Linac Coherent Light Source (LCLS)

Low Level RF Status

2007 LLRF Workshop
Knoxville, TN

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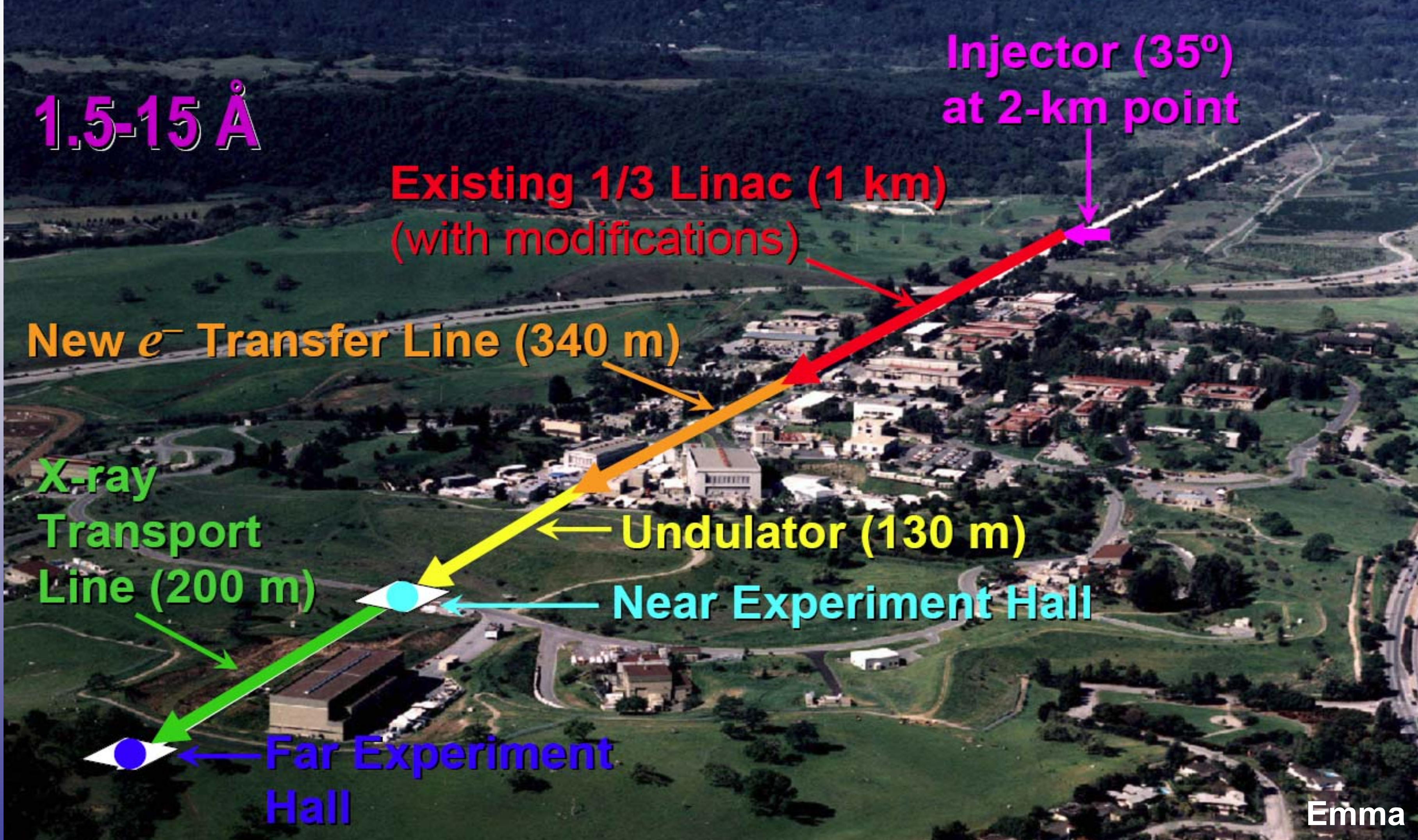
Linac Coherent Light Source at *SLAC*

X-FEL based on last 1-km of existing linac



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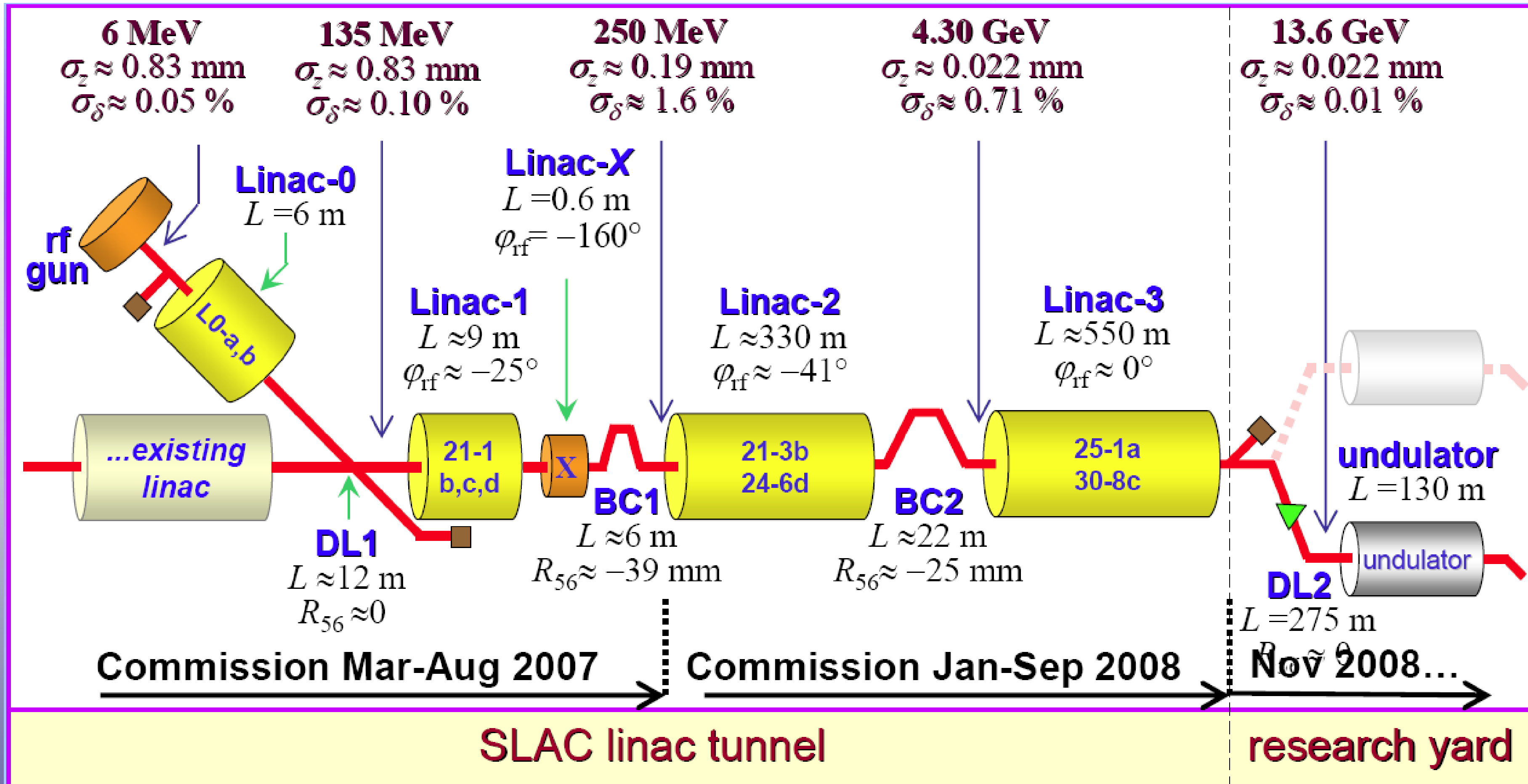
Stanford Linear Accelerator Center

SSRL



X-rays in spring 2009

Emma

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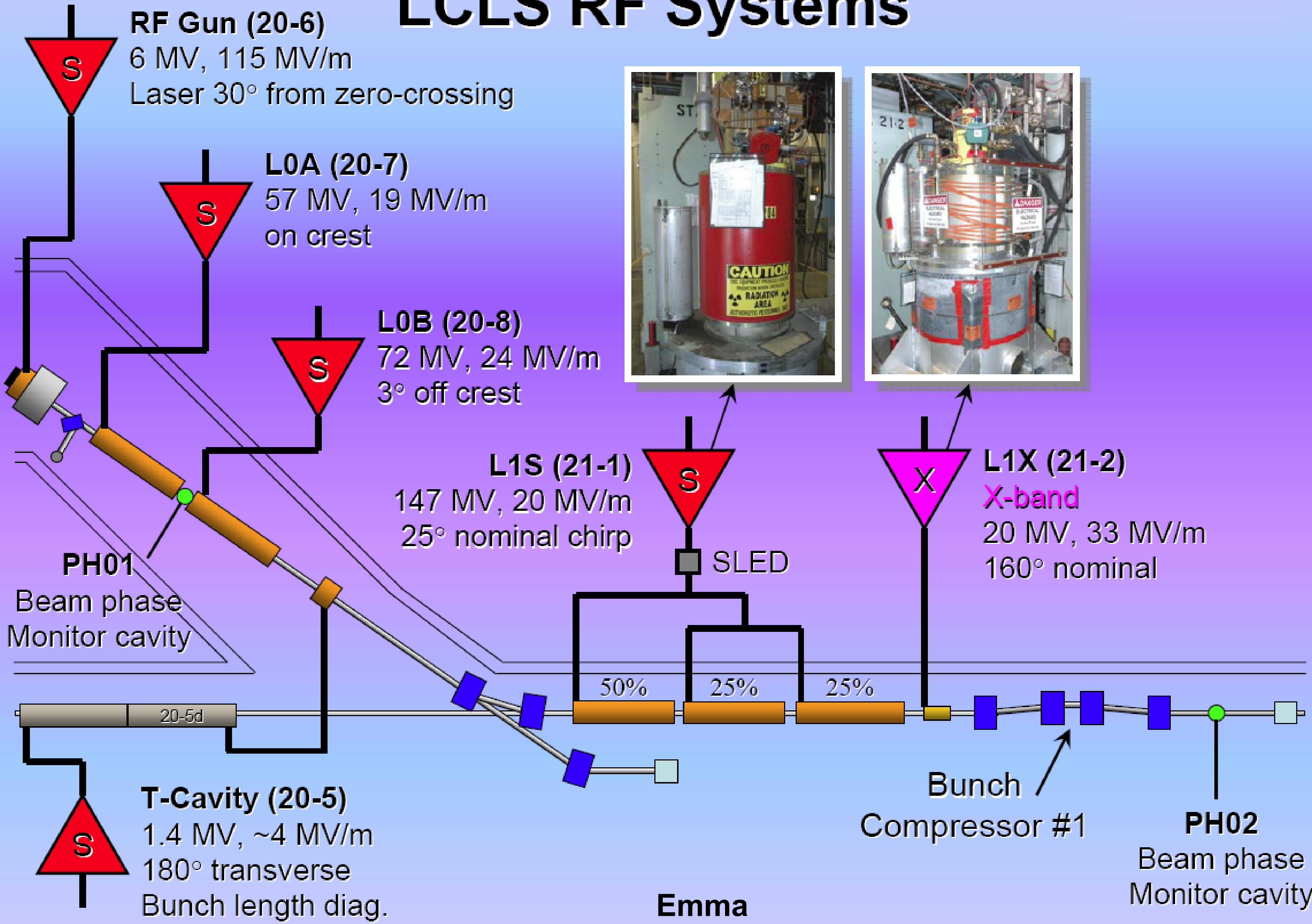
LCLS RF Systems



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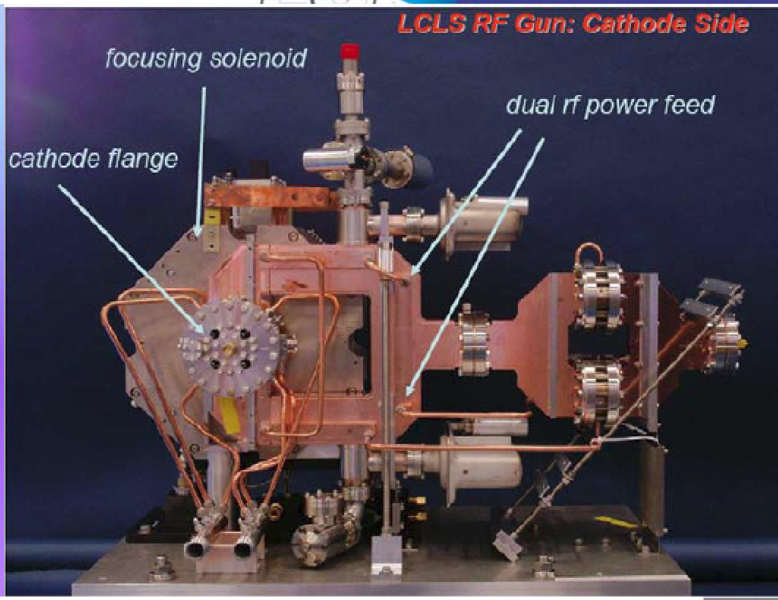
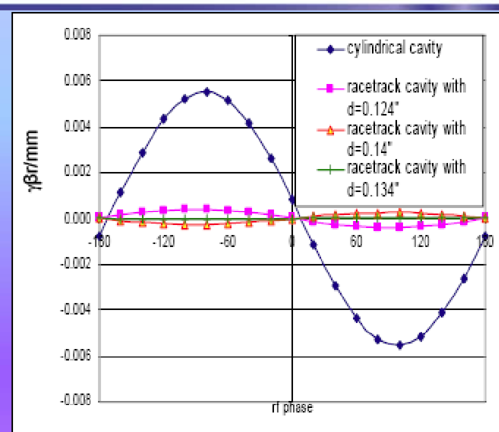
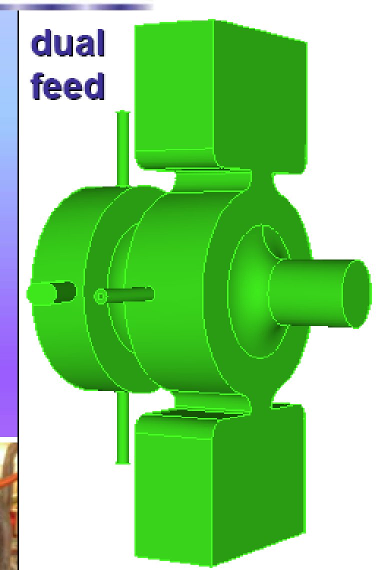
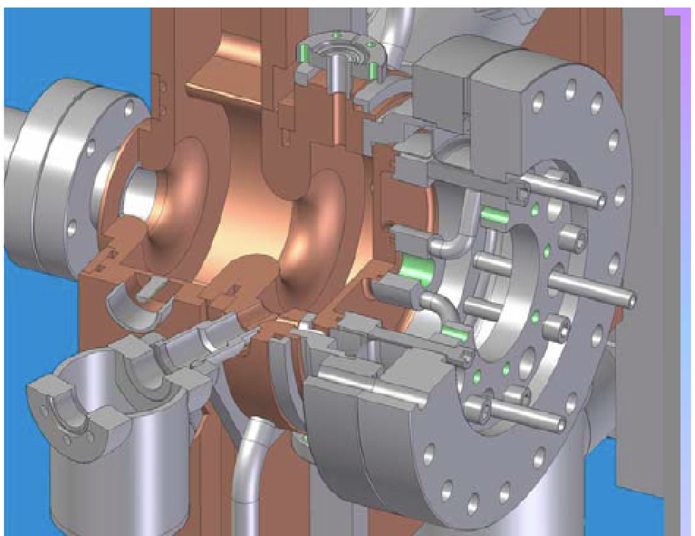
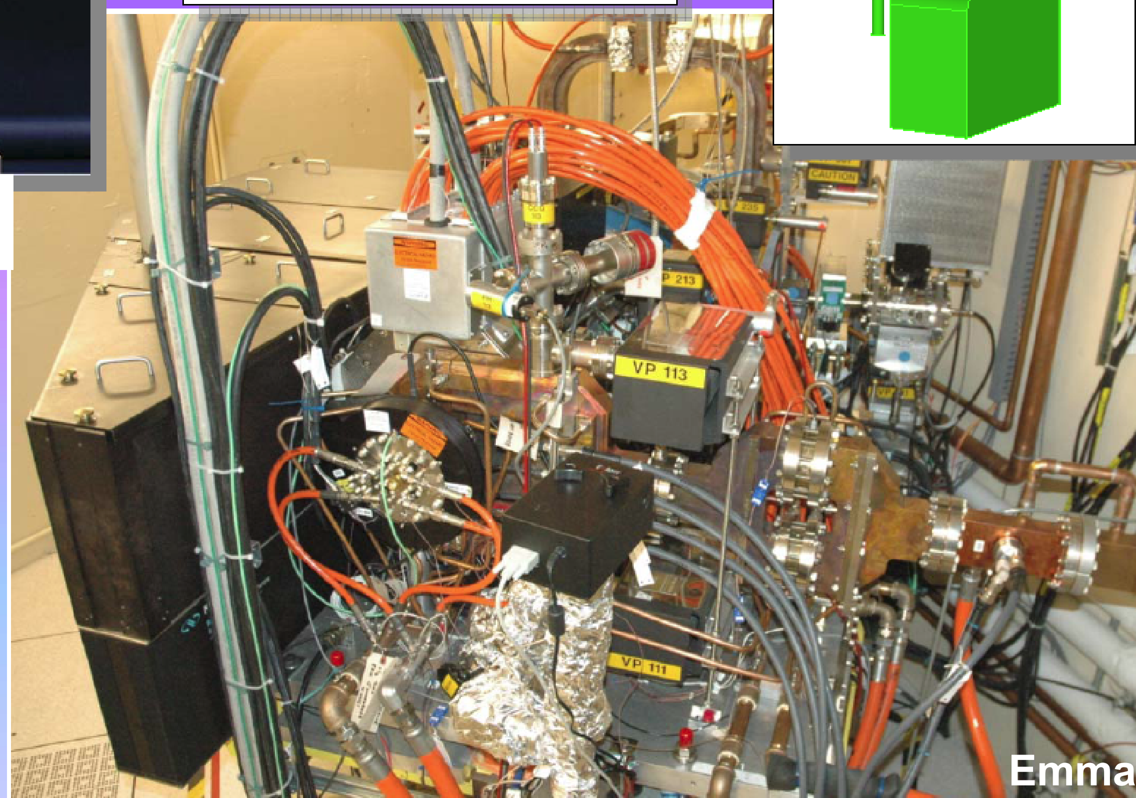






SLAC Designed RF Gun





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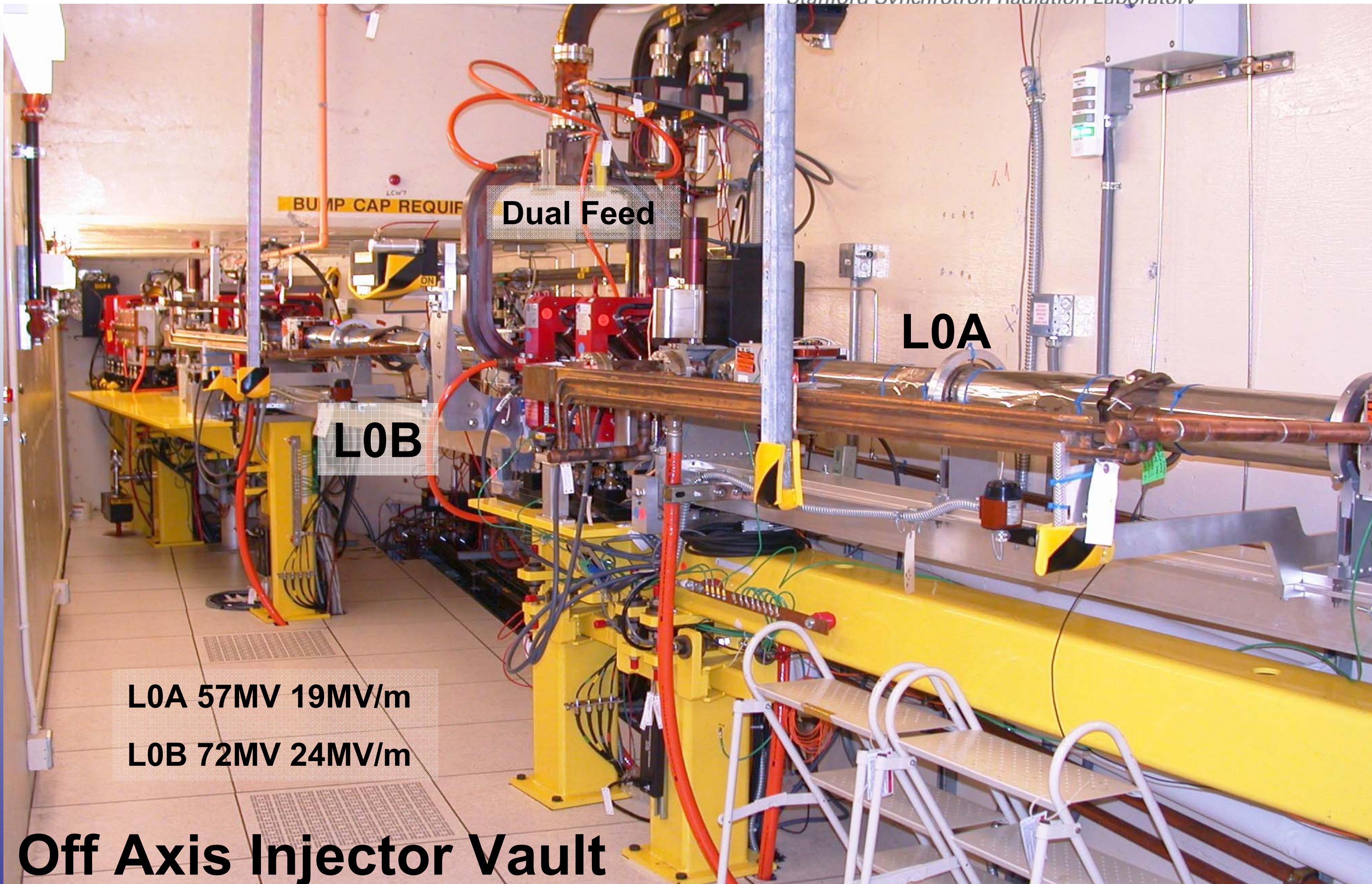

Off Axis Injector Vault

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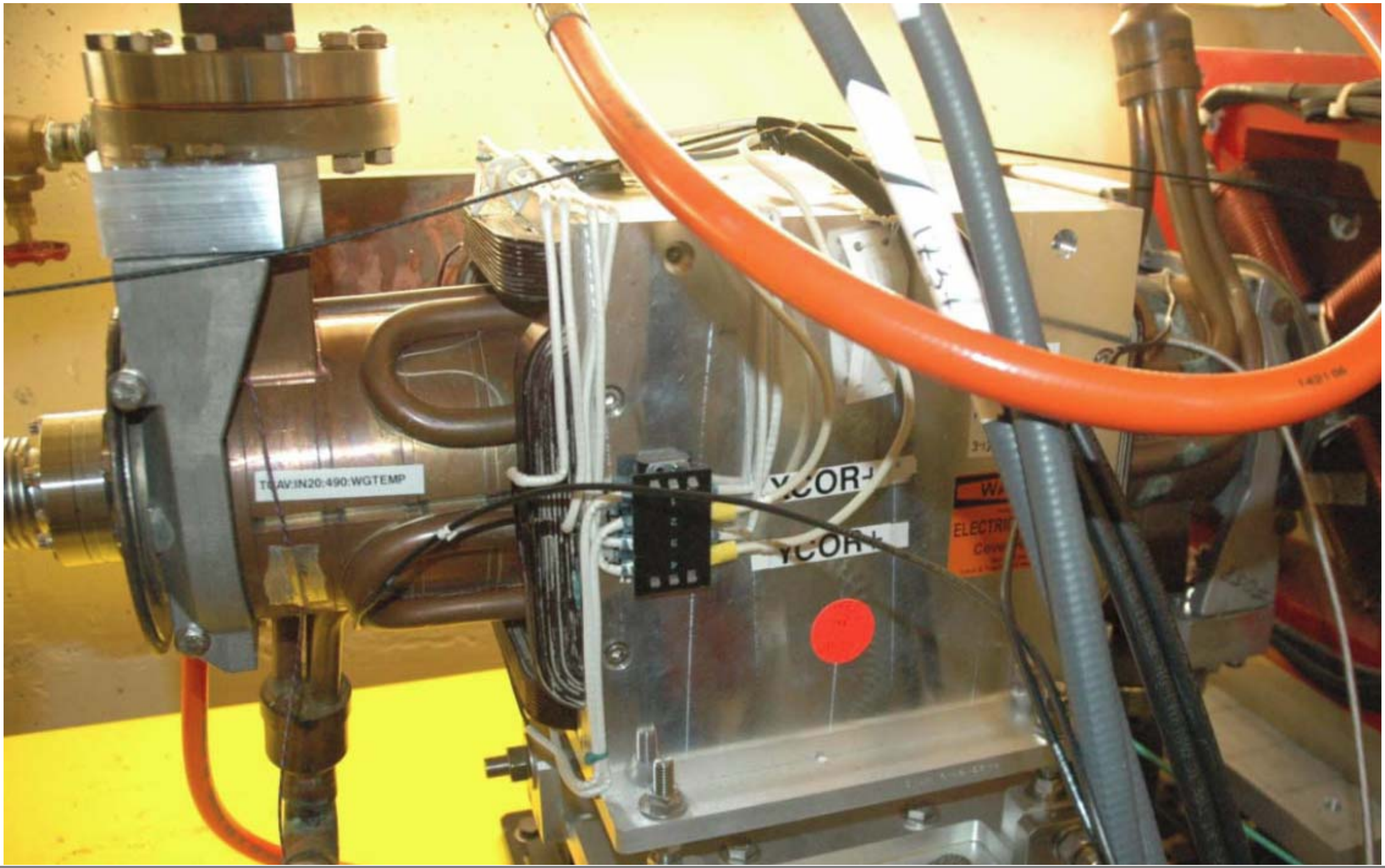
Injector Transverse Accelerator 55cm 1MV

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.



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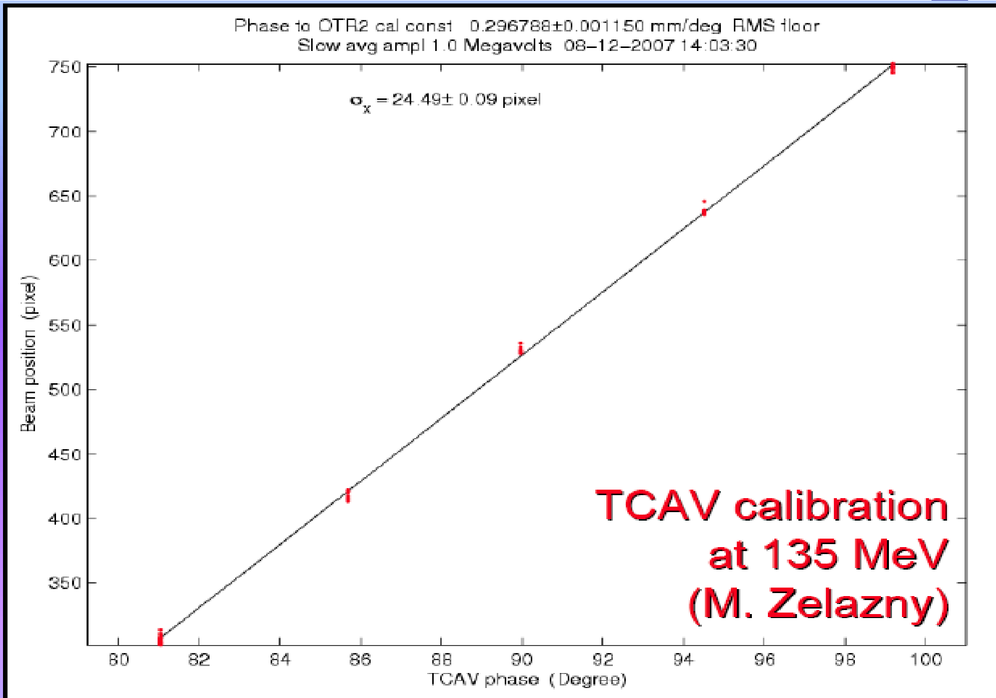
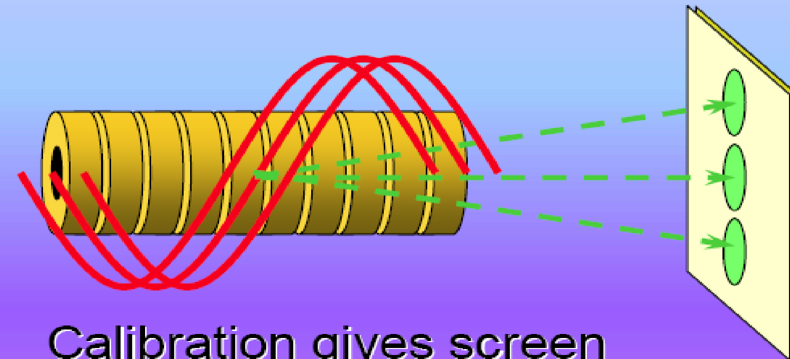
Calibration to Degrees of S-Band



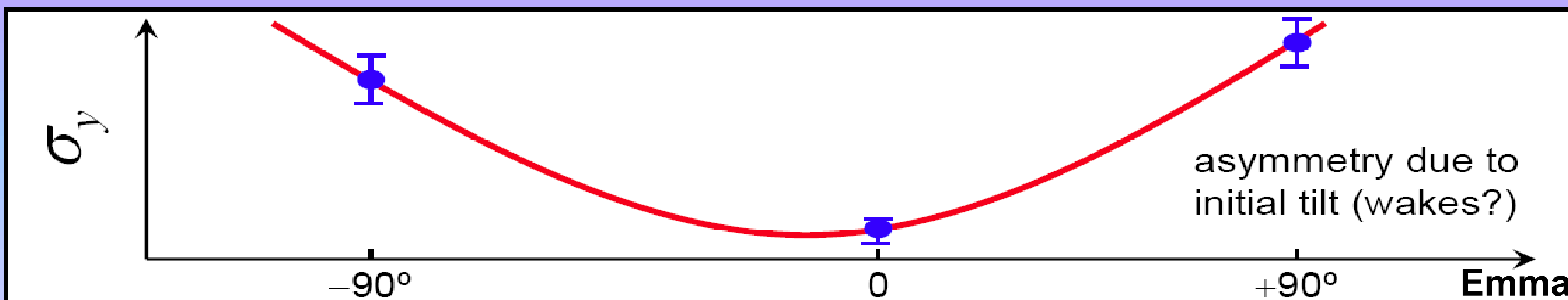


Calibration gives screen pixels per deg-S (P. Krejcik)

Now measure beam size at:

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

Fit beam-size data to parabola…



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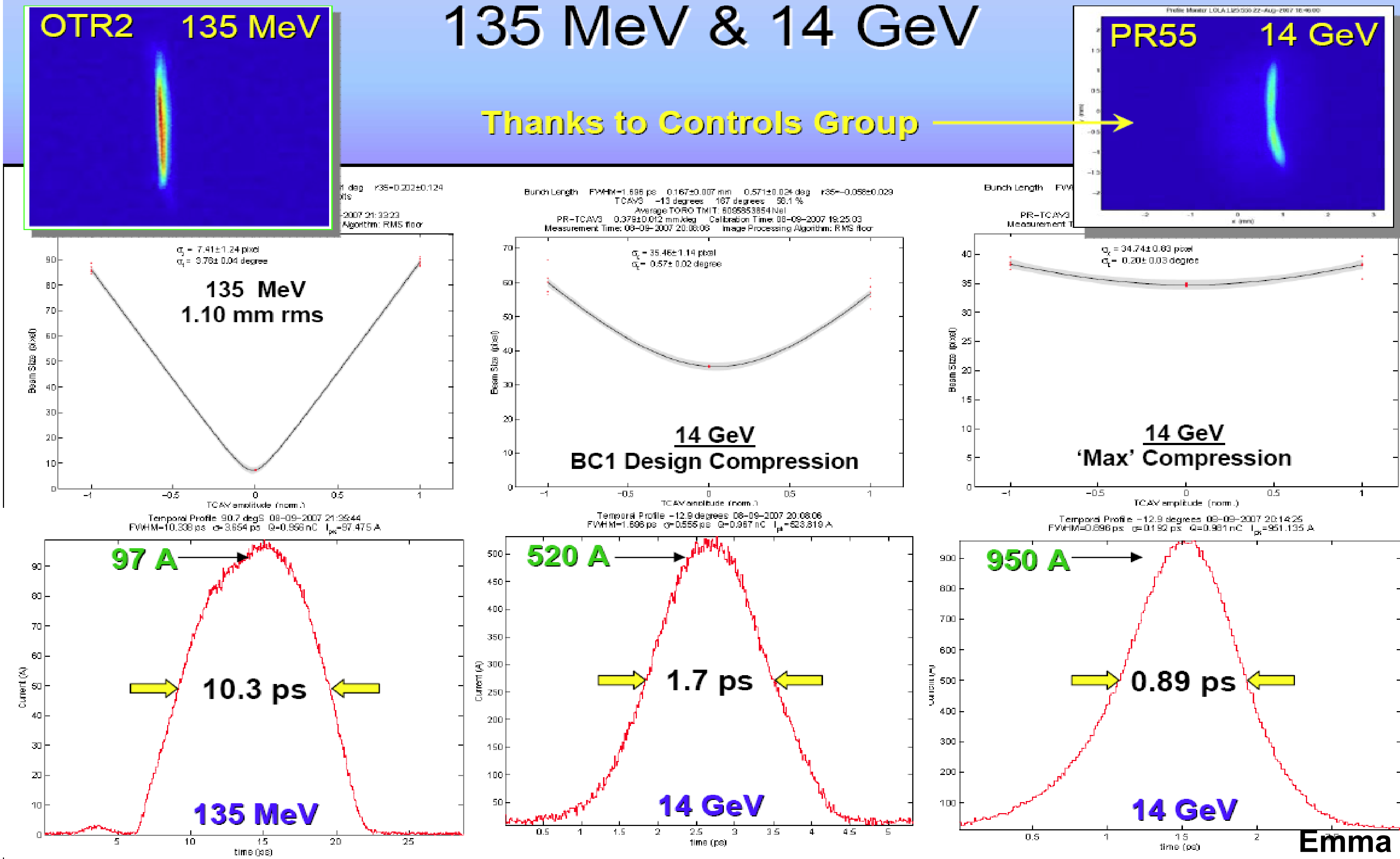
Bunch Length Measurements

Stanford Linear Accelerator Center

Stanford Synchrotron Radiation Laboratory

135 MeV & 14 GeV



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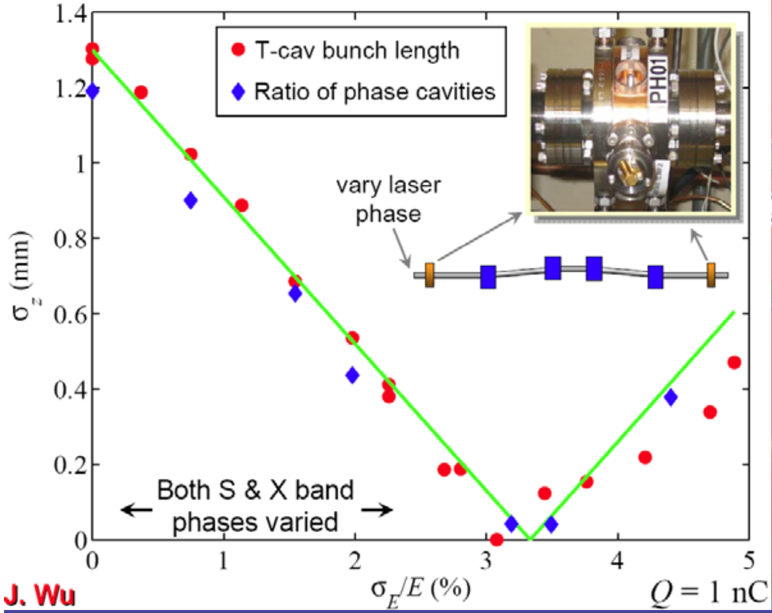
Beam Phase Cavity

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

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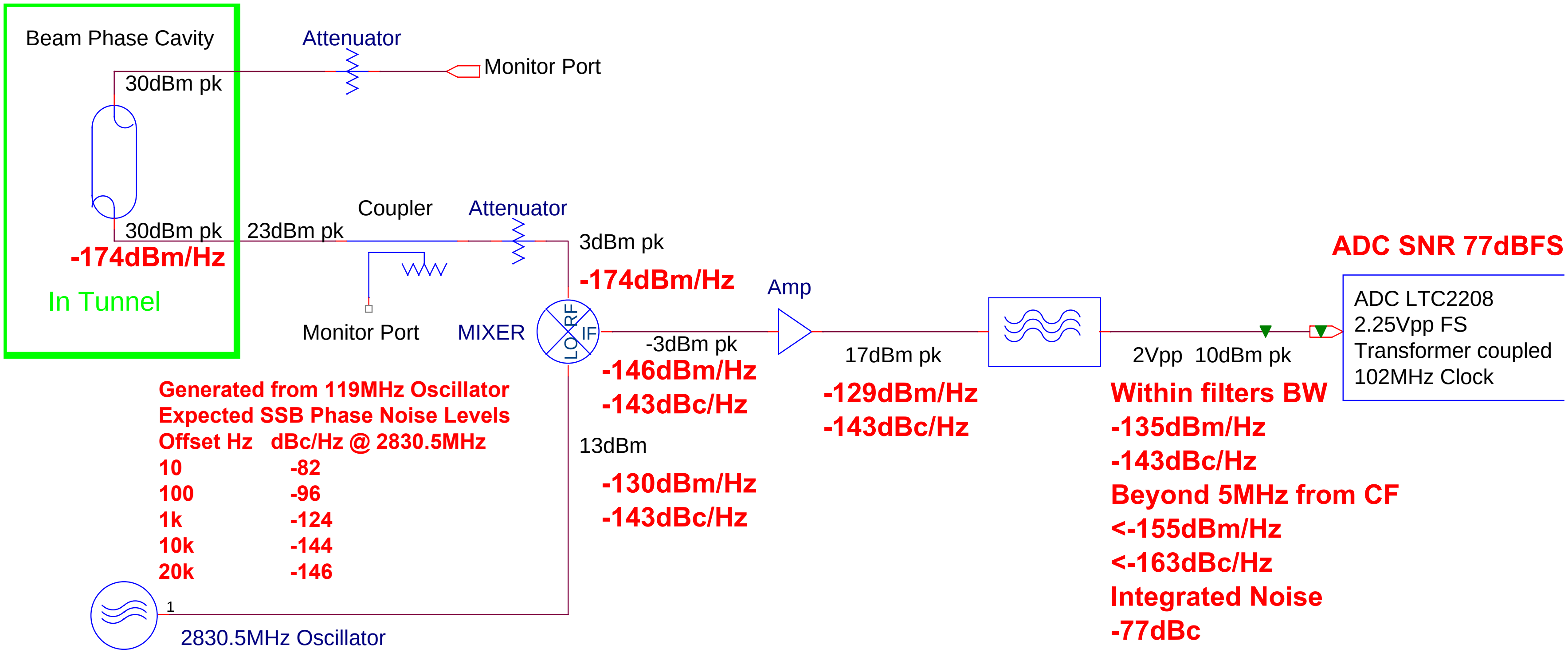
Beam Phase Cavity
Critical Noise Levels and Bandwidths



October 22, 2007
LLRF Workshop

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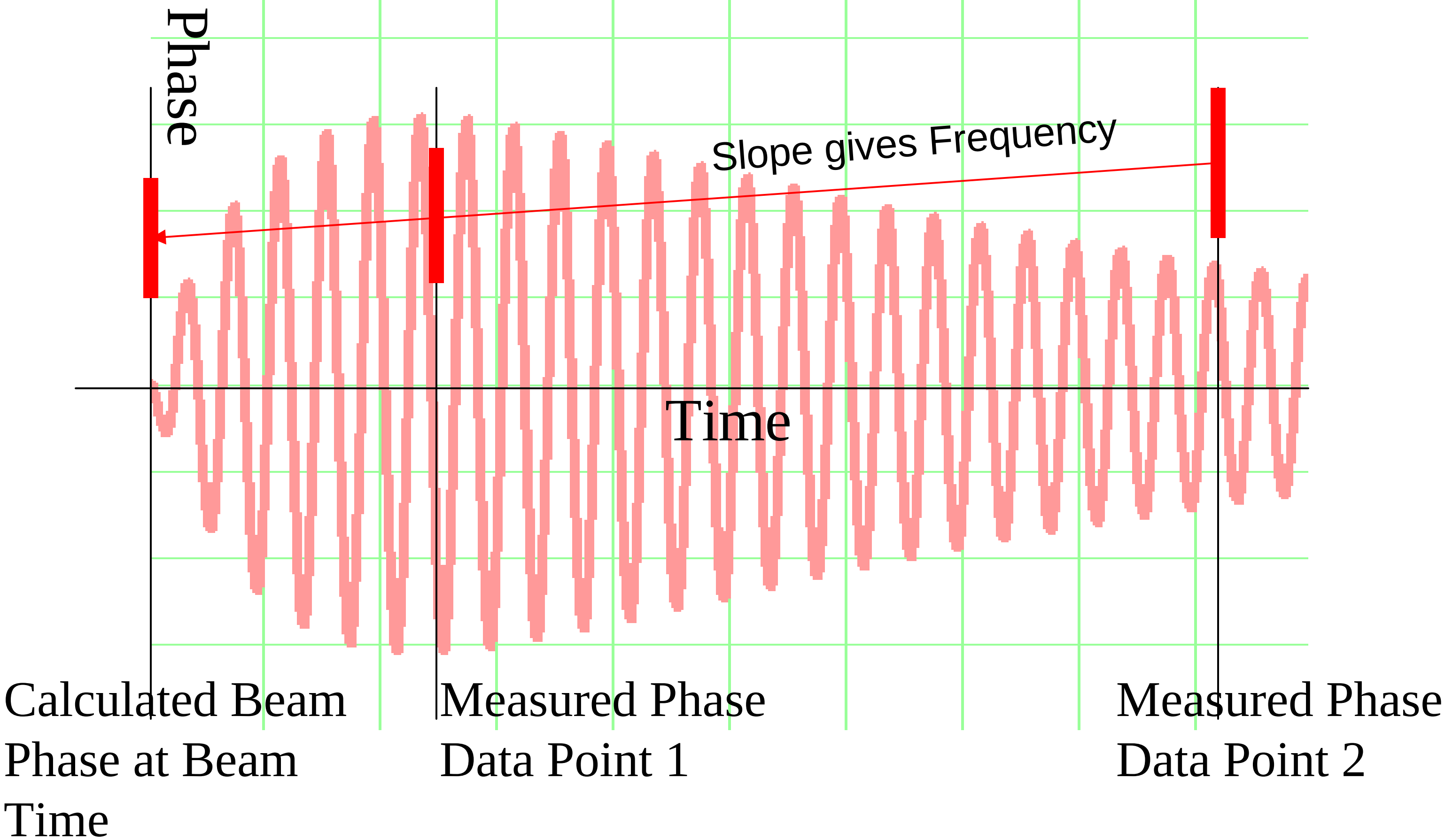
Beam Phase Cavity Analysis



Beam Phase and Cavity Frequency are Calculated from Two Data Points Sent From the PAD.

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X-Band Structure in Main Linac

20MV - 33MV/m

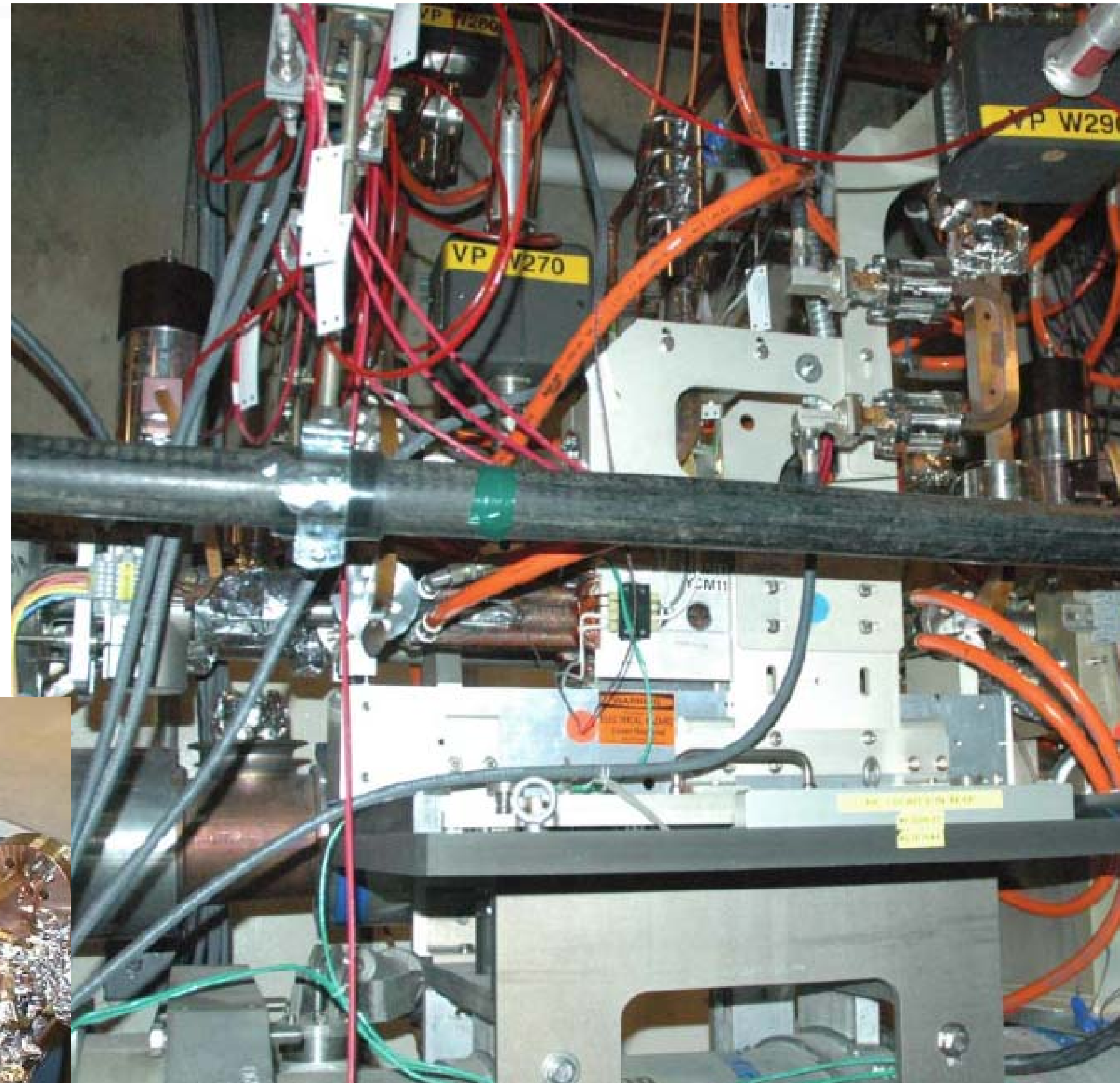
15MW at structure

22MW at the klystron

120nS fill time.

Beam at +160degrees

20° from decelerating crest



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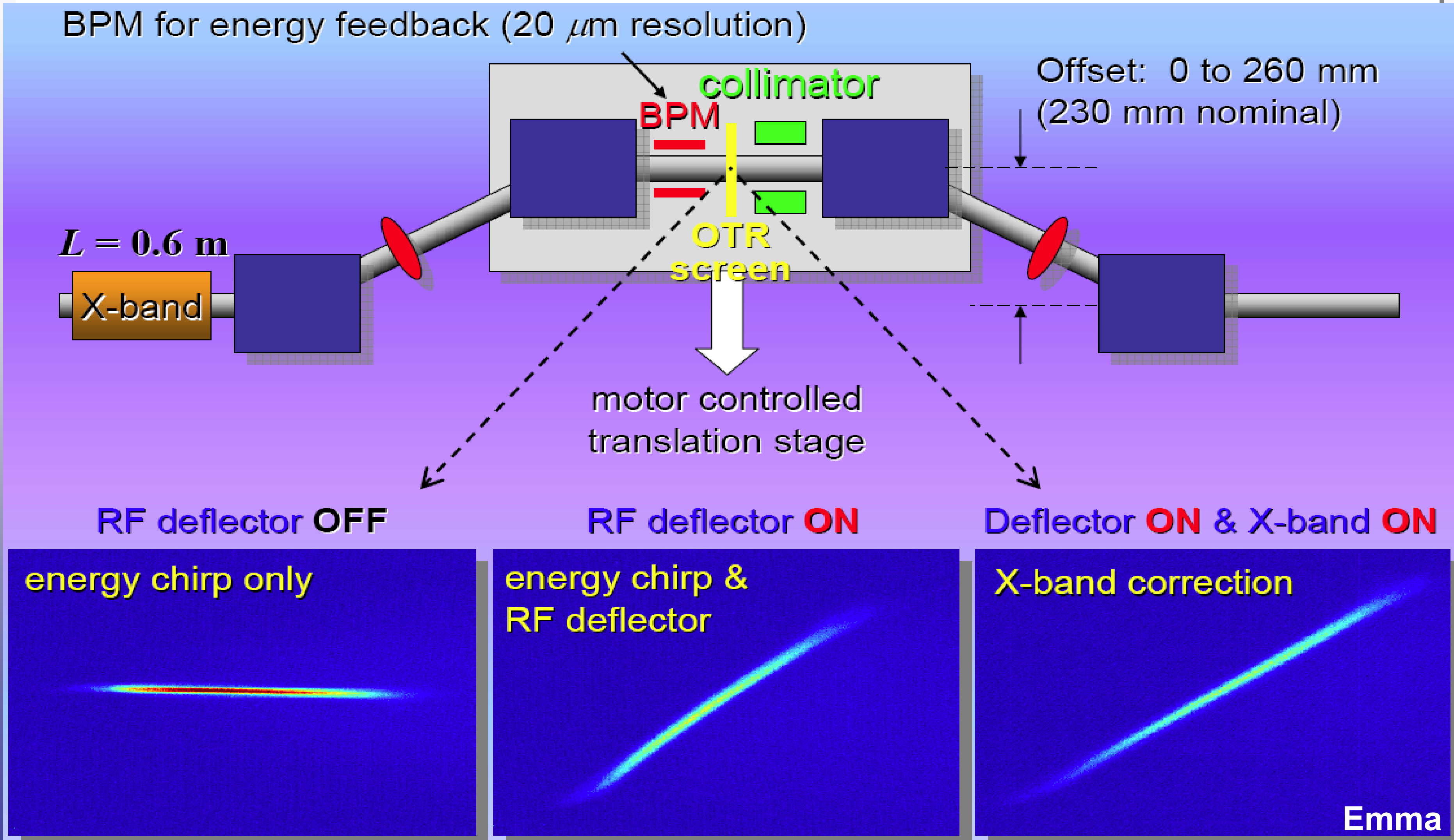
X-Band Station to Linearize Energy Position Correlation



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LCLS RF Jitter Tolerance Budget

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

Parameter	Symbol	LCLS	Unit
Gun timing jitter	Δt_0	0.50	psec
Initial bunch charge	$\Delta Q/Q_0$	2.0	%
mean L0 rf phase	φ_0	0.10	deg
mean L1 rf phase	φ_1	0.10	deg
mean L*h* rf phase X-band	φ_h	0.50	X-deg
mean L2 rf phase	φ_2	0.07	deg
mean L3 rf phase	φ_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 L*h* 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−* energy jitter. All tolerances are rms levels and the voltage and phase tolerances per klystron for L2 and L3 are √*Nk* larger, assuming uncorrelated errors, where *Nk* is the number of klystrons per linac.

P. Emma

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Slow Drift Tolerance Limits

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

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

(Tolerances are peak values, not rms)

P. Emma, J. Wu

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

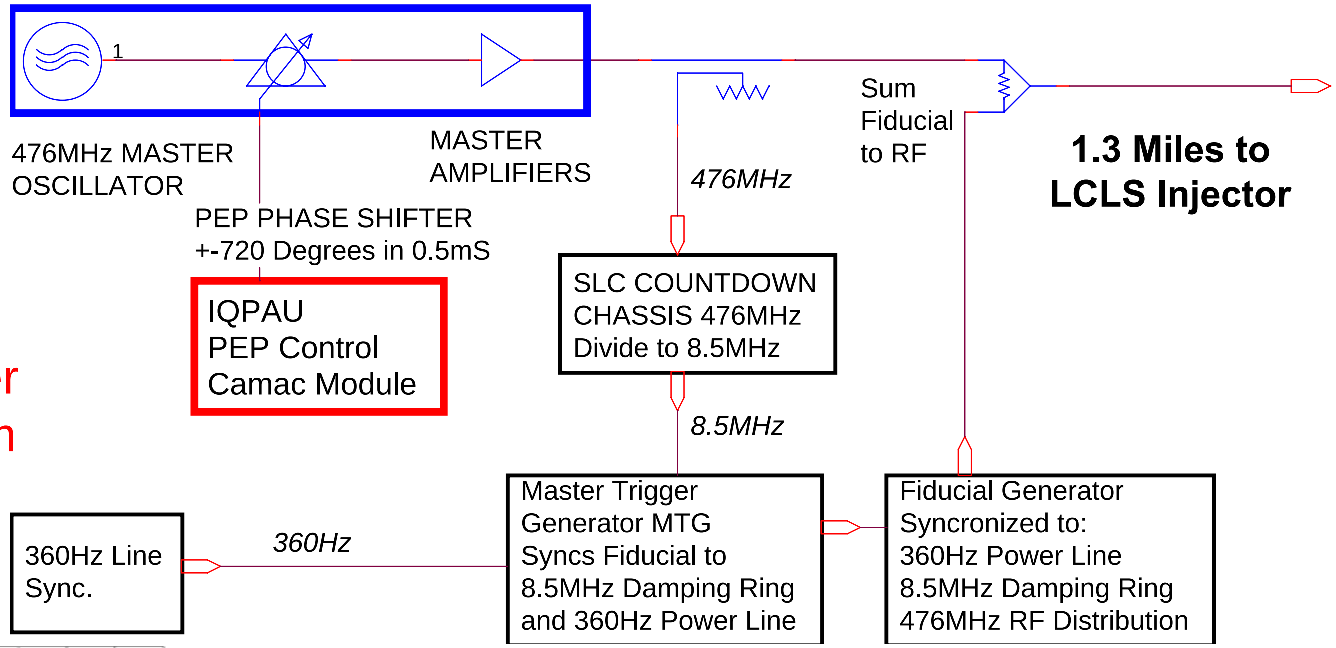
Linac Sector 0 RF Upgrade

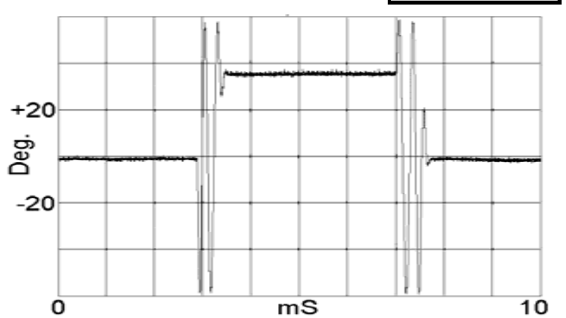
LCLS must be compatible with the existing linac operation including PEP timing shifts

MAIN LINAC (SECTOR 0) RF/TIMING SYSTEM

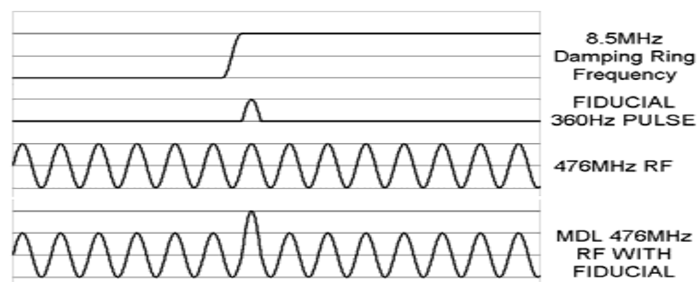
Master Oscillator is located 1.3 miles from LCLS Injector

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

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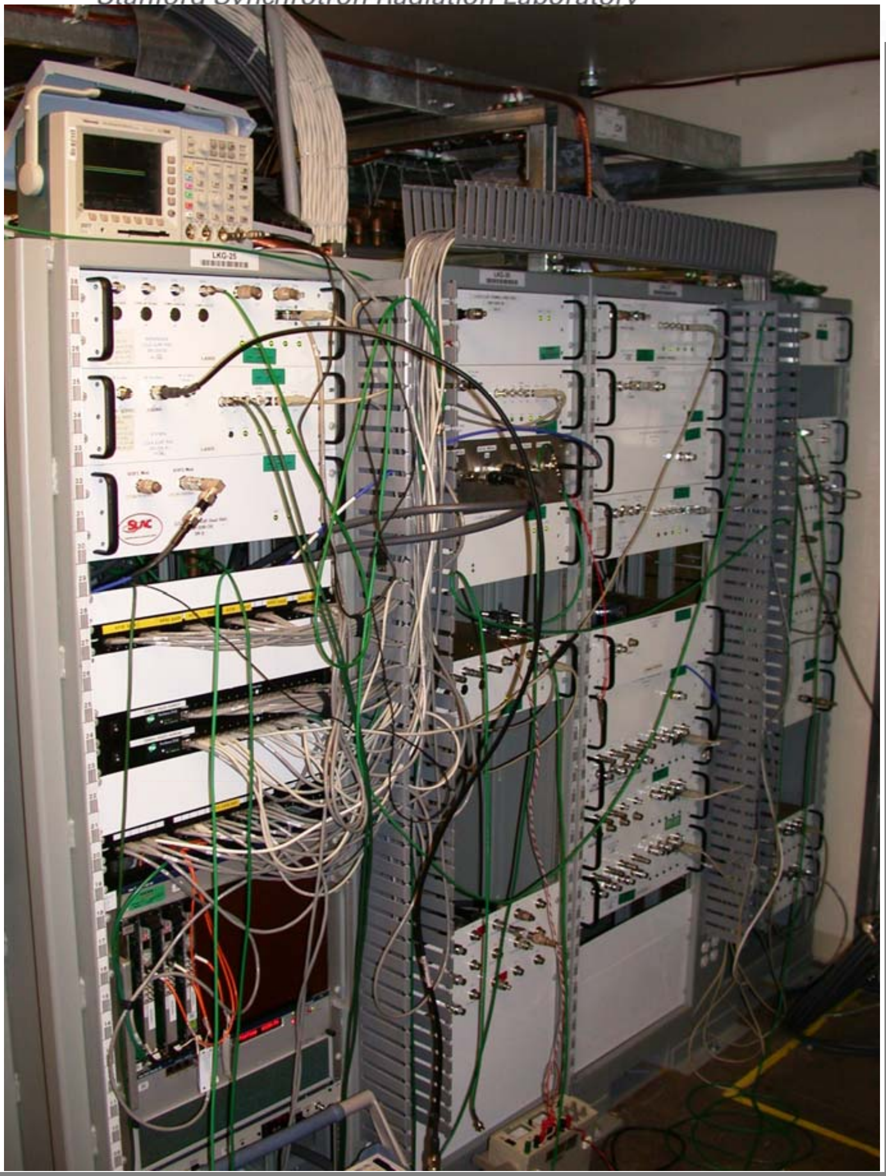
LCLS LLRF System to BC1

- 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.

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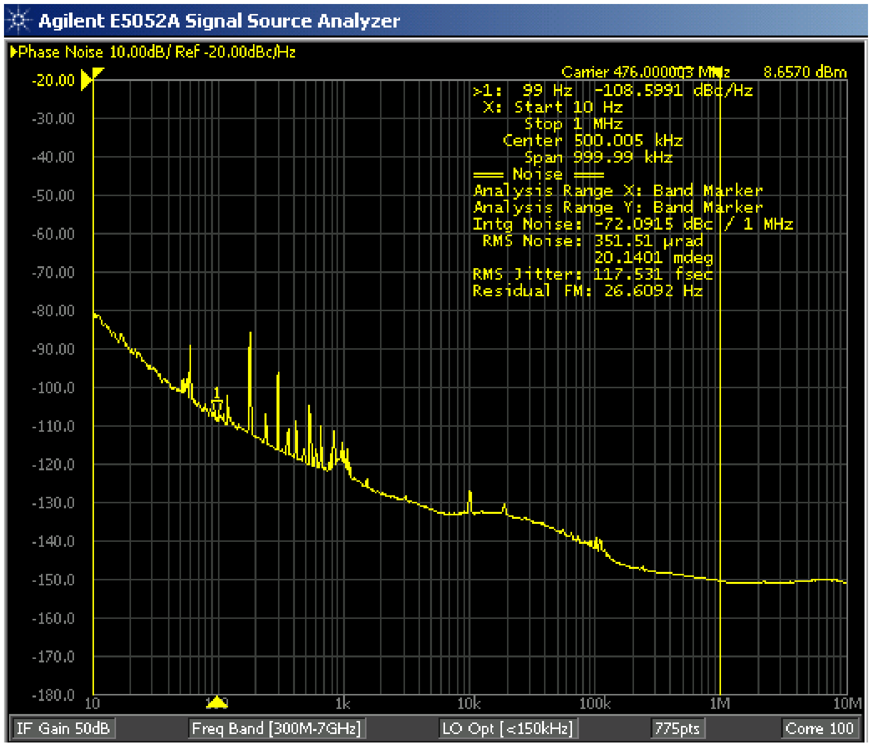
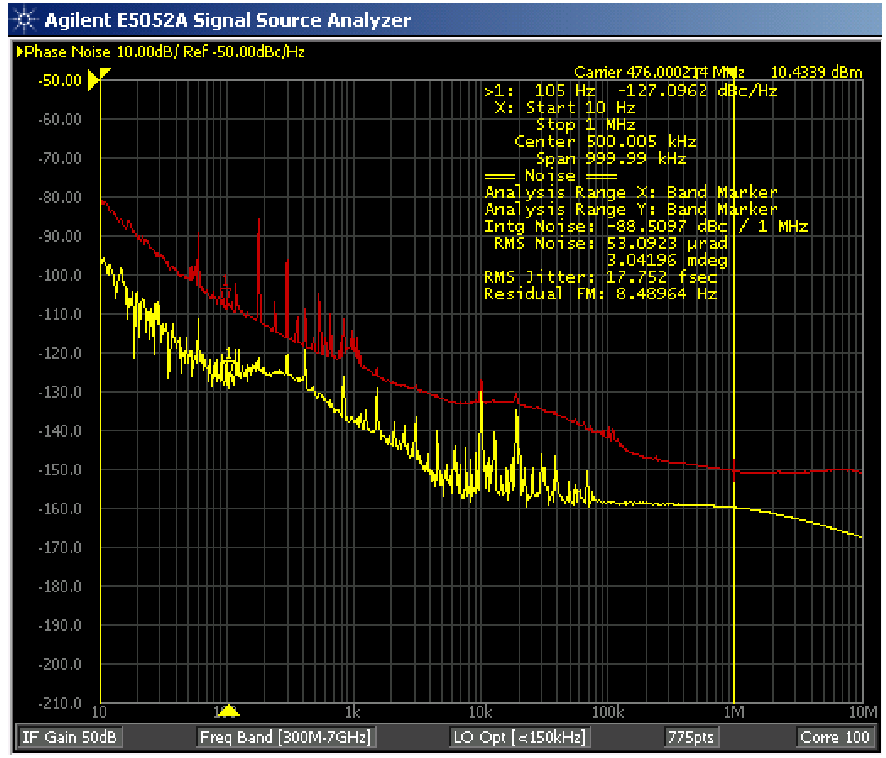
RF Distribution Lab vs. MDL Measurements



Existing Linac MDL Sector 0

126fS rms Jitter 10Hz to 10MHz



LCLS Reference System Lab Measurements

20fS rms Jitter 10Hz to 10MHz

John Byrd LBNL

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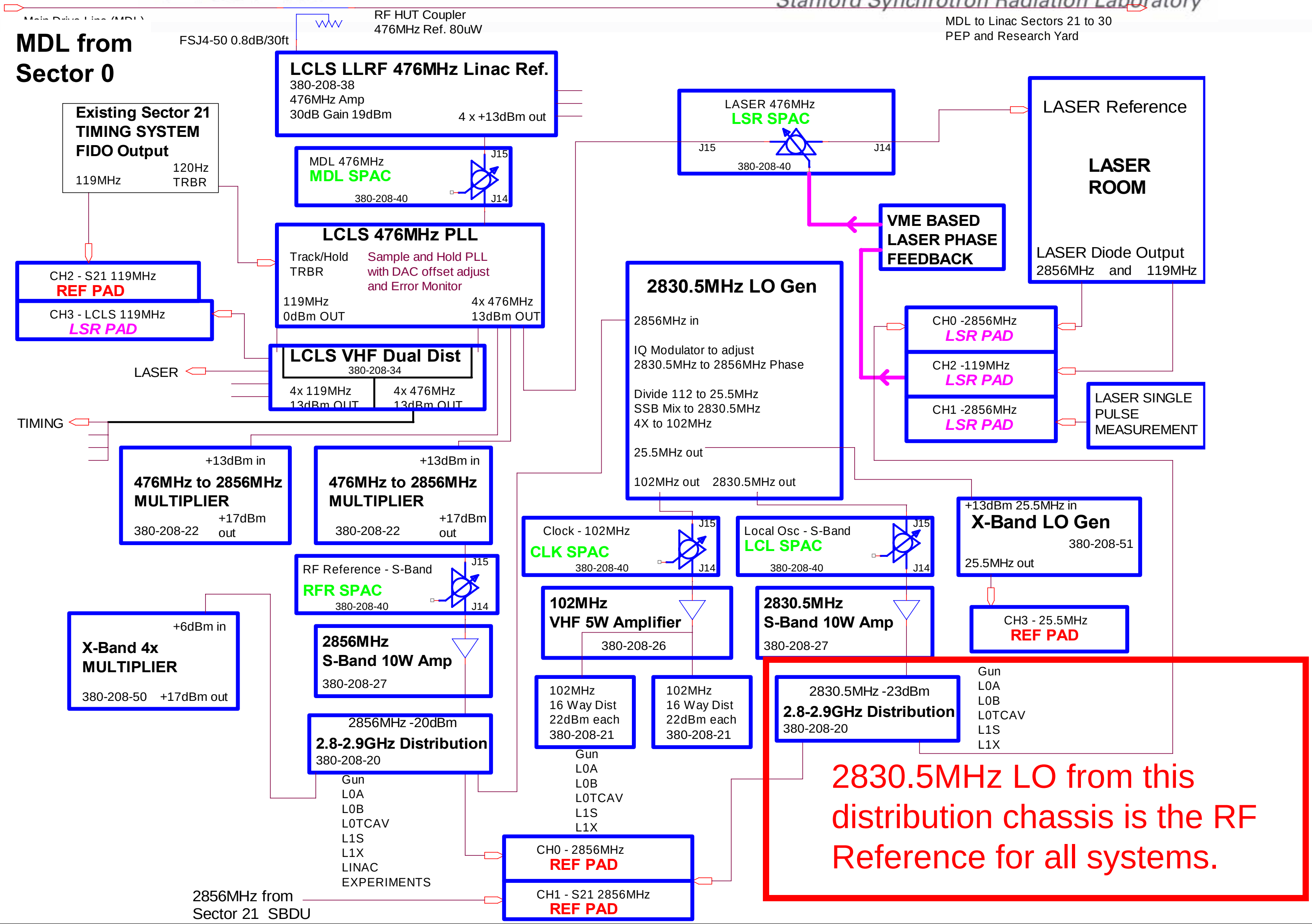
Sector 20 RF Distribution

Stanford Linear Accelerator Center

Stanford Synchrotron Radiation Laboratory



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LCLS New Reference System Lab Measurements

Lab Tests Show Reference System Noise Levels Meet All LCLS Requirements

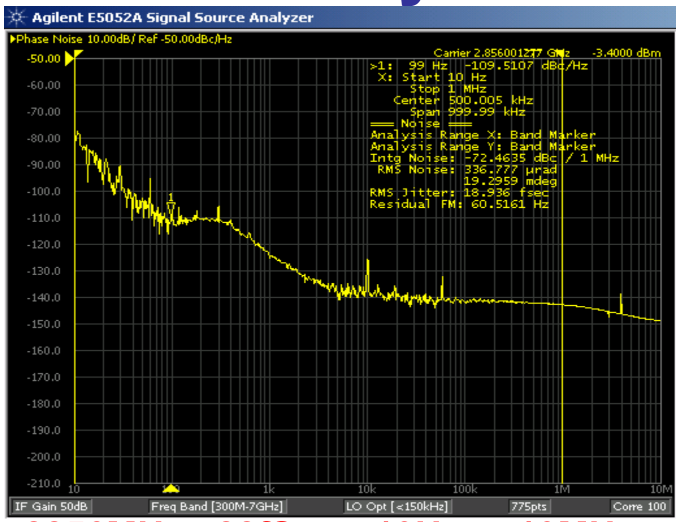
2856MHz = 70fSrms

2830.5MHz = 70fSrms

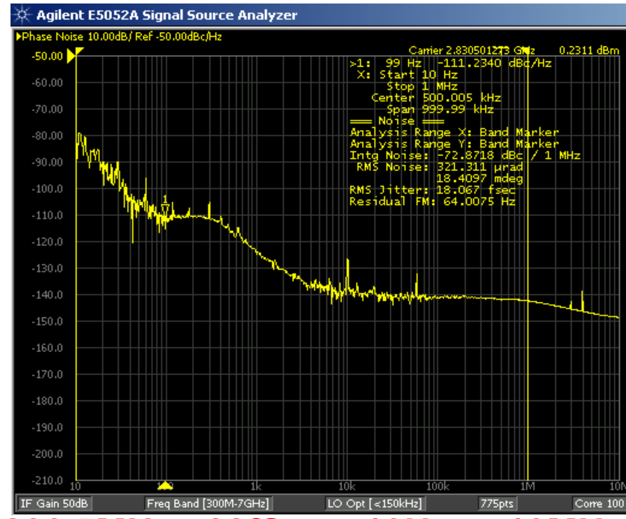
25.5MHz = 2pSrms

102MHz = 2pSrms

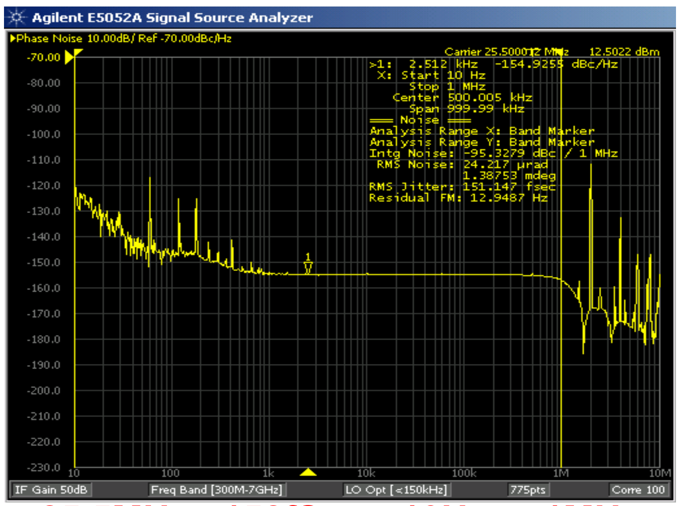
John Byrd - LBNL



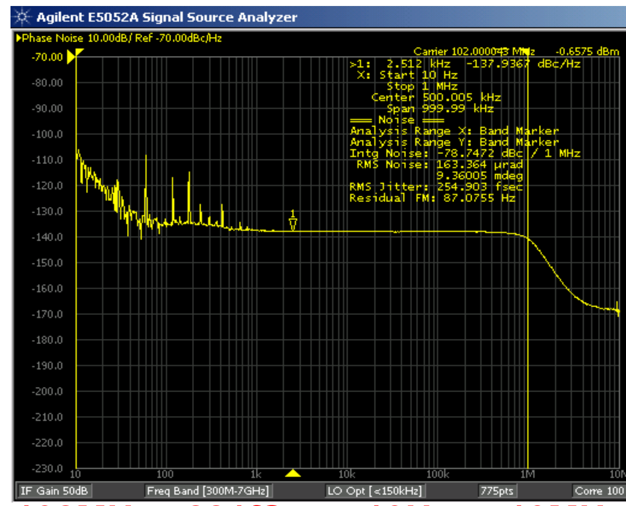
2856MHz : 22fSrms 10Hz to 10MHz



2830.5MHz : 22fSrms 10Hz to 10MHz



25.5MHz : 152fSrms 10Hz to 1MHz



102MHz : 281fSrms 10Hz to 10MHz

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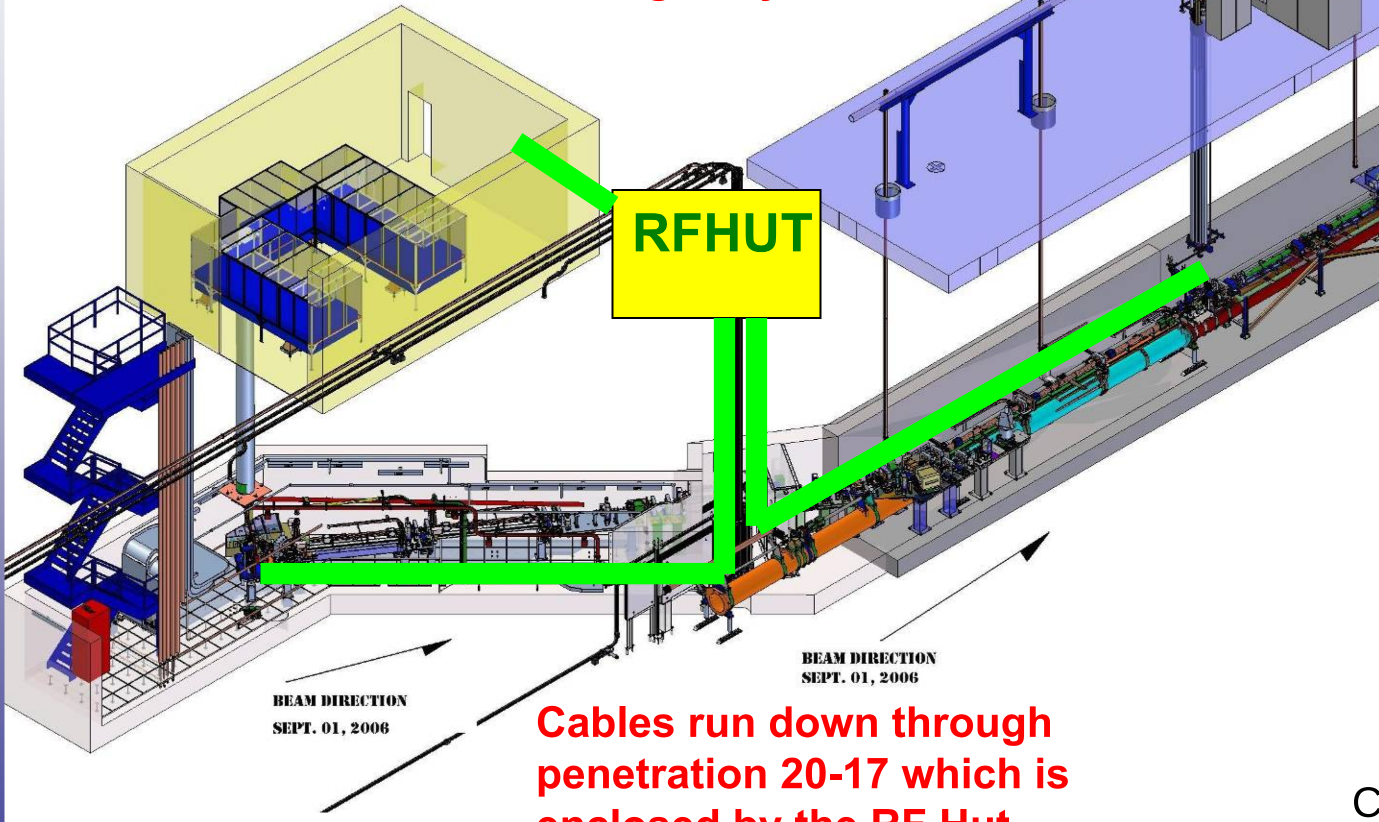
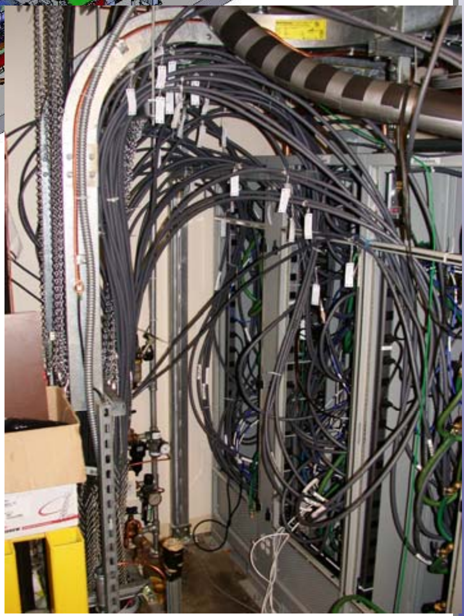
RF Cable Routing

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



Cables run down through penetration 20-17 which is enclosed by the RF Hut



Cables from penetration to RF Racks

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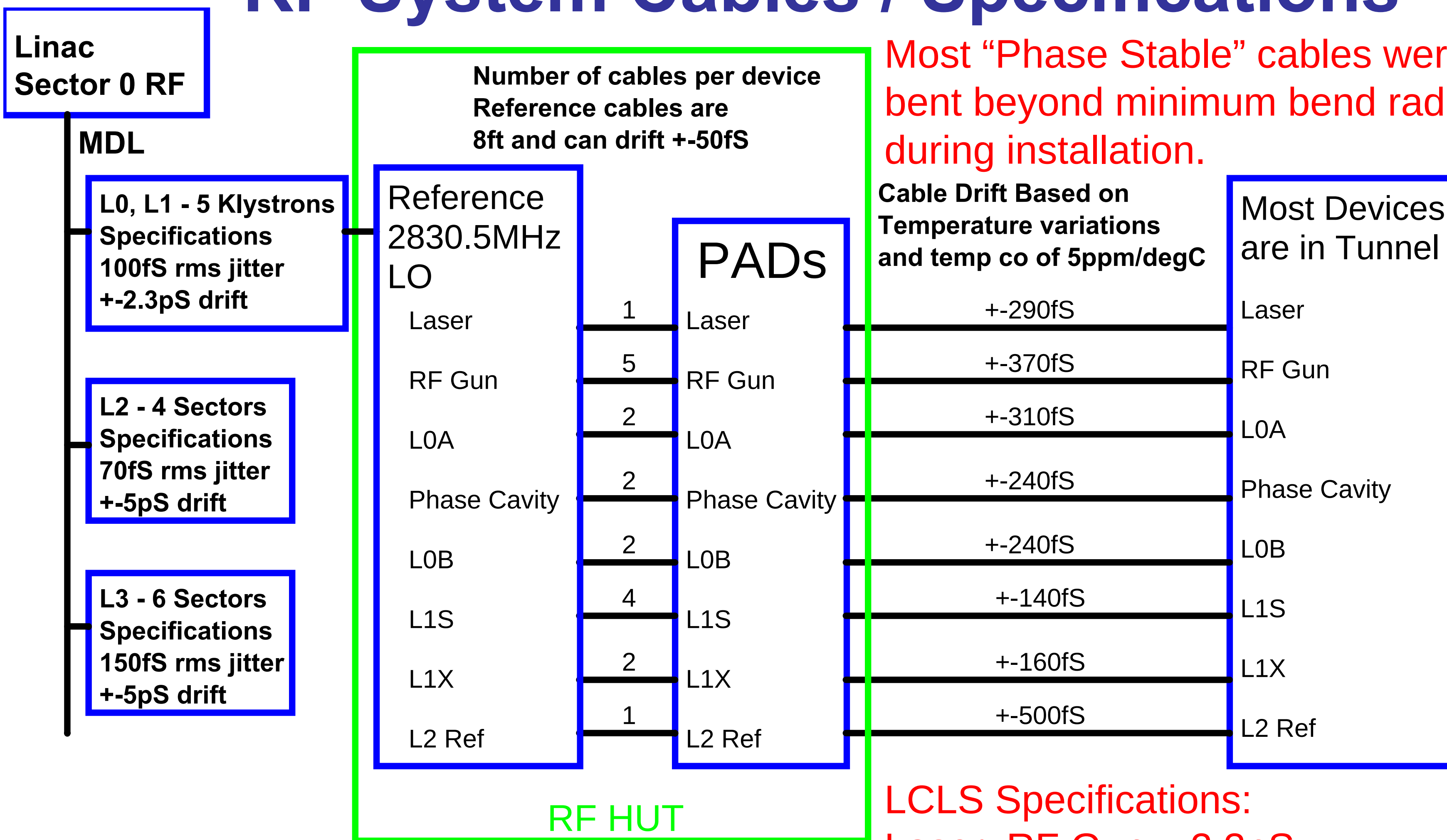
RF System Cables / Specifications

Most "Phase Stable" cables were bent beyond minimum bend radius during installation.



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

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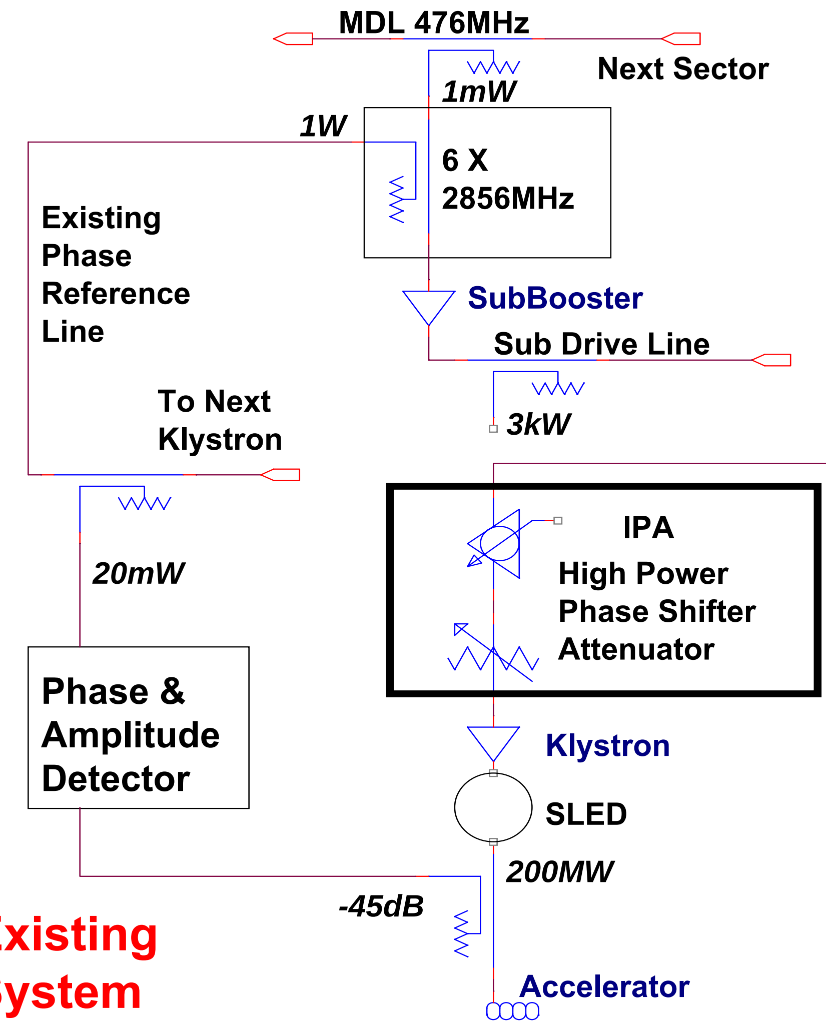
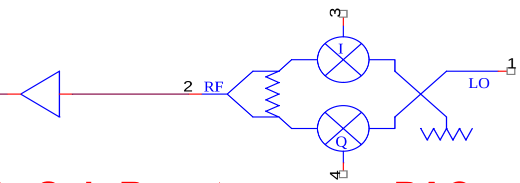
SLAC Linac RF – New Control



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.



Solid State Sub-Booster **PAC**

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.

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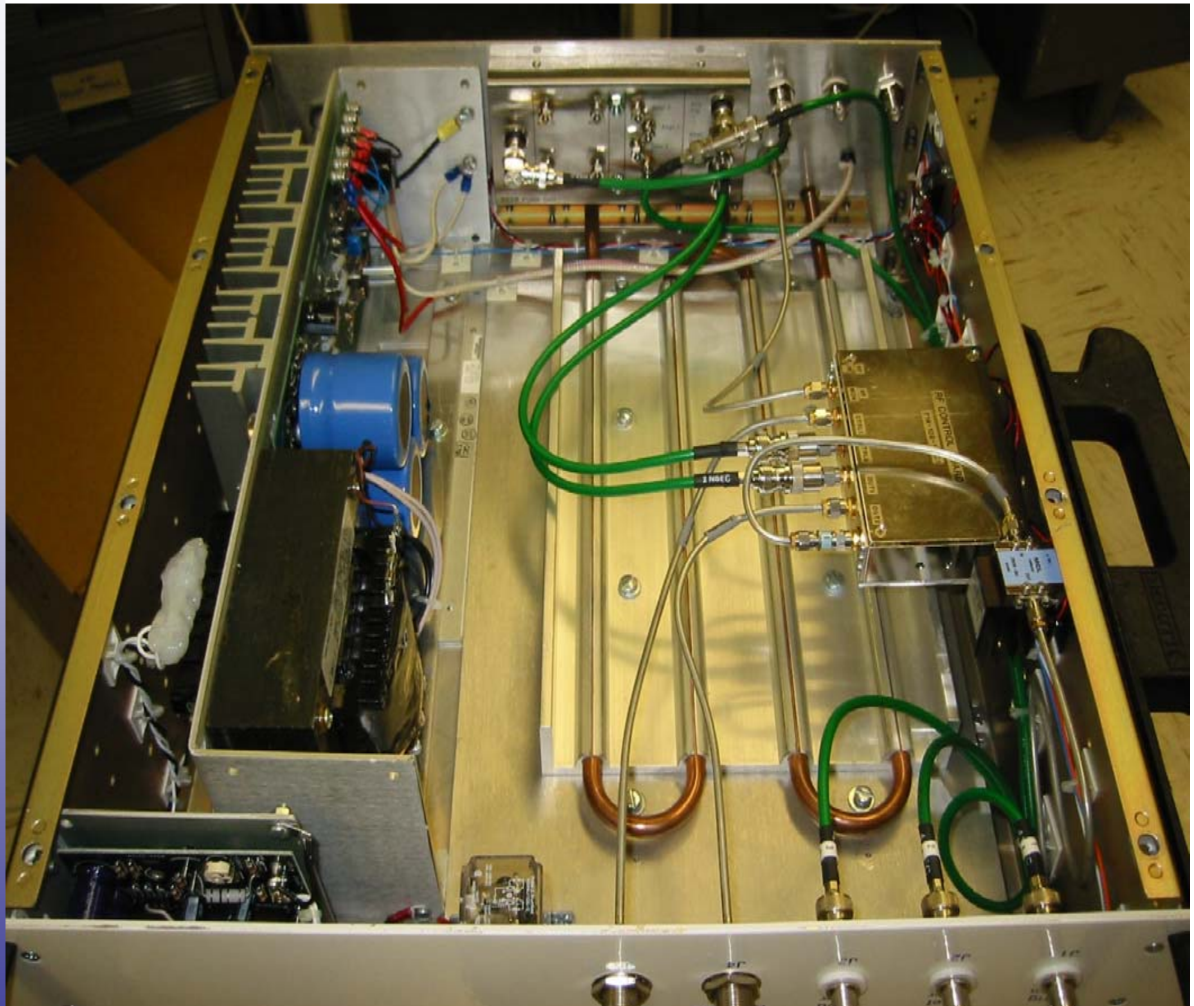
1 kW Solid State S-Band Amplifiers



- >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.

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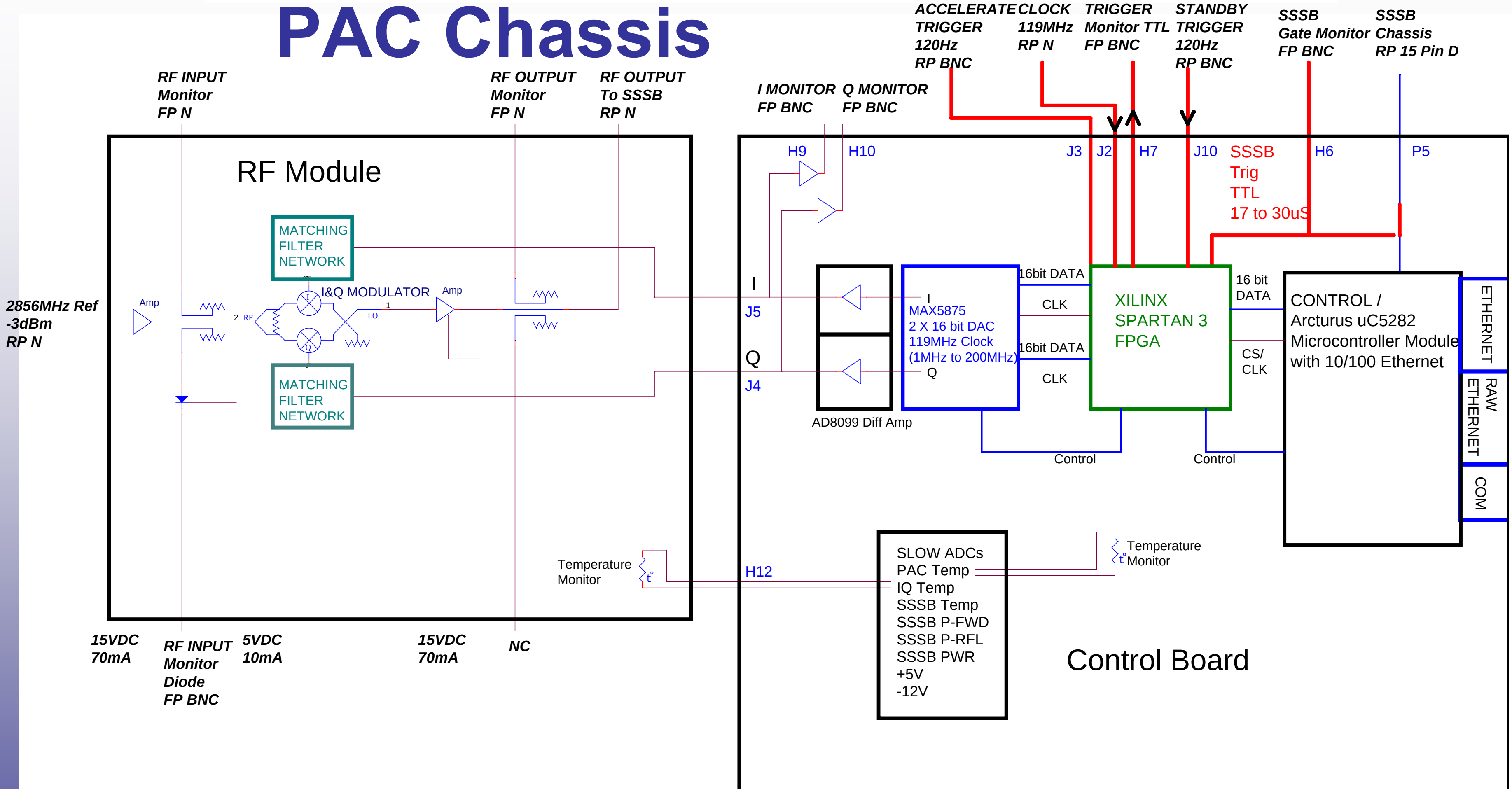
PAC Chassis



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.

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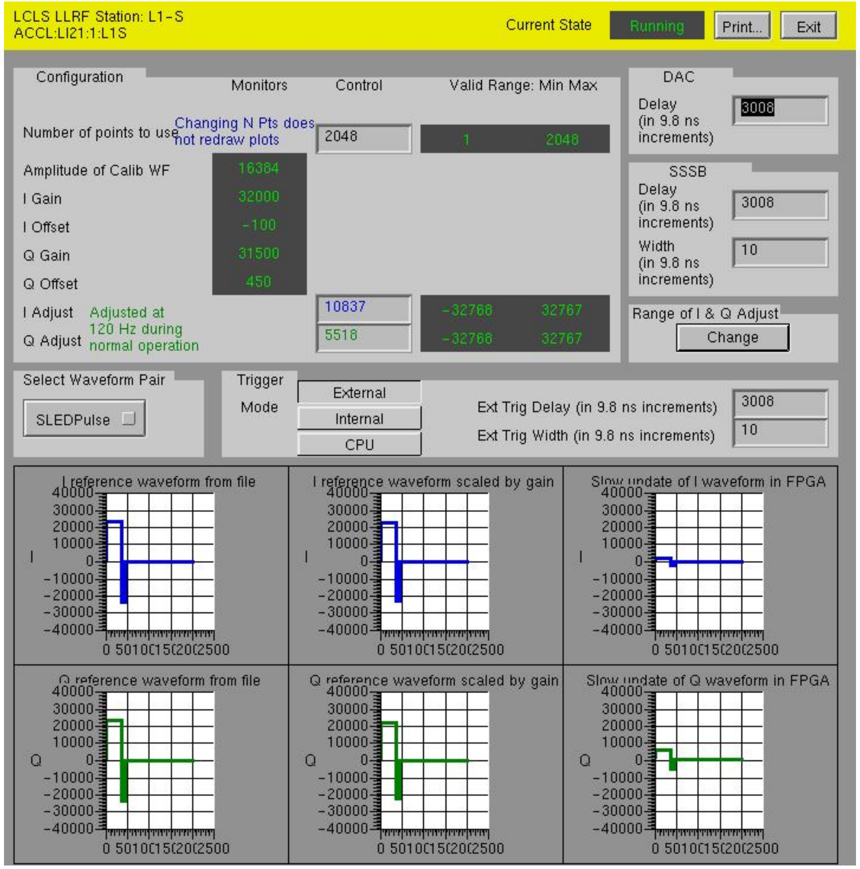
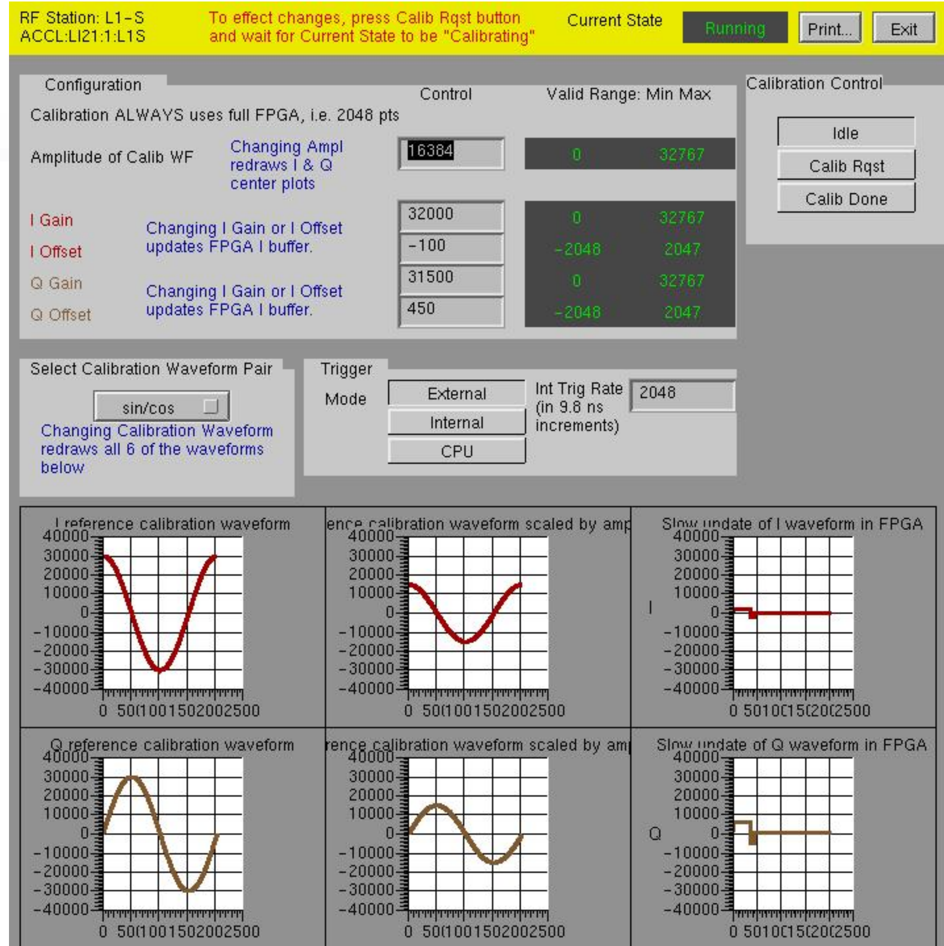
PAC IOC EPICS Panels



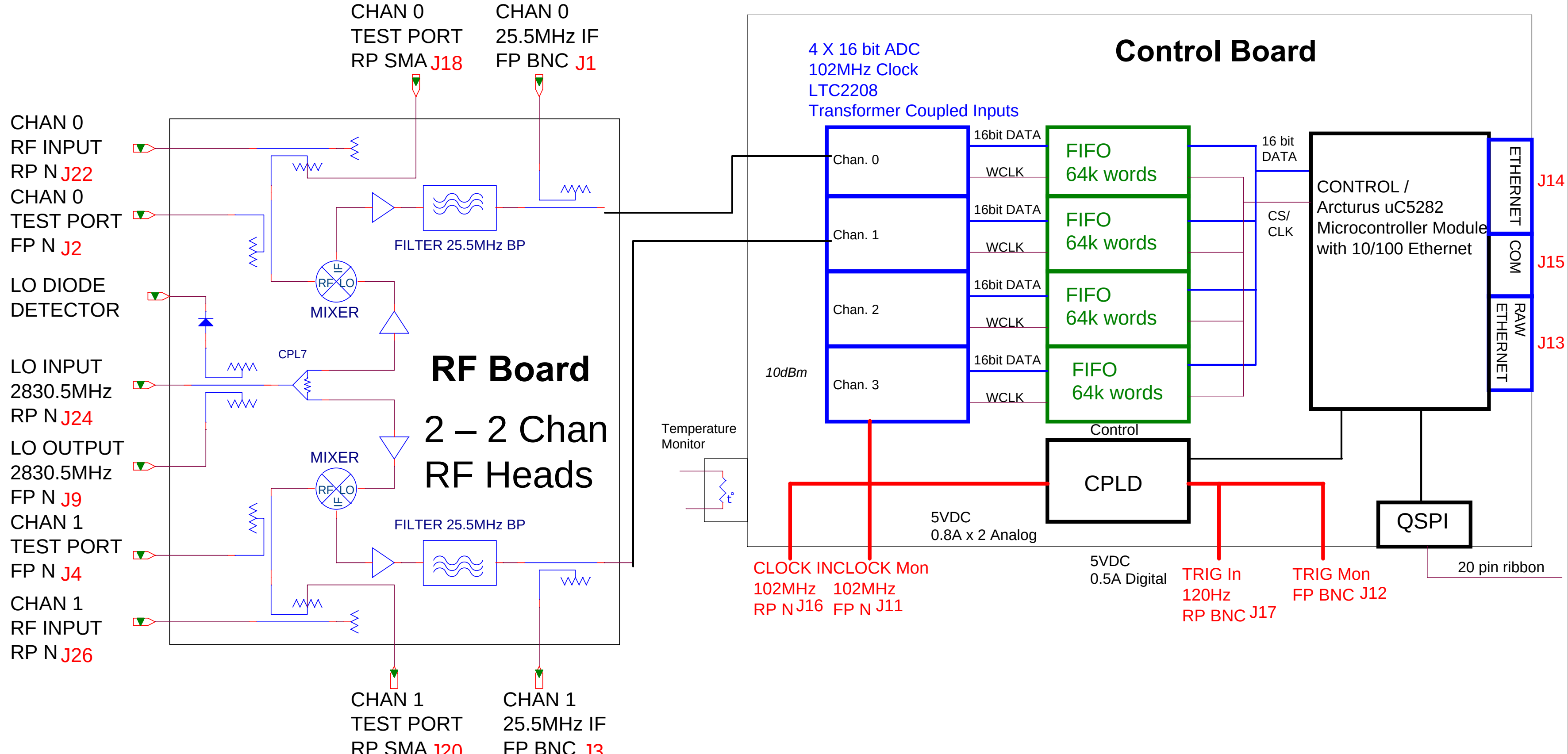
Operational PAC Panel



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.

PAD Chassis



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.

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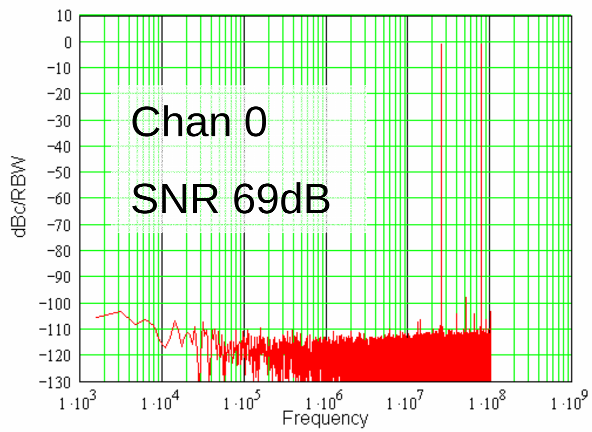
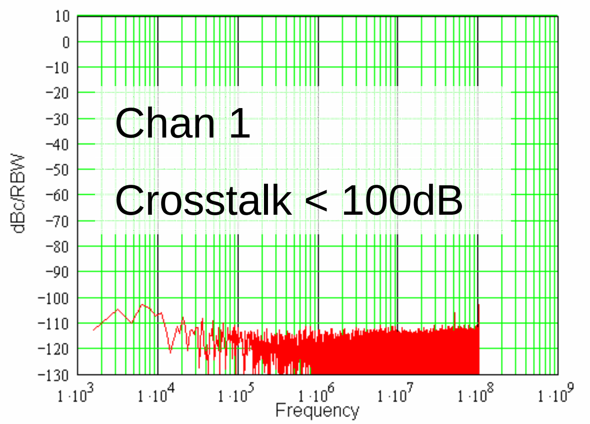
PAD Testing

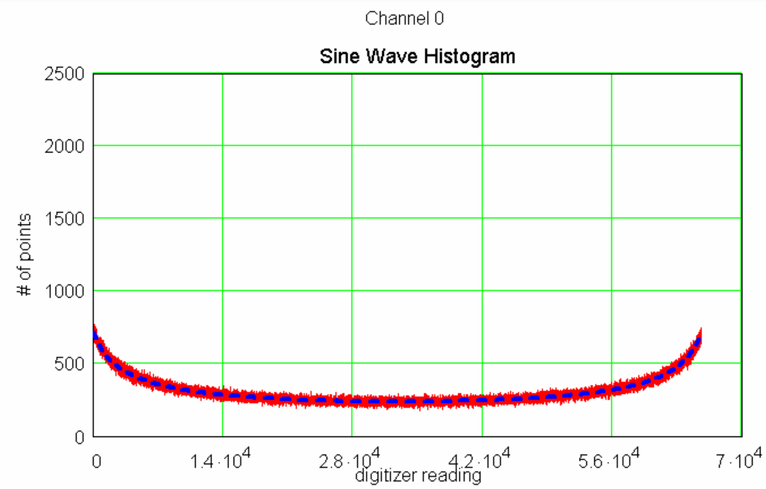


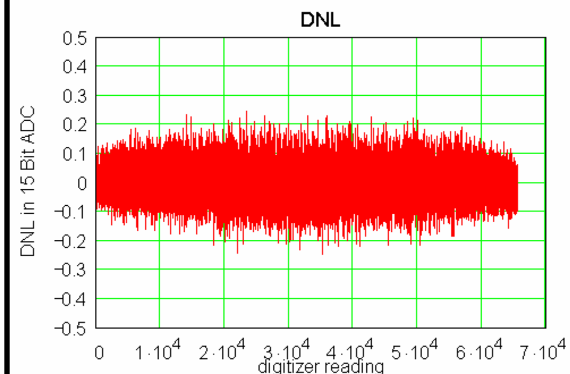
RBW=1556Hz : Channel 0 : Channel 0 signal = +2dBm
51MHz = -98dBm : Total Noise = -67dBm : Nov 29, 2006

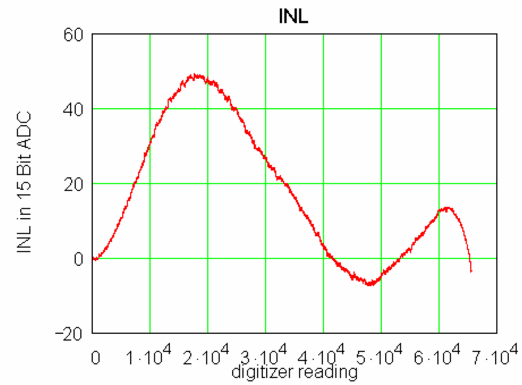


RBW=1556Hz : Channel 1 : Channel 0 signal = +2dBm
51MHz = -106dBm : Total Noise = -68dBm : Nov 29, 2006

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







Sine Wave Histogram shows no missing bits and Differential Nonlinearity of ±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.

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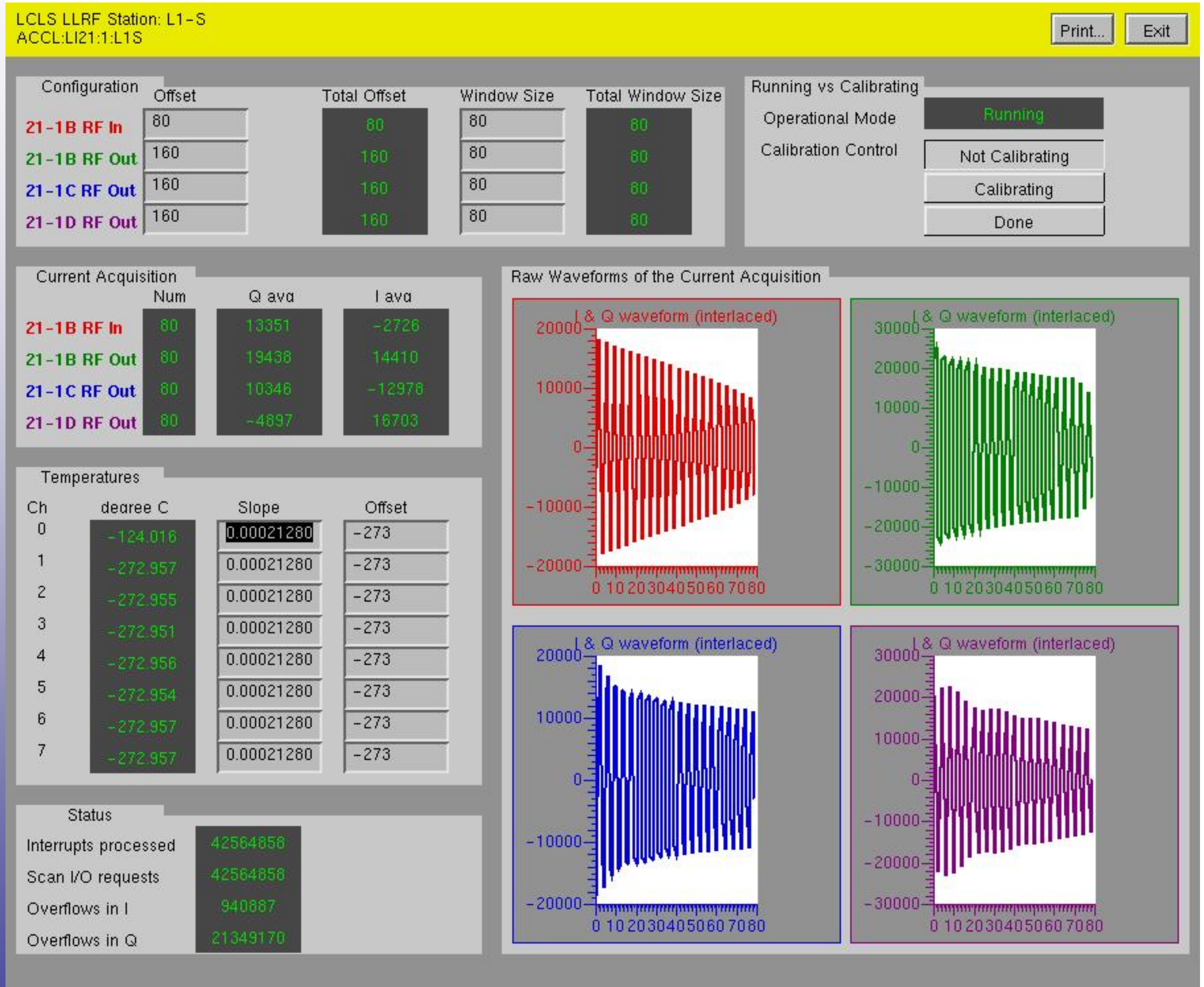
PAD IOC EPICS Panel



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.

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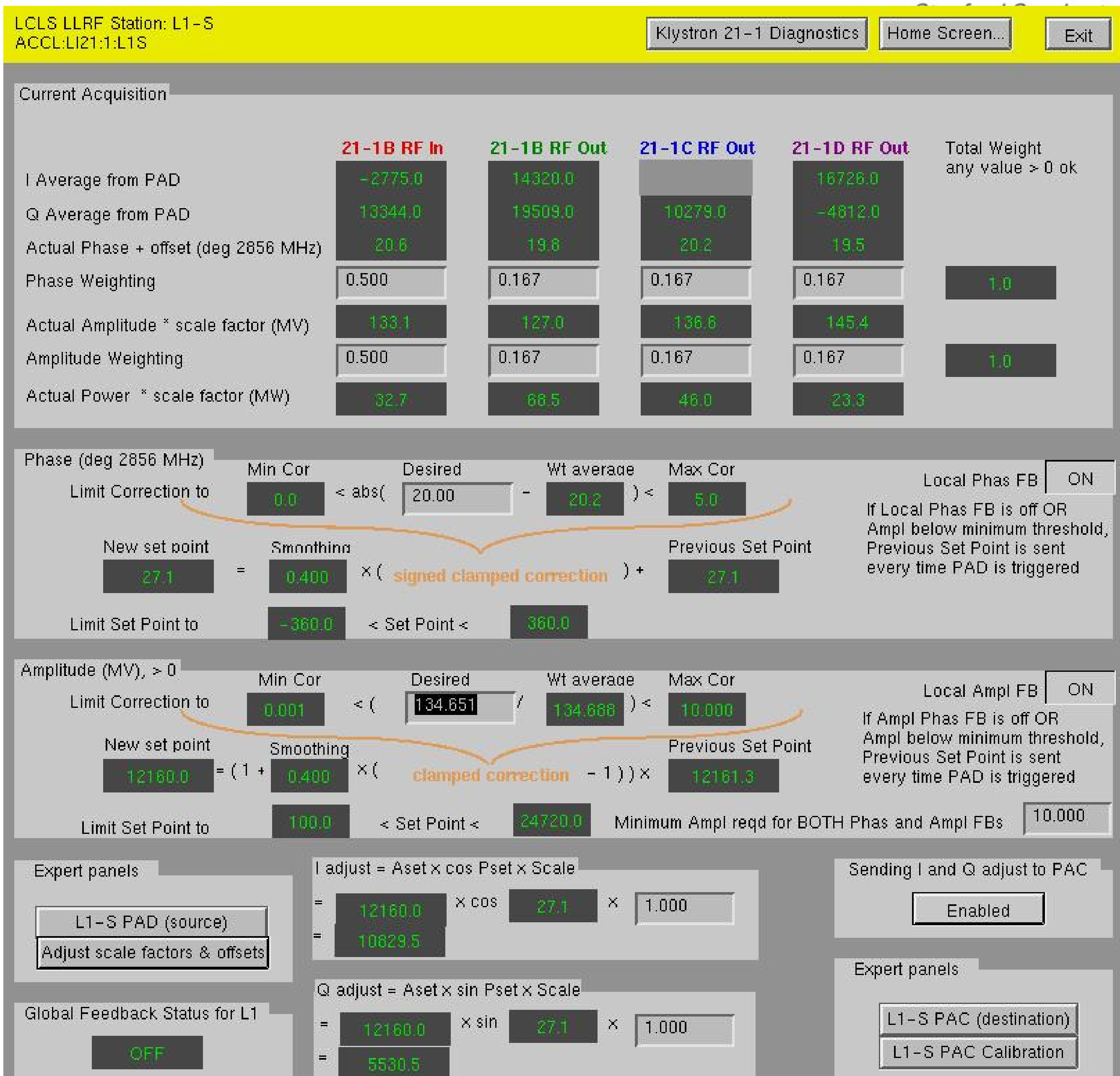
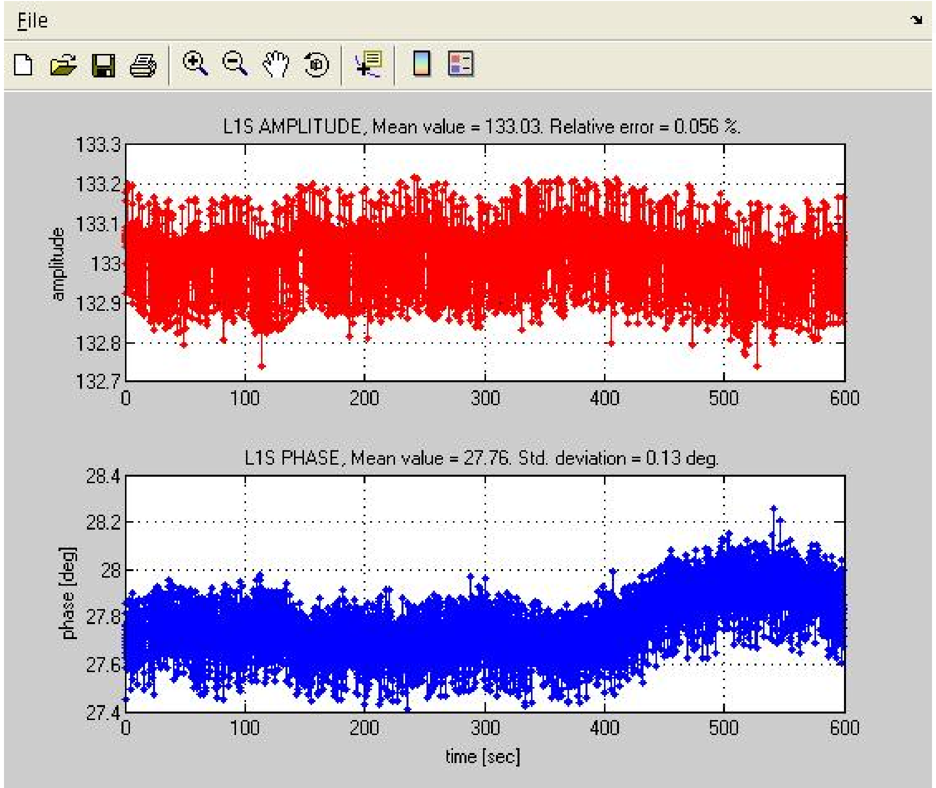
VME Based Feedback IOC

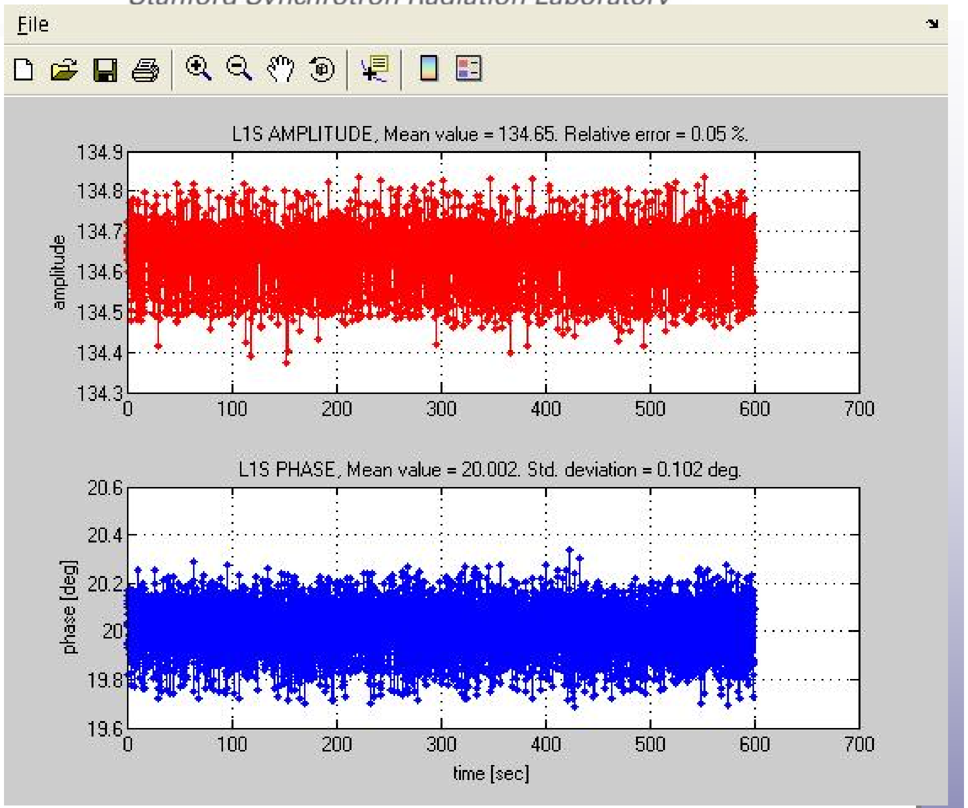


VME based feedback IOC takes data from the PAD I and Q PVs. The I and Q PVs are transformed to phase and amplitude. The phase has a phase offset applied to align 0 phase with peak acceleration and the amplitude has a scale factor applied to read in electron energy gain on crest. The feedback used a weighted 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.

L1S Stability



Feedback Off, 10 Minutes, 0.056%, 0.13º



Feedback On, 10 Minutes, 0.050%, 0.102º

L1S Meets Jitter Specifications (0.1% 0.1º) 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.

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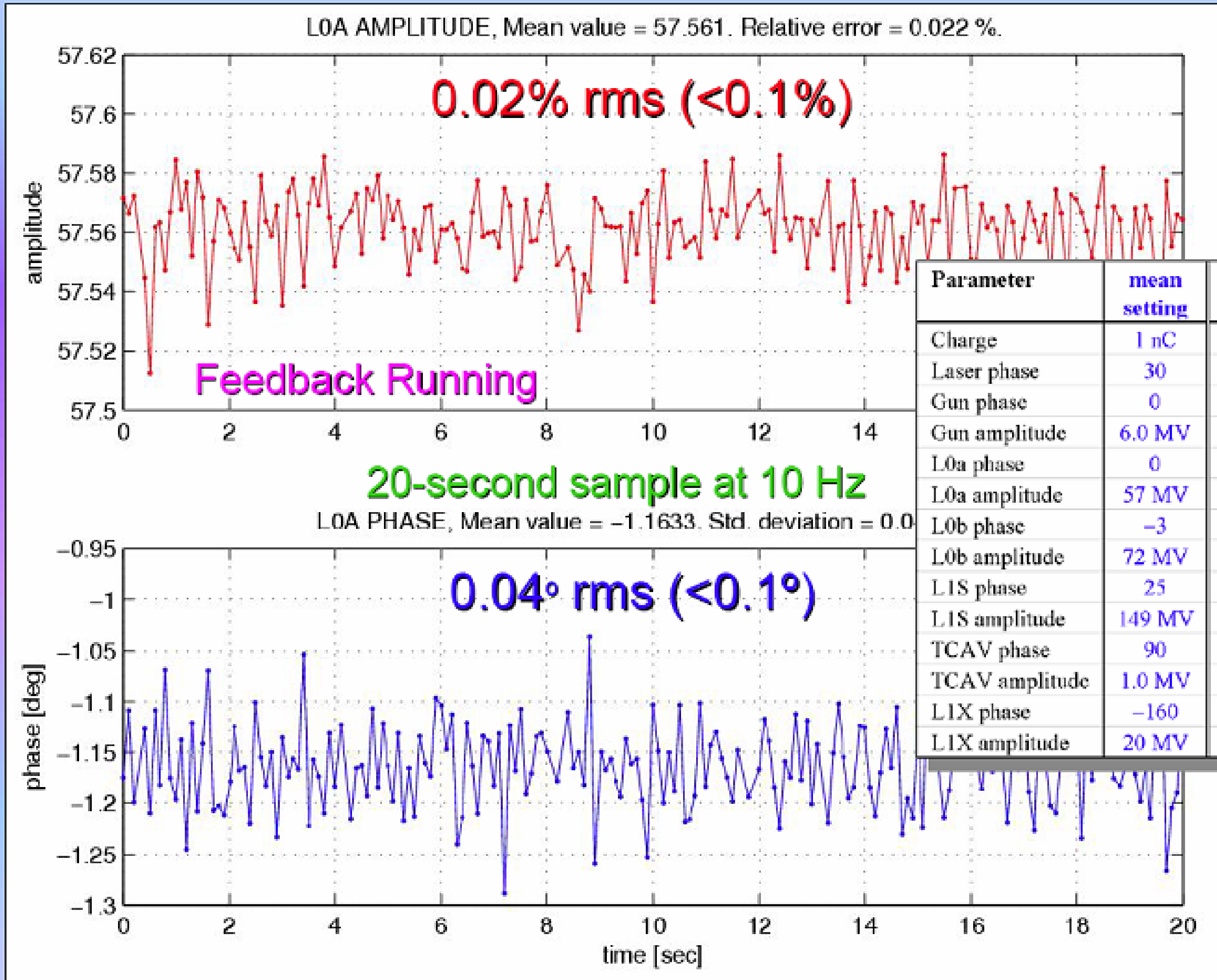
RF Phase and Amplitude Stability (L0a)



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

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LCLS RF System L2 and L3

- 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
- Total of 18 SLAC built RF Chassis
- Are we ready? – Definitely not, but we will turn on anyway.
- Next we need to finish the injector RF system

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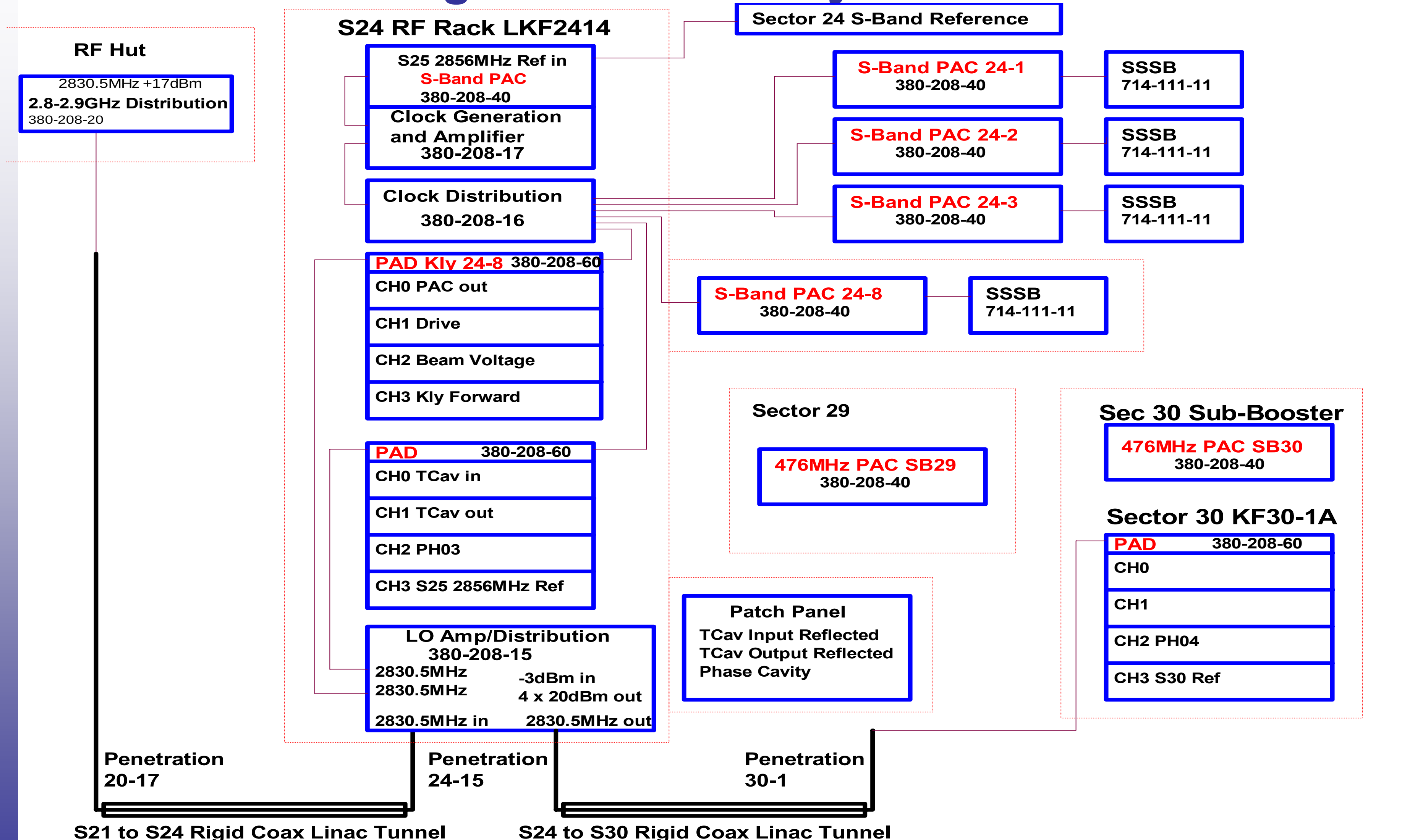
Block Diagram LCLS RF System L2 and L3



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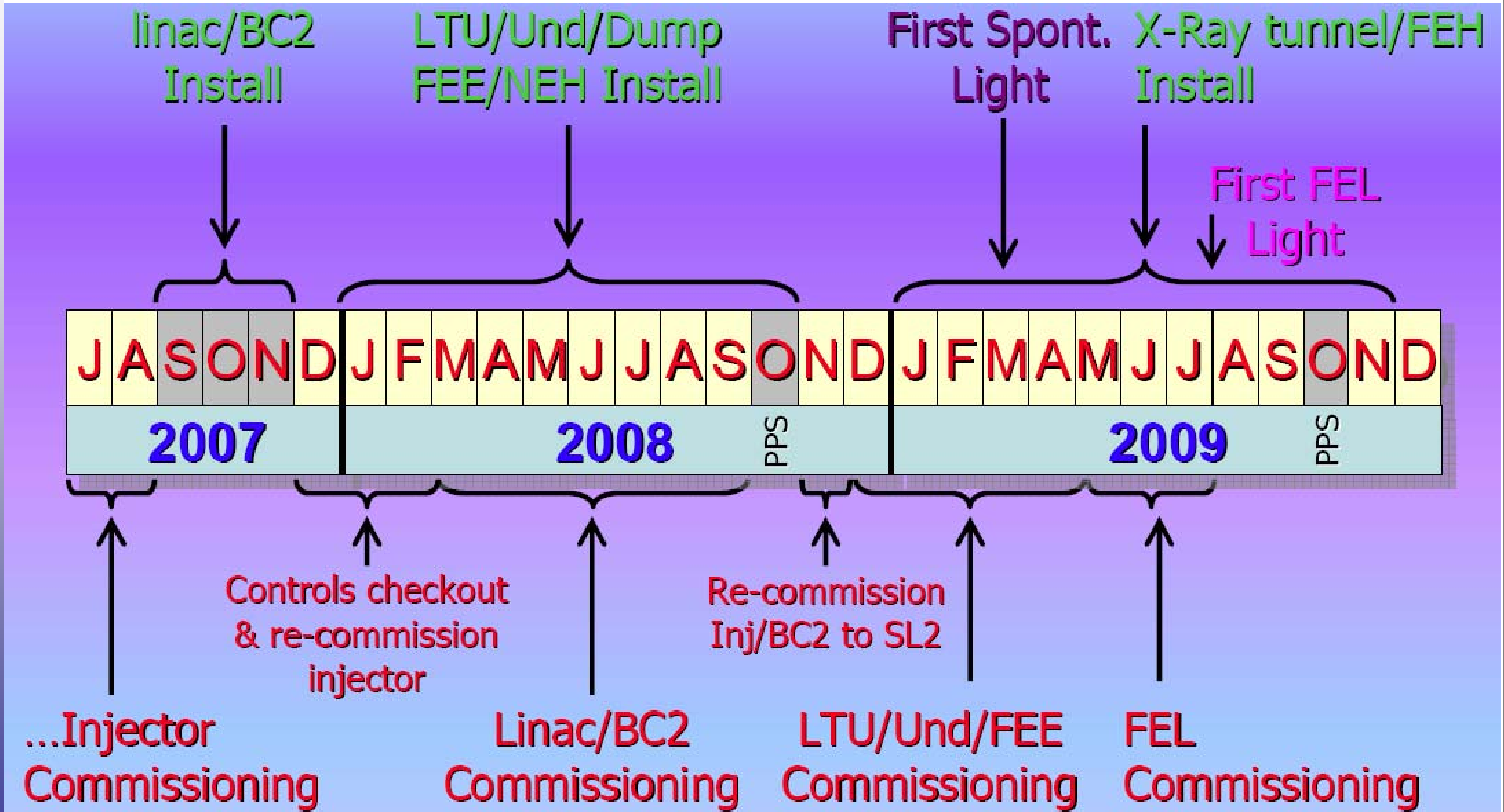
LCLS Commissioning Time-Line



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END

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