CAVITY LIMITATIONS

Gianluigi Ciovati

Thomas Jefferson National Accelerator Facility
Outline

• Residual resistance

• Multipacting

• Field emission

• Quench

• High-field Q-slope
The Real World

![Graph showing Q vs. Accelerating Field]

- Residual losses
- Multipacting
- Thermal breakdown
- Field emission
- RF Processing
- Ideal
- Quench

$Q$ vs. Accelerating Field

$Q$ vs. $50 \text{ MV/m}$
Losses in SRF Cavities

- Different loss mechanism are associated with different regions of the cavity surface

Electric field high at iris

\[
\frac{E_p}{E_{\text{acc}}} \sim 2
\]

Magnetic field high at equator

\[
\frac{B_p}{E_{\text{acc}}} \sim 4.2 \text{ mT}/(\text{MV/m})
\]
Origin of Residual Surface Resistance

- Dielectric surface contaminants (gases, chemical residues, dust, adsorbates)
- Normal conducting defects, inclusions
- Surface imperfections (cracks, scratches, delaminations)
- Trapped magnetic flux
- Hydride precipitation
- Localized electron states in the oxide (photon absorption)

$R_{res}$ is typically 5-10 nΩ at 1-1.5 GHz
Trapped Magnetic Field

- Vortices are normal to the surface
- 100% flux trapping
- RF dissipation is due to the normal conducting core, of resistance $R_n$

\[ R_{res} \approx R_n \frac{H_i}{H_{c2}} \quad \text{H}_i = \text{residual DC magnetic field} \]

- For Nb: $R_{res} \approx 0.3 \text{ to } 1 \text{n }\Omega/\text{mG around 1 GHz}$

- While a cavity goes through the superconducting transition, the ambient magnetic filed cannot be more than a few mG.
- The earth’s magnetic shield must be effectively shielded.
- Thermoelectric currents can cause trapped magnetic field, especially in cavities made of composite materials.

depends on material treatment
Trapped Magnetic Field

![Graph showing frequency vs. Ohms/mG with a linear relationship and a note indicating oxide free.](image-url)
$R_{res}$ Due to Hydrides (Q-Disease)

- Cavities that remain at 70-150 K for several hours (or slow cool-down, < 1 K/min) experience a sharp increase of residual resistance.

- More severe in cavities which have been heavily chemically etched.

![Graph showing the effect of thermal cycles on $R_{res}$](image)
Hydrogen: “Q-disease”

- H is readily absorbed into Nb where the oxide layer is removed (during chemical etching or mechanical grinding).
- H has high diffusion rate in Nb, even at low temperatures.
- H precipitates to form a hydride phase with poor superconducting properties: $T_c=2.8$ K, $H_c=60$ G.

At room temperature the required concentration to form a hydride is $10^3$-$10^4$ wppm.

At 150K it is $<10$ wppm.
Cures for Q-disease

- Fast cool-down
- Maintain acid temperature below ~ 20 °C during BCP
- “Purge” H₂ with N₂ “blanket” and cover cathode with Teflon cloth during EP
- “Degas” Nb in vacuum furnace at T > 600 °C
Q$_0$ Record

Figure 2 – Residual resistance as low as 0.5 nΩ is actually measured on large area cavities, giving an intrinsic quality factor Q$_0$ exceeding 2.10$^{11}$. 
Multipacting

- No increase of $P_t$ for increased $P_i$ during MP
- Can induce quenches and trigger field emission
Multipacting

Multipacting is characterized by an exponential growth in the number of electrons in a cavity.

Common problems of RF structures (Power couplers, NC cavities…)

Multipacting requires 2 conditions:

- Electron motion is periodic (resonance condition)
- Impact energy is such that secondary emission coefficient is >1
One-Point Multipacting

One-point MP

Cyclotron frequency: \( \omega_c \propto \frac{\mu_0 H e}{m} \)

Resonance condition:
Cavity frequency \( (\omega_g) = n \times \) cyclotron frequency

\( \omega_g = n \omega_c \quad n: \) MP order

\( \rightarrow \) Possible MP barriers given by
\[ H_n \propto \frac{m \omega_g}{n \mu_0 e} \quad + \text{SEY, } \delta(K), > 1 = \text{MP} \]

The impact energy scales as
\[ K \propto \frac{e^2 E^2}{m \omega_g^2} \]

Empirical formula:
\[ H_n [\text{Oe}] = \frac{0.3}{n} f_0 [\text{MHz}] \]
Two-Point Multipacting

Empirical formula:

\[ H_n [\text{Oe}] = \frac{0.6}{2n-1} f_0 [\text{MHz}] \]
Two-Side Multipacting

MultiPac 2.1  Electron Trajectory,  N = 10,  24–Apr–2002

z-axis [m], flight time 4.8928 periods
Secondary Emission in Niobium

<table>
<thead>
<tr>
<th>Condition</th>
<th>$K_1$</th>
<th>$K_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>high SEY</td>
<td>$\sim 27$ eV</td>
<td>$\gtrsim 2000$ eV</td>
</tr>
<tr>
<td>typical SEY</td>
<td>$\sim 40$ eV</td>
<td>$\sim 1000$ eV</td>
</tr>
<tr>
<td>low SEY</td>
<td>$\sim 150$ eV</td>
<td>$\sim 750$ eV</td>
</tr>
</tbody>
</table>
MP in SRF Cavities

“Near pill-box” shape

Early SRF cavity geometries (1960s-’70s) frequently limited by multipacting, usually at < 10 MV/m
MP in SRF Cavities

“Elliptical” cavity shape (1980s)

350-MHz LEP-II cavity (CERN)

Electrons drift to equator
Electric field at equator is \(\approx 0\)
\(\rightarrow\) MP electrons don’t gain energy
\(\rightarrow\) MP stops
Cures for Multipacting

- Cavity design

- Lower SEY: clean vacuum systems (low partial pressure of hydrocarbons, hydrogen and water), Ar discharge

- RF Processing: lower SEY by $e^-$ bombardment (minutes to several hours)
Recent Examples of Multipacting

SNS HB54 Qo versus Eacc
Multipacting limited at 16MV/m 5/16/08 cg

MP
Field emission

Qo
E (MV/m)
Field Emission

- Characterized by an exponential drop of the $Q_0$
- Associated with production of x-rays and emission of dark current

![Graph showing SNS HB54 $Q_0$ versus $E_{acc}$]

SNS HB54 $Q_0$ versus $E_{acc}$

![Graph showing SNS HTB 54 Radiation at top plate versus $E_{acc}$]

SNS HTB 54 Radiation at top plate versus $E_{acc}$ 5/16/08 cg
DC Field Emission from Ideal Surface

Fowler-Nordheim model

\[
J = \frac{1.54 \times 10^6 E^2}{\Phi} e^{-6.83 \times 10^3 \Phi^{3/2}/E}
\]

- \(J\): current density (A/m²)
- \(E\): electric field (MV/m)
- \(\Phi\): work function (eV)
Field Emission in RF Cavities

Acceleration of electrons drains cavity energy

Impacting electrons produce:
- line heating detected by thermometry
- bremsstrahlung X rays

Foreign particulate found at emission site

Intensity of x-rays and field emission current is many orders of magnitude higher than predicted by FN theory...

\[ J = k \frac{1.54 \times 10^6 (\beta E)^{5/2}}{\Phi} e^{-6.83 \times 10^3 \Phi^{3/2}/\beta E} \]

\( \beta \): enhancement factor (10s to 100s)
\( k \): effective emitting surface
How to Investigate Field Emission

FE in SC Cavity

Dissection and analysis

Electron trajectory
T-map
Dissection and SEM
Example of Field Emitters

Stainless steel

C, O, Na, In Al, Si

Melted
DC Field Emission Microscope

[Image of DC Field Emission Microscope]

Emission Current

[Images of Carbon samples]

50 MV/m

90 MV/m
Type of Emitters

Smooth nickel particles emit less or emit at higher fields.

- Tip-on-tip model can explain why only 10% of particles are emitters for Epk < 200 MV/m.
Tip-on-tip Model

• Smooth particles show little field emission
• Simple protrusions are not sufficient to explain the measured enhancement factors
• Possible explanation: tip-on-tip (compounded enhancement)
FE onset vs. Particulate Size

![Graph showing the relationship between the electric field onset ($E_{onset}$) for 2 nA FE current (MV/m) and the particle size or scratch width (μm). The graph includes data points for scratch width (red stars) and particle average size (red dots). There are two horizontal lines indicating $E_{acc} = 40$ MV/m (ILC) and $E_{acc} = 30$ MV/m (XFEL). The graph highlights a range between 1.3 μm and 3 μm.](image-url)
Enhancement by Absorbates

Adsorbed atoms on the surface can enhance the tunneling of electrons from the metal and increase field emission.
Intrinsic FE of Nb

Single-crystal Nb samples showed FE onset higher than 1 GV/m.

The work function was obtained from the I-V curves:

\[ \Phi = 4.05 \pm 17\% \text{ eV for Nb (111)} \]
\[ \Phi = 3.76 \pm 27\% \text{ eV for Nb (100)} \]
Cures for Field Emission

• **Prevention:**
  – Semiconductor grade acids and solvents
  – High-Pressure Rinsing with ultra-pure water
  – Clean-room assembly
  – Simplified procedures and components for assembly
  – Clean vacuum systems (evacuation and venting without re-contamination)

• **Post-processing:**
  – Helium processing
  – High Peak Power (HPP) processing
Helium Processing

• Helium gas is introduced in the cavity at a pressure just below breakdown (~10^{-5} torr)
• Cavity is operating at the highest field possible (in heavy field emission regime)
• Duty cycle is adjusted to remain thermally stable
• Field emitted electrons ionized helium gas
• Helium ions stream back to emitting site
  – Cleans surface contamination
  – Sputters sharp protrusions
Helium Processing

Graph showing the relationship between $Q_0$ and $E_{pk}$ [MV/m] before and after helium processing.

Thermometer graph showing temperature change ($\Delta T$ [mK]) with angle (degrees).

Microscopic images showing details at 200 µm and 20 µm scales.
Helium Processing

Before Processing

Starburst & Crater

After

Copper

SEM

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Helium Processing in CEBAF

Improvement of Cavity Performance with Helium Processing

Distribution of Maximum Gradients by Type of Limitation

![Graph showing distribution of maximum gradients by type of limitation.](image)
Figure 1. Radiation reduction with He processing.
Practical Limitations (CEBAF)

- Other
- Quench
- Waveguide vacuum
- Arc rate limited
- 1 Rad/hr from Field Emission
- 1 watt FE loading
High Peak Power Processing

Power = 1.5 MW
Pulse Length = 250 us

\[ E_{\text{acc}}(t \to \infty) = \sqrt{\frac{4\beta P_g r_t/Q_0 Q_0}{(1 + \beta)^2 L}}, \]

\[ E_{pk}(t) = E_{pk} \left[ 1 - \exp \left( \frac{-t}{2\pi} \right) \right], \]

\[ Q_L = \omega \tau_L \]

\[ \beta = \frac{Q_0}{Q_L} \]
High Peak Power Processing

Local melting leads to formation of a plasma and finally to the explosion of the emitter → “star bursts” caused by the plasma.
High Peak Power Processing

For field emission free

\[ E_p \text{ (pulsed)} = 2 \times E_p \text{ (cw)} \]
High Peak Power Processing

Module 4

Bare Vert. Cavity vs. Equipped Hor. Cavity Test
Issues with HPP

- Reduced $Q_0$ after processing
- No experience with HPP above $E_{acc} = 30$ MV/m in 9-cell cavities
- Very high power required

Fig. 2: Cavity C19 before and after HPP. The $Q_0$ recovered partially after warm up to room temperature.
Thermal Breakdown (Quench)

Localized heating
Hot area increases with field
At a certain field there is a thermal runaway, the field collapses

• sometimes displays a oscillator behavior
• sometimes settles at a lower value
• sometimes displays a hysteretic behavior
Thermal breakdown occurs when the heat generated at the hot spot is larger than that can be transferred to the helium bath causing $T > T_c$: “quench” of the superconducting state.
Quench Mechanism

- The RF current produces heat
- Superconductors are bad thermal conductors:
  - Thermal conductivity
  - Kapitza Nb/He interface resistance
- A small normal conducting defect can produce a very large heating (Factor $10^6$ surface resistance!)

Temperature difference between inner surface and helium bath temperature (two dimensional case):

$$T_i - T_B = \frac{\dot{Q}}{A} \left( \frac{d}{\lambda} + \frac{1}{h_k} \right)$$

High thermal and Kapitza conductivity required!!
Thermal Breakdown: Simple Model

The power dissipation (in watts) at the defect is

\[ \dot{Q}_T = \frac{1}{2} R_n H^2 \pi a^2. \]

Heat flow out through a spherical surface:

\[ -4\pi r^2 \kappa \frac{\partial T}{\partial r} = 2 \dot{Q}_T \]

When the defect reaches \( T_c \), the field reaches its maximum value

\[ H_{\text{max}} = \sqrt{\frac{4\kappa(T_c - T_b)}{a R_n}}. \]

Breakdown field given by (very approximately):

\[ H_{tb} = \sqrt{\frac{4\kappa T_c(T_c - T_b)}{r_d R_d}} \]

- \( \kappa \): Thermal conductivity of Nb
- \( R_d \): Defect surface resistance
- \( T_c \): Critical temperature of Nb
- \( T_b \): Bath temperature
Thermal Conductivity of Nb

RRR is the ratio of the resistivity at 300K and 4.2K

\[ RRR = \frac{r(300K)}{r(4.2K)} \]

RRR is related to the thermal conductivity

For Nb: \( l(T = 4.2K) \approx RRR/4 \text{ (W. m}^{-1}. \text{K}^{-1}) \)
Note: $H_{tb}$ has nearly no dependence on $T_B < 2.1$ K
Magneto-thermal Breakdown

- Quench location identified by T-mapping
- Morphology of quench site reproduced by replica technique

Local Magnetic Field Enhancement:
Quench when $\beta H > H_c$
Magneto-thermal Breakdown: Maximum $E_{acc}$

$$E_{acc}^{\text{max}} = d \frac{r H_{c,RF}}{\beta_m \left( H_p / E_{acc} \right)}$$

$r \leq 1$, reduction of the local critical field within the penetration depth, due to impurities or lattice imperfection

$d$, thermal stabilization parameter $\propto \sqrt{\kappa}$

$\beta_m > 1$, geometric field enhancement factor
Type of Defects

Surface defects, holes can also cause TB

0.1 – 1 mm size defects cause TB

No foreign materials found
Optical Inspection

- long distance microscope (Cornell)
  - resolution: 12 μm/pixel (limited by camera)
- University Kyoto and KEK camera system
  - resolution: 7 μm/pixel
  - variable light system for height measurement

Camera light source

9x13 mm
Defects Seen by Optical Inspection

Cell 6, Quench at 16 MV/m on equator

- Holes with sharp edges along the grain boundaries in the equator weld
- Pits around the holes.

- Auger analysis: no foreign material
- EDX analysis: increased content of carbon in black spots
Defects Seen by Optical Inspection

Cell 5, Quench at 23 MV/m on equator

hole in the equator weld

3D image, bump and hole up to 200 µm deep

No foreign material inclusions detected by EDX

Ken Watanabe
Kyoto Camera

M. Hoos, Heraeus
X. Singer, DESY

SEM

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Cures for Quench

• **Prevention: avoid the defects**
  – High-quality Nb sheets
  – Eddy-current scanning of Nb sheets
  – Great care during cavity fabrication steps

• **Post-treatment:**
  – Thermally stabilize defects by increasing the RRR
  – Remove defects: local grinding
Disadvantages:

- > 50 μm material removal necessary after heat treatment
- Significant reduction of yield strength of the Nb

Post-purification for Higher RRR

- Post-purification by solid-state gettering
- use Ti (or Y) as getter material => higher affinity for O, (N, C) than Nb
  - coating of cups or cavity with getter material at 1350 C (Ti) under UHV
  - diffusion of O from Nb to Ti until equilibrium

- 1) Increase of $\text{RRR} = 250-300$ to $\text{RRR} = 500 – 700$
- 2) Homogenizing impurities

Graph showing the variation of RRR with layer position on the cross-section of the sample, μm
Post-purification

Quench Field and niobium RRR
F = 1.3 GHz, T = 1.7 K

- RRR 150
- RRR 250
- RRR > 500

RF limit (No Quench)

CEA Saclay, SEA / GECS

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Post-purification

Benefit of the high temperature heat treatments

- After 800°C
  - Average 23.5 MV/m
- After 1400°C
  - Average 26 MV/m

Number of cells

$E_{acc}$ [MV/m]

Lutz Lilje DESY

27.02.02

Jefferson Lab
How High of RRR Value is Necessary?

- 9-cell ILC cavities

100 µm diameter nc defect
Defect Repair: Local Grinding

Polymond + water for grinding
Polymond: diamond particles in a resin (particle size = 40 ~ 3 um)
Defect Repair: Local Grinding

Before Grinding

After Grinding and EP 50um

Quench at $E_{\text{acc}} = 20 \text{ MV/m}$

Figure 1: $Q_0$ vs $E$ runs at 2.00K and 1.80K.
Summary on Quench

• Big improvement in Cavity fabrication and treatment
  less foreign materials found (at limitations <20MV/m only)

• Visual inspection systems are available

• Many irregularities in the cavity surface are found with this systems
  during and after fabrication and treatment
    pits and bumps
    weld irregularities

• Often one defect limits the whole cavity

• Some correlations are found between defects and quench locations
  at higher fields
    But often no correlation between suspicious pits and bumps and quench
    location

• At gradient limitations in the range >30 MV/m defects are often not
  identified
High-Field Q-Slope ("Q-drop")

- Residual losses
- Multipacting
- Field emission
- Thermal breakdown
- RF Processing
- Ideal
- Quench

Accelerating Field vs. $Q$
The origin of the Q-drop is still unclear. Occurs for all Nb material/treatment combinations.

The Q-drop recovers after UHV bake at 120 °C/48h for certain material/treatment combinations.
Experimental Results on Q-drop

- "Hot-spots" in the equator area (high-magnetic field)
Experimental Results on Q-drop

- Q-drop and baking effect observed in both $TM_{010}$ and $TE_{011}$ modes. TE mode has no surface electric field.

Q-drop: high magnetic field phenomenon

Onset of Q-drop is higher for
- smooth surfaces
- reduced number of grain boundaries
Baking: Material and Preparation Dependence

Baking **works** on cavities made of:

- Large-grain Nb (buffered chemical polished or electropolished)

![Smooth surface, few grain boundaries](image)

- Fine-grain Nb, electropolished

![Smooth surface, many grain boundaries](image)

- Fine-grain Nb, post-purified, BCP

![Smooth surface, fewer grain boundaries](image)

Baking **does not work** on cavities made of:

- Fine-grain Nb, buffered chemical polished

![Rough surface, many grain boundaries](image)
Recipe against Q-drop

- Recipes necessary to overcome the Q-drop, depending on the starting material, based on current data:

  - Large grain/Single crystal niobium
    - Titanization
  - Fine grain niobium
    - Titanization

  - BCP
    - 120 °C/12 h UHV bake

  - EP
    - 120 °C/48 h UHV bake
Baking Effects on Low-field $R_s$ and $H_{c3}$

- Decrease of $R_{BCS}$ due to ↓ of $l$ and ↑ of energy gap
- The physics of the niobium surface changes from CLEAN ($l > 200$ nm) to DIRTY LIMIT ($l \approx 25$ nm $\approx \xi_0$)

$r_{32} = B_{c3}/B_{c2}$: depends on bake temperature and duration

\[ r_{32} = \frac{B_{c3}}{B_{c2}} \]: depends on bake temperature and duration
Models of Q-drop & Baking

- Magnetic field enhancement
- Oxide losses
- Oxygen pollution
- Magnetic vortices
Magnetic Field Enhancement Model

Local quenches at sharp steps (grain boundaries) when $\beta_m H > H_c$

$\beta_m$: Field enhancement factor

- $Q_0(B_p)$ calculated assuming
  - Distribution function for $\beta_m$ values
  - The additional power dissipated by a quenched grain boundary is estimated to be $\sim 17$ W/m

MFE Model: Shortcomings

The model cannot explain the following experimental results:

- Single-crystal cavities have Q-drop
- Seamless cavities have Q-drop
- Low-temperature baking does not change the surface roughness
- Electropolished cavities have Q-drop, in spite of smoother surface
Interface Tunnel Exchange Model

- Interface Tunnel Exchange (ITE) model
  - Resonant energy absorption by quasiparticles in localized states in the oxide layer
  - Driven by electric field $E_0 > \frac{\varepsilon_r \Delta}{e \beta z}$

$$R_s^E = b \left[ e^{-c/E_p} - e^{-c/E_0} \right] + \left( c \frac{E_p e^{-c/E_p} - c}{E_0 e^{-c/E_0}} \right) + \frac{1}{2} \left( \frac{c^2}{E_p^2} e^{-c/E_p} - \frac{c^2}{E_0^2} e^{-c/E_0} \right)$$

ITE Model: Shortcomings

The model cannot explain the following experimental results:

• The baking effect is stable after re-oxidation
• The Q-drop was observed in the TE$_{011}$ mode (only magnetic field on the surface)
• The Q-drop is re-established in a baked cavity only after growing an oxide ~ 80 nm thick by anodization
Oxygen Pollution Model

- Surface analysis of Nb samples shows high concentrations of interstitial oxygen (up to ~ 10 at.%) at the Nb/oxide interface.
- Interstitial oxygen reduces $T_c$ and the $H_{c1}$.

**Magnetic vortices enter the surface at the reduced $H_{c1}$, their viscous motion dissipating energy**

- The calculated O diffusion length at $120^\circ$C/48h is ~ 40 nm.
- Interstitial oxygen is diluted during the $120^\circ$C baking, restoring the $H_{c1}$ value for pure Nb.

### Graph

![Graph showing oxygen concentration as a function of temperature](image)

**Graph: Calculated oxygen concentration at the metal/oxide interface as a function of temperature after 48h baking**

Oxygen Pollution Model: Shortcomings

The model cannot explain the following experimental results:

- The Q-drop did not improve after 400°C/2h “in-situ” baking, while O diffuses beyond λ
- The Q-drop was not restored in a baked cavity after additional baking in 1 atm of pure oxygen, while higher O concentration was established at the metal/oxide interface
- Surface analysis of single-crystal Nb samples by X-ray scattering revealed very limited O diffusion after baking at 145°C/5h
Fluxons as Source of Hot-Spots

- Motion of magnetic vortices, pinned in Nb during cool-down across $T_c$, cause localized heating

- Periodic motion of vortices pushed in & out of the Nb surface by strong RF field also cause localized heating

The small, local heating due to vortex motion is amplified by $R_{BCS}$, causing cm-size hot-spots
Thermal Feedback with Hot-Spots Model

- The effect of “defects” with reduced superconducting parameters is included in the calculation of the cavity $R_s$

- This non-linear $R_s$ is used in the heat balance equation

\[
Q_0 \left( B_p \right) = \frac{Q_0(0) e^{-\theta}}{1 + g \sqrt{1 - \left( \frac{B_p}{B_{b0}} \right)^2}}
\]

Fit parameters:

- $g$ related to the No. and intensity of hot-spots
- $Q_0(0)$ low-field $Q_0$
- $B_{b0}$ quench field

Q-drop: Recent Samples Results

Samples from regions of high and low RF losses were cut from single cell cavities and examined with a variety of surface analytical methods. No differences were found in terms of:

- roughness
- oxide structure
- crystalline orientation

It was found that “hot-spot” samples have a higher density of crystal defects (i.e. vacancies, dislocations) than “cold” samples.