SUPERCONDUCTING RADIO FREQUENCY TECHNOLOGY: AN OVERVIEW

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TECHNOLOGIE DE RADIO-FRÉQUENCE SUPRACONDUCTRICE : VUE D'ENSEMBLE

RÉSUMÉ. Les cavités RF supraconductrices deviennent de plus en plus la solution adoptée pour les projets d'accélérateur de particules de grande échelle, tels que les collisionneurs linéaires, les accélérateurs linéaires de récupération d'énergie (ERL), les lasers à électrons libres ou les anneaux de stockage. Les structures supraconductrices offrent de nombreux avantages par rapport aux structures normales en cuivre. En particulier, elles dissipent moins de puissance RF, permettent d'atteindre des champs accélérateurs plus élevés en mode d'opération CW et délivrent des faisceaux de particules de meilleure qualité. Dans la plupart des cas, les cavités accélératrices sont fabriquées à partir de niobium massif de haute pureté. Les propriétés supraconductrices de ce matériau telles que la température critique, le champ magnétique critique sont supérieures à celles d'autres matériaux supraconducteurs. Les travaux de recherche de cette dernière décennie ont montré que les propriétés métallurgiques – pureté, structure de grains, propriétés mécaniques, et oxydation – ont une influence significative sur les performances de ces structures accélératrices. Cette présentation donne une brève vue d'ensemble de la technologie RF supraconductrice tout en accentuant l'importance des propriétés matérielles du niobium de haute pureté.

ABSTRACT. Superconducting RF cavities are becoming more often the choice for larger scale particle accelerator projects such as linear colliders, energy recovery linacs, free electron lasers or storage rings. Among the many advantages compared to normal conducting copper structures, the superconducting devices dissipate less RF power, permit higher accelerating gradients in CW operation and provide better quality particle beams.

In most cases these accelerating cavities are fabricated from high purity bulk niobium, which has superior superconducting properties such as critical temperature and critical magnetic field when compared to other superconducting materials. Research during the last decade has shown, that the metallurgical properties – purity, grain structure, mechanical properties and oxidation behaviour – have significant influence on the performance of these accelerating devices. This contribution attempts to give a short overview of the superconducting RF technology with emphasis on the importance of the material properties of the high purity niobium.

Approximately four decades ago the use of superconducting cavities in particle accelerators was proposed [1]. Pioneering work in the development of this technology started at Stanford University in 1963 and was soon joined by research at the Kernforschungszentrum Karlsruhe in Germany. These early investigations focused on the use of lead as the superconducting material, which was plated on copper substrates. However a few years later niobium became the choice material for these devices and as the developments showed promising results, more research institutions such as Cornell University, Brookhaven National Lab, Stanford Linear Accelerator Center (SLAC), European Research Center CERN, Deutsches Elektronen Synchrotron (DESY), Japanese Accelerator Center KEK, CEA in France and the University of Wuppertal in Germany started their own developments. The technology turned out to be rather difficult since it combines a variety of disciplines: material science, surface science, solid state science, chemical processing technology, cleaning techniques, rf technology, vacuum technology, cryogenics and strict control of conta-

mination. This complexity naturally caused delays and setbacks in the developments. A better understanding of the underlying physical phenomena responsible for encountered limitations had to be gained.

In recent years superconducting cavity technology has become quite attractive for accelerator builders around the world due to the successes of operating machines such as CEBAF, LEP and the B-factories at KEK and Cornell University. A variety of proposed applications is under consideration/construction in major accelerator centers. This includes, besides the TESLA Linear Collider and the associated 50 GeV FEL, also a whole set of FEL's and energy recovering linacs (ERL's) based on the pioneering work carried out at Jlab's 1 kWatt FEL. In addition to the application of SRF technology to $\beta = 1$ accelerators (β is the ratio of particle velocity to velocity of light), many applications for $\beta < 1$ particle acceleration have evolved, namely spallation neutron sources in the United States (SNS), in Europe (ESS) and in Asia (Korean Spallation Neutron Source, Joint JAERI/KEK Project), transmutation of Nuclear Waste (TRASCO, ASH) and accelerators for rare isotopes (RIA). This increased interest is a result of big recent progresses in the performance of superconducting cavities due to a better understanding of the phenomena, which have in the past been the limitations, such as, e.g. multipacting, field emission and quenches. Improved materials, better surface treatment and assembly procedures contributed significantly to improved cavity performances, and the spectacular success of the TESLA cavities has given the technology a strong boost [2]. Gradients of $E_{acc} > 20$ MV/m and Q -values of $Q \sim 10^{10}$ at 2 K at these high gradients are no longer out of reach. In several cases the theoretical values for the critical field of niobium have been achieved in small devices [3–5].

In the following sections it is attempted to explain the advantages of superconducting cavities over normal conducting cavities in many accelerator designs, to discuss the reasons for the choice of niobium as the material for superconducting cavities and some of the important features of this material, to give a short overview over the basics of superconducting rf technology and its limitations and to give some examples of fabrication technologies presently applied for the construction of accelerating devices.

Why are Superconducting Cavities attractive for Accelerator Projects ?

The strongest case for the use of superconducting cavities can be made for devices, which operate in a continuous wave (cw) mode or at a high duty factor ($> 1\%$). For such modes of operation the power dissipation in the walls of a normalconducting copper structure are significant. As an example one can consider the power dissipation for an accelerator such as CEBAF, if the cavities were made out of copper instead of niobium: CEBAF operates in cw mode at a gradient of $E_{acc} = 5$ MV/m. The dissipated power per unit length is given by

$$P/L = (E_{acc})^2 / (R/Q) * Q_0 \quad (1)$$

(R/Q) is the geometric shunt impedance and in the case of the CEBAF cavities has a value of $R/Q = 960$ W/m. Q_0 is the "quality factor" of the cavity and is inversely proportional to the surface resistance. In the CEBAF cavities –if made of copper–

Q_0 is $\sim 30\,000$ and each cavity would dissipate ~ 450 kW. There are already practical limits to exceed a dissipation of more than 100 kW because the temperature of the cavity would rise above 100°C and cause vacuum degradation, stresses in the material and possibly metal fatigue due to the thermal expansion.

In contrast –as discussed in section III– in a superconducting material such as niobium the temperature dependent surface resistance can be by a factor of 10^5 to 10^6 lower in the superconducting state and accordingly the wall losses in the cavities are reduced to a few Watts. Even though this dissipated power has to be transferred at the temperature of liquid helium –typically around 2 K– and the efficiency of refrigerators, which generate these temperatures, are rather low, a net gain of a factor of 10^2 to 10^3 can be realized. This of course has an enormous impact on the operating costs of such a machine.

Besides the cost advantages there are additional features, which favour superconducting cavities over normalconducting cavities: because the optimization of the shunt impedance, which is determining the wall losses, is not as important in superconducting cavities as in normalconducting cavities, the beam aperture in the cavity can be made much larger. This significantly reduces the sensitivity of the device to mechanical tolerances and the excitation of parasitic modes, which can lead to beam instabilities especially in storage rings or recirculating linacs, is largely reduced. Also the large opening reduces linac component activation due to beam losses. Superconducting cavities are intrinsically more stable than normalconducting cavities and therefore the energy stability and the energy spread of the beam are better. There is always the upgrade potential for the achievable gradients in the cavities as the technology improves. As an example: the design goal for the niobium cavities in CEBAF was 5 MV/m and the end energy of the machine was 4 GeV. Meanwhile, through improvements in procedures for "in situ" cavity processing, the average gradients have been improved by 50% and the machine is capable to deliver electrons of an energy of 6 GeV. For a proton accelerator such as the Spallation Neutron Source (SNS) presently under construction at Oak Ridge National Laboratory reduced beam –gas scattering due to a much better vacuum in the "cold" cavities (they act as a huge cryopump) was another advantage for the use of superconducting cavity technology.

Some Basics of RF Superconductivity for Accelerator Application

A typical accelerating cavity is shown in Figure 1 as a chain of coupled RF cells, which are excited in the transverse magnetic (TM_{010}) mode. In this field configuration longitudinal electric fields parallel to the axis of the resonator are established between the irises of each cell and the rf phase between adjacent cells is 180° . In this case a particle with a velocity close to the velocity of light will experience the maximum acceleration in each cell of the cavity. There are two important quantities, which –in addition to the rf frequency– describe an accelerating cavity:

A). The Q_0 of a cavity is defined as the ratio of stored energy (W) in the cavity to the power (P) lost in the cavity walls per radian per second ($\omega = 2\pi f$)

$$Q_0 = W/(P/\omega) \quad (2)$$

Fig. 1 - A typical accelerating cavity.

Fig.1 - Cavité accélératrice typique.

The Q_0 value is inversely proportional to the surface resistance (R) of the wall material; the proportionality constant is called the geometry factor ($G \sim 280 \Omega$) and depends only on the geometry and the field configuration in the cavity

$$Q_0 = G/R \quad (3)$$

In the superconducting state a high frequency electromagnetic field penetrates only a distance λ (penetration depth ~ 60 nm for niobium at 1500 MHz) into the material. This means that all losses in a cavity – described by a surface resistance – take place in a very thin surface layer. R is described by the microscopic theory of Bardeen-Cooper-Schrieffer [6] (BCS); the electrical resistance of a superconductor decreases at high frequencies accordingly with temperature below the critical temperature (T_c) as long as the frequency of the electromagnetic field is small to the gap energy frequency (~ 700 GHz for niobium)

$$R_{BCS} \sim (\omega^2/T) \exp[-(\Delta/kT_c)(T_c/T)] \quad (4)$$

BCS theory predicts a proportionality between the gap (Δ) and T_c , $\Delta/kT_c \sim 1.75$ (k = Boltzman constant); therefore it is advantageous to work with superconductors of a high critical temperature such as niobium.

B). The accelerating gradient E_{acc} is defined as the maximum energy a charged particle gains in the time varying rf fields by traversing an cavity, divided by the length of the resonator and the charge of the particle. The gradient is proportional to the square root of the stored energy in the cavity

$$E_{acc} = k \sqrt{P Q_0} \quad (5)$$

Figure 2 schematically describes the behaviour of a superconducting niobium cavity operated at a temperature of 1.8K. Theoretically this cavity should exhibit a Q_0 value of $\sim 4 \times 10^{10}$ at a frequency of 1500 MHz and sustain an electromagnetic field up to the superheated critical field of niobium of ~ 240 mT. This translates to an accelerating gradient of $E_{acc} \sim 50$ MV/m and at this field level the Q_0 value should have dropped only by a

Fig. 2 - Schematic and experimental results: behaviour of a 1500 MHz niobium cavity at 1.8 K.

Fig. 2 - Schéma de principe et résultats expérimentaux : comportement à 1,8 K d'une cavité en niobium de 1500 MHz.

factor of 3 due to an intrinsic dependence of the surface resistance on electromagnetic field level [7]. However, as indicated in Figure 2, there are four distinct deviation from this behaviour experimentally observed:

- The Q_0 value is lower due to a **residual resistance** caused by defects and anomalous losses.

Fig. 3 - Experimental temperature dependence of the surface resistance of a 1500 MHz single cell cavity.

Fig. 3 - Variation expérimentale de la résistance superficielle d'une cavité unique de 1500MHz.

An example of an experimentally observed temperature dependence of the surface resistance of a 1500 MHz niobium cavity is shown in Figure 3 [8]. As predicted by Eq. (4) an exponential decrease in $R(T)$ is observed, but at lower temperatures $R(T)$ is limited by a temperature independent residual resistance of a few n Ω . The following contributions to this residual resistance have been found over the years by numerous studies in different laboratories: frozen-in magnetic flux due to insufficient shielding of ambient magnetic fields; normalconducting surface defects or material inclusions; dielectric losses due to particulate contamination, adsorbates or residual gas condensation; macroscopic surface imperfections such as cracks, delaminations or crevices; chemical residue; and hydrogen precipitation ("Q-disease") [9] which can occur in high purity niobium at a temperature around 100 K, if the cavity is kept for several hours in this dangerous temperature region [10]. This degrading phenomenon can be avoided, if the cool-down through the temperature range from 130 K to 70 K occurs rather rapidly (~ 5 K/min) or if the material is hydrogen degassed in an ultrahigh vacuum at $T > 800^\circ\text{C}$.

- At certain field levels Q_0 degradations might occur due to "multipacting".

Multipacting [11] is a high vacuum resonant avalanche effect initiated by emission of secondary electrons in response to impinging primary electrons. Secondaries are accelerated in the cavity fields and generate more secondary electrons when returning to the wall, if the secondary electron emission (SEE) coefficient for this impact energy is larger than 1. Calculations of the trajectories and the impact energies have led to a complete understanding of this phenomenon and to the implementation of cures. By shaping the cavity geometry appropriately to spherical [12, 13] or elliptical [14] cross sections and by administering thorough surface cleaning procedures, which reduce the SEE coefficient, multipacting can be fully eliminated in accelerating cavities. Nevertheless, carelessness in the degree of surface contamination can make multipacting barriers reappear with all their deleterious effects.

- At higher field levels the Q_0 value decreases exponentially due to **field emission loading (FE)** [15].

Beyond a certain field electrons are drawn out of the surface, are accelerated in the cavity rf fields and gain sufficient energy ($\sim$ MeV) to produce heat and bremsstrahlung, when impinging on an opposite surface. This in turn causes an exponential degradation of the Q_0 value. The field emission originates from point like sources – in many cases artificial contamination of micron –sized particles – and the emission current can be described by a modified Fowler-Nordheim correlation. Because of the exponential increase in the losses, FE constitutes a severe limitation to the achievement of higher gradients in cavities. Thorough surface treatment and cleaning procedures adopted from the semiconductor industry such as use of semiconductor grade chemicals, ultrasonic or megasonic agitation, high pressure rinsing with ultrapure water, or "dry ice" cleaning in combination with clean room assembly have been successfully applied to shift the on-set field for field emission to higher gradients. Chemical surface treatment by electropolishing [4] has been demonstrated as a method superior to the buffered chemical

Fig. 4 - Excellent cavity performances achieved with electropolishing

Fig. 4 - Excellentes performances d'une cavité obtenues après électropolissage.

polishing of surfaces and more often cavity performance levels close to the theoretical expectations are being reported. Figure 4 shows some excellent results obtained on niobium cavities after an electropolishing surface treatment. However, one cannot emphasize enough that stringent contamination control measures both for initial cleaning but also for re-contamination control are essential to achieve the promised performance levels of superconducting cavities.

- The experimentally observed "quench" field (at the "quench" field the superconducting material is becoming normalconducting) is typically lower than the theoretically predicted critical field. Causes are defects and anomalous losses in the material, which lead to thermal instabilities. With the help of thermal model calculations a basic understanding of the quench phenomenon has been gained: the simulations predicts a dependence of the threshold fields for the occurrence of thermal instabilities in the form

$$H_q = \sqrt{\kappa(T)/r_d R_d} \quad (6)$$

where r_d is the defect radius, R_d its resistance and $\kappa(T)$ the thermal conductivity of the niobium [16]. The thermal conductivity of commercially available niobium was subsequently improved by multiple electron beam melting under improved vacuum conditions, which reduces the amount of interstitial impurities such as hydrogen, carbon, nitrogen and oxygen; these impurities control the thermal conductivity. Commercially available high purity niobium has a thermal conductivity of typically $\kappa \sim 75$ W/mK at 4.2K.

Cavities made from such high purity niobium are thermally more stable against microscopic defects, which have been identified through diagnostic techniques such as temperature mapping [17] as the culprits for lower field quenches. As a result, the performance levels of the accelerating devices have shifted towards higher gradients.

Cavity Fabrication and Surface Treatment

Niobium has become the material of choice for superconducting cavities, because it is the elemental superconductor with the highest critical temperature and critical magnetic field and

Fig. 5 - 7-cell niobium cavity developed at Jefferson Lab for the upgrade of CEBAF.

Fig. 5 - Cavit en niobium 7 cellules dveloppe au Jefferson Lab pour le CEBAF.

therefore has the potential for achieving high performance levels in accelerator cavities. The material is readily available in various degrees of purity determined by the residual resistivity ratio (RRR) – for cavity application the standard now is $RRR > 250$. As a rule of thumb, the thermal conductivity at 4 K in W/m-K is given approximately by $RRR/4$ [16]. The formability of niobium is comparable with that of OFHC copper and fabrication methods such as rolling, cold forging, deep drawing, hydro forming, spinning, bending, milling, drilling, machining on a lathe are applicable. However, niobium has a very high affinity to gases such as nitrogen, oxygen and hydrogen, which are interstitially dissolved and affect the purity. It is therefore advisable not to exceed temperatures $> 150^\circ\text{C}$ when exposing the material to air. This requires that joining of niobium parts has to happen in a vacuum or an inert gas atmosphere. Typically, niobium cavity parts are joined by electron beam welding in a vacuum of $> 5 \cdot 10^{-5}$ mbar [18].

The purity of niobium can be improved by multiple electron beam melting steps during the manufacturing process and later on by degassing in an ultra high vacuum at a temperature $T > 800^\circ\text{C}$. Solid state gettering at $T > 1200^\circ\text{C}$ in the presence of Ti as the getter material can further improve the purity. Such high temperature heat treatment affects however the mechanical properties of the material: larger grains grow and the material softens – this in some cases requires additional stiffening of the cavities.

The typical fabrication sequence for niobium cavities is as following:

Sheets of high purity material as supplied by the manufacturer are thoroughly inspected for surface imperfections and inclusions of foreign materials; for this purpose eddy current scanning and more recently scanning with more sensitive squid systems was developed at DESY [18, 19]. The accepted sheets are deep drawn into half cells of a cavity and subsequently machined for electron beam welding. Prior to the welding step the parts are degreased and a surface damage layer of app. $30 \mu\text{m}$ is removed by chemical polishing (*buffered chemical polishing BCP*) in a solution of equal parts of hydrofluoric (48 %), nitric (69 %) and phosphoric acids (89 %). This step is very important for achieving full penetration welds with smooth weld beads free of voids and inclusions. Auxiliary cavity parts such as flanges, beam pipes, rf coupler parts and sub-assemblies for integrated helium vessels are manufactured by the above mentioned methods and joined by electron beam welding to the cell section of a cavity. An example of a 7-cell cavity under development at Jefferson Lab is shown in Figure 5. At this stage the newly produced cavity is performance tested in a “cold” test at 2 K, where the Q_0 value is measured as a function of accelerating gradient E_{acc} (see Figure 2). Prior to the test the interior cavity surface, which is exposed to the RF fields in the test, needs to be

cleaned and an additional amount of at least $100 \mu\text{m}$ of material is being removed. This can be done either by *BCP* or by *electropolishing* in a solution of hydrofluoric and sulfuric acids. Electropolishing treatment results in a much smoother surface with very little grain boundary etching when compared to *BCP* and has resulted in superior cavity performances. It is presently the preferred choice for surface treatment of high performance niobium cavities. A very important cleaning step follows after the chemical removal of material from the surface: the cavity surface is for several hours rinsed with jets of high pressure (~ 100 bar) ultrapure water, which removes chemical residue and remaining particulate contamination. Assembly of auxiliary component such as rf couplers, valves and bellows takes place after drying of the cavity in a class 10 clean room. The cavity is then attached to a cryogenic test system and evacuated to a pressure of $< 10^{-7}$ mbar before being cooled down to liquid helium temperatures.

The fabrication and treatment sequence as described aprievately above is rather complex, requires many quality assurance steps and is therefore quite costly. For large accelerator systems such as the proposed TeV collider TESLA the costs must and can be reduced as a recent study by an industrial team has indicated [20]. Cost analysis for the presently produced small quantities of cavities showed that the major cost drivers are machining and electron beam welding and that the costs can be significantly reduced by streamlining these processes. One of the possibilities is the forming of cavities from seamless tubing either by spinning [21] or by hydro forming [3]. Both processes have been developed at various laboratories to a state, where

Fig. 6 - Hydroformed, seamless niobium cavities [19]

Fig. 6 - Cavits en niobium hydroformes, sans soudure.

multi-cell assemblies have been manufactured with performances comparable to the forming-and-welding approach described above. At least for the hydro forming technique well characterized and uniform material properties are essential for successful manufacturing; the hydro forming process itself must be well controlled by computers. An example of cavities hydroformed at DESY is shown in Figure 6.

As mentioned in section II the rf losses in a superconducting cavity occur only in the penetration depth λ of approximately 60 nm. Therefore thin film technology can be used to deposit niobium films of several λ thickness on a copper substrate. This approach has been developed over more than a decade at CERN and has successfully been implemented for the large cavities for the Large Electron-Positron Storage ring (LEP). The technology is especially suited for large devices, where material costs of solid niobium become a large portion of the overall costs, and for more moderate accelerating gradients. At higher gradients as desired for linear collider application niobium thin film cavities suffer from drastic Q-degradations. Investigations are ongoing to understand this phenomenon and first indications are that the quality of the substrate as well as the deposition conditions are important contributors to these performance limitations [22].

Summary

In the last several years significant progress has been made in understanding and eliminating limitations to cavity performances by establishing improved cavity design criteria and cavity treatment and handling procedures. This has attracted a new clientele for application of the technology to a variety of new projects. Many excellent results have been reported by the SRF community for well controlled laboratory tests and in several cases the theoretical limitation for niobium as the material of choice for superconducting cavities has been reached.

The technology is quite complex and the cavity performance is very sensitive to the conditions of the surfaces. All relevant quantities – Q-value, electron loading and quench fields – are influenced by the degree of cleanliness and “flawlessness” of the surface. The implementation of extensive QA procedures during cavity fabrication, as well as contamination control during processing and assembly is essential for successful operation of these devices. The constant search for sources of contamination on equipment, tooling and hardware and the implementation of procedures to eliminate them is a “fact of life” for this technology. $\square$

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