Efforts for High-Q, High-G, and Large-Grain SRF Cavity Technology

Shin Michizono (KEK)
and
Akira Yamamoto (KEK and CERN)

To be presented at Workshop on the Circular Electron-Positron Collider, EU Edition, 2019
To be held at Oxford, 16 April, 2019
Outline

• **Introduction**
  • Advances in Superconducting Accelerator Technology for Particle Physics and Applications

• **Researches for High-Q and High-G**
  • N-doping, N-infusion, and Low-T baking.

• **Efforts for Cost-effective SRF Cavity Fabrication**
  • Large-grain Cavity

• **Summary**
Advances in Collider Accelerators

![Diagram showing the evolution of collider energies and commissioning years](image)

- Lepton Colliders
- Hadron Colliders
- Linear Colliders
- FCC-pp
- SppC
- CLIC
- ILC
- FCC-ee
- CEPC

Year of commissioning

- ISR
- PETRA
- SLC
- LEP II
- TRISTAN
- DORIS
- PEP
- SPEAR
- CESR
- KEKB
- ADONE
- VEPP 2
- PRIN-STAN

Centre-of-mass collision energy (GeV)

10^0, 10^1, 10^2, 10^3, 10^4, 10^5, 10^6, 10^7, 10^8, 10^9, 10^10

Study information provided by M. Benedikt, S. Stapnes, J. Gao, and A. Yamamoto

Courtesy, A. Ballarino
Global Future of the Superconducting Technology for Accelerators,

Future projects/Studies to be realized / anticipated

- **Particle/Nuclear Phys.:** ILC, FCC/HE-LHC, CEPC-SppC, JLEIC / eRHIC, and …
- **Photon Science:** CW-XFEL, and …
- **Neutron Sources:** CSNS, and …
- **Medical Applications:** Therapy, and further to be extended
- **Industrial Applications:** to be extended
Possible Choices of SC Materials for SRF

![Diagram showing critical magnetic fields and temperatures for superconductors](image)

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_c$ [K]</th>
<th>$B_{c1}(0)$ [T]</th>
<th>$B_{sh}(0)$ [T]</th>
<th>$B_{c2}(0)$ [T]</th>
<th>Type</th>
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<tbody>
<tr>
<td>Pb</td>
<td>7.2</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>I</td>
</tr>
<tr>
<td>Nb</td>
<td>9.2</td>
<td>0.18</td>
<td>0.21</td>
<td>0.28</td>
<td>II</td>
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<tr>
<td>NbTi</td>
<td>9.2 - 9.5</td>
<td>0.067</td>
<td>--</td>
<td>1.5 - 14</td>
<td>II</td>
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<tr>
<td>NbN</td>
<td>16.2</td>
<td>(0.02)</td>
<td>0.16</td>
<td>--</td>
<td>II</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>18.3</td>
<td>(0.05)</td>
<td><strong>0.43</strong></td>
<td>28 - 30</td>
<td>II</td>
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<tr>
<td>MgB$_2$</td>
<td>39</td>
<td>(0.03)</td>
<td><strong>0.51</strong></td>
<td>39</td>
<td>II</td>
</tr>
</tbody>
</table>

* Courtesy, H. Padamsee, R. Flükiger,
Features of Superconducting RF

• **Higher Power Efficiency:**
  • More beam power for less plug power,

• **Lower RF Frequency:**
  • Relaxed tolerances & smaller emittance dilution

• **High-Q ($Q_0 = 10^{10}$):**
  • Small surface resistance $\rightarrow$ nearly zero
  • Capable of efficient accelerating

• **Larger aperture**
  • better beam quality w/ larger aperture –
  • lower wake-fields

• **Long beam pulses ($\sim$ms or CW):**
  • intra-pulse feedback (in 1 ms pulse)

• Cryogenics required
Advances in SRF Technology and Accelerators

Progress (1988~)
- TRISTAN
- LEP-II
- HERA
- CEBAF
- CESR
- KEKB
- BES
- cERL

In Operation: \# cavities
- SNS: 1 GeV
- CEBAF 12 GeV \rightarrow 80
- ISAC-II, ARIEL
- Super-KEKB
- Eu-XFEL \rightarrow 800

Under Construction:
- LCLS-II \rightarrow 300
- FRIB \rightarrow 340
- PIP-II \rightarrow 115
- ESS \rightarrow 150
- Shine \rightarrow 600

To be realized:
- HL-LHC-Crab \rightarrow 20
- JLEIC / eRHIC
- ILC-250 \rightarrow 8,000
- FCC
- CEPC/SPPS
SRF accelerators in the world

Largest deployment of this technology to date
- 100 cryomodules
- 800 cavities
- 17.5 GeV (pulsed)

Kitakami proposed ILC site

US infrastructure for
- 35 cryomodules
- 280 cavities
- 4 GeV (CW)

1.3GHz 9 cell cavity
Advances in SRF Field Gradient

EP introduced

Gradient, > X 5 improved

Surface observation available

G. Ciovati, IPAC’13
Advances in L-band SRF Accelerator Technology

- Systematic statistics by C. Ginsburg.
- 2nd pass stat. for 2008 ~ 2012 period:
  Production yield: 94% at > 28 MV/m,
  Average gradient: 37.1 MV/m
European XFEL, SRF Linac Completed

Progress:
2013: Construction started
...
2016: E-XFEL Linac completion
2017: E-XFEL beam start

1.3 GHz / 23.6 MV/m
800+4 SRF acc. Cavities
100+3 Cryo-Modules (CM)
: ~ 1/10 scale to ILC-ML

1 km SRF Linac

Courtesy, H. Weise
European XFEL: SRF Cavity Performance

After Retreatment:

E-usable: **29.8 ± 5.1 [MV/m]**

(RI): E usable 31.2 ± 5.2 [MV/m], w/ 2nd EP
(EZ): E usable 28.6 ± 4.8 [MV/m], w/ BCP (instead of 2nd EP)

>10% (47/420, RI) cavities exceeding 40 MV/m
LCLS-II SRF Linac (SLAC/Ferilab/Jlab Collaboration)

- Linac Tunnel and Klystron Gallery, 3 km 1962–
- LCLS, 3rd km 2009–2018, 2019–
- FACET, 1st and 2nd km 2010–2016
- LCLS-2, 1st 700 m 2020–
- FACET-2, 2nd km 2020–
- LCLS-2 high-energy upgrade, 1st km ≈ 2026–

Alan Fisher, SLAC @ TTC meeting (TRIUMF, Feb., 2019)
SHINE (China)

SHINE Progress

8 GeV CW linac using ~600 cavities
Construction from 2018 to 2025

LC community meeting (Apr. 8, 2019) Shin
MICHIZONO
Achieving S1 Gradient Goal in the US

JLab delivered 8 qualified cavities, all exceeding 35 MV/m, to Fermilab for placement in CM2.

Peak CM-2 Cavity Gradients with all 8 powered at once:
Sum = 258.1 MV, Average = 32.2 MV/m
Beam commissioning in STF-2

32 MV/m operation is confirmed by beam operation on March, 2019!

Achievements in STF-2 accelerator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>~271 MeV</td>
</tr>
<tr>
<td>Beam power</td>
<td>~68 W</td>
</tr>
<tr>
<td>Beam current</td>
<td>~263 nA</td>
</tr>
<tr>
<td>Average gradient @CM1/2a</td>
<td>~32 MV/m</td>
</tr>
<tr>
<td>Capture CM</td>
<td>~20 MV/m</td>
</tr>
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  • N-doping, N-infusion, and Low-T baking.

• Efforts for Cost-effective SRF Cavity Fabrication
  • Large-grain Cavity

• Summary
SRF Cavity and Cryomodule Fabrication Process

- Purchasing Material/Sub-component
- Manufacturing Cavity
  - Surface Processing → N-doping, infusion
- Assembling LHe-Tank
- Qualifying Cavity
- Cavity String Assembly
- Cryomodule Assembly
- Qualifying CMs
## Standard Procedure Established

<table>
<thead>
<tr>
<th>Standard Fabrication/Process</th>
<th>Key Process</th>
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<td>Fabrication</td>
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<tr>
<td>Nb-sheet purchasing</td>
<td>• Material</td>
</tr>
<tr>
<td>Component Fabrication</td>
<td>• EBW</td>
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<td>Cavity assembly with EBW</td>
<td>• Shape</td>
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<td>Process</td>
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<td>EP-1 (~150um)</td>
<td>• Electro-Polishing</td>
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<td>Ultrasonic degreasing with detergent, or ethanol rinse</td>
<td>• Ethanol Rinsing or</td>
</tr>
<tr>
<td>High-pressure pure-water rinsing</td>
<td>• Ultra sonic. + Detergent Rins.</td>
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<tr>
<td>Hydrogen degassing at &gt; 800 C</td>
<td>• High Pr. Pure Water cleaning</td>
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<tr>
<td>Field flatness tuning</td>
<td></td>
</tr>
<tr>
<td>EP-2 (~20um)</td>
<td></td>
</tr>
<tr>
<td>Ultrasonic degreasing or ethanol (or EP 5 um with fresh acid)</td>
<td></td>
</tr>
<tr>
<td>High-pressure pure-water rinsing</td>
<td></td>
</tr>
<tr>
<td>Antenna Assembly</td>
<td></td>
</tr>
<tr>
<td>Baking at 120 C</td>
<td></td>
</tr>
<tr>
<td>Cold Test (vertical test)</td>
<td>Performance Test with temperature and mode measurement</td>
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## Key Process

### Fabrication
- Material
- EBW
- Shape

### Process
- Electro-Polishing
- Ethanol Rinsing or
- Ultra sonic. + Detergent Rins.
- High Pr. Pure Water cleaning
Two main research directions to push high Q at high G:
- High temperature (> 800°C) Nitrogen doping
- Low temperature treatments (~ 50°C - 200°C) with or without Nitrogen

A possible common matrix that ties it all together:
- nano-hydrides?
State of the Art in High-Q and High-G (1.3 GHz, 2K)

- **N-doping (@ 800°C x 48h)**
  - Q>3E10, 35 MV/m

- **Baking (@ 75/120°C)**
  - Q>1E10, 49 MV/m (Bpk-210 mT)

- **N-infusion (@ 120°C x ?h)**
  - 1E10, 45 MV/m

- **Baking (@ 120°C)**
  - 7E10, 42 MV/m

- **EP**
  - 1.3E10, 25 MV/m

Important: insufficient bulk removal or high defect density material (insufficiently annealed) will cause extra residual resistance
N-Doping (@800C) and N-Infusion (@ 120C)

Grassellino et al, Superconductor Science and Technology, Volume 26, Number 10
Low-Temperature Treatment

The New 75/120C Finding

Repeated on second cavity TE1AES009 (fine grain, AES, WC)

It anomaly found during the Low-T Bake

- A thermocouple went faulty and oven went to standby
- Cavity lingered around 75C for about 2 hours, then resumed the 120C 48 hours
The performance confirmed by Cornell and JLab

Courtesy of Liepe, Maniscalco, Cornell

Courtesy of Palczewski, Jlab
What is happening?

- 70°C seems to be another magic temperature in niobium.
- 1960-70s literature studies suggest that 70°C is associated with changes in vacancies, while 120°C changes in dislocations (Bordoni or Hasiguti type process).

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The α and β Peaks in Cold-Worked Niobium

M. W. STANLEY*, Z. C. SZKOPIAK
Department of Metallurgy and Materials Technology, University of Surrey, London, SW11, UK

Received 5 June 1967

Internal-friction measurements (at 1 c/sec) have been carried out over the temperature range from 90 to 290°C on niobium specimens deformed at room temperature. In the as-cold-worked material, a broad peak at about 115°C (α peak) is observed. The α peak increases with the amount of deformation and decreases with increasing interstitial impurity content. On subsequent annealing, the height of the peak decreases by about 50% over the temperature range from 90 to 140°C, and to negligible values from 290 to 340°C.

As a result of annealing for 2 h at 70°C, a group of peaks (β peaks) occurred at about 200°C. The β peaks are independent of the amount of deformation prior to annealing and the interstitial impurity content. On further annealing, the relaxation strength of the peaks increases with temperature up to about 100°C, remains constant between 100 and 240°C, and subsequently gradually decreases to negligibly low values at about 340°C.

The α peak, and its variation with deformation, impurity content, and annealing, can be accounted for in terms of relaxation mechanisms involving dislocations (i.e., a Bordoni- or Hasiguti-type process observed in fcc metals). This is a generally accepted concept at present. The β peaks, on the other hand, could only be adequately accounted for by relaxation processes involving complexes of deformation-created point defects and interstitial impurities.
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• **Efforts for Cost-effective SRF Cavity Fabrication**
  • Large-grain Cavity

• **Summary**
Optimization for Mass-production in the ILC Preparation Stage

- Seeking for the best cost-effective production technology for Nb disk/sheet
  - Very clean surface
    - Important for gradient stability
  - Optimum (could be lower) residual resistance ratio
    - to be optimized with RRR of ~ 150 +/- 50
  - Optimum (medium) grain size
  - Hoping, to slice with better mechanically stability.
    - optimum solution anticipated
Technical Specification for Nb Sheet

- **Electrical Properties**
  - RRR: > 300 (to be further optimized)

- **Chemical contents**
  - see table

- **Microstructure**
  - Re-crystallized 100%
  - Grain-size: ASTM 6 or finer (to be further optimized)
  - Local grain size: ASTM 4-5

- **Mechanical Properties**
  - Ultimate strength: > 140 N/mm², RT
  - Yield strength: TBD (> xx N/mm², RT)
  - Elogation: > 30%
  - Hardness: ≤ 60

- **Shape/size**: TBD
  - Rect. Sheet: ~ 300 mm sq. or
  - Circular sheet: ~280 mm dia. with a center-hole
    - Possibility of Blanking (in consortium: to be discussed)
  - Thickness: 2.8 mm +/- 0.1 mm
  - Flatness: 2 % or better
  - Surface roughness: < 15 mm (RF side)

**Chemical contents: Example**

Chemical analysis of the ingot:
- Ta ≤ 0.05 %
- W ≤ 0.007 %
- Ti ≤ 0.005 %
- Fe ≤ 0.003 %
- Si ≤ 0.003 %
- Mo ≤ 0.005 %
- Ni ≤ 0.003 %

Content of interstitial elements in the annealed Nb:
- H₂ ≤ 2 weight ppm
- N₂ ≤ 10 weight ppm
- O₂ ≤ 10 weight ppm
- C ≤ 10 weight ppm
FG-Nb rolled or LG-Nb sliced from Ingot

Cost Fraction:
- Law Material: ~ 20%
- EB-Refining: ~ 50%
- Sheetig: ~ 30%
A Direction being Investigated for the Nb disk Mass-production

- **Clean surface** from the beginning of Nb sheets
  - Direct slicing from Nb Ingot (having high purity)
    - Proposed and patented in the US, by G. Myneni, P. Kneisel (Jlab) and T. Carneiro (CBMM)
    - Patented in Japan and in Europe, by KEK, Tokyo-Denkai, and others
  - Keep clean surface w/ directly sliced Nb-sheets
    - w/o additional rolling causing contamination and defects
- On the other hand,
  - necessary **mechanical uniformity and stability** for press-work with tighter tolerance in assembly.
A Direction to be Investigated for the Nb disk Mass-production

- **Clean surface** from the beginning of Nb sheets
  - Direct slicing from Nb Ingot (having high purity)
    - Proposed and patented in the US, by G. Myneni, P. Kneisel (Jlab) and T. Carneiro (CBMM)
    - (Patented in Japan and in Europe, by KEK, Tokyo-Denkai, and others)
  - Keep clean surface w/ directly sliced Nb-sheets
    - w/o additional rolling causing contamination and defects
- On the other hand,
  - necessary **mechanical uniformity and stability** for press-work with tighter tolerance in assembly.
Nb Sheet directly cut out
anticipated with medium grain size

- RRR: $\approx 250 \ (\geq 200)$
- Grain size: $< \sim \text{a few cm}$
  - To be optimized for press-work,
- Size: $> 260 \text{ mm}$
- Thickness: $\sim 2.8 \text{ mm}$
- Cleanness:
  - Min. surface work
  - No rolling
Efforts for Self Learning at KEK

EBW

Press

Trim

Chemical process

EBW

Press

Trim

AMADA digital-servo-press
SDE1522
150t, 50strokes/min,
225mm stroke

MORI VKL-253
Vertical CNC lathe

SST EBOCAM KS110 –
G150RM
Chamber (St. St. Chamber)
### Comparisons with high RRR Nb

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>C</th>
<th>O</th>
<th>N</th>
<th>Fe</th>
<th>Si</th>
<th>Ta</th>
<th>RRR</th>
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<tbody>
<tr>
<td>LG (TD)</td>
<td>&lt; 5</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
<td>80</td>
<td>390°</td>
</tr>
<tr>
<td>FG (TD)</td>
<td>&lt; 10</td>
<td>40</td>
<td>100</td>
<td>40</td>
<td>20</td>
<td>20</td>
<td>700</td>
<td>258**</td>
</tr>
<tr>
<td>LG (CBMM)</td>
<td>&lt; 10</td>
<td>&lt; 30</td>
<td>&lt; 30</td>
<td>10</td>
<td>3</td>
<td>20</td>
<td>1034</td>
<td>100°</td>
</tr>
</tbody>
</table>

Measurement RRR: * by KEK, ** by TD

The effect of low RRR and high Ta not seen on Q0.
Gradient Reached with LG Nb-Ingot Sliced

Result from DESY

ILC Gradient

Cavity Spec. 45 MV/m reached
KEK 9-Cell Cavity (KEK-01/02) reached 36/38 MV/m

KEK-01 (Rolled, FG, 2014): Reached 36 MV/m
KEK-02 (Ingot-sliced, LG, 2016): Reached 38 MV/m
Key Issues to be Settled

- Fabrication of Nb sheets
  - Size: 260 mm diameter, ~ 3 mm thick
  - Quantity (in case of ILC-250): ~ 9,000 x 20 = 180,000 disks (~1.2 kg/disk)
- Purity, Residual Resistance Ratio
  - RRR: ~ 250(+/-50) to be investigated (currently > 300 )
- Mechanical uniformity
  - Grain-size: to be optimized (with a level of thickness?)
  - How it can be made with cost-effective process?
    - Adding specific, controlled impurities, controlling environment?
- Best cost effective solution anticipated
  - Nb Ingot with medium grain-size to be a possible solution
Summary

- SRF technology has been much advanced for particle accelerators, and ready for more application.

- High-Q and High-Q is a fundamentally important for future energy and power frontier accelerator systems.
  - N-doping, N-infusion, low-T treatment need to be understood for further application.

- Large Grain direct-sliced from Nb-Ingot is expected as an cost-effective SRF cavity fabrication.
Acknowledgments

This talk has been prepared in communication with

- Euro-CirCol (FCC study body),
- EUCARD-2 (to be succeeded by ARIES),
- US-General Accelerator SRF R&D program (GARD-SRF),
- Tesla Technology Collaboration (TTC), European XFEL, and LCLS-II,
- Linear Collider Collaboration (LCC), and
- SRF accelerator laboratories (DESY, CEA, CERN, JLab, Fermilab, SLAC, KEK, IHEP, and others).

The author would thank for their kindest cooperation to provide various information.