New Ideas & Approaches to Raise CEBAF $Q_0$

- Initial Results and Proposed Studies

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Outline

• Introduction

• Factor of 2 change in $Q_0$ from evaluation at VTA to placement in CEBAF

• Sources of change and mitigation
  – Understanding from past and present effort
  – Mitigations implemented and planned

• New opportunities
  – Frozen flux reduction by Cryogenic Thermal Annealing (CTA)
  – Whole-module degaussing
  – Impurity doping refurbishment cavities?

• Proposal for new studies and tests

• Conclusion
Introduction

- Upgrade done. CEBAF has entered into new era of operation for NP.
  - 320 5-cell cavities plus 80 7-cell cavities in north- & south- linacs
  - High gradient (15–20 MV/m) in CW operation
    - Unprecedented
    - Unique large SRF linac – pushing reliability envelope

- Energy reach is crucial for CEBAF capability
  - Ultimate energy reach is constrained by $Q_0$ given fixed cavity shape and cryo-plant capacity (also RF source and LLRF)

- Energy efficiency is critical for sustainability
  - CEBAF needs to catch up in next few years for efficiency competitiveness
    - CEBAF: 2 GeV, 10 kW @ 2K
    - LCLS-II: 4 GeV, 8(4) kW @ 2K

- Seeking for establishment of new project to raise $Q_0$ of installed cavities in CEBAF: (a) without moving cryomodules out of tunnel; (b) within on-going C50 refurbishment effort.
## Original Cavity and Cryomodule

<table>
<thead>
<tr>
<th></th>
<th>Design</th>
<th>Vertical testing</th>
<th>Cryomodule testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;Eacc&gt;</td>
<td>5</td>
<td>&gt;5</td>
<td>&gt;5</td>
</tr>
<tr>
<td>Q₀ at 2K at 5 MV/m</td>
<td>2.4×10⁹</td>
<td>~ 1×10¹⁰</td>
<td>~ 5×10⁹</td>
</tr>
</tbody>
</table>

### Factor of 2 loss in Q₀

Q₀ met construction spec of 2.4×10⁹

**4x cryo unit -> cryomodule (8.25 m long)**

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**A. Vacuum Shell Flange**  
**B. Magnetic Shield and Inner Superinsulation**  
**C. HOM Load**  
**D. Cavity**  
**E. Shield Superinsulation**  
**F. Helium Vessel**  
**G. Flange Surface on Isolation Valve**  
**H. 40 to 60 K Radiation Shield**  
**I. Shield Helium Supply Line**  
**J. Outboard Cavity Support**  
**K. Axial Support**  
**L. Rotary Feedthrough**  
**M. Fundamental Power Waveguide**  
**N. Tuning Mechanism**  
**O. Helium Vessel Support Rod**  
**P. 2 K Helium Return**  

*Asterisked items shown only once to simplify illustration.*
# Sources of $Q_0$ Change and Mitigation

## Confirmed magnetic sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Understanding</th>
<th>Mitigation</th>
<th>Mitigation implemented?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic strut springs</td>
<td>302 SS, remanent magnetic flux, worse case 6 G at contact</td>
<td>Replace them by 316 SS springs</td>
<td>YES</td>
</tr>
<tr>
<td>Magnetic tuner drive shaft</td>
<td>17-4 PH SS, remanent magnetic flux, worse case 1.7 G at contact</td>
<td>Replace them by 316 SS shaft</td>
<td>NO</td>
</tr>
<tr>
<td>Magnetic bearing</td>
<td>440C SS, remanent magnetic flux typical 0.5 G at contact</td>
<td>Degauss first then re-use</td>
<td>YES</td>
</tr>
</tbody>
</table>

## Other sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Ruled out?</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Q-disease” from hydrogen in niobium material</td>
<td>YES</td>
</tr>
<tr>
<td>Window loss</td>
<td>TBD</td>
</tr>
</tbody>
</table>

Work published at IPAC14 as a contributed talk, THOBB01 “Pursuing the Origin and Remediation of Low Q0 observed in the Original CEBAF Cryomodules”
Sources of $Q_0$ Change and Mitigation (cont.)

<table>
<thead>
<tr>
<th>Source</th>
<th>Testing result in hand?</th>
<th>Further test needed?</th>
<th>Potential benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generated flux from thermal current effect</td>
<td>Initial testing result measured in VTA using a 5-cell dummy cavity</td>
<td>YES</td>
<td>May lead to a “thermal therapy” of in-situ $Q_0$ recovery in CEBAF tunnel</td>
</tr>
<tr>
<td>Additional flux trapping from repeated quenching events</td>
<td>NO</td>
<td>YES</td>
<td>May lead to an improved cryomodule testing procedure for full preservation of cavity $Q_0$ from VTA to tunnel</td>
</tr>
</tbody>
</table>

Sources under investigation/to be investigated

Presently:
- Examination of magnetic flux thermally generated inside the loop formed between niobium cavity and stainless steel rods
- Developing a thermal current model for prediction of generated flux of cavity pair in a cryo-unit.
- A potential “thermal therapy” is being developed for zero out the thermally generated flux.

Series test of thermal current and generated flux using a 5-cell CEBAF cavity

Shichun Huang
Additional flux trapping from repeated quenching events

**Added Average Surface Resistance Due to Accumulated Quench Events**

- **G2: LG, 1.3 GHz, TESLA end cell**
- **RDT-5: FG, 1.3 GHz, TESLA end cell**
- **PJ1-2: LG, 1.5 GHz, CEBAF upgrade end cell**

- **RDT-5: FG, N-doping + EP**
  - Quench at \( E_{acc} = 19 \text{ MV/m} \), data taken just below quench limit

- **G2 after N-doping:**
  - Above N-doping + EP
  - Multipacting Induced quench
  - For which \( E_{acc} = 18-24 \text{ MV/m} \)
  - Data taken \( E_{acc} = 18 \text{ MV/m} \)

- **PJ1-2:**
  - BCP +800Cx2hr +EP4um+120Cx18hr
  - Quench at \( E_{acc} = 33 \text{ MV/m} \)
  - Data taken just below quench limit

- **G2:**
  - CBP +800Cx2hr +EP25um+120Cx48hr
  - Quench at \( E_{acc} = 38 \text{ MV/m} \)
  - Data taken just below quench limit

**Graph Details:**
- **Y-axis:** Added Average Surface Resistance [nano-Ohm]
- **X-axis:** Number of Accumulated Quench Events
# Impact Factors

<table>
<thead>
<tr>
<th>SRF Machine</th>
<th>Duty Factor [%]</th>
<th>Design $Q_0$ [$10^{10}$]</th>
<th>Surface resistance [nΩ]</th>
<th>Relative increase for 4 nΩ added surface resistance</th>
<th>Number of high $Q_0$ cavities</th>
<th>Impact level</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEBAF-original</td>
<td>100</td>
<td>0.24</td>
<td>114</td>
<td>4%</td>
<td>338</td>
<td>Negligible</td>
</tr>
<tr>
<td>CEBAF-upgrade</td>
<td>100</td>
<td>0.72</td>
<td>39</td>
<td>10%</td>
<td>80</td>
<td>Low</td>
</tr>
<tr>
<td>XFEL</td>
<td>0.65</td>
<td>1.0</td>
<td>27</td>
<td>15%</td>
<td>800</td>
<td>Medium</td>
</tr>
<tr>
<td>LCLS-II</td>
<td>100</td>
<td>2.7</td>
<td>10</td>
<td>40%</td>
<td>~300</td>
<td>High</td>
</tr>
<tr>
<td>ILC-baseline</td>
<td>0.65</td>
<td>1.0</td>
<td>27</td>
<td>15%</td>
<td>16000</td>
<td>Medium</td>
</tr>
<tr>
<td>ILC-low loss</td>
<td>0.65</td>
<td>2.0</td>
<td>14</td>
<td>30%</td>
<td>16000</td>
<td>High</td>
</tr>
</tbody>
</table>
New Opportunities

- Frozen flux reduction by CTA
- Whole-module degaussing
- Impurity doping of re-furbished cavities
1-Cell Cavity Testing of CTA

LSF1-3
1.3 GHz
LSF Shape
Large-Grain Nb

Cavity processing:
BCP 60 um + 800Cx2hr + BCP 20 um + 120Cx9hr

30% increase in Q₀
LSF1-3 partial warm to 20 K then re-cool down
Whole-module degaussing

• De-magnetize whole cryomodule
  - Could lead to a solution applicable to cryomodules placed in CEBAF without moving them out of tunnel.
• Feasibility test with a cryo-unit or a quarter module

A. Crawford, Superconducting RF Cryomodule Demagnetization, arXiv:1503.04736
Impurity Doping of Re-furbished Cavities

• Impurity doping (Ti, N) has shown benefit of raising $Q_0$.
• A workable procedure is now available in-house for nitrogen doping due to work for LCLS-II.
• A number of 9-cell XFEL/ILC cavities have been treated with nitrogen doping and tested at JLAB with good $Q$ values up to the regime of 20 MV/m.
• A 7-cell C100-style was nitrogen doped and tested horizontally in a one-cavity cryomodule, with good $Q$ values.
• Therefore...
Impurity Doping of Re-furbished Cavities (cont.)

• At September 22, 2014 C50-12 pre-kickoff meeting, a decision was made to test Nitrogen doping on a CEBAF 5-cell cavity.

• The goal is to raise cavity $Q_0$ in a CEBAF re-work cryomodule beyond what can be imagined before by exploitation of nitrogen doping technique that was made available in-house for LCLS-II $Q_0$ R&D.

• Cavity IA009 was chosen for this study.
New goal: $Q_0 = 2 \times 10^9$ @ 12.5 MV/m

Original C50 goal: $Q_0 = 6.8 \times 10^8$ @ 12.5 MV/m

Achieved $Q_0$ in C50-1...11
Discovery of Surface Defects

Outstanding defects in fusion zone of equator weld of cell #4

4 mm fusion zone

Pit ~400 µm dia. Connected with extended bark regions

Pit ~100 µm dia.

IA009 surface pit statistics in equator regions

Counts of sub-mm dia. pits

Cell#
Expanded Inspection of Surface Defects

Surface Defects in Fusion Zone of Equator Weld

- Only Pit and large flaw counted
Conclusion on Preliminary 5-Cell N-doping

• First attempt in raising $Q_0$ by N-doping (IA009) is not successful, as a result of “grave” Fusion Zone Defect (FZD).

• Optical inspection of 4 more 5-cell cavities revealed similar FZD’s in similar amount.

• FZD’s can be classified into three types: (1) pit; (2) ripple; (3) “large flaw”. They are believed to originate from material/fabrication and therefore can be considered “genetic”.

• FZD is rarely observable on modern-day Nb cavities.

• It seems that “any attempt to further raise the $Q_0$ of these cavities by re-processing may face a brick wall”.
  - Nature FZD and their interplay with N-doping deserve studies.
  - Cure FZD by barrels polishing may help and should be evaluated.
Proposal for New Studies and Tests

- Systematic VTA cavity testing for frozen flux effect.
  - Test the CTA procedure for recovering $Q_0$ of cavities under the standard cavity pair configuration. (High impact potential)
  - Verify the thermal current model that has been developed from one 5-cell dummy cavity test.
  - Develop a CTA recipe of “thermal therapy” to be applied in-situ over all 5-cell cavities currently placed in tunnel.
  - Complete the unfinished C50-12 activities. (Impact the future refurbishment cryomodules)
    - Progressive component addition to cavity pair to pin-point magnetized components.
    - Experiment “local shielding” over the center cells.
    - Assess window loss contribution.
• Test the feasibility of “whole module” de-magnetization.
  - Test with dummy cryo-unit.
    • Series tests with progressively added components around cavity.
    • Assess shielding factors of the inner shield and the outer shield
    • Characterize the magnetization of the shielding itself.
  - Cryogenic test of a cavity pair in a short cryomodule
    • Mini-test of CTA.
    • Study added frozen flux from repeated quench events.
Proposal for New Studies and Tests (cont.)

• Further evaluation of nitrogen-doping for raising $Q_0$ 5-cell cavities, including possible re-doping after barrel polishing.
  – Two cavities in hand:
    • IA008 (N-doping completed)
    • IA011
  – A clear conclusion on N-doping is useful
    • Positive answer sets solid ground for possible future path of Nb$_3$Sn re-treatment.
    • Negative answer sets solid ground for possible future path of “LG cell transplant”

• Fundamental studies of defects in IA009
  – Dissect cavity, make 5 each 1-cell cavities, test with T-mapping, cut out quench area for material studies.
  – Recycle end groups for “C75” cavities with transplanted cells.
Conclusion

- The low $Q_0$ issue of 5-cell CEBAF cavities remains outstanding.
  - Understanding of $Q_0$ damage from magnetized components in hand, one change implemented in C50-11. One more change is to be implemented in C50-12.

- The effort in raising $Q_0$ of placed cavities in CEBAF has led us to explore inexpensive solutions applicable \textit{in-situ} for raising \textit{average} $Q_0$.
  - Cryogenic Thermal Annealing.
  - Whole-module degaussing.

- The effort in raising $Q_0$ for C50 refurbishment by N-doping 5-cell cavities met the issue of genetic FZDs. Further studies needed.

- Effort in $Q_0$ improvement and field emission reduction is related.

- Proposal is to establish a new project, whose objective is to raise $Q_0$ of installed cavities in CEBAF: (a) without moving cryomodules out of tunnel; (b) within on-going C50 refurbishment effort.

- A detailed cost of the proposed studies is being developed ($< 150K$).
Backup Slides
IA009 Actions since 5/5/15

- Cavity vented, removed from test stand, fully dis-assembled.
- Optical inspection of equator regions.
  - Cell number starting at input power coupler side
  - Angle definition: $0^\circ = 12$ o’clock, direction=clock-wise
Outstanding defects in fusion zone of equator weld of cell #4

Pit ~400 µm dia. Connected with extended bark regions

Pit ~100 µm dia.

4 mm fusion zone
Cell #1 Equator Weld

Pits (3 in total, smaller than average)
Cell #1 Equator Weld

speckles (clustered in a few regions, only cell showing this) Nitrogen-rich islands due to insufficient surface removal?
Cell #2 Equator Weld

Pits (13 in total, 2 typical examples shown)

ϕ=185°  ϕ=263°
Cell #2 Equator Weld

Large flaws

$\phi = 14^\circ$

$\phi = 32^\circ$
Cell #3 Equator Weld

Pits (14 total, largest shown)

Curved linear feature (ripple of molten Nb?)
Cell #4 Equator Weld

Pits (45 total, a few typical shown)
Cell #4 Equator Weld

Pits next to ripple

$\Phi = 15^\circ$

$\Phi = 73^\circ$
Cell #4 Equator Weld

Large flaws

ϕ = 52°

ϕ = 334°
Cell #4 Equator Weld

Pits (4 total, largest shown)

Curved linear feature (ripple of molten Nb?)

ϕ=62°

ϕ=200°
Post VTA optical inspection revealed surprisingly large number of defects (pits, ripples and large flaws).

Cell #2 & #4 are the worst – both have large flaws

Cell #1 & #5 are the best; #3 in the middle.

The heavy defect in cell #2 & #4 is consistent with previous finding of cell #2/4 being the most lossy; is also consistent with previous finding of cell #2/4 are among candidate cells responsible for quench at 9 MV/m.

“Cloudy” speckles observed on cell #1 equator weld surface. We suspect these are nitrogen-rich islands due to insufficient EP removal.
5/14/15 Conclusion (cont.)

- Based on good correlation between pass-band measurements and optical inspection results, we conclude both the premature quench and the strong Q-slope of IA009 after nitrogen doping was caused by grave defects in fusion zone of cell #2/4 equator welds.

- From RG’s past experience, there is little chance of further improving the cavity performance by another EP.

- Based on optical inspection data of IA009 (2015) and IA015 (2008), we conclude the “fusion zone defect (FZD)” is a genetic character in all original CEBAF cavities, due to the then cavity EBW technology. Therefore, any attempt to further raise the $Q_0$ of these cavities by re-processing may face a brick wall. We propose to terminate the N-doping CEBAF cavity experiment. Instead, start to evaluate a cure to pit first.

- We seem to have a case of insufficient EP removal in cell #1 of a CEBAF 5-cell cavity.
Carried out optical inspection of four 5-cell CEBAF cavities

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Last surface treatment and performance</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA011</td>
<td>Unknown (most likely BCP)</td>
<td>Cavity received from LP</td>
</tr>
<tr>
<td>IA080</td>
<td>Unknown (most likely BCP)</td>
<td>Cavity dis-assembled from a cryomodule (FEL?) to be re-worked and become C50-12. Cavity have “large grains” all over places – apparently heat treated to high temperature (at least 1250 °C) in its past life.</td>
</tr>
<tr>
<td>IA355</td>
<td>Unknown (most likely BCP)</td>
<td>ibid</td>
</tr>
<tr>
<td>IA008</td>
<td>Nitrogen doping (no cryogenic RF test after nitrogen doping)</td>
<td>Pre-nitrogen doping processing history unknown. Latest cold test on 4/8/2013; 3/12/2013; 10/15/2008</td>
</tr>
</tbody>
</table>
Surface Defects in Fusion Zone of Equator Weld

Only Pit and large flaw counted
IA008 (Nitrogen doped)

pit

Cell 2 $\Phi=132^\circ$

Large flaw

Cell 4 $\Phi=334^\circ$
IA080

(removed from module to be re-worked and become C50-12, “Large grain”)

pit

Large flaw

Cell 1 Φ=204°

Cell 2 Φ=146-148°
IA355

(removed from module to be re-worked and become C50-12, “Large grain”)

pit

Cell 3 $\Phi=154^\circ$

Large flaw

Cell 4 $\Phi=215^\circ$
• No apparent large flaw observed
• BCP etching of inner surface seems much less than other inspected cavities
  i. Visible molten pool ripples
  ii. Visible “blisters” on fusion zone surface