ANALYSIS OF POST-WET-CHEMISTRY HEAT TREATMENT EFFECTS ON NIOBIUM SRF SURFACE RESISTANCE

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R&D on SRF

- Driven by Project Need
  - CW applications
  - Pulse applications
  - High current
  - 4.2 K applications

- Conventional R&D
  - Maximize $E_{acc}$ and $Q_0$
  - Search for alternative materials
  - Process improvement

Overall goal: Minimize construction and operation cost with reliable and efficient SRF cavities
Quality Factor and Surface Resistance

Quality Factor \( (Q_0) = \frac{G}{R_s} \)

\( G = \) Geometry factor (shape dependent)

\[ R_s = R_{\text{res}} + R_{\text{BCS}}(f, T, \Delta, \lambda_L, \xi_0, l) \]

**Possible sources of \( R_{\text{res}} \):**
- Trapped magnetic field
- Normal conducting precipitates
- Grain boundaries, dislocations
- Interface losses
- Subgap states

**Remedies:**
- High treatment heat treatments
- Magnetic shielding
- ___

At temperature below 2K, \( R_s \) is dominated by \( R_{\text{res}} \)
Quality Factor and Surface Resistance

BCS surface resistance results from the interaction between the RF electric field within the penetration depth and thermally activated electrons in a superconductor.

\[ R_{BCS}(f, T, \Delta, \lambda_L, \xi_0, l) = \left( A f^2 / T \right) e^{-\Delta k_B T_c} \]

Minimizing BCS Resistance

- Lower frequency
- Higher \( T_c \) superconductors
- Higher energy gap
- Optimal electronic mean free path


RRR~15
Typical SRF cavity Processes

- ~150 μm heavy BCP/ CBP
- Heat treatment 600-800 °C
- High Pressure Rinse with DI water
- Low temperature baking (100-140 °C for 12-48 hours)
- RF Test

Note: Surface chemistry of ~20 μm is like making new cavity surface
High Temperature Heat Treatment

1970s $\rightarrow$ ~1800 °C UHV HT for ~10 hrs.
1980s $\rightarrow$ ~1300 °C solid state getter, such as Titanium, was used in-side the furnace to "post-purify".
2000s $\rightarrow$ 600-800 °C, mainly just to degas hydrogen absorbed by the Nb during cavity fabrication and surface treatments.

- BCP/ EP needed to remove “polluted” layer after HT
- Reintroduces hydrogen
- May be the cause of strong RF losses

September 23-27, 2013
The standard furnace used for the high-temperature heat treatment of SRF cavities is an ultra-high-vacuum furnace with molybdenum hot-zone; molybdenum (or tungsten) resistive heating elements and cavities are heated by radiation from the heating elements.

**FIGURE 1.** SIMS mass spectra showing difference in H between (a) non-heat treated and (b) heat treated sample.

Ciovati et al, PRSTAB 13, 022002 (2010)
Earlier Results (No post chemistry)

TABLE III. Values of $\Delta/k_BT_c$, $R_{\text{res}}$, $R_{\text{BCS}}$ (4.3 K, $\approx 10$ mT), $Q_0/(100$ mT)$^a$, $B_{p,\text{max}}$, and improvement factors of $Q_0/(100$ mT), $B_{p,\text{max}}$ over the baseline test for all the cavities and rf tests described in Secs. VA 1– VA 4.

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Treatment</th>
<th>$\Delta/k_BT_c$</th>
<th>$R_{\text{res}}$ (n$\Omega$)</th>
<th>$R_{\text{BCS}}$ (n$\Omega$)</th>
<th>$Q_0/(100$ mT) ($\times 10^{10}$)</th>
<th>$B_{p,\text{max}}$ (mT)</th>
<th>$Q_0$ improvement</th>
<th>$B_{p,\text{max}}$ improvement</th>
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<tbody>
<tr>
<td>Baseline 1</td>
<td>(20 $\mu$m BCP)</td>
<td>1.75</td>
<td>11.1</td>
<td>1068</td>
<td>1.05</td>
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<td>1.87</td>
<td>10.3</td>
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<td>(800°C/3 h, 400°C/20 min N$_2$)</td>
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<td>1.97</td>
<td>9.7</td>
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<td>Baking (120°C/12 h)</td>
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<td>1.79</td>
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<td>0.91</td>
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<td>Baseline 2 (5 $\mu$m BCP)</td>
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<td>Baseline 3 (2 $\mu$m BCP)</td>
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<td>Baseline (10 $\mu$m BCP, 600°C/</td>
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$^a$The values of $Q_0/(100$ mT) were measured at $2.0$ K, except for the first tests of the large-grain CEBAF cavity when they were measured at $1.7$ K.

Fine-Grain 9-cell cavity results

- 9-cell cavity results with no chemistry after 800 C HT

No chemistry after high temperature heat treatment
Only requirement in clean furnace

R. Geng, 2010
New “All Nb” furnace is designed with induction heating.

Induction Heating

- Heat the cavity in all Nb environment to the target temperature
- Introduce pure Ar while cooling down (this will dilute H$_2$ and minimize reabsorption)
- Vent the furnace with dry oxygen for better oxidation of the surface of cavity (Surface Passivation)
Reduction in $R_{\text{BCS}}$

$4.6 \times 10^{10}$ @ 20 MV/m

$B_p/E_{\text{acc}} = 4.43$

HT extended up to 1400°C with new furnace

- Ingot Nb cavity from CBMM (RRR~200, Ta~1375 wt.ppm), treatment sequence after fabrication: CBP, BCP, HT, HPR

Samples’ analysis after 1400°C show:

- Reduced H content and ~1 at.% Ti content
- Higher energy gap and reduced broadening parameter

Extended Q-rise

Multiple nano-removal, oxypolishing and EP was done

- No performance degradation while keeping in cabinet for a year
- Extended Q-rise present even after the removal of ~120 nm inner surface
- EP after 30 μm reproduce the baseline performance
HT results for “All Nb Cavity”

- 3 “all Nb” cavities (2 LG and 1 FG) are heat treated up to 1600 °C
- Improvement in Q in medium field range up to ~70%
- Small Q-rise
HT results for Reactor Grade Nb

- RRR ~ 40
- Extended Q- rise up to 35 mT with factor of 2 improvement in Q at 20 MV/m
- Cavity was purified in the presence of Ti and surface removal of ~30 μm before the baseline test

Note: In early 80’s those high Q cavities are made from reactor grade and heat treated at very high temperatures.
Some Theoretical Models on $R_s$ vs $B_p$

- Halbritter model based on NbO$_x$ clusters on the surface causes the low field $Q$-rise
- Two layer superconductors model on $Q$-rise
- Non-linear BCS and thermal feedback model
- Weingarten model based on the surface defects
- Numerical calculation based on the Mattis and Bardeen theory modified to account for moving Cooper pairs under the action of the rf field

MOIOC02, TUP011
Future Works

- The reliability of the proposed process to obtain cavities with $Q_0(2.0\text{K}, 90 \text{ mT, 1.5 GHz})$ of $\sim 4 \times 10^{10}$

- Investigation on the impact of surface impurities on the $Q_0(B_p)$ curve through cavity rf tests and studies on small samples cutout from the cavities.
Conclusions

- High temperature heat treatment \textit{without subsequent chemistry} improves the $Q_0$ in medium field range, compared to that obtained after BCP and low-temperature (120°C/48h) baking

- $Q_0(2\ \text{K},\ 90\text{mT})$ as high as $5 \times 10^{10}$ at 1.5 GHz have been achieved because of an “extended” rise of $Q_0$ with increasing field
  - Related to the presence of impurities (Ti) near the surface
  - Understanding the origin of this effect is a new challenge in the R&D of bulk Nb