Physics of superconducting cavity: towards realizations of high-Q and high gradient cavities

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第14回日本加速器学会年会（2017年8月1日）
electron
Large accelerating electric field

\( E_{\text{acc}} \)
Large accelerating electric field $E_{\text{acc}}$

Small surface resistance $R_s$

Or Large Quality factor $Q_0 \propto \frac{1}{R_s}$
Nb cavity processed by the standard ILC recipe

$T = 2 \text{ [K]}$

$E_{acc}$ (standard ILC recipe)
Nb cavity processed by the N or Ti doping recipe

We want to go beyond the limits of the present technologies!

- **High Q**: (Nitrogen doping)
- **High $E_{acc}$**: (standard ILC recipe)

$E_{acc}$ (MV/m)

$T = 2$ [K]
We want to go beyond the limits of the present technologies!

How?

High $Q$ (Nitrogen doping)

High $E_{acc}$ (standard ILC recipe)

$T = 2$ [K]
Basics towards high gradients
Magnetic field distribution

Low field (Meissner state)

Magnetic field distribution
Magnetic field distribution

Low field (Meissner state)

High field (vortex state)

Magnetic field distribution

Vortex Avalanche

To achieve a high field, a material that can withstand against the vortex penetration up to a high magnetic field should be used.
So we use Nb as the material of SRF cavity. The lower critical field of pure Nb is $B_{c1} \approx 170 \text{ mT} \ (E_{\text{acc}} \approx 40 \text{MV/m for TESLA cavity})$, which is larger than other superconductors.

※ The other reason is the thermal conductivity. Today I do not talk about this topic.
So we use Nb as the material of SRF cavity. The lower critical field of pure Nb is $B_{c1} \approx 170 \text{ mT}$ ($E_{acc} \approx 40 \text{ MV/m}$ for TESLA cavity), which is larger than other superconductors.
Even if ultra pure Nb was used, achieving $B_{c1} \sim 170 \text{ mT}$ ($E_{acc} \sim 40 \text{ MV/m}$) was not a straightforward task.
Even if ultra pure Nb was used, achieving $B_{c1} \approx 170$ mT ($E_{acc} \approx 40$ MV/m) was not a straightforward task.

How did SRF researchers achieve $E_{acc} > 40$ MV/m?
ILC recipe
C. Antoine

27/04/2013

Electropolishing
- Chemical polish: 100-200 μm
- Electropolish: 5-20 μm
- Specific rinsing
- High pressure rinsing (HPR)
- Assembling
- Baking, 120°C, 12-48 hr
- Post-processing
- Test RF
- He processing, HPP

WHY
- Clean welding
- RRR enhancement
- Remove contamination and damage layer
- Get rid of hydrogen
- Remove diffusion layer (O, C, N)
- Ancillaries: antennas, couplers, vacuum ports...
- Decrease high field losses (Q-drop)
- Get rid of “re-contamination”?
- Cavity’s performance
- Decrease field emission

COMMENTS
- Nb = getter material. If RRR/ 10 @ welding => Q/10
- RRR 300-400 now commercially available
- Limitation: BCP ~ 30MV/m; EP => >40 mV/m but lack of reproducibility
- Source of H: wet processes. H segregates near surface in form of hydrides (= bad SC)
- Diffusion layer < ~1μm in bulk, a little higher at Grain Boundaries
- Under evaluation: HF, H₂O₂, ethanol, degreasing,...
- Not always enough (recontamination during assembly)
- In clean room, but recontamination still possible
- Unknown mechanism, first 10 nm of the surface in concern.
- Under evaluation: dry ice cleaning, plasma
- First naked cavity in vertical cryostat, then dressed in horizontal cryostat/accelerating facility
- RF power with/ without He to destroy field emitters (dust particles)
- NB field emission: principal practical problem in accelerators
Electropolish
Chemical etching
100-200 µm

Annealing
800°C, 2h
(or 600°C, 10h)

Electropolish
Chemical polish
5-20 µm

Specific rinsing

High pressure rinsing (HPR)

Assembling

Baking, 120°C, 12-48h

Post-processing

He processing, HPP

WHY
Clean welding

COMMENTS
Nb = getter material.
If RRR/10 @ welding => Q_0/10

Decrease field emission

RF power with/without He to destroy field emitters (dust particles)
NB field emission: principal practical problem in accelerators

C. Antoine
27/04/2013

Electron beam
C. Antoine

27/04/2013

**Electropolish**

- Annealing
  - 800°C, 2h
  - (or 600°C, 10h)
- High pressure rinsing (HPR)
- Assembling
- Baking, 120°C, 12h

**BCP**
- EP
- CPP

**COMMENTS**

- Nb = getter material.
  - If $\text{RRR} < 10$ @ welding $\Rightarrow Q/10$
- $\text{RRR} 300-400$ now commercially available
- Limitation: BCP $\sim 30\text{MV/m}$; EP $\Rightarrow >40\text{ mV/m}$, but lack of reproducibility
- Source of H: wet processes

**WHY**

- Clean welding
- RRR enhancement
- Remove contamination and damage layer
- Decrease field emission
- RF power with/without He to destroy field emitters (dust particles)
- NB field emission: principal practical problem in accelerators
If we skip this step, cavities suffer “Q-disease” due to niobium hydride

“Q-disease”

B. Aune et al., in proceedings of LINAC1990, Albuquerque, New Mexico, USA (1990)
**Electropolish**

Chemical polishing 100-200 μm

Annealing 800°C, 2h

Electropolish 5-20 μm

Specific rinsing

High pressure rinsing (HPR)

Assembling

Baking, 120°C, 12h

Post processing

Test RF

He processing, HP

**WHY**

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If we skip this step, Q would degrade due to the field emissions.

P. Bernard et al.,
In proceedings of EPAC1992, Berlin, Germany (1992)
C. Antoine

Electropolish
- Chemical polishing: 5-20 μm

Annealing
- 800°C, 2h (or 600°C, 10h)

BCP
EP
CBP

Specific rinsing
High pressure rinsing (HPR)

Assembling

Test RF

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Baking, 120°C, 12-48hr

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27/04/2013

Claire Antoine

SRF2013 Tutorial @ GANIL
What is the 120°C-48hours bake?

Without baking

High field Q-drop

What is the 120°C-48hours bake?

At the present day, we know...


By using Low Energy muon spin rotation technique
At the present day, we know

The baked Nb has a layered structure that consists of

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The baked Nb has a layered structure that consists of

1. dirty Nb layer

At the present day, we know

The baked Nb has a layered structure that consists of

1. dirty Nb layer
2. clean bulk Nb

At the present day, we know

The baked Nb has a layered structure that consists of

1. dirty Nb layer and
2. clean bulk Nb.

Dirty Nb  Clean Nb
Since excited quasiparticles increase and contribute to the surface resistance as the gap decreases, a larger gap is desired. The gap in the dirty layer is rather well behaved at a high field! → cure the high field Q drop

Note here $B_{c1}$ is a bulk property and given by the bulk clean SC: $B_{c1} \sim 170$ mT remains after layered.

Gap under a current (narrow!)
Becomes gapless before arriving at the superheating field!
The surface current is suppressed.

- The current suppression means an enhancement of the field limit, because the theoretical field limit is determined by the current density.
- The gap reduction due to the current is further prevented.

\[ \lambda_1 (> \lambda_2) \quad \lambda_2 \]

This slope corresponds to the current density. The surface current is suppressed!

SS case:

SIS case:

Vortices are expelled by the boundary if $\lambda^{(\text{layer})} > \lambda^{(\text{bulk})}$. (left figure)

- M. Checchin et al., in Proceedings of IPAC2016, p. 2254, WEPMR002
References
(recent findings related to the ILC recipe)


解説
● T. Kubo, in proceedings of the International Workshop on Future Linear Colliders (LCWS2016), Morioka, Japan (2016).
● T. Kubo, Journal of the Particle Accelerator Society of Japan, 14, 35 (2017).[日本語]
Nitrogen doping

P. Dhakal

Ti-doping

Electropolishing
Chemical polishing 100-200 µm
Annealing 800°C, 2h (or 600°C, 10h)
Specifc rinsing
High pressure rinsing (HPR)
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C. Antoine
27/04/2013

SRF2013 Tutorial @ GANIL CAS
C. Antoine
27/04/2013

WHY

- Clean welding
- RRR enhancement
- Remove contamination and damage layer
- Get rid of hydrogen

COMMENTS

- Nb = getter material.
  If RRR > 10 @ welding => Q/10

- RRR 300-400 now commercially available

- Limitation: BCP ~ 30MV/m; EP => >40 mV/m but lack of reproducibility

- Source of H: wet processes
  H segregates near surface in form of hydrides (e.g. NbH2)

N-doping treatment

- 800°C UHV, 3 hours
- 800°C N2 injection p=25mTorr
- 800°C N2, 2 minutes
- 800°C UHV, 6 minutes
- UHV cooling
- 5 µm EP

He processing, HPP

Fermilab
Inject $N_2$ gas ($\sim 3 \times 10^{-5}$ Pa) at 800°C for 2 minutes.
Inject N\textsubscript{2} gas (~3 × 10^{-5} Pa) at 800°C for 2 minutes.
Inject $\text{N}_2$ gas ($\sim 3 \times 10^{-5}$ Pa) at 800°C for 2 minutes.
Inject N\textsubscript{2} gas (\(\sim 3 \times 10^{-5}\) Pa) at 800\textdegree C for 2 minutes
Electropolish by 5-7μm
Then we obtain a “high Q”
Why does $Q$ increase as the field increases?
Why does $Q$ increase as the field increases?

Let us begin with a brief review of the surface resistance of SRF cavity.
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The gap is much larger than RF: RF ($\sim$ GHz) cannot break Cooper pair.
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The gap is much larger than RF: RF ($\sim$ GHz) cannot break Cooper pair.

However, when $T > 0$, Quasiparticles (normal electrons) necessarily exist above the gap.
Why does $Q$ increase as the field increases?

Let us begin with a brief review of the surface resistance of SRF cavity.

The gap is much larger than RF: RF ($\sim$ GHz) cannot break Cooper pair.

However, when $T > 0$, Quasiparticles (normal electrons) necessarily exist above the gap. They absorb RF

\[ R_s \neq 0 \]

\[ R_s \approx \int d\varepsilon N(\varepsilon)N(\varepsilon + \hbar \omega) e^{-\varepsilon/kT} \]
Why does $Q$ increase as the field increases?

$$R_s \propto \ln \frac{1}{\text{peak width}}$$

Zero field

$N(\varepsilon)$

$\varepsilon_g/\Delta_0$

Why does $Q$ increase as the field increases?

$$R_s \propto \ln \frac{1}{\text{peak width}}$$

Finite field

The broaden DOS peak reduces $R_s$!

- $R_s$ of ideal dirty SC generally decreases as the field increases: the Q-increase phenomenon is rather natural behavior of dirty SC.

- However, very low RRR($\sim$10) Nb cavities, which are also dirty SC, do not show the “Q-increase”. What is the difference between N and other impurities? What is the role of N?
Disadvantage of N-dope: Q increases but gradient decreases.

The reason is **obvious**!

Interstitial $N$ reduces mean free path: $RRR=300$ ($mfp > 700\text{nm}$) material → $mfp \sim 50\text{nm}$


Then $B_{c1}=170\text{mT}$ → $B_{c1}=130\text{mT}$

$E_{\text{acc}}=40\text{MV/m}$

which corresponds to $E_{\text{acc}}=30\text{MV/m}$!!
Superheating field $B_s$ of dirty Nb

$B_{c1}$ around here

※Tesla空洞の35MV/mは150mTに対応

T. Kubo,
$B_{c1}$ around here

N-dope is not really suited to high gradient application!

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T. Kubo, 
References
(related to the N-dope)

• A. Gurevich, Phys. Rev. Lett. 113, 087001 (2014)
• M. Martinello et al, Appl. Phys. Lett. 109, 062601 (2016)
N infusion
(new ILC recipe?)
They knew

1. The dirty-clean layered structure realized in ILC recipe (120°C-48 hours bake) is the key to high gradients.

2. Nitrogen doping is the key to high Q.

They considered

“Let us combine 1 and 2”

→ Nitrogen infusion
Inject N$_2$ gas (~3 × 10$^{-5}$ Pa) at 120°C for 48 hours.
Inject $N_2$ gas ($\sim 3 \times 10^{-5}$ Pa) at 120°C for 48 hours.

No chemistry.
Inject N\textsubscript{2} gas \((\sim 3 \times 10^{-5} \text{ Pa})\) at 120\textdegree C for 48 hours.
Then we obtain “high-$Q$ & high gradient”
Is nitrogen really playing a role at 160C (BCS reversal)?

YES ✓

- Repeated same procedure with and without nitrogen in furnace at 160C (both of comparable ultra-purity 99.9999%)
- Check if other impurities may be the ones responsible for BCS reversal, rather than nitrogen

Nitrogen played a role
Why is the high gradient possible?
Let us remind the small $B_{c1}$ of N-dope comes from its dirtiness at the depth up to $\mu$m.
Why is the high gradient possible?

Let us remind the small $B_{c1}$ of N-dope comes from its dirtiness at the depth up to μm.

Regraded as a bulk dirty SC $B_{c1}=130$ mT (30 MV/m)
Why is the high gradient possible?

In the N-infusion case, the dirty region is confined in the first tens of nm.

\[ \text{A few tens of nm} \]
Why is the high gradient possible? In the N-infusion case, the dirty region is confined in the first tens of nm.

RF sees dirty and clean SC

$B_{c1}=170\text{mT} \quad (40\text{MV/m})$

A few tens of nm

Screening current

100nm
Why is the high gradient possible?

In the N-infusion case, the dirty region is confined in the first tens of nm.

This effect may also play a role in pushing up gradient.

Vortices are expelled by the boundary if \( \lambda^{\text{layer}} > \lambda^{\text{bulk}} \). (left figure)

Why is the high $Q$ possible?

Open Question

- Probably the similar mechanism as $N$-dope: remind the cavity behavior approaches $N$-dope behavior when baking $T$ increases.

- What is the role of $N$?

- $N$ induces high $Q$, but others do not. This might be the key to understand it.


Flux expulsion
This is really excellent finding, but we do not have enough time to introduce this today.  


References
(related to the flux expulsion)

● S. Posen et al., J. Appl. Phys. 119, 213903 (2016)
Further high-Q and high-Grad
(Ultra) High-Q
\( \text{Nb}_3\text{Sn} \) has attracted much attention as the next generation “high-Q” SRF material.
S. Posen and D. L. Hall, 
4.2K

S. Posen and D. L. Hall,
Why so high $Q$?

The gap is large, so the number of normal electrons at a given $T$ is exponentially small.

Note that BCS’s relation $\Delta = \frac{\pi}{e \gamma E} k_B T_c \approx 1.76 k_B T_c$.
(Ultra) High-Gradient
Stable Meissner state if $B < B_{c1} = 170 \text{mT}$

● Stable Meissner state if $B < B_{c1} = 170 \text{ mT}$
● Metastable at $B > B_{c1} = 170 \text{ mT}$
• Stable Meissner state if $B < B_{c1}=170\text{ mT}$
• Metastable at $B > B_{c1}=170\text{ mT}$
• The world record exceeds $B=200\text{ mT}$, which is close to the ultimate limit!

We need to explore new materials!

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However...

Stable Meissner state at $B < B_{c1} \sim 50 \text{mT}$, which corresponds to $E_{\text{acc}} = 10-20 \text{MV/m}$

However...

- Stable Meissner state at $B < B_{c1} \sim 50\text{mT}$, which corresponds to $E_{\text{acc}} = 10-20\text{MV/m}$
- This region is not stable!
Experimental results have been limited by $B \approx 70\text{mT}$ ($E_{\text{acc}} = 17\text{MV/m}$)

S. Posen and D. L. Hall,
Experimental results have been limited by $B \sim 70\text{mT}$ ($E_{\text{acc}} = 17\text{MV/m}$)
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To go far away from $B_{c1}$, any tiny defects must be removed!
Experimental results have been limited by $B \sim 70\text{ mT}$ ($E_{c}\sim 17\text{ MV/m}$)

J. I. Vestgården, D. V. Shantsev, Y. M. Galperin & T. H. Johansen,
*Scientific Reports* 2, 886 (2012)
How to avoid the avalanches?
Further advanced layered structures

Dirty Nb₃Sn (~100nm)  Clean Nb

The fourfold benefit of the layered structure will improve the maximum $E_{\text{acc}}$ and $Q_0$: (1) the reduction of gap is small in the dirty layer
(2) suppress the surface current and enhance the theoretical field limit
(3) prevent the vortex penetration by the additional barrier
(4) In addition, since a part of current flows on the low loss surface, Nb₃Sn, dissipation decreases and Q increases.

- See also the discussion section of T. Kubo, Progress of Theoretical and Experimental Physics 2015, 063G01 (2015)
- T. Kubo, TTC meeting at Saclay France (2016)
How to avoid the avalanches?

Further advanced layered structures

Dirty Nb$_3$Sn ($\sim$100nm) insulator Clean Nb

Furthermore, introducing the insulator layer (1) prevent the vortex penetration and (2) suppress vortex dissipation, because the vortex core disappears in the insulator layer.

e.g.) \( \text{Nb}_3\text{Sn} / \text{thin insulator} / \text{Nb substrate} \) or \( \text{Nb}_3\text{Sn} / \text{Nb substrate} \)

Note this shows just theoretical field limits. Whether we can achieve them depends on whether a gimmick to avoid vortex penetration works well or not. See T. Kubo, TTC meeting at France (2016) or Supercond. Sci. Technol. to be published (arXiv:1607.01495)

\( B_s(\text{Nb}_3\text{Sn}) = 0.84 \times 540 \text{mT} = 450 \text{mT} \)
\( \lambda_1 = 120 \text{nm} \)

\( B_s(\text{substrateNb}) = 240 \text{mT} \)
\( \lambda_2 = 40 \text{nm} \)

\( B_{\text{opt max}} = \sqrt{(B_s^{(S)})^2 + \left(1 - \frac{\lambda_2^2}{\lambda_1^2}\right)\left(B_s^{(\text{sub})}\right)^2} \)

\( d_s = \lambda_1 \log \left[ \frac{\lambda_1}{\lambda_1 + \lambda_2} \frac{B_s^{(S)}}{B_s^{(\text{sub})}} + \sqrt{\left(\frac{\lambda_1}{\lambda_1 + \lambda_2} \frac{B_s^{(S)}}{B_s^{(\text{sub})}}\right)^2 + \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2}} \right] \)

- T. Kubo, talk at SRF2015, Whistler, Canada (2015), TUBA07.
- T. Kubo, TTC meeting at Saclay France (2016)
References
(related to Ultra high-Q & high-grad)

\[ \text{Nb}_3\text{Sn} \]

- T. Tan et al., Scientific Reports 6, 35879 (2016).
Summary

Superficial introduction to hot topics in SRF

- Basics of SRF
- ILC recipe
- N-dope
- N-infusion
- Flux expulsion
- \( \text{Nb}_3\text{Sn} \) for ultra high-Q SRF
- Layered structure for ultra high-G

Too short to introduce these topics! Please read the references!
Ultra high-Gradient for the ILC 1TeV upgrade!!

- Bare clean Nb (1990s)
- Baking (1990s)
- N-infused Baking (2010s)
- "MgB$_2$ on Nb" sample (2016)

$T = 2 \, [K]$