort with participation of several labs e.g. KEK, JLab, Cornell and DESY [9]. All processes show a significant reduction of field emission. In the next step, the most promising process will be tried out in all participating labs to validate the reproducibility and the applicability to nine-cell cavities.

While most of this surface preparation R&D is directly being applied to baseline cavities it is evident that any of these improvements are also essential pre-requisites to pursue alternative cavity shapes which aim at a lower magnetic peak surface field which comes with an increase of the electric surface peak field thus increasing the danger of field emission limiting the cavity performance.

High-power Accelerator Module Tests

An important test towards a real accelerator is the integration of bare niobium cavities into a cryostat (also called a module). The assembly of accelerator modules consists of many steps:

- Welding of the helium tank to the cavity
- Preparation of the cavities for high-power operation including assembly of the high power coupler and the Higher-Order-Mode (HOM) dampers
- Assembly of the string of cavities in the clean room
- Assembly to the cold mass and insertion in to the cryostat vessel
- Assembly of the warm part of the high power coupler
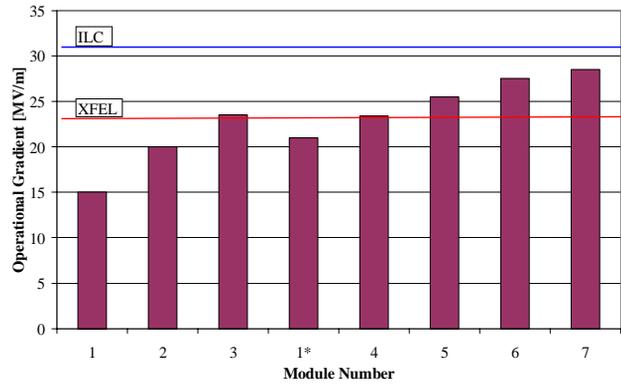- Assembly of the module to the accelerator

Figure 3: Operational gradients of full accelerator module built at the TTF at DESY. Note that the average gradient of the modules is slightly higher which would be accessible with an ideal power distribution.
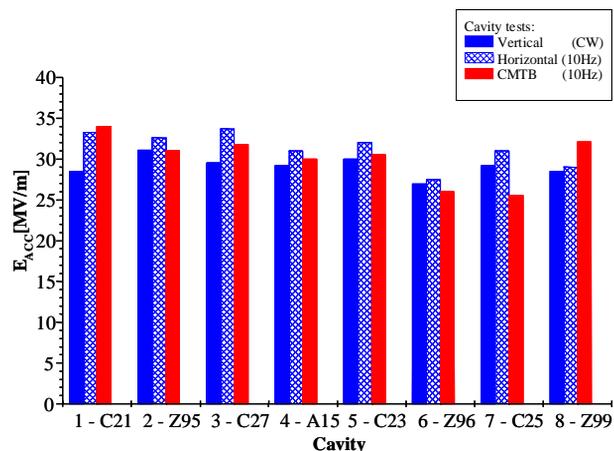

Figure 4: Comparison of the accelerating gradients in low-power (blue) and accelerator module test (red). In module M7 four cavities achieved more than 31.5 MV/m.

The baseline options for the ILC are very similar to the XFEL design like the high power input coupler and the HOM damping scheme. The layout of the cryostats also largely is identical except for the number of cavities, the inter-cavity distance and the focusing quadrupole position. Thus, the performance tests obtained at the TESLA Test Facility (TTF) at DESY are of full relevance for ILC modules.

Over a period of nearly ten years, several modules have been built and high power tested. The results are shown in Fig.3. The results are encouraging as the operational gradients have clearly surpassed the XFEL specification, while the ILC gradients on full modules are being approached. Several cavities have achieved already more that 31.5 MV/m in accelerator modules. As an example the most recent module M7 is being shown in Fig 4. Some of the issues related with cavity performance in accelerators and the improvement of quality control processes during module assembly are being discussed in [10].

07 Accelerator Technology Main Systems

T07 Superconducting RF

The preparatory work for the XFEL has been the strong driving force for the module testing efforts including participation of industrial companies in the module assembly processes. Additional module test capabilities are currently being set up at FNAL and KEK, which will allow further refinements of assembly procedures as well as testing some of the alternate designs.

R&D ON ALTERNATIVE DESIGNS

As said in the introduction, the emphasis of the SRF R&D efforts for the ILC is to ensure performance goals or to reduce costs. Several alternatives are proposed for the ILC SRF system. As can be seen in the next section, the designs have a varying degree of difference to the baseline. Some of these could be introduced as the baseline design straightforwardly with only minor impacts on other systems, provided the tests are successful. Other options need a larger effort of testing which could be e.g. beam tests in a test facility to validate them. Yet another group of designs have a stronger influence on the design of other systems in the ILC.

Cavity Shape

With the accelerating gradient approaching the theoretical limit in the current cavity design several proposals are dealing with the improvement of the shape of the resonators to lower the ratio between peak magnetic surface field B_{peak} and accelerating gradient E_{acc}.

Two new shapes - the re-entrant shape (Cornell University) and the low-loss shape (originally designed for CEBAF) - are being developed [11, 12]. Both new shapes have a lower B_{peak}/E_{acc} and a higher G times R/Q. They have a higher gradient reach since B_{peak} is considered to be the fundamental limit, and lower cryogenic losses. Both shapes have higher risk of field emission since E_{peak}/E_{acc} is 20% higher than in the TESLA shape. The iris aperture is another geometrical difference between the two new shapes. The low-loss shape has a smaller iris aperture by about 15%, whereas the Cornell re-entrant shape has the same aperture as that of the TESLA shape.
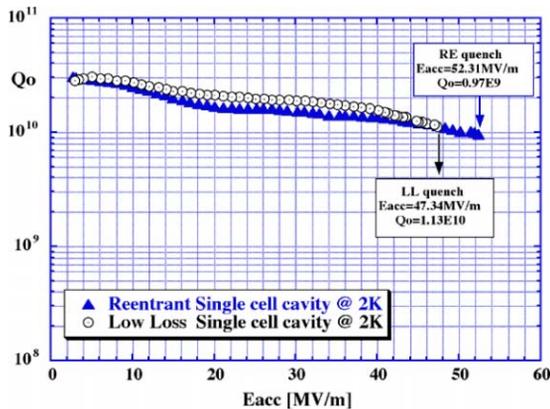

Figure 5: Test results of single cell cavities with a smaller B_{peak}/E_{acc}. Tests performed after surface treatment at KEK.

The first tests of single-cell cavities after surface treatment at KEK are very promising (see Fig.5 and Fig.6). Very high gradients between 45 up to more than 50 MV/m have been obtained in several cavities. Currently, the first multi-cell cavities are under test.
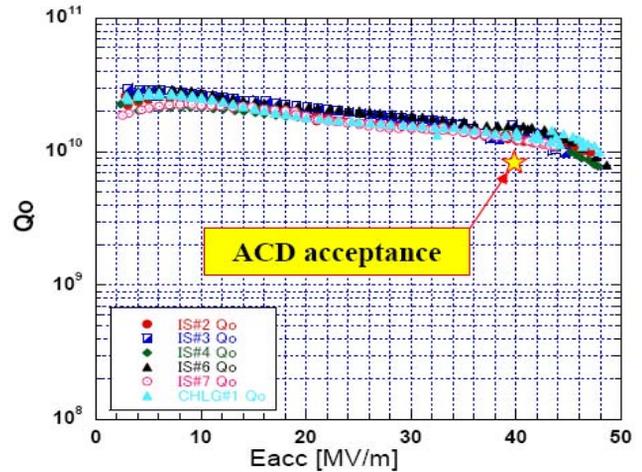

Figure 6: Tests of several single-cell cavities of the low-loss shape which are called Ichiro Shape (IS) in Japan.

Cavity Layout – Superstructure

In striving for highest collider energies not only the gradient in the cavities but also the active acceleration length could be maximized. There are, however, two effects which limit the number of cells per resonator. With increasing number of cells it becomes more and more difficult to tune the resonator for equal field amplitude in every cell. Secondly, in a very long multi-cell cavity 'trapped modes' may be excited by the short particle bunches. These are coupled oscillations at high frequency which are confined to the inner cells and have such a low amplitude in the beam pipe sections that they cannot be extracted by the HOM couplers mounted the beam pipe. Trapped modes may have a detrimental influence on the beam emittance and must be avoided. The nine-cell cavities chosen for ILC appear a reasonable upper limit.

The limitation in the number of cells can be overcome by the superstructure concept proposed by J. Sekutowicz [13]. Several multi-cell cavities are joined by beam tubes of length $\lambda/2$. Within each cavity there is an rf phase advance of π from cell to cell, while the phase advance between adjacent multi-cell units is zero. This ensures that the particles experience the same accelerating field in all cells of the superstructure. The superstructure is supplied with rf power by a single input coupler at one end. The interconnecting pipes have a sufficiently large diameter to permit the flow of RF power from one cavity to the next.

Compared to the layout with separated 9-cell cavities, this superstructure improves the filling factor by 6 % and saves a factor of two in input couplers and waveguide components.

The initial tests of this concept at lower gradients of roughly 15-17 MV/m where successful and are described in detail in [13]. The surface preparation of these long structures is nonetheless not trivial. Therefore a method has been proposed to join two nine-cells with a superconducting joint allowing the treatment of units of comparable length to the baseline design individually. A working joint thus becomes the essential pre-requisite for the superstructure concept. The current state of the R&D is described in [14].

Cavity Material

An exciting development in the alternative R&D is the use of large grain niobium material. Standard material is electron-beam molten to a large niobium rod ('ingot'), which then is forged and rolled to fabricate niobium discs or sheets for the cavity fabrication. The typical grain sizes for standard material are a few ten μm.

At JLab, it has been shown that it is possible to cut discs directly from the ingot and fabricate SRF cavities [15]. As many processes are eliminated from the niobium fabrication processes, this method offers the potential for significant cost saving. One of the critical elements is to find a cost effective cutting method for the discs. Several options exist and are currently being evaluated.
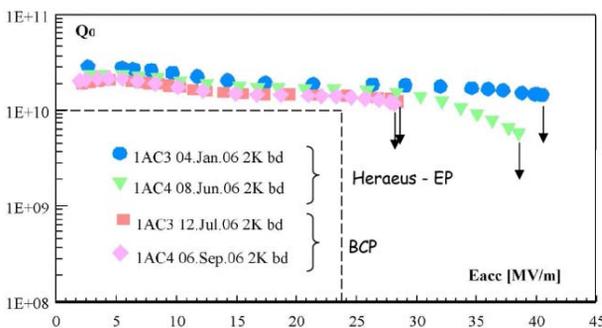

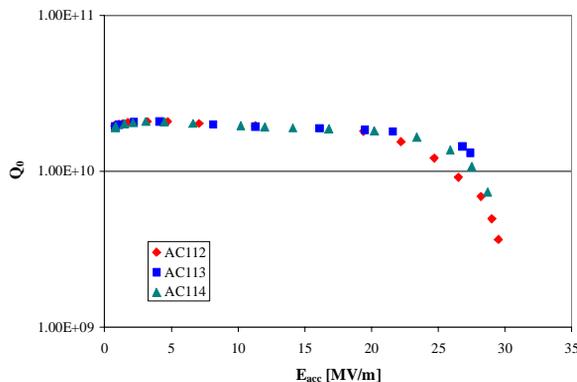Figure 7: Results of large-grain niobium single-cell cavities after etching and EP.

Figure 8: Performance of three nine-cell cavities fabricated from large-grain niobium discs after etching treatment.

The accelerating gradients achieved in single-cell cavities are comparable to those with the standard material.

So far, no conclusive statement on the optimal surface treatment for large grain material can be made. Whereas in some cases a normal etch – allowing further cost savings - gives already good results [15], in other cases it seems that EP is still a necessity to achieve gradients above 35 MV/m (Fig. 7).

The first three nine-cell large-grain niobium cavities have been built within the XFEL project preparation phase and achieved gradients between 27-30 MV/m after etching only (Fig. 8). In a next step these cavities will be subjected to EP with the hope improve their performance.

Taking this material development even one step further is the possibility to fabricate even welded single-crystal cavities. With the appropriate orientation and forming technology, it has been shown that is possible to join two half-cells to a single-cell without the formation of a grain boundary at the weld join. There are so far no fundamental obstacles identified, which would prohibit even the welding of a single-crystal nine-cell cavity. The main problem is rather to have sufficiently large crystals in the niobium ingot which would allow to form single-crystal sheets in a cost efficient way. This development has just started, and several processes for an optimal melting process are being discussed. A more detailed discussion of large-grain and single-grain material is given in [16].

Cavity Fabrication

The standard fabrication method for cavities is the electron-beam welding of cups deep-drawn from niobium sheets. Another approach is to form the body of the cavity from tubes, e.g. using hydroforming where the tube is expanded into a mould on the outside. This could reduce the cost of the cavity fabrication by eliminating a number of welds.

Recently, a nine-cell has been fabricated by forming 3 three-cells and welding those at the irises [17]. So far, the end groups which include the HOM couplers, the field pick-up probe and the port for the high-power coupler of hydroformed cavities are still being welded to the cavities, thus limiting the cost reduction possibilities. An alternative approach is to use a design where a rotational symmetric main coupler port is used [18].

Cavity Preparation

The surface preparation process for superconducting cavities consists of many steps aiming to generate a surface with optimal superconducting properties. Several ideas are currently under investigation to reduce the cost for the preparation processes.

A method to remove the damage layer on the niobium after the forming process and to smoothen the weld in the equator area is centrifugal barrel polishing. This method uses grinding stones for material removal instead of a very long electropolishing. KEK has a long standing experience with this. The results shown in figures 5 and 6 are examples.

Vertical electropolishing is another option which is currently being tried out in Cornell [19]. It features a

simpler setup with less investment cost. Initial results are promising (see figure 9).
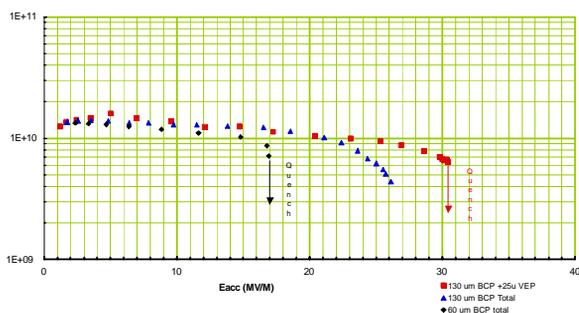

Figure 9: Performance of a nine-cell cavity after etching (black and blue) and after vertical electropolishing (red) at Cornell.

For high accelerating gradients it is necessary that after the electrochemical preparation and the high pressure water rinse an 'In-Situ' bakeout is being applied to the niobium cavities. Saclay has shown that with a 'fast Argon bakeout one can reduce the time needed for this process from 48 hours in vaccum to 3 hours in Argon atmosphere (see figure 10) [20].
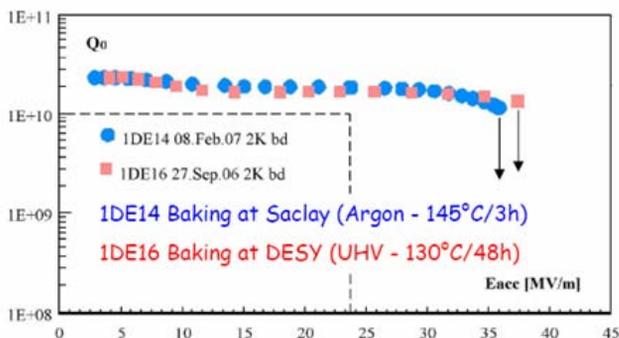

Figure 10: Standard 'in-situ' bakeout process (red) and fast argon baking process (blue) tested on two single-cell cavities.

Another development is dry-ice cleaning where the niobium surfaces of a cavity is being cleaned is a jet of dry-ice snow stabilized with nitrogen gas. The interesting feature here is that this can be done horizontally. Currently, the final assembly step namely the insertion of the main power coupler is done after the final cleaning process. With dry-ice cleaning it would be possible to make a cleaning step after the assembly thus addressing the reproducibility of the module assembly process [21].

Organising the ILC R&D Effort

Several options for the SRF cavities of the ILC exist. So far the R&D effort has been coordinated to ensure the cavity baseline performance by focusing on the final surface preparation steps of th cavities. This program has started and shows the first very exciting results.

In the next step the ILC moves towards are project-oriented structure. With the next milestone for the ILC being the publication of an engineering design report

(EDR) by 2010, a significant effort is needed to produce a detailed engineering for all baseline components in the machine. Nonetheless, it is important to keep the momentum of the alternatives program, as this allows for potential cost savings and a more flexible response to changes of the ILC time scale outside the technically driven schedule.

CONCLUSION AND OUTLOOK

The ILC SRF R&D is progressing in both the baseline design options and the alternatives. With the ILC project, a coordinated R&D program has been set up to improve the yield of the surface preparation processes and the first encouraging results are available. Both new cavity shapes offering potentially higher gradient and thus more operational margin and large-grain niobium material with the potential of a significant cost saving also show very good initial results. This allows for a flexible approach in the overall ILC R&D program to design the ILC most cost effective with the best possible performance.

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