Characterisation of SRF Cavity Materials

George Lewis
Supervisor: Yulia Trenikhina
PARTI/Helen Edwards Final presentation
24 August 2017
Timeline of my Fermilab internship

Weeks at Fermilab

- Introductions
- Reading
- Solo use of SIMS
- Coding of data analysis software
- Analysis of a temperature series of nitrogen infused samples
- Analysis of samples prepared with variations on the 120 °C nitrogen infusion recipe
- In-situ baking and nitrogen treatment
- Analysis of previous work and ongoing experiments
Timeline of my Fermilab internship

Weeks at Fermilab

1  2  3  4  5  6  7  8  9  10

10/4/2017  George Lewis | Characterisation of SRF Cavity Materials
Superconducting radio frequency cavities = Efficient accelerators

+ Less chance of voltage breakdown
+ Each bunch always sees accelerating field
+ Standing waves store large amounts of energy
+ Superconductivity reduces surface resistance
- Power is still dissipated in the cavity walls
- Costs per unit length are very high

Nitrogen treated SRF cavities = Even more efficient accelerators

+ Nitrogen treatment lowers surface resistance (Provides barrier to vortex nucleation)
+ Doping and infusion offer tailored benefits
+ Higher $Q_0$ means lower total costs
± We still need to know more about it!
Background – Secondary ion mass spectrometry

One of the most sensitive surface analysis techniques, can detect impurities < 1 ppm

- Primary ion beam hits sample to produce secondary ions
- Fine control over the primary beam is a major benefit
- Can produce depth profiles and surface maps
- Exact process is complex and cannot be accurately modelled

+ Detects all elements, including H
+ Extremely high sensitivity
+ Choice of primary ion beam gives many possibilities
- High degree of complexity
Data analysis

My analysis program

Raw data

<table>
<thead>
<tr>
<th># Profile Compression</th>
<th># Profile Smoothing 1</th>
<th>C-</th>
<th>O-</th>
<th>#</th>
<th>Sputter Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.9989 15.99</td>
<td>3.2768 3397.1 13788</td>
<td>9.8304 3081.01 38499</td>
<td>16.384 4269.92 91079</td>
<td>22.9376 5106.11 1.342</td>
<td>29.4912 6141.63 1.689</td>
</tr>
</tbody>
</table>

Unmodified output

Modified output

My analysis program

SIMS data analyser

Add files to be analysed
Select peaks
Select extent of smoothing
Savitzky-Golay low-pass filtering
Window length
Polynomial order
Set name for each data set:
Convert sputtering time to depth:
Auto plot extent
Select desired normalisation

10/4/2017 George Lewis | Characterisation of SRF Cavity Materials
Experiments: Temperature series

At what temperature do poorly superconducting nitride phases form?

Sample preparation
- 3 hour bake at 800 °C
- 30 minutes nitrogen infusion at 7 different temperatures

Sample analysis
- Depth profiles taken using SIMS
- Surface images taken using SEM

Prediction
- Temperature trend should roughly follow Fick’s laws

\[ 1^{\text{st}} \text{law}: J = -D \nabla \phi, \quad \text{where} \quad D = D_0 e^{-\frac{E_A}{kT}} \]
- A phase change should produce some visible difference

Figure 3: Animation of a scanning electron microscope

1 Animation by Physics Reimagined
Experiments: Temperature series

At what temperature do poorly superconducting nitride phases form?

SIMS results
Experiments: Temperature series

At what temperature do poorly superconducting nitride phases form?

SEM results

- **800 °C**
- **700 °C**
- **600 °C**
- **500 °C**
- **400 °C**
- **300 °C**
Experiments: Temperature series

At what temperature do poorly superconducting nitride phases form?

Conclusion

- Shape of depth profile changes from 600 to 700 °C
- Accompanied by visual change from ‘star-shaped’ to ‘scaly’ nitrides
- This possibly suggests a phase transition in the region 600 to 700 °C
- Future XRD studies will provide further detail
Experiments: 120 °C nitrogen infusion variations

What are the best parameters for a nitrogen infusion recipe?

Sample preparation
- Standard = 3 hr bake at 800 °C, 48 hr nitrogen infusion at 120 °C & 25 mTorr
- Variations: No 800 °C bake, 96 hr infusion, infusion at 760 Torr (1 atm)

Results

Conclusion
- Specific treatments can be tailored for specific results
Experiments: In-situ sample preparation

How does oxidation change the nitrogen profile?

Sample preparation
- In-situ preparation allows surface analysis before exposure to oxygen

Results

Conclusion
- Trial run using in-situ preparation was successful, oxide layer clearly visible
Conclusion

• Several material characterisation experiments performed

• Experience gained in SIMS, SEM, python, and being a scientist

• Small contribution towards nitrogen-treated SRF cavity research

Finally, to Yulia and all the technical division staff, the internship coordinators and my fellow interns...
Further detail – What is an SRF cavity?

Superconducting Radio Frequency (resonant) Cavity

- Low surface resistance, small power loss
- Surface resistance scales as $f^2$ above 3 GHz
- Ellipsoidal shape prevents multipacting

- Provides efficient acceleration
  - Model cavity as LC circuit which produces oscillating E fields
  - Lorentz force $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$
  - AC resonators permit high power

- Thousands installed worldwide:
  - FAST at Fermilab (27 cells),
  - LEP-II at CERN (176 cells)
  - ILC, future collider (144,000 cells)

Figure 1: Bunch acceleration in an SRF cavity (CERN, 2014 [http://cds.cern.ch/record/1709737](http://cds.cern.ch/record/1709737))
Further detail: Degradation phenomena

- **Hydrogen disease**: Hydrogen dissolved in Nb can precipitate as a lossy hydride. De-gassing by baking at 800 °C and formation of protective oxide solves issue.

- **Multipacting**: Localised, resonant process where an electron avalanche occurs. Requires the time between electron impacts to be an integer number of half RF periods and occur above a threshold energy – this happens at specific $E_{\text{acc}}$.

- **Thermal breakdown**: Small defects (scratches, welding beads etc.) give local non-superconducting regions which heat up, this eventually warms the surrounding Nb above $T_{\text{crit}}$ and the defect grows unstably, quenching the cavity. This can be avoided through taking great care in preparation and by increasing $T_c$.

- **Field emission**: Micron sized particles lead to exponentially increasing electron currents which cause a rise in temperature and sharp decrease in quality factor. Advanced cleaning techniques such as HPR and the use of class 10 clean rooms. (Also possible to destroy particulates through RF manipulation).

- **High Field Q Slope**: Q reduction around 25 MV m$^{-1}$, caused by nanohydrides at penetration depth, EP followed by baking at 120 °C provides an empirical solution.
Further detail: Quality factor

- Quality factors are widely used in physics to describe the selectivity of a signal, generally, Higher Q = Oscillations take longer to die out
- There are several ways of defining Q:
  - \( Q_0 = \frac{f_R}{\Delta f} = 2\pi \frac{\text{Energy stored}}{\text{Energy dissipated}} \text{ per cycle} = \frac{\omega U}{P_d} \)
  - From \( P = \frac{dU}{dt} = VI \) and for an inductor \( V = -L \frac{dI}{dt} \):
    \[
    U = \int_0^\infty \frac{dU}{dt} dt = \int_0^{i_f} L I \frac{dI}{dt} dt = \frac{1}{2} L i_f^2
    \]
  - Using equation for inductance of coil \( L = \mu_0 n^2 l A \) and magnetic induction \( B = \mu_0 nI \) (= \( \mu_0 H \))
    we see that energy stored is \( U = \frac{1}{2} \mu_0 \int_V |H|^2 dV \)
  - Similar manipulations yield \( P_d = \frac{R_s}{2} \int_S |H|^2 dS \)
  - So we end up with:
    \[
    Q_0 = \frac{\omega \mu_0 \int_V |H|^2 dV}{R_s \int_S |H|^2 dS} = \frac{G}{R_s}
    \]

Where G is the geometry factor and depends strongly on cavity shape (but not size).
Further detail: SRF cavities as an LC circuit

- Picture two capacitive plates with a parallel inductor
  - This creates a resonator with frequency \( \omega_0 = \frac{1}{\sqrt{LC}} \)

- Now imagine the inductor becomes many single loops of wire, this eventually forms a pillbox cavity

- Add a beam tube to allow particles to pass through

- Further modify the pillbox cavity to an elliptical one for better field manipulation
Further detail: Primary ion sources for SIMS

- **LMIG:** Liquid Metal Ion Gun uses bismuth (traditionally Gallium but Bi offers a lower melting point)

  Produces short, focused beams for analysis

- **DSC:** Dual Sputtering Column fires cesium/oxygen to enhance yield of electro-positive/-negative atoms respectively and sputters sample fast enough to allow depth profiling
Further detail: Surface resistance in SRF cavities

\[ R_s(T, B) = R_{BCS}(T) + R_{res}(B) \]

- DC superconductors have zero resistance, but not for AC
- High frequency B field penetrates surface layer and induces oscillations in electrons not bound in Cooper pairs
- The motion of these electrons dissipates power
- By considering the current in normal and superconducting regions of the material, it is possible to derive that

\[ R_{BCS} \propto \lambda_i^3 \omega^2 l e^{-\frac{\Delta(T)}{k_B T}} \]

- The residual resistance can be caused by impurities, trapped magnetic flux, and lattice distortions.
Further detail: Challenges

- Instrument issues:
  - LMIG dropout
  - Side emission
  - Network issues
  - Serious hardware failures

- Quantification of data
  - SIMS and SEM are by nature qualitative methods

- Comparing SIMS profiles of different samples
  - Ion behavior varies depending on: operating currents, exposed crystal orientation, sample holder + many more....

- Assimilation of data from different sources
  - Data from Q vs E curves, SIMS, SEM, XRD, TEM and more must be combined and interpreted coherently
Further detail: Magnetic vortices and dirty surfaces

- Vortices can be thought of as a normal conducting core with superconducting currents encircling them which screens the magnetic flux that is confined within them.

- Vortices experience an attractive Lorentz force pulling them to the superconductor’s surface due to interaction with currents.

- There is also a repulsive Lorentz force between the vortex and the applied field which pushes it into the bulk.

- Integrating these forces gives the Gibbs free energy density as a function of depth for the vortex, which shows that there is an energy barrier which in the absence of nucleation points, prevents vortices residing in the bulk.

- $\kappa = \frac{\lambda}{\xi}$ the Ginzburg-Landau parameter can be viewed as a measure of the surface cleanliness (higher if dirty due to shorter mean free electron path), so by considering the case where it varies with depth allows us to analyse the effect of a dirty layer.

- It turns out that a thin dirty layer means that vortices are less stable in the bulk and require a greater field to survive. Also its presence greatly increases the energy barrier which can explain a lower $R_{\text{BCS}}$. 

\[ g(x) = \begin{cases} 1 & x < x_c \\ 0 & x \geq x_c \end{cases} \]

1 Graphs from M. Checchin