ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MO1A02

AN OVERVIEW OF RECENT DEVELOPMENTS IN SRF TECHNOLOGY

R.E. Laxdal, TRIUMF, Vancouver, Canada, V6T 2A3

Abstract

Superconducting Radio-Frequency (SRF) is now the technology of choice for both large and small linac projects. Several challenging projects are in progress or planned that are pushing SRF technology and/or are enabled by SRF technology. This paper gives an overview of the present status of the field.

INTRODUCTION

Present research has been focussed on the key projects of the day, namely LCLS-II, FRIB, ESS as well as preparing for near term future projects ERLs, RISP, EIC and ILC. As LCLS-II represents a cw electron project, much of the elliptical cavity research focus has been on achieving, and maintaining, high Q in a cryomodule environment. The holy grail of projects is still the ILC. Here research is focussed on reliably increasing gradient and quality factor in an effort to reduce costs. Researchers are also pursuing thin films and new materials in order to either reduce the cost of Nb or increase the performance or operating temperature.

SRF BASICS

A characteristic of superconductors is that below some critical temperature, T_c, the DC resistance vanishes, allowing lossless transmission of electrical current. The rf surface resistance does not drop to zero, but still decreases dramatically. SRF technology offers a reduction of ~5 orders of magnitude in rf surface resistance compared to room temperature Cu that, after considering Carnot efficiency of cryogen production, still improves electrical efficiency by more than a factor of 100.

SRF Surface Resistance

The SRF surface resistance is typically described as the sum of a strongly temperature dependent component called the BCS resistance, and a second term called the 'residual resistance' (Fig. 1a).

$$R_s = R_{BCS}(\omega, T) + R_0 \quad \text{with} \quad R_{BCS} = \frac{A(\ell)}{T}\omega^2 e^{-\Delta/kT} \tag{1}$$

The operating temperature is chosen so that R_{BCS} is reduced to an economically tolerable value for cryogenic losses with higher frequency cavities requiring colder operating temperatures. The A term depends on material parameters of the superconductor: the London penetration depth (λ_L), the coherence length (ξ_0) and the electron mean free path (ℓ). For a given temperature and rf frequency R_{BCS} can be optimized by modifications of the mean free path within the first 100nm of the surface and finds an optimum between shorter (dirty) and longer (clean) mean free paths (Fig. 1b).

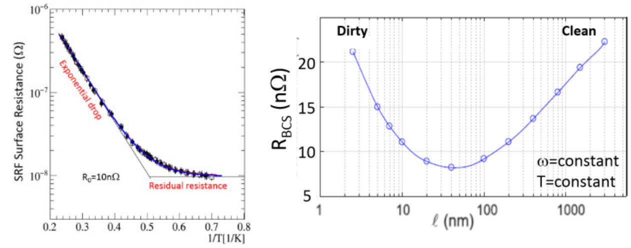

Figure 1: (a) RF surface resistance vs. temperature, and (b) BCS surface resistance as a function of mean free path for constant rf frequency and temperature.

The two most important features of an rf cavity are the accelerating gradient and the quality factor; the first impacts linac length (infrastructure cost) and the second impacts the cryogenic load (operating costs). Note that since the cavity quality factor is roughly proportional to the inverse of the average surface resistance

$$Q_0 = \frac{G}{R_s} = \frac{\omega_0 U}{P_c} \quad \text{and} \quad P_c = \frac{(E_a L)^2}{\frac{R_{sh}}{Q_0} Q_0} \tag{2}$$

then a reduction of surface resistance by four can allow a doubling of the gradient for the same cryogenic load.

Meissner Effect

Niobium is a weak Type-II superconductor. Raising the applied field past a critical value H_{c1} leads to a mixed state (also known as the vortex state) in which an increasing amount of magnetic flux penetrates the material in quantized flux vortices. At a second critical field strength, H_{c2}, superconductivity is destroyed. However, above H_{c1} a metastable state persists up to the superheating field H_{sh} allowed by a surface energy barrier that inhibits vortex nucleation. As rf fields increase in amplitude magnetic vortices with normal cores can nucleate in the near surface and rf losses, hence surface heating occurs. For high gradient performance we need a material that can withstand vortex penetration up to a high peak magnetic field.

Present Performance

SRF research and development [1] have targeted limitations on cavity performance. Extrinsic sources include multi-pacting, field emission, surface residues, trapped magnetic flux, and surface defects. Multipacting is combated with new cavity shapes, better simulation codes and pre-test bake. Field emission has largely been controlled by high pressure water rinse (HPWR) and clean assembly techniques to eliminate particulate contamination. Defects that could cause quench (local heating) are reduced by choosing pure material with high thermal conductivity (RRR>250) and maintaining the purity through fabrication with EB welding and care. A final material removal by electro-polish (EP) or buffered chemical polish (BCP) of

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MO1A02

120-150 microns is found to remove the surface layer damaged during manufacture. Magnetic flux from remnant fields that can be trapped during cooldown and cause loss are controlled with magnetic shielding material.

The intrinsic performance of SRF cavities is determined by the first 100 nm of the inner cavity surface, where rf currents flow within the London Penetration Depth. A main technology driver has been the global effort towards the realization of XFEL (and the ILC) where significant gains have been made in establishing industrially qualified techniques in producing high performing cavities for pulsed operation. Of the 815 cavities delivered for XFEL the average useable gradient in vertical test was an impressive 28.3 MV/m with a reduction to only 27.5 MV/m when tested in the cryomodule [2]. These values can be compared to the goal specification of 23.6 MV/m. Many of the techniques developed for XFEL are being applied successfully in both elliptical and non-elliptical cavities.

Two significant developments impacting the field were the development of high temperature degassing and the 120°C bake. Typically the cavity is heated to 800°C (650°C) in a vacuum furnace for 3 (10) hours to degas hydrogen from the surface. The hydrogen produces lossy hydrides on the surface during cooldown (Q-disease) that reduces the quality factor [3]. After degassing, a final light chemistry is applied to remove any contamination deposited on the surface during the heat treatment.

A 120°C bake under vacuum for 48 hours eliminates the high field Q slope (HFQS) in 1.3 GHz elliptical cavities at 2 K (Fig. 2) [4]. Studies suggest that the 120°C bake promotes the diffusion of oxygen in the bulk from the oxide surface layer. This produces a dirty layer of 20-50 nm with a mean free path of ~10 nm and a reduction in BCS resistance (Fig. 1b). Other studies show that the 120°C bake introduces vacancies in the near-surface layer, which bind hydrogen and prevent its precipitation in nano-hydrides that are responsible for the HFQS (Fig. 2) [5].

ELLIPTICAL CAVITY PERFORMANCE

A main thrust of recent SRF developments is to push the performance of elliptical cavities. New surface treatments, nitrogen doping [6] and nitrogen infusion [7] have been developed to change (in a systematic way) the near-surface nanostructure – impurity, dislocation and vacancy content, in the first hundreds (or less) nanometers of the niobium surface to improve Q or gradient or both.

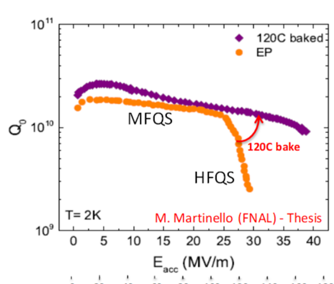

Figure 2: EP'ed cavity before and after 120°C bake.

High Q and LCLS-II

LCLS-II consists of 35 cryomodules each with 8 cavities in an XFEL-like cryomodule for a total of 280 cavities operating at 1.3 GHz. Unlike X-FEL LCLS-II operates CW. LCLS-II, and other cw high beta projects, have concentrated efforts on achieving high Q at modest gradients compatible with cw operation in the range 15-20 MV/m (E_{peak}=30-40 MV/m, B_{peak}=65-85 mT). LCLS-II (boldly) chose N-doping as the baseline recipe with a cavity performance specification of 2.7 x 10^{10} at 16 MV/m and 2 K.

In large part the research effort has focused on perfecting Nitrogen doping as an industrial process (1) to reproducibly reduce R_{BCS}, and (2) to understand and mitigate the main sources of R_0 either enhanced by the doping or exposed due to the reduced value of R_{BCS}.

Nitrogen Doping at 1.3 GHz

Nitrogen doping is a relatively new process that is performed as part of the degassing treatment. After the cavity is baked 3 hours at 800°C the temperature in the furnace is typically maintained constant and nitrogen is introduced at a constant pressure of 25 mTorr. Nitrogen is then left in the furnace for a certain amount of time (minutes) followed by a non-Nitrogen anneal of some minutes more before cooling. After the thermal treatment, the cavity is electro-polished to remove the first 5-10 μm of material from the inner surface in order to get rid of lossy niobium nitride phases. Substantial Q_0 enhancements of 1.3 GHz cavities have been demonstrated. Q_0 values between 3–4×10^{10} at 2 K and 8×10^{10} at 1.8 K can be obtained at gradients of 15-20 MV/m. The N-doping treatment also shows a remarkable behavior in that the Q_0 increases with field from 5–15 MV/m, counter to the general trend of the MFQS using standard recipes (example Fig. 3).

The presence of nitrogen as an interstitial impurity decreases the temperature dependent part of the surface impedance through manipulation of the MFP (Fig. 1b) [8]. The main drawbacks of the N-doping is a reduction in the quench field and an increased sensitivity to flux trapping [9]. Despite success in prototyping studies first articles from the vendors for LCLS-II did not perform as well as the qualifying cavities (Fig. 4a) [10].

To understand the ensuing development, it is useful to look separately at the contribution of the trapped flux to the residual resistance by defining the term R_{fl} – the residual resistance due to flux trapping [11]. The residual resistance

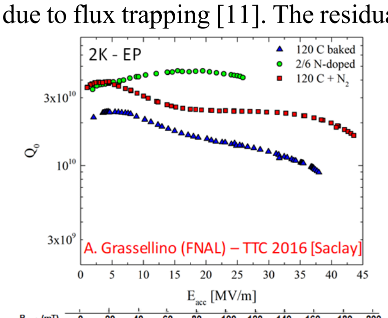

Figure 3: 1.3 GHz elliptical performance for: [blue] standard ILC recipe (120°C bake), [green] N-doped recipe, and [red] nitrogen infusion recipe.

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MO1A02

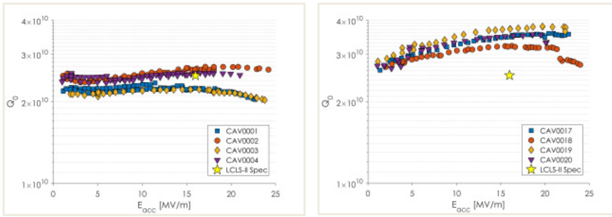

Figure 4: Q vs E of LCLS-II cavities with (a) the original recipe, and (b) the updated recipe.

is a combined product of the background flux, B_{res}, the fraction of the flux trapped, η, and the sensitivity of the residual resistance to the trapped flux, *S,* with

$$R_S = R_{BCS} + R_0 + R_{fl} \text{ where } R_{fl} = S * \eta * B_{res} \quad (3).$$

It is found that the sensitivity of the trapped flux is dependent on the mean free path with an N-doped cavity having a higher S than an un-doped cavity by 3-4 times (Fig. 5a) [12]. Secondly it is found that trapping percentage is impacted by the speed of cooldown – a higher temperature gradient across the cavity at Tc is favoured [13]. Thirdly trapping percentage is impacted by material – heat treatments >800°C helps mitigate poorer expelling material by reducing pinning (Fig. 5b) [14]. Achieving high Q0 through N-doping in industry has now been consistently demonstrated after early teething pains. The gains made in the new process are illustrated in Fig. 4b where LCLS-II cavities from later series comfortably meet the specification [10]. The new understanding is also demonstrated in the performance of completed cryomodules. An initial assembly using first series cavities had an average Q at 16 MV/m and 2 K of 2.1e10 while a later series, FNAL CM-3, was measured with an average Q at 3.5e10 [15]. The SRF community is engaged with vendors to better understand the material production process in terms of flux trapping characteristics [16].

Frequency Dependence of N-Doping

The field dependence of the BCS resistance of N-doped cavities changes as a function of rf frequency. Various cavity frequencies ranging from 650 MHz to 3.9 GHz were tested at FNAL. The conclusion is that the characteristic medium field Q rise due to doping is steeper in higher frequency cavities with a flattening of the slope near 1 GHz [17].

Another interesting result comes from Cornell where a 500 MHz single cell cavity was treated with N-doping and tested at 4.2 K where the BCS resistance is high. Here the Q improved by a factor of two over an undoped case [18].

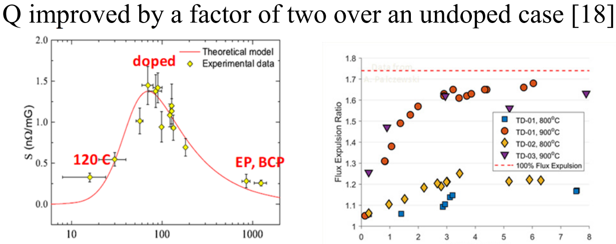

Figure 5: a) Sensitivity to trapped flux as a function of mean free path, and b) Flux expulsion comparing baseline (800°C) treatment and modified (900°C) treatment as a function of temperature gradient across the iris.

High Gradient Studies

New processes that push high gradient with improved Q offer the promise to cut the total cost and operating cost for high energy linear machines like the ILC.

N Infusion

A recent development is the so-called Nitrogen Infusion recipe from FNAL [7]. The process is analogous to the 120°C bake but instead of baking under vacuum the bake is done under low pressure Nitrogen. After the standard 800°C bake, the temperature in the furnace is lowered between 120-160°C without breaking the vacuum. Nitrogen is then introduced at a pressure of 25 mTorr for 48 hours or more. No chemistry is required after treatment. Cavities prepared with this new surface treatment show high accelerating gradients and Q-factors about two times larger than standard 120°C baked cavities (Fig. 3). This thermal treatment (like the 120°C baking) creates an enriched interstitial N layer just below the oxide layer at the near surface [19].

The recipe has proven challenging and not every lab has had the success of FNAL [20]. The treatment is very dependent on the quality of the vacuum in the furnace. At KEK the recipe has succeeded but only 20% of the time [21] with a small gain in both Q and gradient over the baseline. At JLab and Cornell recipes have not increased gradient over the baseline but interestingly some infusion recipes give results that replicate N-doping, with strong anti-Q-slope, suggesting that N-Infusion could replace N-doping as a chemistry free high Q process [22]. Cornell is also looking at other dopants like C and O [23]. Recently FNAL has succeeded in applying N-infusion to a BCP'ed cavity [24].

Low Temperature (Magic) Recipe

A new recipe has now been reported by FNAL (Fig. 6). While performing a standard 120°C bake the cavity was initially rested at 75°C for 4 hours followed by 48 hours at 120°C. In this case no nitrogen and no chemistry were involved. Nevertheless, a gradient of 49 MV/m was achieved (210 mT) with a Q above 1e10 at 2 K [25].

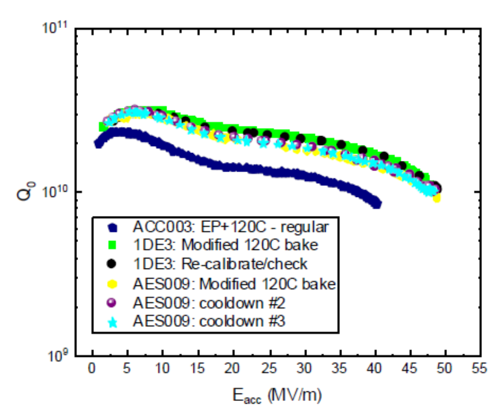

Figure 6: Low temperature bake treatment (FNAL) [25].

29th Linear Accelerator Conf. LINAC2018, Beijing, China JACoW Publishing
ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MO1A02

Material Development

Large Grain Niobium

While most elliptical cavities are made with fine grain RRR material several labs are also pursuing large grain material. The large grain Nb is sliced directly from ingot simplifying the sheet production sequence and reducing material costs [26]. The process has the potential to reduce embedded defects during sheet manufacturing and to reduce the variability in flux trapping characteristics seen in the LCLS-II cavity production. The large grain material is more difficult to form than fine grain and demonstrating industrial production is part of a future development path. DESY (nine cell) and KEK (single cell) have reported impressive high field performance - near 50 MV/m and Q=1e10 (Fig. 7) [27]. Large grain nine cell cavities from PKU prepared by BCP pushed nicely out to ~30 MV/m [28] while RRR=100 material used by KEK achieved >35 MV/m and Q=2e10 in a cold test at JLab [27].

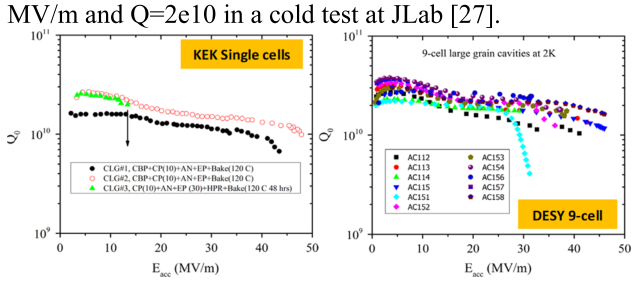

Figure 7: Large grain cavity test results from KEK and DESY.

Nb3Sn Development

Nb3Sn coating via vapor deposition still remains the only new material process that has produced a cavity suitable for acceleration. To date Cornell has achieved a gradient of 18 MV/m at 4.2 K with a single cell 1.3 GHz cavity, with a Q of 2e10, 20x higher than that for Nb (Fig. 8a) [29]. Pulsed performance has reached 26 MV/m. Performance at FNAL is also limited to the 18 MV/m gradient (Fig. 8b) [30]. Research continues globally to optimize the coating with a focus on understanding limitations in the film including defects and tin depleted regions. The question

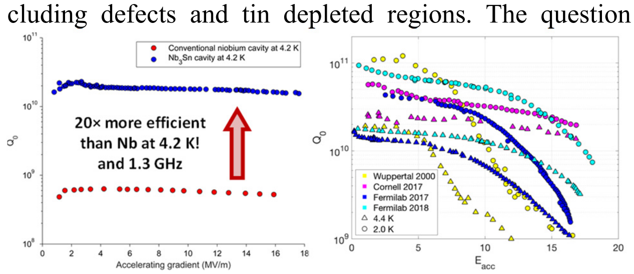

Figure 8: (a) Test results for Nb3Sn from Cornell (left), and (b) FNAL (right).

remains whether 18 MV/m is a fundamental or merely a technical limit. JLab has recently upgraded their coating furnace to be able to coat CEBAF 5-cell cavities with endgroups. At FNAL, a large coating furnace capable of coating 9-cell ILC cavities or 650 MHz 5-cell PIP-II cavities is prepared. At CERN, work has begun on producing Nb3Sn on a copper substrate.

NON-ELLIPTICAL CAVITIES

FRIB

The largest ever SRF hadron accelerator is being built at FRIB. The cavity fabrication is almost complete (340 cavities received) and 50% of the cryomodules are assembled with tunnel installation of the first linear segment complete [31]. Cryomodule qualification is proceeding well with installed cavity performance matching vertical test. A recent beam test with the front end and the first three cryomodules was very successful [32]. FRIB offers a rich data set due to the high cavity numbers. It is noted that the high field Q-slope (HFQS) (without X-rays) is observed in each cavity family with the average onset field coincident at a B_p ~ 85 mT [33]. Interestingly, this corresponds to E_{acc}=20 MV/m for an ILC cavity – similar to the onset field of HFQS with BCP'ed cavities. It begs the question whether high field performance could be improved with EP.

High Performance in TEM Mode Cavities

TEM mode cavities continue to make performance gains. Two examples of state of the art performance are the HWRs fabricated by ANL for PIP-II and processed with EP [34] and a QWR cavity by RISP and tested by TRIUMF using a BCP process [35] - both reached a peak magnetic field of 143 mT. The ANL HWR is particularly noteworthy in that a peak electric field of 135 MV/m was reached. IPN-Orsay is pursuing novel heat treatments with 352 MHz spoke resonator for ESS and Myrte. Here also the cavities reach Bp=140 mT. It is found that the use of Nb caps during the degassing cycle at 650°C can eliminate the need for a final chemical etch even with a Ti jacket yielding a higher Q with a very low residual resistance of R0=1.3 nΩ! [36]. They are also studying flux expulsion as a function of geometry in QWR vs SSR vs DSR [37].

New Cavity Variants

While SSR cavities report excellent results, the adverse impact of strong multipacting (MP) in SSR cavities is also noted by recent test reports, consistent with 3D simulations. TRIUMF has recently designed, fabricated and tested a new variant of SSR termed the balloon cavity [38], that by design reduces multipacting probability and restricts the multipacting regime to low field levels. While traditional SSRs are built like a drum with two end plates and a central spool, the balloon cavity is more like an elliptical cavity with two end shells and no central spool. The cavity is inherently more mechanically stable than the traditional SSR with less ribs required, simplifying fabrication. The design recalls the evolution of the elliptical cavity from the initial pillbox shape to mitigate MP. A cavity at 352 MHz and β=0.3 has been built and tested. The cavity performance matches design with MP limited from 0.2 to 1.8 MV/m well away from the operational gradient at 9 MV/m (Fig. 9) [39].

ODU has fabricated and tested a coaxial HWR for fundamental SRF studies. The goal is to study frequency dependent surface resistance using the fundamental and

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MO1A02

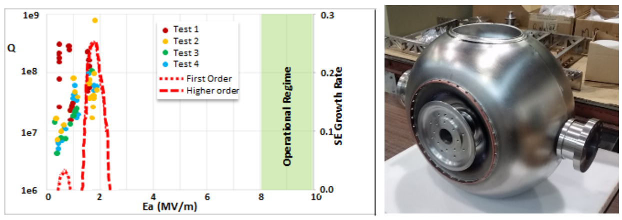

Figure 9: Balloon cavity variant and MP test results.

higher harmonics in the same cold test [40]. TRIUMF has made two cavities, a QWR and an HWR for the same purpose. A collaboration between GSI, IAP Frankfurt and HIM Mainz has successfully produced, installed and beam tested a 217 MHz CH cavity at GSI [41].

Technological Developments

Nb on Cu

The HIE-Isolde project recently installed 20 QWR cavities utilising Nb sputtered on a Cu substrate using DC bias sputtering. Each cavity can work at 6 MV/m, 101 MHz with < 10 W dissipation, at 4.5 K. After early developments they evolved to a seamless substrate, machined from bulk, to achieve the specified performance. After cooldown, partially screened with compensation coils, QSS2 reached unprecedented peak fields for Nb/Cu film technology (Fig. 10) [42]. While still lagging behind bulk niobium in ultimate gradient and Q reach Nb/Cu may be suitable for certain niche applications. CERN, JLab and others are continuing to develop the technology. IMP is also pursuing Nb/Cu as a development towards CiADS.

Hi-Lumi Beam Test

CERN has recently completed the fabrication of two Double Quarter Wave (DQW) deflecting mode cavities, first developed by BNL. The cavities were assembled into a cryomodule and installed in SPS for a proof of principle crabbing demonstration [43].

Low Cost Fabrication of Deflecting Cavity

TRIUMF has succeeded in fabricating and testing a new deflecting cavity variant to be used as an rf splitter [44]. The cavity was fabricated using low cost methods with production via bulk machining of low cost reactor grade Niobium and parts joining via TIG welding.

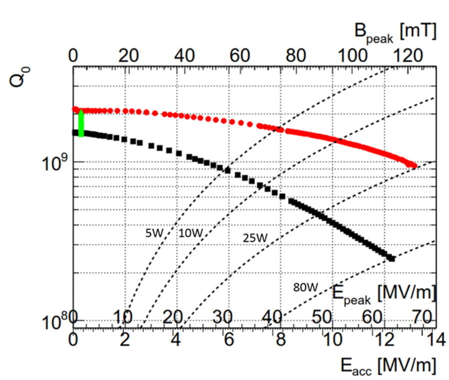

Figure 10: HIE ISOLDE two seamless cavities performance at 4.5 K.

Plasma Cleaning of TEM Cavities

Both IMP and FNAL are developing plasma cleaning for TEM mode cavities. IMP has successfully applied cleaning to a HWR in a vertical test after first depositing pollution on a cavity and then successfully cleaning the surface [45]. FNAL has initiated a program of plasma cleaning on a SSR cavity [46].

FUTURE PATHS

The 120°C bake is known to manipulate the mean free path at the near surface to create a dirty layer of ~50 nm [47]. Interestingly the dirty layer seems beneficial in order to increase the quench field beyond Bc1. Theoretical models are being developed that show that a high κ coating on clean Nb can enhance the field of first flux penetration [48][49]. N infusion and the low temperature bake variations provide additional means to manipulate the dirty layer.

MuSR findings from TRIUMF show that baking at 120°C enhances the field of first flux entry in ellipsoid samples while a layer of high κ and T_c material on niobium enhances the field of first entry by ~40% to a value near H_{sh} consistent with the `dirty layer' hypothesis [50].

ILC and other projects are looking for reproducible robust recipes that can be replicated in industry. We know that variations in the dirty layer produce significant variations in performance from N-Infusion results. The strategy moving forward will be to engineer a surface layer on bulk Nb to reproducibly optimize the performance beyond pure Nb. Thin film research and theory are continuing in parallel with work on Nb3Sn, MgB2 and SIS layers. Alternatively, it is suggested that vortex nucleation time presents a `time barrier' that may be more important than the surface barrier (H_{sh}) in governing flux penetration. Such a barrier would favour higher frequencies and influence thin coating choice towards slower materials. [51].

Stay tuned!

ACKNOWLEDGMENTS

Many thanks to the following for supplying material: P. Dhakal (Jlab), S. Posen (FNAL), M. Liepe (Cornell), D. Longuevergne (IPN-Orsay), C. Madec (Saclay), W. Venturini Delsolaro (CERN), K Umemori (KEK), H. Sakai (KEK), H. Podlech (IAP), K. Liu (PKU).

I also acknowledge contributions from the following by liberally stealing from their fine work: A. Grassellino (FNAL), D. Gonnella (SLAC), M. Martinella (FNAL), M. Checchin (FNAL), A. Romanenko (FNAL), F. Dziuba (IAP), T. Kubo (KEK,ODU), J. Delayen (ODU).

REFERENCES

[1] H. Padamsee, "50 years of success for SRF accelerators – a review", Supercond. Sci. Technol. 30, 053003 (2017) p. 23.

[2] N. Walker *et al.*, "Performance Analysis of the European XFEL SRF Cavities, from Vertical Test to Operation in Modules", presented at the 27th Linear Accelerator Conf. (LINAC'16) Lansing, Michigan, Sep. 2016, p. 657. doi:10.18429/JACoW-LINAC2016-WE1A04

[3] B. Bonin and R. Roth, "Q-Degradation of Niobium Cavities due to Hydrogen Contamination" in *Proc. 5th Workshop on RF Superconductivity (SRF'91),* Hamburg, Germany, Oct. 1991, p 210.

[4] L. Lilje *et al.*, Nucl. Instrum. Methods Phys. Res. **A516** (2004) p. 213.

[5] A. Romanenko *et al.*, Appl. Phys. Lett. 102, 232601 (2013).

[6] A.Grassellino *et al.*, Supercond. Sci. Technol. 26, 102001 (2013).

[7] A. Grassellino *et al.*, Supercond. Sci. Technol. 30, 094004 (2017).

[8] M. Martinello *et al.*, "Effect of interstitial impurities on the field dependent microwave surface resistance of niobium", Appl. Phys. Lett. **109** (2016) p. 062601.

[9] D. Gonnella, J. Kaufman and M. Liepe, "Impact of nitrogen doping of niobium superconducting cavities on the sensitivity of surface resistance to trapped magnetic flux", J. Appl. Phys 119 (2016), p. 073904.

[10] D. Gonnella, "Achieving High Q_0 is LCLS-II Cavity Production" TTC Milano (Feb. 2018).

[11] M. Martinello, PhD thesis, IIT (Dec. 2016) p. 5.

[12] M. Checchin *et al.*, Supercond. Sci. Technol. 30, 034004 (2017).

[13] T. Kubo, "Flux trapping in superconducting accelerating cavities during cooling down with a spatial temperature gradient", Prog. Theor. Exp. Phys. (2016) p. 053G01.

[14] S. Posen *et al.*, "Efficient expulsion of magnetic flux in superconducting radiofrequency cavities for high Q0 applications", J. Appl. Phys 119 (2016) p. 213903.

[15] S. Posen *et al.*, "Magnetic Flux Expulsion Studies on Niobium", presented at the 18th Int. Conf. RF Superconductivity (SRF'17), Lanzhou, China, Jul. 2017.

[16] S. Posen, C. Antoine, and A. Yamamoto, "Summary of WG2", TTC Riken (Jun. 2018).

[17] M. Martinello *et al.*,"Advancement in the Understanding of the Field and Frequency Dependent Microwave Surface Resistance of Niobium" Lanzhou, China, Jul. 2017, p. 364. doi:10.18429/JACoW-SRF2017-TUYAA02

[18] F. Furuta *et al.*, "RF Test Result of a BNL N-Doped 500 MHz B-Cell Cavity at Cornell", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, p. 2440. doi:10.18429/JACoW-IPAC2018-WEPMF036

[19] M. Checchin *et al.*, "New Insight on Nitrogen Infusion Revealed by Successive Nanometric Material Removal", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18),* Vancouver, Canada, Apr.-May 2018, p. 2665. doi:10.18429/JACoW-IPAC2018-WEPMK016

[20] M. Wenscat, "Infusion R&D at DESY", TTC Riken (Jun. 2018).

[21] K. Umemori, "Recent results of N-infusion at KEK/J-PARC", TTC Riken (Jun. 2018).

[22] P. Dhakal, "Update on infusion studies at JLab", TTC Riken (Jun. 2018).

[23] P. Koufalis, "Update on infusion studies at Cornell", TTC Riken (Jun. 2018).

[24] A. Grassellino, "Update on high Q/high G R&D @ FNAL", TTC Riken (Jun. 2018).

[25] A. Grassellino *et al.*, "Accelerating fields up to 49 MV/m in TESLA-shape superconducting RF niobium cavities via 75°C vacuum bake", arXiv:1806.09824.

[26] P. Kneissel *et al.*, "Review of ingot niobium as a material for superconducting radiofrequency accelerating cavities", NIM **A774** (2015), pp. 133-150.

[27] P. Dhakal, "Ingot Niobium for Efficient and Potentially Low Cost SRF Cavities", TTC Riken (Jun. 2018).

[28] Jiankui Hao *et al.*, "Fabrication, Treatment and Test of Large Grain Cavities", in *Proc. 18th Int. Conf. RF Superconductivity (SRF'17)*, Lanzhou, Jul. 2017, p. 700. doi:10.18429/JACoW-SRF2017-THXA04

[29] M. Liepe, private communication.

[30] S. Posen, "Nb_3Sn Results from FNAL", TTC Riken (Jun. 2018).

[31] C. Compton, "FRIB Cavities and Cryomodule Production", TU1A04, this conference.

[32] E. Pozdeyev, "First Acceleration at FRIB", WE2A01, this conference.

[33] K. Saito, "Cavity Performance from FRIB".

[34] Z. Conway, "Optimizing TEM Mode Cavity Performance", TTC Riken (Jun. 2018).

[35] R. Laxdal, "HWR/QWR Test Data", TTC Riken (Jun. 2018).

[36] D. Longuevergne, private communication.

[37] D. Longuevergne, "Flux trapping studies on low beta cavities", TTC Milano (Feb. 2018).

[38] Z. Yao *et al.*, "Design and Fabrication of a β=0.3 SSR1 for RISP", in *Proc. 28th Linear Accelerator Conf. (LINAC'16)*, East Lansing, MI, USA, Sep. 2016, p. 226. doi:10.18429/JACoW-LINAC2016-MOPLR041

[39] Z. Yao *et al.*, "Fabrication and Test of a β=0.3 325 MHz Balloon Single Spoke Resonator", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, p. 3934. doi: 10.18429/JACoW-IPAC2018-THPAL123

[40] H.K. Park *et al.*, "Investigation of Low Temperature Baking on the Surface Resistance of Niobium Between 325 MHz and 1300 MHz Using a Coaxial Half Wave Cavity", TUPO031, this conference.

[41] W. Barth *et al.*, "First Acceleration of Heavy Ion Beams with a Superconducting Continuous Wave HIM/GSI CW-linac", TU2A01, this conference.

[42] W. Venturini Delsolaro, "Seamless Quarter Wave Resonators for HIE-ISOLDE", TU1A05, this conference.

[43] R. Calaga, "HL-LHC WP4 Crab Cavities & RF", TTC Riken (Jun. 2018).

[44] D. Storey *et al.*, "Fabrication of a SRF Deflecting Cavity for the ARIEL-Linac", in *Proc. 18th Int. Conf. RF Superconductivity (SRF'17)*, Lanzhou, China, July 2017, p. 524. doi: 10.18429/JACoW-SRF2017-TUPB063

[45] Y. He *et al.*, "HWR performance and performance recovery in IMP", TTC Riken (Jun. 2018).

[46] P. Berutti, "Plasma Cleaning R&D at FNAL", TTC Riken (Jun. 2018).

[47] A. Romanenko *et al.*, Appl. Phys. Lett. **104**, 072601 (2014).

ISBN: 978-3-95450-194-6 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2018-MO1A02

[48] T. Kubo and A. Gurevich, "A unified theory of surface resistance and the residual resistance of SRF cavities at low temperatures", presented at the *18th Int. Conf. RF Superconductivity (SRF'17)*, Lanzhou, China, July 2017 (slides only).

[49] Mattia Checchin *et al.*, "Ultimate gradient limitation in niobium superconducting accelerating cavities", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16),* Busan, Korea, May 2016, pp. 2254-2257. doi:10.18429/JACoW-IPAC2016-WEPMR002

[50] T. Junginger, W. Wasserman and R.E. Laxdal, "Superheating in coated niobium", Supercond. Sci. Technol. 30, No. 12, published 7 Nov. 2017.

[51] A. Romaneko, "Pathway to High Gradients in Superconducting rf Cavities by Avoiding Flux Dissipation", presented at *9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018 (slides only).