SLAC-WP-099

S-Band RF Load Upgrade Program for SLAC Linac

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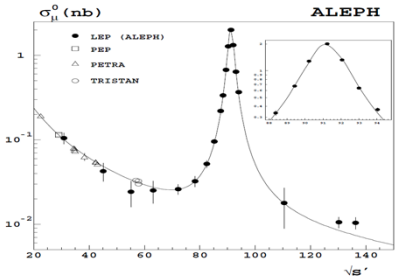
Stability of SLAC Linac vs. Program Runs

Z-Boson resonance → $\frac{dE}{E} \cong \frac{2.5}{91.2}$ i.e. **~2.7%**



B-Boson resonance → Linac served as an injector. Stability of linac system did not play a major role. Stability of HER and LER systems were required.

FEL → Specification of the bunch parameters and stabilities are tight. Level of required LCLS linac stabilization is ~**0.02%**

The modern energy stability requirement for linac systems and subsystems is $\mathbf{10^{-3}}$ to $\mathbf{10^{-4}}$

Major Contributors to the Beam Energy Jitter

Major Contributors are:

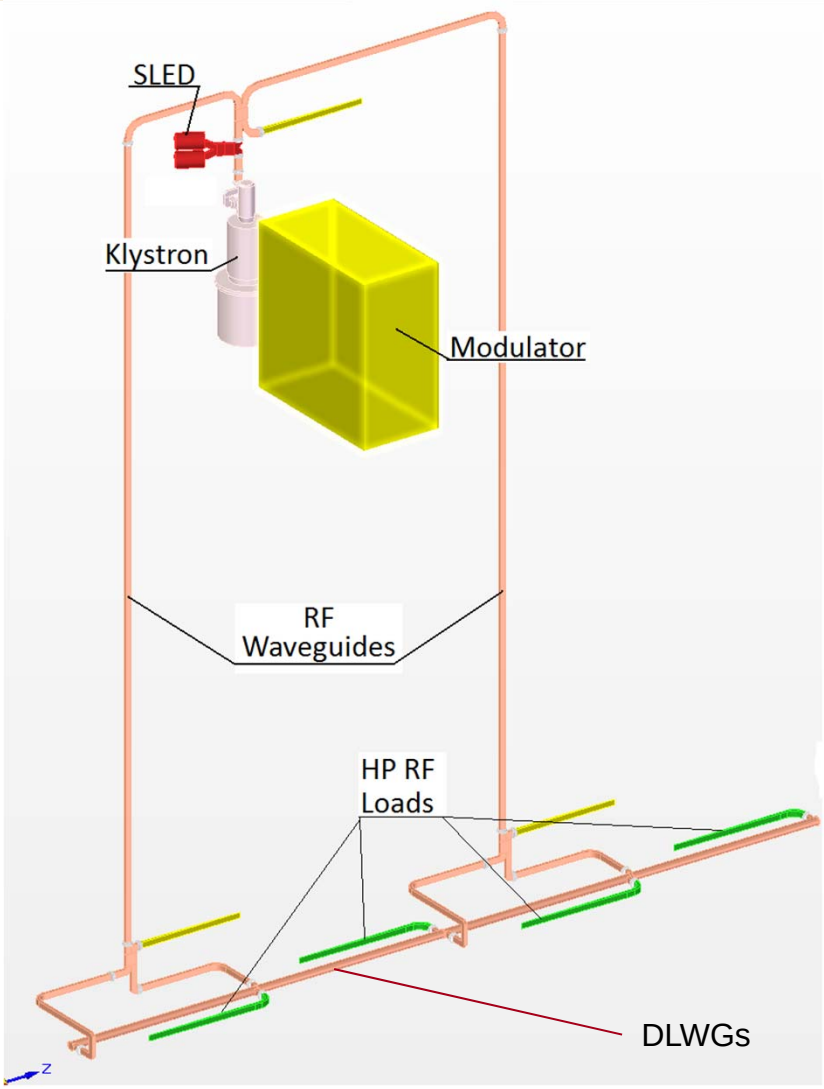
- Thyratrons (fast, high-power switch)
- RF Load (high-power RF terminator)

80 RF stations serve the LCLS, accordingly there are:

- 80 thyratron tubes
- 320 RF loads

Neither the thyratrons nor the loads were originally designed to support the new FEL-required stability

Both devices currently operate in stressed modes



Motivation

- Original SLAC RF loads designed for **2 MW** maximum peak input power
- Klystrons gradually upgraded, delivering **6.5+ MW** peak power at load
- SLAC Linac Energy Doubler (SLED) cavities added, termination power now **24 MW** peak
- The RF terminations (**Loads**) need upgrading to accommodate the present RF linac configuration

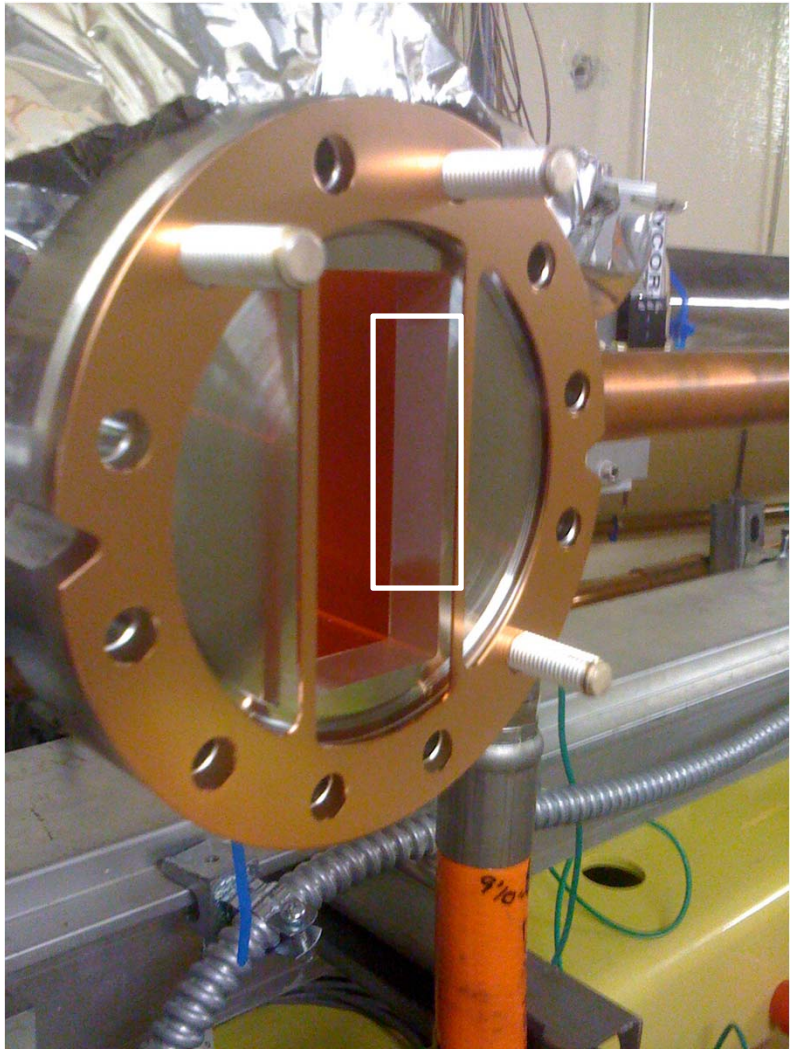
Breakdowns and multipactoring inside vacuum known to cause:

- Outgassing and sputtering (**Particle contamination in beam line**)
- Unstable reflected RF power ***(Electron / X-ray beam energy jitter)***

Outline

- Benchmarking of original SLAC RF loads
- Detailed consequences of inadequate termination
- Design of new, all-metal, high-power RF loads
- Project status
- Long term project goals

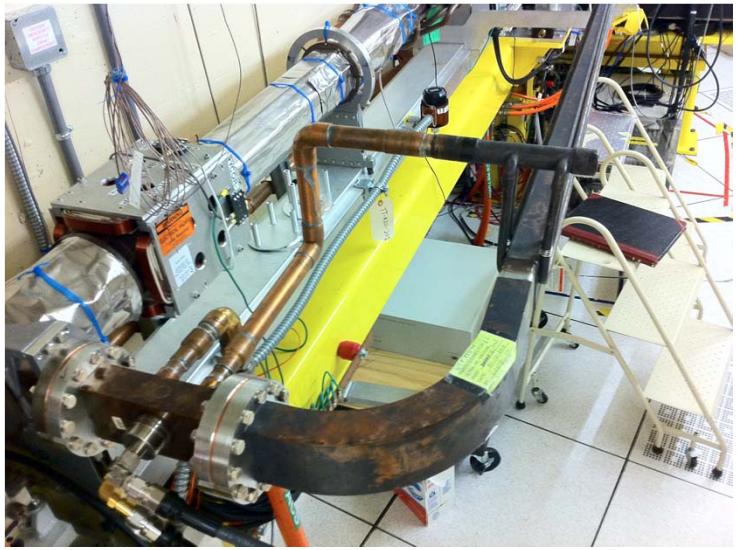
Natural Evidence of High RF Power Instabilities



Output RF waveguide port of an accelerating section with disassembled load

The shiny Cu is covered by gray particles:

- Indicates sputtering of the load's RF absorption layer
- Sputtered particles are sucked into accelerating channel

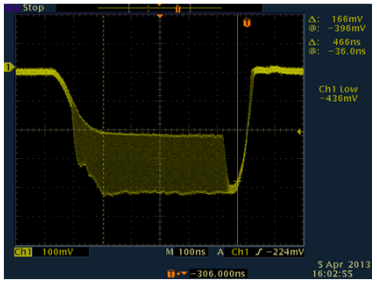


High Power Tests of Original RF Loads

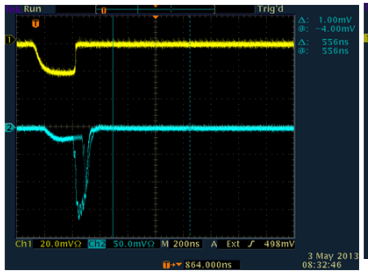
- Tests of loads at mW (Network Analyzer) level are OK
- ***High Power*** test requirement: peak power >15 MW, 1 us pulse and at 120 Hz
- No tested load passed this RF power spec

Different of Refl. Power waveforms from load-to-load

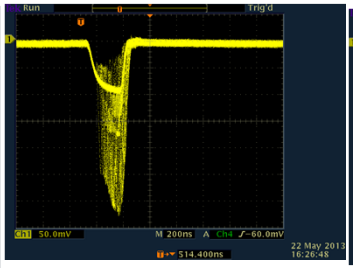
#504 at 3 MW



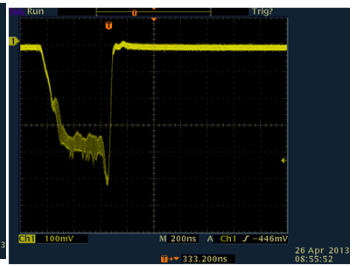
#2040 at 0.5 MW



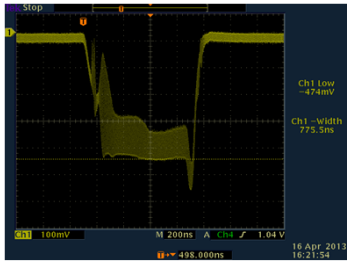
#1074 at 1 MW



#1929 at 7 MW

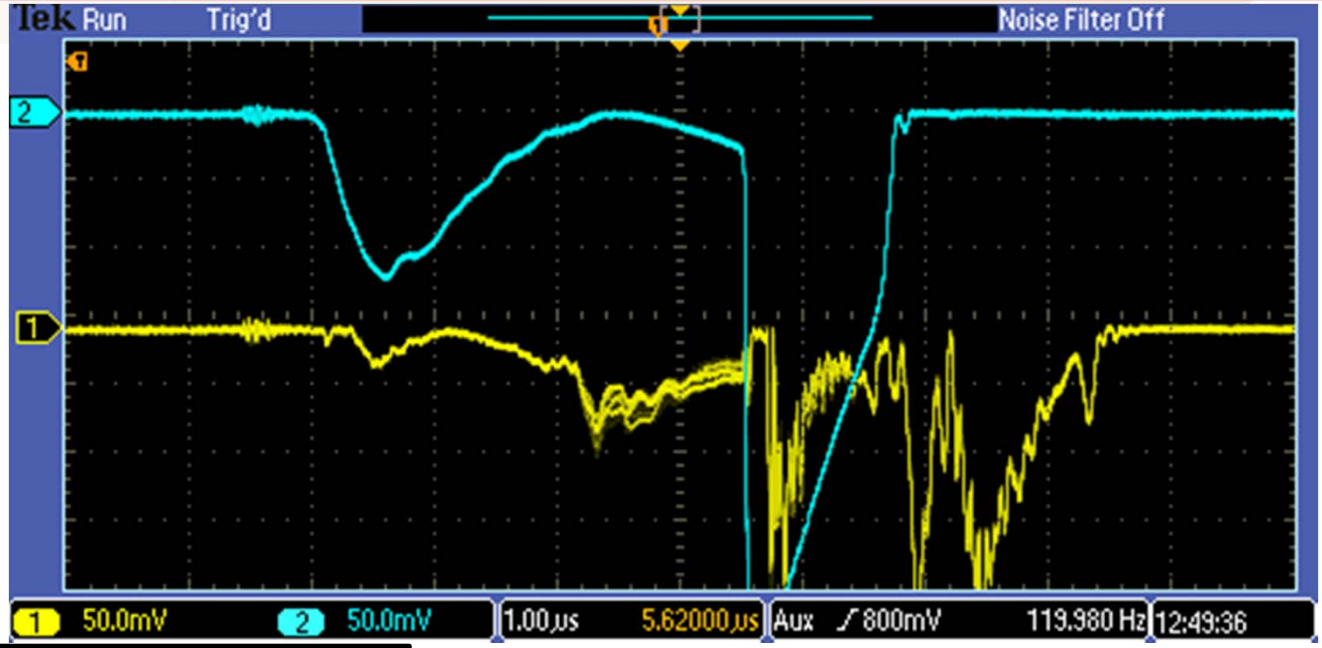


#1646 at 13 MW



Reflected RF Power Waveforms from Loads: <u>Unstable amplitudes and random phases propagate back to klystron through accelerating structures.</u>

SLED Output and Refl. Power at Klystron (typical)



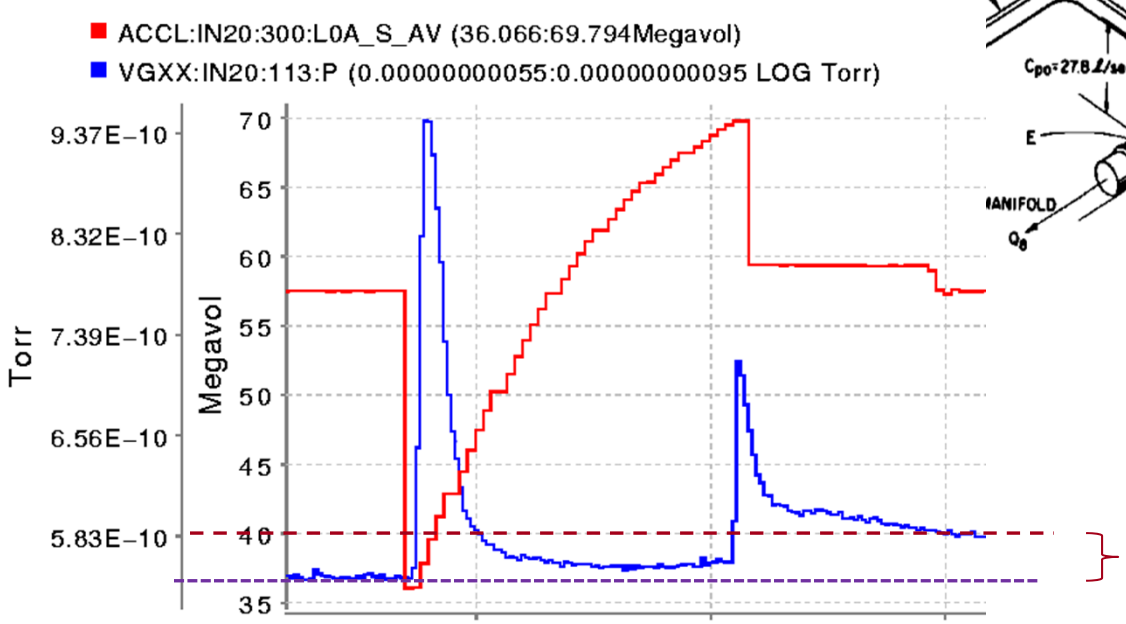
Ch 2 = Forward power from SLED output
Ch 1 = Reflected power waveguide port at klystron output

- Instability seen in refl. power after pulse travels to load and back
- Unstable termination takes place on all SLAC klystron stations
- Spare/unused RF loads are not acceptable (designed for 2 MW peak only)

Implications for Better RF Termination

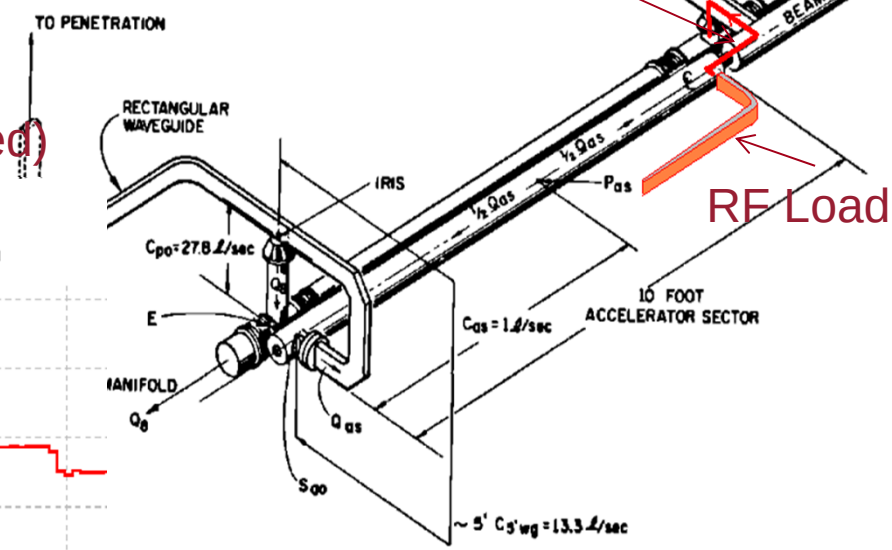
1) Reduced outgassing / multipactoring:

- Shorter RF processing times means readiness for beam delivery is faster
- Reduced photoinjector operating cost (photocathode vacuum quality improved)



Long recovery time

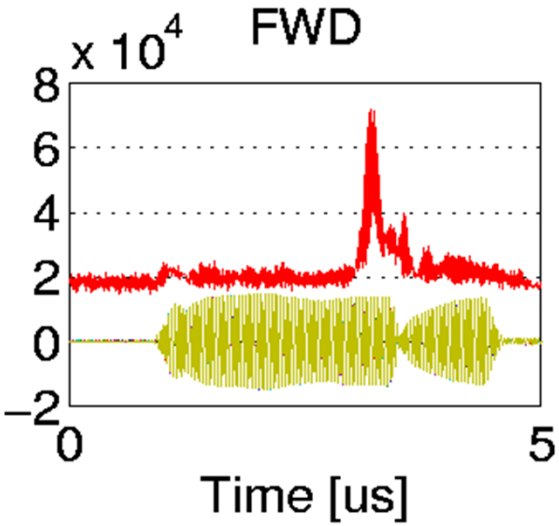
Gas burst is pumping through small aperture



Implications for Better RF Termination

2) Improved RF amplitude & phase stability

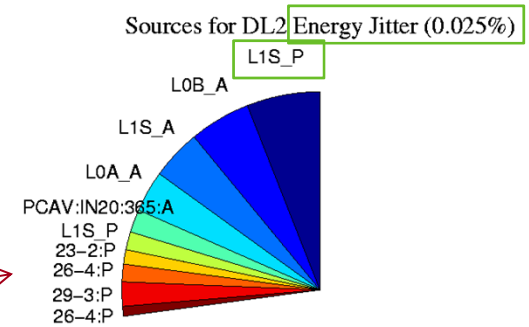
- Jitter from Refl. Power interference seen to account for **~1/3 of RF energy jitter**
- Every RF station contributes some increment of energy jitter to the beam
- Different implications for different parts of accelerator…

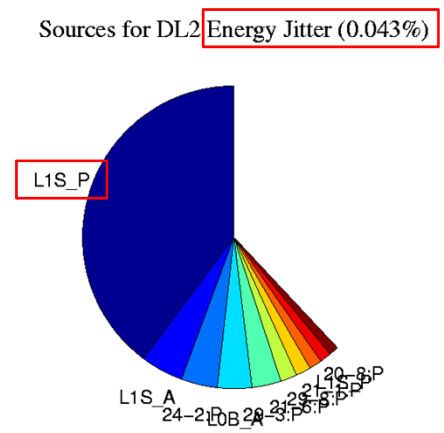


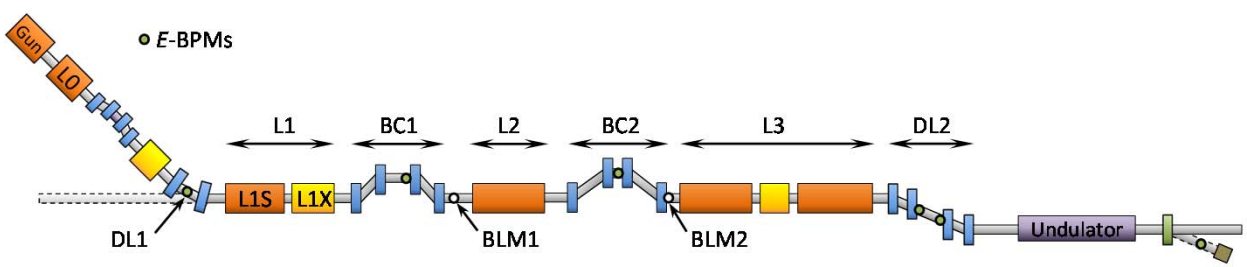
Implications for Better RF Termination

"Critical stations"

- Single stations before BC1 contribute **~50x** more effectively to jitter than those downstream
- Any failure of these critical stations immediately seen as primary jitter sources
- Refl. power avoided in critical stations by:
  - *Frequent, manual* tuning of RF pulse forms
  - *Restricting* modulator output power







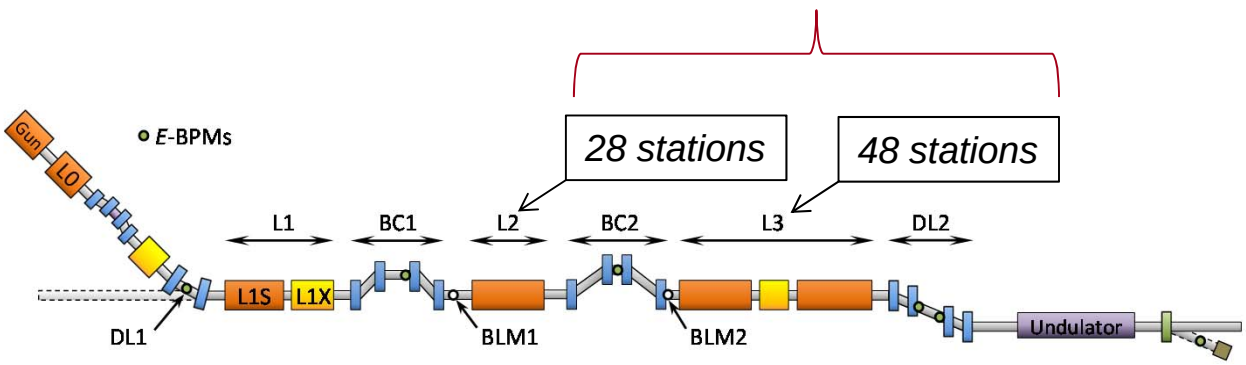
$$\sigma_{E,\text{beam,final}} = \left|1 + R_{65,\text{L2}} R_{56,\text{BC1}}\right| \sigma_{E,\text{beam,injector}}$$

$$\approx 48\,\sigma_{E,\text{beam,injector}}$$

Implications for Better RF Termination

"Non-critical stations"

- 76 RF accelerating stations in L2 / L3
- *Nominal* stability of these stations is sufficient
- The est. ~1/3 additional jitter from Load Refl. Power is *uncontrolled,* an open opportunity for improvement

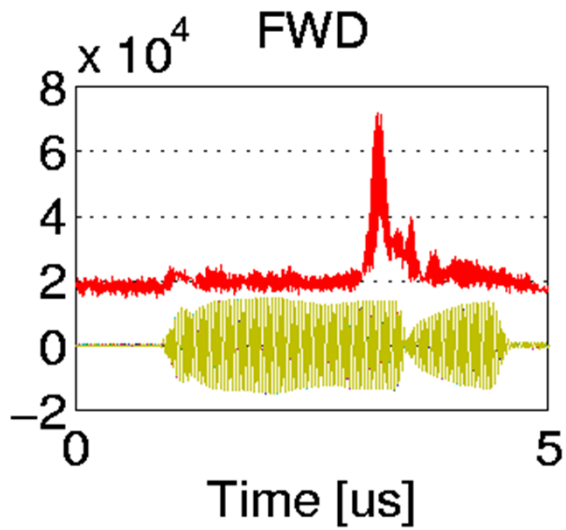


Implications for Better RF Termination

2) Improved RF amplitude & phase stability

***Passively stabilize* a known jitter source**

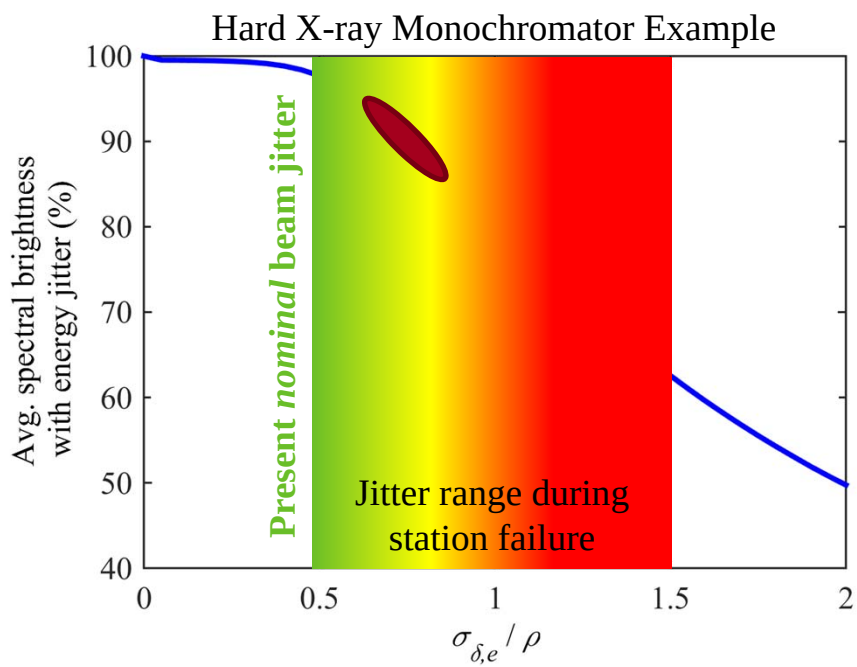
- Critical stations:
  - *Relax* allowed operating range
  - *Reduce* maintenance issues & costs
- Non-critical stations:
  - *Reduce* L2 / L3 jitter contributions
  - *Add previously unavailable contingency to beam energy stability*



Implications for Better RF Termination

3) *Better effective average spectral brightness* when using x-ray monochromator / self-seeding:

- Goal: Beam energy jitter < ½ SASE bandwidth
- Now jitter meets this goal *at best,* **but with ~*zero contingency***
- Improved loads reduce jitter, *passively maintain higher brightness*



Implications for Better RF Termination

- High-power RF termination goes beyond the LCLS
- Multi-MW RF power termination using the surface resistance technology proposed is a new advancement
- Potential applications of RF power termination in designs for, e.g., high order mode suppressors (LCLS-II, energy recovery linacs, stealth technology, etc.)

New RF Load Specification

- 320 loads support LCLS runs
- Only vacuum dry RF load approaches will be considered

Parameters	Short Pulse	Long Pulse
Pulse Width (μs)	1.0	4.0
Peak Power (MW)	30	12
Operating Frequency (MHz)	2.856	
Bandwidth (MHz)	20	
Input vswr	< 1.1	
Repetition Rate (Hz)	120	
Average Power (kW)	6.0	
Cooling Temperature (° C)	45	
Cooling Water Flow (m^3/hr)	1.2	
Cooling Pressure (kg/cm^2)	5.8	
Vacuum Leak Rate (Torr l/sec)	$2x10^{-10}$	

Reliable RF peak power termination and RF load lifetime requires careful study with *practical and repeatable solutions* for the current linac requirements

Basic of All-metal Waveguide Attenuation

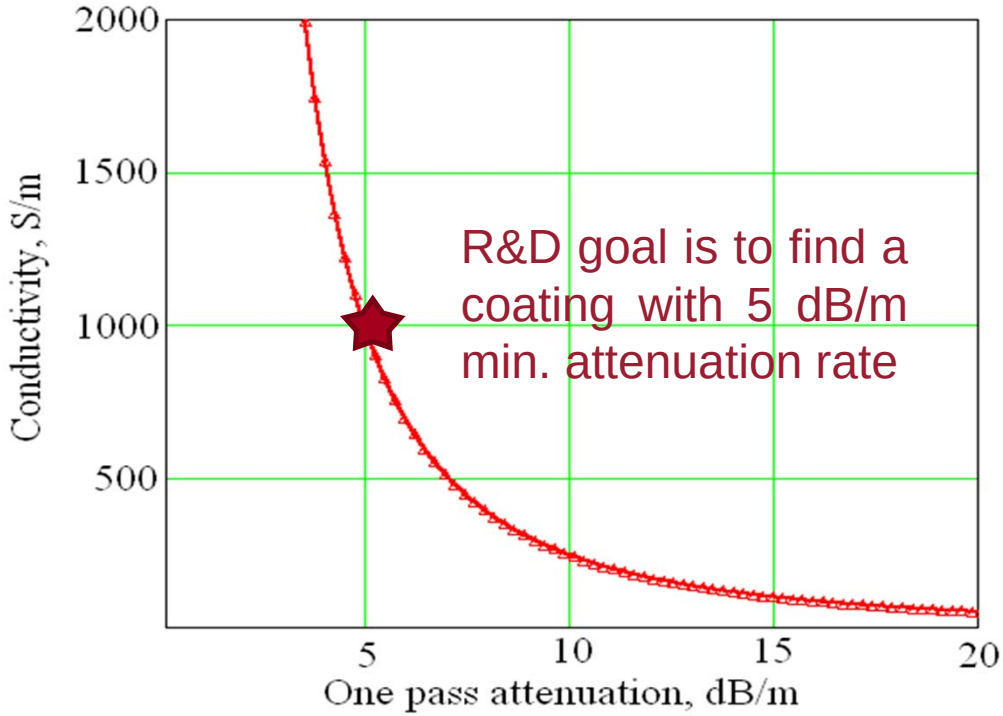
WR284: a= 2.84” and b=1.34”

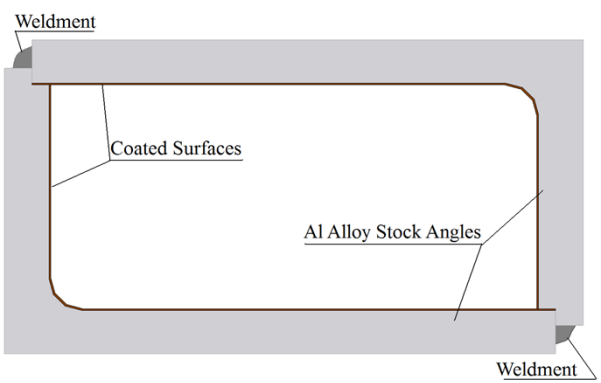
Attenuation of the TE10 mode in the WR284 waveguide

$$\alpha = \frac{R_s}{Z_0}\cdot\frac{2}{a}\cdot\frac{\left(\frac{\lambda}{2a}\right)^2}{\sqrt{1-\left(\frac{\lambda}{2a}\right)^2}} + \frac{R_s}{Z_0}\cdot\frac{1}{b}\cdot\frac{1}{\sqrt{1-\left(\frac{\lambda}{2a}\right)^2}}$$

$Z_0 = 120\pi \quad Ohm$ and

$$R_s = 10.88 * 10^{-3} * \sqrt{\left(\frac{10^7}{\sigma}\right)\frac{1}{\lambda}}$$

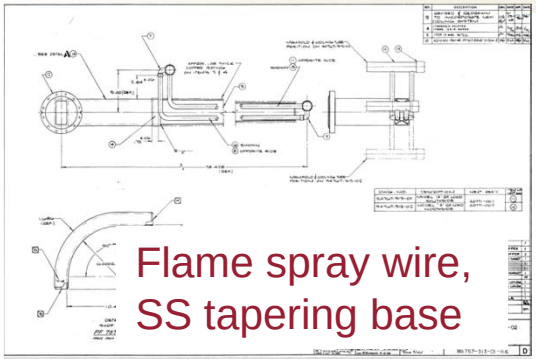




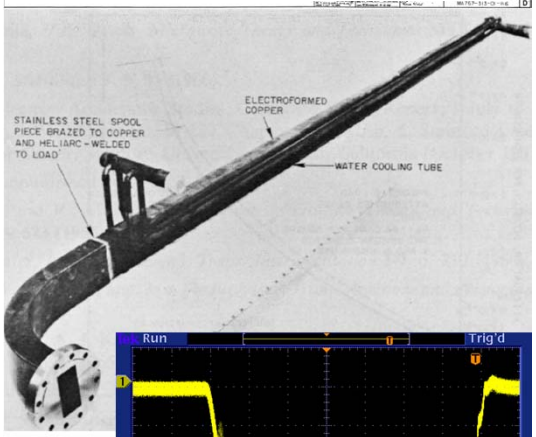
Most affordable solution: no matching impedance insertions, no brazing, no extrusion of the walls, no expensive mode converters, and no additional cooling system are needed.

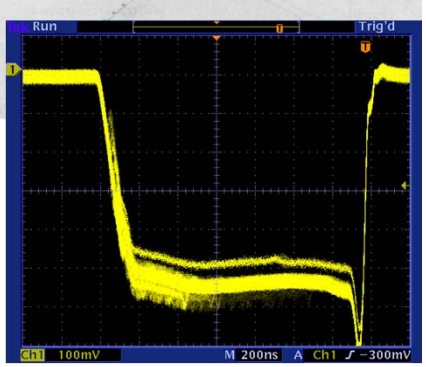
The minimal cost would be **~$4k per load**.

Original and Improved RF Loads

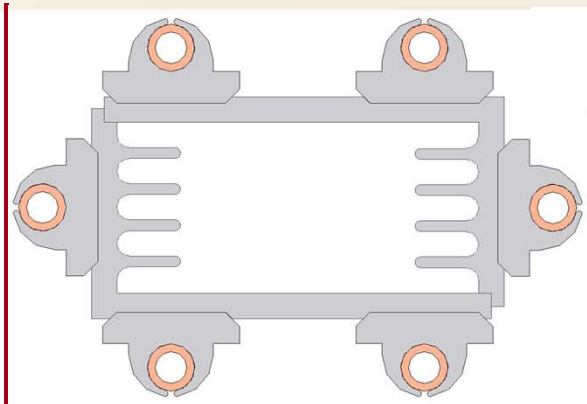


Flame spray wire,
SS tapering base

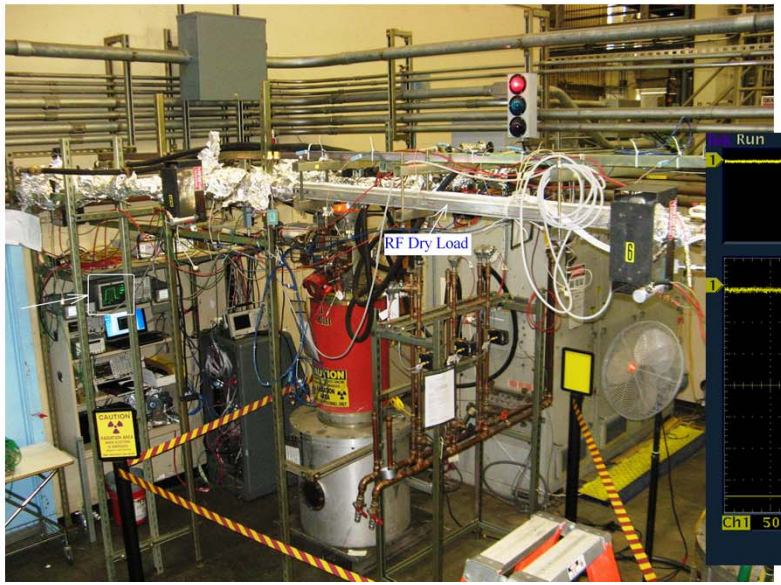


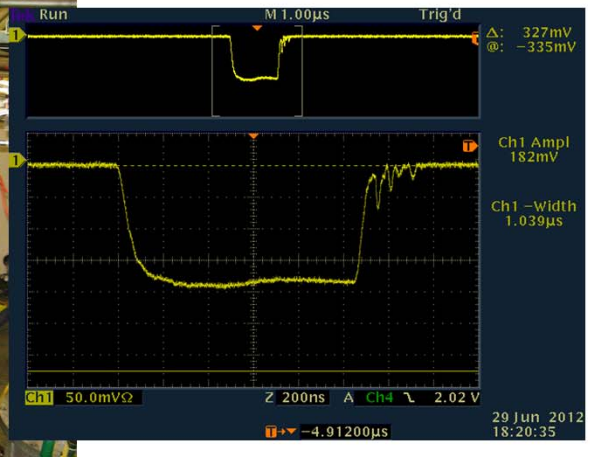


Original RF Load



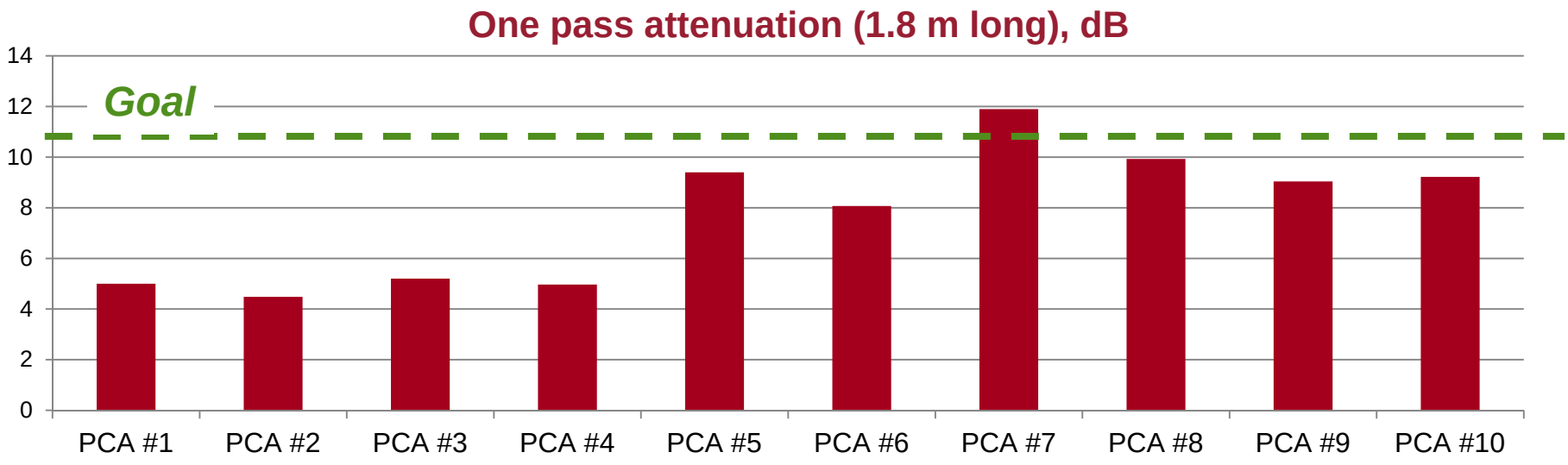
Plasma spray atomized powder,
Kerfs on H-plan WG walls,
No tapering





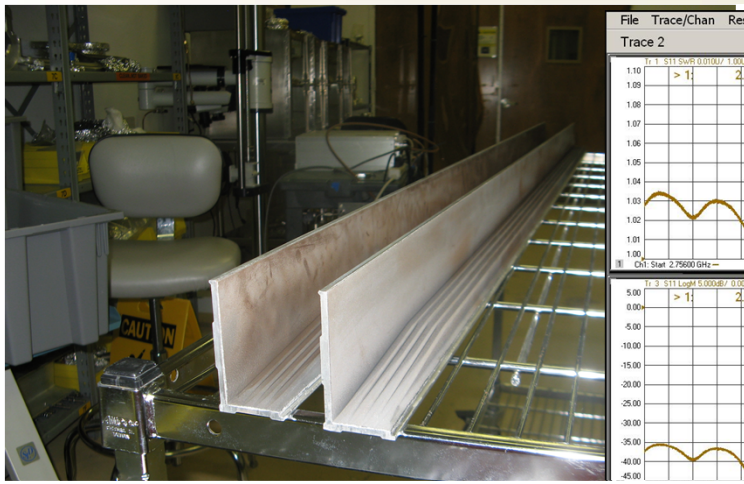
Up to 30 MW peak, 1 usec, 5 Hz (no H2O cooling) in 2012

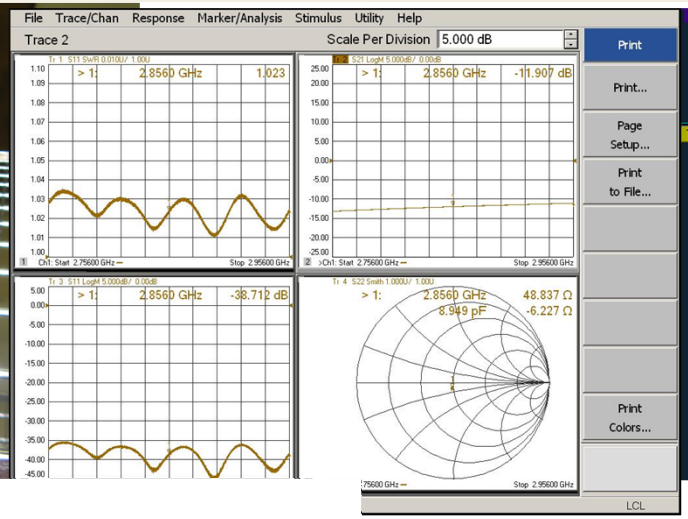
First Multi-MW RF Loads:
RF Attenuation with FeCrAl Matrix Plasma Spray

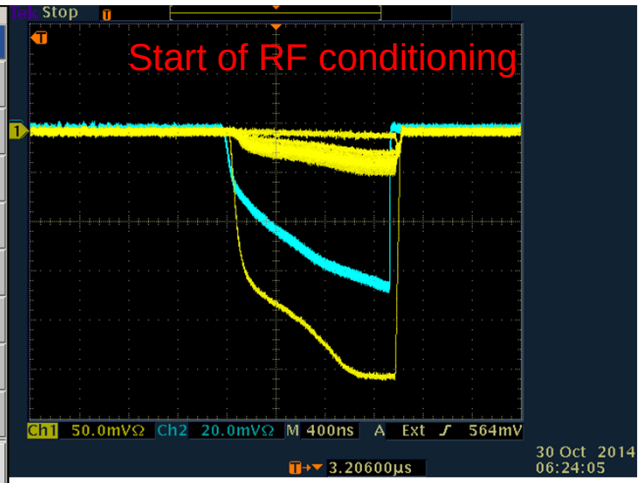


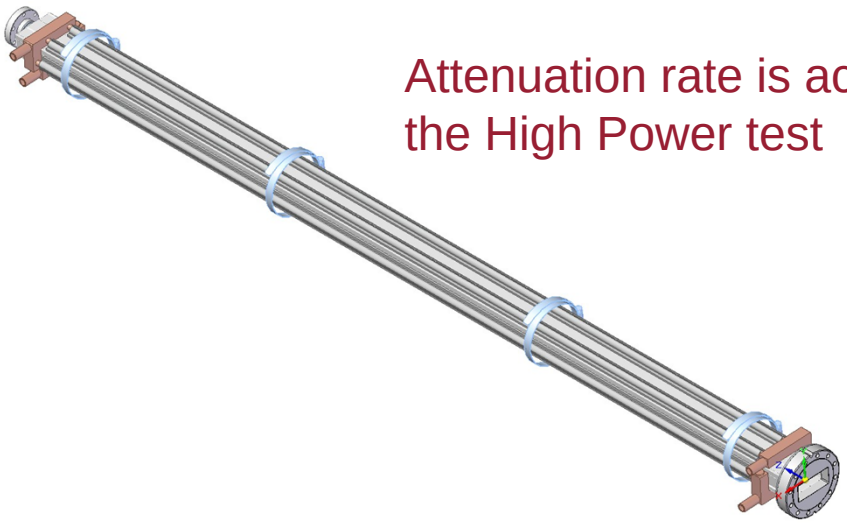
- First prototype batch showed encouraging results
- Reproducibility of the RF surface resistivity by APS Materials, Inc. (Dayton, OH) was unacceptable
- Local vendor Metal Fusion, Inc. (Redwood City, CA) under consideration now, offer faster / direct SLAC control of the thermal spay process for High Power RF applications

Example High Power Test of PCA #7

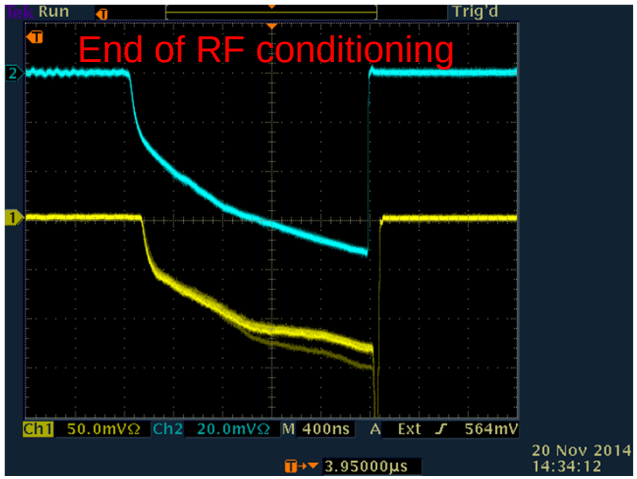






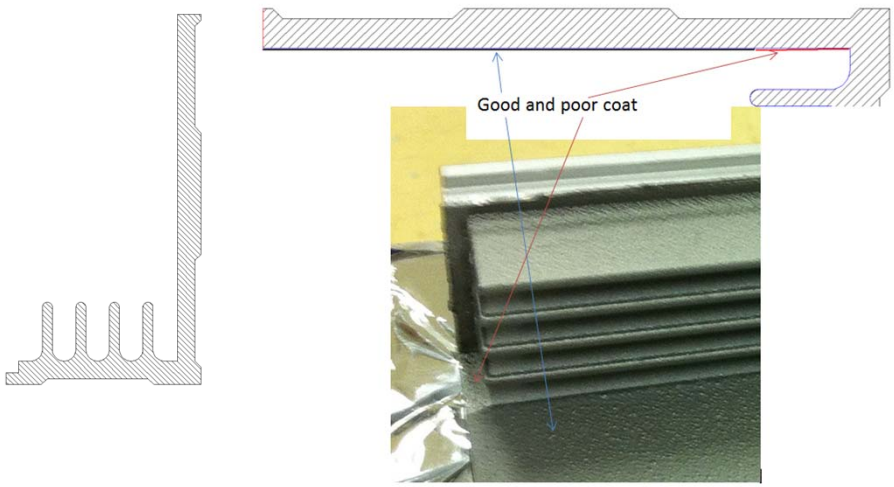


Attenuation rate is acceptable but the High Power test is not



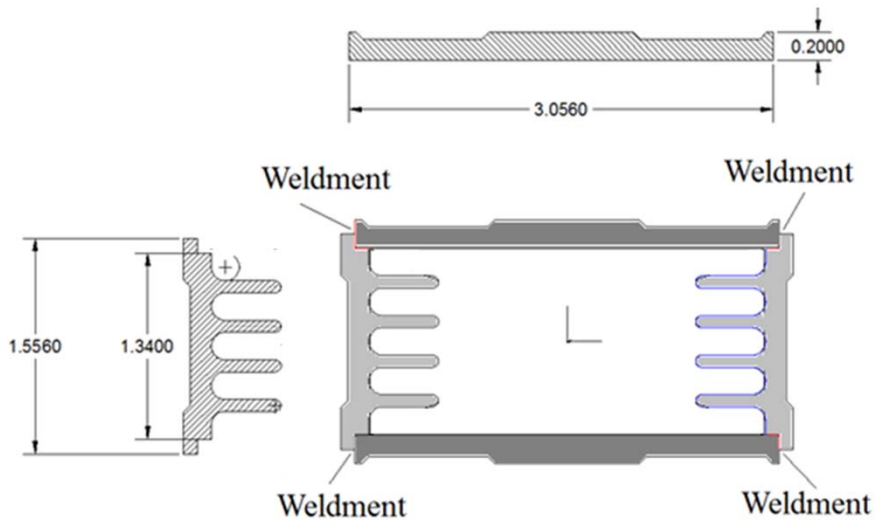
Improved Waveguide Design

Unevenness in E- and H- wall sizes



Gun nozzle / coating angle in corners also contributed to poor reproducibility

Updated Design

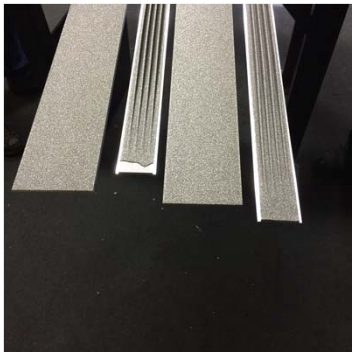


Updated Design:

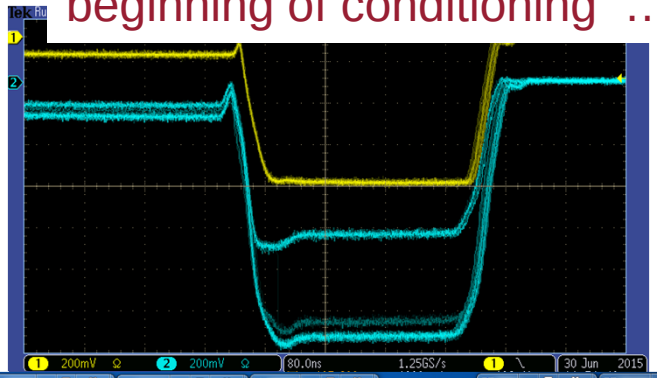
- Four welding corners to ease gun nozzle angle optimization
- New spray technology is employed
- Minor optimization in the RF Load design

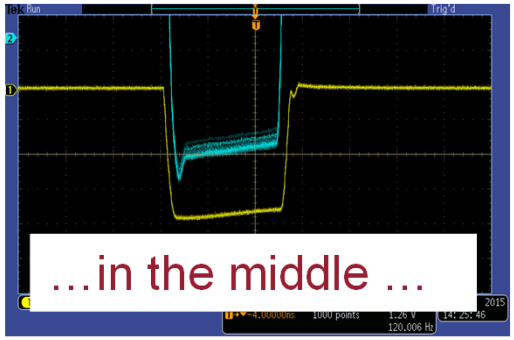
Two preproduction pilot RF Loads was fabricated

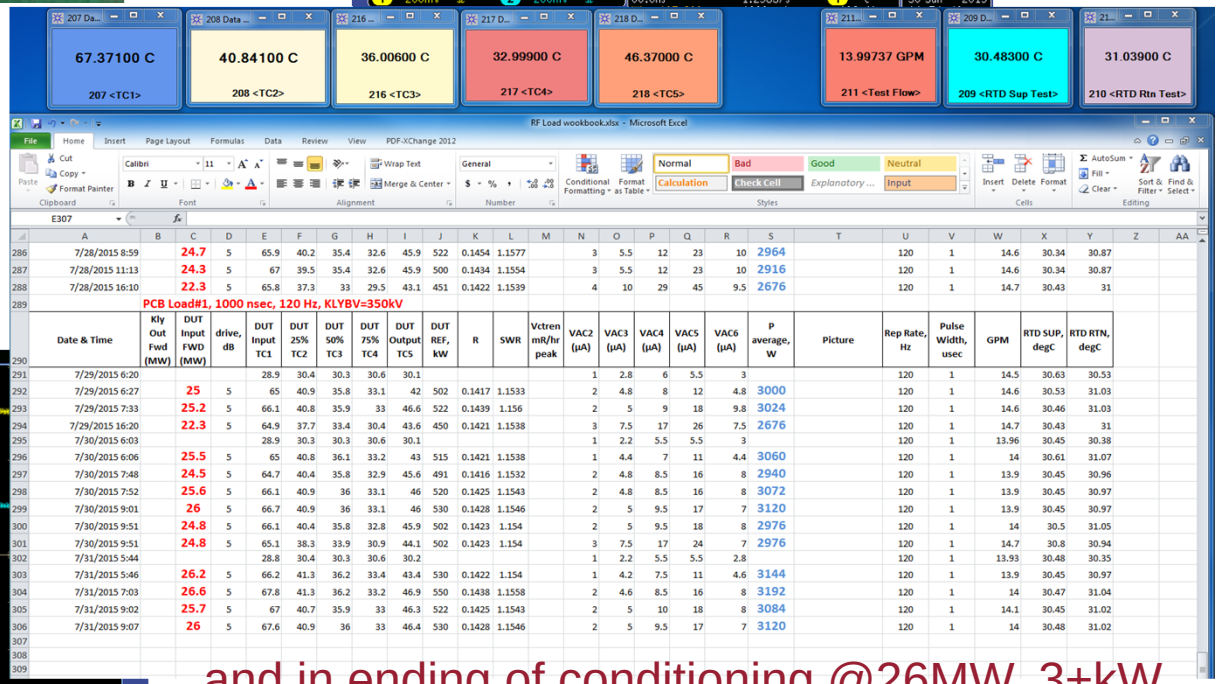
High RF Power Test of Pilot RF Load #1 (PCB RF Load #1)



FWD and REF RF powers in the beginning of conditioning …

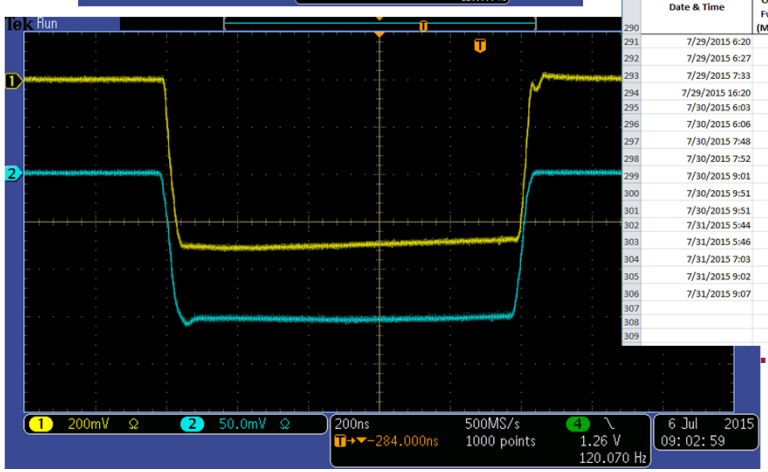






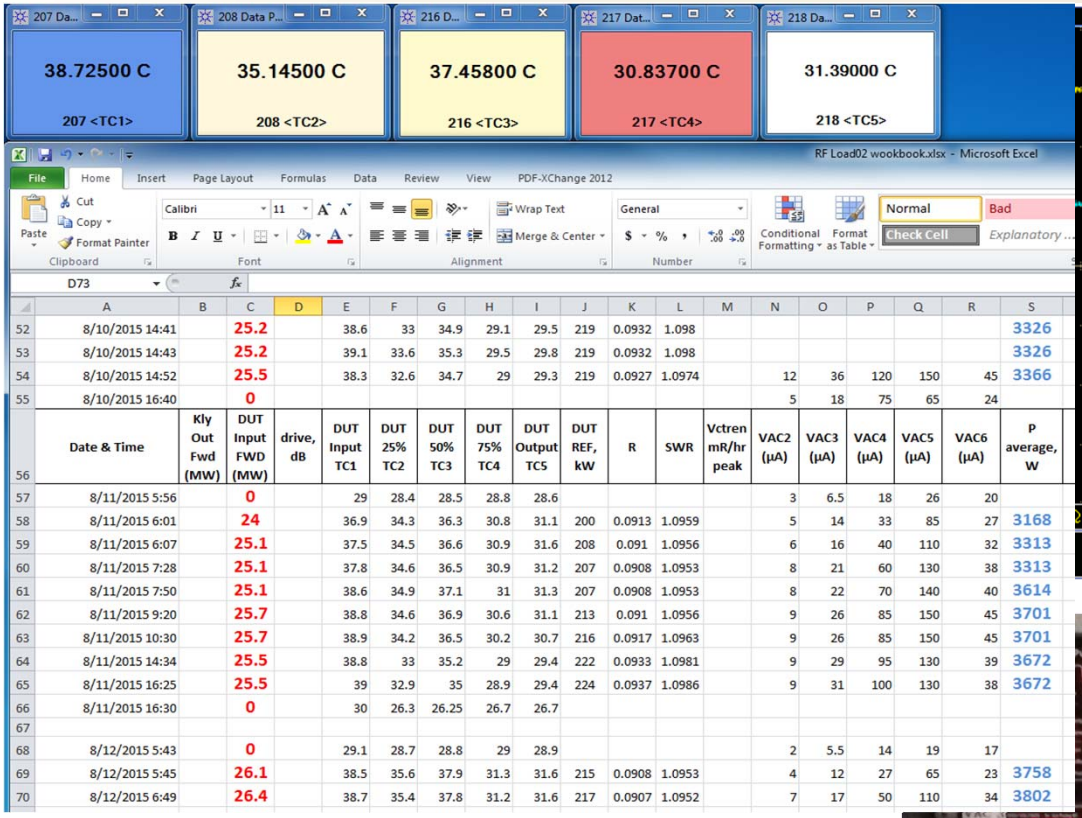
PCB Load#1, 1000 nsec, 120 Hz, KLYBV=350kV

Date & Time	Kly Out Fwd (MW)	DUT Input FWD (MW)	drive, dB	DUT Input TC1	DUT 25% TC2	DUT 50% TC3	DUT 75% TC4	DUT Output TC5	DUT REF, kW	R	SWR	Vctren mR/hr peak	VAC2 (µA)	VAC3 (µA)	VAC4 (µA)	VAC5 (µA)	VAC6 (µA)	P average, W	Picture	Rep Rate, Hz	Pulse Width, usec	GPM	RTD SUP, degC	RTD RTN, degC
7/28/2015 8:59		24.7	5	65.9	40.2	35.4	32.6	45.9	522	0.1454	1.1577		3	5.5	12	23	10	2964		120	1	14.6	30.34	30.87
7/28/2015 11:13		24.3	5	67	39.5	35.4	32.6	45.9	500	0.1434	1.1554		3	5.5	12	23	10	2916		120	1	14.6	30.34	30.87
7/28/2015 16:10		22.3	5	65.8	37.3	33	29.5	43.1	451	0.1422	1.1539		4	10	29	45	9.5	2676		120	1	14.7	30.43	31
7/29/2015 6:20				28.9	30.4	30.3	30.6	30.1					1	2.8	6	5.5	3			120	1	14.5	30.63	30.53
7/29/2015 6:27		25	5	65	40.9	35.8	33.1	42	502	0.1417	1.1533		2	4.8	8	12	4.8	3000		120	1	14.6	30.53	31.03
7/29/2015 7:33		25.2	5	66.1	40.8	35.9	33	46.6	522	0.1439	1.156		2	5	9	18	9.8	3024		120	1	14.6	30.46	31.03
7/29/2015 16:20		22.3	5	64.9	37.7	33.4	30.4	43.6	450	0.1421	1.1538		3	7.5	17	26	7.5	2676		120	1	14.7	30.43	31
7/30/2015 6:03				28.9	30.3	30.3	30.6	30.1					1	2.2	5.5	5.5	3			120	1	13.96	30.45	30.38
7/30/2015 6:06		25.5	5	65	40.8	36.1	33.2	43	515	0.1421	1.1538		1	4.4	7	11	4.4	3060		120	1	14	30.61	31.07
7/30/2015 7:48		24.5	5	64.7	40.4	35.8	32.9	45.6	491	0.1416	1.1532		2	4.8	8.5	16	8	2940		120	1	13.9	30.45	30.96
7/30/2015 7:52		25.6	5	66.1	40.9	36	33.1	46	520	0.1425	1.1543		2	4.8	8.5	16	8	3072		120	1	13.9	30.45	30.97
7/30/2015 9:01		26	5	66.7	40.9	36	33.1	46	530	0.1428	1.1546		2	5	9.5	17	7	3120		120	1	13.9	30.45	30.97
7/30/2015 9:51		24.8	5	66.1	40.4	35.8	32.8	45.9	502	0.1423	1.154		2	5	9.5	18	8	2976		120	1	14	30.5	31.05
7/30/2015 9:51		24.8	5	65.1	38.3	33.9	30.9	44.1	502	0.1423	1.154		3	7.5	17	24	7	2976		120	1	14.7	30.8	30.94
7/31/2015 5:44				28.8	30.4	30.3	30.6	30.2					1	2.2	5.5	5.5	2.8			120	1	13.93	30.48	30.35
7/31/2015 5:46		26.2	5	66.2	41.3	36.2	33.4	43.4	530	0.1422	1.154		1	4.2	7.5	11	4.6	3144		120	1	13.9	30.45	30.97
7/31/2015 7:03		26.6	5	67.8	41.3	36.2	33.2	46.9	550	0.1438	1.1558		2	4.6	8.5	16	8	3192		120	1	14	30.47	31.04
7/31/2015 9:02		25.7	5	67	40.7	35.9	33	46.3	522	0.1425	1.1543		2	5	10	18	8	3084		120	1	14.1	30.45	31.02
7/31/2015 9:07		26	5	67.6	40.9	36	33	46.4	530	0.1428	1.1546		2	5	9.5	17	7	3120		120	1	14	30.48	31.02

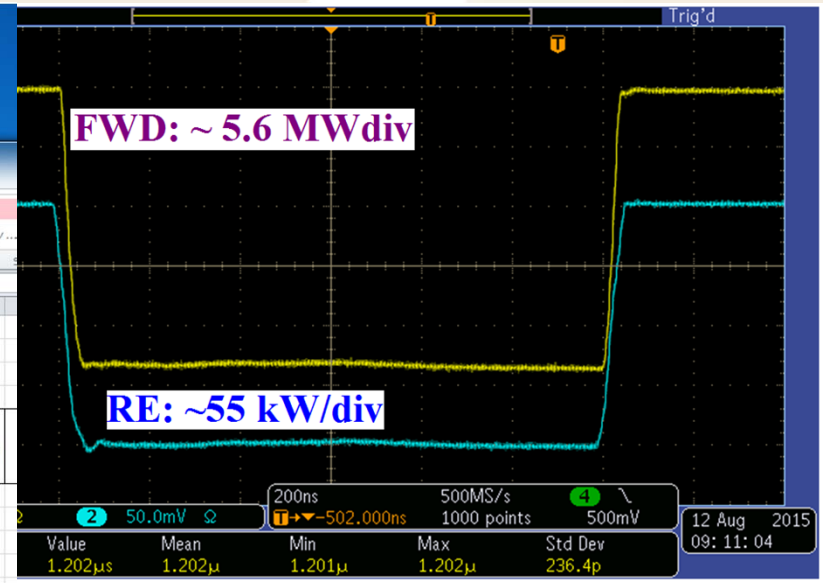


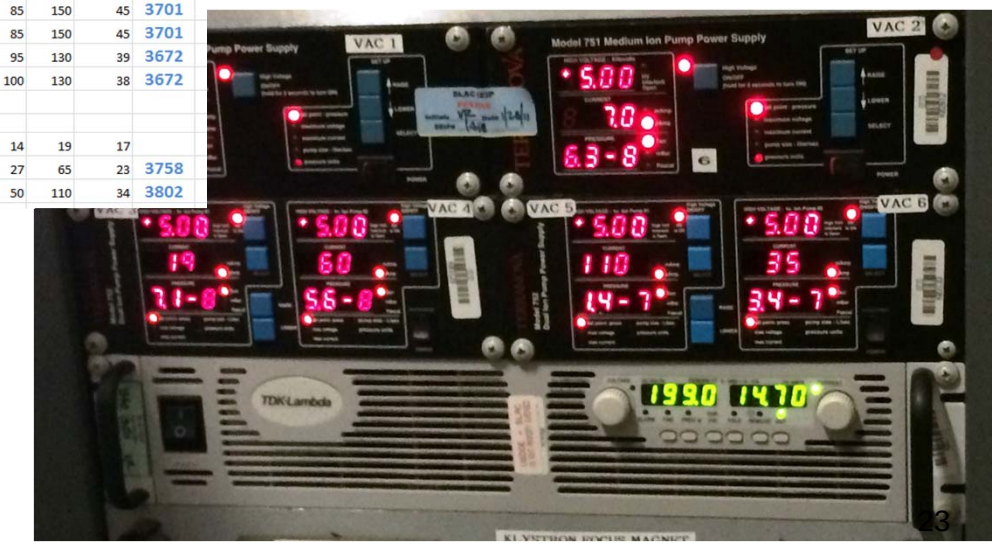
… and in ending of conditioning @26MW, 3+kW

High Power Test of Pilot RF Load #2



	Date & Time	Kly Out Fwd (MW)	DUT Input FWD (MW)	drive, dB	DUT Input TC1	DUT 25% TC2	DUT 50% TC3	DUT 75% TC4	DUT Output TC5	DUT REF, kW	R	SWR	Vctren mR/hr peak	VAC2 (µA)	VAC3 (µA)	VAC4 (µA)	VAC5 (µA)	VAC6 (µA)	P average, W
52	8/10/2015 14:41		25.2		38.6	33	34.9	29.1	29.5	219	0.0932	1.098							3326
53	8/10/2015 14:43		25.2		39.1	33.6	35.3	29.5	29.8	219	0.0932	1.098							3326
54	8/10/2015 14:52		25.5		38.3	32.6	34.7	29	29.3	219	0.0927	1.0974		12	36	120	150	45	3366
55	8/10/2015 16:40		0											5	18	75	65	24	
56																			
57	8/11/2015 5:56		0		29	28.4	28.5	28.8	28.6					3	6.5	18	26	20	
58	8/11/2015 6:01		24		36.9	34.3	36.3	30.8	31.1	200	0.0913	1.0959		5	14	33	85	27	3168
59	8/11/2015 6:07		25.1		37.5	34.5	36.6	30.9	31.6	208	0.091	1.0956		6	16	40	110	32	3313
60	8/11/2015 7:28		25.1		37.8	34.6	36.5	30.9	31.2	207	0.0908	1.0953		8	21	60	130	38	3313
61	8/11/2015 7:50		25.1		38.6	34.9	37.1	31	31.3	207	0.0908	1.0953		8	22	70	140	40	3614
62	8/11/2015 9:20		25.7		38.8	34.6	36.9	30.6	31.1	213	0.091	1.0956		9	26	85	150	45	3701
63	8/11/2015 10:30		25.7		38.9	34.2	36.5	30.2	30.7	216	0.0917	1.0963		9	26	85	150	45	3701
64	8/11/2015 14:34		25.5		38.8	33	35.2	29	29.4	222	0.0933	1.0981		9	29	95	130	39	3672
65	8/11/2015 16:25		25.5		39	32.9	35	28.9	29.4	224	0.0937	1.0986		9	31	100	130	38	3672
66	8/11/2015 16:30		0		30	26.3	26.25	26.7	26.7										
67																			
68	8/12/2015 5:43		0		29.1	28.7	28.8	29	28.9					2	5.5	14	19	17	
69	8/12/2015 5:45		26.1		38.5	35.6	37.9	31.3	31.6	215	0.0908	1.0953		4	12	27	65	23	3758
70	8/12/2015 6:49		26.4		38.7	35.4	37.8	31.2	31.6	217	0.0907	1.0952		7	17	50	110	34	3802





This is the first RF load that can be accepted for an installation in the LCLS Injector.

Three-Phase Plan Overview

Phase I (present-term R&D)

- Establish and demonstrate RF Load fabrication methodology, high power handling

Phase II

- Limited rollout to critical LCLS RF stations (L0A, L0B, L1S)

Phase III

- Major, full-production rollout to remaining L2 and L3 stations

Proposed Strategic Plan

Assumption: Phase 1 (R&D) complete

Phase 2, Critical stations:

1. Fabrication of 10 ea. RF Loads.
2. RF load life time experiments on Klystron Lab RF Test Stand (RF absorber degradation issues at 25 MW peak, 3 kW average, 120Hz).
3. Plan installation of loads in critical LCLS stations (L0A, L0B, and L1S).
4. Installation of RF loads on the LCLS Injector during summer or winter break period (TBD).

Proposed Strategic Plan

SLAC

Assumption: Phase 2 complete

Phase 3, Major rollout:

1. License company to fabricate
2. Purchase loads for one sector (32 ea. x $4k =$128k). Inspection of delivery and acceptance HP RF tests (24 hr run per each load). Store acceptable RF loads for linac installation.
3. Work plan for replacements. Paperwork for storage of old RF loads. WPC for the linac installation (a job is one person during two working weeks).
4. Replacement of 32 RF loads. Estimate 2 loads replaced per 8 hours.
5. Vacuum leak checks and RF processing activities.
6. Repeat 2 through 5 for each of 10 sectors.

LCLS:80 stations, 320 loads, $1.3M (M&S), 1 year for acceptance tests, one quarter for installation & RF processing @ $0.8M

Three-Phase Plan Overview

Phase I

- Optimize spray technology to obtain required RF attenuation rates and reproducibility
- Fabricate preproduction pilot RF Loads for high power tests
- Perform HP RF Load life time experiments
- Perform proof-of-principle RF station stabilization test
- Provide recommendation for SLAC installation

Phase II (Linacs 0 and 1, critical stations)

- Fabricate pilot RF Loads for critical LCLS stations (L0A, L0B, L1S)
- High Power Test pilot loads and select best candidates
- Install to L0A, L0B, and L1S

Phase III (Linacs 2 and 3)

- License company to fabricate
- Purchase 32 RF Loads per LCLS sector
- High Power Acceptance Test of delivered loads
- Storage and plan for replacement

Backup Slides (a support of my slides #3 and #4)

SLAC

SLAC Linac RF Sources Before HEP Run

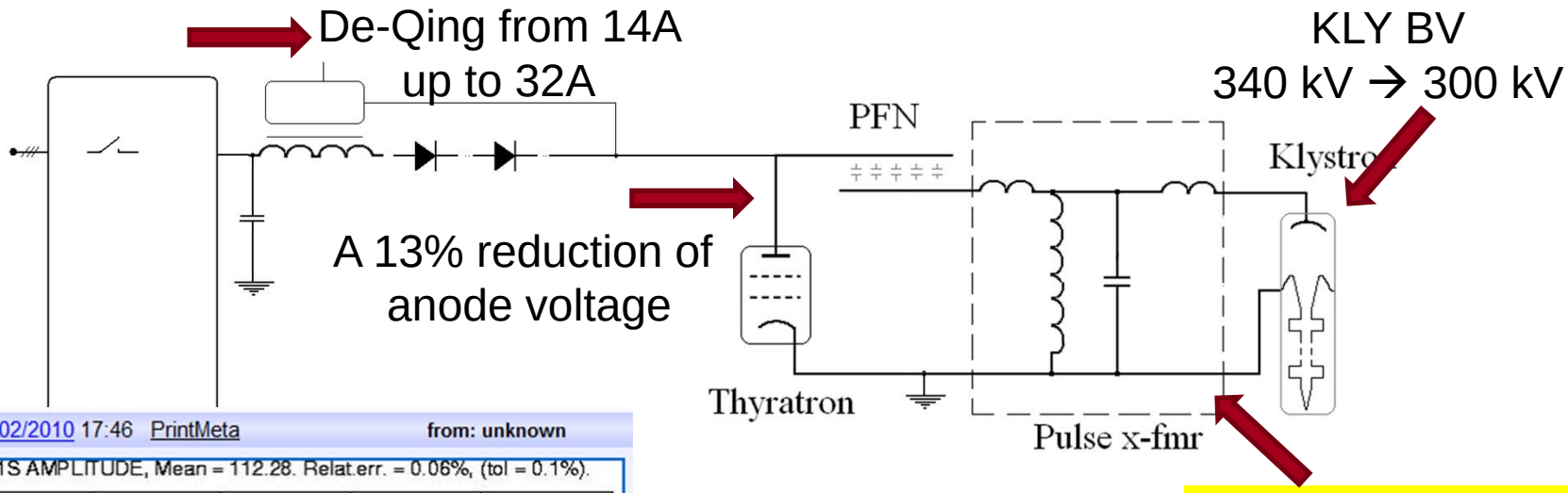
Table 10-5 Klystron endurance run results

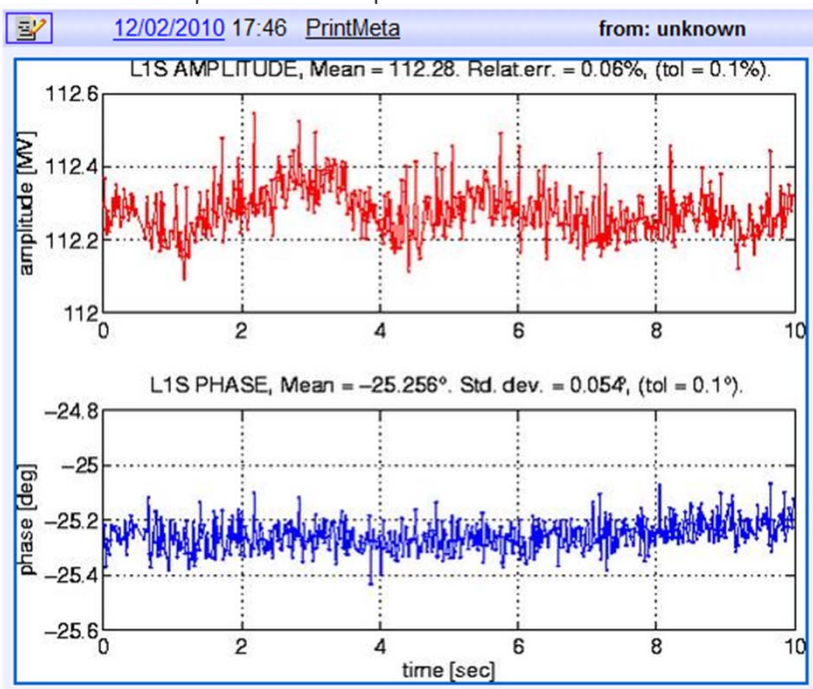
Sector pair	Operating level: Reference voltage	Klystron beam voltage	Klystron peak output power (MW)	Repetition rates	Average operating hours per socket	Cumu klyst failu
3/4	115	240–250	19–22	60	1175	1
5/6	115	240–250	19–22	360	1050	6
7/8	105	220–230	16–18	60	1200	—
9/10[a]	105	220–230	16–18	180	1140	—
13/14	105	220–230	16–18	360	1135	2
15/16	90	195–205	11–14	60	1200	1
17/18	90	195–205	11–14	360	1190	—

[a] This pair of sectors began the run approximately 60 hours after the others.

Source: “Blue Book”

Pulse-to-Pulse Stability of L1S Modulator





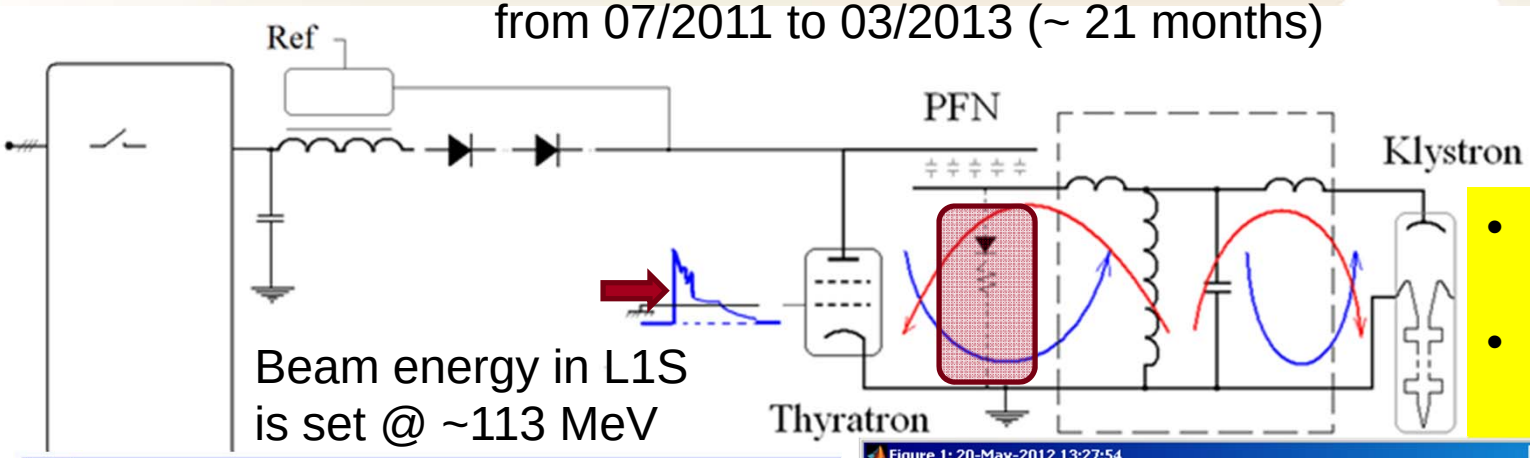
RF pulse width is 1.5 usec *)

~30% reduction of reactive energy in the pulse x-fmr

There is a soft & relaxing deionization & recovering in the thyratron. It has NO back-swing jitter at all. There was aprox. 20% phase jitter reduction

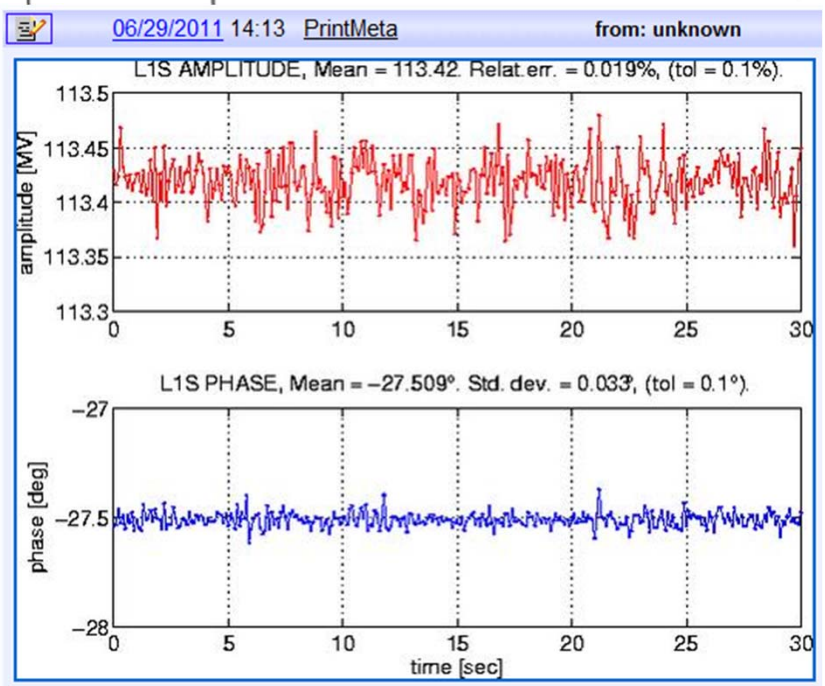
Pulse-to-Pulse Stability of L1S Modulator

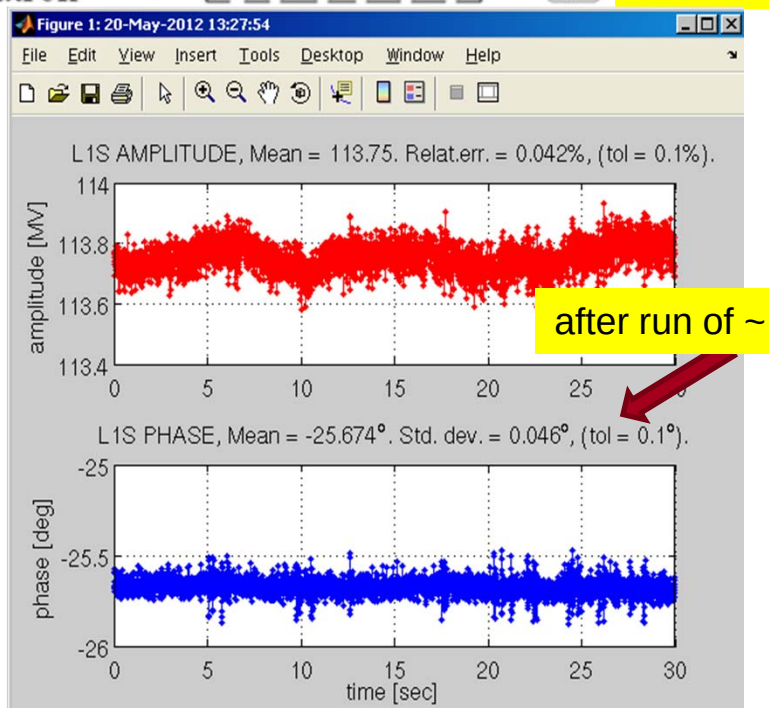
from 07/2011 to 03/2013 (~ 21 months)



Beam energy in L1S is set @ ~113 MeV

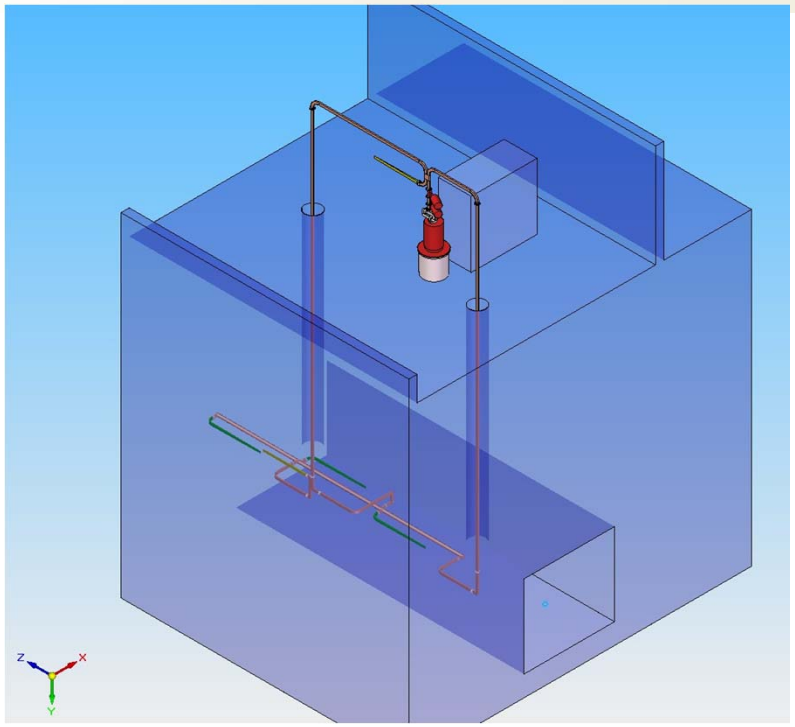
- Detuned SLED mode
- 1.0 usec RF pulse width

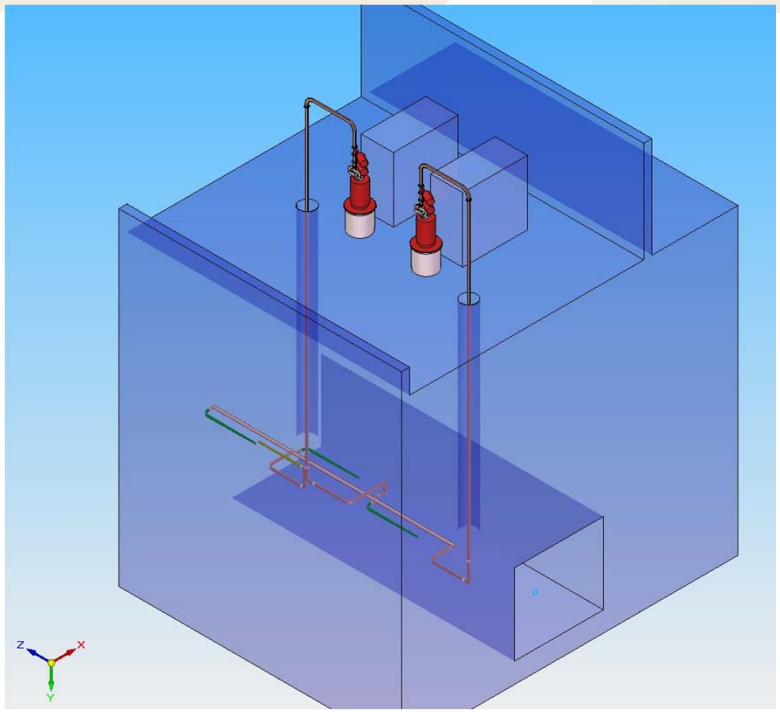




after run of ~ 11 months

System Approach for Unstressed L1S Station





Two modulators in the L1S configuration

A reduction of the thyratron anode voltage leads to the reduction of current through devise and accordingly to a sufficient reduction of the reactive energy in x-fmr (a square rule!). There will be less thyratrons for a salvage.

There will be more a headroom to reach a high peak current mode in BC1
A beam phase control is more flexible.