R&D at JLAB Towards High Performance Superconducting RF Cavities

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The Jefferson Lab has recently upgraded to a 12 GeV accelerator. The future Electron-ion Collider will be 7/8 of a mile around, featuring magnets and experimental halls. The lab aims to explore new frontiers in nuclear physics and particle research.
HISTORICAL MILESTONES

1908 : Kamerlingh Onnes (Liquefied Helium)
1911 : Kamerlingh Onnes (Discovery of superconductivity)
1928-34 : Meissner (Discovered superconductivity of Nb)
1924 : Gustaf Ising (First Publication of RF acceleration)
1928 : Rolf Wideroe (Build first RF accelerator)
1947 : Luis Alvarez (USA) (Build first DTL 32 Mev protons)
1947 : W. Hansen (USA) (Build first 6 MeV e-accelerator, Mark I)
1961 : W. Fairbank (Stanford) (First proposal for superconducting accelerator for e⁻)
1964 : Fairbank, Schwettman and Wilson (Stanford) (First acceleration of e⁻ with SC lead cavity)
1970 : J. Turneaure (Stanford) , Epeak = 70 MV/m and Q ~ 10^{10} in 8.5 GHz cavity
1968-81 : M. McAshan, A. Schwettman, T. Smith, J. Turneaure, P. Wilson (Stanford) Developed and Constructed the Superconducting Accelerator

Since then, many superconducting accelerators were built and many more are constructing and making plans for many new facilities.
A resonant cavity is the high-frequency analog of a LCR resonant circuit.

RF power at resonance builds up high electric fields used to accelerate charged particles.

Energy is stored in the electric & magnetic fields.

\[ Q = \frac{\Delta f}{f} \]
Surface current ($\propto H$) results in power dissipation proportional to the surface resistance ($R_s$)

$$\frac{dP_c}{ds} = \frac{1}{2} R_s |H|^2$$

Total power dissipation in cavity wall

$$P_c = \frac{1}{2} \int s R_s |H|^2 \, ds$$

Stored energy in cavity

$$U = \frac{1}{2} \mu_0 \int_V |H|^2 \, dV$$

Cavity quality factor

$$Q_0 = \frac{\omega_0 U}{P_c} = \frac{\omega_0 \mu_0}{R_s} \frac{\int_V |H|^2 \, dV}{\int s |H|^2 \, ds} = G \frac{G}{R_s} \quad G = \omega_0 \mu_0 \frac{\int s |H|^2 \, ds}{\int s |H|^2 \, ds}$$

$Q_0 \sim 10^4$ for normal conducting and $Q_0 \sim 10^{10}$ for superconducting cavities.
SRF Cavity

- Building bocks of modern particle accelerators.
- Mainly made from superconducting bulk Niobium.

Shape and size varies on the type of applications.
Why Niobium?

- Elemental superconductor with highest $T_c$ (= 9.25K)
- Highest critical field ($H_c$ ~ 200 mT).
- Chemically quite inert, however it is covered with thin oxide layers.
- It can be machined and deep drawn easily and available as bulk and sheet material of many shape, size and purity.
- It has minor disadvantage because it getters gas like hydrogen, oxygen which are found to be detrimental to SRF cavity performance.
Performance is measured as $Q_0(E_{\text{acc}})$ Curves.

Q-factor ($Q_0$): $Q_0 = \frac{G}{R_s}$, $G$ constant shape dependence
**Surface Resistance**

\[
R_S = R_{BCS} + R_0 + R_{Fl}
\]

\(R_{BCS}\) defines by BCS resistance on the Bardeen-Cooper-Schrieffer theory of superconductivity:

\[
R_{BCS} = \left( \frac{1}{T} \right) A(\lambda_L, l, \Delta, \xi_0, f_0, T_c) e^{-\frac{\Delta}{k_B T}}
\]

\(R_0\) defines the residual resistance depends on the purity, subgap states, dislocations, imperfections ....

\(R_{fl}\) defines the resistance due to the trapped flux during the cooldown (vortex dissipation).

High Q \(\rightarrow\) minimize \(R_S\)
SURFACE RESISTANCE

$R_{s}$ (n$\Omega$)

$1/T$ (1/K)

4.2K

BCP

1400 ºC/3 h

2K (10-20 n$\Omega$)

$R_{BCS}$

$R_{res}$
SURFACE RESISTANCE

• Minimizing $R_0$ via heat treatments, chemical and mechanical polishing.

• Minimizing $R_{BCS}$ via material diffusion (reduce mfp to optimal value). No clear evidence on increase in gap ($\Delta$) yet.

• Minimizing $R_{FL}$ via better magnetic shielding and/or better cooldown technique that minimize the trapping of residual magnetic field.
SURFACE RESISTANCE

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• Minimizing $R_{BCS}$ via material diffusion (reduce mfp to optimal value). No clear evidence on increase in gap ($\Delta$) yet.

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The hydrogen dissolved in bulk niobium under certain conditions (holding at temperature 75-150K for extended period of time) during cool down precipitate as a lossy hydride at the niobium surface.

**Hydrogen can be mitigated by**
- rapid cooldown through the danger temperature zone
- degassing hydrogen by heating the Nb cavity in vacuum
• Work started to understand the role of high field Q-slope with hydrogen (niobium hydrides) and passivation of Nb surface during heat treatment.

• The improvement on Q have been observed following the heat treatments with lower hydrogen concentrations.

800°C/ 3hrs heat treatment removes gross hydrogen  

Ciovati et al, PRSTAB 13, 022002 (2010)

Issue: residual gas absorbed during the cooldown, need post furnace surface removal via BCP or EP.
INDUCTION FURNACE

• New dedicated clean induction furnace was designed and installed in order to explore the surface passivation parameters.
• The furnace is capable to going higher than 2000°C in UHV environment.
• The furnace is equipped with gas (N2, O2, Ar, H2) handling system.

Increase in $Q_0$ was observed when the cavity was heat treated at high temperature (1400-1600°C) mainly due to the reduction in residual resistance.
CONCLUSION#1

• High temperature heat treatment mainly used for hydrogen degassing and mechanical healing of SRF cavities.

• The reduced interstitial impurities and dislocations and defect sites plays role on residual resistance and can be minimized with high temperature heat treatment in clean environment.
Minimizing $R_0$ via heat treatments, chemical and mechanical polishing.

Minimizing $R_{BCS}$ via material diffusion (reduce mfp to optimal value).

Minimizing $R_{FL}$ via better magnetic shielding and/or better cooldown technique that minimize the trapping of residual magnetic field.
Ti-Doping

- Exceptionally high Q was observed on 1.5 GHz cavity when cavity was heat treated at 1400°C/3hrs in the presence of Ti source in furnace.
- Investigation found that ~ 1 at.% of Ti was diffused with in ~2 μm on RF surface resulted in the increase in Q and more importantly the positive Q(E) dependence.

• First demonstration of Q-rise via doping
• No electropolishing after doping

P. Dhakal et al., IPAC’12, p. 2651 (2012)
High Q was achieved due to the reduction in BCS.

Surface resistance due to Ti-doping

Reduced dissipation due to the current-induced broadening of the quasiparticle density of states in dirty limit.
Mean free path dependence of BCS surface resistance

\[ R_{BCS} = \left( \frac{1}{T} \right) A(\lambda_L, l, \Delta, \xi_0, f_0, T_c) e^{-\frac{\Delta}{k_B T}} \]

Lower BCS resistance is expected in medium purity Nb, higher quality factor was observed in cavities made from medium and low purity niobium ingots.
Fermi Lab explored the surface passivation technique and found that the nitrogen doping followed by surface removal by EP produce the similar results those were obtained via Ti diffusion.

Process include 800C heat treatment followed by Nitrogen injection for few mins (2-10) at 800 C.

This has been grown so fast that it became “production recipe” for LCLS-II cavities.

Even though the dramatic enhancement on Q has been observed the gradient of doped cavities are limited to medium gradient ~20 MV/m.

Once again the same mechanism as Ti-doping $R_{BCS}$ reduction due to N-doping.
Successive electropolishing increase the breakdown field with reduction in $Q_0$. Temperature mapping quench location detection.
N-doping/Coupon Study

Nb-surface due to nitrogen doping

Successive EP remove the surface pinning

D. Gonnella, IPAC 16
Earlier work on Nitrogen doping to achieve high Q with high $E_{\text{acc}}$

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Treatment</th>
<th>$\Delta/k_B T_c$ (nK)</th>
<th>$R_{\text{res}}$ (n$\Omega$)</th>
<th>$R_{\text{BCS}}$ (n$\Omega$)</th>
<th>$Q_0(100 \text{ mT}) \times 10^{10}$</th>
<th>$B_{p,\text{max}}$ (mT)</th>
<th>$Q_0$ improvement</th>
<th>$B_{p,\text{max}}$ improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>LG CEBAF</td>
<td>Baseline 1 (20 $\mu$m BCP)</td>
<td>1.75</td>
<td>11.1</td>
<td>1068</td>
<td>1.05</td>
<td>118</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LG CEBAF</td>
<td>Heat treatment 1</td>
<td>1.87</td>
<td>10.3</td>
<td>825</td>
<td>1.52</td>
<td>134</td>
<td>45%</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td>(800°C/3 h, 400°C/20 min N₂)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LG CEBAF</td>
<td>Baking (120°C/12 h)</td>
<td>1.97</td>
<td>9.7</td>
<td>614</td>
<td>1.88</td>
<td>136</td>
<td>79%</td>
<td>15%</td>
</tr>
<tr>
<td>LG CEBAF</td>
<td>Baseline 2 (5 $\mu$m BCP)</td>
<td>1.79</td>
<td>5.6</td>
<td>971</td>
<td>0.91</td>
<td>108</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LG CEBAF</td>
<td>Heat treatment 2 (800°C/3 h, 400°C/20 min N₂, 120°C/6 h)</td>
<td>1.90</td>
<td>8.4</td>
<td>675</td>
<td>1.13</td>
<td>118</td>
<td>24%</td>
<td>9%</td>
</tr>
<tr>
<td>LG CEBAF</td>
<td>Baseline 3 (2 $\mu$m BCP)</td>
<td>1.80</td>
<td>7.9</td>
<td>933</td>
<td>1.07</td>
<td>112</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LG CEBAF</td>
<td>Heat treatment 3 (800°C/3 h, 400°C/20 min)</td>
<td>1.92</td>
<td>3.2</td>
<td>697</td>
<td>1.89</td>
<td>112</td>
<td>77%</td>
<td>0%</td>
</tr>
<tr>
<td>SC ILC</td>
<td>Baseline (10 $\mu$m BCP, 600°C/10 h, 13 $\mu$m BCP)</td>
<td>1.75</td>
<td>4.7</td>
<td>782</td>
<td>0.75</td>
<td>109</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC ILC</td>
<td>Heat treatment (800°C/3 h, 400°C/20 min N₂, 120°C/6 h)</td>
<td>1.87</td>
<td>4.8</td>
<td>576</td>
<td>1.05</td>
<td>117</td>
<td>40%</td>
<td>7%</td>
</tr>
<tr>
<td>SC ILC</td>
<td>Baking (120°C/48 h)</td>
<td>1.98</td>
<td>8.2</td>
<td>414</td>
<td>0.94</td>
<td>115</td>
<td>25%</td>
<td>6%</td>
</tr>
<tr>
<td>FG ILC</td>
<td>Baseline (122 $\mu$m VEP)</td>
<td>1.80</td>
<td>5.7</td>
<td>724</td>
<td>0.92</td>
<td>122</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FG ILC</td>
<td>Heat treatment (800°C/3 h, 400°C/20 min)</td>
<td>1.85</td>
<td>4.5</td>
<td>656</td>
<td>1.46</td>
<td>137</td>
<td>59%</td>
<td>12%</td>
</tr>
<tr>
<td>FG ILC</td>
<td>Baking (120°C/24 h)</td>
<td>2.00</td>
<td>7.9</td>
<td>437</td>
<td>1.40</td>
<td>179</td>
<td>52%</td>
<td>47%</td>
</tr>
<tr>
<td>LG ILC</td>
<td>Baseline 3 (1 $\mu$m BCP)</td>
<td>1.83</td>
<td>4.9</td>
<td>831</td>
<td>1.16</td>
<td>119</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LG ILC</td>
<td>Heat treatment (800°C/3 h, 120°C/12 h)</td>
<td>2.00</td>
<td>4.2</td>
<td>412</td>
<td>1.44</td>
<td>128</td>
<td>24%</td>
<td>8%</td>
</tr>
</tbody>
</table>

Probably not enough nitrogen

LOW TEMPERATURE BAKING IN N2

• The vacuum heat treatment procedure started with the 800 °C/3h degassing step followed by lowering the temperature to the (120-160°C) range.
• furnace reaches ~ 200-300 °C, at which point the nitrogen partial pressure is increased to ~25 mTorr.
• Once the temperature has fallen to the desired value (120-160 °C), which is within ~2 hours, the temperature is held for ~46 hours

P. Dhakal et al., PRAB, 2018
LOW TEMPERATURE BAKING IN N2

Standard ILC EP recipe
LOW TEMPERATURE BAKING IN N2

1.5 GHz, 2.0K

$Q_0$

$10^{10}$

$10^{11}$

$E_{acc} (MV/m)$

46.5 MV/m

- Baseline
- Baseline+120C/48hrs
LOW TEMPERATURE BAKING IN N2

![Graph showing the relationship between $\sigma^o$, $E_{acc}$ (MV/m), and conditions such as Baseline, Baseline+120C/48hrs, and Baseline+120C/48hrs+3hr+120C/48hrs @ 25 mtorr N2. The graph indicates a peak at 46.5 MV/m.](image)

1.5 GHz, 2.0K
Higher temperature is beneficial for Q in medium field however, the gradient decreases.
Low Temperature Baking in N2

High Q with no $E_{\text{acc}}$ degradation, process still need optimization.
Low Temperature Baking in N2

<table>
<thead>
<tr>
<th>Test</th>
<th>$\Delta/K_B T_c$ (nm)</th>
<th>mfp (nm)</th>
<th>$R_{res}$ (nΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>1.82±0.02</td>
<td>164±27</td>
<td>2.2±0.1</td>
</tr>
<tr>
<td>+120C/48h</td>
<td>1.86±0.02</td>
<td>26±7</td>
<td>4.6±0.2</td>
</tr>
<tr>
<td>+800C/3h+ 120C/48h@25mtorr N2</td>
<td>1.84±0.02</td>
<td>28±5</td>
<td>1.9±0.1</td>
</tr>
<tr>
<td>+10 um EP</td>
<td>1.81±0.02</td>
<td>164±23</td>
<td>1.2±0.1</td>
</tr>
<tr>
<td>+800C/3h+ 160C/48h@25mtorr N2</td>
<td>1.80±0.02</td>
<td>54±14</td>
<td>1.0±0.1</td>
</tr>
<tr>
<td>+10um EP</td>
<td>1.79±0.02</td>
<td>122±16</td>
<td>0.5±0.1</td>
</tr>
<tr>
<td>+800C/3h+ 140C/48h@25mtorr N2</td>
<td>1.80±0.02</td>
<td>26±87</td>
<td>0.9±0.1</td>
</tr>
</tbody>
</table>

Lower mfp after N2 infusion is similar to doped and conventional low temperature baked cavity, still need more careful investigation if this can give us the lowest BCS resistance and its field dependence.
SAMPLE COUPONS STUDY

(a) Sample F9: 800°C/ 3h

(b) Sample F1: 800°C/ 3h+N₂@120°C

(c) Sample F1: 800°C/ 3h+N₂@140°C

(d) Sample F1: 800°C/ 3h+N₂@160°C
SIMS Analysis

- Higher surface N2 concentration
- No change in bulk properties

Magnetization

P. Dhakal et al., PRAB, 2018
SAMPLE COUPONS STUDY

Nb$_2$O$_5$ and NbN$_{(1-y)}$O$_y$ exists within first 10nm in low temperature N infused sample.
CONCLUSION#2

• \( R_{\text{BCS}} \) decreases due to reduction of mean free path as a result of material diffusion (Ti or N2) within the rf penetration depth.

• The Q-rise phenomenon can be explained by the reduced dissipation due to the current-induced broadening of the quasiparticle density of states in dirty limit.

• Accelerating gradient can be preserved when the cavity is heat treated at lower temperature in the presence of nitrogen.
SURFACE RESISTANCE

- Minimizing $R_0$ via heat treatments, chemical and mechanical polishing.

- Minimizing $R_{BCS}$ via material diffusion (reduce mfp to optimal value).

- Minimizing $R_{FL}$ via better magnetic shielding and/or better cooldown technique that minimize the trapping of residual magnetic field.
**FLUX TRAPPING**

Phase diagram of Type-II superconductor

- Magnetic flux will be trapped during the cooldown
- It is found that the trapping depends on the temperature gradient during the cooldown

Single vortex can dissipate a power ~ 2 μW and the increase in residual resistance can be ~ 2 nΩ/mG due to the vortex dissipation.

Vortex Dissipation

The amount of flux trapping is found to be dependent of the temperature gradient along the cavity during the cooldown.

\[ T_{\text{top}} > T_c \]
\[ T_c \]
\[ T_{\text{bottom}} < T_c \]
\[ \Delta T = T_{\text{top}} - T_{\text{bottom}} \]

Cavity cooldown from bottom and NC/SC boundary moves up

\[ B_a = 40 \text{ mG} \]
WHERE DOES THE FLUX TRAP?

- Magnetic flux traps during cavity cooldown on impurities sites, hydrides and oxides precipitates, lattices imperfections and surface contaminations.
- Grain Boundaries and dislocations.
- The normal precipitates acts as an attractive pinning centers.
- The pinning by grain boundaries takes place through the electron scattering mechanism.
- Both Abrikosov and Josephson vortices contribute to RF loss.
Earlier measurement on SRF cavities showed $dR_s/dB_a \sim 0.4 \text{ n}\Omega/\text{mG}$.

$dR_{res}/dB_a$ measured in a fine-grain, electropolished bulk Nb cavity was $0.6 \text{ n}\Omega/\text{mG}$ and the difference in $R_{res}$ between “fast” and “slow” cool-down was $\sim 1.5 \text{ n}\Omega$.

Much higher values of $dR_{res}/dB_a \approx 3-4 \text{ n}\Omega/\text{mG}$ as well as larger increase of $R_{res}$ for “slow” cool-down compared to “fast” cool-down were obtained for fine-grain, nitrogen-doped Nb cavities.

Values of $dR_{res}/dB_a$ between $\sim 0.06 \text{ n}\Omega/\text{mT}$ and $\sim 0.2 \text{ n}\Omega/\text{mG}$ were reported for a large-grain bulk Nb cavity treated by electropolishing (EP) and baking at 120 °C in ultra-high vacuum and cooled in temperature gradients ranging between $\sim 1 \text{ K/m}$ and $\sim 70 \text{ K/m}$.
We measure the flux expulsion and flux trapping studies on LG cavities with different impurities in order to see the correlation of purity (bulk RRR) and surface preparations (EP, LTB and N-doping).

Q0(T) data were taken from 4.3-1.6K to extract the residual resistance as a function of residual field (applied) in Dewar in two condition of slow ($\Delta T_{\text{iris-iris}} < 0.1K$) and fast ($\Delta T_{\text{iris-iris}} > 4K$) (total 40 cooldown and rf tests).

Flux expulsion ratio = $B_{\text{sc}}/B_{\text{nc}}$
All field trapped

Partially trapped
Perfect expulsion
1.5-1.7 depending on shape of cavity
FLUX TRAPPING ON LG CAVITIES SURFACE (EP)

<table>
<thead>
<tr>
<th>Cavity</th>
<th>$\Delta T&gt;4K \left( B_{sc}/B_{n} \sim 1.5 \right)$ dRres/dBa n$\Omega$/mG</th>
<th>$\Delta T&lt;0.1K \left( B_{sc}/B_{n} \sim 1 \right)$ dRres/dBa n$\Omega$/mG</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC1N1 (RRR=60)</td>
<td>0.13 ±0.01</td>
<td>0.51 ±0.02</td>
</tr>
<tr>
<td>KEK-R5 (RRR=107)</td>
<td>0.10 ±0.02</td>
<td>0.28 ±0.04</td>
</tr>
<tr>
<td>G2 (RRR=486)</td>
<td>0.11 ±0.01</td>
<td>0.57 ±0.02</td>
</tr>
</tbody>
</table>
FLUX Expulsion FG/LG

Increase expulsion with heat treatment @1000C

from S. Posen FG{

\( B_{sc}/B_n \)

\( \Delta T (K) \)
CONCLUSION #3

• The flux trapping sensitivity is lower on cavities made from large grain niobium compared to the fine grain counterparts subjected to the same surface treatments.
• Cavities made from large grain niobium show good flux expulsion regardless of the RRR of host materials suggest the interstitial impurities may have less effect on flux expulsion/trapping.
• Grain boundaries and segregation of impurities (including N2 in doped cavities) may be the primary host for flux pinning/trapping.
Thank you for your attention.