Summary Report

Superconducting RF Materials Workshop

Fermilab, 23-24 May 2007

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Executive Summary

A workshop on superconducting radio frequency (SRF) materials held recently at Fermi National Accelerator Laboratory brought together approximately 50 researchers from academia, laboratories, and industry. The workshop focused on basic science that underpins SRF technology. Context was provided by invited review presentations from recognized leaders in the SRF scientific community, who provided both ILC-specific and general goals of materials research. Thus, discussions generally centered on *directed* research toward solving problems and exploiting opportunities specific to SRF technology. The workshop program covered fundamental limits of SRF, materials properties, materials characterization, new materials, innovative processing techniques, and niobium production.

This document highlights the important findings broken down by the program units above. This document also discusses their implications for broader SRF science and technology in the U.S., including impact on the International Linear Collider (ILC) and Department of Energy Office of High Energy Physics (DOE-HEP) programs. Out of this discussion, three action items have emerged for the organizing committee:

1. ***Provide input to the FY2008 DOE-HEP Small Business Innovative Research (SBIR) topic descriptions pertinent to SRF technology.***
2. ***Determine a mechanism for continuation of the workshop that is consistent with its present charge and the recommendations from the Marx sub-panel concerning a Low-Temperature Superconductor Workshop (LTSW)-like format for the SRF community.***
3. ***Communicate to DOE-HEP and NSF-HEP funding needs and opportunities described by participants, inasmuch as the ability of the workshop to produce vigorous scientific discussions depends on having robust programs at the participating institutions. At present, many activities are bootstrapped to other programs.***

Workshop materials can be located online at:
http://tdserver1.fnal.gov/project/workshops/RF_Materials/

Contents

Background

The Workshop on SRF Materials, held in the Wilson Building at Fermilab, 23-24 May 2007, was a national workshop devoted to basic understanding of materials used to construct superconducting RF cavities and generate huge electric field gradients from them. This workshop was partly an expansion of a series of regional workshops (Midwest SRF Materials Collaboration), held semiannually in 2005 and 2006. It is more basic in scope than the larger International Workshop on RF Superconductivity, the 13th of which will be held in Beijing in October 2007.

The workshop was intended to bring together SRF practitioners, materials and surface scientists, and experts from universities, national labs, and industry to encourage teaming of ideas and expertise. The workshop focused on basic R&D in the context of technology development, including discussion of new ideas outside the basic plans for projects such as ILC. This spirit was motivated by the lack of understanding of fundamental issues, the need to validate, confirm, and optimize the largely empirical progress being made in SRF science and technology, and the desire to extend the range of SRF science vertically toward theory and basic science.

All present SRF cavities are made from niobium. In principle, this means that the physics of niobium superconductivity determine the limits to RF superconductivity, although the particular mechanism how this occurs is not known and was debated in this workshop. However, it is possible to arrive at estimates of limiting behavior based on the properties of very pure niobium. In particular, the critical field is slightly above the magnitude of equatorial fields in the best single-cell cavities made to date, suggesting that present best practice (> 40 MV m^{-1} for the Tesla cavity shape) is very close to the ultimate limit.

The fact that most cavities attain lower gradients, e.g. < 30 MV m^{-1} for the Tesla cavity shape, even after state-of-the-art processing, however, attests to the need for better understanding. It is well known that contaminants reduce the strength of superconductivity in niobium; for instance, dissolved oxygen will reduce all properties in proportion to the oxygen content. Therefore, a second theme of the workshop addressed superconductivity of niobium itself, and the various characterization, quality control (QC), and quality assurance (QA) steps to determine niobium purity and properties.

It is also well known that the RF behavior arises within a skin of ~50 nm depth. This implies that the region of interest is not the niobium bulk but its surface. A third theme of the workshop addressed broadly the effects of surface coatings on superconductivity, surface probes, characterization techniques of surfaces and interfaces, surface roughness, the effects of grain boundaries, and so on. Because the electromagnetic fields are generated by such a thin region, aberrations in the geometry on the order of the skin depth can produce local "hot spots" where superconductivity is quenched. Protruding grains, for instance, enhance magnetic fields near the equatorial welds. Electric fields can be enhanced near the iris regions by dirt, dust, and other particulates left behind after cleaning, leading to field emission problems. Discussions addressed scratches, surface roughness, attached particles, and other issues in terms of their fundamental effects on behavior, characterization techniques, and processing steps to remediate surface damage.

The present dominance of niobium in SRF cavity production provided three additional areas of discussion: innovative ways to prepare niobium surfaces, production of niobium sheet and its specifications, and opportunities for SRF beyond the limit of niobium. "Standard" cavity processing routes use deep drawing of niobium sheet to form the basic half-cell shape and electron beam welding to join half-cells into a cavity. These steps are followed by complex etching and annealing steps to remove surface structural damage and chemical contamination and heal disorder. Alternative processes that achieve smooth, chemically clean, passive surfaces without using dangerous acids and/or are fast and cheap are highly desirable. Also, the need for tight mechanical tolerances, especially for welds, places stringent demands on formability and shape control. These requirements, in turn, necessitate a very detailed specification for niobium sheet, which may interfere with the need to reduce the cost of raw sheet as much as possible.

Very exciting discussions took place in areas looking to break the "niobium monopoly" above. A positive result of the past Midwestern workshops was the incorporation of theorists into the SRF community, who have provoked a rethinking of the limiting behavior of RF fields. Provided that magnetic flux can be completely excluded from thin superconducting layers, it may be possible to incorporate hard superconductors on top of base niobium layers to produce surface breakdown fields > 0.5 T and electric field gradients > 100 MV m^{-1}.

Overall Important Findings

1. A new era may be emerging where the internal surface of RF cavities is engineered by design. This includes the formation of superconducting layers and multilayers, application of coatings, removal or mitigation of roughness, and passivation or protection.
2. Ideas based on Alex Gurevich's theory* continue to vigorously explore new avenues for breaking the "niobium monopoly". (* A. Gurevich, *Applied Physics Letters* **88**, 12511). Interest has now expanded to include experimentalists with capabilities to potentially produce cavities to test this theory by the end of FY08. These research projects should receive high priority.
3. The workshop community has broadened to include a large number of new academic scientists, who have provided new ideas and tools that have the potential for accelerating breakthroughs in understanding. The RF microscope, scanned laser microscope, scanning tunneling microscope, and orientation imaging microscope stand out in particular. Research proposals from these groups should be encouraged.

4. There exists no analog of the "short sample test", a vital research tool used in the development of high field superconducting magnets, in the SRF community. That is, small experimental samples produced by researchers cannot be taken to a facility that applies high-frequency electromagnetic fields to the surface of the sample of the order found in actual SRF cavity operation. A possible exception is the microwave test cell ("mushroom") at LANL. Such a facility could provide rapid turnaround in understanding, especially in view of the new participation of basic materials researchers, and should be highly sought. Also, single-cell cavities and other resonators, possibly of small size, could be used to test new surface preparation and coating methods.
5. Progress in understanding the interrelationships between surface structure, surface chemistry, and RF cavity performance continues to accumulate, albeit at a slow pace. Efforts that coordinate surface studies with samples taken from actual cavities, for which operational data and processing history is known, made the best progress. In particular, new data on oxygen contamination and surface oxide formation suggests that oxygen diffusion cannot fully explain the effects of cavity baking, contrary to the understanding of the past decade (or more).
6. Many alternatives to established processing and characterization routes were proposed. These include: new scanned local probes, some of which might be implemented inside cavities; new cleaning techniques that are cheaper and environmentally friendly; and new routes for correlating structure, composition, and properties.

As a final comment, a significant portion of work has been supported with modest seed funds or by bootstrapping work to other programs not related to SRF R&D. Some research efforts are on a precipice, where they will be forced to leave the budding SRF community without directed programmatic support. Funding of research proposals, perhaps in the form of a national center or institute, by DOE, NSF, and other agencies is urgently needed.

Detailed Session Summaries

Session 1 – Fundamentals of RF Superconductivity

- *Theoretical limit of RF superconducting state:* A central debate about the nature of the transition between superconductivity and the normal conducting state under RF conditions was initiated in the first workshop session and continued as an undercurrent throughout the entire workshop. On one hand, Alex Gurevich (FSU) described how vortex penetration is the key event that leads to dissipation and eventual breakdown of a cavity at high gradients. Since the formation of small vortex loops can take place in picoseconds, the oscillating electromagnetic fields at 1GHz are still quasi-static relative to the superconducting condensate. However, the dynamic time scales for the normal electrons inside the vortex core is 1 µs, and this jump in time scales from quasi-static to dynamic produces very complicated physics. On the other side of the debate, Hasan Padamsee (Cornell) reviewed the theory behind the superheating field, a field at which superconductivity is only metastable within the Ginzburg-Landau formalism. Since the time scale for collapse of the most extreme of metastable states is 1 µs, a superheated superconducting state is stable relative to the nanosecond RF variations. Present work seeks to extend this theory from the region near the critical temperature to lower temperatures by using the

Eilenberger equations. At present, both theories are not developed sufficiently to be definitive, and both theories continue to stimulate experimental ideas to test them.

- *RF superconductivity beyond the capability of niobium:* An important corollary to Gurevich's model is that it is possible to design multilayer structures that persist vortex-free to fields many times the maximum surface field of niobium, thereby driving up the possible RF gradient by a similar factor. In this manner, it is possible to choose the RF breakdown field by manipulating the thickness and composition of insulating and superconducting layers. While simple experiments could be easily performed on thin films, a conformal coating technique would be required to realize this possibility on a complex shape such as an SRF cavity. Padamsee's description of superheating predicts similar improvement can be obtained for *bulk* materials with higher critical field, such as Nb_3Sn, although this has not been achieved in practice.
- *Experimental limits to cavities:* The review by Ciovati emphasized the present state of knowledge of how various factors seem to limit cavity performance:
  - *Roughness:* Roughness clearly plays a role in locally enhancing magnetic field, which degrades performance. However, the important length scale is difficult to determine. It is also difficult to achieve uniform roughness over large areas.
  - *Tantalum impurities:* It was noted that Ta variations did not seem to affect performance, suggesting that the Ta content limit specified for cavity-grade niobium could be relaxed to ~1500 wt. ppm to reduce cost.
  - *Oxygen impurities:* Oxygen dissolved in niobium and oxides formed on the niobium surface continue to be chief candidates for performance loss. The oxide coating on Nb surfaces appears to undergo complicated changes as a function of time, temperature, reaction atmosphere, and other parameters, making it difficult to discern particular features that must be avoided. This complexity makes the cost-purity-performance envelope difficult to optimize.
  - *Hydrogen impurities:* Hydrogen remains a challenging topic. Dissolved hydrogen could result in the formation of niobium hydrides at low temperatures, which increase surface resistance. Measurements of surface hydrogen are not always reliable because they can be affected by the environment of the measuring apparatus.
  - *Grain boundaries:* Experiments on cavities processed by an identical route using small-grain, large-grain, and single crystal niobium do not show strong differences in performance. It may be concluded that grain boundaries are not a significant limiting factor for performance. While past experiments suggest grain boundaries can be more susceptible to flux penetration, discussion of the present results concluded that many grain boundaries in cavities might not be oriented properly to admit flux easily.
  - *Thermal breakdown:* The Kapitza resistance for transferring heat across the niobium surfaces can limit the rate at which heat is removed from a RF cavity. Experiments to appropriately prepare the outside cavity surface might be needed. Thermal transfer data shown at the workshop indicates that this is not a limiting factor for 1.3 GHz cavities, although this conclusion might not be valid for higher frequencies.

Session 2 – Materials Properties and Surface Characterization

- *Review of surface treatments and property changes in cavity experiments:* Hasan Padamsee provided the following insights about what is important and what can be given lower priority:

- *High-field Q slope:* The degradation of cavity resonance parameter at high electric field gradients is directly correlated with the appearance of hot spots along the equatorial regions of cavities. This is the region where the surface magnetic field is highest.
- *Roughness:* The important difference between buffered chemical polishing (BCP) and electropolishing (EP) of cavities is the smoother finish for EP, which produces better performance. Roughness introduces regions where magnetic field is enhanced due to geometrical effects.
- *Pollution model:* Low-temperature baking, e.g. 48-hours at 100 °C, improves the cavity performance. The possible mechanism is motion of surface oxygen into solution with the bulk niobium beneath the top 50 nm layer, thereby improving quality of the surface superconductor. However, results are not always consistent and are also not always supported by surface science. Growth of an oxide layer does not appear to correlate with cavity degradation. Correlated, systematic surface-science studies are needed to verify the oxygen diffusion model.
- *Grain boundaries:* Hot spots in a temperature map did not correlate with grain boundary locations, suggesting they do not limit cavity behavior. Grain boundaries could be reservoirs of contaminants, however.
- *Benign surface features:* The following were argued by Hasan to not cause dissipation at high electric field gradients: adsorbed layers, hydrogen, heat transfer.

- *Is oxygen benign?:* Low-temperature baking in ultra-high vacuum was shown to convert surface Nb_2O_5 into bulk niobium sub-oxides via x-ray photoelectron spectroscopy (XPS). The surface oxide layer re-formed upon exposure to air. This suggests that sub-oxides are always present in the surface SRF layer, and that the "good" (~30 MV m^{-1}) gradients obtained on the cavities probed by XPS are representative of the niobium sub-oxide. Baking to remove the oxide completely also did not improve cavity performance.
- *Niobium nitrate a possible bad actor?* Romanenko from Cornell dissected a cavity and probed separate regions known to be hot spots (in the process of quenching at a certain electric field gradient) and cold spots (regions still strongly superconducting). XPS and Auger electron spectroscopy were used to correlate signatures of nitrogen (from NO_3) with the hot spots but not with cold spots. This leads to the interesting speculation that chemical residues buried during the polishing process could play a role in cavity dissipation. Since BCP uses a mixture of HF and HNO_3 acids, niobium nitrates could be bound at the surface after converting niobium pentafluoride etch products.
- *New tools to probe the niobium surface:*
  - *Scanning RF microscopy:* A difficulty with many characterizations is that they are static or quasi-static and do not test true RF conditions cavities will face. Two talks discussed the great potential for using scanning RF microscopy to probe cavities at GHz frequencies.
  - *Laser scanning microscopy:* Lasers can be combined with RF techniques to probe the field and current patterns in a superconductor carrying a microwave signal. Such a system could detect the early formation of hot spots and help elucidate the mechanism of breakdown.
  - *Scanning tunneling microscopy and point-contact spectroscopy:* A collaboration between IIT and ANL uses a tunneling microscope to probe directly the superconducting gap at the niobium surface. First results reveal

that the presence of an oxide coating does not affect the gap magnitude. Baking produces only subtle variations in the gap profile, although the exponential sensitivity of the BCS surface resistance to the gap profile may mean that these subtleties are important.

- *Atom probe microscopy with mass spectrometry:* Sharp tips made from the cross-section of a niobium piece extracted from a cavity can be eroded atoms at a time, with the eroded atoms passing through a mass spectrometer to determine their type. This allows a 3-dimensional atomic picture of the tip to be built up. While the Northwestern U. group of Seideman has shown they can make tips from SRF cavity pieces, a concern is whether the heavy fabrication requirements alter the samples from their true make-up.
- *Combined OIM and FIB for electron microscopy:* New scanning electron microscopes can be configured to detect the niobium grain orientation at the surface using orientation imaging microscopy (OIM). Many systems are now integrated with a focused ion beam (FIB) to allow specific grains with specific orientations, or the boundaries between grains, to be isolated and cut out from the sheet. The extracted samples can be thin enough for direct analyses with scanning and transmission electron microscopes. These tools can provide direct analyses of grains and grain boundaries at suspected trouble spots.
- *Thermal transfer models* have become sufficiently advanced to allow quantitative probing of heat transfer over small scales.

- *Test cavities for small experimental samples:* A mushroom-shaped RF cavity at LANL has capabilities to simulate a full RF field load, in excess of 200 mT, on small flat samples. Such a facility can thereby accommodate small specimens produced by experimental investigations, possibly removing the necessity of making an entire cavity just to test an idea. Alternatively, in some encapsulated single cell cavities, possibly of small size may be used to test new surface preparation and coating methods.

Session 3 – New Materials for the Future

- *New possibilities based on past work:* Anne-Marie Valente (JLab) reviewed several past efforts using A15 and B1 materials. Generally speaking, higher critical temperature is desirable due to the fact that the BCS surface resistance is a decreasing function of T/T_c. Compounds with higher T_c generally also have higher critical field, potentially raising the theoretical limits (following either Gurevich or Padamsee model) for RF superconductivity. Of the compounds reviewed, the B1 structure (Nb,Ti)N appeared to be the most promising to revisit.
- *Atomic layer deposition:* ANL personnel presented a novel technique that could provide an experimental test of Gurevich's multilayer model. The key to their technique are paired chemical reactions at the cavity surface applied in alternating steps. Chemical reactions take place between a gas flowing past a surface or through a cavity via chemisorption. The terminating atoms on the chemisorbed layer prevent further reaction for that layer, yet they can also be prepared to catalyze a subsequent reaction with a different gas. In this way, one and only one molecular layer is built up at a time, and this occurs in a conformal manner. Roughness also should decrease with increasing thickness. Several experiments are underway to grow multilayers on niobium, smooth niobium surfaces, passivate the niobium surface, and apply useful coatings to the niobium.

- *Magnesium diboride coatings:* MgB_2 is a new compound to explore in cavities with several potential advantages. It is a stoichiometric line compound, so composition gradients are not possible. Very pure MgB_2 is presently made on niobium using chemical and physical vapor deposition, making the internal coating of cavities a logical extension of an existing process. Low surface resistance has also been demonstrated in films intended for communications devices.

Session 4 – Innovative Processing Techniques

- *Standard vs. alternate processing techniques:* Clarie Antoine summarized the present standard processing regimen that has evolved largely based on empirical findings. This process is expensive, time consuming, and is not fully integrated. There are many opportunities for new ideas to be effective here, some of which could positively impact the ILC baseline process. A few of these ideas are being used at some laboratories. Alternative processing techniques that could reduce cost and improve throughput (that were not discussed elsewhere in this session) include:
    - *Carbon dioxide washing:* Dust and debris are mechanically removed by the action of dry ice, which leaves no liquid residue.
    - *Helium plasma processing:* A glow discharge is initiated with helium gas.
    - *High RF power processing:* Asperities are melted by forcing them to emit electrons and heat up.
    - *Nb surface coating:* A "good" very pure Nb layer could be applied on top of the Nb sheet metal, reducing or removing the necessity to deeply etch the surface.
    - *Non hydrofluoric acid etching:* Alternative etchants, such as salt solutions, exist for removing the damaged portion of the Nb sheet that are safer and environmentally more desirable.
    - *Sonication:* High-frequency acoustics (ultrasonic, megasonic) are used to remove particles from the Nb surface.
- *Particle removal by gas-cluster ion bombardment:* Multiple presentations explored the use of GCIB, a standard process used by the semiconductor industry, to clean niobium. Experimental tests are underway, with some preliminary results showing improvement of surface roughness and removal of contaminants. A central question is whether this surface treatment is better or more cost-effective than the present EP and rinsing. A concern is that the high impact energy could adversely affect the properties of the niobium surface.
- *Plasma cleaning techniques:* Another standard technique derived from Nb thin-film deposition techniques is dry etching with reactive plasmas. TJNAF collaborations have explored halogen gases, e.g. boron trifluoride, for this purpose. While preliminary work has yielded promising results, a concern is the formation of undesirable surface phases, e.g. niobium borides, due to reactions with the plasma. Electron cyclotron resonance could be simple to apply within an operating cavity as a dry etching route by sweeping a magnet on the outside of the cavity. In this case, chemical reaction with an ionized gas can be minimized. This is an interesting alternative to wet processing of cavities.
- *Chemical mechanical polishing:* Large-area grinding and polishing could be applied prior to welding to remove surface damage. However, this could be more labor intensive and time consuming than the present process.

Session 5 – Niobium Processing

- *Niobium processing overview:* Waldemar Singer presented several provoking thoughts in reviewing the state of the art. A general theme is a community-wide debate over the preferred conditions of the niobium sheet.
    - *Purity:* High Ta content did not alter performance when compared to low Ta content for cavities with moderate (< 30 MV m^{-1}) performance. A slight reduction of performance for high Ta content was noticed above 30 MV m^{-1}, although the cost savings may offset the performance falloff.
    - *Formability:* Fine grained material (as for ILC baseline procurement) is very desirable based on formability criteria, but it is difficult to obtain uniform grain size across the thickness of rolled and annealed sheets supplied by various vendors. Single crystal Nb produces excellent formability, shape stability, and smoothness, but is still being developed and is very expensive. Large-grain Nb is more compatible with vendor annealing treatments, but produces unfavorable roughness, anisotropic mechanical properties, and deep-drawing behavior. These trade-offs continue to be weighed.
    - *Mechanical properties:* Grain boundaries do not appear to adversely affect mechanical properties. Yield strength and elongation vary with respect to crystallographic orientation of grains.
    - *Alternative forming:* Seamless tube hydroforming and spinning + flow forming have produced cavities with good performance.
- *Mechanical modeling:* Progress was reported in modeling the deformation and recrystallization behavior of niobium. Progress is aided tremendously by orientation imaging microscopy, experimental studies on single crystals, and computational advances.
- *Alternate sheet processing:* Techniques for refining grain size and manipulating grain orientation have emerged recently. These techniques could improve the formability.
- *Welding:* TIG welding techniques similar to those used to weld titanium are being explored as an alternative to electron beam welding.

Appendices

- First Call and Charge from Claire Antoine to workshop participants
- Introductory slide from Helen Edwards describing workshop intentions
- Workshop program
- Summary slides from Claire Antoine and Lance Cooley
- Workshop participants

Call for Workshop of RF Superconducting Materials

SRF technology has reached maturity thanks to advances in materials, fabrication and preparation techniques over the past 20 years. The performance of bulk Nb cavities is approaching theoretical limits. Consistent achievement of high performance in cavities is one of the upcoming challenges. From basic manufacturing and treatment processes such as forming, welding, and electropolishing to fundamental RF dissipation theories, there are many issues to be further understood and explored. We also need to find ways to evolve beyond the “bulk niobium limit” for the next generation of accelerators.

Understanding the underlying physics of materials, fabrication and treatment processes as well as the physics of limiting phenomena has helped improve empirically discovered treatments. Selecting an efficient combination of treatments has brought significant cost savings. SRF will continue to benefit from theoretical and experimental expertise within and beyond the SRF community. Therefore it will be important to improve the information exchange and interaction between the SRF community and labs interested in fundamental materials research. Superconducting magnets have benefited greatly from such broadening of interactions.

Recently Fermilab hosted the “Midwestern SRF Materials Research Meeting”, which brought important new contributors to interact with the SRF field. There is strong motivation in the community to organize on a larger scale. Fermilab therefore proposes to host a similar national workshop as a follow-up.

The goals of the workshop are to form a coordinated SRF materials research activity, promote inter-disciplinary studies, further expand SRF research to more universities, invite early industry participation and strengthen the collaboration between national laboratories and academic institutes. As such, its focus will be different from the SRF international workshop.

The workshop will encourage further understanding, new ideas to push the fundamental limit, and open up a new research frontier. It will be organized in the form of invited talks and working group discussions. Invited talks will be categorized to review talks and topical talks. Group discussions will be divided into brief presentations and round-table discussions. Following are the main research topics:

- Fundamentals of RF superconductivity
- Material properties of superconductor
- Fabrication of superconducting materials
- Processing of materials
- Surface Characterizations
- Industrial collaboration

The workshop will be an effort to bring universities, labs and industries to work together to expand the scope of the fundamental research of RF superconducting materials. The workshop will reinforce the effort to improve the prospects for ILC. The knowledge gathered at the workshop will benefit future projects in high energy physics, nuclear physics and basic energy science. It should also provide an informal review for ideas, research activities or collaborative proposals. The workshop will be held from May 23 - 24, 2007.

Workshop scientific committee members:
Helen Edwards (Fermilab, Chair)
Alex Gurevich (Florida State University)
Charles Reece, Peter Kneisel (Jlab)
Hasan Padamsee (Cornell)
Chris Compton, Tom Bieler (MSU)

Mike Pellin, Maria Iavarone (ANL)
Bruce Strauss (DOE)

International advisors:
C. Antoine (Saclay/Fermilab/ Co-chair), W. Singer (DESY), K. Saito (KEK).

Local organizing members: C. Antoine, M. Bruce, C. Cooper, N. Dhanaraj, H. Edwards, K. Swanson, Genfa Wu.

SRF Materials Workshop

The need to bring together SRF practitioners, materials and surface scientists, experts from universities, national labs, and industry - teaming of ideas and expertise

why it is effective/ necessary/useful… to do basic R&D along with technological developments

R&D is a way to confirm/ optimize (/choose among) empiric improvements

The physics behind ultimate limitations is still not well understood. It is of basic scientific interest

Better understanding will lead to new ideas and to better paths for development and improved preformance

SRF Materials Workshop

May 23 & 24, 2007

Fermilab, Wilson Hall

Wed. May 23		**Location: Curia II Topic**	**Author**	**Affiliation**
08:30		Welcome	**H. Edwards**	**Fermilab**
	08:40	**Introduction to the workshop**	**B. Strauss**	**DOE**
		Session 1:Fundamental of RF superconductivity		
		Session Chair :	Peter Kneisel	JLAB
08:40	09:00	Introduction talk on SRF issues about materials and surfaces	G. Ciovati	JLAB
09:00	09:20	Mechanisms for high field dissipation and multilayers for raising the ultimate fields	Alex Gurevich	FSU
09:20	09:40	Physics of the Ultimate RF critical magnetic field (superheating field)	Padamsee/J. Sethna	Cornell
09:40	10:10	**30 minutes Discussion**		
10:10	10:30	Coffe Break		
		Session 2: Material properties of superconductor & Surface Characterizations		
		Session chair :	Hasan Padamsee	Cornell
10:30	10:50	Introduction: Opening remarks to update the experimental and theoretical situation for the High-Field dissipation (high field Q-Slope)	Hasan Padamsee	Cornell
		2.1 Surface analysis		
10:50	11:10	Overview: Survey of characterization methods, XPS, SIMS, TEM…	Michael J. Kelley	College of William and Mary
11:10	11:30	Surface oxide studies on solid Niobium for Superconducting RF Accelerators using variable photon energy XPS	Hui Tian	JLAB
11:30	11:50	Surface Analysis of samples dissected from a cavity with high-field Q slope (XPS, Auger, EBSD, SIMS, Optical Profilometry)	Olexander Romanenko	Cornell
11:50	12:10	Overview: Scanning RF Microscopy	Judy Wu	U Kansas
12:10	13:10	Lunch Break		
		2.2 RF/ superconducting properties		
13:10	13:30	Imaging of Microwave Currents and Microscopic Sources of Nonlinearities in Superconducting Resonators	Steven Anlage	U Maryland
13:30	13:50	Correlation between XPS and temperature maps for nearly oxide-free niobium	Grigory Eremeev	Cornell
13:50	14:10	Overview: Review of RF measurement of samples	Charlie Reece	JLAB
14:10	14:30	Tunneling Spectroscopy and Surface Modification of Nb for SRF Cavity Development	John Zasadzinski	ANL/IIT
14:30	14:50	A Novel Method to Measure the Absolute Value of the Magnetic Penetration Depth in Superconductors	Steven Anlage	U Maryland
14:50	15:20	*Coffe Break and poster*		
		Posters (pending)		
		Superconducting Electromagnetic Metamaterials	Steven Anlage	

		Imaging of Microscopic Sources of Resistive and Reactive Nonlinearities in Superconducting Microwave Devices	Steven Anlage	
15:20	15:35	Atomic scale chemical analyses of niobium superconducting radio frequency cavity	Kevin Yoon	Northwestern Univ.
15:35	15:55	Analytical electron microscopy studies and transport characteristics of large grain niobium for SRF cavity	Z. H. Sung	FSU
15:55	16:10	Heat transfer measurements of niobium for SRF cavities	S.K. Chandrasekara n	MSU
16:10	16:25	Critical magnetic field measurement of MgB2	Tsuyoshi Tajima	LANL
16:25	16:55	**30 minutes Discussion**		
Thu. May 24		**Location: 1 West** **Topic**	**Author**	**Affiliation**
		Session 3: New Materials for the Future		
		Session chair :	David Larbalestier	FSU
08:30	08:50	Overview: New materials for SRF cavities	Anne-Marie Valente	JLAB
08:50	09:10	Atomic layer deposition	Mike Pellin	ANL
09:10	09:30	MgB2 thin film and its application to RF cavities	X. Xi	Penn State
09:30	10:00	**30 minutes Discussion**		
10:00	10:20	Coffe Break and poster		
		Session 4: (innovative) Processing of materials		
		Session chair:	Lance Cooley	Fermilab
10:20	10:40	Overview: Unconventional cavity processing techniques	Claire Antoine	Fermilab/CEA Saclay
10:40	10:55	In-situ surface treatment of SRF cavities with Gas Cluste … fect on the maximum gradient and Q-slope of the cavity	David	TEL Epion Inc
10:55	11:10	Plasma etching of Niobium surface	Marija Raskovic	Old Dominium Univ.
11:10	11:20	ECR plasma: a possible in-situ cavity processing technique	Genfa Wu	Fermilab
11:20	11:40	Novel Surface Treatments for RRR Niobium	Roy Crooks	Black Laboratory
11:40	11:50	Advanced Nb oxide surface modification by cluster ion beams	Z. Insepov	ANL
11:50	12:00	Chemical Mechanical Polishing for Obtaining Very Smooth Surfaces:	Sinan Muftu	Northeastern Univ.
12:00	12:30	30 minutes Discussion		
12:30	13:30	**Lunch Break**		
		Session 5: Niobium production		
		Session chair :	Chris Compton	MSU
13:30	13:50	Introduction: Metallurgical and Technological Request for High Purity Niobium in SRF Application	W. Singer	DESY
13:50	14:10	Overview of the RRR Nb Specifications and the Evolution of SRF Technology	Ganapati Rao Myneni	JLAB
14:10	14:30	Microstructural Refinement of Niobium for Superconducting RF Cavities	K. T. Hartwig	Texas AM, MSU
14:30	14:50	Preliminary investigation of a model for predicting	D. Baars	MSU

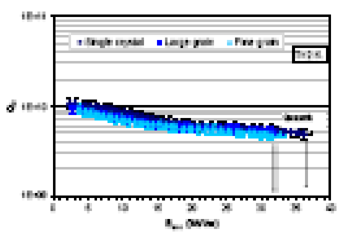
		recrsytallization in Nb		
14:50	15:10	Orientation Effect on Recovery and Recrystallization of Deformed Niobium Single Crystals for Superconducting RF Cavities	V. Levit	Ohio State U
15:10	15:30	Coffee break and poster		
15:30	15:50	Textures of Niobium Sheet	Peter R. Jepson	H.C. Starck Inc
15:50	16:10	The Potential of TIG Welding Technology For SRF Cavity Fabrication	C. Compton	MSU
16:10	16:40	30 minutes Discussion		
16:40	17:00	Summary Talk of the Workshop	C. Antoine	Fermilab/CEA Saclay
19:00	20:30	Dinner at Chez Leon		
		Acknowledgement		

Session 1 : fundamental limits

- Nearly "perfect" cavities can be achieved
- Flux line penetration (AG) vs superheating (HP)
  - Time scales of GL domain vs flux line vs GHz
  - What is the vortex penetration mechanism ?
- Tc and Bc remain relevant parameters to maximize performance
  - Materials with higher Bc
  - Taking advantage of thin superconductors to raise Bc1(ML) above Bc(Nb)
- Heat transfer: Kapitza issues obstruct new ideas to add more interfaces?
- Are there ways to reduce the present requirements of near perfection?

 Session 1 : Fundamental of SRF

- We know GB are weak links (but dc vs rf…)
- All optimized cavities have similar Qslope and quench, with or w/o GB !
  - Even these have hot spots.



Beyond Niobium

- Theory and experiments starting to join
- How do we verify that success happens?

Session 2 : Material properties and characterization

Surface Studies

- SIMS, XPS are complementary – need combined and coordinated studies
- TEM, scanned probe microscopy – need resources, very targeted studies
- Surface morphology – mind the scale!
- New probes (scanning RF, strip resonator, Bc3)
- Area probes average; local probes may miss important details

Session 2 : Material properties and characterization

Surface Studies, cont.

- Problem areas are local; but over what scale?
- Some things thought to be problems simply aren't (?!)
  - Oxygen -- cavities with various mixtures of Nb_2O_5, NbO_2, NbO behave the same

Mapping and post-mortem techniques :

- Hot spots, TMap: only radar for problems?
- Volume of interest: -5nm to -10 nm under the surface ?
- *Interesting ideas: dissecting cavities, study mono/bicrystals Laser-produced hot spots, Laser as in-situ probe*

Session 2 : Material properties and characterization

RF / Superconducting properties

- Coupling with surface analysis!
- Comparison between single samples and whole cavities should be relevant
- Mushroom test platform: access to RF properties, comparison against DC
- Are there other parameters "easy" to measure that could give us better prediction of the cavity behavior?
  - Bc3
- Thermal transfer: influence of annealing, grain boundaries….

SRF materials workshop discussions

Session 3: New materials for the future

- T/Tc matters for Rs, so higher Tc helps even if the superconductor is not perfect
  - Reprise: Are there ways to reduce the requirements of perfection?
- New techniques are promising not only for making superconductors or multilayers…
  - Conformality due to flowing vapors and surface catalyzation of desired chemical reaction
  - Want line compounds – MgB2
- … and provide new versatility
  - We are on the eve of a new era (functionalized coatings?)
  - We are involving new people (chemists)! Continue!

May 23-24, 2007 SRF materials workshop 7

SRF materials workshop discussions

May 23-24, 2007 SRF materials workshop 10

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Session 4: Surface processing

- How heavily do "dry" treatments modify the surface?
  - "molecular peening" should cause damage and reduce RRR
  - Temperature and surface mobility should heal damage
  - What are consequences of resolidification of sputtered / molten ejecta?
  - What are consequences of energetic implants due to plasma?
- New surface treatments shouldn't create a new problem!
- Interesting ideas: chemical-mechanical polishing of sheets or ½ cells => reduced etching afterwards

May 23-24, 2007 SRF materials workshop 8

SRF materials workshop discussions Session 4: Innovative processing methods

- How can we overcome the variability of the present surface preparation processes
  - Systematic studies of the damage layer is needed
  - Modification of the fabrication process ?
- What do we need to address? Surface removal (what thickness, why), particle contamination, surface modification regarding secondary emission, field emission… Are all these issues compatible between themselves?
- Do we need complementary or alternative techniques?

Interesting ideas: chemical-mechanical polishing of sheets or ½ cells => reduced etching afterwards

May 23-24, 2007 SRF materials workshop 11

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Session 5: Niobium

- Single crystals and very small grains are desirable (for forming and flatness); Forming and roughness (BCP) difficulties relate to "large grains" at a scale between those above.
  - Is there no way out?
- Do we want a certain texture of Nb?
- Can we relax some of the specs (e.g. Ta); do we need to strengthen some?
- Damage layers !

May 23-24, 2007 SRF materials workshop 9

SRF materials workshop discussions Session 5: Niobium production

- What knowledge do we need to get reproducible production of the adequate material
- How can we practically get reproducible production of the adequate material
- Are there specific textures/ orientations with more favorable behavior (forming, magnetic transition field, work function….), how can we optimize it.
- What do we still need to know? (e.g. recrystallization behavior @ welding, cold mechanical resistance of welded parts…)

May 23-24, 2007 SRF materials workshop 12

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