Cavity Process

S. Aderhold\textsuperscript{1}, S. Cheł\textsuperscript{2}, E. Elsen\textsuperscript{1}, F. Eozénou\textsuperscript{2}, L. Lilje\textsuperscript{1} and D. Reschke\textsuperscript{1}

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Abstract

After a long period of thorough optimisation a standard recipe for the production of 1.3 GHz superconducting RF cavities has been established. These cavities will be used for the European XFEL and are foreseen for the International Linear Collider ILC. The recipe is documented in the following and residual options are explained. Quality assessment and control is key to reaching high gradients in a reproducible manner. Some elements of the quality assessment are outlined.

\begin{footnotesize}
\textsuperscript{1} DESY, Hamburg, Germany
\textsuperscript{2} CEA, Saclay, France
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1 Introduction

The goals of the activities in Work Package 6, High Gradient Cavities, are focussing on reaching a high yield of superconducting cavities sustaining a high electric field and hence a high accelerating gradient. Individual high-gradient cavities have been produced in the laboratory and exceeded gradients of 30 MV/m. A recipe has emerged that describes the manufacturing steps. This recipe is the basis for the mass production of cavities and will be described below. Consequently it is assumed that the manufacturing process of such cavities is sufficiently well understood to yield high-performance cavities. To achieve a high yield in the production process thus necessitates high reproducibility of the manufacturing process and consequently stringent quality assessment.

Several preparatory steps have been taken to improve the reproducibility of the production and to assess the properties of the cavities. These steps will be exercised in the production of new cavities. In the meantime, ILC-HiGrade has been refining the methods on existing cavities produced for the FLASH upgrade at DESY and for the preparation of the European XFEL.

2 Preparation process

Key to reaching high fields in superconducting RF cavities is a smooth and clean niobium inner surface. This is trivially understood for field emission where any pointed or pronounced structure or feature on the surface enhances the local electric field and leads to emission of electrons which are hence accelerated and may even get trapped in the cavity structure. Considerable progress has been made in the past years to eliminate the occurrence of field emission up to moderate and even high fields. Another gradient limitation is related to the superconductor itself: locally the critical magnetic field may be exceeded and the superconductor becomes normal conducting. This effect typically arises in areas where the magnetic field anyhow assumes extreme values. For the ILC cavities the so-called equator, i.e. the welding seam between cavities half-cells, lies in this area of highest magnetic field.

The production and preparation process that yields cavities with such surface conditions has been developed, refined and iterated several times over the past years. A standard has been established. This cycle has yielded single cavities that exceeded 40 MV/m in the vertical test. However, the production of larger numbers of cavities following this recipe still shows a considerable spread of the maximum gradients ([1],[2]), which has to be addressed.

Two methods of surface treatment are still under consideration: Buffered chemical processing (BCP) and electro-polishing (EP). Both have been shown to achieve satisfying cavity gradients, although there is a tendency that peak fields are higher for EP, cf. section 3.

Performance and cost efficiency are both crucial for a mass production of superconducting cavities. The cavity fabrication process has been cost optimised by welding the vessel before the vertical test, which results in fewer handling steps. However, the cavity cannot be electro-polished with the mounted vessel. Hence this simplification is only applicable to cavities that are foreseen to undergo a short final BCP, so that peak gradient performance may be limited. For electro-polished cavities the process needs to be modified: an additional fine polishing step must be done before welding the helium vessel.

The individual processing steps are explained in Figure 1.
Figure 1: Workflow of surface preparation for cavities with He vessel welded before or after vertical acceptance test [2]. The two lines refer to EP and BCP preparation cycles.

Deep-drawn niobium half-cells are electron-beam welded to produce 9-cell cavities. Electron-beam welding is the method of choice: the partial melting of niobium and fusing of the parts under good vacuum conditions yields welding seams that consist of pure niobium with only a small contamination of foreign materials.

After completing all welding seams the production of the cavity itself is finished. However, the rolling of the niobium sheets and deep-drawing leaves a damage layer on the inner cavity surface that has to be removed. A layer of 110-140 \( \mu \text{m} \) thickness is removed by electro-polishing (EP), the bulk electro-polishing step. After a brief high-pressure water rinse the outside is etched using BCP.
During the electro-polishing sulphur may segregate and stick to the inner cavity surface. This sulphur is known to be a possible origin for field-emission and has to be removed. An ethanol rinse cleans the surface from the deposits.

Subsequently the cavity is baked at 800°C to remove mechanical stress in the material, to degas the niobium from trapped hydrogen and to anneal the surface.

The cavity assumes its final shape after the tuning procedure in which the individual cells are mechanically deformed to correspond to the 1.3 GHz operating frequency.

At this stage the fine treatment commences, which includes inner surface cleaning and flange mounting. The processing steps differ for EP and BCP treatment. In the former case an additional 40 µm layer of Nb is removed, the cavity is water rinsed (HPR) and temporary flanges are mounted. Again an ethanol rinse removes the sulphur deposits and a six-fold HPR concludes the process so that the He vessel can be welded. In the latter case the flanges are immediately mounted, the cavity is rinsed (HPR) and the He vessel is welded. The BCP continues and removes 10 µm of material. The cleaning concludes with a water rinse (HPR). These procedures of cavity preparation with He vessel welding before acceptance test have been developed for the European XFEL ([3],[4]) and offer two variants for the preparation of high-gradient cavities for the ILC.

From then on further processing steps are identical: accessories are assembled and again the cavities are thoroughly rinsed (six times HPR). Subsequently the cavities are baked at 120°C for 48 hours. This step is introduced to prevent a phenomenon that is called “high-field Q-slope” or “Q-drop”. An exponential drop of the quality factor Q can be observed at higher gradients corresponding to peak surface magnetic fields above about 90 mT [5] in vertical tests of the cavity. While the origin of the Q-drop is not fully understood to date the treatment has shown empirically that it improves the quality factor and hence the cavity performance considerably.

Table 1 shows an overview on the workflow for the ILC-HiGrade cavities, which will be selected for thorough investigation and post-production treatment. The main difference is the initial omission of the He vessel-welding to allow both for re-treatment and better quality control.

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<td>Manufacturer</td>
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<td>preparation</td>
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<td>versus vertical EP</td>
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Table 1: Preparation model of the ILC-HiGrade cavities showing the engagements of the various laboratories and the variants of the preparatory steps.

### 3 Comparison BCP and EP

Surface preparation is key to the performance of 1.3 GHz superconducting cavities. The ILC project pursues electro-polishing as the main process for chemical surface treatment since it has been shown to yield higher gradients. The manufacturing process is identical to the EP-based process for the European XFEL. In 2008, a comparative study between two potential finishing surface preparation methods was made at DESY with the focus to reduce cost in the overall cavity production cycle. The two processes studied were:

- application of electro-polishing for the final finishing process and
- usage of a short etching process.

The preparation processes were followed through to the level where the helium vessel is welded onto the cavity. Only then a RF performance test was carried out in line with the assumption on the likely scenario for a mass production of cavities for the European XFEL or the ILC, where fully dressed cavities will be delivered to the laboratories for the quality control RF performance test in the cryostat. The results are summarised below.

- The first conclusion drawn from this data is that the cavity process simulating the mass production scenario yields very similar results to the earlier process, which has not included fully dressed cavities, i.e. the He vessel had not been welded. Thus both final processes can be implemented in a streamlined mass production scenario.
- The second conclusion is that the final electro-polishing process gives slightly better performance, which has been demonstrated in earlier studies.
- The third observation is that there is still a wide scatter of performance. Whilst average performance is above the goals for the European XFEL, some cavities show very poor performance, even below 20 MV/m. This is not acceptable for either project.

Initial studies indicate that the scatter is related to the mechanical fabrication process. Defects on the surface could be identified using thermal mapping methods identifying the region limiting the cavity performance. Subsequent usage of optical inspection yielded results and has shown surface defects at these locations. In a mass production environment, these cavities would need to be discarded (or repaired). Thus, a targeted quality control process including optical inspection methods is mandatory.

A decision of using European XFEL type cavities within the ILC-HiGrade programme has thus been taken. This will allow focussing the R&D programme on the improvements of the cavity surface preparation process while not being disturbed by potential cavity design variations that may affect the cavity performance. The material of choice will be fine-grain
niobium. As alternative material selections are explored in other laboratories participating in the ILC R&D effort, the European programme assumes the responsibility of maturing the most promising surface process for very high accelerating gradients.

The processing tools developed in the ILC-HiGrade programme will serve as an important tool for cavity production with full defect-mapping using spatially resolved temperature monitoring under cold conditions with resistors and the second sound method. Subsequent optical inspection will allow feedback to the European XFEL main production as well as guidance for higher gradients needed for ILC.

Following this initial quality control step, the ILC cavity preparation, which mainly consists of an electro-polishing surface treatment, will be applied and a second vertical test will be carried out. Finally, as a potentially cost saving preparation step a vertical electro-polishing setup will be applied to compare performance to the ILC standard recipe.

Considerable effort focussed on reaching an agreement with the European XFEL project on the manufacturing details. The general timeline and procurement procedures have been settled. The general test sequence as described above has been agreed upon with the participating laboratories.

4 Vertical EP - Improvement of the process

At CEA a system for vertical electro-polishing (EP) is under design. The goal is to simplify the operations of the most crucial surface treatment process needed for the superconducting niobium cavities, namely electro-polishing. So far, most systems rely on electro-polishing in a horizontally mounted cavity, which entails a mechanical rotation of the cavity. Consequently the setup is mechanically much more complex than a simple vertical system which allows, e.g. a much easier draining of the hazardous process liquids. An initial design of the facility is now available (cf. Figure 2).

With this new EP station, the final sequence of surface preparation on ILC type cavities will be possible. The goal is not to develop new EP bath or new preparation recipes, but to strictly follow a reference treatment on 1.3 GHz 9-cell cavities in vertical position in order to gain a solid statistics sample on the performance of cavities.

*Figure 2: 3d model of the new vertical EP station to be built at CEA Saclay*
5 Optical inspection

Since August 2008 the prototype of a high-resolution camera system developed at KEK and Kyoto University [6] has been available at DESY. It allows inspection of the inner surface of cavities with a level of detail unprecedented hitherto.

Up to now 26 cavities have been inspected and some experience has been gained with the tool [7],[8]. This led to the proposal of improving subtle features of the camera system in collaboration with KEK and Kyoto University. The goal is to improve the accuracy and contrast of the camera and to automate the inspection process. The camera is intended to be used both as a research instrument in the laboratory, investigating the defects that limit the accelerating gradient, as well as a possible part of quality assurance in a cavity mass production.

One example that shows the potential of the optical inspection at early preparation stages is depicted in Figure 3. The cavity has been inspected consecutively in each step of the surface preparation cycle and a defect has been observed and traced throughout all stages. Initial hints for a defect are visible before any surface treatment and a clear pit-like defect emerges after bulk surface removal. The cavity was tested in the vertical test stand, equipped for temperature mapping of the surface. The area with the defect was confirmed to heat up and thus limiting the performance of the cavity.

The ability to detect performance-limiting defects in early production steps provides a tool of quality control that does not rely on the cavity to be fully prepared up to the final vertical test. It thus bears the potential to shorten the production cycle. Complemented by additional repair steps such as local grinding and local re-melting that are currently under investigation at various laboratories it may help improving the production yield of high-gradient cavities.

Currently the manually driven inspection of a full cavity takes roughly 2-3 days and is error prone. To be really useful it is hence mandatory to automate the inspection process to the maximum possible extent. Images taken under standard conditions will be taken and can be automatically analysed. The working group has decided early on to build the corresponding robot.

Figure 3: Defect traced through all stages of the cavity processing (yellow ring): a) before surface treatment, b) after bulk surface removal and c) after final treatment and RF-test. The size of the defect is ~0.5 mm.
The current status of the development of a fully automated optical inspection has now yielded a design for the Optical Bench for Automated Cavity inspection with High resolution on short Timescales (OBACHT), a 3d-model is shown in Figure 4. It consists of a linear drive that slides the fabricated cavity over the horizontal rod that houses the camera. The camera itself may rotate by 360° to cover the full azimuth angle. A guide system will ascertain that the camera slides properly over the rod so that any impact with the cavity wall is inhibited.

The design has significantly profited from the experience with the inspection of the 26 cavities on the initial optical test bench. The emphasis was to develop a mechanically stiff bench system with high precision movement and ease of operation. It is expected that the processing time with roughly 1000 pictures for a single cavity can be reduced to 2-3 hours.

![Figure 4: 3d model of the automated optical inspection setup under construction at DESY](image)

### 6 2\textsuperscript{nd} Sound

In another step to improve quality control on vertical test with acceptable timescales a setup for the second sound detection of localised heating spots is under development. The method was pioneered at Cornell University ([9],[10]). The setup will allow with a relatively small number of sensors (less than ten) to make a triangulation on the second sound waves generated by a thermal quench of a superconducting cavity. This system is much more simple than the classical temperature mapping system composed of a complex setup of roughly 100 temperature sensors which have to be rotated around the cavity under test.

A permanent installation to the test cryostats is planned thus reducing the preparation time for the cryogenic cold tests. An interesting option to be tested in a prototype setup soon is the test of cavities equipped with a helium vessel. If feasible, the system would allow testing the complete European XFEL series cavity production with system that will allow localising heating spots.

A first measurement with the set-up that is under construction at DESY is shown in Figure 5. From the time difference between the actual quench, read off from the reflected power signal
and the time of the second sound wave arriving at the sensor (oscillating superleak transducer, OST) the distance to the quench location can be calculated via the known propagation speed. The distance between quench location and OST determined by the second sound measurement is consistent with the location of the quench that has been found by temperature mapping in the same test.

![Graph](image)

*Figure 5: First signal of 2nd Sound observed at DESY. The change in reflected power indicates the cavity quench; the signal arrives at the OST after a few ms.*

## 7 Conclusion

The cavity production process has been defined and forms the basis for the negotiations with the manufacturers. Two final surface treatment schemes are viable for SRF cavities. For higher gradients, as required for the ILC, the method of choice is electro-polishing. The industrial manufacturing has to be complemented by detailed quality control. New tools developed in the ILC-HiGrade framework will ascertain the high quality of the produced cavities. This effort forms the basis for the high-gradient performance of the ILC-HiGrade cavities and hence for the cavities for the ILC.

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## References


