State-of-the-Art and Future Prospects in RF Superconductivity

Kenji Saito*

High Energy Accelerator Research Organization (KEK) / Michigan State University (MSU), FRIB

- Specifics and Constrains in SRF Cavities
- SRF Performance on Niobium Cavities Over The Past 50 Years
- Future Prospects

* Moving from KEK to MS, FRIB
Surface resistance is very small and very small intrinsic surface heating.

- **Unexpected phenomenon dominates the heating and limits the performance.**
- **Cavity performance strongly depends on the surface.**
- **Thermal conductivity @ superconducting state is very small.**
- **High thermal conductivity of the cavity wall @ low temperature is very important.**
Field emission and Multipacting are related to surface contamination, which are mitigated by making clean SRF surface.

Thermal instability occurs at surface defects, which is suppressed by using high thermal conductivity Nb: High pure niobium.

Hydrogen Q-disease happens by niobium-hydride doped hydrogen during surface processing. This is cured by hydrogen degassing.
Understanding & Technologies Over Past 50 Years

1965 ~ 1975
- Stanford University IHEP
  - Pb, Nb materials, CP, EP

1975 ~ 1980
- Elliptical/Spherical cavity shape against multipacting
  - Cornell University Muffinten

1978 ~ 1985
- Heavy Ion application
  - Germany, Kalushuhe Nuclear Institute (KFK)
  - Argonne National labs (ANL)
  - Mechanical Tuner
    - California Institute of Technology (CLTEC), State University of New York

1978 ~ 1985
- Cleanroom, Ultrapure Water against Field emission

1975 ~ 1980
- Purification of Nb, Y or Ti purification, High T annealing

1980 ~ 1990
- Recirculating machine
  - CEBAF (Jlab), DALLINAC (Darmstadt)
  - FEL 1995 ~
    - Jlab-FEL, JAERI FEL

1990 ~ 2008
- High Gradient application
  - TESLA (DESY)
  - EP+Bake against Q-slope
    - HPR, CBP
  - Eacc ~ 30MV/m

2006 ~
- Many light source applications
  - Storage Ring ‘90~2000
    - TRISTAN (KEK)
    - HERA (DESY)
    - LEP-II (CERN)

2015 ~
- Heavy ion 1978 ~
  - ATLAS (ANAL)
  - JAERI Tandem buster
    - INFIN LEGNRO

2014 ~
- SNS 2006 ~
  - RIA

2014 ~
- FRIB, ....

High current 1996 ~ 2010
- KEKB
- CESER
- 1A
- Many light source applications

FEL 995 ~
- Jlab-FEL, JAERI FEL

Large Grain Nb

High gradient cavity shape

Eacc ~ 5MV/m

Horizontal EP, Degassing, Baking, High RRR Nb production
Multipacting

MP limited the gradient seriously in the early SC cavity R&D in Stanford Uni.

Courtesy of H. Padamsee

1 point MP
SRF Clean Surface by Adopting Semiconductor Technologies

Particles are seeds of FE!

Use ultrapure water, cleanroom assembly

Before and After images show the effectiveness of using semiconductor technologies for cleaning surfaces.
Vapor Pressure vs. T

Vendor High Purity Nb Material Production

Change of RRR over melting times

Max 93 128 289 323 378 396 370
Average 46 90 183 240 296 301 329
Min 23 54 109 181 202 235 295

Crucial conditions
1) higher vacuum
2) larger molten surface
3) multi-melting

Melting Cycles

Maximum RRR
Titanification
Chemical Processing for Production Cavities

Buffered Chemical Polishing, CEBAF

Horizontal Electropolishing, TRISTAN
World Wide SC Accelerators in 1990'

- Nb coated on Copper cavities

- LEP-II

- CEBAF

- South Linac Cryomodules

- TRISTAN

- HERA

~ 5MV/m CW operation
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  - Y or Ti purification, High T annealing

**1980 ~ 1990**
- New cavity shape
  - High Grain Nb
- Large Grain Nb

**1990 ~ 2000**
- Storage Ring
  - TRISTAN (KEK)
  - HERA (DESY)
  - LEP-II (CERN)
- Recirculating machine
- HPR, CBP
- Eacc ~ 5MV/m

**1995 ~**
- Jlab-FEL, JAERI FEL
- Heavy ion 1978 ~
  - ATLAS (ANAL)
  - JAERI Tandem buster

**2000 ~ 2010**
- KEKB
- CESER
- Many light source applications
- High current 1996 ~ 2010
- TESLA (DESY)
- EURO XFEL
- High gradient application
  - 1990 ~ 2008
  - TESLA (DESY)

**2010 ~ 2015~**
- High gradient cavity shape
- Heavy ion 2015 ~
  - ATLAS (ANAL)
  - JAERI Tandem buster
- SNS 2006 ~
  - RIA

**2014 ~**
- FRIB, ....
High Pressure Water Rinsing (HPR)

From ultrapure water system
Pressure regulator
Filter
Rotation

TRISTAN rinsing method

HPR rinsing

Courtesy of P.Kneisel

Graph showing E acc [MV/m] vs. E peak [MV/m] with Q-slope, TESLA500-target, and TESLA2000 target.
Superiority of EP on HG and Baking Effect of High Field Q-Slope

BCP limits HG to ~25 MV/m but EP pushes it to 40 MV/m

BCP degrades HG but EP recovers the HG.

EP+ Bake eliminates the Q-slope

BCP+ Bake works partially on Q-slope

Courtesy of Saclay

Before Bake
After Bake

S-3 Cavity : CP after EP & EP after CP
No Heat treated, RRR=230

S-3 cavity : EP, HPR, No bake
S-3 cavity : EP, HPR, Bake(120°C)

EP+ Bake eliminates the Q-slope

BCP+ Bake works partially on Q-slope
High Gradient Cavity Shape for 50MV/m

Cavity shape designs with low Hp/Eacc

<table>
<thead>
<tr>
<th></th>
<th>TESLA</th>
<th>LL</th>
<th>RE</th>
<th>IS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter [mm]</td>
<td>70</td>
<td>60</td>
<td>66</td>
<td>61</td>
</tr>
<tr>
<td>Ep/Eacc</td>
<td>2.0</td>
<td>2.36</td>
<td>2.21</td>
<td>2.02</td>
</tr>
<tr>
<td>Hp/Eacc [Oe/MV/m]</td>
<td>42.6</td>
<td>36.1</td>
<td>37.6</td>
<td>35.6</td>
</tr>
<tr>
<td>R/Q [W]</td>
<td>113.8</td>
<td>133.7</td>
<td>126.8</td>
<td>138</td>
</tr>
<tr>
<td>G[W]</td>
<td>271</td>
<td>284</td>
<td>277</td>
<td>285</td>
</tr>
<tr>
<td>Eacc max</td>
<td>41.1</td>
<td>48.5</td>
<td>46.5</td>
<td>49.2</td>
</tr>
</tbody>
</table>

TTF: TESLA shape
Reentrant (RE): Cornell Univ.
Low Loss(LL): JLAB/DESY
Ichiro—Single(IS): KEK

Courtesy of J.Sekutowicz
History of upgraded gradient in SRF

- **1st Breakthrough!**
  - High pressure water rinsing (HPR)

- **2nd Breakthrough!**
  - New Shape

- **Chemical Polishing**
  - RE, LL, IS shape

- **Electropolishing (EP)**
  - + HPR + 120°C Bake

Date [Year]:
- '91
- '93
- '95
- '97
- '99
- '00
- '03
- '05
- '07

Eacc,max [MV/m]:
- 10
- 20
- 30
- 40
- 50
- 60
- 70

K.Saito IPAC2012 Talk
12GeV CEBAF Upgrade by State-of-Art

Mainly HPR

By the state-of-the-art procedures: BCP + HPR + Improved cavity clean assembly

Improved by factor 2

Improved by factor 4

1) Higher gradient due to LL shape.
2) High Q performance due to LL shape.
3) Possible 25MV/m operation by EP + Baking, which brings a big operation margin.
4) State-of-art technology pushes the performance very much.

Courtesy of C. Reece
16 9-cell cavities (10 built by ACCEL/RI and 6 by AES) processed and tested at JLab since July 2008.

Each of the 3 failed cavities is limited by extraction cell.

Hpk 160-180 mT

Courtesy of R.Gen
ILC Baseline Gradient and Recent Achievement

Gradient Scatter (up to 2nd-pass proc.)

16 9-cell cavities (10 built by ACCEL/RI and 6 by AES) processed and tested at JLab since July 2008

Each of the 3 failed cavities is limited by one cell

Hpk 75-90 mT

Hpk 160-180 mT

Courtesy of R.Gen
ILC Baseline Gradient and Recent Achievement

Gradient Scatter (up to 2nd-pass proc.)

16 9-cell cavities (10 built by ACCEL/RI and 6 by AES) processed and tested at JLab since July 2008

85% accept

31.5 35 37 40 41 47

Theoretical limit
TESLA shape

36.9 +/- 1.85 MV/m (-10% from the limit)

Hpk 75-90 mT

Hpk 160-180 mT

Presumed distribution accept performance

10% σ=5%

Courtesy of R.Gen

Theoretical limit
TESLA shape
Large Grain Nb Cavities

Directly sliced Nb sheet from Ingot

Quench-sites inspected in AC151-AC158 so far: no "obvious defects", just etching pits (all over the cavity) and grain boundaries

Details: D. Reschke's poster TUPO046
Improvement of High Gradient in Various SRF Fields

Achieved Peak Surface Magnetic Field in L-band SRF Niobium Cavities
(Circle: Single-Cell Cavity; Triangle: Multi-Cell Cavity)

- DESY AC155, AC158
  - Hpk 1910-1950 Oe
  - New 9-cell record

- DESY Z93, AC146 & JLab RI27
  - Hpk 1810 - 1830 Oe
  - 9-cell record

- Cornell LR1-3
  - Hpk 2065 Oe
  - single-cell record

- ESS Elliptical, spoke
- FRIB QWR, HWR
- CEBAF 4 GeV
- CEBAF 12 GeV
- Project X
- XFEL
- ILC 500 GeV
- ILC 1 TeV

-Courtesy of R. Gen

- Best elliptical
- Best QWR, spoke
- Best HWR
- 650 Oe > 95% confidence

RLGENG21Jan2011
Fundamental Field Limit with Nb Cavity

Superheating Model

\[ H_{sh}(T) = c(\kappa)H_c\left(1 - \left(\frac{T}{T_c}\right)^2\right) \]

\( C(\kappa) = 1.05 \)

\[ E_{acc} = H_{sh} / (H_p / E_{acc}) = \frac{2000(\text{Oe})}{36(\text{Oe}/[\text{MV}/\text{m}])} \quad 56\text{MV}/\text{m} \]
Future Prospects in SRF Cavity

- High gradient shape ~15% upgrade
- Improved space factor ~10% upgrade
- Martial improve ~10% upgrade

Nb bulk Cavity  50~60MV/m fundamental Limit: Vortex entry @ Hc1

Exploring New Materials for 100~200MV/m & High Q

- Stopped Nb$_3$Sn(~1995) by weak link grain boundary effect
- Failed in HTS (1990') due to fundamental reason (d-wave)

Thin Film Multi-Layer Cavity

Alex Gurevich, APL 88, 012511 (2006)

20~30 years beyond

Understand Substrate boundary

Niobium Coated Film Cavity

Develop best coating technology
Superconducting Materials
No way to SRF application: High-Tc d-wave cuprates are SRF unsuitable: $R_s \propto T^2$

Classic HTSs are s-wave superconductors: $R_s \sim \exp(-\Delta/k_B T)$.

If weak link mechanism is solved, excellent performance is expected.
No way to SRF application:
High-Tc d-wave cuprates are SRF unsuitable: \( R_s \propto T^2 \).

Classic HTSs are s-wave superconductors: \( R_s \sim \exp(-\Delta/k_B T) \).

If weak link mechanism is solved, excellent performance is expected.

\( \Delta \) is the superconducting gap.

\( Nb_3Sn \) is a classic HTS, however, not yet achieved the expected performance due to weak link mechanism at grain boundary.
Alex's Idea of TFML (complicated)

Overcoming niobium limits (A. Gurevich, 2006):

- Keep niobium but shield its surface from RF field to prevent vortex penetration.
- Use nanometric films (w. d < \( \lambda \)) of higher Tc SC:
  - \( H_{c1} \) enhancement
- Example:
  - NbN, \( \xi = 5 \text{ nm}, \lambda = 200 \text{ nm} \)

\[
H_{c1} = 0.02 \text{ T} \\
H'_{c1} = 4.2 \text{ T} \times 200
\]

High \( H_{c1} \) => no transition, no vortex in the layer.
Applied field is damped by each layer.
Insulating layer prevents Josephson coupling between layers.
Applied field, i.e. accelerating field can be increased without vortex nucleation.
Thin film w. high Tc => low \( R_{\text{BCS}} \) at low field => higher \( Q_0 \)
Potential TFML Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$ (K)</th>
<th>$H_c$ [T]</th>
<th>$H_{c1}$ [mT]</th>
<th>$H_{c2}$ [T]</th>
<th>$\lambda(0)$ [nm]</th>
<th>$\Delta$ [meV]</th>
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<tr>
<td>Nb</td>
<td>9.2</td>
<td>0.2</td>
<td>170</td>
<td>0.4</td>
<td>40</td>
<td>1.5</td>
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<tr>
<td>$B_{0.6}K_{0.4}BiO_3$</td>
<td>31</td>
<td>0.44</td>
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<td>20</td>
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<td>200</td>
<td>2.6</td>
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<td>MgB$_2$</td>
<td>40</td>
<td>0.32</td>
<td>20-60</td>
<td>3.5-60</td>
<td>140</td>
<td>2.3; 7.1</td>
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<td>$Ba_{0.6}K_{0.4}Fe_2As_2$</td>
<td>38</td>
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High-$T_c$ d-wave cuprates are SRF unsuitable ($R_s \propto T^2$ instead of $R_s \propto \exp(-\Delta/T)$)

Large s-wave gap (good for SRF) is usually accompanied by low $H_{c1}$ (bad for SRF)

K.Saito IPAC2012 Talk

M. Iavarone et al., PRL 89, 187004 (2002)
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Courtesy of A. Gurevich

M. Iavarone et al., PRL 89, 187004 (2002)
Thin Films: Niobium – State of The Art

1.5 GHz Nb/Cu cavities, sputtered w/ Kat 1.7 K \( (Q_0=295/R_s) \)

Bulk Nb like performance

- Find best film coating technology
- Study the effect of substrate; Grain, Orientation, Preparation
New Material Hunting

High Peak short pulsing method

Klystron

1

55dB

10dB

Cryostat

Cavity

Mode converter

Bend

Load

Forward and reflected power trace
S15-1, H=23mT

Hpeak (mT)

Qo

X-band

100nm MgB₂/20nm Al₂O₃/Nb

T=7K

T=10K

T=4K

T=30K

T=40K

T=50K

T=60K

T=70K

T=80K

Power (W)

Time (µs)

Forward

Reflected

10dB

45dB

B

45dB

B

55dB

45d

B

1

2

3

4

5

6

7

Courtesy of SLAC

Qₒ = 100nm MgB₂/20nm Al₂O₃/Nb

X-band
The SRF performance of Nb bulk cavity has been very much improved in last two decades and is reaching the fundamental limit ~60MV/m.

This state-of-the-art technology is based on the well understanding of performance limits and thanks to its suitable feedback to technology R&D; High Purity Nb material vendor production, Electropolishing, High pressure water rinsing, Ultrapure water, Cleanroom assembly, Baking, Hydrogen degas annealing and so on.

Thin film multi-layer (TFML) coated cavity is proposed as the post niobium cavity for the gradient 100-200MV/m.

MgB$_2$, NbN, Nb$_3$Sn are most candidate materials for TFML.

Thin film coating technology has its specific issues learning from Nb film coated cavity, therefore TFML might not be straightforward to achieve the expected performance, it will take a time.

High peak puls measurement method is very suitable for new material hunting. This method could make faster finding the new material.
Backup Slides
Bulk Nb ultimate limits: not far from here!

The hot spot is not localized: the material is ~ equivalent at each location
=> cavity not limited /local defect, but by material properties?

Cavité 1DE3:
EP @ Saclay
T-map @ DESY
Film: courtoisie
A. Gössel + D. Reschke
(DESY, Début 2008)
EBW defects limiting the gradient around 20 MV/m

twin defects causing quench 17 MV/m. Cavity by a new vendor
Defect Elimination by Tumbling/CBP

FNAL ILC 9-cell cavity

Before CBP (equator EBW seam)

After CBP

December 2010, FNAL succeeded in improving the gradient by CBP+Annealing+EP (40μm) from 18MV/m limit to 35MV/m