RECENT DEVELOPMENTS IN SRF CAVITY SCIENCE AND PERFORMANCE*

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Abstract

The performances of SRF cavities made of high purity bulk niobium have been improving in the last few years and surface magnetic fields (B_p) close to the thermodynamic critical field of niobium have been achieved in a few cases. The recommendation made in 2004 in favor of SRF as the technology of choice for the International Linear Collider (ILC), requires improving the reliability of multi-cell cavities operating at accelerating gradients (E_{acc}) of the order of 35 MV/m. Additionally, a better understanding of the present limitations to cavity performance, such as the high-field Q-drop is needed.

This contribution presents some recent developments in SRF cavity science and performance. Among the most significant advances of the last few years, new cavity shapes with lower ratio B_p/E_{acc} were designed and tested. Cavities made of large-grain niobium became available, promising lower cost at comparable performance to standard fine-grain ones and several tests on single-cell cavities were done to gain a better understanding of high-field losses. In addition, studies to improve the reliability of electropolishing are being carried out by several research groups.

INTRODUCTION

The proposed version of the International Linear Collider relies on radio-frequency superconductivity (SRF) to accelerate electrons and positrons beams up to 500 GeV in the center-of-mass. Approximately 20,000 1.3 GHz 9-cell niobium cavities capable to achieve an accelerating gradient of 35 MV/m will have to be built for this project. Both the huge number of cavities involved and their operation at surface magnetic fields close to the material limit pose an unprecedented challenge to the technology and reliability of SRF. Several laboratories and universities worldwide are undertaking many R&D projects to provide a solid base for the ILC design goals. The implementation of the XFEL at DESY, with the production of approximately 1,000 "ILC-style" cavities, will benefit from these activities and could be an excellent "pilot-project" for the ILC.

Among the most significant advances in the last two years, several new cavity shapes had been designed with the objective to reduce the B_p/E_{acc} ratio and the cryogenic losses. Single-cell cavities with these new shapes were able to reproducibly achieve gradients of the order of 50 MV/m. Single- and multi-cell cavities made from large-grain niobium are being built and tested in several laboratories with comparable performance to fine-grain Nb cavities. Basic studies on the so-called "high field Q-drop" and the low-temperature baking are being carried out to understand the causes of these phenomena. In addition, studies on the high-pressure rinse (HPR) and alternative techniques such as dry-ice cleaning are being pursued to optimize the cavity cleaning procedure and to reduce the occurrence of field emission, still in many cases the limitation of cavity performance. Finally, studies on electropolishing aim at an optimization of the process in order to reduce some of the issues associated with it, which cause a spread in the cavities performance. In the following sections, all these topics will be discussed in more details.

HIGH-GRADIENT CAVITY RESULTS

Three new cavity shapes proposed for ILC had been designed at different laboratories (see Ref. [1] for a review): Low Loss (LL) shape at DESY, Reentrant (RE) shape at Cornell and Ichiro shape (IS) at KEK/DESY, this last cavity being very similar to the LL shape. Since superconductivity ceases above a critical magnetic field value, which depends on the material of choice, new shapes with lower B_p/E_{acc} ratio than the original TESLA shape were designed. This is accomplished by reducing the iris radius and increasing the volume in the equatorial area, where the magnetic field is concentrated. Figure 1 shows a comparison among the different cavity shapes and Table 1 lists the main RF parameters.

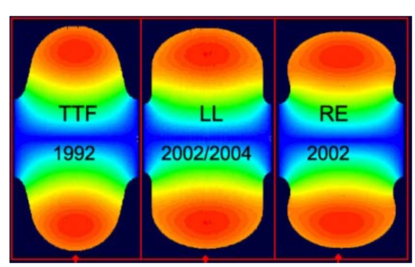

Figure 1: Comparison of single-cell shapes proposed for ILC.

Three single-cell cavities of the LL, RE and IS shapes were processed and tested at KEK [2]. The surface preparation consisted of centrifugal barrel polishing (CBP), 10 μm removal by buffered chemical polishing (BCP), annealing at 750 °C for 3 h, 80 μm removal by electropolishing (EP), HPR for 1 h, assembly in class 10

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clean room, evacuation and baking at 120 °C for 48 h. The test results at 2 K, shown in Fig. 2, were excellent for all three cavities and E_{acc}-values between 47 MV/m and 52 MV/m were achieved reproducibly. The corresponding B_p-values achieved in the three single-cells were between 170 mT and 185 mT, close to the thermodynamic critical field of Nb at 2 K.

Table 1: RF Parameters of the Various Cavity Shapes

	TESLA	LL	RE	IS
Iris diameter [mm]	70	60	60	61
E_p/E_{acc}	2.0	2.36	2.28	2.02
B_p/E_{acc} [mT/MV/m]	4.26	3.61	3.54	3.56
R/Q [Ω]	114	134	136	138
G [Ω]	271	284	284	285

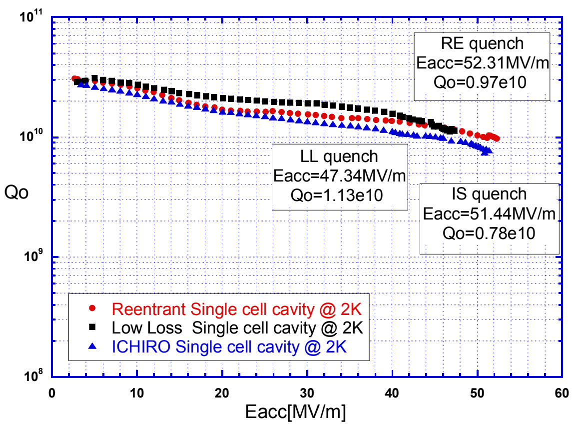

Figure 2: RF test results of the single-cells with different shapes, from Ref. [2].

The best results in multi-cell cavities were obtained at DESY with 9-cell cavities of the TESLA shape treated by electropolishing and reaching gradients between 35 MV/m and 40 MV/m at 2 K, as shown in Fig. 3 [3]. Nevertheless, field emission still prevents to achieve such high gradients on a routine basis. A 9-cell IS cavity recently built at KEK showed an unexpected problem with multipacting in the beam pipe region, verified by simulations [4] which so far had been limiting E_{acc} to ~ 30 MV/m.

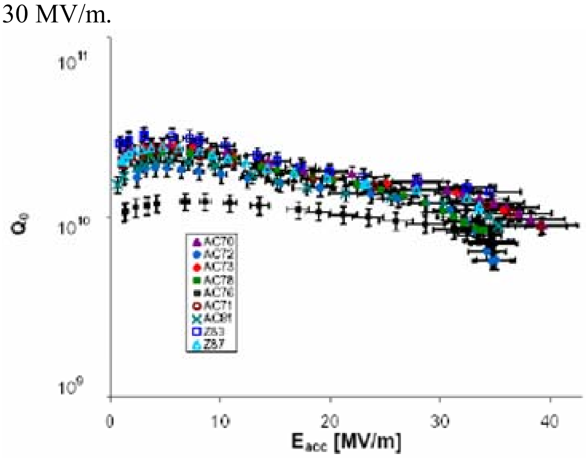

Figure 3: Best performances of 9-cell TESLA cavities [3].

R&D ON NIOBIUM

Large-Grain Cavities

In 2005 cavities made of large-grain (cm-size) Nb were developed at JLab [5]. The Nb sheets are directly sliced from an ingot by wire-EDM or saw-cut and subsequently formed into half-cells by standard deep drawing. Two single-cell cavities at 2.3 GHz were made from single-crystal Nb from CBMM and achieved E_{acc}-values up to 45 MV/m at 2 K, as shown in Fig. 4. Possible advantages of this new technique are the reduced cost of the Nb sheets and better quality control, due to a simpler fabrication process. In addition, very smooth surfaces were obtained just by BCP. Several single-cell cavities of various shapes at 1.3 GHz and 1.5 GHz were built and tested at JLab and routinely achieved B_p-values of the order of 140-160 mT, limited by quench. As an example, Fig. 5 shows the performance of three TESLA shaped single-cell cavities from material of three different vendors. The surface treatments consisted of 40 µm removal by BCP, annealing at 600 °C for 10 h, 40 µm BCP, post-purification at 1250 °C for 3 h, 50 µm etch by BCP, 1 h HPR, dried for 2-3 h in class 10 clean room, assembly, evacuation and baking at 120 °C for 12 h.

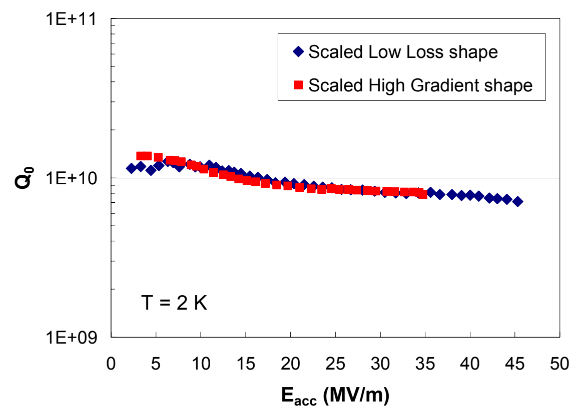

Figure 4: Performance of 2.3 GHz single-cells made of single-crystal niobium. The limitation was quench at B_p = 150 mT in the scaled High Gradient shape cavity and at B_p = 160 mT in the scaled Low Loss shape cavity [5].

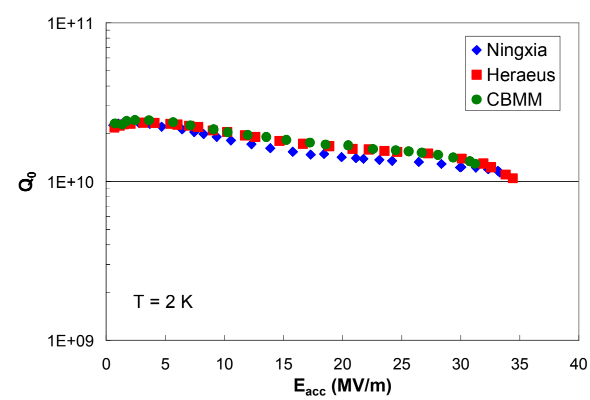

Figure 5: Performance of 1.3 GHz TESLA single-cells made of large grain niobium [6].

Two single-cell cavities made of RRR ~ 500 large-grain Nb built at DESY and treated by EP achieved E_{acc}-values between 37 MV/m and 41 MV/m [7]. Multi-cell large-grain cavities are being fabricated both at DESY and JLab. A 7-cell 1.5 GHz High Gradient (HG) cavity made of large-grain Nb from CBMM and treated by BCP achieved E_{acc} = 26 MV/m at JLab.

A comparative study between 2.2 GHz single-cell cavities of the same scaled HG shape made of fine-grain (Wah Chang), large-grain (Wah Chang) and single-crystal (CBMM) niobium was done at JLab to evaluate the influence of grain boundaries on cavity performance [8]. No such correlation was found, as it can be seen in Fig. 6, after the cavities were post-purified, treated with BCP and baked at 120 °C.

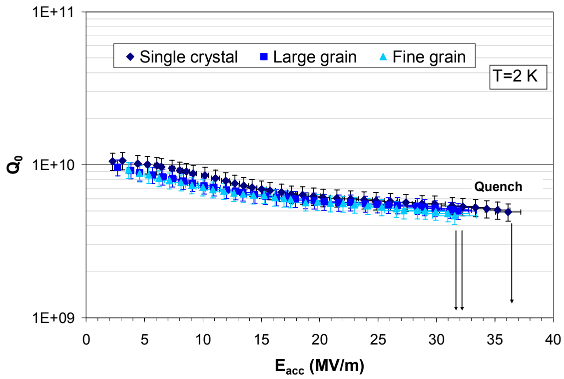

Figure 6: Q_0 vs. E_{acc} for single-cell cavities with the same shape made of niobium with different grain size [8].

Material Studies

New techniques have recently been used to investigate the properties of the Nb used for SRF cavity production: 3D atom-probe tomography is emerging as a very powerful tool to analyze the composition of the niobium surface [9]. The results show a "smooth" transition from the natural oxide Nb_2O_5 to Nb_2O in about 10 nm from the surface. In addition, interstitial oxygen concentrations of 5-10 at.% were found at the oxide/metal interface.

The possibility of flux penetration across grain boundaries of large-grain Nb samples has been studied at University of Wisconsin by magneto-optical imaging [10]. Evidence for preferential flux penetration at fields lower than H_{c1} was found in some but not all of the samples. Issues such as the step and the orientation at the boundary could play a role and requires further investigation.

R&D ON Q-DROP AND BAKING

R&D on Q-drop

The Q-drop appears as a sharp decrease of Q_0 starting at B_p ~ 100 mT in absence of field emission and limits the performance of high purity Nb cavities regardless of the grain size or surface treatment (EP or BCP). Although no clear universally accepted explanation for these anomalous losses exists, it was found that a low-temperature (100 – 140 °C) "in-situ" bake-out of the cavities allows a significant reduction of the losses. Recent experiments at Cornell University [11], and repeated at JLab showed that the modifications of the surface caused by baking are limited to a depth of about 22 nm. This was discovered by anodizing a previously baked cavity until the Q-drop re-appears. An additional bake-out still reduces the Q-drop, as shown in Fig. 7 in a large-grain single-cell tested at JLab.

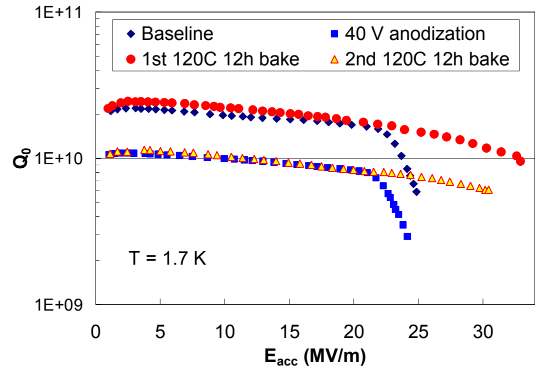

Figure 7: Q_0 vs. E_{acc} for a 1.5 GHz large-grain cavity of the CEBAF shape showing the re-occurrence of the Q-drop after anodizing at 40 V.

Temperature-maps reveal that the Q-drop is associated with "hot-spots" in the region of high magnetic field. RF tests on large-grain single-cells, done at Cornell [12] and JLab [13], could not univocally associate the "hot-spot" location with grain boundaries, as shown for example in Fig. 8.

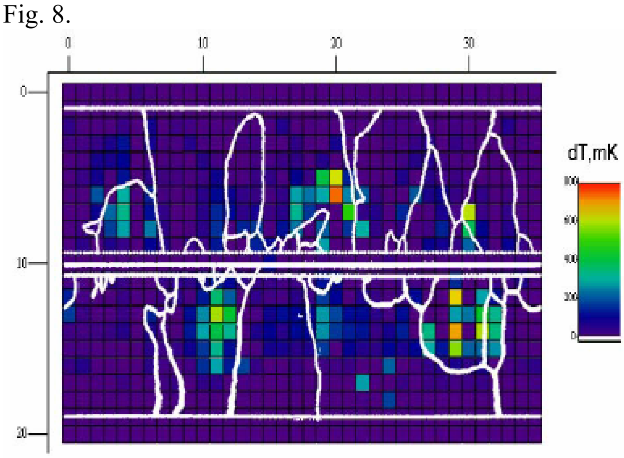

Figure 8: Temperature map in the Q-drop region of a large grain single-cell. The white lines show the grain boundary location [12].

Several models have been proposed in the past years to explain the origin of the Q-drop but none of them has been able to explain all the experimental results (see Ref. [14] for a review). A "hot-spot" model, based on the additional heating due to locally depressed superconducting parameters has been proposed recently in Ref. [15]. In addition, an improved model based on reduced H_{c1} due to interstitial oxygen contamination in the near surface region has been developed in Ref. [16]. Both these models require further experimental verification and quantitative comparison with the existing data.

R&D on Low-Temperature Baking

As for the Q-drop, a clear explanation of the baking effect is still missing. Assuming oxygen diffusion being involved in the baking effect, Saclay has been developing a "fast baking" (145 °C, 3 h) in clean room air as an alternative to the "standard" UHV baking (120 °C, 48 h). The results so far have not been satisfactory and the Q-drop is still present [17]. A slight reduction of the Q-drop was obtained when the baking atmosphere was done in argon atmosphere [18].

Recent studies conducted at JLab showed that the duration of the UHV baking at 120 °C could be reduced from 48 h to 12 h with similar effect on the Q-drop [19]. In some cases, the increase in residual resistance which usually occurs with baking was less marked with lower baking time.

The reduction of the Q-drop by baking is stable after the cavity is exposed back to air, high-pressure rinsed or by removing the surface oxide layer with hydrofluoric acid. In addition, recent tests on the same cavity of Fig. 7 done at JLab show that 120 °C seems to be a safe temperature to bake at: the performance of the cavity did not degrade after the cavity is successively baked in 1 atm of pure oxygen for 12 h, then for an additional 48 h and after baking the cavity "wet" (the water from rinsing was not removed) in air for 12 h (Fig. 10). This may indicate that at 120 °C the natural oxide layer decomposition is minimal and the pentoxide acts as an excellent barrier against diffusion of gases into the bulk. After the "wet" cavity was baked in air at higher temperature for 12 h, a degradation of the performance occurred: baking at 180 °C increased both the BCS and the residual resistance, the quench field decreased and a strong Q-slope was present. The additional losses represented by the Q-slope were ohmic. No field emission was present in any of these tests.

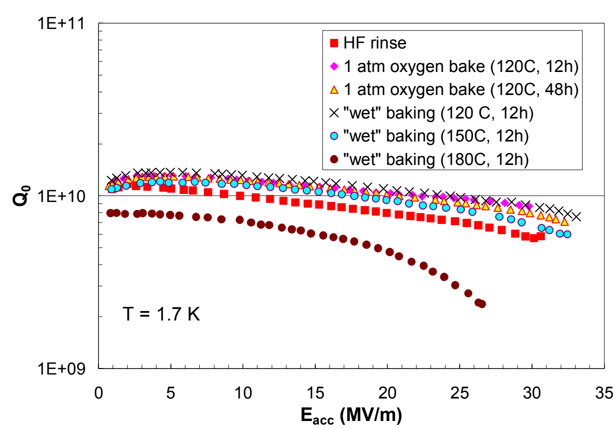

Figure 10: Q_0 vs. E_{acc} for a 1.5 GHz large-grain cavity of the CEBAF shape after various bakes. The treatments shown in the legend were done sequentially in time after the 2[nd] UHV baking shown in Fig. 7.

Baking allows recovering from the Q-drop in fine-grain and large-grain cavities treated by EP. Recovery after a BCP surface treatment is always successful in large-grain Nb, but less successful in fine-grain Nb [20]. This aspect is also not understood.

R&D ON IMPROVING RELIABILITY

High-Pressure Rinse and Dry-Ice Cleaning

High-pressure (~80-100 bar) rinse with ultra-pure water is the technique routinely used to clean the surface of SRF cavities from contaminants, which cause field emission. Nevertheless, the time, the procedure and the type of nozzle employed varies significantly among different laboratories. 1.3 GHz 9-cell cavities, for example, are rinsed for as long as 16 h: this procedure applied to the 20,000 cavities for ILC would require an equivalent time of approximately 36.5 years and 192 million litres of ultra-pure water. A study of the properties of the HPR jet was recently started at INFN-Milan with the intention to optimize the HPR parameters [21]. The force, the profile and the angular dependence of the jet were measured and Fig. 11 shows the static water pressure variation on the cavity wall for a TESLA cavity. The study of Ref. [21] showed that jet structure evolves from a jet with a well defined core to a completely turbulent one as the distance from the HPR head axis increases: this could result in different cleaning properties at the iris and at the equator of the cavity.

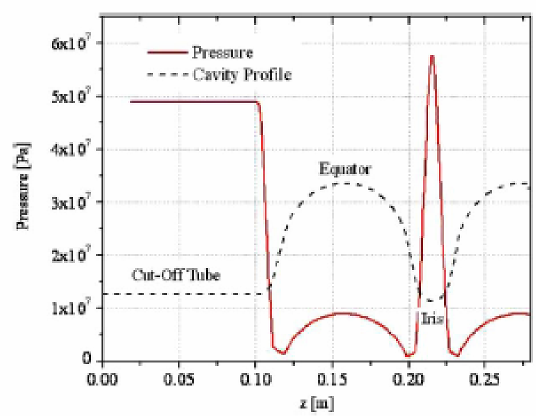

Figure 11: Water pressure variation on the cavity wall along the axis for a TESLA cavity [21].

DESY is pursuing a complementary cleaning method for SRF cavities as a possibility fo horizontal cleaning in a cavity string: dry-ice cleaning. The method consists of spraying liquid CO_2 at ~50 bar through a nozzle on the cavity surface. The relaxation of the liquid CO_2 in the nozzle results in a snow/ice mixture which removes particulates and hydrocarbons by sublimation-impulse method [22]. The dry-ice cleaning was optimized over the last few years and TESLA single-cells, which were not high-pressure rinsed, were tested up to 38 MV/m without field emission.

Electropolishing

EP is a necessary step to achieve B_p > 170 mT in SRF cavities, close to the thermodynamic critical field of Nb. Nevertheless, the process which is currently used has some drawbacks: it is costly, time consuming, problems with Q-disease and field emission due to sulphur contamination were found.

A study recently carried out at Saclay showed that sulphur production and corrosion of the aluminium cathode are strongly related to the acid bath composition, which should be constantly monitored during the process [23]. The problem with Q-disease, due to the diffusion of hydrogen into the Nb during EP, had been addressed at KEK [24] but was recently reported on 9-cell cavities processed at DESY and the causes of it are still under investigation.

Cornell University is pursuing vertical EP as a way to reduce the cost and the processing time.

Electron-Beam Weld

The quality of the electron-beam welds (EBW) at the iris and equator of the cavities' cells is crucial to achieve high accelerating gradients. The weld area is rougher than the rest of the surface, which can cause geometric field enhancement and a premature quench of the cavity. While there is no significant R&D carried out on this topic, the CBP technique developed at KEK [25] helps in smoothing the weld area (Fig. 12). In addition, CBP would automate the manual grinding of visual defects and imperfections which is routinely done on Nb dumb-bells, prior to EBW.

Figure 12: Picture of the inner surface of the equatorial EBW before (left) and after (right) removing 60 μm by CBP.

SUMMARY AND CONCLUSIONS

The decision to build the ILC based on Nb SRFcavities poses great challenges to the technology, both in terms of performance and reliability. Several R&D projects are being carried out in many laboratories and universities throughout the world to address some of the open issues. In the following I summarize some of the progress recently made:

- A recipe based on CBP and EP, applied on newly designed single-cells, led to the achievement of B_p-values close to the thermodynamic critical field of Nb and to new records in terms of accelerating gradients.
- The fabrication of cavities made of large-grain Nb is emerging as a viable option to reduce the material cost without sacrificing the performance.
- The Q-drop is not caused exclusively by losses at grain boundaries in Nb.
- Baking is the only known remedy against the Q-drop and its effect seems to be related to a change of the properties of the Nb up to a depth of about 20 nm. 120 °C is the optimum temperature and the baking time can be reduced to 12 h.
- Cleaning techniques such as HPR are being studied in detail in order to be optimized for mass-production. Dry-ice cleaning may become a complementary cleaning method.
- Work is being done to better understand and to improve the EP process.

In conlusion, significant progress has been made in the last few years towards improving the reliability and the performance of SRF cavities. This effort needs to continue with even greater intensity in the future years to meet the ILC specifications.

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