LCLS-II Prototype Cryomodule Testing at Fermilab

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Lee Teng Internship Final Presentation
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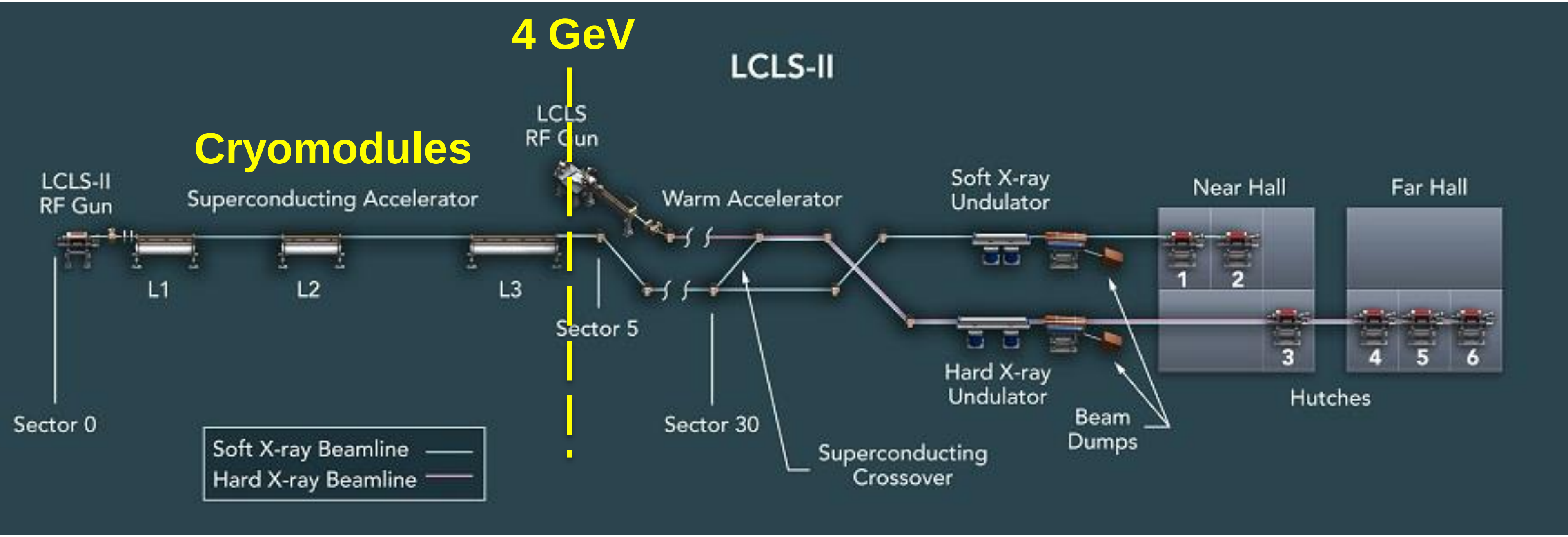
In partnership with: LCLS-II, Lehigh University, Illinois Accelerator Institute

Outline

- Introduction
  - LCLS-II
  - Crymodule 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 → 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)

(Image courtesy of Fermilab's Techincal Division)

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

8 cavities per one module

(Image by K. Sirorattanakul; Jun 6, 2016)

Prototype cryomodule (pCM) at Fermilab's Technical Division

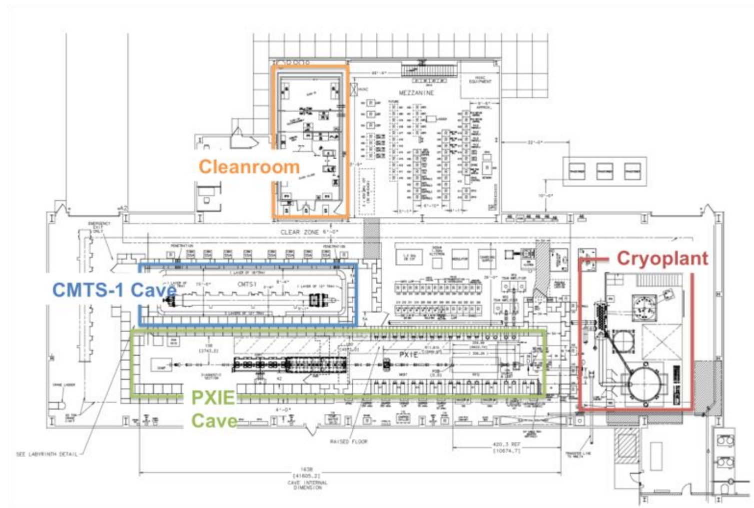
First two 1.3 GHz cryomodules are pCMs.

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)



CMTF Location and Layout

(E. Harms et. al., SRF2015)

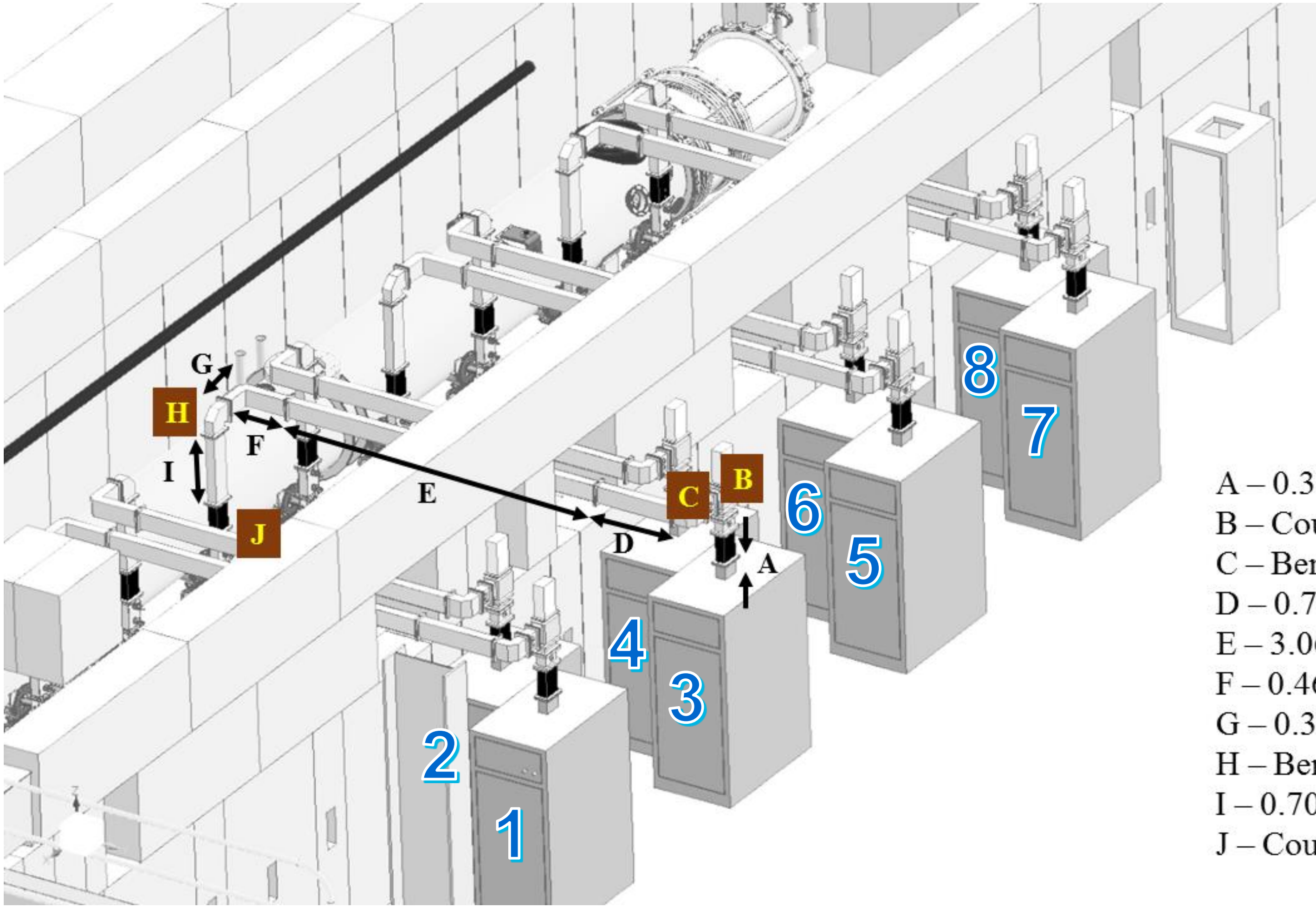
Purposes of Cryomodule Testing

- 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]:

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

2. $$E_{acc} = \sqrt{4\, P_{forward} Q_0 \frac{(r/Q)}{L}}$$

CMTS1 RF System Layout



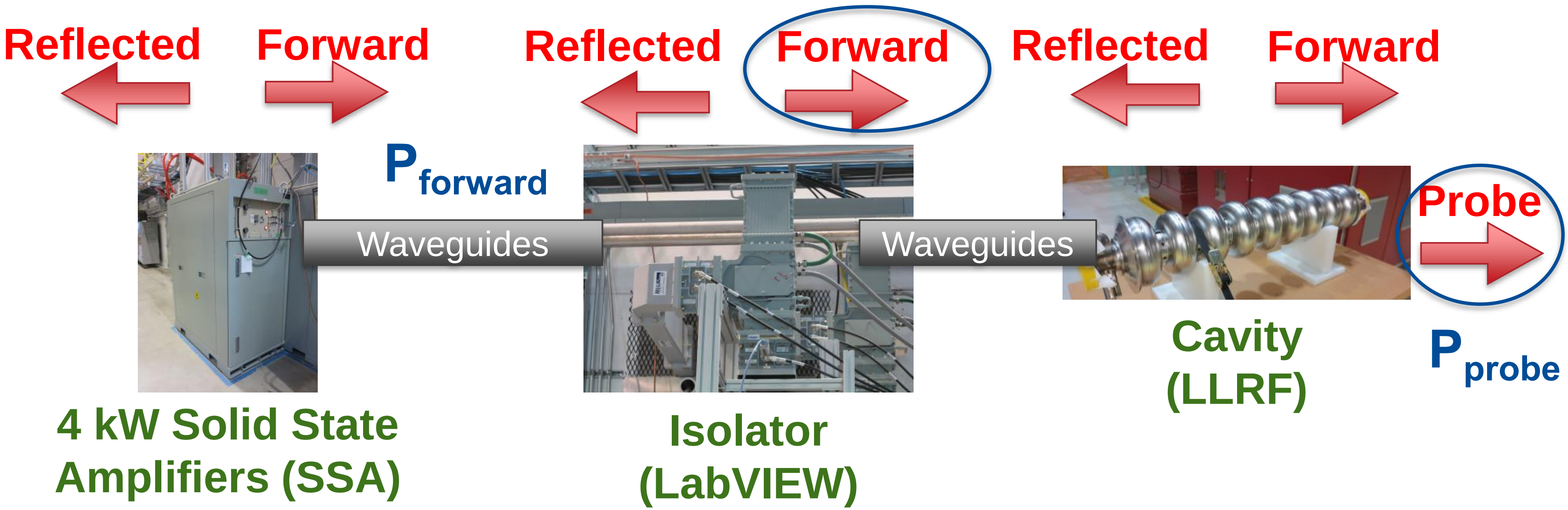
A – 0.30 m
B – Coupler + Isolator
C – Bend
D – 0.76 m
E – 3.06 m
F – 0.46 m
G – 0.30 m
H – Bend
I – 0.70 m
J – Coupler

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

Amplifiers → Isolators → Waveguides → Directional Couplers → Cavities

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



(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

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Waveguides Attenuation (Theory)

- Straights Section [5]:

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

  - WR-650 (a = 6.5 in., b = 3.25 in.) made from Aluminum 6061-T6
  - Surface resistance, $R_s =$ = 1.43 x 10^{-2} Ohms
  - Impedance, $\eta =$ = 3.77 x 10^{2} m^2 kg s^{-3} A^{-2}
  - Critical angular frequency, $\omega_c =$ = 5.71 x 10^{9} rad/s

(Images courtesy of MEGA Industries, LLC)

- Bends: Power loss = 0.01%

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

(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)

SSA #	2	3	5	6	7
SSA Output (W)	668.1	2195	2107	1539	1055
Calculated Loss (%)	2.22	2.37	2.37	2.22	2.37
Measured Loss (%)	2.22	6.01	6.90	7.73	6.13

- *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
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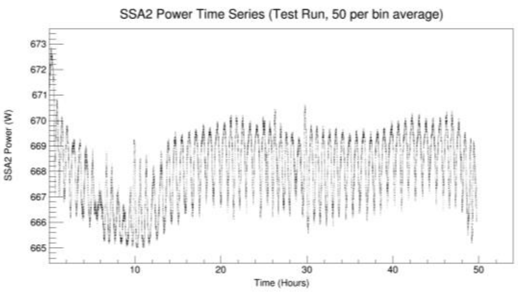
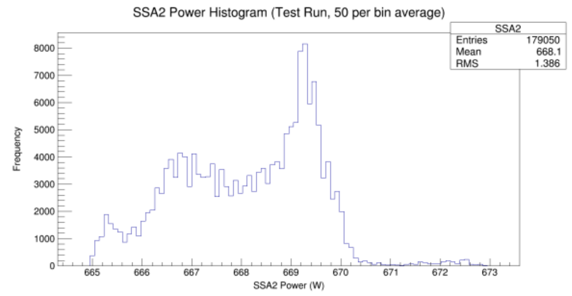
SSA Performance: Stability





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

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

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

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

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

$$E_{acc} = \sqrt{4\, P_{forward} Q_0 \frac{(r/Q)}{L}}$$

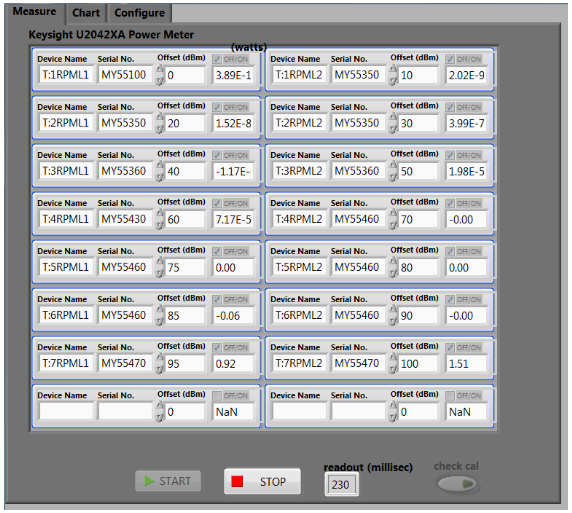
Error from power ~ 1%

Purposes of this Study

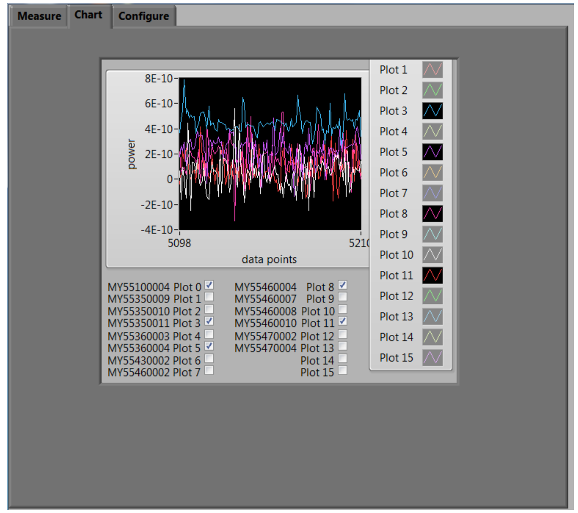
1. Analyze CMTS1's RF system
    a. Calibrations for Power Readouts (SSA vs LLRF)
    b. Stability of output from the solid state amplifiers (SSA)

2. ***Develop graphical interfaces to monitor the test***

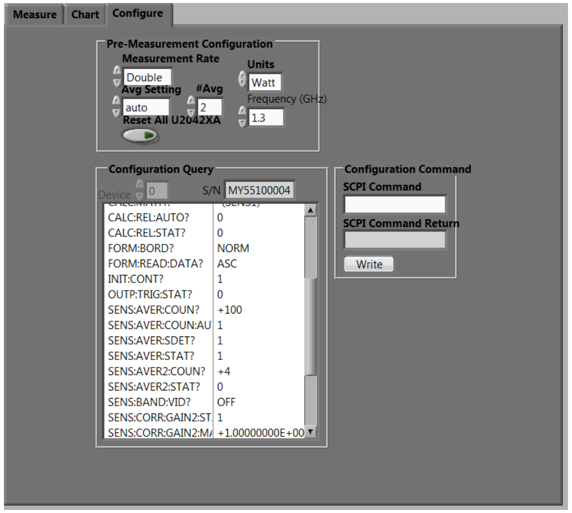
LabVIEW Interface for Power Readouts



Main Page

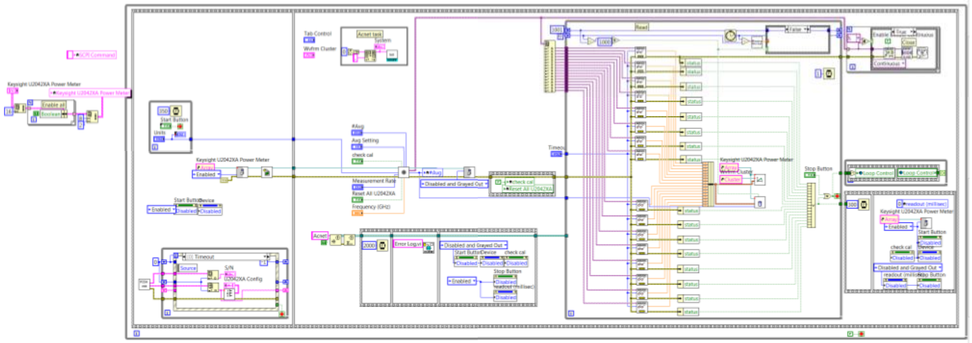


Plots



Settings

(Courtesy of D. Slimmer)

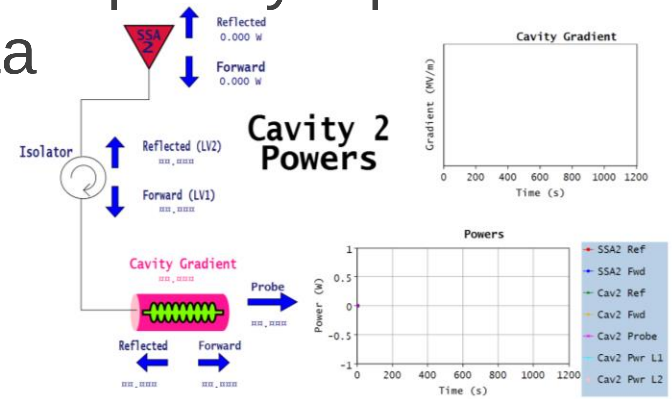


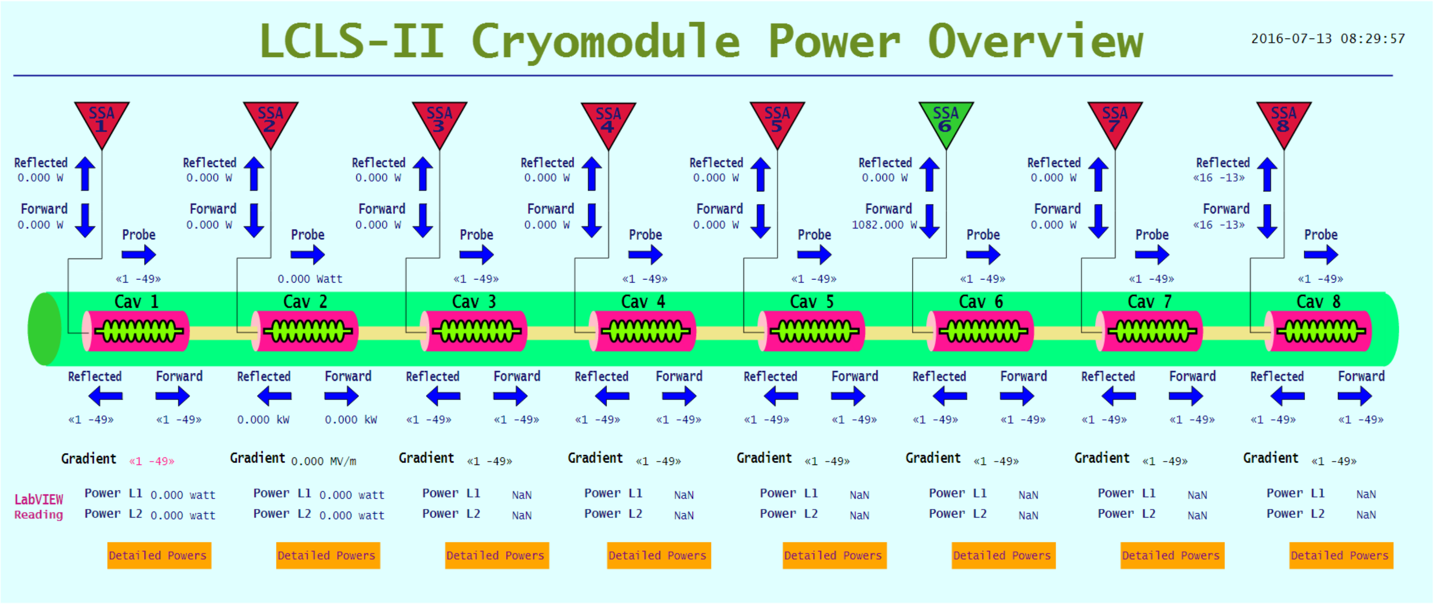
Main Program

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

[1] T. Arkan *et al.*, “LCLS-II 1.3 GHz Design Integration for Assembly and Cryomodule Assembly Facility Readiness at Fermilab,” in *Proc. 17th Int. Conf. on RF Superconductivity (SRF2015)*, Whistler, BC, Canada, Sep. 2015, paper TUPB110, pp. 893–897.

[2] E. Harms *et al.*, “Fermilab Cryomodule Test Stand Design and Plans,” in *Proc. 17th Int. Conf. on RF Superconductivity (SRF2015)*, Whistler, BC, Canada, Sep. 2015, paper TUPB013, pp. 566–570.

[3] E. Harms, “Prototype Cryomodule Testing Plan,” presented at LCLS-II FAC Review, Fermilab, Batavia, IL, USA, Jul. 2016.

[4] T. Powers, “Theory and Practice of Cavity RF Test Systems,” U.S. Particle Accelerator School (USPAS), 2011.

[5] S. Orfanidis, “Chapter 9: Waveguides,” in *Electromagnetic Waves and Antennas*, New Brunswick, NJ, USA: Rutgers University, 2008, pp. 362–410.

[6] J. Hartman and G. Bakos, “Vartools: A program for analyzing astronomical time-series data,” *Astronomy and Computing*, vol. 17, pp. 1–72, Oct. 2016, to be published.

[7] M. Zechmeister and M. Kurster, “The generalised Lomb-Scargle periodogram. A new formalism for the floating-mean and Keplerian periodograms,” *Astronomy and Astrophysics*, vol. 496, pp. 577–584, Jan. 2009.

[8] W. Press, S. Teukolsky, W. Vetterling, and B. Flannery, *Numerical Recipes in C*. New York, USA: Cambridge University Press, 1992.

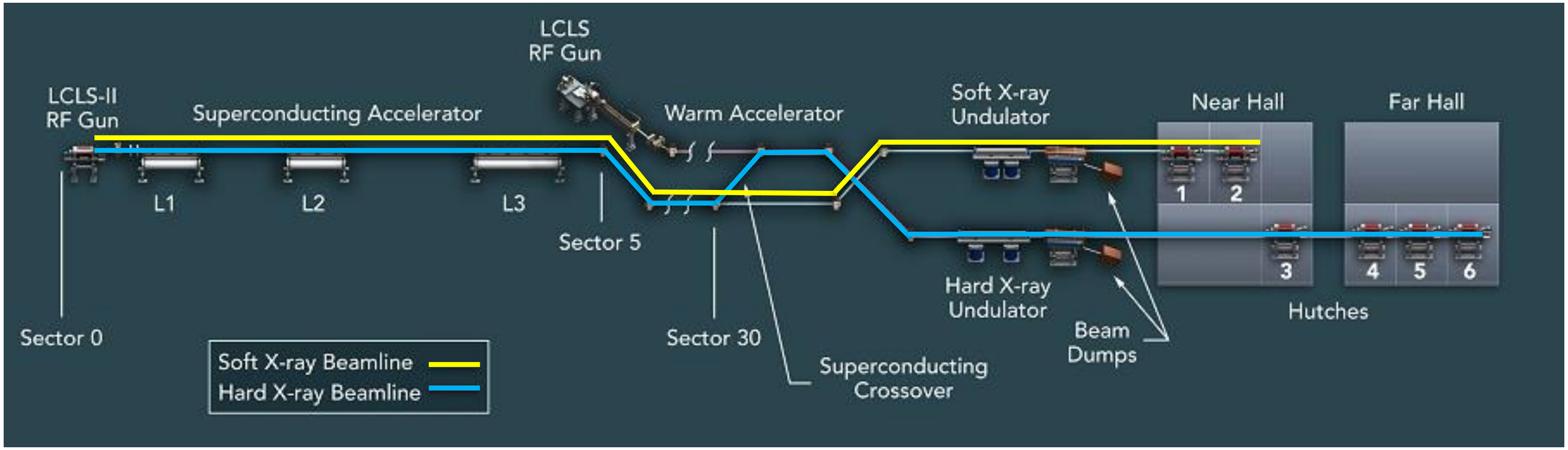
Question(s)?

Fun Fact:

I was named after this character, “Pangpond.”

Backup: Detailed LCLS-II

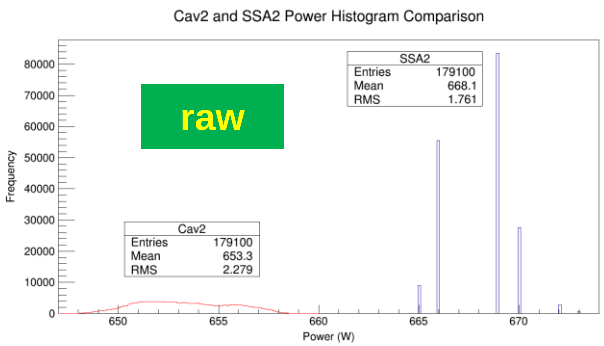
- X-ray Free Electron Laser (FEL) using existing SLAC tunnel
- LCLS-II is an upgrade of LCLS to be completed in 2020
  - Maximum energy of accelerated electrons = 15 GeV
  - Energy of X-ray produced: 250 eV – 25 keV
    - Soft X-ray < 5 keV, up to 929 kHz
    - Hard X-ray > 5 keV, up to 120 Hz

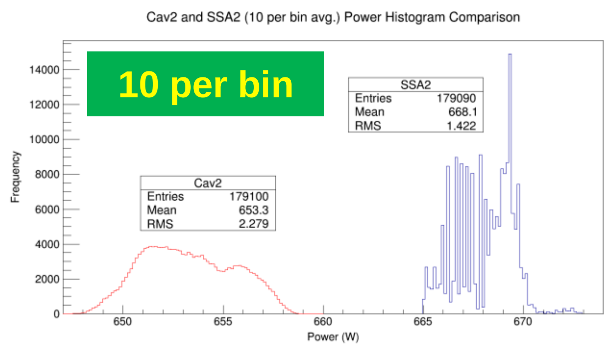


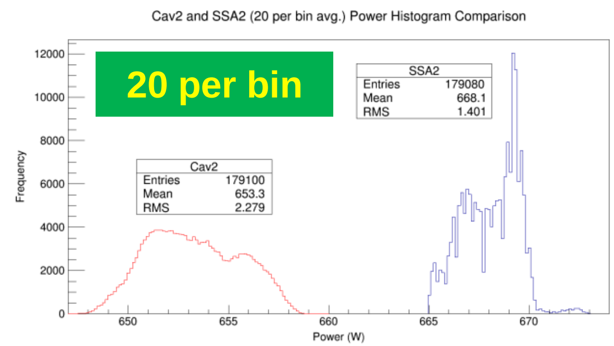
(Images courtesy of LCLS-II Project Team with modifications)

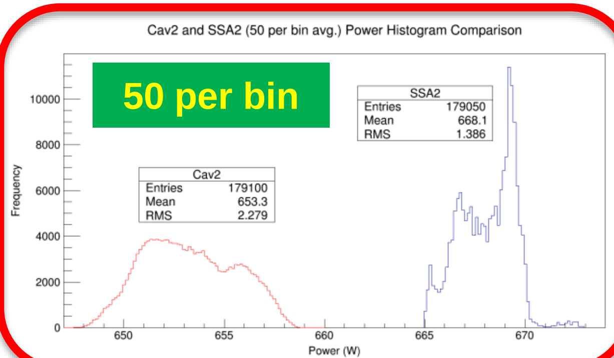
Backup: Histogram for SSA Binning Average

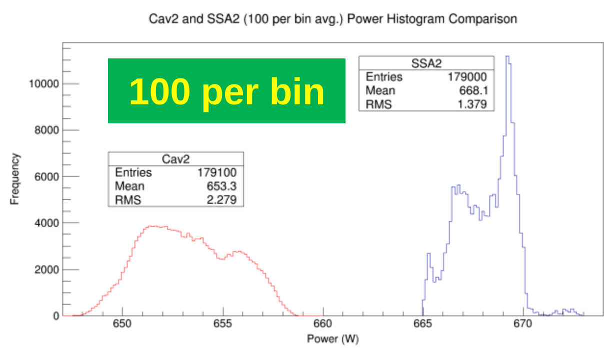
- Below are histograms comparing raw LLRF power (left) with binning SSA power (right) for SSA #2







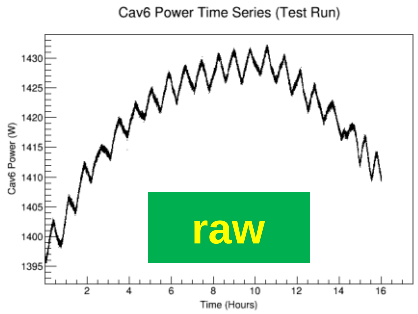




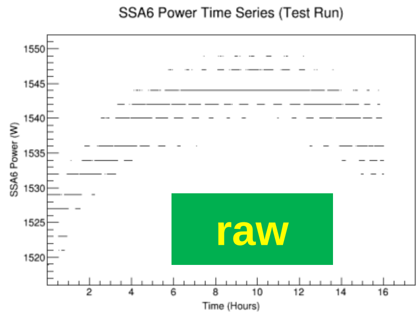
50 data points per bin works the best

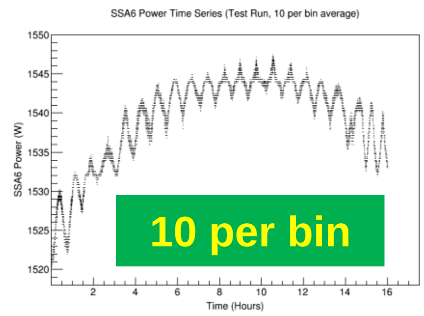
Backup: Time Series for SSA Binning Average

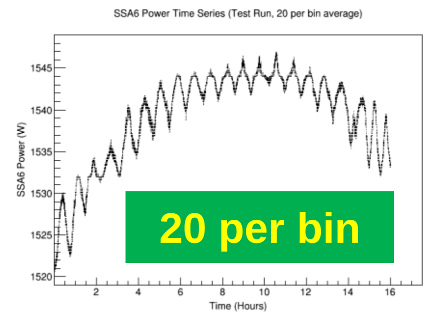
- Waveforms are preserved through the waveguides
- Below are comparison of time series of LLRF and SSA power for SSA #6

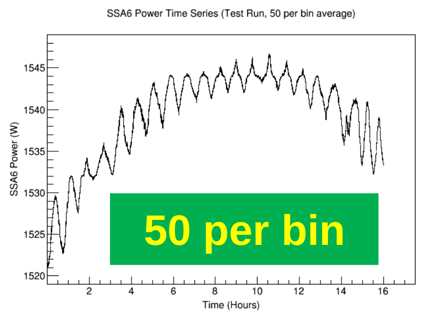


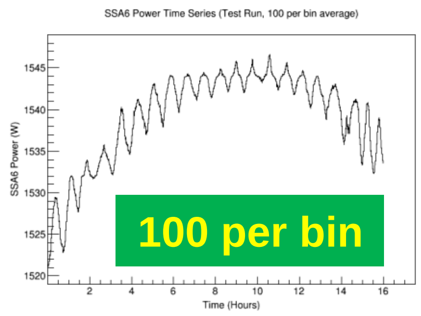
LLRF (Cavity) Power





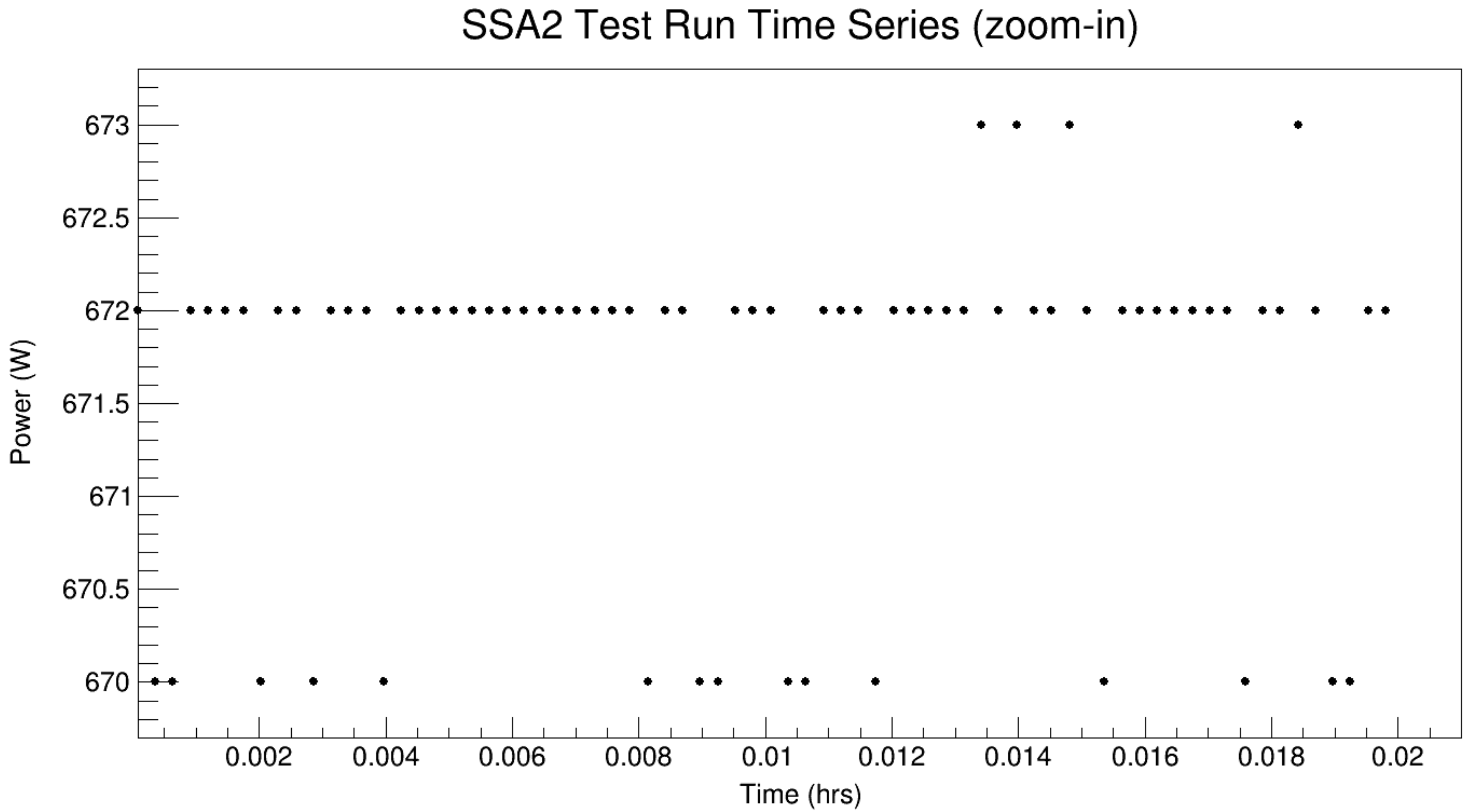






SSA Power

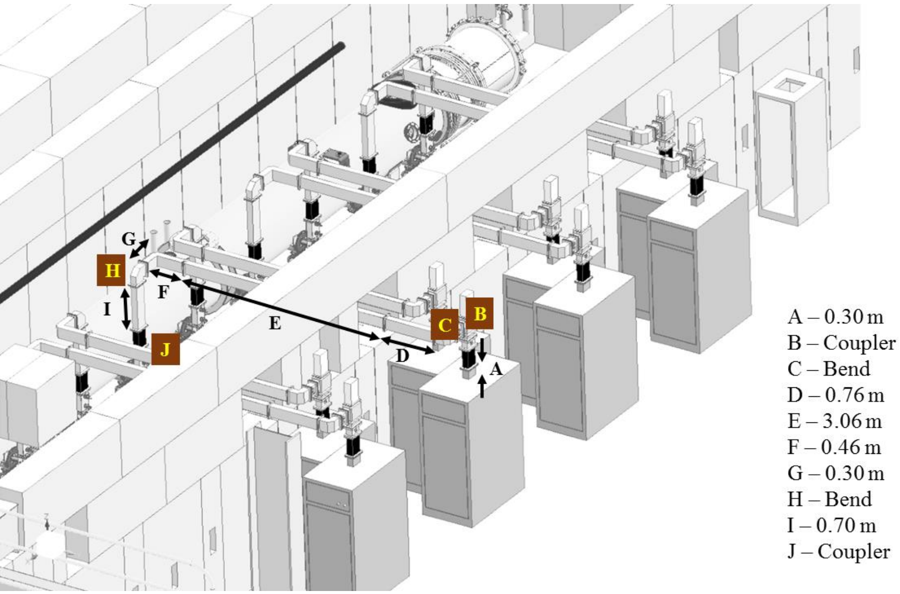
Backup: X-axis zoom-in for raw output from SSA



Backup: Attenuations (Straights)

- Rectangular Waveguide (WR-650)
  - a = 6.5 in.
  - b = 3.25 in.
  - Material: Aluminum 6061-T6
    - Conductivity = 2.506 x 10^{7} Siemens/m
  - $R_s = \sqrt{\frac{\omega\mu}{2\sigma}}$ = 1.43 x 10^{-2} Ohms
  - $\eta = \sqrt{\frac{\mu}{\varepsilon}}$ = 3.77 x 10^{2} m^{2} kg s^{-3} A^{-2}
  - $\omega_c = \frac{c\pi}{a}$ = 5.71 x 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 x 10^{-3} dBm/m

Backup: Attenuations (Others)



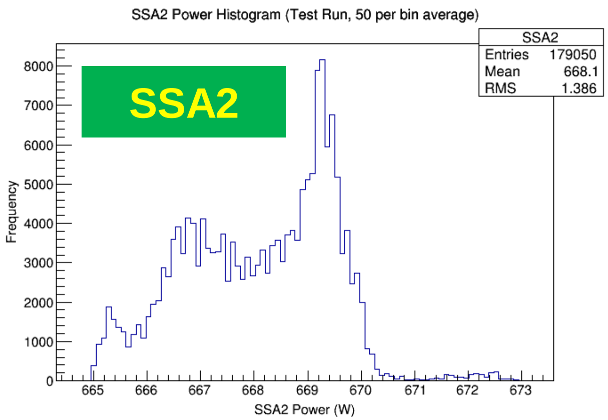
(E. Harms et. al., SRF2015, with modifications)

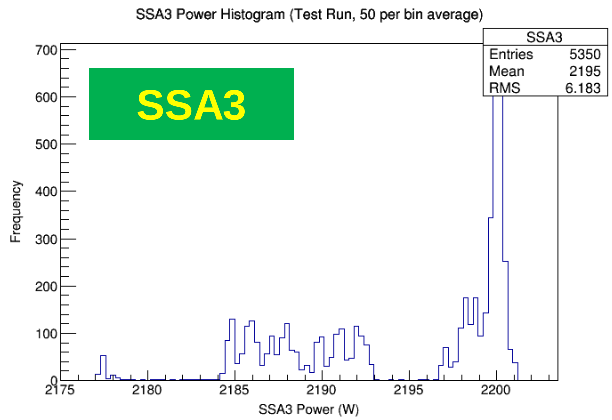
- VSWR: Voltage Standing Wave Ratio
- Reflection coefficient = $\frac{VSWR-1}{VSWR+1}$
- Power loss = Refl. Coef. Squared

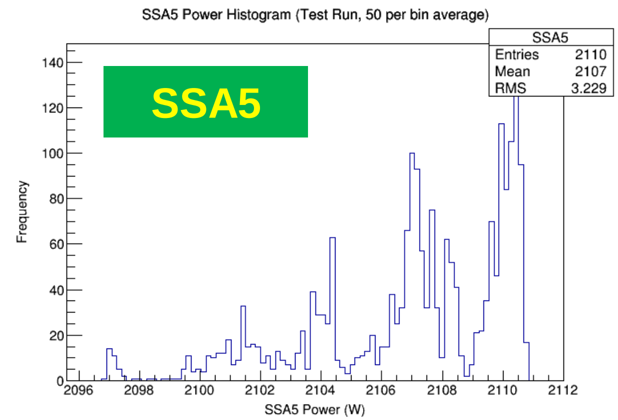
- For bends; VSWR = 1.02
- For main arm coupler; VSWR = 1.05
- For side arm coupler; VSWR = 1.25

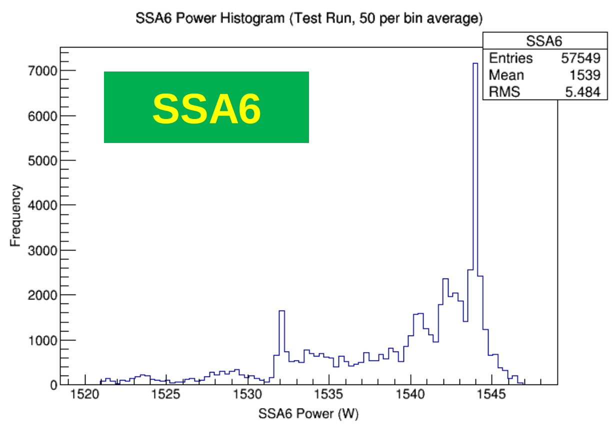
Sections	Input Power (W)	A	B	C	D	E	F	G	H	I	J (Output; W)
SSA 2	668.1	667.7	659.6	659.6	-	655.7	655.1	654.6	654.5	653.7	**653.2**
SSA 3	2,195	2,194	2,167	2,167	2,164	2,151	2,149	2,147	2,147	2,144	**2,143**
SSA 5	2,107	2,106	2,080	2,080	2,077	2,065	2,063	2,061	2,061	2,058	**2,057**
SSA 6	1,539	1,538	1,519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

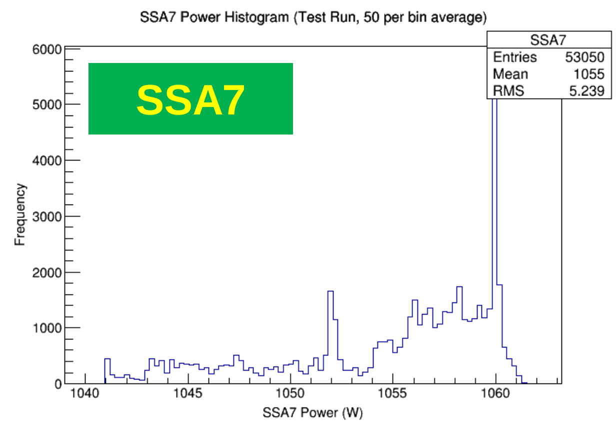
Backup: Histograms for SSA Output



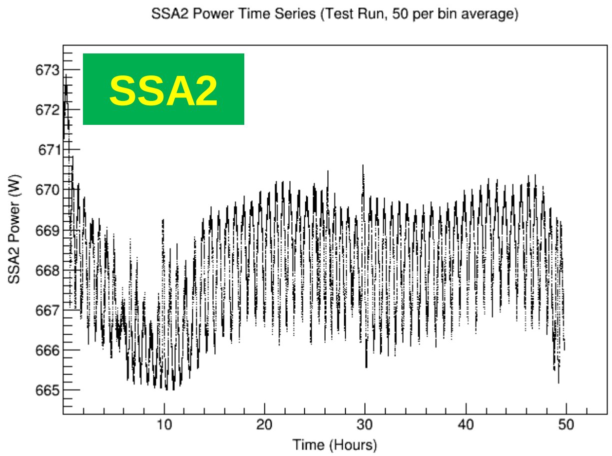


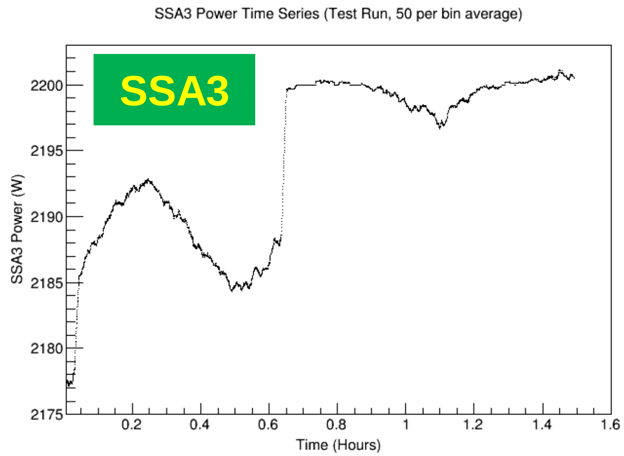


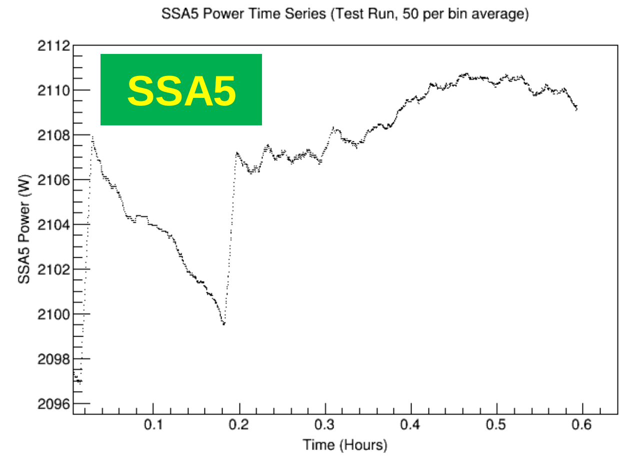


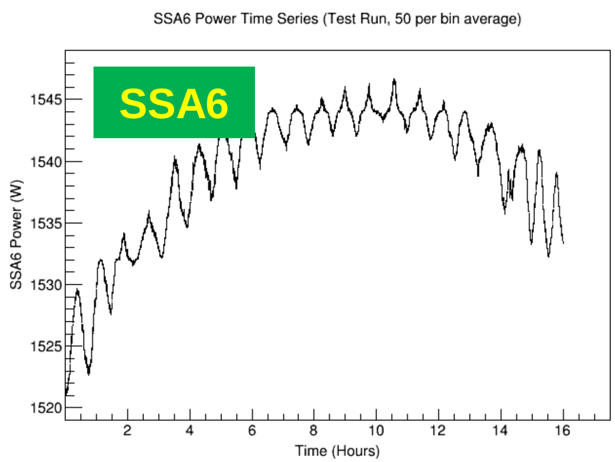


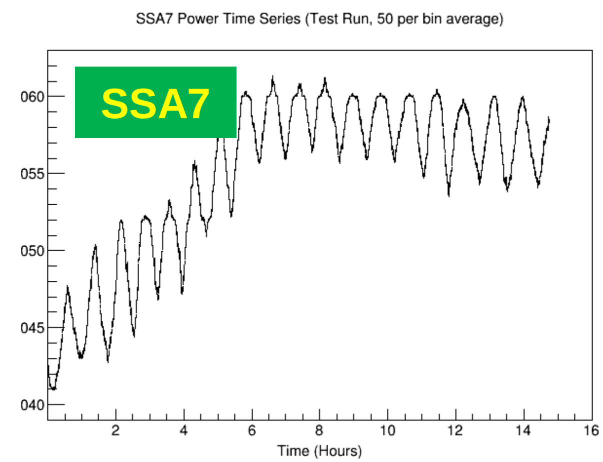
Backup: Time Series for SSA Output





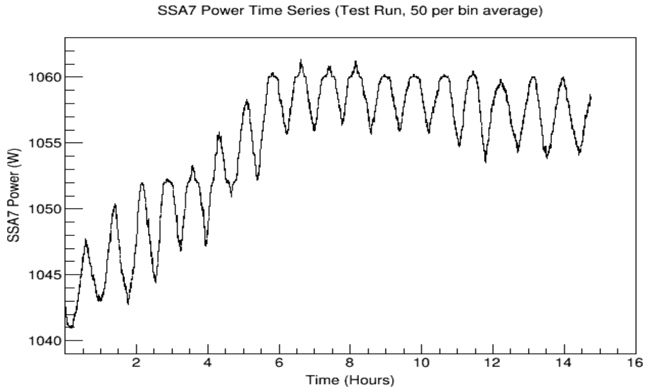




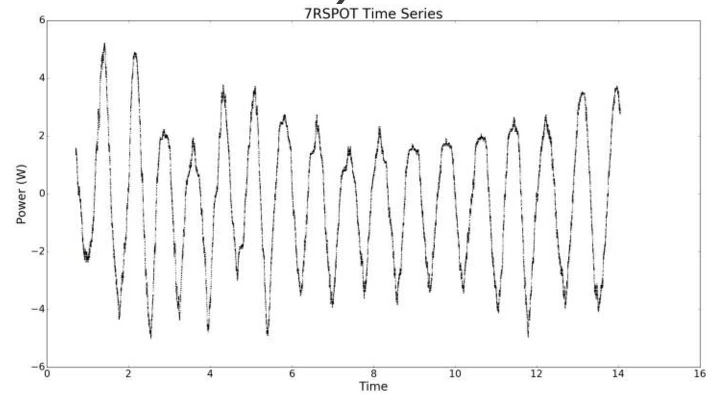


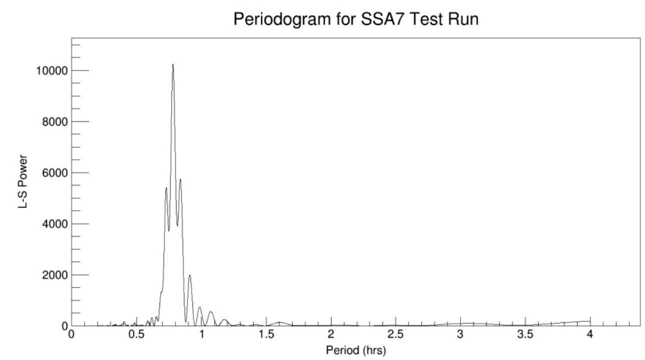
Backup: Parasitic Oscillations

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



Median Smoothing Subtraction

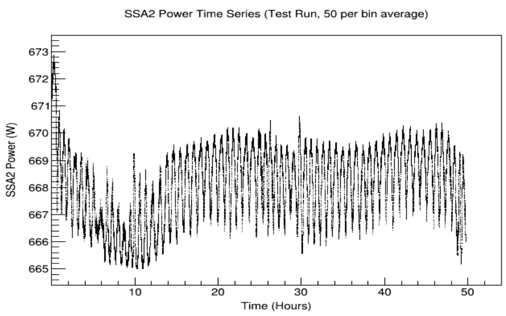




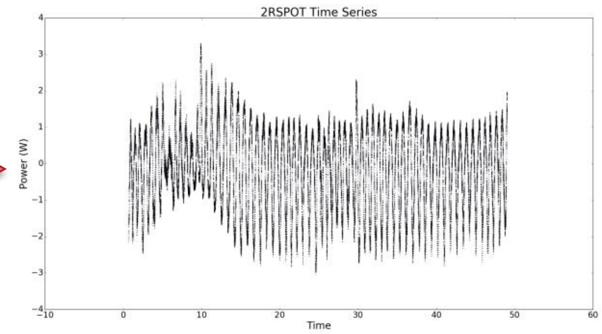
SSA #	2	6	7
Period (Hrs)	0.79	0.79	0.78

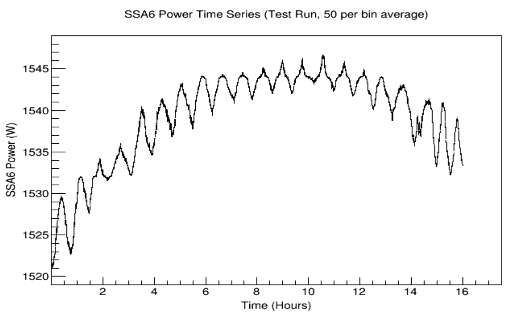
Backup: Median Smoothing Subtractions

Before

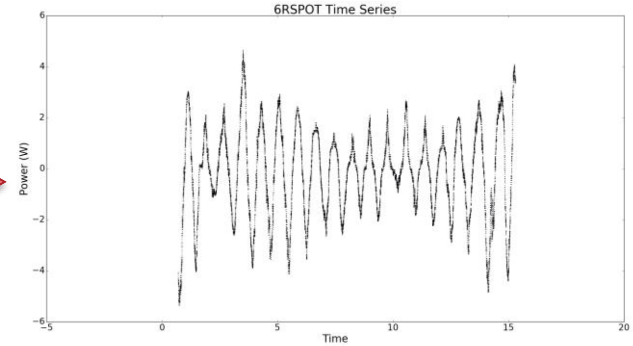


SSA2

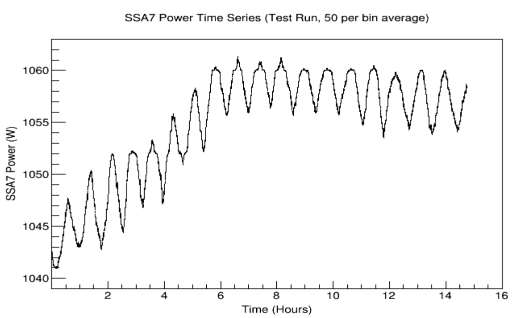




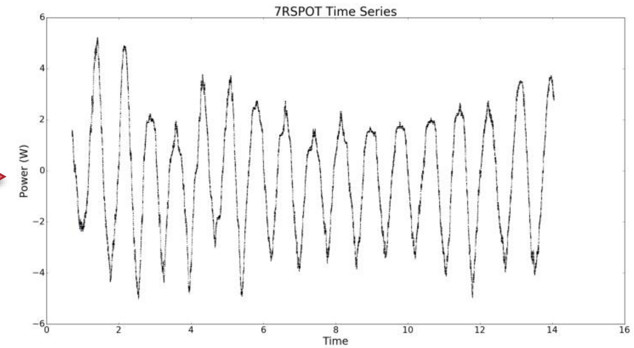
SSA6



After



SSA7



Backup: Periodograms