High Performance Large-Grain Cavities for the ILC

SRF2021, MSU (virtual)
2021/June/30
KEK, Accelerator laboratory, CASA  Kensei Umemori
Collaborator/Acknowledgement

- KEK
  - Takeshi Dohmae, Ashish Kumar, Takayuki Saeki, Masashi Yamanaka
  - CASA-SRF group members
  - CFF group members
  - All of supporting staffs for KEK-STF activity
- DESY
  - Detlef Reschke
- JLAB/ORNL
  - Gigi Ciovati, Rongli Geng
- ESS
  - Daniele Sertore
- IHEP
  - Peng Sha
- Peking Univ.
  - Jiankui Hao
Outline

• World-wide activity on LG cavity development
  • DESY
  • ESS
  • JLAB
  • IHEP
  • Peking Univ.

• LG cavity development for ILC at KEK
  • Mechanical strength
  • Cavity fabrication
  • RRR and cavity performance

• Summary
World-wide activity on LG cavity development
Performance of Large-Grain Niobium Cavities at DESY

Excellent cavity performances achieved and profound experience

> **Vertical test results**
  - About **20% higher Q-value** on average for standard EP surface treatment up to 16 MV/m

> **Large-grain XM-3 pre-series cryomodule**
  - European XFEL pre-series cryomodule XM-3 with 7 large-grain + 1 fine-grain cavities
  - **cw operation with excellent results and stability.**
  - → stable operation at 17 MV/m and Q-value of $2.3 \times 10^{10}$ at 2K
  - Long term operation of two further lg cavities in FLASH modules

> **Goal:**
**Pressure equipment directive (PED) compatible fabrication**
  - Material characterization with **warm and cold traction** tests
  - hardness tests
  - RRR measurements
  - cutting, forming, welding processes under investigation
  - surface-sensitive characterization & analysis of cavity test data
New cavity productions

Cooperation with SHINE and preparation of cw-upgrade for European XFEL

> Four LG nine-cell Eu-XFEL style cavities for SHINE
  - order by SARI placed @ Research Instruments (RI)
  - Ningxia Niobium material w/o large central grain
  - cavities fabricated and treated “ready to test” w/o helium tank
  - DESY supervises fabrication and surface treatment process @ RI
  - Vertical acceptance test expected in Sep/Oct 2021

> Preparation next DESY order of 10 LG cavities
  - Material procurement started
  - Cavity fabrication planned in 2022/2023

> LG back-plate of all SRF gun cavity
  - Present fabrication of two 1.6-cell all SRF gun cavities:
    Back-plate and cathode material made of LG material
  - Production of next two cavities for further optimization of fabrication and beam-dynamics in preparation
INFN LASA has designed and developed Medium Beta ($\beta = 0.67$) cavities for the Superconducting Section of the ESS Linac. As part of this activity, we have developed a Large Grain prototype.

- CBMM (Brazil) produced a high RRR ($\approx 300$) Large Grain Nb ingot with a diameter compatible with the MB ESS cavities
- Heraeus GmbH in Hanau sliced then the ingot into disks with the proper thickness necessary for the cavity fabrication.

Afterwards, the sheets were BCP treated and dehydrogenated at 700 °C. The cavity was assembled starting from forming the sheets to half cell, welding the dumbbell and then the whole cavity. We treated the cavity with a standard BCP to remove 180 μm and dehydrogenation at 600 °C for 10 hours. Finally, we removed 20 μm with BCP and prepared the cavity for Vertical Test at INFN LASA.

The cavity was limited by quench. After some conditioning around the multipacting region (8-12 MV/m) the cavity had no radiation up to the quench field.
Total 10 LG 5-cell cavities were fabricated for CEBAF cryomodule rework program.

Eight cavities were installed to CM C75-01.

The CM has been installed in the CEBAF tunnel and will be tested in August 2021.

High performance of LG cavity

Rongli Geng, IPAC2015

TTF end-cell shape, single-cell

Low-loss shape, single-cell

High-Q and high gradient were obtained.

Figure 2: Summary of RF performance of ten C75 cavities tested as single-cavities in a vertical cryostat. The arrows indicate the breakdown field.

Figure 5: Picture of the CM C75-01 inside the CMTF.
CEPC 650 MHz 1-cell LG Cavities (IHEP)

- Two 650 MHz 1-cell LG cavities have received EP, and reached $4.6 \times 10^8@28\text{MV/m}$ (650S8) and $3.6 \times 10^8@32\text{MV/m}$ (650S7).

Compared to the 1.3 GHz cavities EP studied for years, 650 MHz cavities have different radial sizes, interior surface, volumes and so on, which require a lot of EP parameters optimization work.

Vertical test results of 650 MHz LG cavities.

Equator after BCP
Equator after EP

IHEP, Peng Sha
LG activity at Peking Univ.

- 6 large grain 9-cell cavities were fabricated by PKU/OSTEC
- BCP 180µm + 800°C 3h + BCP 30µm
- Eacc > 25 MV/m
- Q₀ ~ 1.6-2.4E10 @ 16 MV/m, 2.0 K

- Two 9-cell large grain cavities
- Electron beam energy 10-20 MeV
- Operation in pulse mode
  - macro pulse duration 1-5 ms,
  - avg. current ~ 1 mA,
  - duty factor ~ 5%

- BCP 180µm + 800°C 3h + BCP 30µm (no EP, no N-doping)
- Q₀ ~ 1.5-1.8E10 @ 16 MV/m & 2.0 K (w/o helium jacket)
- Q₀ ~ 1.4-1.5E10 @ 16 MV/m & 2.0 K (w/ helium jacket)
- Eacc ~ 19-26 MV/m
LG cavity development for ILC at KEK
Requirement for ILC SRF cavities

• Specification
  ➢ VT: Eacc > 35 MV/m, Q₀ > 0.8e10
  ➢ CM: Eacc > 31.5 MV/m, Q₀ > 1.0e10

• Cost reduction → Direct slice Nb
  ➢ RRR
  ➢ Ta contents
  ➢ LG, MG

• Issues to be investigated
  ➢ Mechanical strength
  ➢ Cavity fabrication process
  ➢ Thermal conductivity, RRR → Cavity performance
Manufacture method of Large and Medium-Grain Nb discs

- Nb melting
- Direct slice of LG ingot
- Niobium ingot (Raw material)
- Direct slice of MG ingot
- Ingot, forged and annealed
- Slicing image by wire-saw

- Large Grain (LG) Disc
  - Grain Size >> 1 cm
- Medium Grain (MG) Disc
  - Average Grain Size < 1 mm

- * Aiming for clean, mechanically stable, and cost-effective SRF cavity production.

* The “Nb forged ingot” technology originated by ATI, and SRF (GHz) cavities were fabricated and RF tested by KEK and JLab, to qualify this approach, in collaboration of ATI, ODU/BSCE, JLab, and KEK.
## Results of KEK LG/MG cavities

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Grain size</th>
<th># of cells</th>
<th>RRR (RT/Tc)</th>
<th>Ta-content</th>
<th>Results (π-mode)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tokyo Denkai</td>
<td>LG</td>
<td>Single</td>
<td>496</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>CBMM</td>
<td>LG</td>
<td>Single</td>
<td>107</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Tokyo Denkai</td>
<td>LG</td>
<td>9-cells</td>
<td>496</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>CBMM</td>
<td>LG</td>
<td>3-cells</td>
<td>242 ~ 298</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>CBMM</td>
<td>LG</td>
<td>9-cells</td>
<td>242 ~ 298</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>ULVAC</td>
<td>LG</td>
<td>3-cells</td>
<td>500</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>ULVAC</td>
<td>LG</td>
<td>3-cells</td>
<td>363</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>ATI</td>
<td>MG</td>
<td>Single</td>
<td>494</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

※ R-16/16b, R-17/17b, R-18b are under processing
※ Plan to fabricate high-RRR LG 9-cell & MG 9-cell cavities
Tensile test at KEK

High Performance Large-Grain Cavities for the ILC

Tensile testing machine with a cryostat

Example of LG tensile test at 4K

Example of MG tensile test at RT
### Mechanical strength for LG and MG

**Kensei Umemori, 2021/June/30, SRF2021**

**High Performance Large-Grain Cavities for the ILC**

**Ashish Kumar, MOPCAV004 & Masashi Yamanaka, WEPFDV005 in SRF2021**

<table>
<thead>
<tr>
<th>Temp.</th>
<th>Measurement</th>
<th>FG (RRR=242)</th>
<th>MG (RRR &gt; 300)</th>
<th>LG (RRR=291)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT</td>
<td>Tensile strength [MPa]</td>
<td>157</td>
<td>146</td>
<td>84 +/− 3</td>
</tr>
<tr>
<td></td>
<td>0.2 % proof strength [MPa]</td>
<td>44</td>
<td>45</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>Elongation [%]</td>
<td>37</td>
<td>20</td>
<td>75</td>
</tr>
<tr>
<td>LHe(4K)</td>
<td>Tensile strength [MPa]</td>
<td>832</td>
<td>378</td>
<td>611 +/− 132</td>
</tr>
<tr>
<td></td>
<td>0.2 % proof strength [MPa]</td>
<td>516</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elongation [%]</td>
<td>7</td>
<td>2</td>
<td>6</td>
</tr>
</tbody>
</table>

- Tensile strength of LG Nb is around half of FG Nb at RT. Variation of strength is issue. (Although above data does not show the variation.)
- Mechanical property of MG Nb is close to FG Nb at RT and around half at 4K.
- Elongation of MG at KEK test is lower, but manufacturer show higher elongation. Discrepancy is under investigation.
Anisotropy of grains sometimes make difficulties on cavity fabrication. Deformation, cracks, etc.

Figure 6: Photo of inner surface of half-cell equator (left) and 3D-data measured by laser microscope (right). 3D measured area is different from left photo.
**RRR vs cavity performance**

Takayuki Kubo  
「Comments on Niobium RRR and SRF cavity performance for ILC」  
@TTC, RIKEN 2018

**Summary of experimental data**

- **Estimated quench field as functions of RRR and normal defect size**

Other heat sources with the same amount of dissipation as normal defect with the sizes shown here also lead to the similar results.

0.2μm

1μm

5μm

10μm

- **Kensei Umemori, 2021/June/30, SRF2021**

- **High Performance Large-Grain Cavities for the ILC**
High Performance Large-Grain Cavities for the ILC

Kensei Umemori, 2021/June/30,
SRF2021

Results of LG cavities

High RRR LG: $E_{acc} = 38 \sim 42 \text{ MV/m}$
Mid RRR LG: $E_{acc} = 32 \sim 42 \text{ MV/m}$
KEK selected high RRR LG for further study.

Takeshi Dohmae
## Results of KEK LG/MG cavities

<table>
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<tr>
<th>Supplier</th>
<th>R1</th>
<th>R5</th>
<th>KEK-2</th>
<th>R10/ R10b</th>
<th>KEK-4/ KEK-5</th>
<th>R-16/ R16b</th>
<th>R-17/ R17b</th>
<th>R-18/ R18b</th>
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<tr>
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<td>ULVAC</td>
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<td>ATI</td>
<td></td>
</tr>
<tr>
<td>Grain size</td>
<td>LG</td>
<td>LG</td>
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<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Results (π-mode)</td>
<td>42 MV/m</td>
<td>31 MV/m</td>
<td>38 MV/m</td>
<td>38 / 42 MV/m</td>
<td>34 / 32 MV/m</td>
<td>-- / -- MV/m</td>
<td>-- / -- MV/m</td>
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Summary

• Large Grain (LG) /Medium Grain (MG) Niobium cavities have been investigated all over the world.

• Some of LG cavities have been or will be operated with beam.

• KEK has been performing LG/MG R&D towards cost reduction of ILC cavity fabrication.

• Mechanical strength, Cavity fabrication and cavity performance have been investigated.

• KEK selected high-RRR Nb for further LG/MG R&D.