WHERE NEXT WITH SRF?*

G. Ciovati#, Jefferson Lab, Newport News, VA 23606, U.S.A.

Abstract

RF superconductivity (SRF) has become, over the last ~20 years, the technology of choice to produce RF cavities for particle accelerators. This occurred because of improvements in material and processing techniques as well as the understanding and remediation of practical limitations in SRF cavities. This development effort span ~40 years and Nb has been the material of choice for SRF cavity production. As the performances of SRF Nb cavities are approaching what are considered to be theoretical limits of the material, it is legitimate to ask what will be the future of SRF. In this article we will attempt to answer this question on the basis of near-future demands for SRF-based accelerators and the basic SRF properties of the available materials. Clearly, Nb will continue to play a major role in SRF cavities in the coming years but the use of superconductors with higher critical temperature than Nb is also likely to occur.

INTRODUCTION

The use of RF superconductivity (SRF) in particle accelerators for scientific research has become increasingly widespread over the last ~20 years. Niobium, either as bulk or thin film, has been the only material used to build SRF cavities for accelerator projects in this timeframe. The performance of SRF cavities is summarized by a plot of the cavity quality factor, Q_0, as a function of the accelerating gradient, E_{acc}. Collaborative efforts among laboratories and universities throughout the world greatly contributed to the improvements of the performance of SRF cavities, which has approached in several instances that to be considered the theoretical limit of the material. This is a tremendous achievement, particularly when one considers that the Nb surface area exposed to the RF fields in the cavity is of the order of ten meter square, in comparison to the depth of the surface layer whose properties determine the cavity performance, of the order of ~100 nm.

Not only the ultimate performance of SRF cavities has improved but also the reliability of the overall technology has improved as well. For example, the availability of the beam from the Spallation Neutron Source superconducting Linac, with all related support systems, has reached 98%, with less than one beam trip per day and a downtime of less than 5 min/day [1]. A recent survey of beam availability from SRF accelerators worldwide reported an average downtime from SRF and support systems of ~3.7% (mainly caused by issues with RF power and cryogenics) [2].

Research and development of superconducting materials alternative to Nb for RF cavity applications has been pursued by many laboratories and universities throughout the world since the early days of SRF, back in the 1970s, but none has met, so far, the requirements of particle accelerator projects throughout the years. Renewed efforts and new ideas on how to overcome some of the limitations of materials with higher critical temperature, T_c, than Nb have occurred since the past ~10 years.

In the following sections of this article we will present a brief outlook of SRF-related accelerator projects as well as providing an historic perspective of thin-film SRF technology. This might give some hints about the timeframe and the possible conditions for a superconductor other than Nb to be used for the production of SRF cavities. The implications from possible advancements in the R&D of both bulk Nb and thin film technology will also be discussed with respect to future accelerator projects.

A rather comprehensive review of SRF technology R&D for future accelerator projects, complete with all relevant references, can be found in [3].

SRF AND FUTURE ACCELERATOR PROJECTS

Electron Linacs

Among electron Linacs, the Cornell Energy Recovery Linac (ERL) is a 5 GeV, 100 mA, continuous wave (CW) electron Linac to be built at Cornell University, requiring close to ~380, 1.3 GHz, 7-cell cavities. A similar project is a 3 GeV, 100 mA, CW, ERL to be built at KEK, Japan, and using ~200, 1.3 GHz, 9-cell cavities.

The Next Generation Light Source (NGLS) is a 2.4 GeV, 300 μA average current, CW Linac to be built at LBL, requiring ~190, 1.3 GHz, 9-cell cavities.

The largest electron Linac project is the International Linear Collider (ILC), a 500 GeV, 10.8 MW, pulsed accelerator, requiring over 16,000, 1.3 GHz, 9-cell cavities. The site and timeline for this project are yet to be decided. About 800 cavities of the same type as those for ILC are currently being built for the X-FEL project at DESY, Germany.

Proton/Heavy Ions Linacs

Among proton Linacs, the success of the SNS project spurred the proposal for new SRF proton Linacs in Europe and Asia. The European Spallation Source (ESS) is a 2.5 GeV, 5 MW, pulsed accelerator to be built in Lund, Sweden, and requiring ~200 cavities at 352.2 (double-spoke) and 704.4 MHz (5-cell). A similar accelerator is the Superconducting Proton Linac (SPL)

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#gciovati@jlab.org

proposed at CERN. Project-X is an accelerator complex to be built at FermiLab, which includes a 3 GeV, 1 mA, CW Linac consisting of SRF cavities at 162.5 MHz (half-wave resonators), 325 MHz (single-spoke) and 650 MHz (5-cell).

MYRRHA is a 400 MeV, 3 mA, CW proton Linac for an Accelerator Drive System (ADS) demonstrator to be built in Mol, Belgium. ADSs are proposed as a way to generate electricity from sub-critical nuclear reactors and to transmute radioactive nuclear waste into elements with shorter lifetimes. Such facilities are planned to be built in India, China and Japan as well, each requiring a proton Linac with beam energy of ~1 GeV and 10-30 mA average current [4]. With the exception of the one proposed in Japan, the Linacs for ADS will operate in CW.

FRIB is a CW heavy-ion accelerator with energies up to 400 MeV/u, 400 kW beam power, to be built at Michigan State University. It requires a total of ~330 cavities at 80.5 MHz (quarter-wave) and 322 MHz (half-wave).

BULK NIOBIUM CAVITIES

All of the accelerator projects mentioned in the previous Section rely on bulk Nb technology. In this Section we briefly review the state-of-the-art performance of L-band bulk Nb cavities over the past ~30 years and mention some open issues and advancements related to Nb.

The Gradient Frontier

A plot of the highest E_{acc} measured in both single-cell and multi-cell cavities throughout the years can be found in Ref. [5]. Gradients above ~45 MV/m have been achieved in the past ~7 years on single-cell cavities having shapes designed to minimize the ratio of the peak surface magnetic field, B_p, to the E_{acc}. Few multi-cell cavities of such shape have been built but haven't achieved yet the same level of performance as the single-cell cavities.

Figure 1 shows the same data of Ref. [5] scaled by the ratio B_p/E_{acc}, which shows that even multi-cell cavities have reached B_p-values of ~200 mT at 2.0 K, which is within 10% of what is considered to be the superheating critical field, B_{sh}, at that temperature. The B_p-values corresponding to the gradient specifications for several accelerator projects are also shown in Fig. 1. These values are a factor ~2.5 lower than the state-of-the-art and are driven by both cost-optimization and reliability arguments. The ILC is the only project proposed so far which would benefit from pushing the gradient frontier beyond what has been demonstrated with bulk Nb.

The Q_0 Frontier

Figure 2 shows a plot of the highest Q_0 measured at low field (~10 mT), 2.0 K and 1.3 GHz throughout the years [6]. Data measured at 1.5 GHz and scaled to 1.3 GHz are shown in the same plot. The data show that values corresponding to the maximum Q_0 predicted by the BCS theory have been achieved. Nevertheless, the quality factor at the operating gradient is usually lower than that at low field. Such dependence is referred to as "Q-slopes" and has different characteristics at low, medium and high B_p-values and the causes for such "slopes" are still being debated.

Unlike for the determination of an "optimum operational gradient", the only reason for the relatively low Q_0-specifications shown in Fig. 2, is reliability. A way to reliably increase the Q_0-value would be beneficial for any SRF accelerator project. Higher Q-values can be achieved by reducing the He bath temperature and therefore the BCS surface resistance, but this approach results in increased cryogenic costs. For example, the Q_0-specification of ERL projects relying on 1.3 GHz cavities is 2×10^{10} at a lower temperature of 1.8 K.

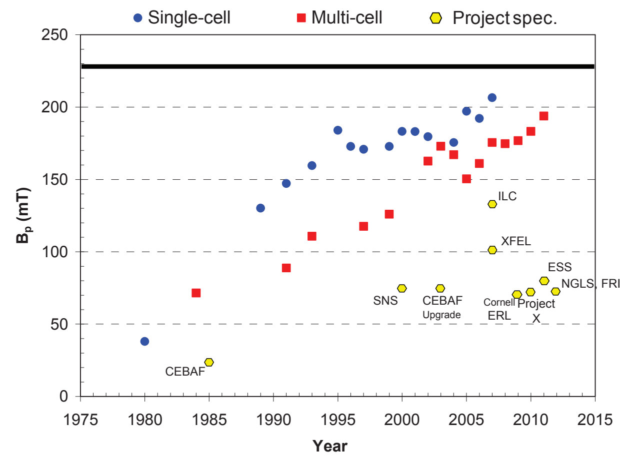

Figure 1: Highest B_p measured at 2 K over the years in single and multi-cell L-band elliptical cavities. The yellow "hexagon" symbols indicate the specifications for several projects. The thick solid line indicates the H_{sh}-value calculated using Ginzburg-Landau (GL) equations with GL-parameter, $\kappa_{GL}\approx1$, resulting in $H_{sh}\cong1.2H_c$ [7].

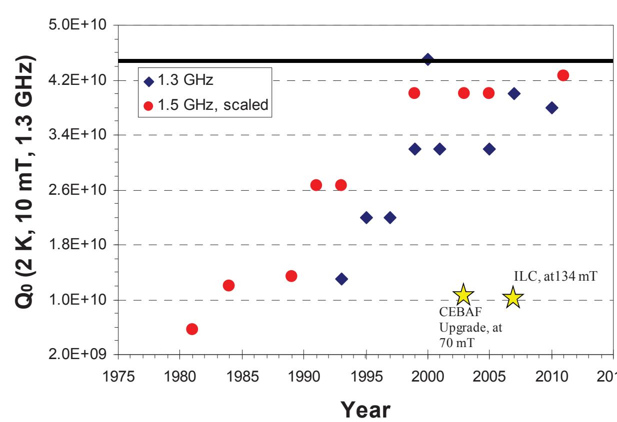

Figure 2: Highest Q_0(2 K, ~10 mT, 1.3 GHz) measured over the years for elliptical cavities. The "star" symbols show the specifications at the indicated B_p-values for two projects using this type of cavities at 2.0 K. The Q_0 specification for the CEBAF Upgrade project was scaled from 2.07 K to 2.0 K. The thick solid line indicates the maximum of the Q_{BCS}-value which should be obtainable at 2.0 K and 1.3 GHz [6].

Ingot Nb Technology

Ingot Nb technology was introduced as a possible alternative to the standard fine-grain Nb in 2004 and since then has been the focus of several R&D efforts on both material science and technology aspects. Such efforts culminated in the highest accelerating gradient measured at 2.0 K in a 1.3 GHz, 9-cell multicell cavity at DESY [8] and the highest Q_0-value at 1.5 GHz, 2.0 K, 90 mT at Jefferson Lab [9]. The demonstration of such high-performance, combined with the possibility of reduced material and cavity preparation costs, makes this technology very attractive for any future SRF accelerator project.

Open Issues

In spite of the remarkable achievements of bulk Nb technology for SRF cavity application, there are many open issues both on the scientific and technological sides. For instance, there is still a significant lack of understanding of the changes in the $Q_0(B_p)$ curves caused by the several different surface treatments applied to SRF cavities. There exist theoretical models and measurements which highlight the influence of hydrides, defective oxides, lattice defects, trapped flux, surface topography and non-linear BCS surface resistance. These topics are reviewed in greater detail in Refs. [3, 10].

From the technology point of view, the reduction of particulate contamination leading to field emission is still a very important issue for SRF accelerators. Improvements in this area would allow increasing gradient specifications without decreasing the yield of qualified cavities. Improvement in the control of particulate contamination is especially needed during assembly of cavity “strings” which are going to be installed into cryomodules.

ALTERNATIVE MATERIALS R&D

A superconductor suitable for SRF cavity application should be s-wave and with low normal state resistivity. These conditions assure a low surface resistance. For an alternative material to have theoretically a better performance than Nb, it should have a higher energy gap and superheating field. Among the possible candidates which are or have been explored for SRF cavity application, Nb_3Sn is the most promising one, having an energy gap about twice as high as that of Nb and a calculated H_{sh} value at 0 K of ~420 mT, compared to ~240 mT for Nb. However, there exist only few attempts at measuring H_{sh} of Nb_3Sn for $T << T_c$ and the values achieved so far have been below those obtained with Nb.

Whereas, theoretically, the highest RF field which can be applied to a superconductor is H_{sh}, recent calculations [11] show that the surface resistance at that field would be significantly reduced from the low-field value and also dependent on the level of impurities in the material. In addition, impurities or defects may reduce the surface barrier which allows extending the Meissner state above the lower critical field H_{c1}. These issues would limit significantly the highest field which can be stored in a cavity with a high Q_0. Theoretically, a solution to this problem was proposed by Gurevich in 2006 and consists of creating superconductor-insulator-superconductors multilayers, with the superconductor being thinner than the RF penetration depth [12].

In the following we will give a historical perspective of SRF-related thin film R&D which may help in predicting future developments being discussed in the next Section.

Thin Films R&D: Historic Perspective

Two well-documented cases of thin films R&D leading to application in a real particle accelerator are the development of niobium on copper cavities at CERN, Switzerland and INFN-Legnaro, Italy. R&D on Nb/Cu started at CERN in ~1980, where the diode sputtering technique was used. In 1985, the coating technique was changed to magnetron sputtering and R&D continued until 1992 where the production of ~270, 352.2 MHz, 4-cell cavities for the LEP accelerator started. The cavity production lasted until 1996. Since then, R&D on magnetron sputtering technology continued until ~2003, in an attempt to achieve the best possible performance and evaluating the possible application of the technology to low-β cavities. Between ~1996 and ~1999, ~20, 400 MHz single-cell cavities were produced for the LHC project. R&D on DC biased diode sputtering was done at INFN-Legnaro in ~1991-1996, followed by the production of ~44, 160 MHz, quarter-wave resonators between ~1998 and ~2003. R&D on magnetron sputtering of Nb on Cu was done between 2003 and ~2007. The performance at 4.5 K of sputtered Nb/Cu cavities for these projects was characterized by a strong Q-degradation and by field emission, limiting E_{acc} to ~8 MV/m.

R&D on Nb_3Sn had been pursued by several laboratories and universities since 1973. A comprehensive review of these efforts can be found in [13]. The longest activities were carried out in Germany at Siemens from 1973 until ~1983 and at University of Wuppertal, from ~1989 until 1997. X-band pill-box-type cavities at Siemens achieved a maximum B_p-value of ~90 mT and a maximum Q_0-value of ~1.7×10^9 at 4.2 K. L-band single-cell cavities from University of Wuppertal and tested at Jefferson Lab reached a maximum B_p-value of ~50 mT and a maximum Q_0-value of ~1×10^{10} at 4.2 K. In both cases, the preparation method was based on the diffusion of Sn on a bulk Nb substrate at high-temperatures. In spite of the encouraging results, R&D on Nb_3Sn stopped since ~1997.

R&D efforts using the same technique developed in Germany have been restarted at Cornell University and Jefferson Lab in 2011 and 2012, respectively.

Thin Films R&D: Recent History

Significant R&D activities are being carried out since the last ~10 years, involving a variety of materials and techniques. On the development of Nb/Cu films, Jefferson Lab has been focused on energetic condensation methods since ~2002 which are being pursued more recently also by CERN, LBNL and Alameda Applied Sciences, Corp. Activities on Nb compounds and A15 materials are being pursued at INFN-Legnaro using a variety of techniques at Argonne National Lab with the Atomic Layer Deposition method and at Saclay. R&D on MgB_2 is also ongoing since ~2003 at the group of X. X. Xi first at Temple University, then at Pennsylvania State Univ., using the Hybrid Physical-Chemical Vapor Deposition method and more recently as collaboration between LANL and Superconducting Technologies, Inc., using the Reactive Evaporation method. Up to now, the focus everywhere has been on developing the coating techniques to produce films with good crystalline structure and DC superconducting properties, whereas very few RF measurements have been done.

In summary, past experiences have shown that ~5-7 years of focused R&D needed to occur before a thin-film technology was ready to meet the requirements for an accelerator project. Such requirements have increased since then. R&D efforts on thin films with new materials and techniques are ongoing already since the past ~10 years. It seems reasonable to predict that an additional ~10 years might be needed before any such new materials and techniques would result in SRF cavities reliably achieving performance specifications of future accelerators.

SRF ACCELERATORS WITH HIGHER EFFICIENCY

As mentioned earlier, any SRF accelerator would benefit from cavities operating at higher Q_0-value and higher temperature. In this Section we will discuss two examples of future SRF accelerators which could find a broad use in society, such as ADS and a Compact Light Source (CLS), and how possible future improvements in the efficiency of SRF cavities would impact such projects.

ADS projects would generate electricity with inherently safe nuclear reactors, therefore reducing the World's dependence on fossil fuels. CLSs are based on Compton scattering of a relativistic electron beam with an intense, high peak-power laser beam, and would produce high intensity, collimated X-ray radiation for a wide variety of applications such as radiological imaging, phase contrast imaging X-ray spectroscopy, etc. [14].

Figure 3 shows the $Q_0(B_p)$ and $Q_0(E_p)$ measured on 1.5 GHz, single-cell cavities made of bulk Nb and Nb_3Sn, respectively, which have the highest Q-values at 2.0 K and 4.2 K, respectively. Let's assume that future R&D on bulk Nb and thin films will allow to reliably produce multi-cell cavities in the GHz range having a Q_0(2.0 K, 70 mT) = 4×10^{10} with Nb or a Q_0(4.2 K, 70 mT) = 1×10^{10} with alternate materials. In presenting the examples we'll assume that Nb_3Sn will be such material.

For the ADS example, let's consider an SNS-type Linac operating in CW. Thirty 6-cell, β=0.61 cavities installed in 10 cryomodules and operating at 12 MV/m (70 mT) would accelerate the beam from 186 MeV to 375 MeV. Sixty 5-cell, β=0.81 cavities installed in 15 cryomodules and operating at 16 MV/m (70 mT) would accelerate the beam up to 1 GeV. Assuming a static heat load of 20 W/cryomodule at 2.0 K or ~60 W/cryomodule at 4.2 K, the AC power required to operate a cryoplant for such accelerator is shown in Table 1, depending on the cavity operating temperature and Q_0 values mentioned above for Nb or Nb_3Sn. These values represent a ~30% reduction with Nb with high-Q_0 at 2.0 K, or ~60% reduction with Nb_3Sn with high-Q_0 at 4.2 K compared to a Q_0(2.0 K, 70 mT) = 8×10^9 obtainable with today's Nb technology. The cost of a new cryo-plant with the cooling power listed in Table 1 operating at 4.2 K is expected to be ~20% lower than the 2.0 K one. It should be noted also that for such kind of accelerator, with a current of ~20 mA, the cost of the RF power would be about a factor of ten higher than that for cryogenics.

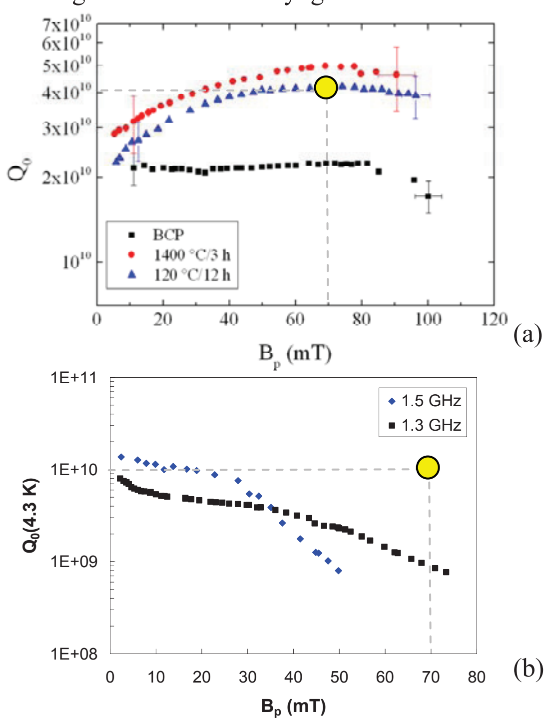

Figure 3: (a) $Q_0(B_p)$ measured at 2.0 K in a large-grain, 1.5 GHz Nb single-cell cavity [8]; (b) $Q_0(B_p)$ measured at 4.2 K in a 1.5 GHz and a 1.3 GHz Nb_3Sn single-cell cavities [15]. The yellow circles show Q_0-values which might be achievable at ~70 mT in the future in multi-cell cavities at 2.0 K and 4.2 K with Nb and Nb_3Sn, respectively, and which are used in the examples discussed in the text.

Table 1: Cooling and AC power required for a 2.0 K or 4.2 K cryo-plant for an ADS accelerator using Nb or Nb_3Sn with the high Q_0-values mentioned in the text.

	Nb at 2.0 K	Nb_3Sn at 4.2 K
Total heat load (kW)	~1	~3.6
Cooling capacity (kW)	1.5	5.4
Efficiency (W/W)	2000	350
AC power (MW)	3	1.89

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For the CLS example, we'll consider a CW, 20 MeV electron Linac such as that being developed at Jefferson Lab for this purpose [16]. Building this type of accelerator with SRF cavities is viable only if it would operate at 4.2 K, because of the very low efficiency of 2 K refrigerators with only ~100 W of cooling power. The current design uses two 400 MHz, 3-cell cavities operating at a gradient of 7.7 MV/m with a Q_0-value of 3.5×10^9. With the possible future Nb_3Sn scenario, the Linac could be built with two 1.5 GHz, 7-cell cavities operating at a gradient of 12 MV/m, for example the same type used for the CEBAF Upgrade, and reduce the dynamic losses by a factor of ~5. Additional cost savings would come from the reduced cost of both cavities and cryomodule.

CONCLUSIONS

The remarkable achievements of SRF science and technology over the past 40 years positioned it as the technology of choice for many future accelerators for a variety of applications.

SRF cavities based on bulk Nb technology satisfy the requirements of SRF accelerators planned to be built over the next decade. The operating parameters specified for such cavities are at about half of what has been demonstrated to be achievable with Nb, with the exception of ILC. This suggests that there is still a significant performance margin which could be gained by improving the reliability of operation at high Q_0 or high surface fields. The successful development of ingot Nb over the past decade indicates that R&D on bulk Nb hasn't reached the end.

R&D on new coating techniques for Nb thin films and alternate materials is being pursued in many places. The adaptation of some of these techniques to coat SRF cavities is only at the beginning and it might take another decade before one such technique and material would have demonstrated a performance acceptable for future accelerator projects. In fact, it might be likely that only the initiation of accelerator projects which require a cavity performance beyond that achievable with Nb would provide the resources and the focus needed. It is likely that either large-scale future accelerators, such as a muon collider or the next electron-positron collider, or the need for widespread small-scale accelerators would dictate such performance requirements.

As it was recognized already in the 1970s, Nb_3Sn is, theoretically, one of the most promising alternate materials to bulk Nb. If renewed efforts on this material will confirm the limits of "thick" Nb_3Sn films obtained by vapor diffusion, the multilayer approach could provide a possible solution. In any case, it is very likely that Nb, either as bulk or thin film, will still be used in the foreseeable future for SRF cavities as it would provide a good superconducting "screen" substrate even for thin films of alternate materials.

We have discussed two examples where high Q_0-values at medium gradient, which could be within reach in the future with Nb at 2.0 K or Nb_3Sn at 4.2 K would result in significant improvements in the efficiency of SRF accelerators. Such improvements could also be obtained by increasing the efficiency of RF sources and cryo-plants, two essential components of an SRF accelerator. In the face of a future with increasing limited resources worldwide, the pursuit of higher efficiency, equivalent to lower cost/MeV, might in fact be a decisive factor for the realization of future accelerators.

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