

# REVIEW OF SRF MATERIALS WORKSHOP

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## Abstract

The performance of niobium cavities has approached the theoretical hard limit. Yet the consistent achievement of higher performing cavities remains the greatest challenge. To further understand the basic materials science, a workshop was held at Fermilab in May 2007 to present and discuss the fundamental and experimental limitations, and propose new ideas [1].

## INTRODUCTION

As a niobium cavity undergoes material preparation, manufacturing, processing and final RF testing to its limit, many changes to the material could affect the final cavity performance. The workshop program focused on the niobium material production, innovative processing, surface analysis, RF superconducting properties and the fundamental RF superconductivity. The workshop also invited the presentations on researches focused on the new materials beyond the current dominating material: niobium.

Overall issues encountered in SRF include materials and surfaces such as surface roughness, impurities, oxide, grain boundaries and thermal properties [2,3]. These affect the cavity performance in terms breakdown field and surface resistance before field emission. While high field dissipation could be better explained by vortex dynamics [4], a careful calculation of superheating field may suggest the current understanding of ultimate breakdown field could be greatly improved [5].

Experimental result from high field region has not been well connected to many models including vortex model [3]. Many well developed surface analysis equipments and characterization techniques have been used to understand the material surface and its intrinsic physical properties [6]. New techniques such as laser surface interaction [7], Tunneling spectroscopy [8] and near-field RF scanning [9] could help to further understand the subtle nature of RF surfaces. Temperature mapping studies concluded the cavity performance limitation comes from a few isolated hot spots. Unfortunately, the surface studies focusing on hot-spots have been limited [10].

Looking beyond the hard limitation set by intrinsic niobium critical magnetic field, experimental technique and alternative material has been proposed to extend the current SRF material studies well into the future [11]. Atomic layer deposition showed good promise to realize the multi-layer surface engineering [4]. Among the new materials, MgB<sub>2</sub> and its fabricating technique seemed feasible [12].

Based on the nature of application driven SRF technology, the surface studies mostly provided more process verification than the process guidance historically [13]. Decades of processing development successfully pushed the cavity performance close to current perceived theoretical limit [5]. The limitation to the state of art processing has been the poor reproducibility. Some effort has been devoted to less damaging chemical mechanical polishing [14], alternative electropolishing [15], plasma dry etching and cleaning [16,17] and gas clustered ion beam processing [18].

In addition to the high field and processing limitations, the practical cavity performance can also benefit from the optimized niobium material manufacturing and well engineered cavity forming [19,20].

## THEORETICAL ADVANCEMENT

Vortex could penetrate into the surface through residual earth field, thermal electric currents and strong enough local RF magnetic field typically at high accelerating gradient. The vortices penetrate through the weakest spot or RF surface imperfections such as defects or grain boundaries. Once a vortex moves in, subsequent oscillating field causes it to diffuse and annihilate with anti-vortex. The vortex movement has a time scale same as RF period; it could be best described as "jump" in supersonic speed [4]. As Gurevich calculated, the "jump" is the dominating local heat source which comprises as a hot spot. Since the vortex penetration is still considered to be happening around critical field, one of the solutions to delay the vortex penetration is to utilize the surface barrier feature of a very thin superconducting slab [4].

The remaining unknown is what is the exact magnetic field level that vortex starts to enter the superconductor and causes the loss. The past models reviewed by Padamsee [3] showed overly simplified formulae and temperature extension which resulted pessimistic limitations for niobium and worst in the case of high  $\kappa$  superconducting materials. As stated by Padamsee, the simple energy balance approach used in line nucleation model overly simplified the meta-stable state under which the critical field is not the same as equilibrium critical field. It does not bode well for uniform, flat and pure superconductor which is typical for modern day niobium cavities. Another inconsistency of earlier line nucleation model was the simple linear extrapolation from DC superheating field to RF superheating field. Sethna proposed a more generic theoretical framework based on Eilenberger equation to safely cover the lower temperature region where energy barrier calculation and linear stability analysis can be worked out [5].

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## NEW RESULTS AND SURFACE CHARACTERIZATION TECHNIQUE

Oxygen diffusion model suggested the region right below surface oxide layer would be improved during low temperature baking [2,21], which was responsible for removing high field Q-slope. A 400°C in-situ baking showed that nearly all the oxide was gone and the oxygen content at surface region would be greatly improved [22]. Yet the cavity test results showed the Q-slope remained. Ereemev concluded surface oxide may follow different diffusion process than those previously modeled or there may be other impurities involved which needs further cut out sample studies for the 400°C baked cavities.

For those cavities showing high field Q-slope (without baking), the sample was cut out following T-map indication for further analysis. The XPS result revealed no oxide difference between the hot spot and regular surface samples [10]. Surface roughness and grain distribution also remained indifferent. The only difference picked up by AES was the slight nitrogen signal in four hot spot samples while no such signal in regular samples.

Surface oxide studies by Variable Photon Energy XPS on non cavity samples also concluded the oxide layer modified by low temperature baking did not seem to contribute the high field Q-slope improvement [23].

Other than oxide studies, several other new technique may be helpful such as laser scanning microscopy, near field scanning microwave microscope, tunneling spectroscopy and grain boundary studies using combined tools such as focused ion beam cutting and high resolution TEM and EELS [24].

Laser scanning microscope uses laser to heat the superconductor resonator surface to induce the resonant signal change which would be proportional to local RF currents. Such technique could be used to identify the defects and study the surface current enhancement at grain boundary [7].

Near field microwave may be able to use the same RF frequency as in a cavity to study the sample, especially at grain boundary [9]. The important issue would be to keep necessary resolution at higher frequency and increase the field strength to that comparable to cavity surface.

Tunneling spectroscopy measures the tunneling current between sample and the point contacting probe tip in order to calculate the electron state density and band gap. The measurements between baked and unbaked niobium sample showed no apparent change in band gap, except the inelastic behavior of interface [8]. Careful theoretical work and further experiment are under development.

Many devices were built to directly measure surface resistance on a small sample with limited success [25]. The newly designed mushroom cavity was the latest effort to measure surface resistance, and also the super heating critical field [26]. The base cavity was constructed from copper to reduce the cost and also allow quick heat dissipation in the event of high power pulsing test.

The phonon peak study of different treated niobium could provide ways to bring back phonon peak so the

enhanced thermal conductivity of niobium can provide extra capacity to ward off potential hot spot induced quench [27].

## NEW MATERIALS

For a material to be better suited for SRF cavities than pure solid niobium it has to have higher critical field than niobium to sustain higher local magnetic field; it also has to have relatively higher transition temperature and lower normal state resistivity to be able to have lower surface resistance [11]. Several compound superconductors in A-15 and B-1 series all satisfy the above requirement with Nb<sub>3</sub>Sn and MgB<sub>2</sub> exceptionally well positioned in Vaglio's chart [28].

Ultra high quality MgB<sub>2</sub> film has been achieved through hybrid physical-chemical vapor deposition [12]. A two staged process has been proposed to coat a single cell cavity [12]. A boron film will be coated to the cavity inner surface by heating the cavity at 400-500°C during the gas flow of B<sub>2</sub>H<sub>6</sub> and H<sub>2</sub>. Second stage requires the cavity heated at ~850-900°C while Mg vapor reacts with the boron film.

Atomic layer deposition (ALD) is a staged chemical vapor deposition self limited by surface reaction [29]. A typical deposition uses two chemical precursors one at a time. Each step limits the surface growth by one atomic layer. ALD is conformal to the substrate, pin-hole free and can achieve coating with very uniform thickness. These advantages make it very attractive to achieve high quality multilayer film proposed by Gurevich [4]. It can also be used to cap the niobium surface with layers such as Al<sub>2</sub>O<sub>3</sub> to prevent oxygen diffusion during baking. This allows one to study the oxygen effect in niobium cavities.

## INNOVATIVE PROCESSING

Standard processing has been very helpful to bring the current record breaking cavity performance. Yet the processes have been expensive, time consuming and less reliable in achieving high performance, especially in multi-cell niobium cavities. As summarized by Antoine, alternative processing are available and being perfected [13]. Three processes were designed to combat field emission. Dry ice (CO<sub>2</sub>) removes the surface particles by mechanical force much like high pressure water rinsing, but does not leave residual. It has the potential to be applied to cavities already assembled in a cryomodule. Helium processing has been demonstrated in reducing field emission moderately [30]. High power processing improves the performance by burning out field emitters. It successfully raised a multicell cavity gradient from 12 MV/m to 25 MV/m [31]. Ultrasonic and megasonic rinsing has been successful to remove some strong bonded sulfur particles in electropolished cavities [32]. Alternative acid-free electropolishing solutions do exist as demonstrated by Palmieri [33] and Crooks [15]. Another idea to avoid surface defect is not through aggressive etching but applying the high purity film to bring the RF surface layer to highest quality.

Gas clustered ion beam (GCIB) is another tool to combat the field emission. Sample treated by GCIB of oxygen showed not only the field emitters were removed but also the surface was greatly smoothed [18]. The concerns about the surface oxide modification and crystal lattice damage need to be carefully tested. Both cavity testing and sample analysis are being conducted.

Plasma etching and cleaning are also pursued to avoid hazardous acid handling in standard processing. Preliminary result with reactive gas plasma such as chloride and boron trifluoride has been successful [16]. The limitation for the process is the undesired chemicals such as niobium borides left on etched surface. Careful control of the sample temperature may help.

Electron cyclotron resonance (ECR) plasma has the potential to convert the plasma processing to a truly on-situ post processing [17]. External magnetic field can be applied to cavity resonance field to limit the plasma only inside the cavity cell while the cavity is closed and equipped with regular RF input coupler. Upon finishing processing, the cavity can remain closed until connected to beam line. Preliminary result showed the process is feasible and effective in sulfur removal.

Chemical mechanical polishing (CMP) uses abrasive and reactive slurry to remove surface layer. Initial study showed a niobium sample at 1  $\mu\text{m}$  roughness (Ra) improved to 10 nm in total 70 minutes [14]. However, the polishing could be labor intensive in a cavity environment. At least, this technique could have the benefit of very smooth surface with thin damage layer. With the reduced electropolishing time, cavity performance could improve.

## NIObIUM PRODUCTION

As niobium material being prepared, several preferred condition could be beneficial for final cavity performance. As summarized by Singer [19], purity, grain distribution and mechanical properties are important factors for successful cavity production. Tantalum is the most concentrated impurities in niobium. Current experimental

data showed the high tantalum content could bring adverse influence for high performing cavities above 30 MV/m. Fine grain material puts burden on sheet manufacturer to obtain uniformly distributed grain size through out the bulk of material [34]. The current vendor processes is relatively costly and prone to introduce the contamination and defects. Equal Channel Angle Exchange (ECAE) is proposed to reliably achieve uniform fine grain niobium. Preliminary result showed the possibility to obtain deep drawn friendly niobium texture [35]. Large grain niobium sheet was claimed to use much less processes to produce. The limitations were unexpected forming behavior and rough grain boundaries. The single crystal proves to be best suited for cavity production [20], yet the extra cost based on current forming technology [36] did not justify the performance gained over the large grain niobium.

To understand niobium deformation and recrystallization, extensive simulation model has been established and the work is under development [37].

TIG welding has been proposed to reduce the welding cost compared to electron beam welding. Current result showed the cleanliness of welding environment needs to be optimized [38].

## CONCLUSIONS

The workshop has brought in many parties who became interested in SRF technology. Many collaboration and experiments have been initiated after the workshop. Many were reporting their new findings in this same workshop. We foresaw another productive SRF materials meeting in near future.

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