Report from SRF2013: *The SRF World Today*

**16th International Conference on RF Superconductivity**

SRF 2013 covered the latest advances in the science, technology, and applications of superconducting RF.

~390 participants from >35 institutions

The program:
- 10 tutorial talks in pre-series @ GANIL
  - http://pro.ganil-spiral2.eu/events/cw/srf2013/
- 62 invited review talks
  - https://indico.in2p3.fr/conferenceOtherViews.py?confId=8939
- ~350 contributed posters
  - All papers will appear soon on JaCOW
- 3 “hot-topic” discussion sessions

10/17/2013
Report from SRF2013:  
*The SRF World Today*

1. Status of SRF-based accelerator projects in the world - scale and quality in comparison with CEBAF, esp. 12 GeV  
   *John Mammosser*

2. SRF cavity processing techniques - the latest standard and the emerging  
   *Ari Palczewski*

3. SRF non-bulk materials - what is new and promising?  
   *Anne-Marie Valente-Feliciano*

4. Nb high-Q pursuits - what is new, what is the best seen, what understanding and control is needed yet?  
   *Pashupati Dhakal*
Status of Accelerator Based Projects SRF2013
Outline:

**SRF Based Projects:**
- XFEL
- FRIB
- Cornell ERL
- ADS China
- ESS
- Atlas Upgrade
- IFMIF
- Project X
XFEL-Europe
XFEL - DESY

• 220/640 Cavities fabricated, 111 delivered
• Rate 4/week ending in mid 2015
• Two Vendors both with new facilities for
  – EP
  – HPR
  – Cleanroom assembly
  – QA, RF and Mechanical
• Cavities delivered fully processed ready for testing in helium vessel
  – Only additional HPR necessary
Nb to Cavities, DESY
PHASE 2: WORKSTATIONS IN ASSY HALLS

Warehouse
Alignment Area AL-WS1 & 2
Roll-out Area RO-WS1 & 2
Coupler Area CO-WS1 & 2
Reception Area REC-WS1
Clean room Area CO-WS1 & 2
SA-WS1 & 2
Cantilever Area CA-WS1
Shipment Area SH-WS1 & 2

the XFEL Village
**XFEL- Performance**

Prior surface treatment.
**EP 110-140 μm (main EP), outside BCP, ethanol rinse, 800° C annealing, tuning**

Final surface treatment - two alternative options
1. Final EP of 40 μm, ethanol rinse, high pressure water rinsing (HPR) and 120° C bake
2. Final BCP of 10 μm (BCP Flash), HPR and 120° C bake.

Integration of the helium tank, assembly of HOM, pick up and high Q antennas and shipment to DESY for 2K RF acceptance test
**XFEL - Performance Comparison**

Average **maximum gradient:**
(30.9 ± 4.4) MV/m
EZ: (30.4 ± 4.5) MV/m
RI: (32.3 ± 4.1) MV/m

Average **usable gradient:**
(29.0 ± 3.9) MV/m
EZ: (28.4 ± 4.0) MV/m
RI: (30.6 ± 3.1) MV/m

C100 Emax Distribution
- Design goal = 19.2 MV/m
- Cryomodule Admin Limit - 25 MV/m
- VTA Test Data for C100-1 - C100-10
- Commissioning Data for C100-1 - C100-7, C100-8, C100-10
- VTA Average = 27.4 MV/m
- Commissioning Average = 22.2 MV/m

Preliminary accounting for gradient reductions:
- Capping VTA Admin limit to 25 MV/m reduces VTA average to 24.9 MV/m
- Cryostat riser limits (50 – 60W per cavity) account for reductions in 21% of the cavities
- Assembly / Testing “events” account for reductions in ~5% of the cavities

- **Acceptance Criteria:**
  "...maximum gradient > 26 MV/m with an unloaded Q₀ of ≥ 1x10¹⁰ and a X-ray level lower than 1x10⁻² mGy/min."
  (with 26 MV/m to give 10% margin compared to 23.6 MV/m design gradient)

- If acceptance criteria passed
  ⇒ preparation for transport + string assembly

- If acceptance criteria is not passed
  ⇒ re-treatment at DESY
  (Reminder: No performance guarantee by the vendors, i.e. the risk of unexpected low gradient or field emission is with DESY)

- **“Usable Gradient”**:
  i) Quench
  ii) Q₀ < 1x10¹⁰
  iii) radiation > 1x10⁻² mGy/min
<table>
<thead>
<tr>
<th>Vertical Test Performance Cavity Vendor</th>
<th>C100 2.07K (R1)</th>
<th>XFEL 2.0K (1/3-Ri/2/3 - Z)</th>
<th>C100 Yield</th>
<th>XFEL Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>VTA Admin Limit</td>
<td>27.0/Rad/Pd/Quench</td>
<td>26.0/Rad/Qo/Quench</td>
<td></td>
<td></td>
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<tr>
<td>Eacc (Avg Maximum)</td>
<td>27.4</td>
<td>28.1 ±7.8</td>
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<td></td>
</tr>
<tr>
<td>Qo (Low Field)</td>
<td>1.3E10</td>
<td>2.2e10</td>
<td></td>
<td></td>
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<tr>
<td>Eacc (Usable )</td>
<td></td>
<td>29.0 ±3.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VTA Yield First Pass</td>
<td>62/86</td>
<td>50/79</td>
<td>72.1%</td>
<td>63.3%</td>
</tr>
<tr>
<td>VTA Yield Second Pass</td>
<td>18/21</td>
<td>13/17</td>
<td>85.7%</td>
<td>76.4%</td>
</tr>
<tr>
<td>No Success First and Second Pass</td>
<td>3/86</td>
<td>3/79</td>
<td>3.5%</td>
<td>3.8%</td>
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</tbody>
</table>
Performance Comparison Cryomodules

- Cryomodules are built at CEA by CEA staff
- 3 Modules fabricated to date: PXFEL2-1, PXFEL3-1, PXFEL2-2

The team (~10 persons)
## A closer look at two modules

<table>
<thead>
<tr>
<th></th>
<th>PXFEL2-1</th>
<th></th>
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<th>PXFEL3-1</th>
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<tr>
<td></td>
<td>cav1</td>
<td>cav2</td>
<td>cav3</td>
<td>cav4</td>
<td>cav5</td>
<td>cav6</td>
<td>cav7</td>
<td>cav8</td>
<td>Avg</td>
<td>HOM</td>
<td>Vertical test</td>
<td>DESY assembly</td>
<td>CEA Assembly</td>
<td>Vertical test</td>
<td>CEA Assembly</td>
<td></td>
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<td></td>
<td></td>
<td>-7.1</td>
<td>0.0</td>
<td>-40.7</td>
<td>-6.2</td>
<td>-6.3</td>
<td>-5.6</td>
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<td>-6.4</td>
<td>+1.5</td>
<td>0.0</td>
<td>+6.2</td>
<td>+15.6</td>
<td>+3.7</td>
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<tr>
<td></td>
<td>CEA Assembly</td>
<td>26.2</td>
<td>33.5</td>
<td>16</td>
<td>34.5</td>
<td>37</td>
<td>28</td>
<td>29.5</td>
<td>32</td>
<td>29.6</td>
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<td>-14.9</td>
<td>-7.4</td>
<td>-9.1</td>
<td>+16.1</td>
<td>-8.5</td>
<td>-14.5</td>
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</tbody>
</table>
Cornell ERL
Cornell ERL

5 GeV, 100 mA CW beam, 8 pm emittance, 2 ps bunches

~200 W HOM power/cavity
CW operation, \( Q(1.8 \,\text{K}) = 2 \times 10^{10} @ 16.2 \,\text{MV/m} \)

Total 64 cryomodules, each:
- six packages of 7-cell cavity/Coupler/tuner
- a SC magnets/BPMs package
- five regular HOMs/two taper HOMs

Linac B
285 m with 29 cryomodules

Staff: 45

nominal length: 9.8 m
Cornell Cryomodule Test Bed Results

- **HTC-1**: Follow vertical assembly procedure as closely as possible.
- **HTC-2**: Include side mounted, **high power RF input coupler**.
- **HTC-3**: Full cryo-module assembly: high power RF input coupler and **beam line HOM loads**.

Footnote:
Cornell Vertical Test Results
FRIB – Facility for Rare Isotope Beams

- 400 KW beam >200 MeV/u Oxygen to Uranium
- Currently at CD2-3A
- Start of civil construction April 2014
  - Total $ 730M, 180 employees
  - CD4 in 2020
- SRF Infrastructure at MSU
  - 27000 sq. ft. production facilities under construction
  - Complete in April 2014
Production Required

- $\beta = 0.041$
  - 3 Cryomodules, 12 Cavities
- $\beta = 0.085$
  - 11 Cryomodules, 88 Cavities
- $\beta = 0.29$
  - 12 Cryomodules, 72 Cavities
- $\beta = 0.53$
  - 18 Cryomodules, 144 Cavities
SRF Mass Production Will Occur In New MSU SRF Facility
27,000 sq. ft. SRF High Bay - Building Completion: April 2014
Performance

- 23 FRIB-relevant cavity prototypes have been successfully tested
  - 8 $\beta=0.041$ cavities, 11 $\beta=0.085$ cavities, 5 $\beta=0.53$ cavities
Cryomodule Design

First FRIB-style Quarter Wave Construction: Cavities Operate At

- Magnetic Shield
- Solenoid Leads
- 2K
- Solenoid
- Alignment Support
- FRIB Bayonet Connections
- Coldmass Support Rails
- ANL RF Coupler
- Vacuum Vessel Base Plate

Projected Heat Load

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<tr>
<th>Temperature</th>
<th>Static</th>
<th>Dynamic</th>
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<tr>
<td>2 K</td>
<td>5.8 W</td>
<td>32.0 W</td>
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<td>4.5 K</td>
<td>30.4 W</td>
<td>2.1 W</td>
</tr>
<tr>
<td>38/55 K</td>
<td>168.1 W</td>
<td>33.4 W</td>
</tr>
</tbody>
</table>

S. Miller: THIOA04

M. Leitner, SRF 2013, Slide 15
Cavity Production

- Production cavities are procured using a phased approach
  - 2 development cavities, undressed (no helium vessel)  
  - 10 dressed pre-production cavities (with helium vessel)  
  - Production cavities

- Production Cavities Fabrication Status:
  - First development cavities have been successfully fabricated and delivered
    - $\beta=0.53$ Roark Welding & Engineering Co., Inc. (received and certified)
    - $\beta=0.29$ Roark Welding & Engineering Co., Inc. (received)
    - $\beta=0.085$ Pavac Industries, Inc. (delivery early 2014)
  - $\beta=0.53$ FRIB production contract placed for 144 cavities.
  - Rest of cavity production contracts will be placed by end of this year.

- FRIB project procured $13.2$M of niobium material
Roadmap of ADS Project in China

Goal in 2014, 5 MeV

Goal in 2015, 10 MeV

Stage 1: Research facility
(~10 MWt, ~2023)
key technology R&D

Stage 2: Exp. facility
(~100 MWt, ~2030)

Stage 3: Demo facility
(~1000 MWt, ~2040)

“strategic Priority Research Program” of the Chinese Academy of Sciences
# ADS China

<table>
<thead>
<tr>
<th></th>
<th>Spoke 012</th>
<th>HWR 010</th>
<th>HWR 015</th>
<th>Spoke 021</th>
<th>Spoke 040</th>
<th>Ellip 063</th>
<th>Ellip 082</th>
<th>Unit</th>
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<td>Freq.</td>
<td>325</td>
<td>162.5</td>
<td>162.5</td>
<td>325</td>
<td>325</td>
<td>650</td>
<td>650</td>
<td>MHz</td>
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<tr>
<td>$\beta g$</td>
<td>0.12</td>
<td>0.09</td>
<td>0.14</td>
<td>0.21</td>
<td>0.40</td>
<td>0.63</td>
<td>0.82</td>
<td>-</td>
</tr>
<tr>
<td>Aperture</td>
<td>35</td>
<td>40</td>
<td>40</td>
<td>50</td>
<td>50</td>
<td>100</td>
<td>100</td>
<td>mm</td>
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<tr>
<td>$U_{acc}$</td>
<td>0.82</td>
<td>0.78</td>
<td>1.82</td>
<td>1.64</td>
<td>2.86</td>
<td>10.26</td>
<td>15.63</td>
<td>MV</td>
</tr>
<tr>
<td>$E_{peak}$</td>
<td>32.5</td>
<td>25</td>
<td>32</td>
<td>24/31</td>
<td>25/32</td>
<td>29/38</td>
<td>28/36</td>
<td>MV/m</td>
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<tr>
<td>$B_{peak}$</td>
<td>46</td>
<td>50</td>
<td>40</td>
<td>50/65</td>
<td>50/65</td>
<td>50/65</td>
<td>50/65</td>
<td>mT</td>
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<td>Temp.</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>4.5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>K</td>
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<tr>
<td>$P_{loss}$</td>
<td>10 (70nΩ)</td>
<td>10 (70nΩ)</td>
<td>15.5 (70nΩ)</td>
<td>16.8 (70nΩ)</td>
<td>6.5</td>
<td>21</td>
<td>39</td>
<td>W</td>
</tr>
<tr>
<td>Number</td>
<td>12</td>
<td>6</td>
<td>6</td>
<td>28</td>
<td>72</td>
<td>28</td>
<td>85</td>
<td>-</td>
</tr>
</tbody>
</table>

Operation At 4.5K injectors and possible 2K for rest
Bpk – 65mT
Prototyping on-going

Courtesy of IHEP
Performance Comparison

- **FERMI – SSR1**

  Tested in Dec, 2012
  
  - Bulk BCP 150 um
  - Annealing 750 C, 3 hours
  - Light BCP 30um
  - Baking 100 C, 48 hours

  - Q0=5.8x10^6 @6MV/m, 4K;
  - Q0=3.4x10^6 @7MV/m, 4K

  No quench but heavy MP and FE. Testing ended of FE.
ESS

LINAC layout

<table>
<thead>
<tr>
<th>Component</th>
<th>Length (m)</th>
<th>Input Energy (MeV)</th>
<th>Frequency (MHz)</th>
<th>Geometric β</th>
<th># of Sections</th>
<th>Temp (K)</th>
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<td>RFQ</td>
<td>4</td>
<td>$75 \times 10^{-3}$</td>
<td>352.2</td>
<td>--</td>
<td>1</td>
<td>$\approx$ 300</td>
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<tr>
<td>DTL</td>
<td>19</td>
<td>3</td>
<td>352.2</td>
<td>--</td>
<td>3</td>
<td>$\approx$ 300</td>
</tr>
<tr>
<td>Spoke</td>
<td>52</td>
<td>50</td>
<td>352.2</td>
<td>0.45</td>
<td>14 (3c)</td>
<td>$\approx$ 2</td>
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<tr>
<td>Low Beta</td>
<td>57.5</td>
<td>200</td>
<td>704.4</td>
<td>0.63</td>
<td>10 (4c)</td>
<td>$\approx$ 2</td>
</tr>
<tr>
<td>High Beta</td>
<td>215</td>
<td>500</td>
<td>704.4</td>
<td>0.75</td>
<td>19 (8c)</td>
<td>$\approx$ 2</td>
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<tr>
<td>HEBT</td>
<td>100</td>
<td>2500</td>
<td>--</td>
<td>--</td>
<td>--</td>
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</tr>
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</table>
Lund, Sweden

Investment: 1478 M€ / ~10y
Operations: 89 M€ / y
Decomm.: 346 M€
(Cost per 2008-01-01)
Linac R&D in progress

IPHI RFQ at CEA-Saclay

SC triple spoke cavity, ANL

SC 5 cell cavity for 704 MHz, CEA and CNRS

http://www.jpaw.com
Two parallel 125 mA Deuteron beams at 40 MeV will collide that within a few years will reach the expected display commercial nuclear fusion reactor.

- $Q_0$ recovered
- Quench occurring on one HPR port
THE LIPAC CRYOMODULE

- **8 Half Wave Resonators** (operating temperature 4.4 K)
  - CW operation (70 kW max)
  - Vertical position
  - One room temperature window
- **8 RF Power Couplers**
  - CW operation (70 kW max)
  - Vertical position
  - One room temperature window
- **8 Superconducting Solenoid Packages**
  - Focusing solenoid with shielding
  - H & V steerers
  - Cold BPM
- **Cryostat**

### Target Values of complete Cryomodule

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>175 MHz</td>
</tr>
<tr>
<td>$\beta$ value of the HWR</td>
<td>0.094</td>
</tr>
<tr>
<td>Accelerating field $E_a$</td>
<td>4.5 MV/m</td>
</tr>
<tr>
<td>Unloaded Quality factor $Q_0$ for $R_c=20$ nΩ at nominal field</td>
<td>$1.4 \times 10^6$</td>
</tr>
<tr>
<td>Beam aperture HWR/SP</td>
<td>40 / 50 mm</td>
</tr>
<tr>
<td>Freq. range of HWR tuning syst</td>
<td>± 50 kHz</td>
</tr>
<tr>
<td>Freq. Resolution of tuners</td>
<td>200 Hz</td>
</tr>
<tr>
<td>Max. transmitted RF power by coupler in CW (for LIPAc)</td>
<td>70 kW</td>
</tr>
<tr>
<td>Max. reflected RF power in CW</td>
<td>20 kW</td>
</tr>
<tr>
<td>External quality factor $Q_{ex}$</td>
<td>$6.3 \times 10^4$</td>
</tr>
<tr>
<td>Magnetic field $B_z$ on axis max.</td>
<td>6 T</td>
</tr>
<tr>
<td>$\int B \cdot dl$ on axis</td>
<td>1 T.m</td>
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<tr>
<td>Field at cavity flange</td>
<td>$\leq 20$ mT</td>
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<tr>
<td>CBPM position meas. Accuracy</td>
<td>0.25 mm</td>
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<tr>
<td>CBPM phase meas. accuracy</td>
<td>2 deg</td>
</tr>
<tr>
<td>Total Static/Dynamic Heat losses</td>
<td>18 / 120 W</td>
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</table>
## Cavity Types & Quantities

*Source: Vyacheslav Yakovlev*

<table>
<thead>
<tr>
<th>Section</th>
<th>Energy MeV</th>
<th>$E_{acc}$ MV/m</th>
<th>$B_{max}$ mT</th>
<th>$Q @ 2K \times 10^9$</th>
<th>Installed Cavities</th>
<th>Processed Cavities</th>
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<tr>
<td>SSR0 ($\beta_g=0.11$)</td>
<td>2.5-11</td>
<td>9.0</td>
<td>66</td>
<td>6.5</td>
<td>18</td>
<td>22</td>
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<td>SSR1 ($\beta_g=0.22$)</td>
<td>11-41</td>
<td>11.0</td>
<td>65</td>
<td>11</td>
<td>20</td>
<td>24</td>
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<tr>
<td>SSR2 ($\beta_g=0.42$)</td>
<td>41-179</td>
<td>10.0</td>
<td>69</td>
<td>13</td>
<td>44</td>
<td>53</td>
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<tr>
<td>650 MHz ($\beta_g=0.61$)</td>
<td>179-559</td>
<td>16.5</td>
<td>70</td>
<td>15</td>
<td>42</td>
<td>51</td>
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<tr>
<td>650 MHz ($\beta_g=0.9$)</td>
<td>559-3000</td>
<td>16.8</td>
<td>63</td>
<td>20</td>
<td>152</td>
<td>183</td>
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<tr>
<td>1300 MHz ($\beta_g=1$)</td>
<td>3000-8000</td>
<td>25</td>
<td>107</td>
<td>10</td>
<td>224</td>
<td>270</td>
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The PXIE demonstrator

- Front-end demonstrator PXIE is under construction (25 MeV, 1mA)
  - Goal = validate Project X concept & eliminate technical risks (compact lattice layout)
  - Beam operation planned between 2016 & 2018
  - Cavities under fabrication

See P. Ostroumov MOP066

See A.I. Sukhanov MOP014

Beam Parameters of RAON

<table>
<thead>
<tr>
<th>Particle</th>
<th>Driver Linac</th>
<th>Post Acc.</th>
<th>Cyclotron</th>
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<tbody>
<tr>
<td>H⁺</td>
<td>O⁺8</td>
<td>Xe⁺54</td>
<td>U⁺79</td>
</tr>
<tr>
<td>Beam energy (MeV/u)</td>
<td>600</td>
<td>320</td>
<td>251</td>
</tr>
<tr>
<td>Beam current (μA)</td>
<td>660</td>
<td>78</td>
<td>11</td>
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<tr>
<td>Power on target (kW)</td>
<td>&gt; 400</td>
<td>400</td>
<td>400</td>
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SRF Cavities

Superconducting cavity

For U beam

RISP: 0.047, 0.120, 0.30, 0.51

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>QWR</th>
<th>HWR</th>
<th>SSR1</th>
<th>SSR2</th>
</tr>
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<tbody>
<tr>
<td>$\beta_0$</td>
<td>-</td>
<td>0.047</td>
<td>0.12</td>
<td>0.30</td>
<td>0.51</td>
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<tr>
<td>$F$</td>
<td>MHz</td>
<td>81.25</td>
<td>162.5</td>
<td>325</td>
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<tr>
<td>Aperture</td>
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<td>40</td>
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<tr>
<td>$Q_{R_L}$</td>
<td>Ohm</td>
<td>21</td>
<td>42</td>
<td>94</td>
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<tr>
<td>$R/Q$</td>
<td>Ohm</td>
<td>468</td>
<td>310</td>
<td>246</td>
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<tr>
<td>$V_{acc}$</td>
<td>MV</td>
<td>1.05</td>
<td>1.52</td>
<td>2.22</td>
<td>4.20</td>
</tr>
<tr>
<td>$E_{peak}/E_{acc}$</td>
<td></td>
<td>5.6</td>
<td>5.0</td>
<td>4.4</td>
<td>3.9</td>
</tr>
<tr>
<td>$B_{peak}/E_{acc}$</td>
<td></td>
<td>9.3</td>
<td>8.2</td>
<td>6.3</td>
<td>7.2</td>
</tr>
<tr>
<td>$Q_{cell}/10^9$</td>
<td></td>
<td>2.1</td>
<td>4.1</td>
<td>9.2</td>
<td>10.5</td>
</tr>
<tr>
<td>Temp.</td>
<td>K</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

(Ep = 35MV/m)
SRF Test Facility Layout

- DI water Supply [6x6m²]
- Cryoplant [15x8m²]
- Vacuum Furnace (class1000) [8x8m²]
- HPR (class100) [6x6m²]
- Assembly Leak Test (class 16) [10x6m²]
- Cryomodule Assembly [12x8m²]
- CM Test Bench [8x4m²]
- CM Test Benches [8x4m²]
- CM Stock Area [12x6m²]
- Inspection (Microscope) [8x4m²]
- Ultrasonic cleaning [8x4m²]
- BCP [8x8m²]

Process Line  Moving line by trail/crane  Cleanroom  Total Area: 59.2 x 16.2m² ~ 960m²
Atlas Upgrade, ANL

ANL ATLAS Intensity Upgrade Cryomodule

- Seven $\beta = 0.077$, 72.75 MHz quarter-wave cavities
- Four 9-Tesla superconducting solenoids
- Replaces 3 old cryomodules with split-ring cavities
- Total design voltage is 17.5 MV, expected 4.5K cryogenic load is 70 W
- Will be operated to provide $\sim20$ MV, 4.5K cryogenic load is 85 W

5.2 m long x 2.9 m high x 1.1 m wide
Cavity Results

5 QWRs were tested in TC3

- Highly optimized EM design, conical shape, minimized ratio $B_{\text{peak}}/E_{\text{acc}}$, $E_{\text{peak}}/E_{\text{acc}}$
- Only wire EDM is applied for machining of the Nb joints to be EB welded
- EP after all mechanical work including He vessel is completed

![Graphs showing cavity results](image)
New Cryostat Design

Cavity String Assembly andCooldown

---

**Jan. 2013**

**June 2013**

**August 2013 (Test for 2 wks)**
- All cavities $E_{AC}>10$ MV/m
- Tuners cycled through full range
- Low microphonics, +/- 2 Hz for periods of minutes up to days
- Solenoids aligned to 120 μm RMS

**October 2013**
- Need to place string in stand (above) and
- Replace pickup loops (too much coupling)
- Squeeze one cavity by +5 kHz

---

**Cavity temperature during 1st cool down**

<table>
<thead>
<tr>
<th>Date</th>
<th>CAVITY_1</th>
<th>CAVITY_2</th>
<th>CAVITY_3</th>
<th>CAVITY_4</th>
<th>CAVITY_5</th>
<th>CAVITY_6</th>
<th>CAVITY_7</th>
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<td></td>
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<tr>
<td>7/20/13</td>
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<td>7/22/13</td>
<td></td>
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<tr>
<td>7/23/13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**July 2013**

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KEK - Activities

Purpose of fabrication of cavities on the KEK site

- Development of a mass production technology in order to fabricate more than 16000 cavities within 3 to 5 years for ILC project

- Improvement of yield ratio = Stable quality
- Reduce the cost drastically
- Development of mass production technologies

Cooperation with STF

Establish the Cavity Fabrication Facility

Collaboration with many companies

Development on the KEK site

Speed up the R&D

Realization of ILC
Q-E curve of vertical test at STF

KEK-0 (First product)
Acceleration gradient attained 29 MV/m, did not meet the ILC specification (31.5).
Compact ERL (cERL) at KEK

**Apparatus of cERL**

**Requirements of cERL main linac**
- Frequency: 1.3 GHz
- Gradient: 15 MV/m
- \(Q_0 > 1 \times 10^{10}\)
- Beam current: max 100 mA (100 mA (in) + 100 mA (out))

**cERL parameters**
- Red: initial case

**ERL-model-2 cavity:** 600 mA can be circulated in design

**Parameters of cERL main linac**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>1300 MHz</th>
<th>(E_{acc})</th>
<th>15-20 MV/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q_0)</td>
<td>1e+10</td>
<td>Coupling</td>
<td>3.8% (1.9%)</td>
</tr>
<tr>
<td>(R_{sh}/Q)</td>
<td>897 Ω (1007 Ω)</td>
<td>(Q_o \times R_s)</td>
<td>289 Ω</td>
</tr>
<tr>
<td>(E_p/E_{acc})</td>
<td>3.0 (2.0)</td>
<td>(H_p/E_{acc})</td>
<td>42.5 Oe/(MV/m)</td>
</tr>
</tbody>
</table>

**P_{loss} = \frac{V_c^2}{(R/Q)Q_0}\**

P_{loss} = 25 W/m (15 MV/m)

**35 MeV single-loop ERL**

**HOM-BBU calculation (w/o HOM randomization)**

**Simulation by BI**

Calc by R. Hajima,
KEK-ERL Model-1 (HOM: 6x2)

**TESLA (HOM: 5x2)**

(TESLA 20 mA)
Spiral2

**Accelerator Basic Configuration**

- Heavy ion source (A/q=6) and RFQ - optional upgrade
- QWR 88MHz (β = 0.07)
- QWR 88MHz (β = 0.12)
- Neutron For Science
- d⁺: 20 MeV/n
- HI: 14.5 MeV/n

**Total length: 65 m (without HE lines)**
- Slow (LEBT) and Fast Chopper (MEBT)
- RFQ (1/1, 1/2, 1/3) & 3 re-bunchers
- 12 QWR beta 0.07 (12 cryomodules)
- 14 (+2) QWR beta 0.12 (7+1 cryomodules)
- 1.1 kW Helium Liquifier (4.5 K)
- Room Temperature Quadrupoles
- Solid State RF amplifiers (10 & 20 KW)
- 6.5 MV/m max $E_{acc} = \frac{V_{acc}}{L_{opt}}$ with $V_{acc} = \int E_{ac}(z) dz$

**Parameters**

<table>
<thead>
<tr>
<th>Particles</th>
<th>H⁺</th>
<th>$^3$He²⁺</th>
<th>D⁺</th>
<th>Ions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q/A</td>
<td>1</td>
<td>2/3</td>
<td>1/2</td>
<td>1/3</td>
</tr>
<tr>
<td>I (mA) max.</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>W₀ max. (MeV/A)</td>
<td>33</td>
<td>24</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>CW max. beam power (KW)</td>
<td>165</td>
<td>180</td>
<td>200</td>
<td>44</td>
</tr>
</tbody>
</table>
Cavity Performance

- Q0 vs. E (MV/m)
- Vertical test results T=4.2K
- SpinRA2 operating range: 10 W
- QWRA - B 0.07
- Epeak (MV/m)
- SpinRA2 operating range: 10 W
Report from SRF2013 Accelerator Seminar: The SRF World Today

SRF cavity processing techniques - the latest standard and the emerging

Ari D. Palczewski, SRF Scientists
Jefferson Lab, USA
10/17/2013
Highlights from SRF2013 - processing

• Review – how a cavity is made
• XFEL standard vs. C100 surface prep
• Cavity weld prep – chemistry and handling (informal discussions with industry and DESY)
• New welding – laser welding in Argon environment
• Standard horizontal Electo-polishing (EP)
• Alternative EP – Vertical EP (9 cell)
• Alternative EP - Bipolar EP (no HF)
• Alternative EP - ionic liquid EP (no HF)
• Alternative to bulk chemistry (and possible zero chemistry) – Centrifugal barrel polishing (CBP)
How Cavities Are Made

Niobium is cleaned, etched and electron beam welded

Graphic from Hitoshi Hyano
Cavity surface treatment standard (XFEL) vs. (C100)

Surface treatment after welding.
EP 110-140 μm (main EP), outside BCP, ethanol rinse, 800°C annealing 2 hrs.

Final surface treatment - two alternative options
1. Final EP of 40 μm, ethanol rinse, high pressure water rinsing (HPR) and 120°C bake
2. Final BCP of 10 μm (BCP Flash), HPR and 120°C bake.

No need for ethanol rinse because of low temperature (below 25C) from external water cooling) and no bulk EP – ethanol rinsing required for bulk EP at JLab to remove sulfur even at low temperatures
(New) Standard weld prep XFEL vs. JLAB

Machining prep

Abandoned years ago by many labs because of weld pits from trapped particles, but has better tolerance for eccentricity and easier tooling.

Acid etch/cleaning

<table>
<thead>
<tr>
<th>HNO₃ (65%) + HF (40%) + H₃P₀₄ (85%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Buffered chemical polish [BCP112]</td>
</tr>
<tr>
<td>Hand agitation</td>
</tr>
<tr>
<td>3-6µm</td>
</tr>
<tr>
<td>+ DI water triple rinse/ultrasonic</td>
</tr>
<tr>
<td>in DI 10 min.</td>
</tr>
</tbody>
</table>
Weld assembly (XFEL) vs. JLab

• Dry in clean area with fully gowned personal with nitrogen blow off of all edges.
• Assembled in clean room with fully gowned personal.
• Transported in bag to EBW machine (iso 6/7) with partially gowned personal.

Is the extra cost associated with this worth the money? Depending on DESY, Zanon or RI this is only done for high field regions welds.

Should JLab implement some of these standards? Should JLab consider interlocking weld prep which was abandoned years ago because of weld bubbles?
New welding (tested at FNAL) – Laser welding

Prashant Khare - RRCAT in India

31MV/m Q>1e10!
On first prototype

500W (avg.) Nd:YAG laser

- Can be used with optical fiber to make all inside welds
- Promises – higher through-put, lower initial costs and lower operations costs, and can be done in non-vacuum environments
Electro-polish facilities

Horizontal EP
• Asia: KEK
• Euro: DESY, Zanon, RI
• USA: FNAL/ANL, JLab

Vertical EP
• Asia: KEK
• Euro: Saclay, INF
• USA: Cornell, JLab

1DE1: Horizontal EP + 70 µm VEP
- Parameters: 6V & >24L/min
- Bright and smooth surface

- Performance before/after baking similar to HEP
- High gradient maintained after VEP

Aspects to improve:
- Low removal rate at 19° C: 0.2µm/min
- Asymmetry: removal rate higher in the upper part of the cell (x 3)

Presented by F. Eozénou, 1st LCC/ILC cavity group meeting, 2013
1st achievement of 40MV/m w/ VEP + TESLA 9-cell

- A9 re-HPR
- ILC BCD
- Radiation

Pi-mode, 2.0K
Eacc max=38MV/m, Qo = 9.0e9
Rad ~1.0mR/hr, Limited by quench.

Development of an Integrated Cavity Processing (ICP) System: Pushing cavity processing technology

✓ Hydrophobic PTFE membrane proven to efficiently block hydrogen bubbles created at cathode and without affecting the electropolishing process.

✓ Spline shaped cathode increases cathode surface area, flow inside of membrane-protected cathode transports hydrogen bubbles away.

Put on hold since 2012 (over 18 months) because of facilities move – major set-back for VEP at JLab

Jlab’s CBP+VEP reaches 35MV/m - 2012
Non-standard EP - Bipolar EP

- Bipolar EP: Electropolishing Without Fluorine (‘HF) in a Water Based Electrolyte of sulfuric acid
- Electrolyte modification from 9:1 solution of 95% H2SO4:49% HF to dilute H2SO4. Working concentration is 5-10 wt% H2SO4.
- Works with existing EP tooling with minor modifications.

Allan Rowe - FNAL

Choline Chloride:Urea (1:4) + 97 g/l Sulfamic
Temperature = >120°C
Current density (A/cm²)=0.3
Niobium cathode

Promising but still needs a lot of work

V. Pastushenko @ INFN/LNL
Low beta cavities (spoke/quarter/half) - EP

Quarter wave 72.75MHz
Quad cathode EP @ ANL

In the past most non-elliptical cavities were only chemically treated with BCP

<table>
<thead>
<tr>
<th>Peak Surface Magnetic Field</th>
<th>166 mT</th>
<th>175 mT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Surface Electric Field</td>
<td>117 MV/m</td>
<td>84 MV/m</td>
</tr>
</tbody>
</table>
Alternative to bulk chemistry (CBP)

- Fill cavity with abrasive median and usually a liquid
- Hermitically seal the cavity - run in machine for a set time
- Clean cavity (water rinse, ultrasonically clean, HPR ....)
- Reduce media grit size and repeat
- Light chemistry still needed at end
- Creates uniform and hopefully defect free surfaces

SCRF cavity
Cavity rotation direction

Turret rotation direction

Working principle of CBP

Outward force

Horizontal force

Inner niobium surface

Media
Alternative to bulk chemistry (CBP)

Cavities CBP’ed in last 2 years: JLAB

FNAL
- Nine Cell (TE1XXXX)
- 7 different cells
- ACC015, NR002, AES006, AES012, AES016
- AC114 – Large Grain
- IHEP02 – Large Grain
- Cat05 – Aluminum
- Single Cell (TE1XXXX)
- JL001, JL002, ACC001, ACC004, ACC006, CAT001–CAT004, PAV007, PIPP001, 1DE20, IHEP02
- RICU001 (several others as well)
- TACAES001 & 002 (~40 runs)

RRCAT
- Multiple single cell

JLAB
- Multicell TB9NR001
- 3.5GHz gun cavity
- Single cell RDT4
- LSF-1,2,3 (copper)
- G1G2F1F2PS-1307 6 sets of beam pipes (Cu and Nb)

INFN
- Over 10^6 GHz (resonate vibration)

DESY
- Machine setup and beginning to process

Cornell
- Beginning to process multi-cell

RRCAT
- Multiple single cell

Alternative to bulk chemistry (CBP)

5 fold increase of cavities process by CBP over the last two years from the two years prior – FNAL’s CPB program is leading the way by a large margin

JLab trailing in a distance second
(CBP) with zero post chemistry at FNAL

- See TUP030 (Grassellino/Cooper, FNAL)

Large grain single cell
4 step CBP - 800°C heat treatment (with end caps)
Q slope limited
High temperature heat treatment

See - Pashupati Dhakal

Nb high-Q pursuits - what is new, what is the best seen, what understanding/control is needed yet?
Report from SRF2013 Accelerator Seminar: The SRF World Today

SRF non-bulk materials - what is new and promising?

Oral session- Wednesday Sep, 25

**Basic R&D New materials**

Thin film deposition techniques
Multilayers, MgB$_2$ I
Multilayers, MgB$_2$ II

Poster session – Tuesday Sep, 24

Anne-Marie Valente-Feliciano
Jefferson Lab, USA
10/17/2013
CERN LEP 2  272 x 353MHz Nb/Cu 4-cell cavities  also LHC

INFN Legnaro  52 x 160 MHZ Nb/Cu QWR
1.5 GHz Nb/Cu cavities, sputtered w/ Kr @ 1.7 K (Q_0=295/R_{s})

RRR_{max}= 40

Columnar grains, size ~ 100 nm
In plane diffraction pattern:
(110) fiber texture ⊥ substrate plane

Equi-axed grains, size ~ 1-5 μm
In plane diffraction pattern:
zone axis [110]

Heteroepitaxy
Nb (110) //Cu(010) , Nb (110) //Cu(111), Nb (100) //Cu(110)

RRR_{max} = 28

1.5 GHz Nb/Cu cavities, sputtered w/ Kr @ 1.7 K (Q_0=295/R_{s})

Bulk Nb

1.5 GHz Nb/Cu

Fundamental Quench

Multipacting

Resistive losses

LEP II

350MHz Nb/Cu (4.2K)

RRR_{max} = 40

Accelerating Field

50 MV/m

50

25

20

15

10

5

0

0

10

10

10

10

10

10

10

Oxide-free films

Standard films

Courtesy: P. Jacob – EMPA
Energetic Condensation

Condensing (film-forming) species: hyper-thermal & low energies (>10 eV).

Additional energy provided by fast particles arriving at a surface ⇒ number of surface & sub-surface processes ⇒ changes in the film growth process:

- residual gases desorbed from the substrate surface
- chemical bonds may be broken and defects created thus affecting nucleation processes & film adhesion
- enhanced mobility of surface atoms
- stopping of arriving ions under the surface

⇒ Changes in
- morphology
- microstructure
- stress

As a result of these fundamental changes, energetic condensation allows the possibility of controlling the following film properties:

- Density of the film
- Film composition
- Crystal orientation may be controlled to give the possibility of low-temperature epitaxy
Thin film deposition techniques
High Impulse Power Magnetron Sputtering

CERN
G. Terizziani, S. Calatroni

LBNL
A. Anders, R. Mendleberg

JLAB
L. Phillips

nearly perpendicular incidence!
ion trajectory possible collision
Thin film deposition techniques
High Impulse Power Magnetron Sputtering

Nb/Cu cavities produced at CERN both by DC cylindrical magnetron sputtering and cylindrical HiPIMS with Kr

Note: - Substrate preparation is SUBU (by opposition to electropolishing for the best 1.5GHz DCMS Nb/Cu cavities to date)
- Measurement at higher fields than 11MV/m prevented by interlock system due to radiation
Thin film deposition techniques

Other energetic condensation techniques: CED, ECR

Co-axial Energetic Deposition (AASC Inc.) – collaboration with Jlab, ANL, LANL, CERN

KEK06 hydro-formed copper cavity, CBP at FNAL (Cooper), coated at AASC, tested at LANL (Tajima, Haynes)

Good results on Nb/Cu samples (RRR:12-110)

Several attempts of Nb coating on both Cu and bulk Nb cavities. Transition from flat samples to cavity coating is a challenge
Thin film deposition techniques

Other energetic condensation techniques: CED, ECR

Tune thin film structure and quality with ion energy and substrate temperature: RRR values from single digits to bulk Nb values on a variety of substrates (on Cu: 5 – 300).

Gap measurements performed by PCT (point contact tunneling spectroscopy-ANL) show a superconducting gap (1.56-1.62meV) similar to bulk Nb ($\Delta_{\text{Nb bulk}} = 1.55\text{meV}$ measured on the same setup) for hetero-epitaxial ECR Nb films on polycrystalline Cu.
Thin film deposition techniques
Magnetron sputtering development for HIE-ISOLDE - CERN

Strong development program focused on bias diode sputtering method:

- Increasing baking and coating temperatures
- Increasing sputtering power (global deposition rate)
- Layered coatings
- Sputtering gas, venting gas
- Global film thickness
- Local film thickness

HIE-ISOLDE needs 39.6 MV from 32 independently phased QWR, project schedules are always tight and physicists are waiting for the beam.

Project oriented R&D, several parameters changed at a time.

HIE ISOLDE specifications recently met, (with 30% margin in power)

We are on track to start series production for the first phase up to 5 MeV/u.

R&D at INFN-LNL and at CERN continues with encouraging results, which could benefit phase II and phase III (low beta), and future machines.
Measurement setups for materials beyond bulk Nb

**Quadrupole resonator @ CERN**
- 400, 800, 1200 MHz
- Almost identical magnetic field configuration
- Ratio of $B_{peak}$ to $E_{peak}$ is proportional to $f_{res}$
- $B_{max} \approx 60$ mT
- Temperatures 1.6 -12 K
- Reproducible measurements
- Upgrade design in collaboration with HZB, Berlin

 Resolution for $R_s$ measurement:
0.44\,\text{n}\Omega \@ 5\,\text{mT}

collaboration with Jlab for ECR Nb/Cu and ML/Nb measurements

**SIC (TE011) cavity @ Jlab**
- 7.5 GHz sapphire-loaded TE011
- Calorimetry
- $B_{max} \approx 20$ mT currently, improving to higher fields
- Temperatures 1.6 -50 K
- $\lambda$ measurements thru frequency shift (T)
- Reproducible measurements

**IPN Orsay/CEA Saclay –TE011 @ 3.988 GHz and magnetometry**
- $H_{c1}$ direct value
- Perpendicular
- Local
- No border effect
- Fields up to 150 mT, 2-40 K

S. Aull et al.
G. Eremeev et al.
C. Baumier, C. Antoine, G. Martinet…
S. Posen, M. Lieppe

$B_{c1}$ of Nb$_3$Sn witness sample measured directly via muon-SR by Anna Grassellino et al.

$B_{c1} \sim 20\text{-}30 \text{ mT}$

-> agrees well with cavity measurement
Transition temperature is ~ 17.85 K. The best of three samples shows very smooth surface with no residual tin contamination.

Recent measurements of surface resistance of several ECR films, bulk Nb sample, and Nb₃Sn sample as a function of temperature at 7.4 GHz.

- Preliminary studies with samples have been done. RF measurements on a sample indicated the transition temperature of 17.9 K and RF surface resistance of about 30 μΩ at 9 K and 7.4 GHz.
- The horizontal insert has been built and inserted in the furnace. The first furnace run has been done at 1200 °C for 2 hours.
- R&D furnace for Nb₃Sn development was ordered in October 2012, delivered in August 2013, and is being commissioned.
MgB$_2$- Hybrid Physical Chemical Vapor Deposition

MgB$_2$ thin film samples especially prepared by HPCVD have shown excellent properties relevant to SRF applications, which warrants the coating of practical-size cavities and study the performance as a cavity.

LANL is implementing a cavity coating system based on HPCVD Challenges in reproducing the results from Temple University
A boron film was deposited first (A) and then annealed in Mg vapor (B).

The process is being optimized.

The top three films show $T_c$ above 37 K with a RRR of 2.

- superconducting Nb CW cavity designs require about 20 to 60 W at 4 K
- MgB2 films can achieve similar surface resistance at 8 -12 K.
- It makes it possible to use cryocoolers for heat removal.
- The cryomodule without liquid cryogens is considerably simplified. No liquid filling ports or internal piping, liquid reservoirs, or internal gas piping is required. Cryocoolers.
- Ideally, a high thermal conductivity material like copper would be best for the cavity.
- The thermal conductivity of Nb is about 200 W/mK, so even Nb would be usable as a substrate if MgB2 cannot be deposited on copper.
Multilayers – the Model


Enhancement of $H_{c1}$ for Thin SC films with $d < \lambda$  (1)
Applied field is reduce by each layer.
Niobium surface screening: allows higher field in the cavity
NbN thin film: higher TC → higher $Q_0$
Insulating layer prevents Josephson coupling between layers
Accelerating field can be increased without high field dissipation
High $H_{c1}$ → no vortex in the layer

Work from Cornell - S. Posen et al.

Evaluation of the thermodynamic potential $G(x)$ of single vortex as function of its position across the SIS structure and evaluation of HSH from evaluation of the vortex entry energy barrier in the London theory
SIS multilayer films have $B_{c1}= 0$ & rely on energy barrier as the bulk does
SIS $B_{sh}$ is very close to bulk $B_{sh}$
Small potential gain but very difficult to fabricate
• May not be superior for SRF applications—they are useful in DC applications
• $B_{c1}$ is not a limit for cavities made from small-$\xi$ superconductors! No need for $B_{c1}$ enhancement!
• Strong optimism for bulk films

See reply from A. Gurevich in ArXiv

Work from KEK (Kubo et al.)

Formulation derived from Maxwell equation and London equation to describe the RF electromagnetic field attenuation for the multilayer coating model
Some SC material may be more suitable than others and thickness is critical

Proof of principle is necessary … now more than ever…
Multilayers – based on NbN

By tailoring thin film growth parameters, and also using SQUID magnetometry we were able to demonstrate shielding beyond the critical field of Nb also using NbN-based trilayers.

Field (Oe)

Long Moment (emu)

$T = 4.5 \text{ K}$

$H_{c1}$-NbN-based-Multilayer $\sim 220 \text{ mT}$

$H_{c1}$-bulk Nb $= 170 \text{ mT}$
Multilayers – based on NbN

CEA Saclay – Molecular Beam Epitaxy

Effective screening of the surface, prevents early vortex penetration
→ RBCS is improved with the use of higher TC SC
→ Rres is not dramatically degraded compared to Nb
→ Room for improvement: better understanding of interaction with substrate needed

Strong indication that $R_{BCS}$ is improved with ML
Could probably be improved with the use of thicker layers (complete screening)

Very promising preliminary results

C. Baumier et al.
Multilayers-based on NbTiN

NbTiN/AlN by ALD - ANL

Explore via ALD various Sc materials: Nb1-xTixN, TiN, MoN, NbSi, NbC, NbCN
And insulators: MgO, Al2O3, AlN…
Collaboration with Jlab

(NbF5, TiCl4) + NH3
(NbCl5, TiCl4) + Zn + NH3

Δ = 2.3 meV ± 0.1

T. Proslier et al.
Multilayers-based on NbTiN

NbTiN/AlN by Sputtering-JLab

SIS structures based on NbTiN and AlN have been coated at 450°C in-situ on bulk Nb and Nb/a-Al₂O₃ substrates after a 24h-bake at 600°C. The samples are then annealed at 450°C for 4 hours.

The SIS structure coated on the Nb exhibits a $T_c$ for the NbTiN of 16K. RF measurements are ongoing [6].

The SIS structure coated on the ECR Nb/(11-20)Al₂O₃ film exhibits a suppressed $T_c$ for the Nb film compared to the measurement prior to the SIS coating. This is most likely due to the Nb oxide reduction and oxygen diffusion during the bake at 600°C. The NbTiN has a $T_c$ of about 15K.
**Multilayers-based on MgB$_2$**

**Enhancement of $H_{c1}$ in thin MgB$_2$ films**

Temple University  
X. Xi et al.

- 2 group of samples were studied:
  - Single crystalline thin films on SiC(0001) substrate
  - Polycrystalline thin films on amorphous MgO layer on SiC(0001)

- $H_{c1}(5K)$ is enhanced when the film thickness decreases, for films on both single crystal SiC substrate and polycrystalline MgO films.

- $H_{c1}(5K) \sim 2000$ Oe in 100nm-thick MgB$_2$ film.
Beyond bulk Nb material

- In depth sample studies. Quality samples produced.
- First results with multilayers show some field enhancement
- Undisputable proof of principle for the S-I-S multilayer structure concept needed
- Progress towards cavity coating both for Nb films and multilayers in most institutions involved
- Significant synergy between all the institutions active in the field of materials beyond bulk Nb:

Jlab closely collaborates with College William & Mary, ANL, LBNL, MIT, AASC Inc., Temple university, CERN on the development of Nb films and S-I-S Multilayer structures

Key note talk:”Quantum Measurement with "Trapped" Microwave Photons in a SRF Cavity”- M. Brune – S. Harouche Team (2012 Nobel Prize Laureat), Laboratoire Kassler-Brossel

Collaboration with JLab for ECR Nb based toroidal mirrors
Report from SRF2013 Accelerator Seminar: The SRF World Today

Nb high-Q pursuits - what is new, what is the best seen, what understanding/control is needed yet?

Pashupati Dhakal
Jefferson Lab, USA
10/17/2013
R&D on SRF

• Driven by Project Need
  * CW applications
  * Pulse applications
  * High current
  * 4.2 K applications

• Conventional R&D
  * Maximize $E_{\text{acc}}$ and $Q_0$
  * Search for alternative materials
  * Process improvement

Overall goal: Minimize construction and operation cost with reliable and efficient SRF cavities
Quality Factor and Surface Resistance

Quality Factor \( (Q_0) = \frac{G}{R_s} \)
\( G = \) Geometry factor (shape dependent)

\[ R_s = R_{\text{res}} + R_{\text{BCS}}(f, T, \Delta, \lambda_L, \xi_0, l) \]

**Possible sources of** \( R_{\text{res}} \)
- Trapped magnetic field
- Normal conducting precipitates
- Grain boundaries, dislocations
- Interface losses
- Subgap states

**Remedies:**
- High treatment heat treatments
- Magnetic shielding

At temperature below 2K, \( R_s \) is dominated by \( R_{\text{res}} \).
Quality Factor and Surface Resistance

BCS surface resistance results from the interaction between the RF electric field within the penetration depth and thermally activated electrons in a superconductor.

\[ R_{BCS}(f, T, \Delta, \lambda_L, \xi_0, l) = \left( Af^2/T \right) e^{-\Delta/k_B T} \]

Minimizing BCS Resistance

- Lower frequency
- Higher \( T_c \) superconductors
- Higher energy gap
- Optimal electronic mean free path

High Temperature Treatment Results

Reduction in $R_{BCS}$

$\sim 2 \text{n}\Omega$

$\sim 1 \text{n}\Omega$

$R_{res}$

$4.6 \times 10^{10} @ 20 \text{ MV/m}$

$B_p/E_{acc} = 4.43$

Extended Q-rise

Large Grain G1-G2 (RRR ~ 200, Ta ~ 1375 wppm) CEBAF O C shape single-cell, 1.474 GHz

$Q_0$ vs $B_p$ (mT)

- Baseline (BCP) - 01/31/2011
- 1400C/3h HT - 02/08/2011
- Baseline (EP) - 09/13/2013
- 1400C/3h HT - 10/4/2013

T = 2.0 K

MP/quench

P. Dhakal et al, TUIOC04, SRF 13
HT results for “All Nb Cavity”

- 3 “all Nb” cavities (2 LG and 1 FG) are heat treated up to 1600 C
- Improvement in Q in medium field range up to ~70%
- No extended Q-rise

P. Dhakal et al, TUIOC04, SRF 13
HT results for Reactor Grade Nb

- RRR ~ 40

- Extended Q- rise up to 35 mT with factor of 2 improvement in Q at 20 MV/m

- Cavity was purified in the presence of Ti and surface removal of ~30 μm before the baseline test

Note: In early 80’s those high Q cavities are made from reactor grade and heat treated at very high temperatures.
Thermal Cycling @ HZB

Cavity Quality before thermal... Cavity quality factor after...

The temperature gradient across the cavity need to be minimized

\[ U_{\text{thermo}} = (S_{\text{Niobium}} - S_{\text{Titanium}}) \cdot \Delta T \]

Oliver Kugeler
Julia Vogt
High Q Cavities for the Cornell ERL  

Ralf Eichhorn

Initial Cool down at 16.2 MV/m

- $Q(2.0 \text{ K}) = 2.5 \times 10^{10}$
- $Q(1.8 \text{ K}) = 3.5 \times 10^{10}$
- $Q(1.6 \text{ K}) = 5.0 \times 10^{10}$

10 K Thermal Cycle at 16.2 MV/m

- $Q(2.0 \text{ K}) = 3.5 \times 10^{10}$
- $Q(1.8 \text{ K}) = 6.0 \times 10^{10}$
- $Q(1.6 \text{ K}) = 10.0 \times 10^{10}$
Fermi Lab Nitrogen Doping

Fermi Lab started to inject gas in furnace during HT after the initial encouraging results from JLAB

Low field Q-rise similar to that observed at JLAB

Anna Grassellino
Cornell Experience with Nb doping

- Rapid low field Q-rise and tend to saturate at high field

- No clear evidence on how much material should be removed after baking cavity in the presence of N₂
Theoretical Buzz on Q-rise

Calc for:
\( \lambda = 32 \text{ nm} \)
\( \xi = 40 \text{ nm} \)
\( \Delta/T_c = 1.85 \)
\( \text{mfp} = 50 \text{ nm} \)

Why increasing?

Mattis-Bardeen


B. Xiao and C. Reece
**JLAB Status in High Q**

**N₂ treatment procedure**
- UHV Heat treatment at 800 °C/3h
- Rapid cooling to 400 °C, admit \(5 \times 10^{-6}\) Torr N₂ for 15 min
- Cool to 120 °C and hold for 12 h (optional)
- No chemical etching afterwards!!! Just degreasing and HPR

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**Dedicated furnace with controlled gas injection system**

G. Ciovati et al. 2010

Induction Furnace

JLAB Status in High Q

- So far the heat treatment are focused on temperature as a parameter (800-1600 °C)
- Studies showed the Ti doping in SRF cavities, cause the extended Q-rise
- Sample studies with point contact tunneling, magnetizations and AC susceptibility are underway
- Nitridation in cavities with optimal partial pressure of nitrogen, eliminating final chemistry.
High Q Status

• Search for high Q is an ultimate goal for the future CW accelerators
• Current research is mostly **Trial and Error**, and lack the physics based research
• Samples studies from the cavity cut out as well as from coupons to understand the loss mechanism is necessary.
• The high Q has been observed in contaminated surface. The role of contaminant in Nb as well as its interactions with other interstitial impurities (H, O, N, C), dislocations and vacancies need to be understood
• The **universal theoretical model** that fits all Q-rise, Q-slope and Q-drop is still lacking. The current model by Xiao et al explain the extended Q-rise
Conclusions

• Several research lab are pursuing high Q research in both R&D SRF cavities as well as cryomodules.

• Doping in the SRF cavities seem to increase quality factor, however the mechanism hasn’t been understood.

• Controlled experiments as well as the sample studies are needed.