SRF TECHNOLOGY—PAST, PRESENT AND FUTURE OPTIONS*

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

Abstract

Cavities for all recent superconducting radio frequency (SRF) projects (CEBAF, SNS, KEKB and TTF) have been built from high–purity polycrystalline niobium with a residual resistance ratio (RRR) greater than 250. The procedures and processes used from the initial production of the high—RRR polycrystalline niobium sheets to the finished cavities are complex, numerous and very expensive, and the yield of SRF cavities meeting high performance specifications is low. CBMM – Jefferson Lab invented the large grain and single crystal niobium technology, and the use of niobium sliced directly from the ingots is expected to change the SRF technology outlook with fewer, and more streamlined, production processes that will not only be cost-effective but also promise to generate high yield [1]. In this paper we will show that less stringent commercial niobium specifications are required and explore the processes and procedures that will lay the foundation for producing SRF cavities with good quality factors at high peak magnetic fields in order to make this technology friendlier for future scientific and technological applications.

INTRODUCTION

The pioneering idea of applying RF superconductivity in electron linear accelerators was initiated at Stanford University, USA in the early 1960 [2]. The X-band niobium cavities by Stanford (TM010, baked at 100 °C) and Siemens AG (TE011) reached very impressive peak surface magnetic fields of 108 and 160 mT respectively [3,4]. These cavities were built from low-purity niobium ingots and the process and procedures used were similar but as varied as today. Even at this early stage of bulk niobium SRF technology development, the cavities performance limitation was recognized to be due to electron-multipactoring and/or electron field-emission loading which unfortunately is often still the case.

For simplicity this paper on solid niobium RF superconductivity technology is divided into three sections. “Past” covers from the early developments to the CEBAF construction start-up. “Present” focuses on the evolution of polycrystalline niobium SRF technology leading to large-grain, single-crystal niobium cavities. “Future Options” explores the possible simplification of the complex and expensive process and procedures and use of cost-effective low-purity ingot niobium slices.

RF SUPERCONDUCTIVITY—PAST

Due to space limitations, we refer readers to two excellent review articles-: the first by M. Tigner, on “RF Superconductivity for Accelerators – Is It a Hollow Promise” [5] and the second by H. Padamsee on “High Purity Niobium for Superconducting Accelerator Cavities” [6] for detailed information on RF superconductivity advances until 1979 and 1988 respectively. This paper is a condensed version of G. Myneni’s recent JLab colloquium presentation. However, the two most important crucial points will be discussed: 1) multipactoring of the L-band cavities and 2) switching to the use of RRR polycrystalline niobium sheets.

Cavity Shape and Multipactoring

The L-band cavities’ performance characteristic (low Q_0 and E_{acc}) was rather poor in comparison to X-band cavities which performed extremely well. It was recognized that the L-band cavities, because of their large surface area and unfavorable geometry (for thorough cleaning of the surface), were suffering from multipactoring at very low accelerating gradient of 2—4 MV/m. Unfortunately, the possible recontamination of the L-band cavities due to their relatively larger volume and prolonged pump downs with unclean vacuum pumping systems was not recognized. As a result the L-band pill box cavity with the best optimized shape, $H_{pk/}$ E_{acc} (~3 mT/MV/m) and $E_{pk/}$ E_{acc} (~2), became unpopular and elliptical cavities with unfavorable $H_{pk/}E_{acc}$ (~4.7 mT/MV/m) and $E_{pk/}$ E_{acc} (~2.6) parameters replaced them. The severity of the recontamination issue continued even with the elliptical cavities due to dirty vacuum pumping systems. Successful resolution will be described in the next section in greater detail.

Polycrystalline Niobium

The unloaded quality factor of the TM010 X-band cavities machined from low-purity niobium ingots, at low gradients, was extremely high (~10^{11}@1.25 K with 100 °C bake) and peak magnetic fields over 160 mT were reached in TE011 cavities [3,4]. An impressive lowest residual resistance of ~ 1 nΩ was recorded in the cavities made with low–purity niobium. SRF cavity fabrication then switched to reactor grade-lower-quality rolled niobium sheets instead of ingot niobium. One reason appears to be that ingot niobium was not readily available and another seems to be the prohibitive cost of the L-band cavities machined directly from the ingot niobium [7]. It is likely that the rolled niobium sheets were embedded with inclusions during the production process due to the apparently poor quality–control procedures available during that period. The heat dissipated by the unintentionally embedded impurities was assumed to be responsible for premature quenches due to the poor thermal conductivity of the lower-purity niobium. To improve the chance of reaching higher accelerating

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*Supported by JSA, LLC under U. S DOE DE-AC05-06OR23177

#rao@jlab.org

gradients, high-RRR polycrystalline niobium sheets were specified for cavity fabrication for achieving thermal stability and to sustain high gradients. However, the inevitable increase in BCS surface resistance (R_{BCS}) losses due to the larger electron mean path in high–RRR material was apparently not given due consideration. The lower quality factor, at a given operating temperature, resulting from the relatively high R_{BCS} –losses provides a larger positive feedback mechanism and increases the possibility of further reduction in the quality factor with high-RRR material compared to the low-purity ingot material which had proven its high performance–capability beyond any doubt in X-band cavities.

SRF TECHNOLOGY—PRESENT

CEBAF was the first large scale CW electron accelerator (220 m active accelerator structure) built with >250 RRR polycrystalline niobium sheets. Most of the niobium sheets for CEBAF's Cornell LE5 cavities were made from CBMM's Brazilian pyrochlore ore. Again due to space limitations we refer readers to biennial SRF workshop proceedings to learn more on the progress of SRF technology. Of particular interest is a recent review of the status of the present technology by P. Kneisel [8]. In the following paragraphs we will review the specifications of the polycrystalline niobium sheets, the progress made towards the understanding and possible elimination of multipactoring and/or field emission in the SRF accelerator structures and the invention of CBMM-Jefferson Lab large-grain single-crystal niobium technology.

Niobium sheet Specifications

The original polycrystalline niobium sheet specifications originated at Stanford University and led to the successful deep drawing of the resonator cavity half cells [9]. Later the high RRR requirement was added by Cornell University to thermally stabilize the cavities. The present day polycrystalline niobium sheet specifications (particularly >90% re-crystallization and yield strengths) are mutually exclusive [10]. The niobium vendors had to take additional steps such as a "kiss pass" to raise the yield strength or very careful annealing. In the case of a "kiss pass" a surface damage layer on the niobium sheets is introduced. Therefore additional chemical etching needs to be carried out for removing the damage layer. This undoubtedly introduces more hydrogen and raises the cost of production processes.

Multipactoring and Field Emission

During the early CEBAF cavity production process and procedure development period it was realized that the oil–lubricated turbo-mechanical pumps and particulate–laden ion pump system combinations were re-contaminating the processed clean cavity surfaces with hydrocarbons and particulates, leading to multipactoring and/or field emission respectively. By careful evacuation of the cavity pairs it has been shown that both multipactoring and field emission can be eliminated. The final limitation of the cavity performance was quenching, as shown in Fig. 1.

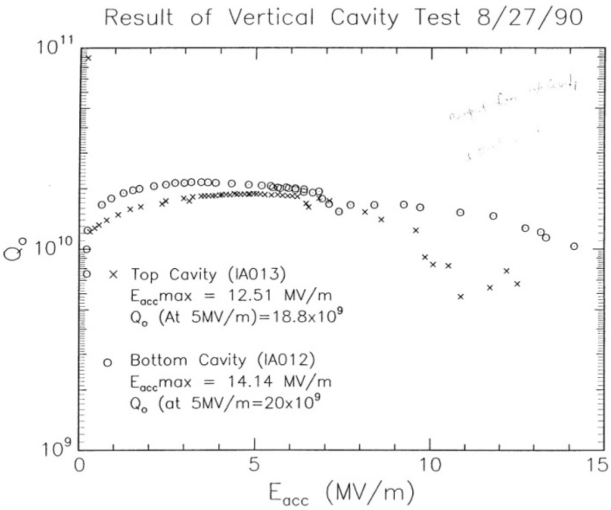

Figure 1: Good performance of CEBAF cavities.

CEBAF developed the use of hydrocarbon–free turbo pumping systems for contamination–free evacuation of cavities during the early 1990's. However, due to heavy pressure to deliver the cryomodules into the tunnel and because the unmodified cavity test stands, with the contaminating pumping systems, were providing the cavities with the specified performance (E_{acc} >5 MeV/m and $Q_0 > 2\times10^9$), the new pumping systems were not put into use during CEBAF construction. However, the performance of the cavity pairs degraded by more than 20% from vertical tests to operational performance in the installed cryomodules. Later, cleaner vacuum systems were used carefully during the entire JLab FEL cryomodule production process, from test stand to final assembly into cryomodule and beam lines, in addition to high-pressure water rinsing [11]. As a result the cavity performance was maintained without any degradation from vertical test stand to installed cryomodules. JLab organized a vacuum contamination control workshop in 1997 and shared with the worldwide SRF community its experience, in the prevention of recontamination of cavity surfaces from vacuum systems.

Large Grain Single Crystal Niobium Technology

The major technical drawback of the polycrystalline niobium sheet cavity technology, besides the expensive and complex process and procedures, can be analyzed and summarized with the help of Figure 2. One can see from the micrograph that the buffered chemical polished (BCP) polycrystalline niobium has honeycomb structure due to differential etching of randomly oriented grains. Such a honeycomb structure will hold particulates and it will be difficult to remove them with simple water rinsing after the chemical etch process, thereby leading to field emission. However, electro-polishing is known to etch the surface much more smoothly and independently of the individual grain orientations and to provide better cavity performance [4]. In either case hydrogen will be introduced and absorbed into niobium and requires high temperature annealing for removal of hydrogen. During SNS cavity (803 MHz) development, the initial 800 °C annealing used for hydrogen degassing drastically changed the cavity field flatness and made it unsuitable for accelerator use. Subsequent studies have confirmed that the deformation of the cavity was due to micro-yielding of the enlarged re-crystallized grains and their grain boundaries [12]. Further studies as part of a Cooperative Research and Development Agreement (CRADA) between CBMM's Reference Metals Company Inc. and Jefferson Lab lead to the birth of the large-grain single–crystal niobium technology that is presently receiving interest worldwide [1].

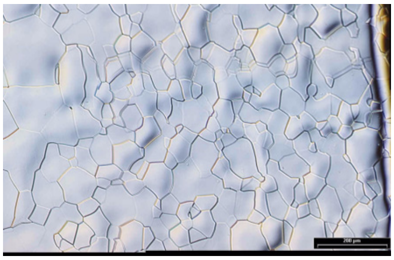

Figure 2: Micrograph of Etched Niobium

RF SUPERCONDUCTIVITY—FUTURE OPTIONS

Prospects for pushing the limits of RF superconductivity are getting greater attention in order to contain the costs of future SRF technology (both low- and high–beta accelerator structures) in particle accelerator systems for a wide variety of applications [13]. The International Linear Collider (ILC) will be based on SRF technology with an anticipated cavity performance requirement of 35 MeV/m at a quality factor of 1×10^{10} during qualification tests. At present this high–performance necessity and the needed cost containment, seems highly optimistic if it is based on polycrystalline niobium technology. A scientific understanding of the SRF cavity high-field Q-slope and quench limits must be pursued for making educated quick progress to meet the requirement in a timely manner.

Polycrystalline RRR >300 Niobium

In this final section we will discuss the choice between high–RRR polycrystalline sheets and moderate–purity ingot niobium slices in order to make an educated selection of the type of niobium material. The process steps involved in producing polycrystalline niobium sheets are numerous, expensive and need rigorous QA. The cavities produced from polycrystalline niobium require electro-polishing, hydrogen degassing and must be rinsed with high pressure water systems. The yield of the cavities meeting the specifications is currently very low due to the irreproducibility and the potential failure of any one of these numerous process steps. Only this technology is being actively considered for ILC and it is planned to be further developed. This could be a very troublesome decision knowing the pitfalls and enormous time it took for developing the technology so far, and the possible limitations with respect to R_{BCS} losses.

Ingot Niobium—Moderate Purity Slices

The X-band cavities have amply demonstrated the high performance potential of the low-purity ingot niobium at the onset of the RF superconductivity developments in the early 1970s. The process steps involved in the production are proven and are very few in comparison with polycrystalline niobium. No costly or complex QA is required. Simple BCP will provide the smooth surfaces and appropriate use of surfactants and simple mega-sonic rinsing is likely to be adequate to obtain high performance accelerator structures. The cost of these ingot niobium slices are expected to be a half of the polycrystalline RRR >300 Niobium sheets [14].

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