LCLS-II Prototype Cryomodule Testing at Fermilab

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Lee Teng Internship Final Presentation
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Outline

• Introduction
  – LCLS-II
  – Cryomodule Testing at CMTF
• CMTS1’s RF System Analysis
  - Power Readouts Calibration
  - Performance of Solid State Amplifiers
• Interfaces Development
• Conclusions
• Future Plans
Linear Coherent Light Source II (LCLS-II)

- X-ray Free Electron Laser (FEL) at existing SLAC tunnel
- LCLS-II is an upgrade of LCLS to be completed in 2020
  - normal conducting linac $\rightarrow$ superconducting linac

(Image courtesy of LCLS-II Project Team)
LCLS-II Superconducting RF Cryomodules

- First of its kind running in continuous wave (CW) mode
- Fermilab is responsible for designing the cryomodules.
- Together with JLab, we will assemble, and test
  - Thirty-five 1.3 GHz Cryomodules (17 Fermilab; 18 JLab)
  - Two 3.9 GHz Cryomodules (Fermilab)

Niobium TESLA-style 9-cell superconducting cavity [1]

8 cavities per one module

Prototype cryomodule (pCM) at Fermilab’s Technical Division

First two 1.3 GHz cryomodules are pCMs.
Cryomodule Testing at Fermilab

• Fermilab’s Cryomodule Testing Facility (CMTF)
  – First test stand, CMTS1, commissions its first operation in July 2016 for LCLS-II Cryomodules testing [2]
  – Can be cooled down to 2 K

pCM in CMTS1

(Image by K. Sirorattanakul; Aug 2, 2016)
**Purposes of Cryomodule Testing**

- Characterize both the *cryomodule’s and each cavity’s performance* to ensure that they meet the stringent minimum acceptance criteria from SLAC/LCLS-II Collaboration
- Some of these parameters out of more than 20 are [3]:
  - Connection between cryo and RF
  - Magnetic operational effect and shielding
  - Coupler conditioning
  - Intrinsic Quality Factor, $Q_0$ & Heat Load
  - Gradient, $E_{acc}$ (MV/m) ---- Two methods to calculate [4]:

$$E_{acc} = \sqrt{P_{probe}Q_2 \frac{(r/Q)}{L}}$$

$$E_{acc} = \sqrt{4P_{forward}Q_0 \frac{(r/Q)}{L}}$$
Amplifiers → Isolators → Waveguides → Directional Couplers → Cavities

(E. Harms et. al., SRF2015, with modifications)

A – 0.30 m
B – Coupler + Isolator
C – Bend
D – 0.76 m
E – 3.06 m
F – 0.46 m
G – 0.30 m
H – Bend
I – 0.70 m
J – Coupler
Power Readouts

- Power will be read from three locations through Fermilab’s Accelerator Control System (ACNET)
  - Default acquisition rate = 1 Hz
  - Waveform capturing at rate up to 10 kHz

4 kW Solid State Amplifiers (SSA)

(Isolator (LabVIEW)

Waveguides

Cavity (LLRF)

Probe

$P_{\text{forward}}$

$P_{\text{probe}}$

Images by K. Sirorattanakul; Aug 3, 2016
Purposes of this Study

1. Analyze CMTS1’s RF system
   a. Calibrations for Power Readouts (SSA vs LLRF)
   b. Stability of output from the solid state amplifiers (SSA)

2. Develop graphical interfaces to monitor the test
Purposes of this Study

1. Analyze CMTS1’s RF system
   a. **Calibrations for Power Readouts (SSA vs LLRF)**
   b. Stability of output from the solid state amplifiers (SSA)

2. Develop graphical interfaces to monitor the test
Waveguides Attenuation (Theory)

- **Straights Section** [5]:
  \[
  \alpha_c = 8.686 \frac{R_s}{\eta b} \left(1 + \frac{2b}{a}\right) \frac{\omega_c^2}{\omega^2} \frac{1}{\sqrt{1 - \frac{\omega_c^2}{\omega^2}}} = 8.32 \times 10^{-3} \text{ dBm/m}
  \]
  - WR-650 \((a = 6.5 \text{ in.}, b = 3.25 \text{ in.})\) made from Aluminum 6061-T6
  - Surface resistance, \(R_s = 1.43 \times 10^{-2} \text{ Ohms}\)
  - Impedance, \(\eta = 3.77 \times 10^2 \text{ m}^2 \text{ kg s}^{-3} \text{ A}^{-2}\)
  - Critical angular frequency, \(\omega_c = 5.71 \times 10^9 \text{ rad/s}\)

- **Bends:** Power loss = 0.01%

- **Couplers:**
  - Main arm power loss = 0.01%
  - Side arm power loss = 0.06%

(Images courtesy of MEGA Industries, LLC)

(Image by K. Sirorattanakul)
Waveguides Attenuation (Results)

• Calculated
  – SSA #1, 3, 5, 7 --- Total Loss = 2.37%
  – SSA #2, 4, 6, 8 --- Total Loss = 2.22%

• Comparison between the calculated loss and the measured loss from test runs (only for SSA #2, 3, 5, 6, 7)

<table>
<thead>
<tr>
<th>SSA #</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSA Output (W)</td>
<td>668.1</td>
<td>2195</td>
<td>2107</td>
<td>1539</td>
<td>1055</td>
</tr>
<tr>
<td>Calculated Loss (%)</td>
<td>2.22</td>
<td>2.37</td>
<td>2.37</td>
<td>2.22</td>
<td>2.37</td>
</tr>
<tr>
<td>Measured Loss (%)</td>
<td>2.22</td>
<td>6.01</td>
<td>6.90</td>
<td>7.73</td>
<td>6.13</td>
</tr>
</tbody>
</table>

• SSA #2 is well-calibrated.
• Complete calibrations are still needed for SSA #3, 5, 6, 7.
Purposes of this Study

1. Analyze CMTS1’s RF system
   a. Calibrations for Power Readouts (SSA vs LLRF)
      b. Stability of output from the solid state amplifiers (SSA)

2. Develop graphical interfaces to monitor the test
SSA Performance: Stability

<table>
<thead>
<tr>
<th>SSA #</th>
<th>2</th>
<th>3</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Power (W)</td>
<td>668.1</td>
<td>2195</td>
<td>2107</td>
<td>1539</td>
<td>1055</td>
</tr>
<tr>
<td>Duration (Hrs)</td>
<td>49.75</td>
<td>1.5</td>
<td>0.6</td>
<td>16</td>
<td>14.75</td>
</tr>
<tr>
<td>RMS (%)</td>
<td>2.08</td>
<td>0.28</td>
<td>0.15</td>
<td>0.36</td>
<td>0.50</td>
</tr>
<tr>
<td>Parasitic Period (hrs) [6, 7, 8]</td>
<td>0.79</td>
<td>-</td>
<td>-</td>
<td>0.79</td>
<td>0.78</td>
</tr>
</tbody>
</table>

RMS is within 2% during continuous operation up to two days duration. Parasitic oscillations are systematic.

Error from power ~ 1% (could be larger due to higher spread at cavity than SSA)

Error from power ~ 1%

SSA output only in integers, improved by binning average (50 per bin).
Purposes of this Study

1. Analyze CMTS1’s RF system
   a. Calibrations for Power Readouts (SSA vs LLRF)
   b. Stability of output from the solid state amplifiers (SSA)

2. Develop graphical interfaces to monitor the test
LabVIEW Interface for Power Readouts

Main Page

Plots

Settings
(Courtesy of D. Slimmer)

Main Program

ACNET
Synoptic Displays

- Graphical interfaces using Fermilab-developed synoptic display platform to display real-time data
  - Powers
  - Temperatures
  - External Magnetic Fields (undergoing)
Conclusions

1. Analyze CMTS1’s RF system
   a. Calibrations for Power Readouts (SSA vs LLRF)
      ✓ Calculated and measured losses through the waveguides match for SSA #2. Complete calibrations are needed for SSA #3, 5, 6, and 7.
   b. Stability of output from the solid state amplifiers (SSA)
      ✓ Power output from SSA is stable up to two days with RMS less than 2%, which contributes only 1-2% error to gradient calculations. Parasitic oscillations are systematic.

2. Develop graphical interfaces to monitor the test
   ✓ Necessary graphical interfaces to monitor the test were developed.
Future Plans

- Cold testing plan to begin mid-August.
- Testing of the prototype will last around 90 days, until late 2016.
- Production cryomodules will be tested on a 28-day cycle beginning in 2017.
Acknowledgment

• Many thanks to
  – Elvin Harms, my mentor
  – David Slimmer for guiding and helping me with LabVIEW
  – People at AD/Control Synoptic support (Denise Finstrom, Linden Carmichael)
  – People at CMTS1
  – Illinois Accelerator Institute for sponsoring Lee Teng internship
  – Eric Prebys and Linda Spentzouris for coordinating Lee Teng internship

• Programs and libraries used:
  – LabVIEW
  – ROOT
  – Synoptic
  – Python (numpy, matplotlib)
  – The VARTOOLS Light Curve Analysis Program (written in C)
References


Fun Fact:
I was named after this character, “Pangpond.”
Backup: Detailed LCLS-II

- X-ray Free Electron Laser (FEL) using existing SLAC tunnel
- LCLS-II is an upgrade of LCLS to be completed in 2020
  - Maximum energy of accelerated electrons = 15 GeV
  - Energy of X-ray produced: 250 eV – 25 keV
    - Soft X-ray < 5 keV, up to 929 kHz
    - Hard X-ray > 5 keV, up to 120 Hz
Backup: Histogram for SSA Binning Average

- Below are histograms comparing raw LLRF power (left) with binning SSA power (right) for SSA #2

50 data points per bin works the best
Backup: Time Series for SSA Binning Average

- Waveforms are preserved through the waveguides
- Below are comparison of time series of LLRF and SSA power for SSA #6

Waveforms are preserved through the waveguides.

Below are comparison of time series of LLRF and SSA power for SSA #6:

- **LLRF (Cavity) Power**
  - Raw
  - 10 per bin
  - 20 per bin
  - 50 per bin
  - 100 per bin

- **SSA Power**
  - Raw
Backup: X-axis zoom-in for raw output from SSA

SSA2 Test Run Time Series (zoom-in)

Power (W)

Time (hrs)
Backup: Attenuations (Straights)

- Rectangular Waveguide (WR-650)
  - $a = 6.5$ in.
  - $b = 3.25$ in.
  - Material: Aluminum 6061-T6
    - Conductivity = $2.506 \times 10^7$ Siemens/m

- $R_s = \sqrt{\frac{\omega \mu}{2\sigma}} = 1.43 \times 10^{-2}$ Ohms

- $\eta = \sqrt{\frac{\mu}{\varepsilon}} = 3.77 \times 10^2$ m$^2$ kg s$^{-3}$ A$^{-2}$

- $\omega_c = \frac{c\pi}{a} = 5.71 \times 10^9$ rad/s

- $\alpha_c = 8.686 \frac{R_s}{\eta b} \frac{(1 + (2b/a)(\omega_c^2/\omega^2))}{\sqrt{1 - \omega_c^2/\omega^2}} = 8.32 \times 10^{-3}$ dBm/m
Backup: Attenuations (Others)

- VSWR: Voltage Standing Wave Ratio
- Reflection coefficient = \( \frac{VSWR-1}{VSWR+1} \)
- Power loss = Refl. Coef. Squared

- For bends; VSWR = 1.02
- For main arm coupler; VSWR = 1.05
- For side arm coupler; VSWR = 1.25

(E. Harms et. al., SRF2015, with modifications)

<table>
<thead>
<tr>
<th>Sections</th>
<th>Input Power (W)</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J (Output; W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSA 2</td>
<td>668.1</td>
<td>667.7</td>
<td>659.6</td>
<td>659.6</td>
<td>-</td>
<td>655.7</td>
<td>655.1</td>
<td>654.6</td>
<td>654.5</td>
<td>653.7</td>
<td>653.2</td>
</tr>
<tr>
<td>SSA 3</td>
<td>2,195</td>
<td>2,194</td>
<td>2,167</td>
<td>2,167</td>
<td>2,164</td>
<td>2,151</td>
<td>2,149</td>
<td>2,147</td>
<td>2,147</td>
<td>2,144</td>
<td>2,143</td>
</tr>
<tr>
<td>SSA 5</td>
<td>2,107</td>
<td>2,106</td>
<td>2,080</td>
<td>2,080</td>
<td>2,077</td>
<td>2,065</td>
<td>2,063</td>
<td>2,061</td>
<td>2,061</td>
<td>2,058</td>
<td>2,057</td>
</tr>
<tr>
<td>SSA 6</td>
<td>1,539</td>
<td>1,538</td>
<td>1,519</td>
<td>1,519</td>
<td>-</td>
<td>1,510</td>
<td>1,509</td>
<td>1,508</td>
<td>1,508</td>
<td>1,506</td>
<td>1,505</td>
</tr>
<tr>
<td>SSA 7</td>
<td>1,055</td>
<td>1,054</td>
<td>1,042</td>
<td>1,042</td>
<td>1,040</td>
<td>1,034</td>
<td>1,033</td>
<td>1,037</td>
<td>1,032</td>
<td>1,031</td>
<td>1,030</td>
</tr>
</tbody>
</table>
Backup: Histograms for SSA Output

SSA2 Power Histogram (Test Run, 50 per bin average)

SSA3 Power Histogram (Test Run, 50 per bin average)

SSA5 Power Histogram (Test Run, 50 per bin average)

SSA6 Power Histogram (Test Run, 50 per bin average)

SSA7 Power Histogram (Test Run, 50 per bin average)
Backup: Time Series for SSA Output

SSA2 Power Time Series (Test Run, 50 per bin average)

SSA3 Power Time Series (Test Run, 50 per bin average)

SSA5 Power Time Series (Test Run, 50 per bin average)

SSA6 Power Time Series (Test Run, 50 per bin average)

SSA7 Power Time Series (Test Run, 50 per bin average)
Backup: Parasitic Oscillations

- Parasitic Oscillations = undesired oscillations in electronics
- Subtract median smoothing and run Lomb-Scargle Algorithm implemented in VARTOOLS.
- Sample: SSA7 (both plots have different scale!)

<table>
<thead>
<tr>
<th>SSA #</th>
<th>Period (Hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.79</td>
</tr>
<tr>
<td>6</td>
<td>0.79</td>
</tr>
<tr>
<td>7</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Median Smoothing Subtraction
Backup: Median Smoothing Subtractions

Before

SSA2

SSA6

SSA7

After
Backup: Periodograms

Periodogram for SSA2 Test Run

Periodogram for SSA6 Test Run

Periodogram for SSA7 Test Run