CEBAF SRF Performance During Initial 12GeV Commissioning

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Outline

• 12 GeV Project
• C100 RF system
• C100 Commissioning
• Operational Experience
• Summary
12 GeV Upgrade Project

- 11 New cryomodules (C100)
- New RF power sources (13 kW)
- Refrigeration
- Magnets
- Additional arc-beamline
- Extraction system
- New experimental area Hall D
C100 Cryomodule

- Seven cell Cavity, 0.7 m long (high $Q_L$)
- 8 Cavities per Cryomodule
- Fits the existing Cryomodule footprint

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High $Q_L$ Challenges

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental frequency $f_0$</td>
<td>1497 MHz</td>
</tr>
<tr>
<td>Accelerating gradient $E_{acc}$</td>
<td>$&gt; 20$ MV/m</td>
</tr>
<tr>
<td>Input coupler $Q_{ext}$</td>
<td>$3.2 \times 10^7$</td>
</tr>
<tr>
<td>Active length</td>
<td>0.7 m</td>
</tr>
<tr>
<td>$r/Q$</td>
<td>1300 $\Omega$/m</td>
</tr>
<tr>
<td>Tuning sensitivity</td>
<td>0.3 Hz/nm</td>
</tr>
<tr>
<td>Pressure sensitivity</td>
<td>420 Hz/torr</td>
</tr>
<tr>
<td>Lorentz force frequency sensitivity $K_L$</td>
<td>~2 Hz/(MV/m)$^2$</td>
</tr>
</tbody>
</table>

Field startup

Field stability

Phase noise plot of microphonics

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RF System for C100 Cavity

- LLRF (PC/104)
- Pre-Amp
- Klystron 13 kW
- Circulator
- Directional Coupler
- HV PS
- RF amp drive
- Cavity Probe Signal
- Signal
- FPC
- Tunnel
- Service Building
- Conduit

- Stepper Controller (PC/104)
- Stepper
- Piezo Driver
- Piezo
- Heater Controller (PC/104)
- Heater
- Cavity Interlocks (PC/104)
- Interlocks
- EPICS
- Ethernet
- One LLRF / Cavity
- One Klystron / Cavity
- One System / Zone
  - Stepper
  - Piezo
  - Heater
  - HPA
  - Interlocks

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RF System

- Single Zone
  - Eight 13 kW Klystrons
  - Four HV Power Supply

- Total (10 + 1 zones)
  - 80 Klystrons (13 kW)
  - 8 Klystrons (8 kW, C100-0)
RF System

- Single Zone
  - 8 LLRF Controllers
  - Stepper Controller
  - Piezo Amplifier
  - Interlocks Controller
  - High Power Amplifier Controller
  - Cryomodule Heater Controller

- Total (11 zones)
  - 88 LLRF Controllers
RF System

- RF Board
- FPGA Board
- PC/104
- Modular Interface Boards
- PC Power Supply
Acronyms used in the slides

- **SEL (Self Excited Loop)**
  - Cavity resonates at its own frequency (Phase Locked Loop like)
  - Constant forward power

- **GDR (Generator Driven Resonator)**
  - Cavities are locked to reference
  - Forward power not constant (reacts to detuning)
C100 Commissioning

- RF system commissioned into waveguide shorts
- SRF commissioning using LLRF
  - $E_{\text{max}}$ for individual cavities
  - Field Emission measurements
  - $Q_0$ measurement
  - Operable gradient for cryomodule
  - Performed in SEL
- LLRF Commissioning & Machine operations
  - Cavities are operated in GDR
## C100 Commissioning - Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>C100-1&amp;2 were installed and commissioned</td>
</tr>
</tbody>
</table>
| 2012 | C100-1&2 were operated during 6 GeV Nuclear Physics run.  
      | C100-2 was operated up to 108 MEV and 465 μA  
      | May – Began 18 month CEBAF shutdown |
| 2013 | Installed and commissioned eight C100 cryomodules |
| 2014 | January completed C100 commissioning and began beam operation/commissioning  
      | March commissioned C100-0 (Installed in Injector) |
## Gradients in C100 During Commissioning

<table>
<thead>
<tr>
<th>Zone</th>
<th>SRF Commissioning</th>
<th>2.2 GeV/Pass</th>
</tr>
</thead>
<tbody>
<tr>
<td>C100-1</td>
<td>110 MV</td>
<td>94.01 MV</td>
</tr>
<tr>
<td>C100-2</td>
<td>120</td>
<td>93.8</td>
</tr>
<tr>
<td>C100-3</td>
<td>124</td>
<td>76.58</td>
</tr>
<tr>
<td>C100-4</td>
<td>105</td>
<td>79.24</td>
</tr>
<tr>
<td>C100-5</td>
<td>110</td>
<td>100.31</td>
</tr>
<tr>
<td>C100-6</td>
<td>113</td>
<td>101.8</td>
</tr>
<tr>
<td>C100-7</td>
<td>113</td>
<td>103.81</td>
</tr>
<tr>
<td>C100-8</td>
<td>109</td>
<td>100.17</td>
</tr>
<tr>
<td>C100-9</td>
<td>117</td>
<td>101.15</td>
</tr>
<tr>
<td>C100-10</td>
<td>116</td>
<td>87.57</td>
</tr>
<tr>
<td>C100-0</td>
<td>116</td>
<td>82.3</td>
</tr>
</tbody>
</table>
Operational Experience - CEBAF Commissioning

- **Commissioning**
  - 2.2 GeV/pass
    - C100 - 934 MeV
    - C50  - 457 MeV
    - C20  - 808 MeV
  - Injector design energy – 123 MeV

- **Opportunities for Improvement**
  - Reducing Field Emission
  - Enhanced Cryomodule Heater Configuration
  - Microphonics Detuning

- **Other Observations**
  - RF Control Loop Optimization
  - Klystron Drive Cables
Operational Experience - Field Emission

- Field Emission heats Beamline
- Vacuum Pump faults
- Vacuum Interlock drops Zone out of RF
Operational Experience - Field Emission

Cavity Gradients impacting Beamline Vacuum activity
Helium Processing

- Introduce helium gas into cavity vacuum space
- Run RF to clean cavity surfaces
- Warm up and pump down to remove residual gas
- Improves high-field Q, reduces x-ray production and greatly reduces incidence of arcing at the cold ceramic window
Helium Processing

- Performed on C100-5 cryomodule
Operational Experience - Cryomodule Heater Configuration

- C100-1
- Cavities 6 and 7 have very high detuning

Total heat vs Detuning in SEL

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## Operational Experience - Cryomodule Heater Configuration

- **When RF was off**
  - Only Electric Heat

- **When RF was on**
  - RF + Electric Heat

<table>
<thead>
<tr>
<th>He Level Percentage</th>
<th>He Level Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Level Stable</td>
<td>Liquid Level not Stable</td>
</tr>
</tbody>
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Operational Experience - Cryomodule Heaters

- Single Heater Control for the Cryomodule

- Return riser became a choke point as additional heat was applied

- Solution - Individual Cavity Heater Control
Microphonics - Mechanical Tuner Modification

- Design allows for 25 Hz Peak Detuning
- Actual peak detuning (18 Hz) was higher than expected in first cryomodules (C100-0,1,2,3)
- A detailed vibration study was initiated which led to the following design change
- A minor change to the tuner pivot plate substantially improved the microphonics detuning for the CEBAF C100 Cryomodules
- While both designs meet the overall system requirements the improved design has a larger RF power margin

<table>
<thead>
<tr>
<th>Microphonic Detuning</th>
<th>C100-1</th>
<th>C100-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS (Hz)</td>
<td>2.985</td>
<td>1.524</td>
</tr>
<tr>
<td>6s (Hz)</td>
<td>17.91</td>
<td>9.14</td>
</tr>
</tbody>
</table>

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C100 Cavity Gradients

- The drops show the cavity faulting during the day due to construction.
- RF Power could not compensate for the rapid detuning

Between 7 AM and 5 PM
Operational Experience – Microphonics Detuning

- Reduced Gradients in C100-0

Plan

- Collect Microphonics data from all C100s
- Investigate Piezo Algorithm
- Possibly switch out C100-0 for later production C100
RF Control Loop Optimization

- We observed 4 kHz oscillation when LLRF is locked
- Higher gain
  - Reduced 4 kHz oscillation
  - .....but control system less stable
- Loop Phase mismatch between SEL and locked condition
  - Simulation didn’t show
  - Latency issue between the two logic chains in the FPGA
  - Systematic 30 degree difference

Microphonics – compensated

4 kHz

Forward Power in GDR

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Operational Experience - Crosstalk on Klystron drive cables

- Crosstalk on Drive Cables
  - Causing cavity trips on GMES fault
  - Repaired connectors and problem went away
- Crosstalk on Klystron Internal Cable
  - Terminated the input
  - Still had 15-25 watts forward power and gradient in the cavity!
  - Investigating pulling klystron solenoid and replacing cables with better shielded cables

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Future Plans

- Helium Processing this summer to minimize Field Emission
- Installation of Individual Cryomodule Heater Control System
- Microphonics Detuning analysis, Piezo Algorithm studies and Implementation
- Control Loop Optimization
  - Investigate the loop phase mismatch between SEL and GDR
- Klystron Drive Cables
  - Detect the source of crosstalk
Summary

- CEBAF Initial commissioning goals achieved
  - 2.2 GeV/pass
  - 123 MeV from Injector
  - CD4A – 5 months ahead of schedule
- Beam delivery to experimental halls
- Plans for improving operability
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Questions?