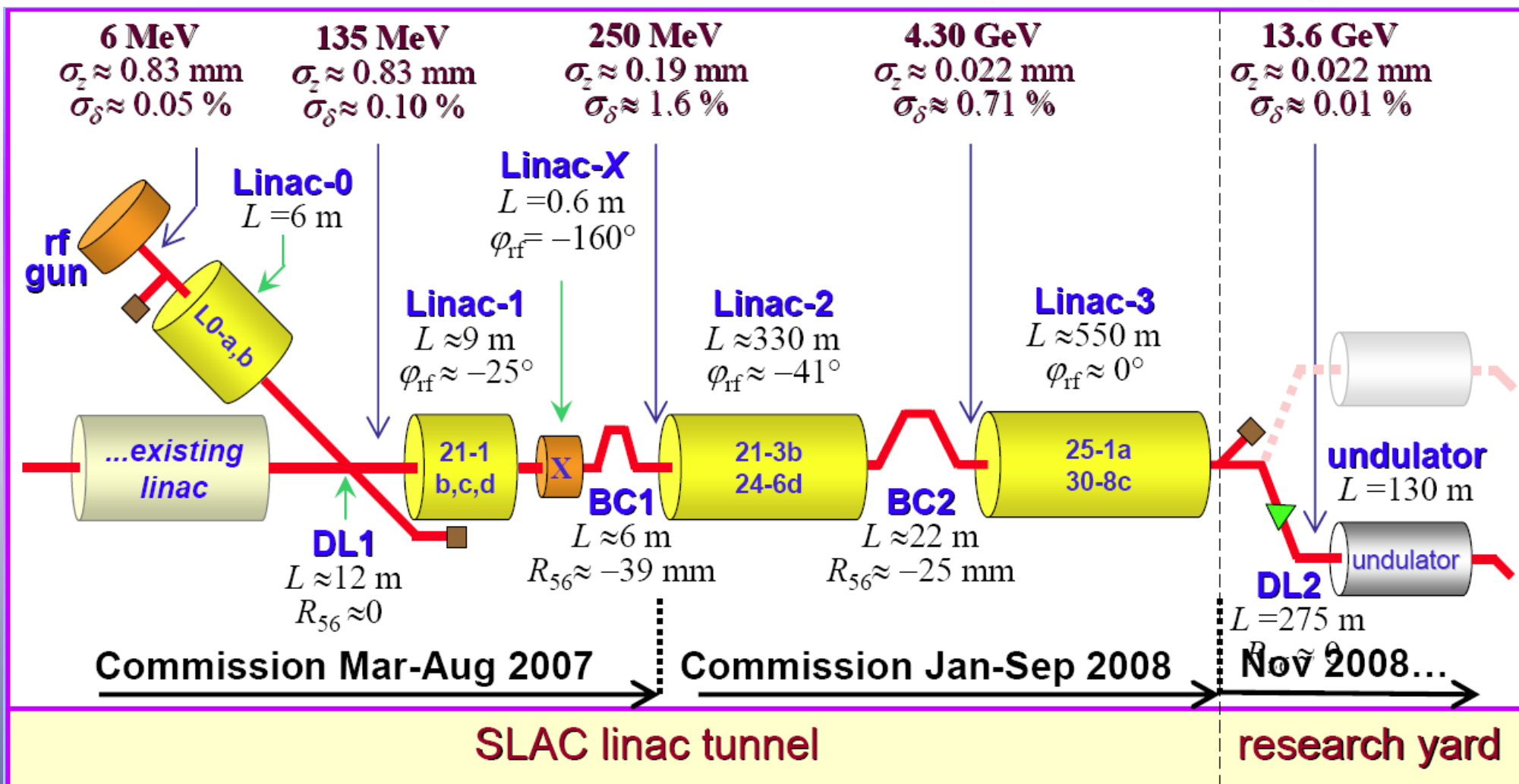


# Linac Coherent Light Source (LCLS)

## Low Level RF Status

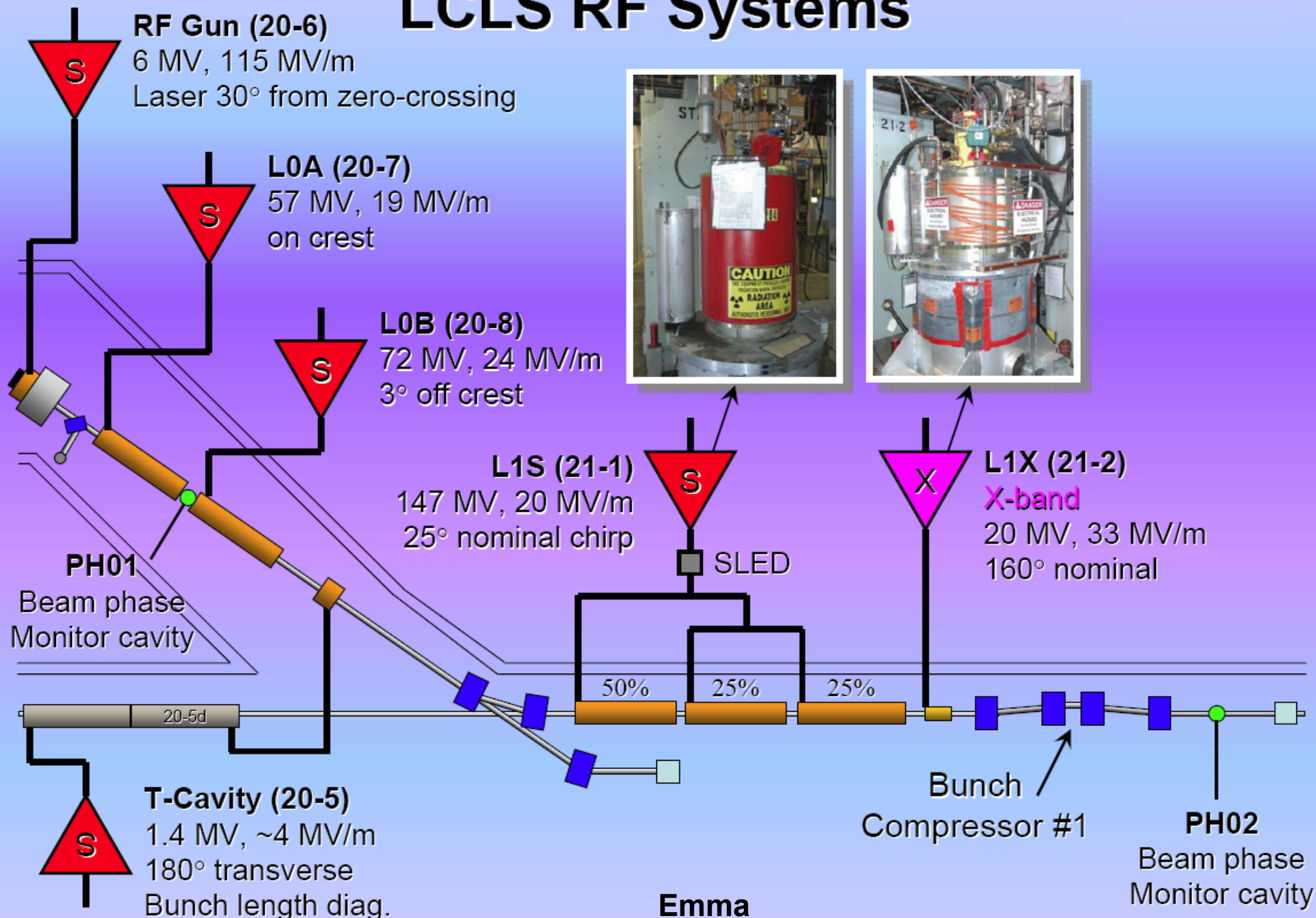
**LCLS FAC**  
**October 30, 2007**



# X-rays in spring 2009

Emma

# LCLS RF Systems



October 30, 2007

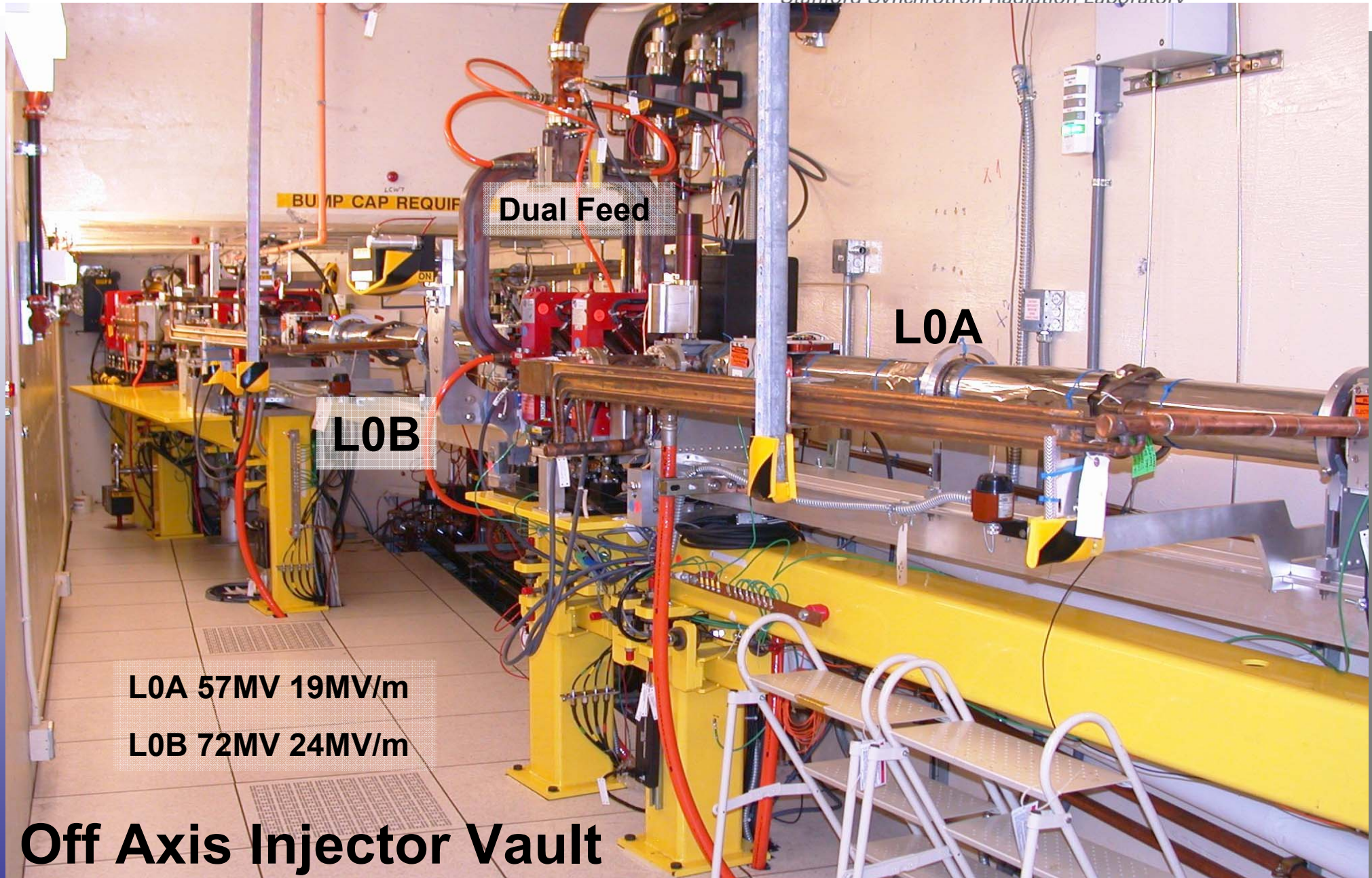
FAC

Ron Akre, Dayle Kotturi

[akre@slac.stanford.edu](mailto:akre@slac.stanford.edu), [dayle@slac.stanford.edu](mailto:dayle@slac.stanford.edu)







October 30, 2007

FAC

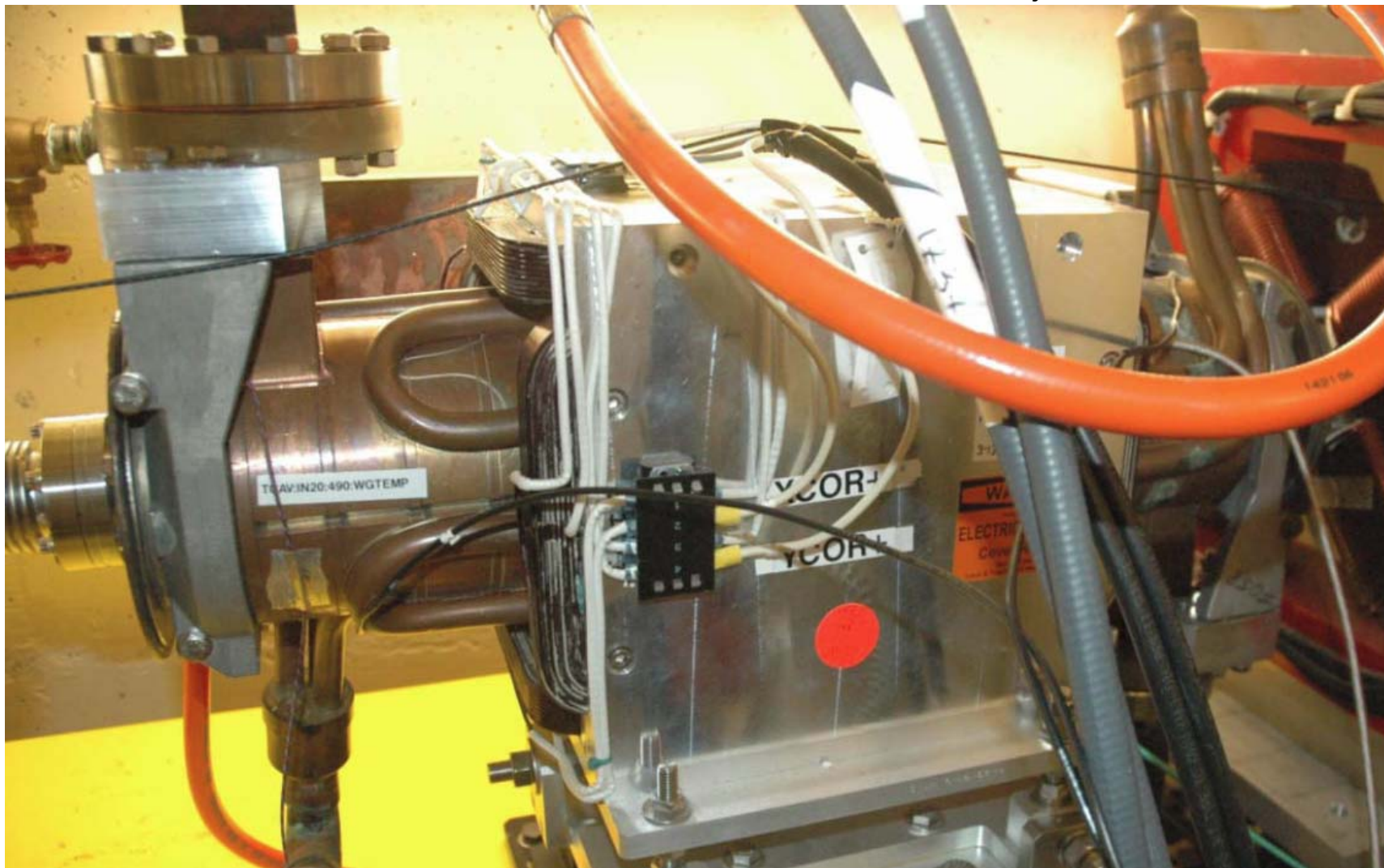
Ron Akre, Dayle Kotturi

[akre@slac.stanford.edu](mailto:akre@slac.stanford.edu), [dayle@slac.stanford.edu](mailto:dayle@slac.stanford.edu)

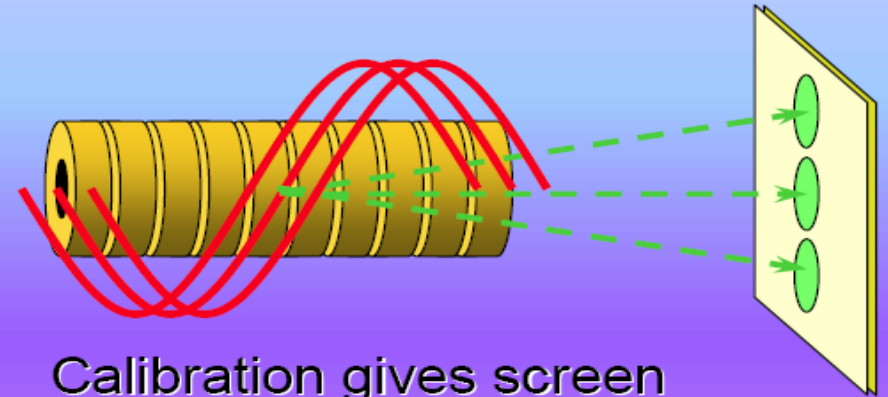
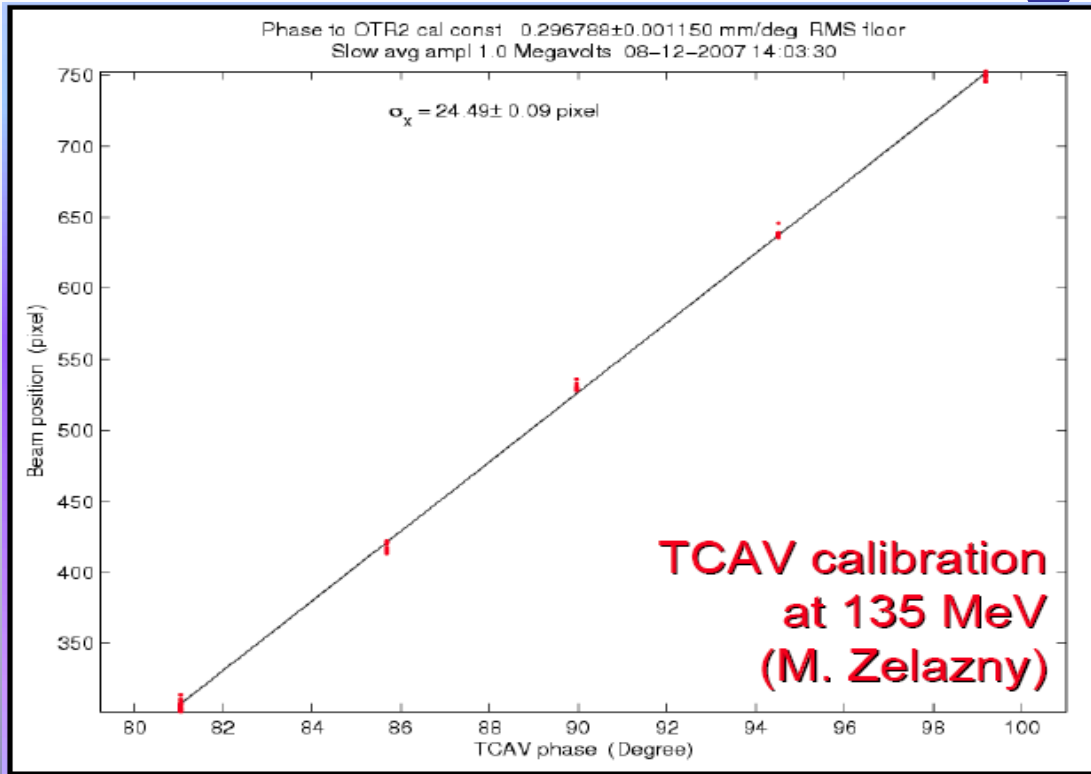


# Injector Transverse Accelerator 55cm 1MV

Powered from 20-5 Linac Klystron Accelerator Output. The klystron station is up stream of LCLS. The transverse accelerator is located in the off axis injector.



# Calibration to Degrees of S-Band

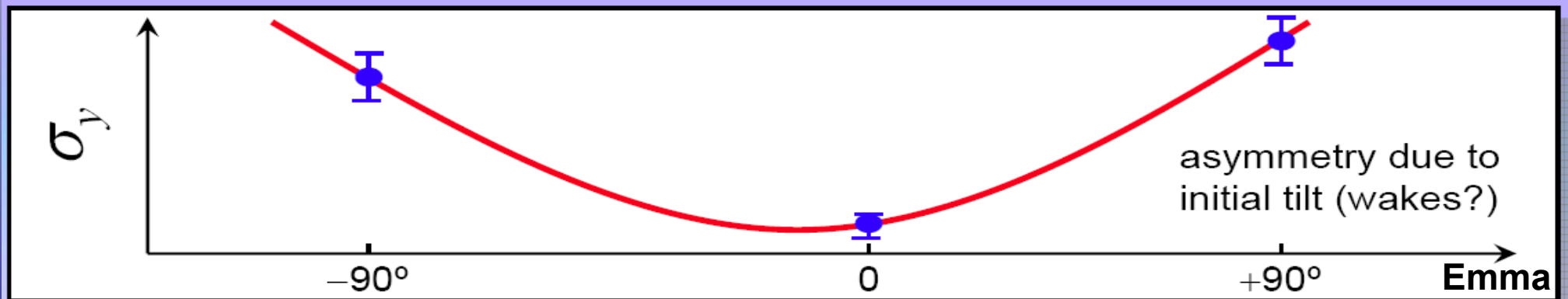


Calibration gives screen pixels per deg-S (**P. Krejcik**)

Now measure beam size at:

1. **positive zero-crossing,**
2. **negative zero-crossing, &**
3. **with RF off**

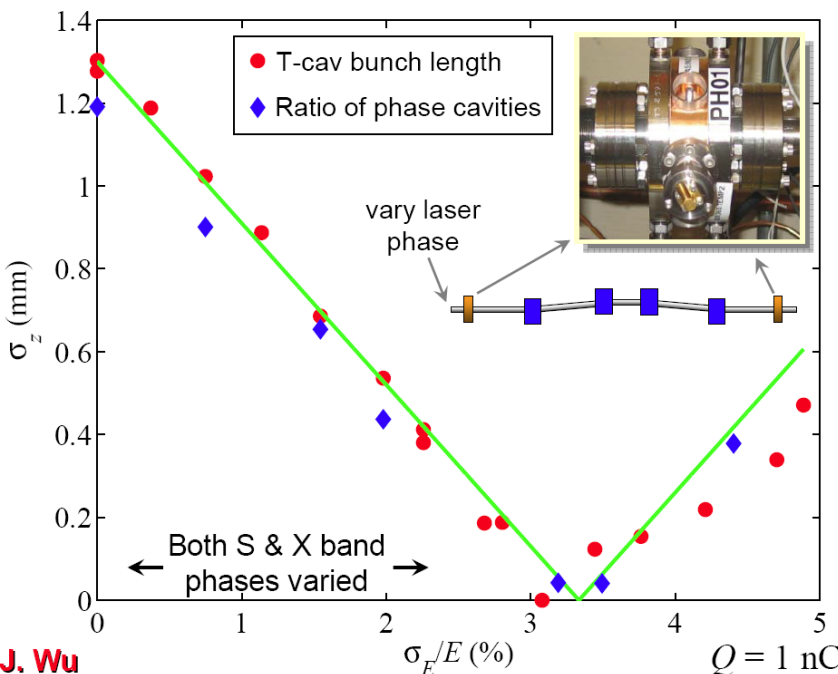
Fit beam-size data to parabola...





# Beam Phase Cavity

Located between L0A and L0B.  
 Single cell cavity at 2805MHz. 51MHz below RF frequency to lower from dark current generated in the RF Gun. 2805MHz is 25.5MHz below Local Oscillator to enable beam phase measurement against LO reference. Measurement below correlates differences in beam phase between cavities before and after BC1 to bunch length.



J. Wu



Frequency = 2805MHz

$Q_{\text{Loaded } \beta=1} = 6200$

Time Constant = 700ns

Temperature Coefficient = 50kHz/°C

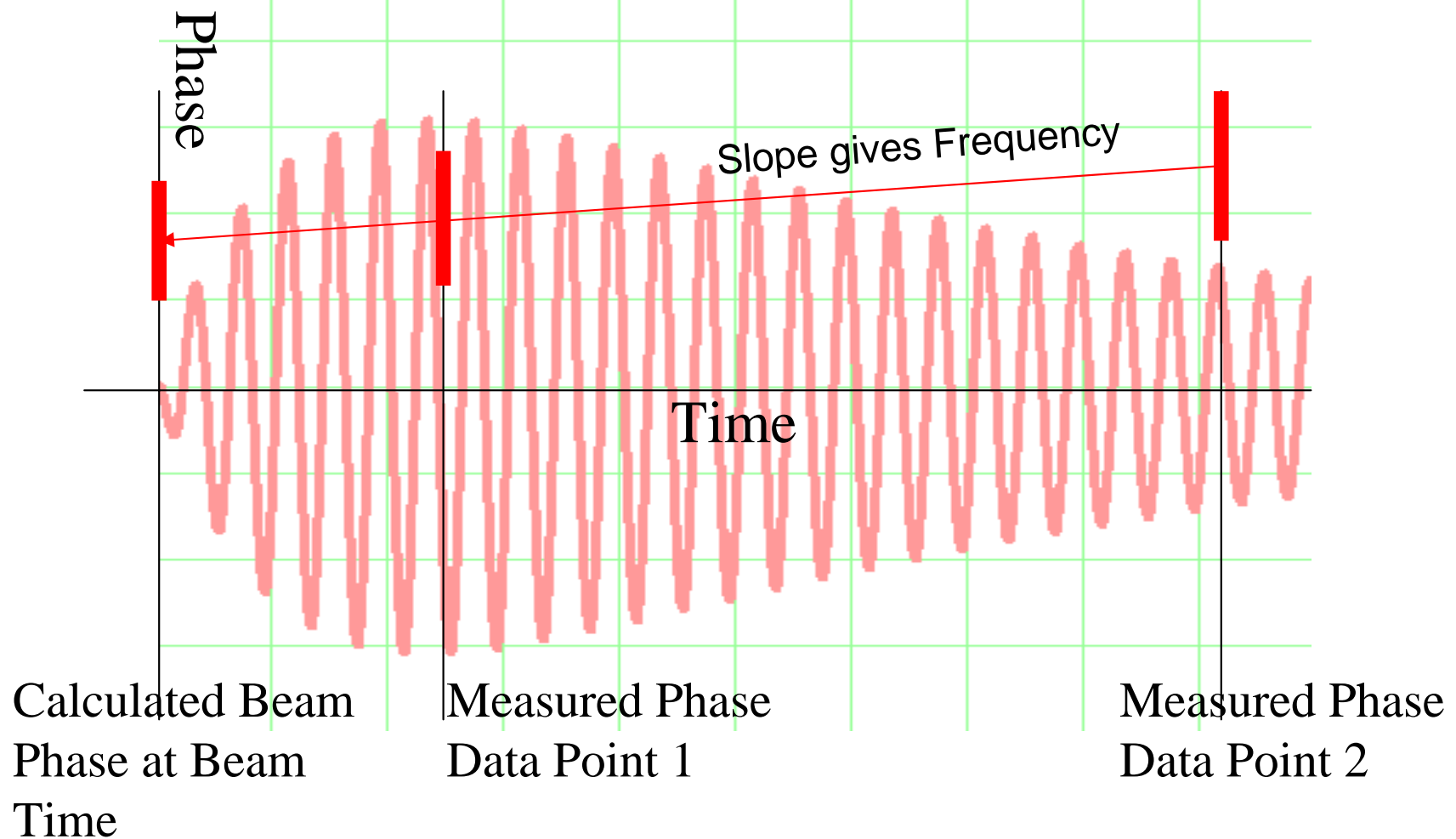
October 30, 2007

FAC

Ron Akre, Dayle Kotturi

[akre@slac.stanford.edu](mailto:akre@slac.stanford.edu), [dayle@slac.stanford.edu](mailto:dayle@slac.stanford.edu)

# Beam Phase Cavity Analysis



Beam Phase and Cavity Frequency are Calculated from Two Data Points Sent From the PAD. Software remains to be commissioned.



# X-Band Structure in Main Linac

20MV - 33MV/m

15MW at structure

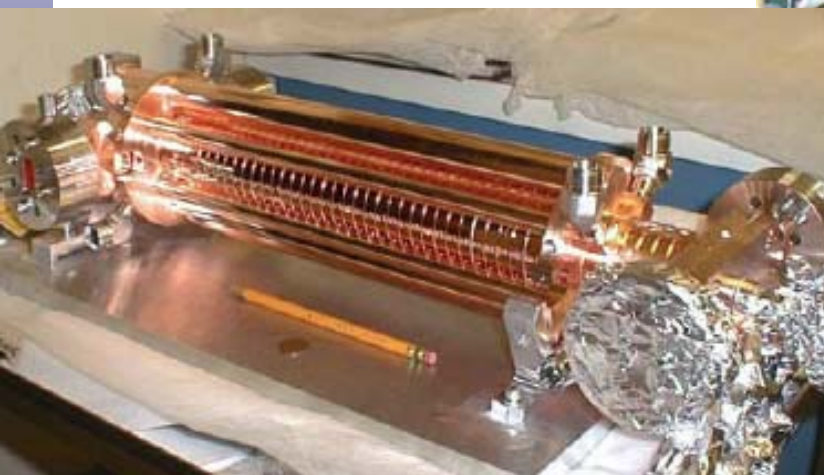
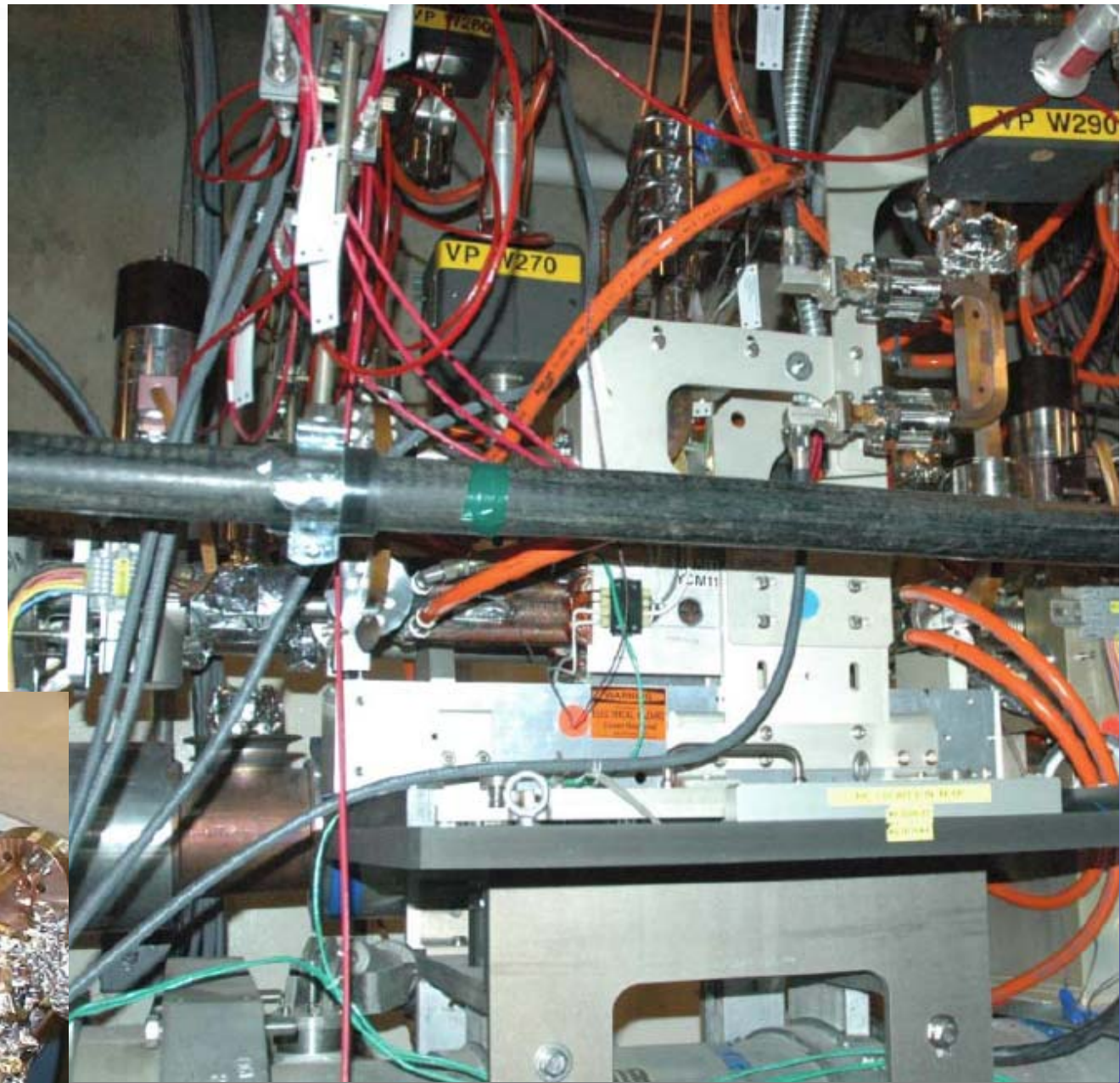
22MW at the klystron

120nS fill time.

Beam at +160degrees

20° from decelerating crest

Needs new TWT driver



October 30, 2007

FAC

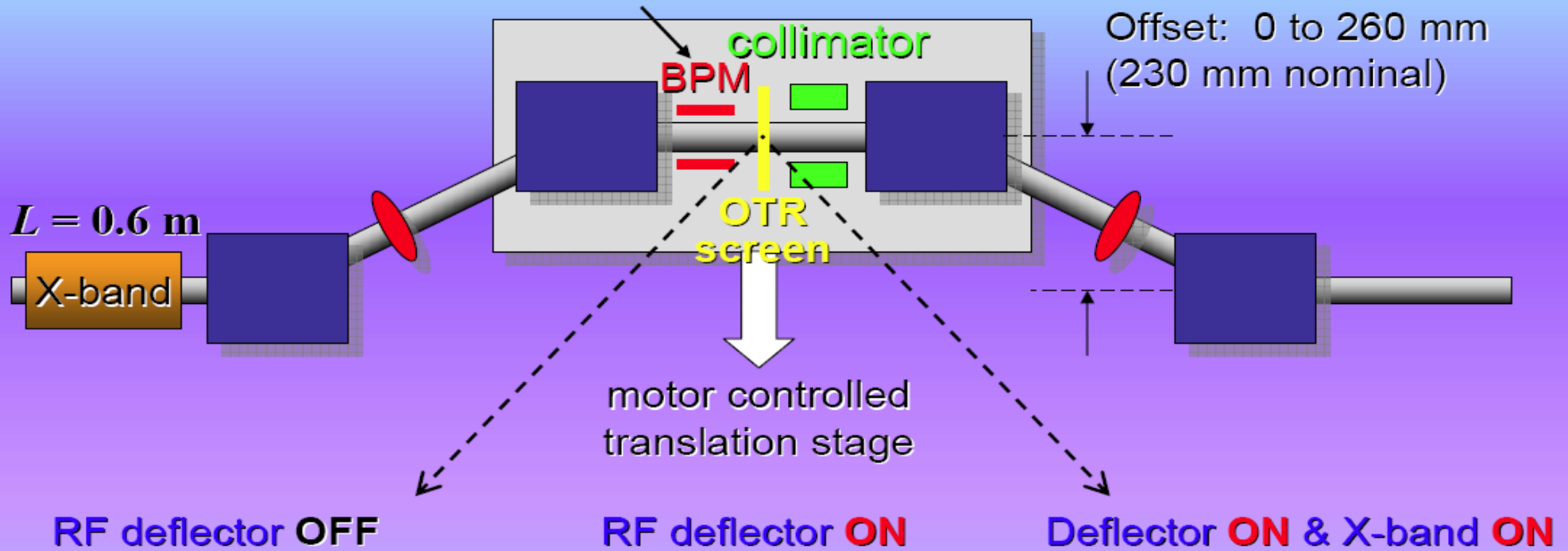
Ron Akre, Dayle Kotturi

[akre@slac.stanford.edu](mailto:akre@slac.stanford.edu), [dayle@slac.stanford.edu](mailto:dayle@slac.stanford.edu)



# X-Band Station to Linearize Energy Position Correlation

BPM for energy feedback (20  $\mu\text{m}$  resolution)



energy chirp only

energy chirp & RF deflector

X-band correction

Emma



# LCLS RF Jitter Tolerance Budget

$$|\langle \Delta E/E_0 \rangle| < 0.1\% \quad \text{and} \quad |\Delta I/I_0| < 12\%$$

Parameter	Symbol	LCLS	Unit
Gun timing jitter	$\Delta t_0$	0.50	psec
Initial bunch charge	$\Delta Q/Q_0$	2.0	%
mean L0 rf phase	$\varphi_0$	0.10	deg
mean L1 rf phase	$\varphi_1$	0.10	deg
mean Lh rf phase X-band	$\varphi_h$	0.50	X-deg
mean L2 rf phase	$\varphi_2$	0.07	deg
mean L3 rf phase	$\varphi_3$	0.15	deg
mean L0 rf voltage	$\Delta V_0/V_0$	0.10	%
mean L1 rf voltage	$\Delta V_1/V_1$	0.10	%
mean Lh rf voltage	$\Delta V_h/V_h$	0.25	%
mean L2 rf voltage	$\Delta V_2/V_2$	0.10	%
mean L3 rf voltage	$\Delta V_3/V_3$	0.08	%

## Lowest Noise Floor Requirement

0.5deg X-Band = 125fS  
 Structure Fill time = 100nS

Noise floor = -111dBc/Hz  
 @ 11GHz 10MHz BW  
 -134dBc/Hz @ 476MHz

**RMS tolerance budget for <12% rms peak-current jitter or <0.1% rms final e<sup>-</sup> energy jitter. All tolerances are rms levels and the voltage and phase tolerances per klystron for L2 and L3 are  $\sqrt{Nk}$  larger, assuming uncorrelated errors, where  $Nk$  is the number of klystrons per linac.**

P. Emma

# Slow Drift Tolerance Limits

(Top 4 rows for  $\Delta\varepsilon/\varepsilon < 5\%$ , bottom 4 limited by feedback dynamic range)

Gun-Laser Timing	$\pm 2.4^*$	deg-S
Bunch Charge	$\pm 3.2$	%
Gun RF Phase	$\pm 2.3$	deg-S
Gun Relative Voltage	$\pm 0.6$	%
L0,1,X,2,3 RF Phase (approx.)	$\pm 5$	deg-S
L0,1,X,2,3 RF Voltage (approx.)	$\pm 5$	%

(Tolerances are peak values, not rms)

**P. Emma, J. Wu**

\* for synchronization, this tolerance might be set to  $\pm 1$  ps (without arrival-time measurement)



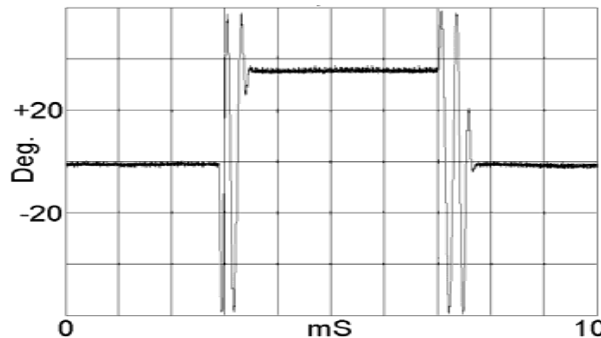
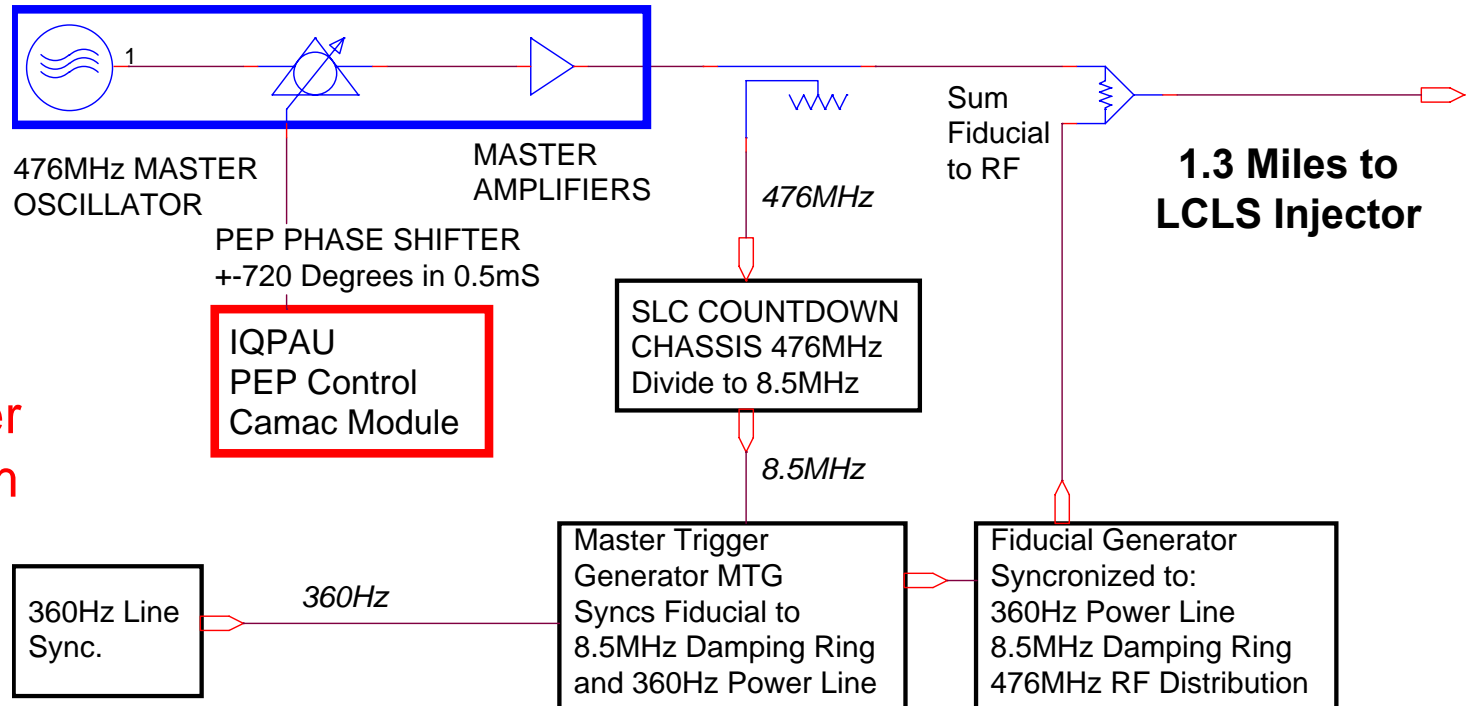
# Linac Sector 0 RF Upgrade

LCLS must be compatible with the existing linac operation including PEP timing shifts

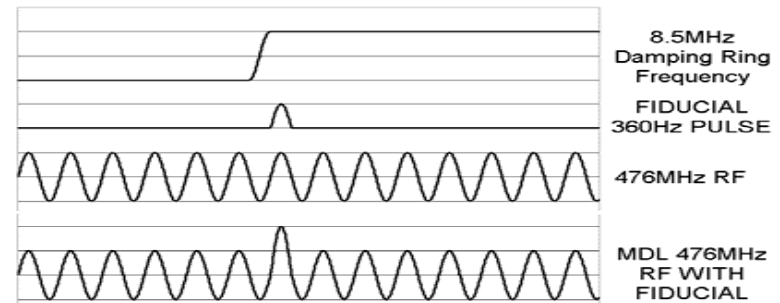
MAIN LINAC (SECTOR 0) RF/TIMING SYSTEM

Master Oscillator is located 1.3 miles from LCLS Injector

Measurements on January 20, 2006 at Sector 21 show 30fS rms jitter in a bandwidth from 10Hz to 10MHz

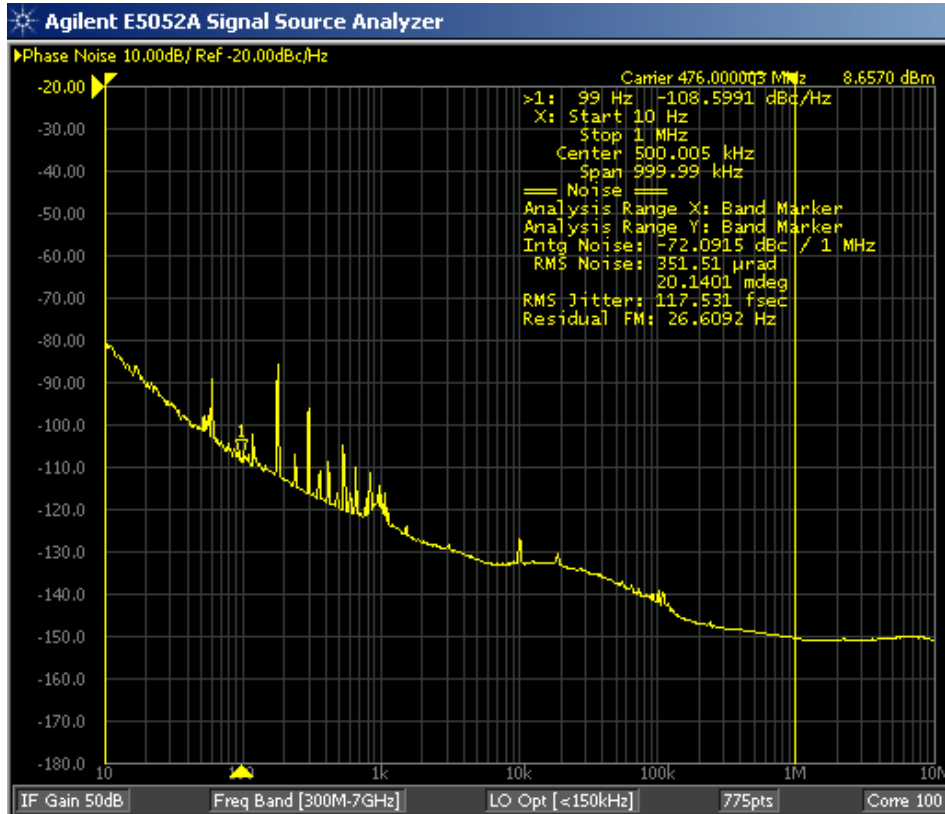


PEP PHASE SHIFT ON MAIN DRIVE LINE



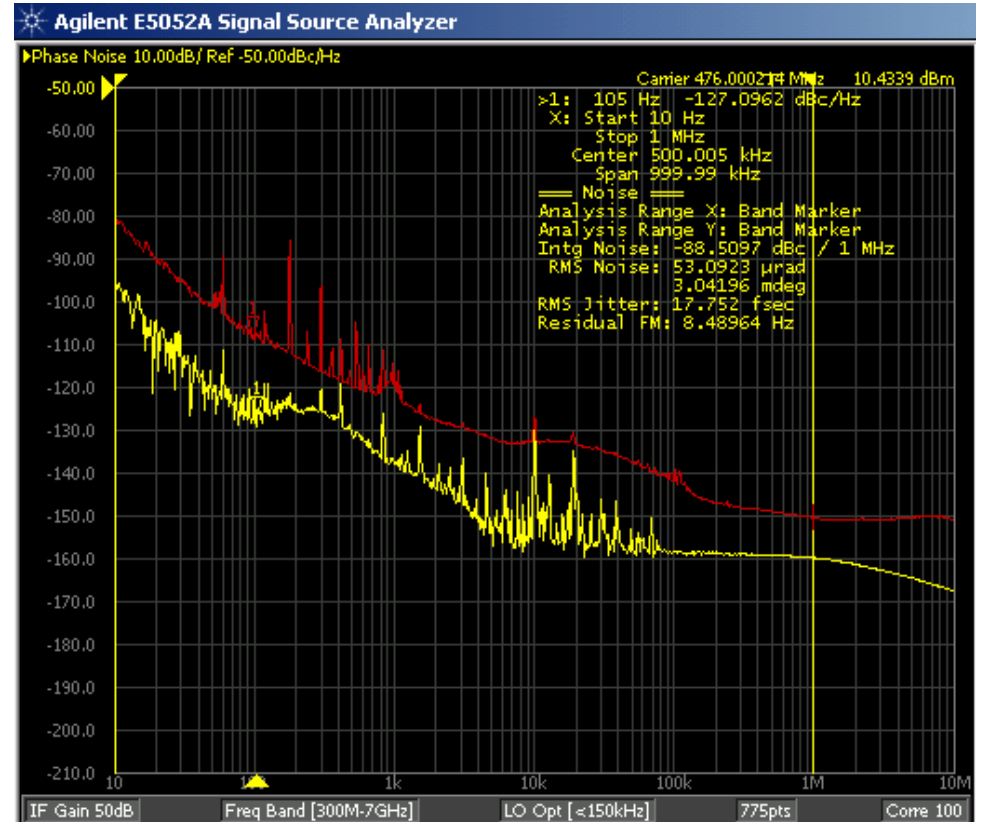
MDL RF with TIMING Pulse - Sync to DR

# RF Distribution Lab vs. MDL Measurements



Existing Linac MDL Sector 0  
Before July 2007

126fS rms Jitter 10Hz to 10MHz



LCLS Reference System Lab Measurements

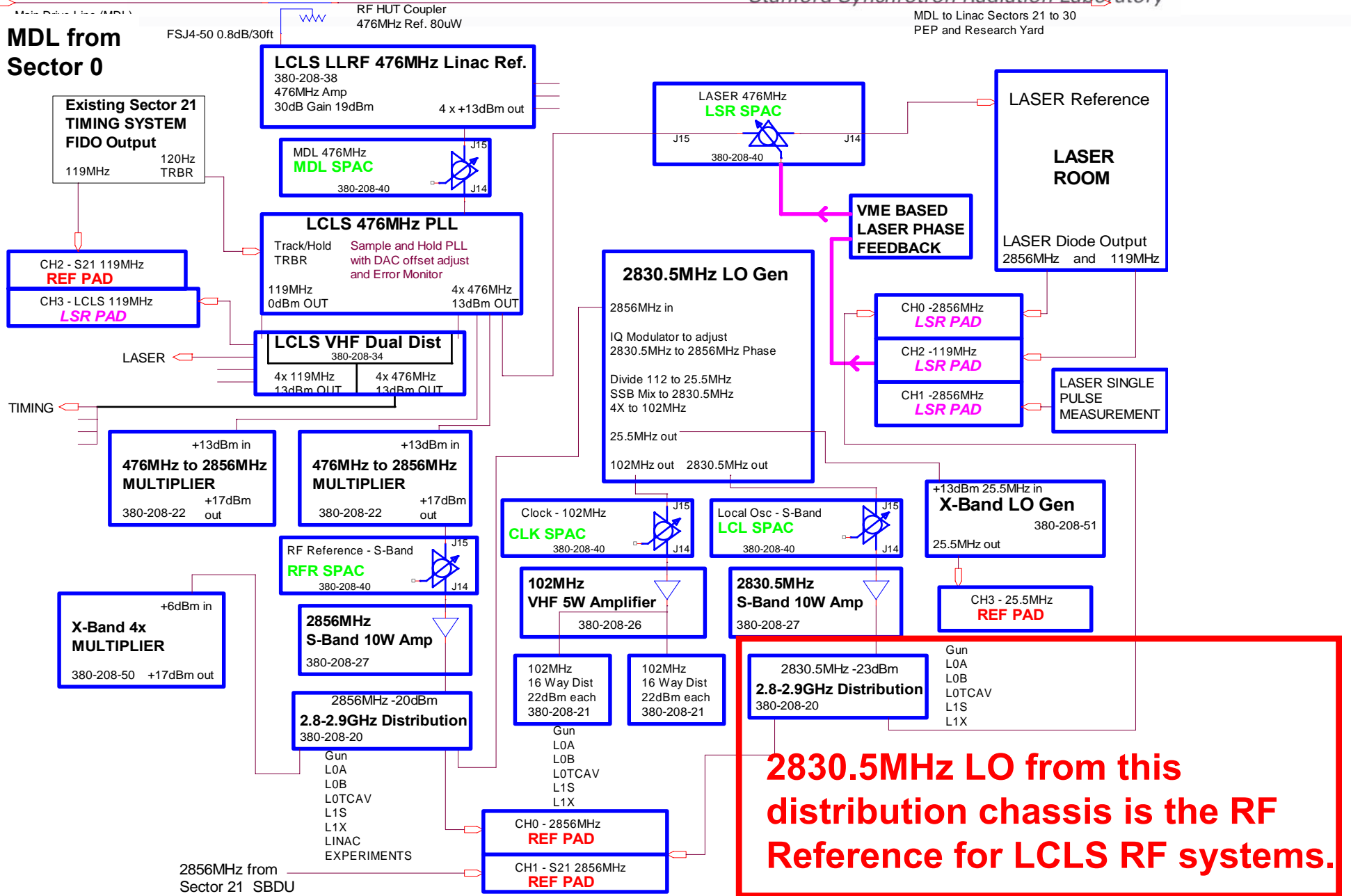
20fS rms Jitter 10Hz to 10MHz

John Byrd LBNL

**In July 2007 both the Master Oscillator and Master Amplifier were upgraded. An increase in stability was noticed.**



MDL from Sector 0



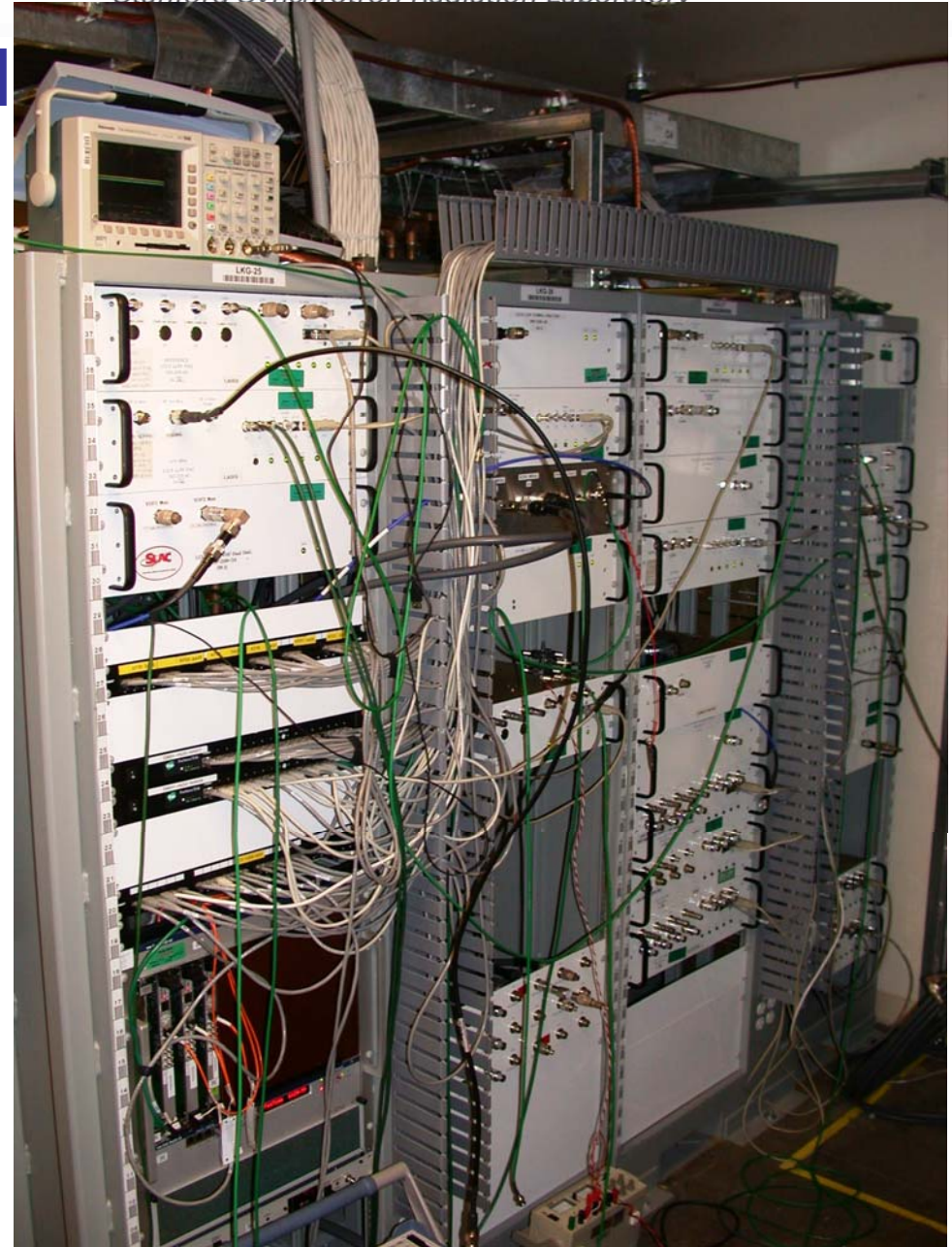
**2830.5MHz LO from this distribution chassis is the RF Reference for LCLS RF systems.**

# LCLS LLRF System to BC1

- RF Feedback for Six RF Stations
  - Gun – 5 Chassis
  - L0A – 4 Chassis
  - L0B – 4 Chassis
  - TCav – 4 Chassis
  - L1S – 4 Chassis
  - L1X – 4 Chassis
- Laser Reference and Feedback – 2
- Two Phase Cavities – 1 Chassis
- Reference System – 21 Chassis

**Total of 49 SLAC built RF chassis were installed and turned on last run.**

Four short racks in a temperature controlled RF Hut contain the RF reference system as well as Phase and Amplitude Detectors (PADs) for critical RF measurements.





# LCLS New Reference System Lab Measurements

**Lab Tests Show  
Reference System  
Noise Levels Meet  
All LCLS  
Requirements**

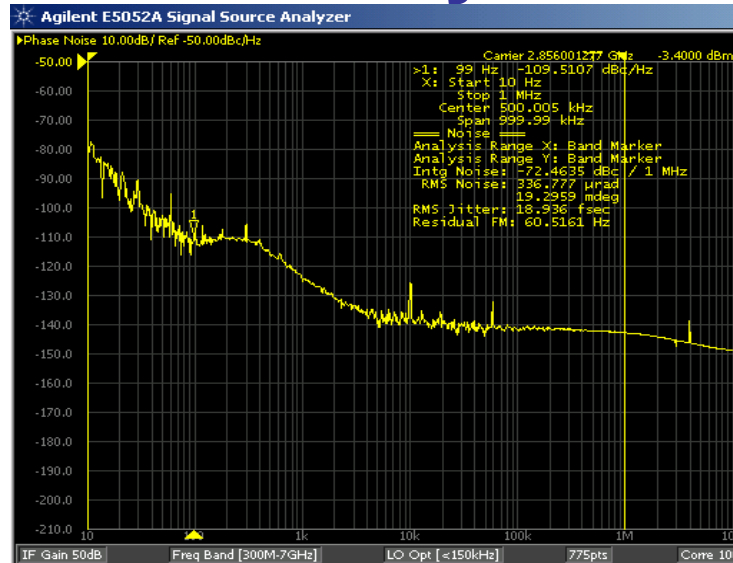
**2856MHz = 70fSrms**

**2830.5MHz = 70fSrms**

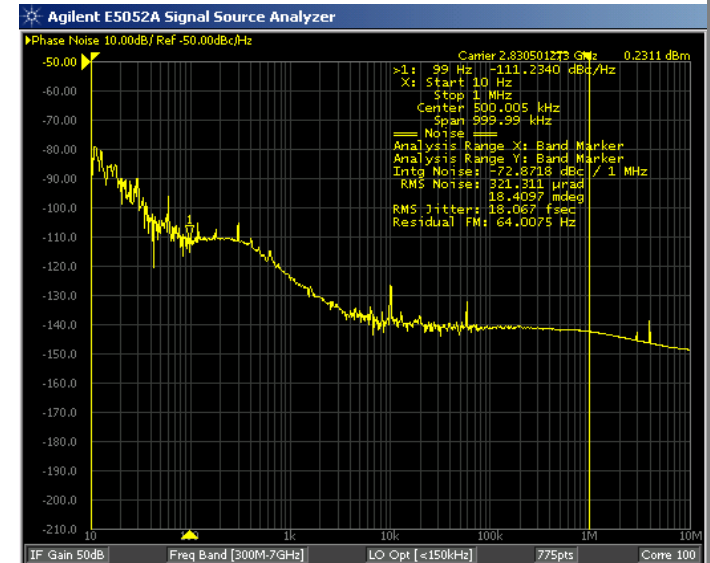
**25.5MHz = 2pSrms**

**102MHz = 2pSrms**

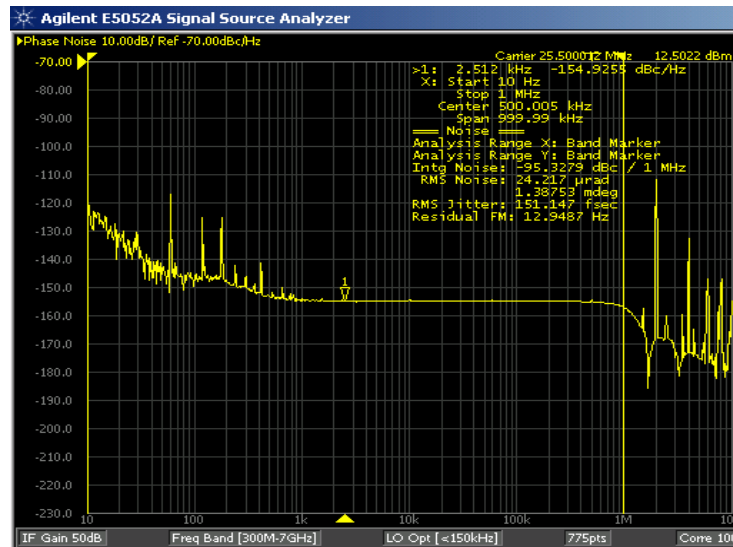
John Byrd - LBNL



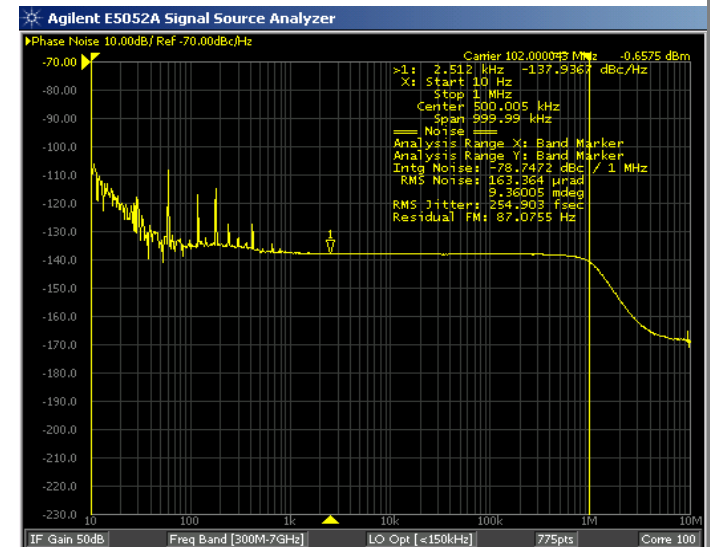
**2856MHz : 22fSrms 10Hz to 10MHz**



**2830.5MHz : 22fSrms 10Hz to 10MHz**



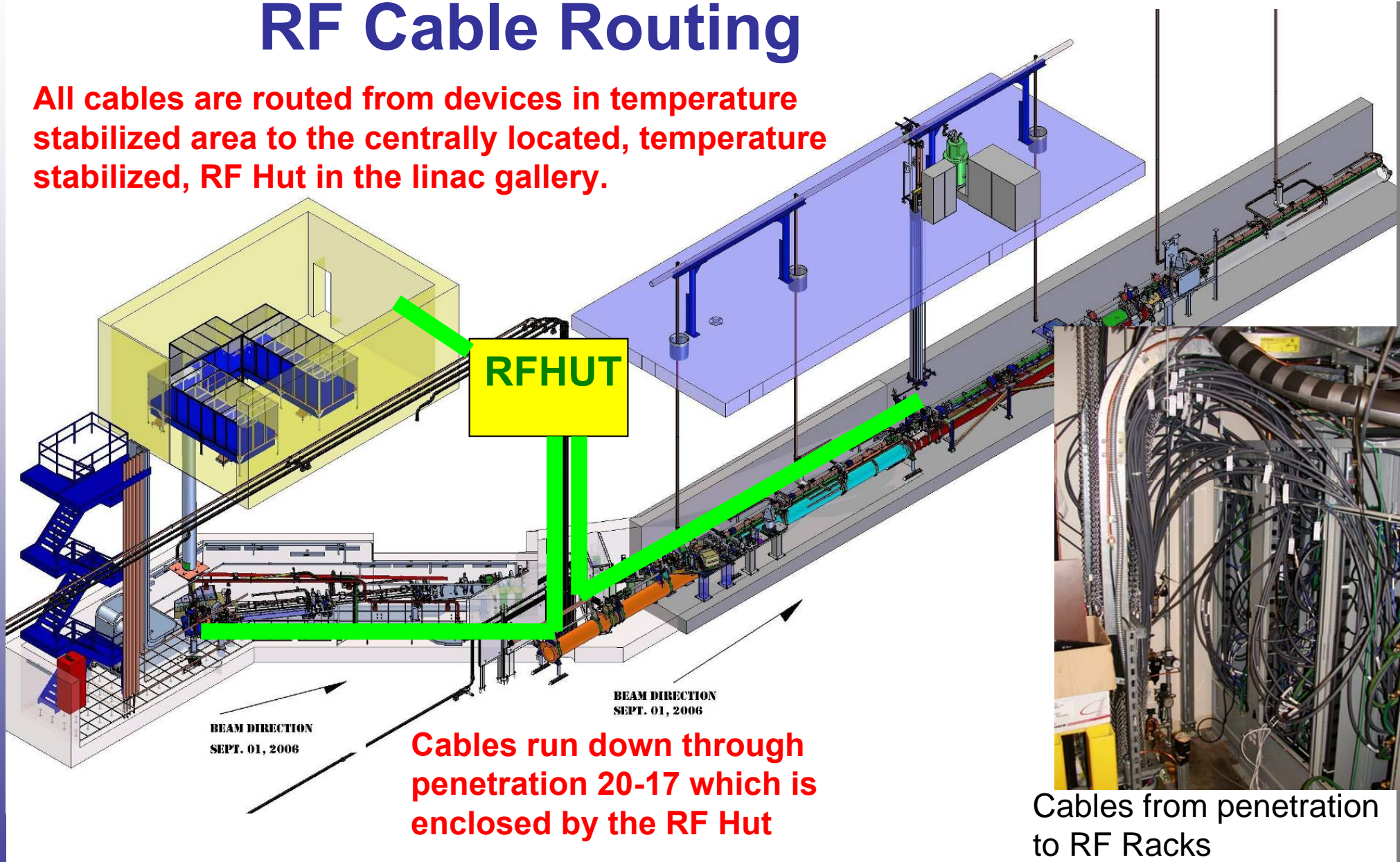
**25.5MHz : 152fSrms 10Hz to 1MHz**



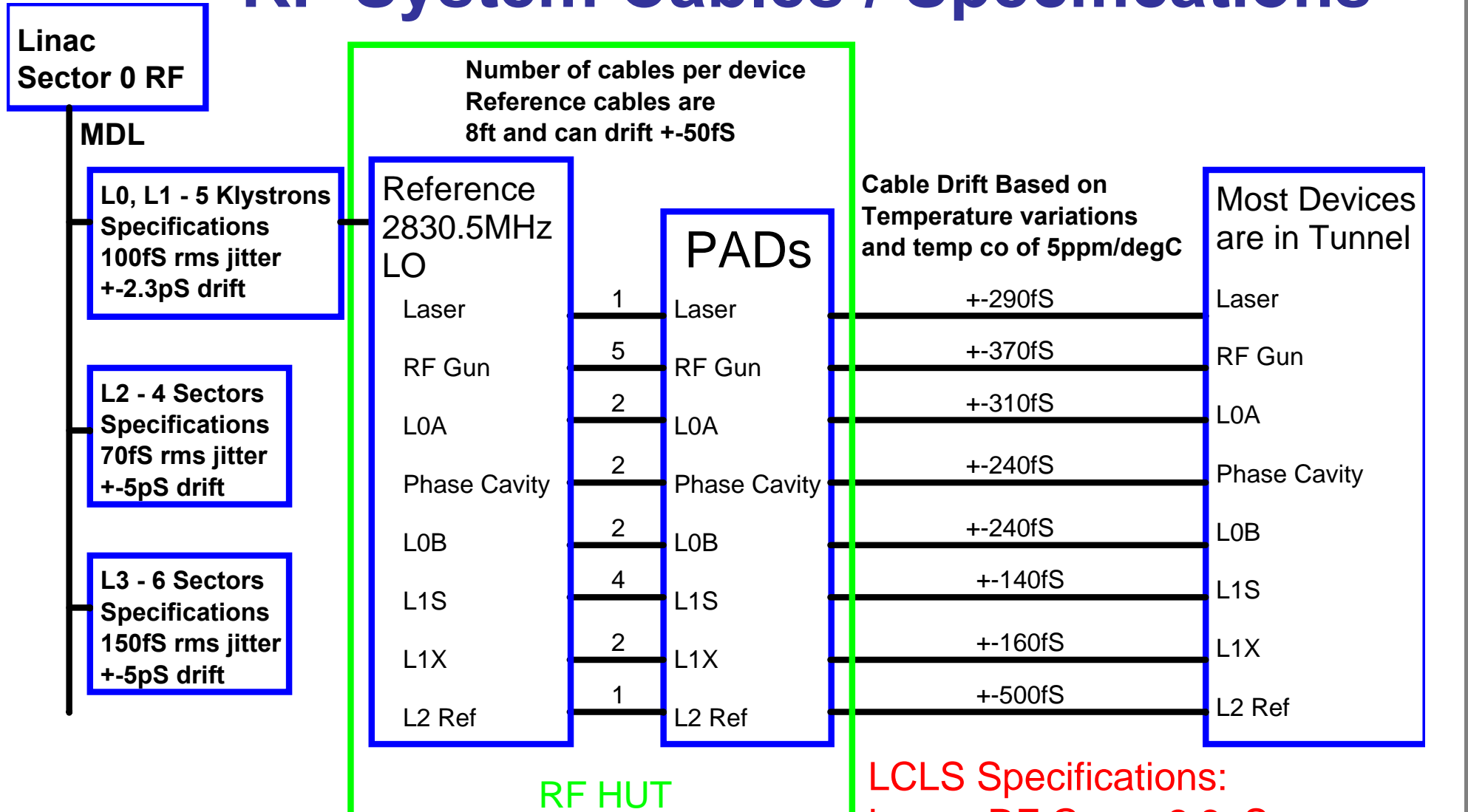
**102MHz : 281fSrms 10Hz to 10MHz**

# RF Cable Routing

All cables are routed from devices in temperature stabilized area to the centrally located, temperature stabilized, RF Hut in the linac gallery.



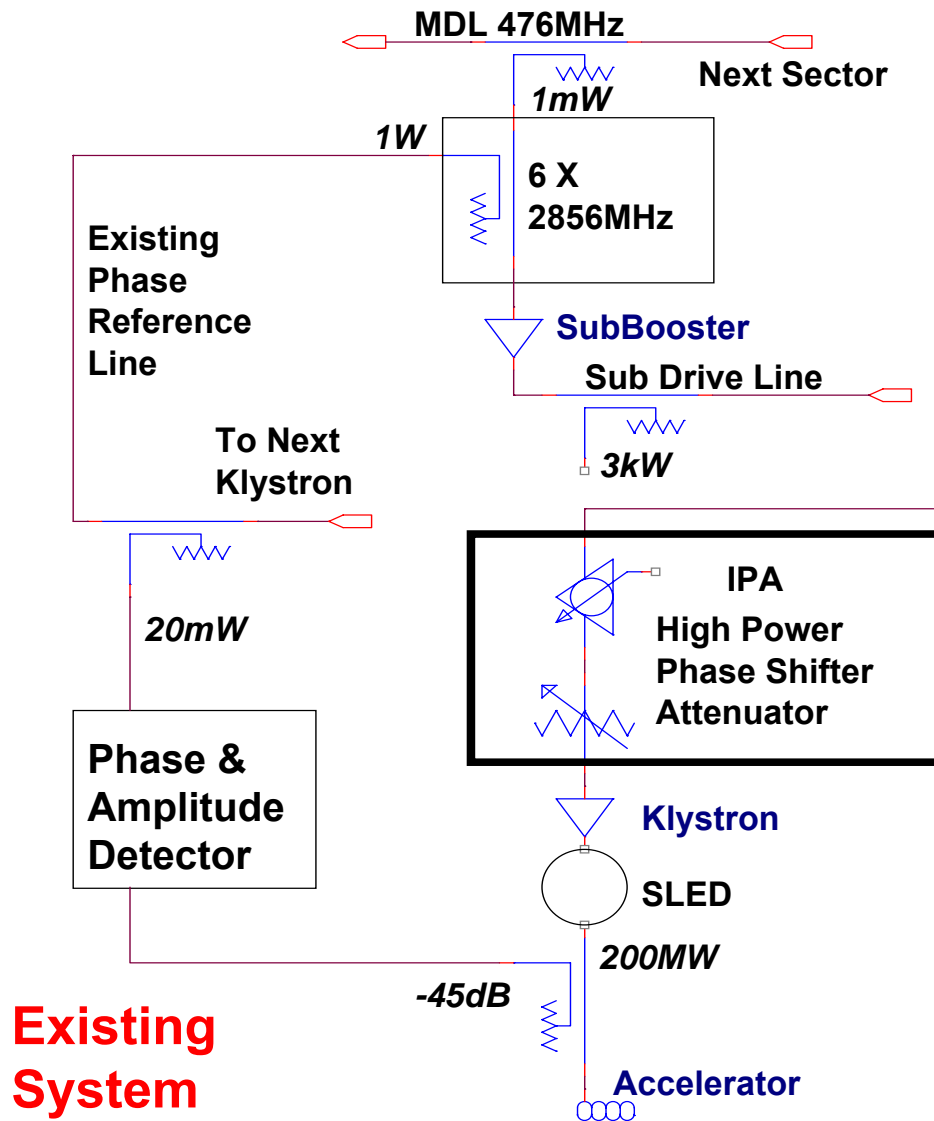
# RF System Cables / Specifications



**LCLS Specifications:**  
 Laser, RF Gun – 2.3pS  
 L0A, L0B, L1S, L1X, L2, L3 – 5pS

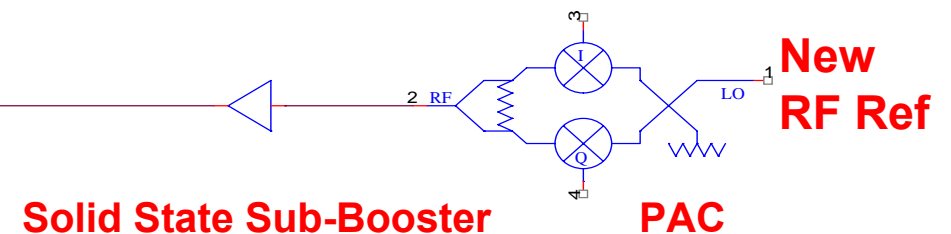


# SLAC Linac RF – New Control



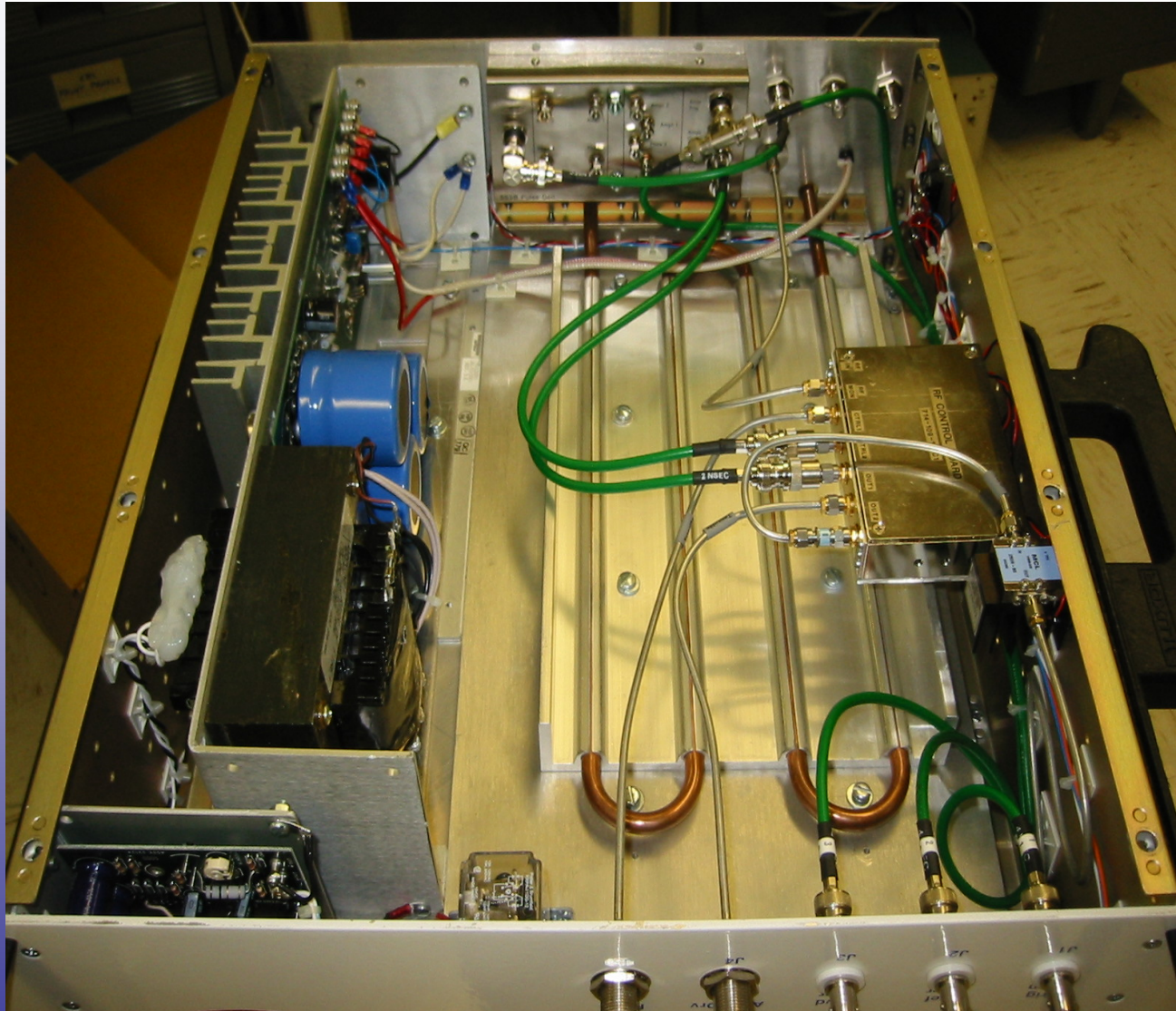
**Existing System**

The **new** control system will tie in to the IPA Chassis with 800W of drive power available. The RF Reference will be from the new RF reference system.



I and Q will be controlled by the PAC chassis, running 16bit DACs at 102MHz. Waveforms to the DACs will be set in an FPGA through a microcontroller running EPICS on RTEMS.

# 1 kW Solid State S-Band Amplifiers



- >800W peak at 2856MHz
- 5 units installed and operational last run
- Added phase noise not measurable
- Trigger comes from Beam Containment System (BCS)  
Need to change to 48V pulse on Twin BNC connector.
- Amplifier module from Microwave Amplifiers Ltd.

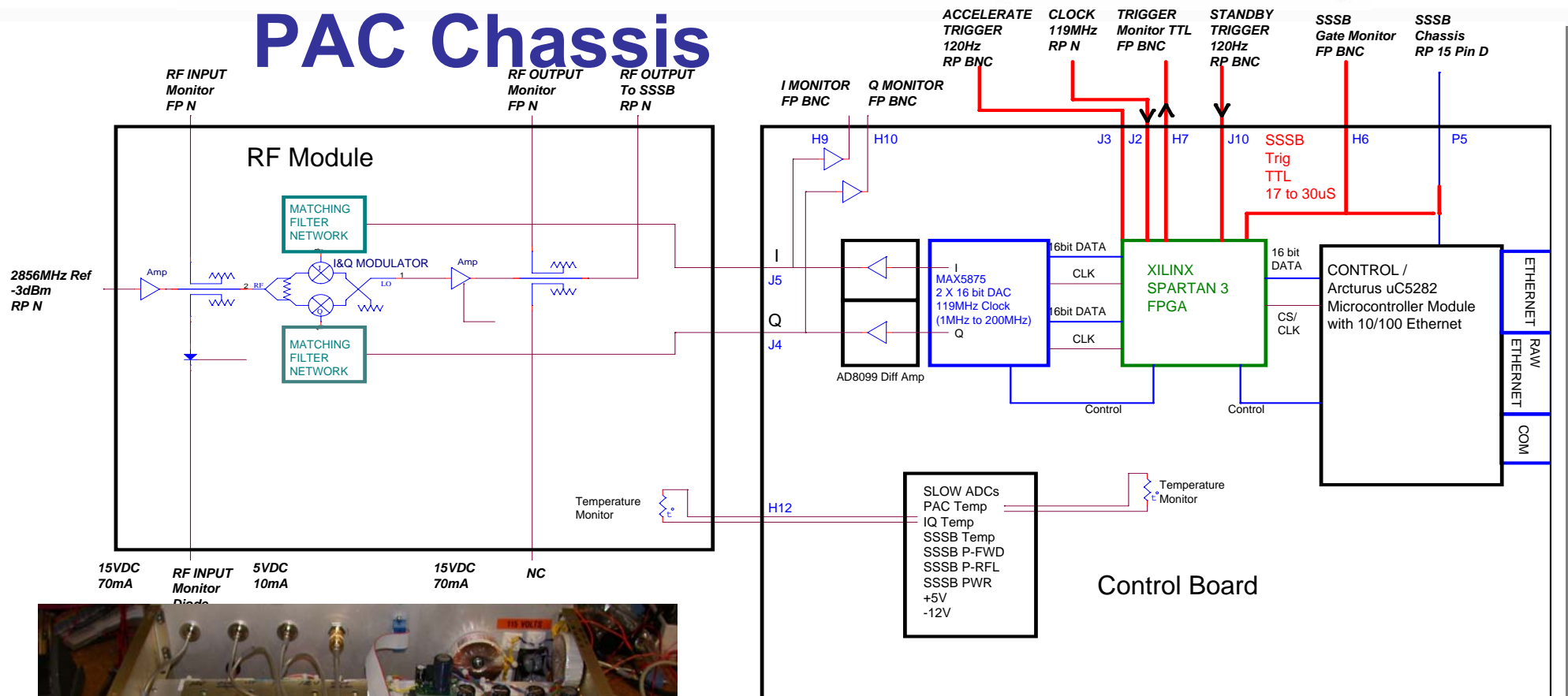
October 30, 2007

FAC

Ron Akre, Dayle Kotturi

[akre@slac.stanford.edu](mailto:akre@slac.stanford.edu), [dayle@slac.stanford.edu](mailto:dayle@slac.stanford.edu)

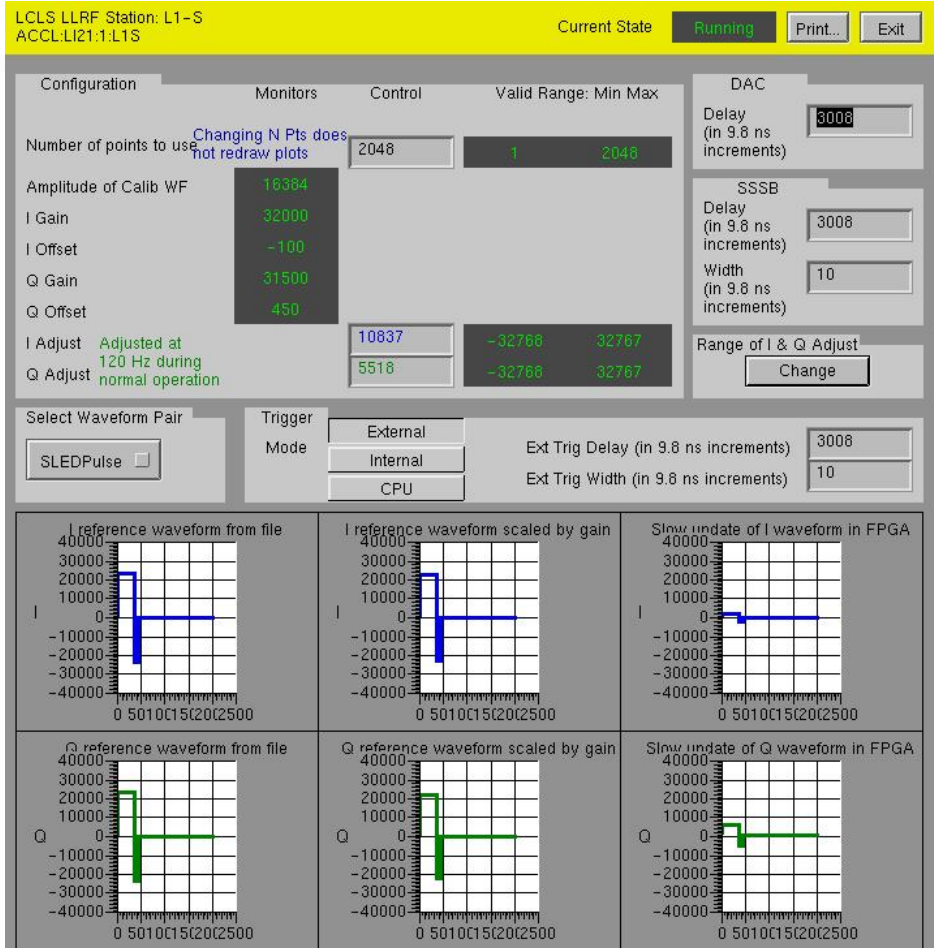
# PAC Chassis



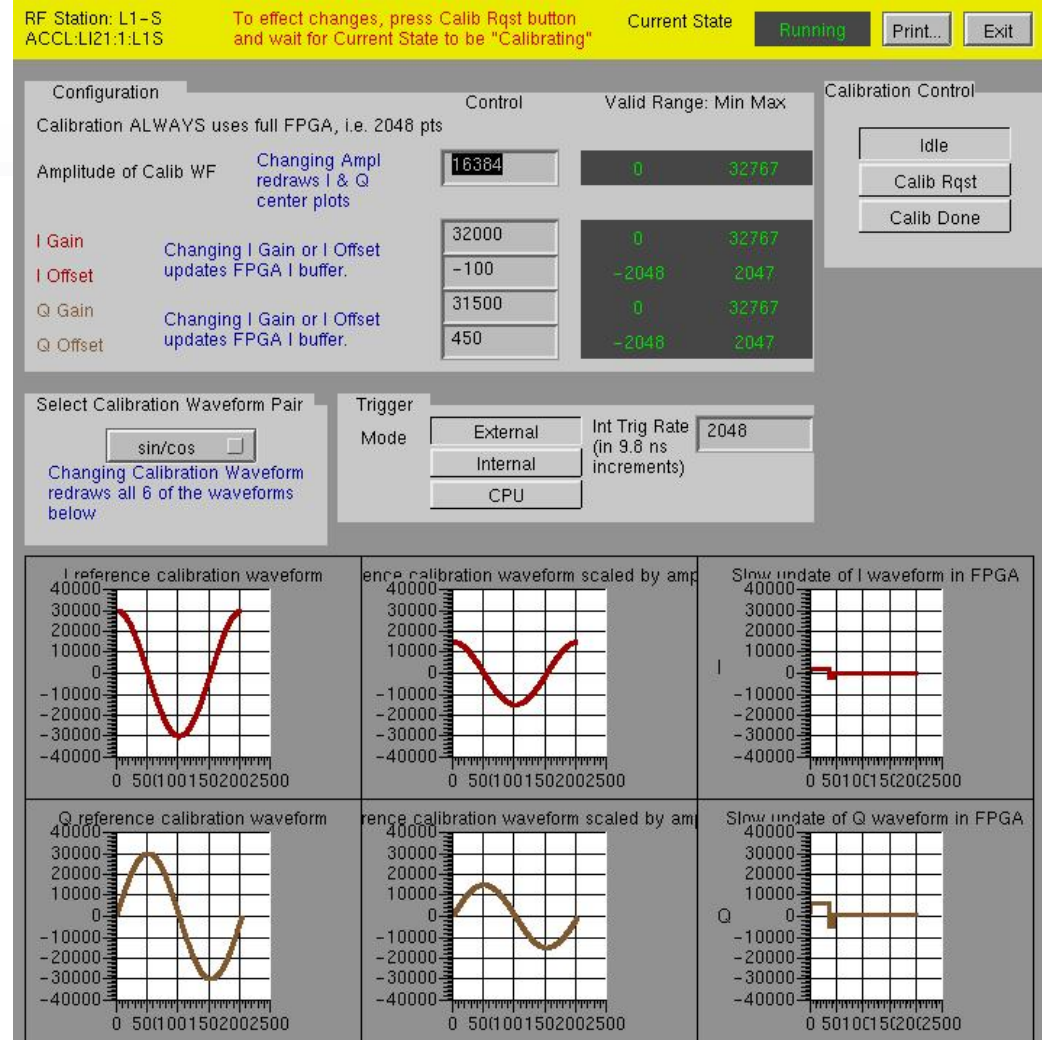
S-Band PAC chassis has an EPICS on RTEMS Coldfire IOC used to load registers and waveform memory on an FPGA. On a trigger the FPGA puts out two 2048 point waveforms which run I and Q inputs on an RF modulator. In calibration mode a single side band modulator is created by sine and cosine waveforms on the I and Q channels.



# PAC IOC EPICS Panels



Operational PAC Panel



Calibration PAC Panel

In operation mode the PAC receives PVs "I Adjust" and "Q Adjust" which are used to transform a preloaded waveform and then load the FPGA. A future upgrade will have the FPGA transform the I and Q waveforms with the loading of 4 matrix elements. In calibration mode the I and Q Offsets are determined to minimize feedthrough in the RF modulator with the gains set to zero. The modulator gains are then set to maximum and then adjusted down to suppress the opposite sideband in a Single Side Band modulator.

October 30, 2007

FAC

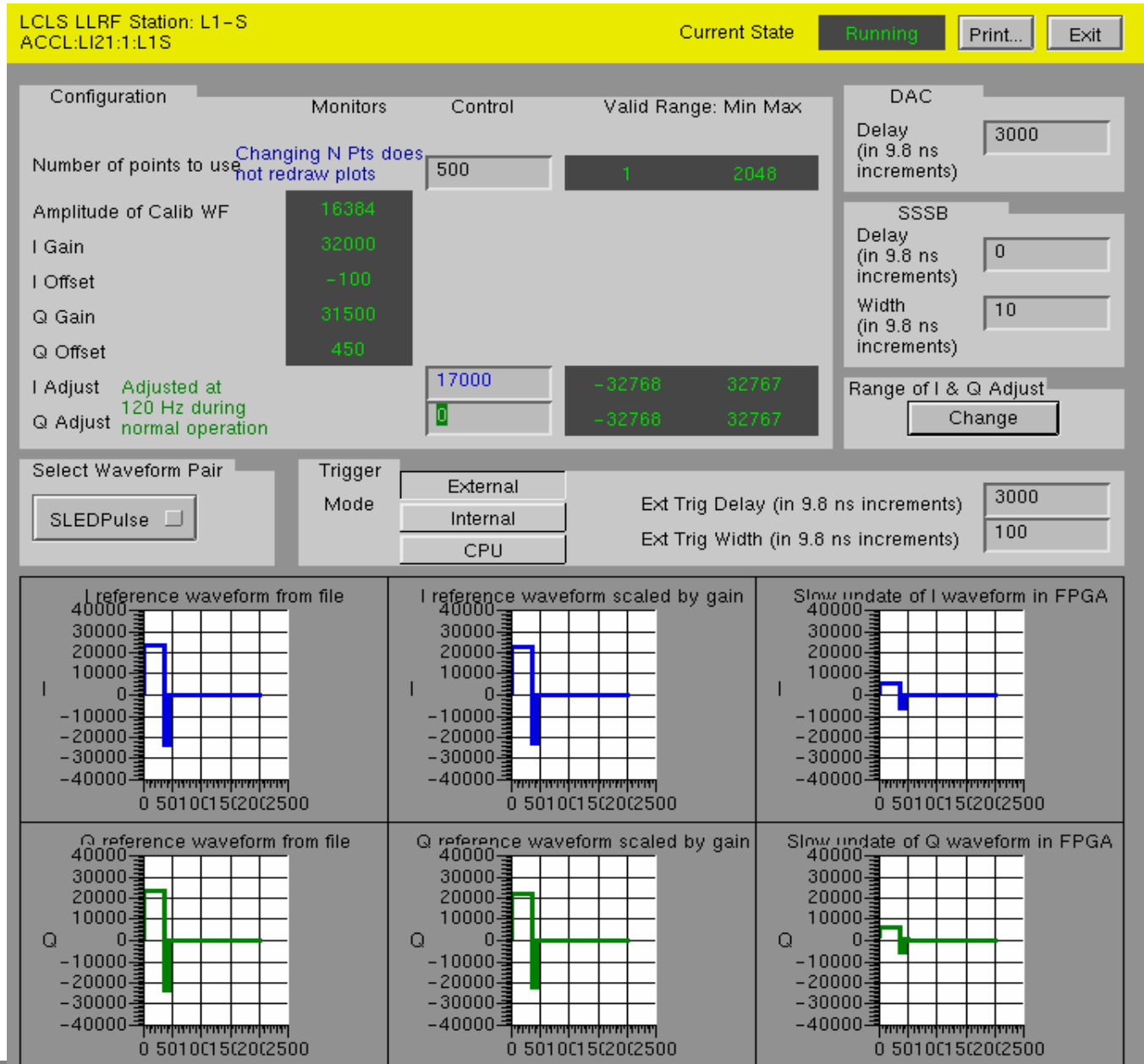
Ron Akre, Dayle Kotturi

[akre@slac.stanford.edu](mailto:akre@slac.stanford.edu), [dayle@slac.stanford.edu](mailto:dayle@slac.stanford.edu)



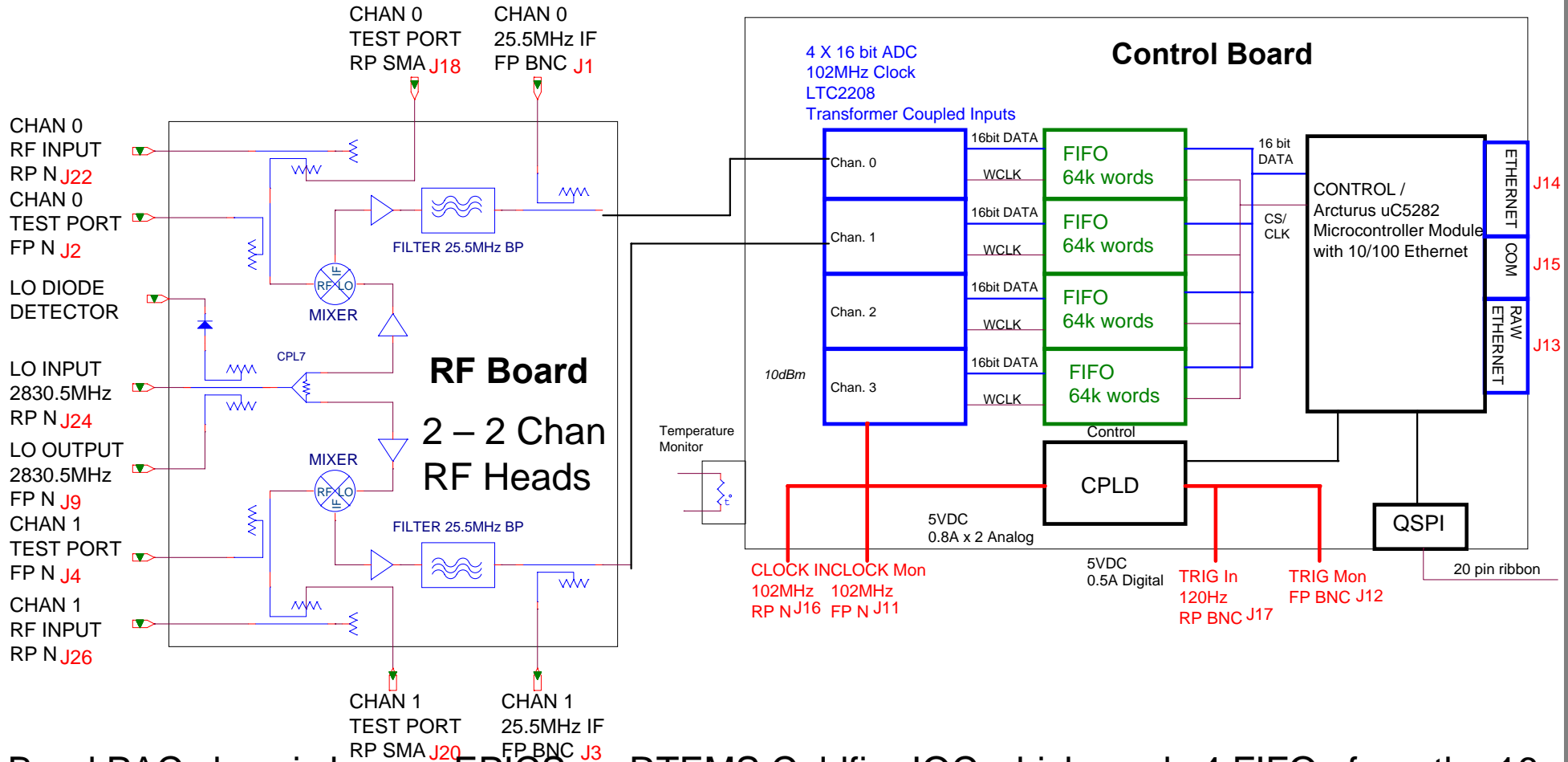
# Operational PACs

- Four Ref. System
- Laser
- Gun
- L0-A
- L0-B
- TCav
- L1-S
- L1-X



# LCLS PAD Chassis

Stanford Linear Accelerator Center  
Stanford Synchrotron Radiation Laboratory



S-Band PAC chassis has an EPICS on RTEMS Coldfire IOC which reads 4 FIFOs from the 16 bit 102MHz ADCs. The 4 channel control board is connected to two RF heads, each of which has 2 channels. The RF is down mixed with the 2830.5MHz LO reference to 25.5MHz IF, which is digitized at 102MHz. The IOC does the down conversion to base band, averages over a specified number of points, up to 512, and the set the EPICS I and Q records.

October 30, 2007

FAC

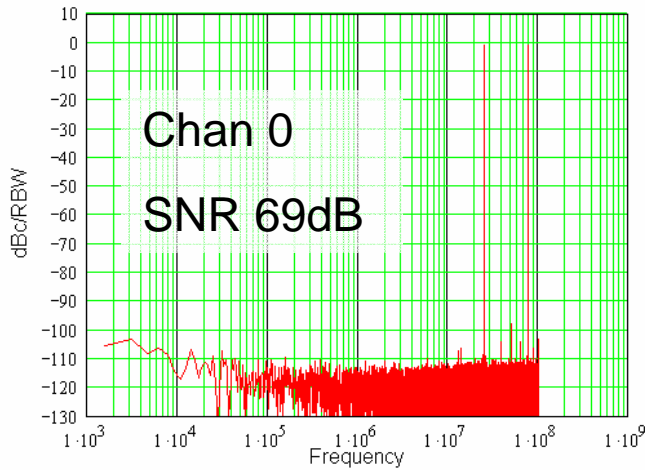
Ron Akre, Dayle Kotturi

[akre@slac.stanford.edu](mailto:akre@slac.stanford.edu), [dayle@slac.stanford.edu](mailto:dayle@slac.stanford.edu)

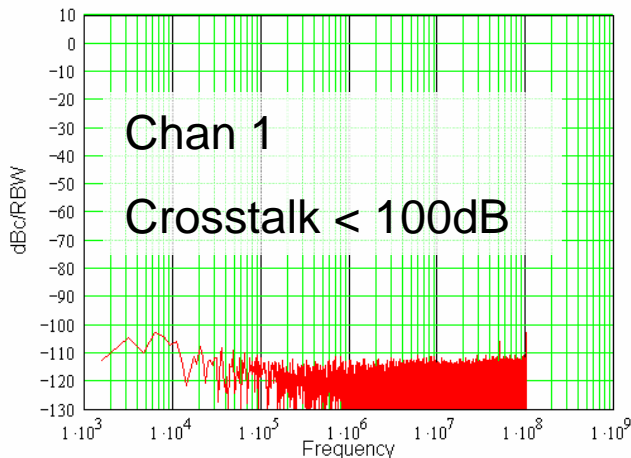




# PAD Testing

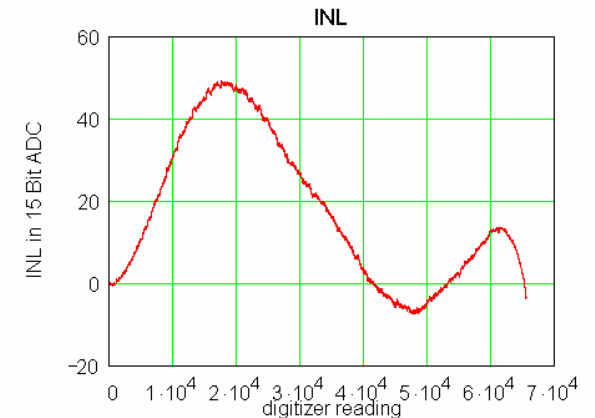
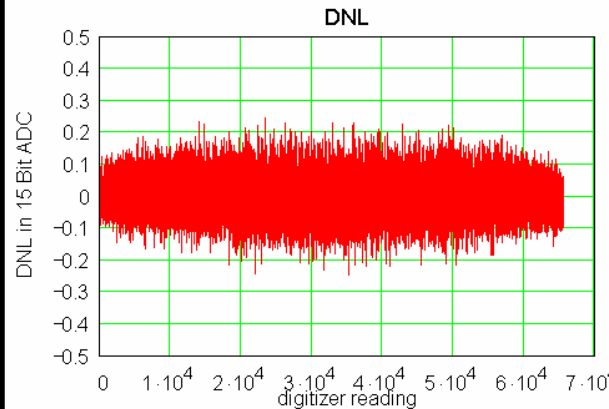
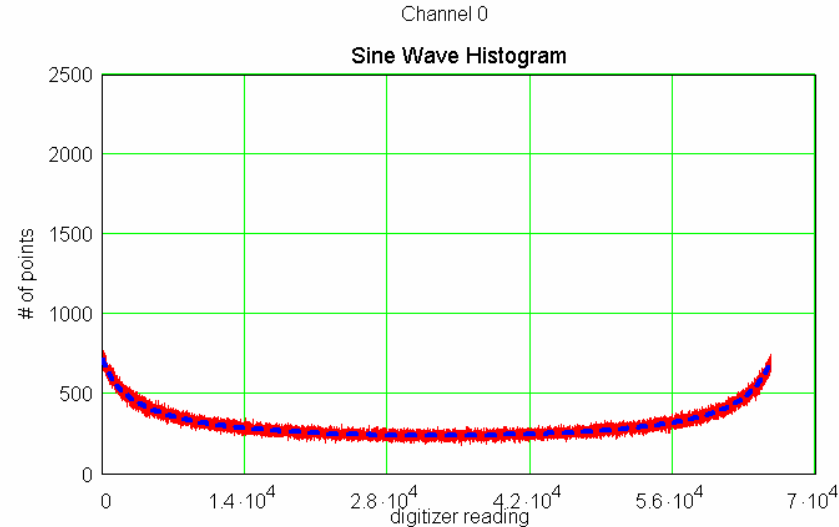


RBW=1556Hz : Channel 0 : Channel 0 signal = +2dBm  
51MHz = -98dBm : Total Noise = -67dBm : Nov 29, 2006



RBW=1556Hz : Channel 1 : Channel 0 signal = +2dBm  
51MHz = -106dBm : Total Noise = -68dBm : Nov 29, 2006

Plots with +2dBm into chan 0.  
16 plots taken per board.



Sine Wave Histogram shows no missing bits and Differential Nonlinearity of  $\pm 0.2$  LSBs. The Integral Nonlinearity is large due to nonlinearities in the function generator used. The lower SNR of 69dB is due mainly to the 4:1 impedance transformers used on both clock and signal inputs.

# PAD IOC EPICS Panel

LCLS LLRF Station: L1-S  
ACCL:LI21:1:L1S

Print... Exit

Configuration	Offset	Total Offset	Window Size	Total Window Size
21-1B RF In	80	80	80	80
21-1B RF Out	160	160	80	80
21-1C RF Out	160	160	80	80
21-1D RF Out	160	160	80	80

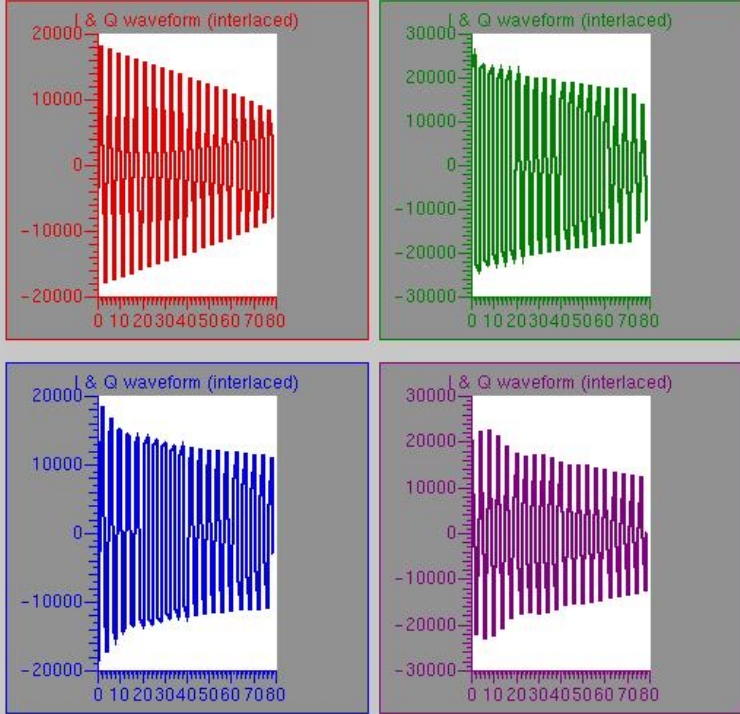
Running vs Calibrating

Operational Mode: **Running**

Calibration Control: Not Calibrating, Calibrating, Done

Current Acquisition	Num	Q avd	I avd
21-1B RF In	80	13351	-2728
21-1B RF Out	80	19438	14410
21-1C RF Out	80	10346	-12976
21-1D RF Out	80	-4897	16703

Raw Waveforms of the Current Acquisition



Temperatures	Ch	deegree C	Slope	Offset
	0	-124.016	0.00021280	-273
	1	-272.957	0.00021280	-273
	2	-272.955	0.00021280	-273
	3	-272.951	0.00021280	-273
	4	-272.956	0.00021280	-273
	5	-272.954	0.00021280	-273
	6	-272.957	0.00021280	-273
	7	-272.957	0.00021280	-273

Status	Value
Interrupts processed	42564858
Scan I/O requests	42564858
Overflows in I	940887
Overflows in Q	21349170

The Coldfire EPICS IOC reads digitized data from 4 FIFOs. A window is set in the data by selecting an offset and window size. The data within the window is down converted to baseband and an average I and Q calculated. The data shown here is from station L1S, a SLED cavity is used to power 3 accelerator structures. Channel 0 is the Input to the B structure, channels 1, 2, and 3 are outputs to the B, C, and D structures.

The temperature monitors are shown here not working, we have more work to do.

# Operational PADs

- Reference System
- Laser
- Gun
- L0 (A&B)
- L1-S
- TCav
- X-Band
- Phase Cavity
- Six Klystron diagnostic

L0 A and B PAD

LCLS LLRF Station: L0 A and B  
ACCL:IN20:350:L0

Configuration	Offset	Total Offset	Window Size	Total Window Size
L0A In	100 = 3 +	103	400	400
L0A Out	0 = 3 +	3	400	400
L0B In	0 = 3 +	3	400	400
L0B Out	0 = 3 +	3	400	400

Current Acquisition	Num	Q avg	I avg
L0A In	400	-1767	-8077
L0A Out	400	-8167	1514
L0B In	400	6358	8883
L0B Out	400	-8245	2179

Ch	deegree C	Slope	Offset
0	13.237	0.00001520	0
1	23.383	0.00021280	-273
2	54.380	0.00021280	-273
3	23.995	0.00021280	-273
4	-272.974	0.00021280	-273
5	-272.974	0.00021280	-273
6	-272.970	0.00021280	-273
7	-272.977	0.00021280	-273

Status	Value
Interrupts processed	1780127
Scan I/O requests	1780127
Overflows in I	3729269
Overflows in Q	2679923

Waveforms of the Current Acquisition

Waveforms of the Current Acquisition

Gun 1 PAD

LCLS LLRF Station: RF GUN  
GUN:IN20:1:GN1

Configuration	Offset	Total Offset	Window Size	Total Window Size
Cell 1A	0 = 3 +	3	400	400
Cell 1B	0 = 3 +	3	400	400
Cell 2A	0 = 3 +	3	400	400
Cell 2B	0 = 3 +	3	400	400

Current Acquisition	Num	Q avg	I avg
Cell 1A	400	-9998	-3009
Cell 1B	400	-1	-6

Waveforms of the Current Acquisition

Waveforms of the Current Acquisition



# VME Based Feedback IOC

LCLS LLRF Station: L1-S  
ACCL:LI21:1:L1S

Klystron 21-1 Diagnostics

Home Screen...

Exit

Current Acquisition

	21-1B RF In	21-1B RF Out	21-1C RF Out	21-1D RF Out	Total Weight any value > 0 ok
I Average from PAD	-2775.0	14320.0		16726.0	
Q Average from PAD	13344.0	19509.0	10279.0	-4812.0	
Actual Phase + offset (deg 2856 MHz)	20.6	19.8	20.2	19.5	
Phase Weighting	0.500	0.167	0.167	0.167	1.0
Actual Amplitude * scale factor (MV)	133.1	127.0	136.6	145.4	
Amplitude Weighting	0.500	0.167	0.167	0.167	1.0
Actual Power * scale factor (MW)	32.7	68.5	46.0	23.3	

Phase (deg 2856 MHz)

Limit Correction to:  $0.0 < \text{abs}(20.00 - 20.2) < 5.0$

New set point:  $27.1 = 0.400 \times (\text{signed clamped correction}) + 27.1$

Limit Set Point to:  $-360.0 < \text{Set Point} < 360.0$

Local Phas FB:  ON

If Local Phas FB is off OR  
Ampl below minimum threshold,  
Previous Set Point is sent  
every time PAD is triggered

Amplitude (MV), > 0

Limit Correction to:  $0.001 < (134.651 / 134.688) < 10.000$

New set point:  $12160.0 = (1 + 0.400) \times (\text{clamped correction} - 1) \times 12161.3$

Limit Set Point to:  $100.0 < \text{Set Point} < 24720.0$

Local Ampl FB:  ON

If Ampl Phas FB is off OR  
Ampl below minimum threshold,  
Previous Set Point is sent  
every time PAD is triggered

Minimum Ampl reqd for BOTH Phas and Ampl FBs: 10.000

Expert panels

L1-S PAD (source)

Adjust scale factors & offsets

Global Feedback Status for L1:  OFF

I adjust =  $A_{set} \times \cos P_{set} \times \text{Scale}$   
 $= 12160.0 \times \cos 27.1 \times 1.000$   
 $= 10829.5$

Q adjust =  $A_{set} \times \sin P_{set} \times \text{Scale}$   
 $= 12160.0 \times \sin 27.1 \times 1.000$   
 $= 5530.5$

Sending I and Q adjust to PAC:  Enabled

Expert panels

L1-S PAC (destination)

L1-S PAC Calibration

VME based feedback IOC takes data from the PAD I and Q PVs. The I and Q PVs are transformed to phase and amplitude. The phase has a phase offset applied to align 0 phase with peak acceleration and the amplitude has a scale factor applied to read in electron energy gain on crest. The feedback used a weighted average of the 4 PAD channels to determine a phase and amplitude value for the 2 separate feedbacks. After feedback corrections are done the phase and amplitude are converted to I and Q and the new values sent to the PAD.

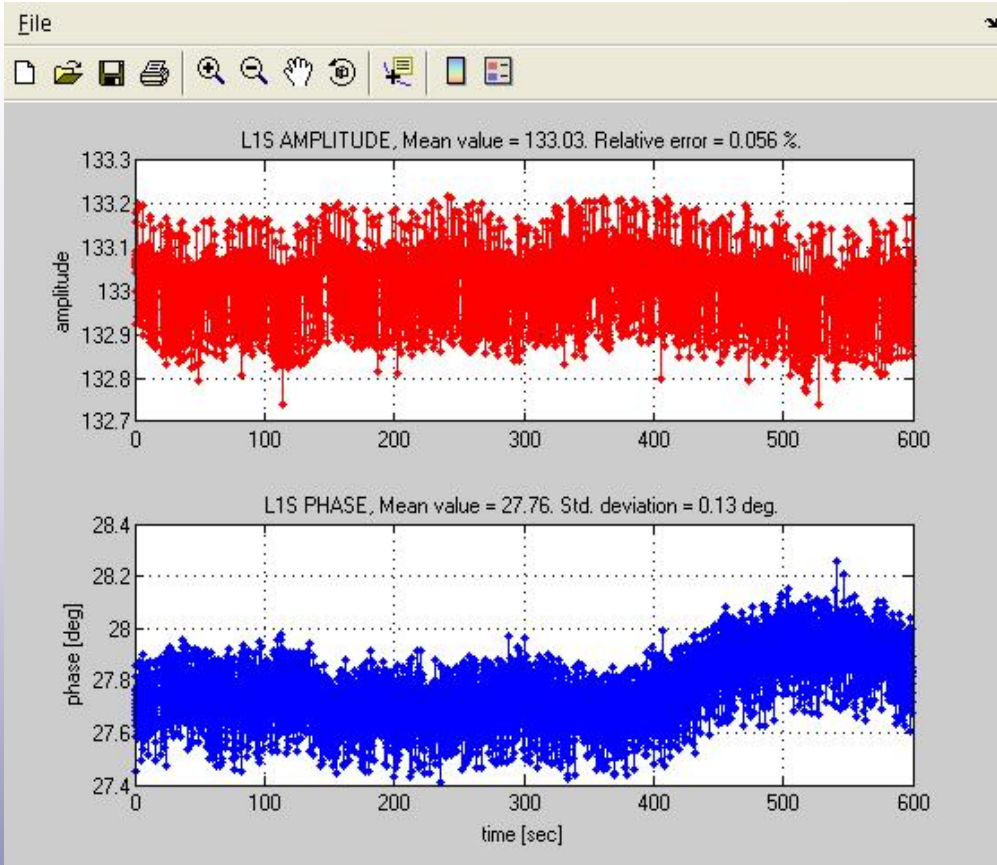
Dayle Kotturi



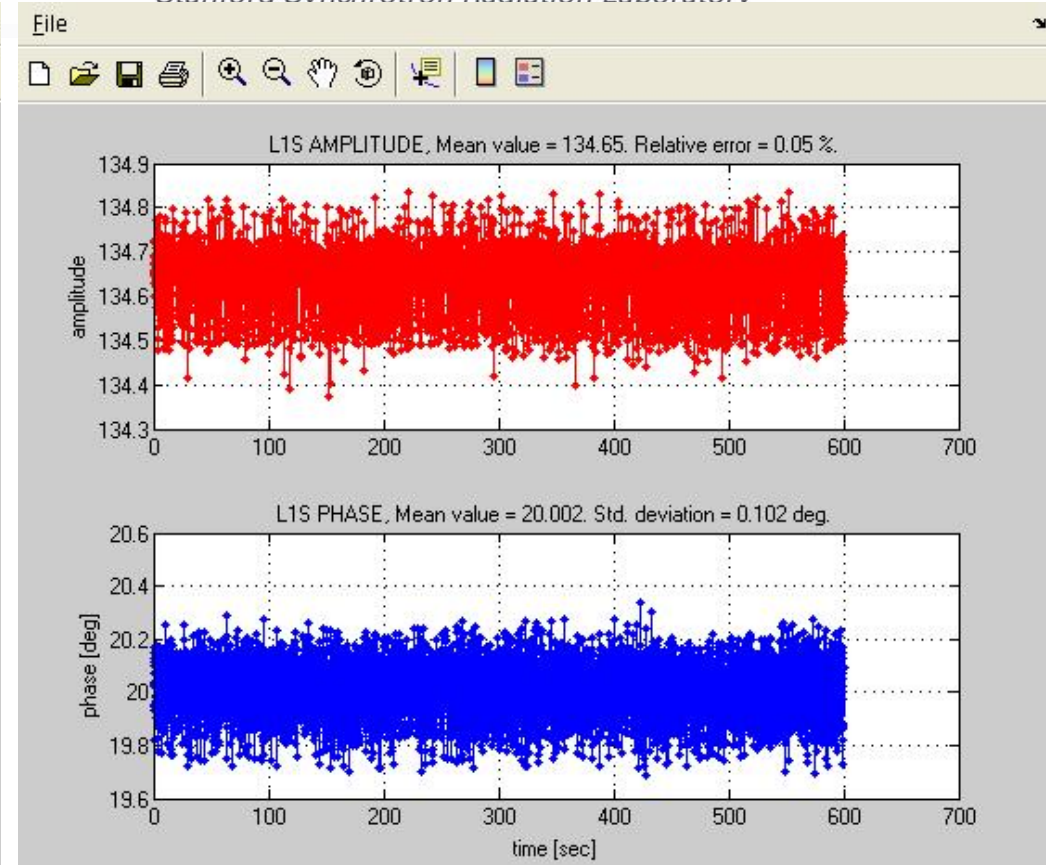
# L1S Stability

Stanford Linear Accelerator Center

Stanford Synchrotron Radiation Laboratory



Feedback Off, 10 Minutes, 0.056%, 0.13°



Feedback On, 10 Minutes, 0.050%, 0.102°

L1S Meets Jitter Specifications (0.1% 0.1°) for 10 minutes with feedback on. **All stations except X-Band met specifications consistently near the end of the run.** The above data was taken with Matlab routines reading the EPICS records from the VME based feedback.

October 30, 2007

FAC

Ron Akre, Dayle Kotturi

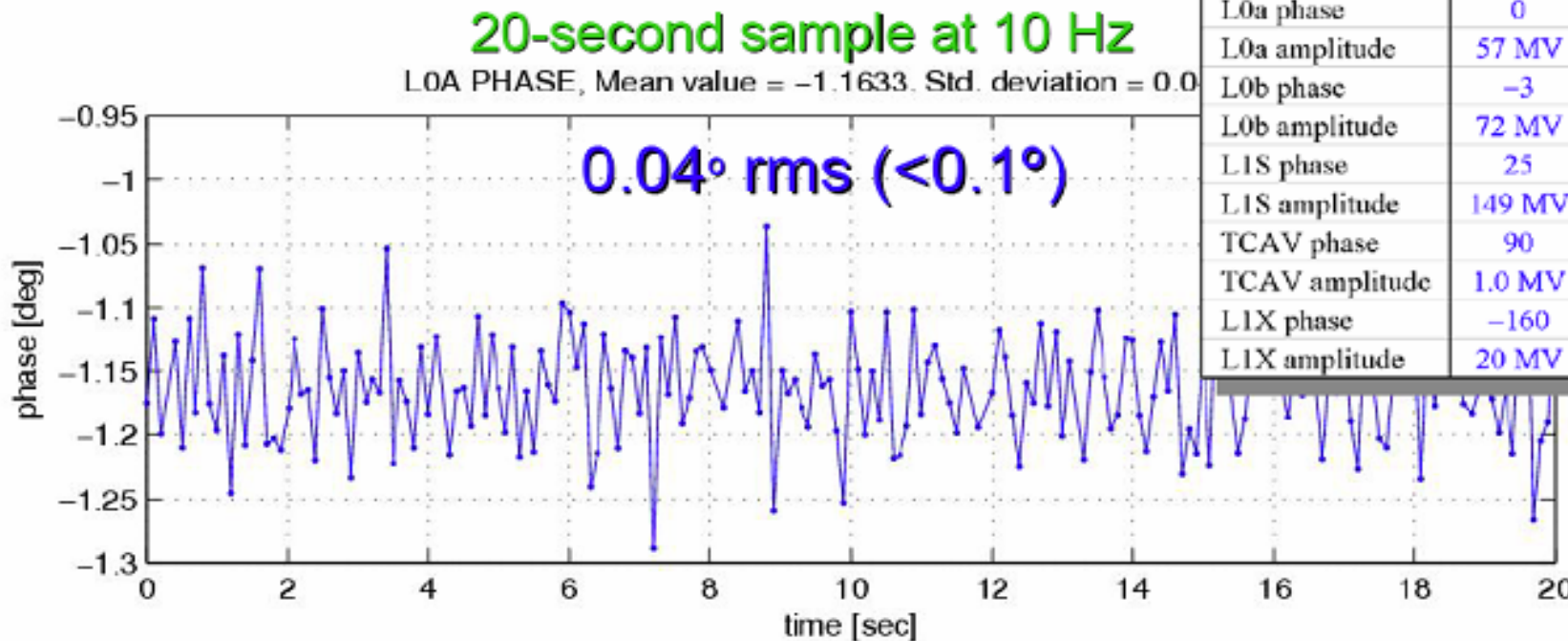
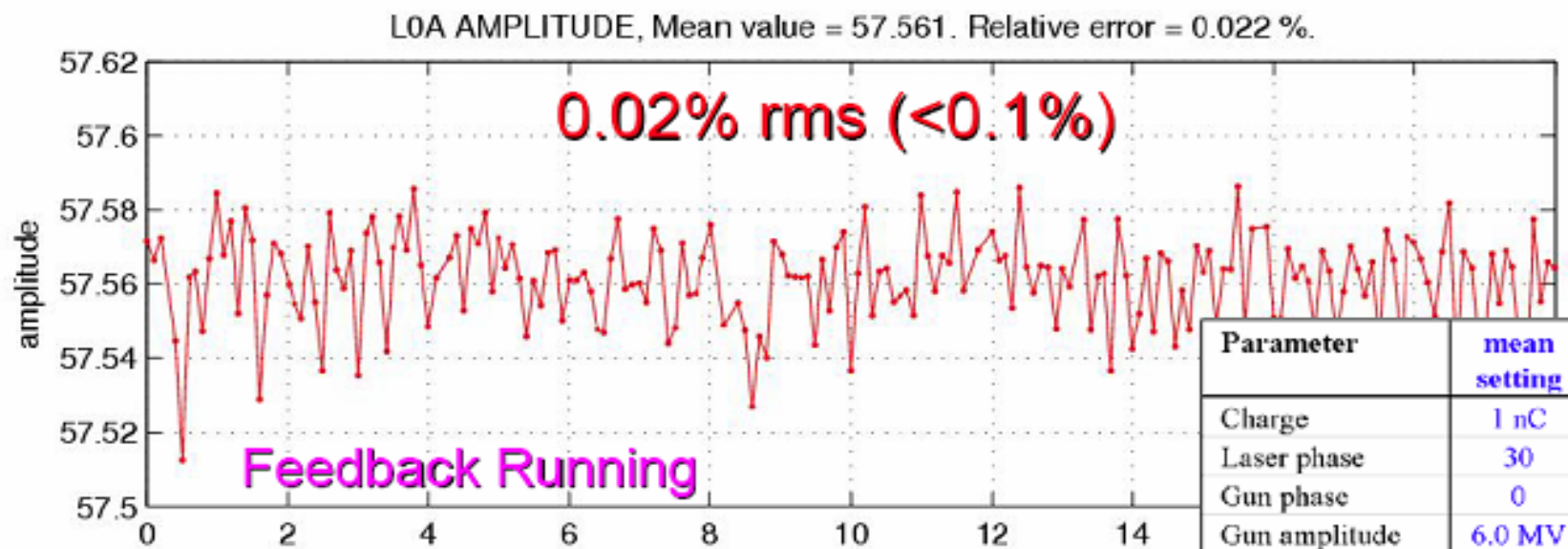
[akre@slac.stanford.edu](mailto:akre@slac.stanford.edu), [dayle@slac.stanford.edu](mailto:dayle@slac.stanford.edu)





# RF Phase and Amplitude Stability (L0a)

New RF systems meet jitter tolerances (that day)



Parameter	mean setting	rms tol.	rms meas.	unit
Charge	1 nC	2	1.1	%
Laser phase	30	0.5	0.2	degS
Gun phase	0	0.1	0.03	degS
Gun amplitude	6.0 MV	0.1	0.02	%
L0a phase	0	0.1	0.04	degS
L0a amplitude	57 MV	0.1	0.02	%
L0b phase	-3	0.1	0.08	degS
L0b amplitude	72 MV	0.1	0.03	%
L1S phase	25	0.1	0.09	degS
L1S amplitude	149 MV	0.1	0.06	%
TCAV phase	90	0.5	0.3	degS
TCAV amplitude	1.0 MV	0.5	0.2	%
L1X phase	-160	0.5	0.3	degX
L1X amplitude	20 MV	0.5	0.2	%

Emma



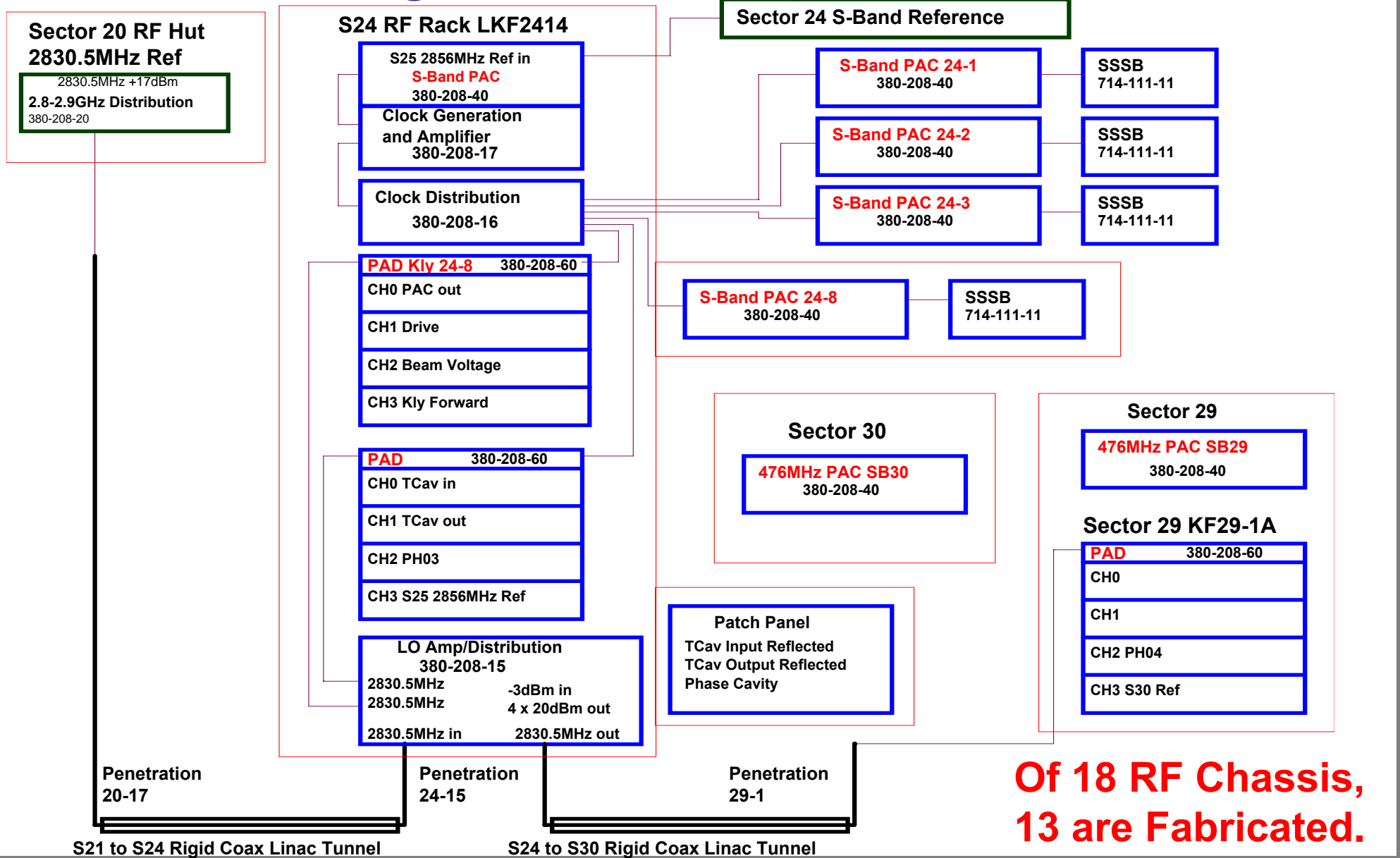


# LCLS RF System Remaining Tasks

Turn On December 2007 – 4 weeks

- Control of 3 RF stations for L2
- Two Sector Controls (16 RF stations) for L3
- Transverse Cavity Control
- Phase Reference Line in Tunnel (8 Sectors)
- Two Beam Phase Cavities
- Modifications to 4 SSSB Chassis for new BCS
- New Phase Locked Oscillator under design for Injector
- Software for all above systems

# Block Diagram LCLS RF System L2 and L3



**Of 18 RF Chassis,  
 13 are Fabricated.**

## LLRF Software Tasks

- To be completed before next run begins
  - Migration of code installation (from afs to nfs)
  - Addition of private ethernet for PAD->VME and VME->PAC traffic
  - Sector 24 PACs software
  - L2 TCav software
  - L2 Phase cavity software
- To be completed during next run
  - Laser upgrade commissioning
  - L2 commissioning of RF systems
  - L2 longitudinal feedback commissioning



## LCLS LLRF Summary

- Will have most hardware installed by February 08.
- Software development is ongoing.
- Beam synchronous acquisition and 120Hz feedback efforts will continue through the run. This is the largest effort remaining in the LLRF system.
- Need new type of X-Band Sub-Booster to drive klystron.
  - Will be looking at NLC design TWTs and solid state
- The above work completes the LCLS LLRF system.