LCLS-II

RF Design

Chris Adolphsen

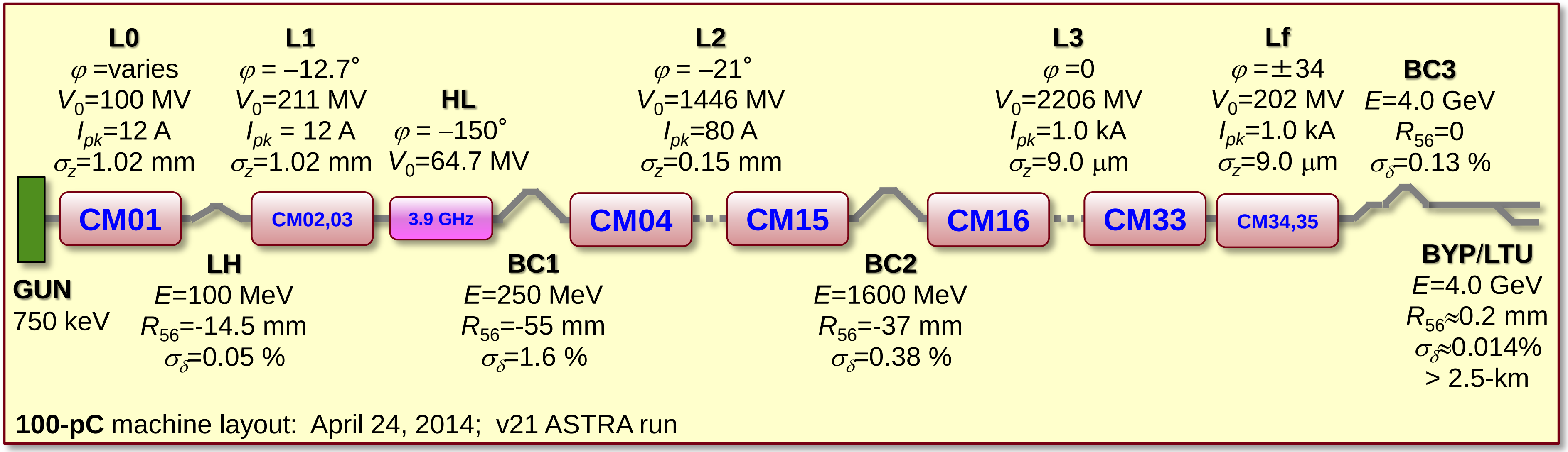
LCLS-II Director's Review

August 19-21, 2014

SLAC NATIONAL ACCELERATOR LABORATORY
BERKELEY LAB Lawrence Berkeley National Laboratory
Argonne NATIONAL LABORATORY
Cornell University
Fermilab
Jefferson Lab

U.S. DEPARTMENT OF ENERGY Office of Science

Linac Layout, Gradients, Spares and Cavities per Source



Linac Sec.	V_0 (MV)	φ (deg)	Acc. Grad.* (MV/m)	No. Cryo Mod's	No. Avail. Cav's	Spare Cav's	Cav's per Amp.
L0	100	varies	16.3	1	8	1	1
L1	211	-12.7	13.6	2	16	1	1
HL	-64.7	-150	12.5	2	16	1	1
L2	1446	-21.0	15.5	12	96	6	48
L3	2206	0	15.7	18	144	9	48
Lf	202	±34	15.7	2	16	1	1

One SSA Per Cavity

One Klystron per 6 CMs

RF Power per Cavity

$$P_i(Q_L,\Delta f_c)=\frac{V_c^2}{4(R/Q)Q_L}\left[\left(1+\frac{I_b}{V_c}\frac{R}{Q}Q_L\cos\phi_b\right)^2+\left(2Q_L\frac{\Delta f_c}{f}+\frac{I_b}{V_c}\frac{R}{Q}Q_L\sin\phi_b\right)^2\right]$$

- Δf_c is the cavity detuning – run offset to zero second term
- Spec for 100 uA beam initially and up to 10 Hz detuning variation
- Set QL = 4.1e7 – this minimizes power for 300 uA beam and 10 Hz offset
  - Do not want to increase QL further as BW is only 32 Hz with this choice
- Current * Voltage = 1.7 kW at 16 MV/m (on crest)
- Need 2.6 kW with no frequency offset and no overhead
- Need 3.8 kW with 10 Hz offset, 6% overhead for losses and 10 % overhead for tuning

Other Requirements

- Stability: RF feedback will be used to achieve 0.01% amplitude and 0.01 deg phase level stability on a few second time scale (detailed specs on next slide)
  - Beam energy FB stabilizes longer term energy variations
- Reasonable efficiency, although not a major cost driver
- High availability (< 1% of down time for the full system)
- Proven, off-the-shelf designs
- Low cost

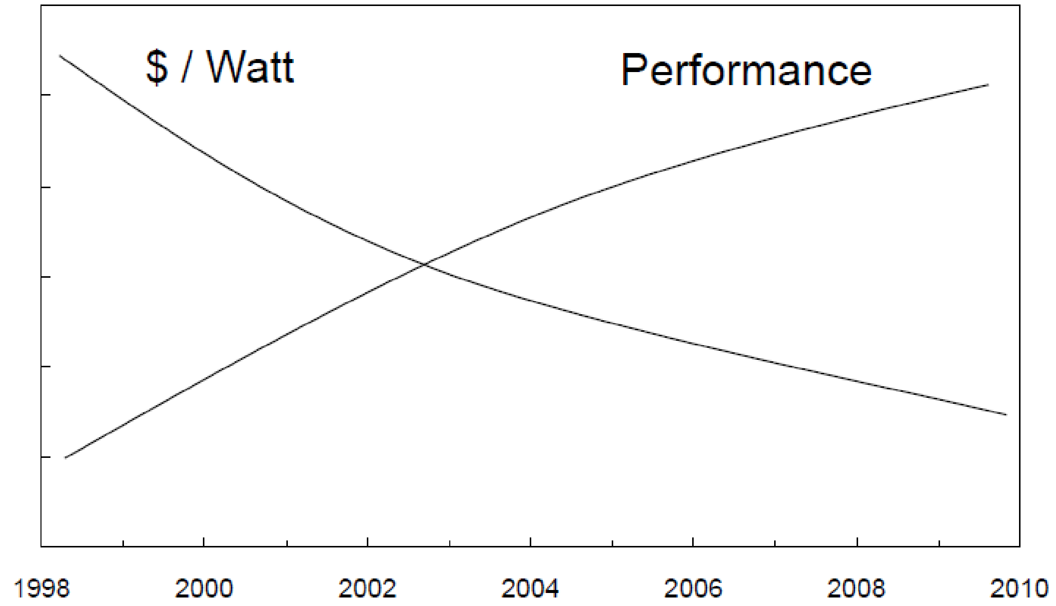
Source Options

- General Considerations
  - High power source feeding multiple cavities least expensive
  - However piezo-actuators critical to keep cavity gradient stable (not proven)
  - Use single source per cavity upstream of BC1, and multiple cavities per source downstream if viability demonstrated
- Single Source per Cavity Options
  - Klystrons become costly per W at low power and lowest cost verisons only ~ 40 % efficient
  - IOTs have higher efficiency (~ 60 %) but higher cost
  - Solid State Amplifiers (SSAs) cost competitive but currently have low efficiency (35%) - however, high availability (modular), and cost likely to decrease and efficiency increase (expect > 40 % soon).

SSA Si Transistor Trends

Trends in LDMOS Cost vs Performance

No Scale



This behavior has enabled entire industries where no commercially available / viable solution was possible before

Operational Cost Saving with GaN Transistors

	Si LDMOS	GaN HEMT
Power per Transistor Pair	160 W	400 W
Transistor efficiency	43 %	60 %
Combination efficiency	86 %	90 %
AC-RF efficiency	35 %	51 %
Annual power cost (280 units at 3.8 kW)	910 k$	620 k$

There should also be a ~ 30% cost/unit savings given less modules are needed

Source Choices

- Use 3.8 kW Solid State Amplifiers (SSAs) to drive single cavities
  - Have cost quotes from six vendors
  - 10 SigmaPhi 10 kW units operated ~ 10 khr at ELBE/HZDR
- Use 300 kW klystrons to drive 48 cavities (6 CMs) - aimed at future 300 uA operation (182 kW needed initally)
  - Max power available and near practical limit for rf distribution
  - Developed by Toshiba for KEK ERL Demo, and by CPI for HZB and TRIUMF applications
  - No long term operation experience but not pushing limits - CPI and e2V have been selling 110 -120 kW tubes

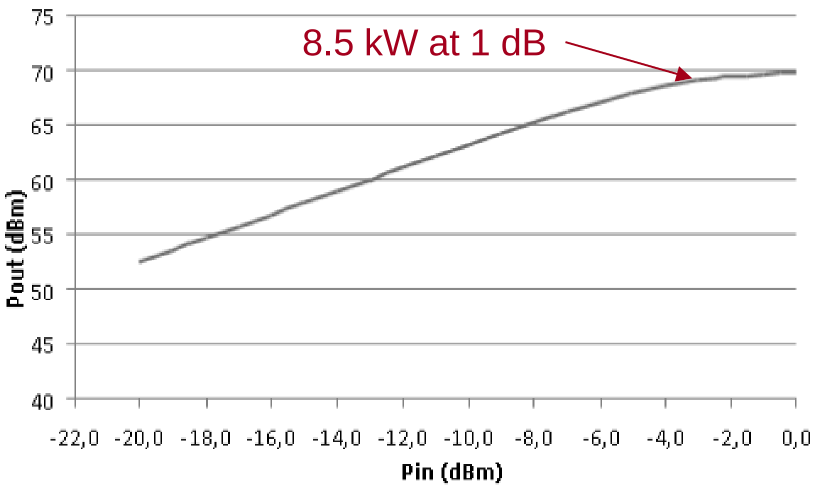
SigmaPhi 10 kW CW Solid State Amplifier

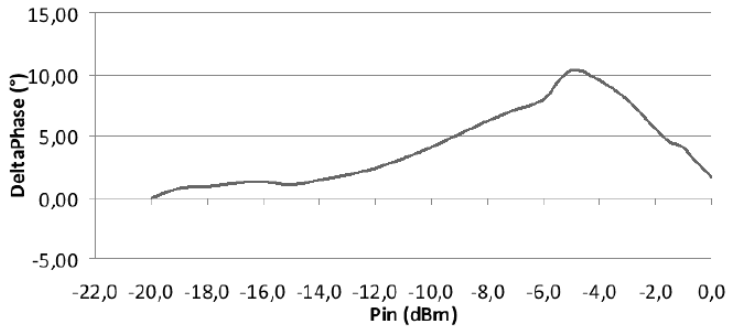
Consists of eight 1.25 kW water-cooled modules - each module has eight 160 W, isolated transistor units that are summed in a coaxial combiner – the output of the each module drives a common WR650 waveguide

Newer units with higher power transistors produce 16 kW in one rack

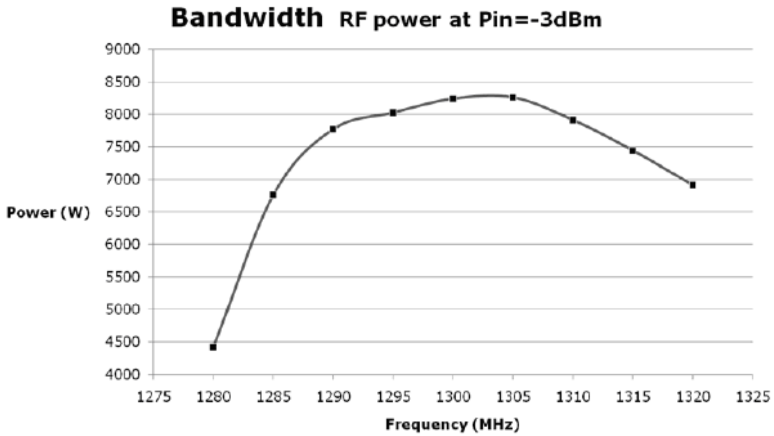
Ten 10 kW units at ELBE/HZDR and a 5 kW unit at Cornell

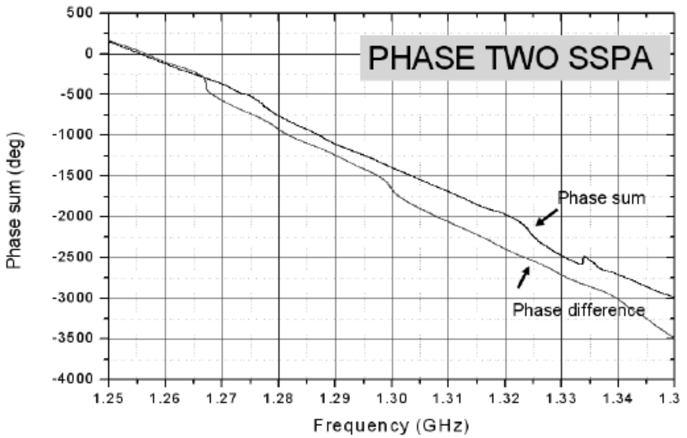
SigmaPhi 10 kW SSA Performance at ELBE





Wide BW – need only few hundred kHz for LCLS-II





*Hartmut Büttig, MOPC128, IPAC2011

SigmaPhi BLA5000 CW 1300 MHz Specs

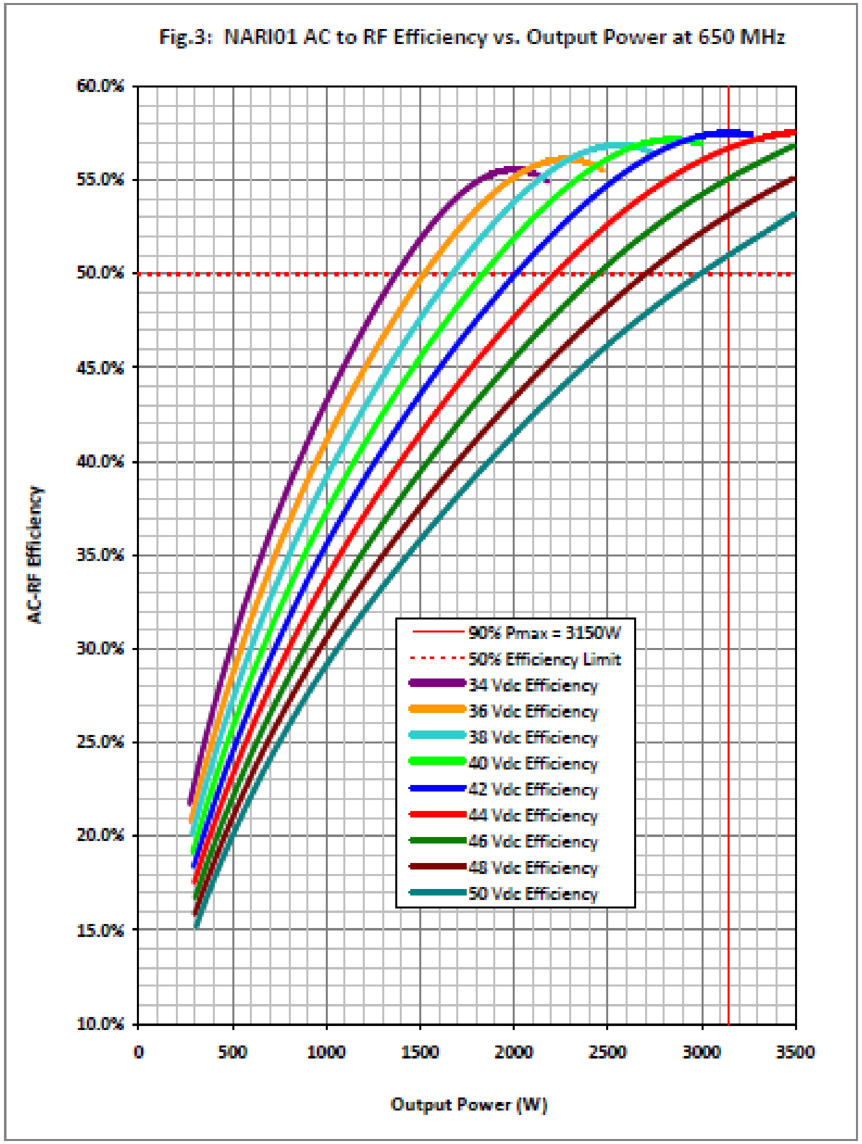
RF SPECIFICATIONS	
Frequency range	1300 MHz +/- 5 MHz
Linear Gain	67 dB
Gain flatness in frequency range	+/- 0.2dB
CW and pulse output power (1dB compression)	5000W min
Amplifier Biasing	Class AB Operation
Blanking input	Upon request
RF Rise Time	< 100 ns
RF Fall Time	< 70 ns
Input Noise Figure	8 dB max.
Output Noise Power	- 99dBm @ 1 Hz
IN/OUT Impedance	50 ohms
Input V.S.W.R.	1,5 max.
Output Harmonics 2nd order/3rd order	-45 dBc min/-60dBc min
Amplitude Stability/temperature	± 0,20% / °C
Power RF efficiency	h=43% typ at 5kW output
Max output VSWR	∞ up to 1.5kW CW
	∞ up to full power for short pulses
Max output VSWR with optional waveguide circulator	∞ at full power

But only quote 35%
AC -to- RF Efficiency

Example Operating Curves: NAUTEL 3 kW, 650 MHz SSA for PX

AC-RF efficiency = 54%

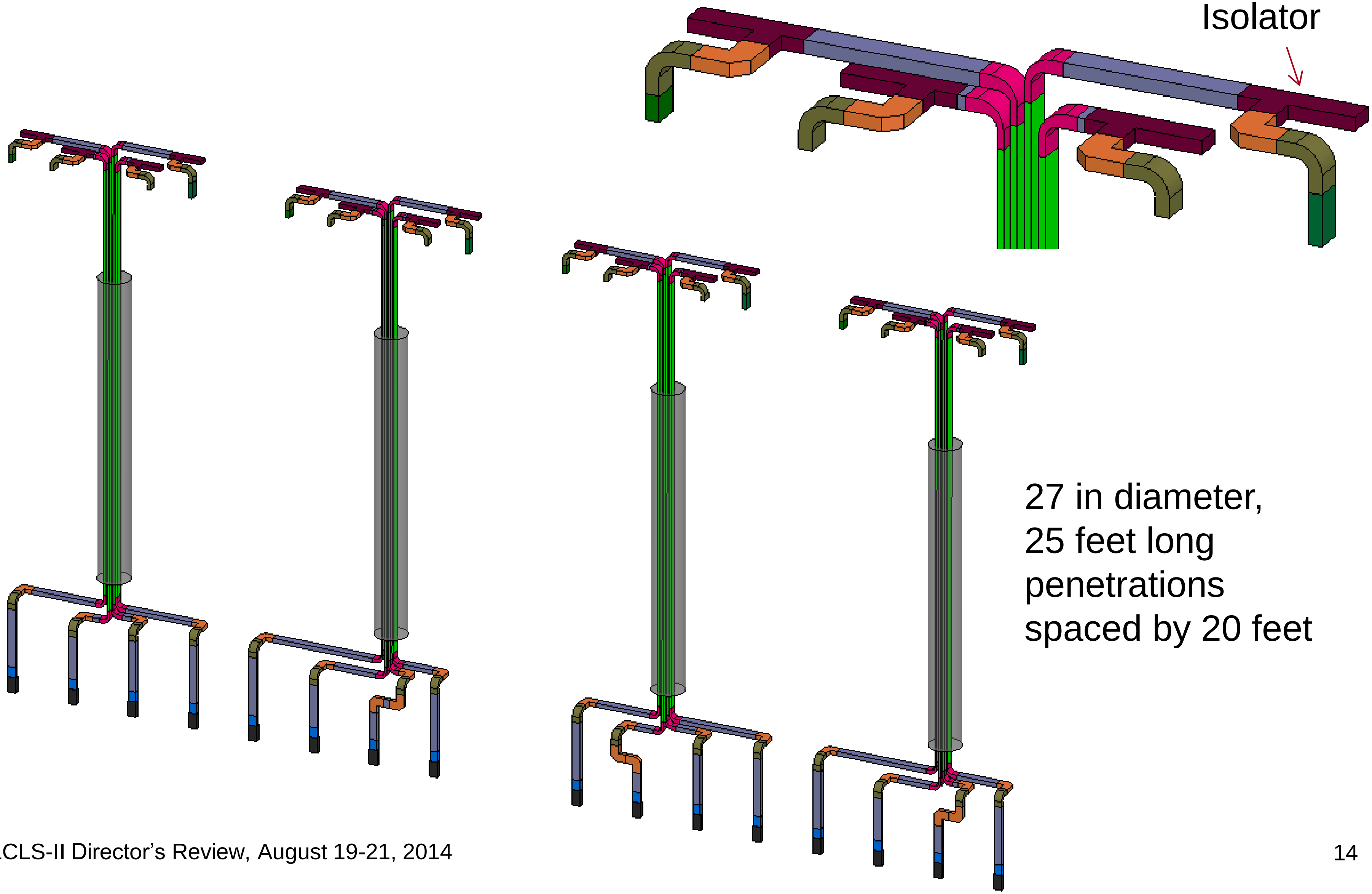
Adjust drain voltage depending on operating power range to maintain high efficiency



SLAC Klystron Gallery

27 Inch Diameter Penetration

SSA Waveguide System



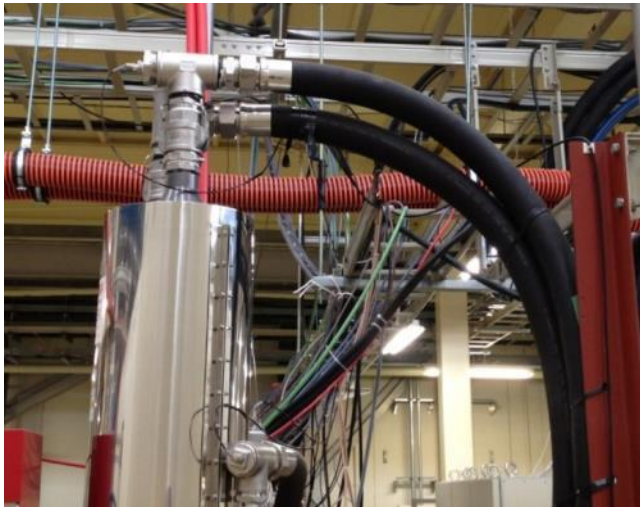
27 in diameter,
25 feet long
penetrations
spaced by 20 feet

Toshiba E37750 300 kW CW Klystron

Need 5 Units plus 1 Reserve

Beam Voltage	49.5 kV
Beam Current	9.8 A
Output Power	305 kW
Input Power	34 W for sat.
Perveance	0.89 uP
Efficiency	63.2 %
Gain	39.5 dB

Klystron Connections



CPI 300 kW Klystron

Communications & Power Industries

1.3 GHz, 300 kW, CW Klystron with 58% efficiency, 6 MHz bandwidth. This device was designed to operate nominally at 290 kW for accelerator applications.

FEATURES

- Oil Immersed Gun
- Solenoid Focused
- Water Cooled

VKL-7967A

Typical Operating Parameters		
Item	Value	Units
Beam Voltage	61	kV
Beam Current	8.5	A
Frequency	1.3	GHz
Ave. Power	300	KW
Gain	45.9	dB
Efficiency	58 *	%
Duty	CW	
Drive Power	8	W

* 66% in saturation.
At 49 kV, 54% efficiency with 155 kW output

One unit delivered to TRIUMF, one being tested for HZB

Commercial HV DC Supply

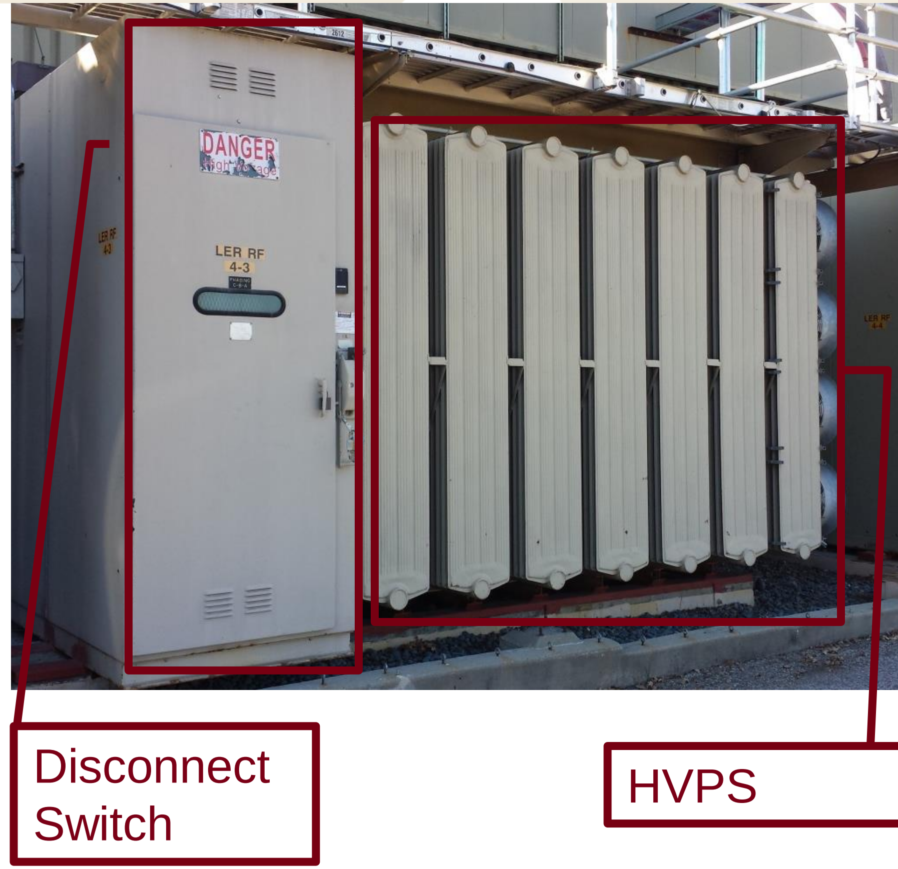
Thompson 540 kVA, 55 kV PS for NSLS II - 95 % efficient

12 kV AC In
50 kV Out

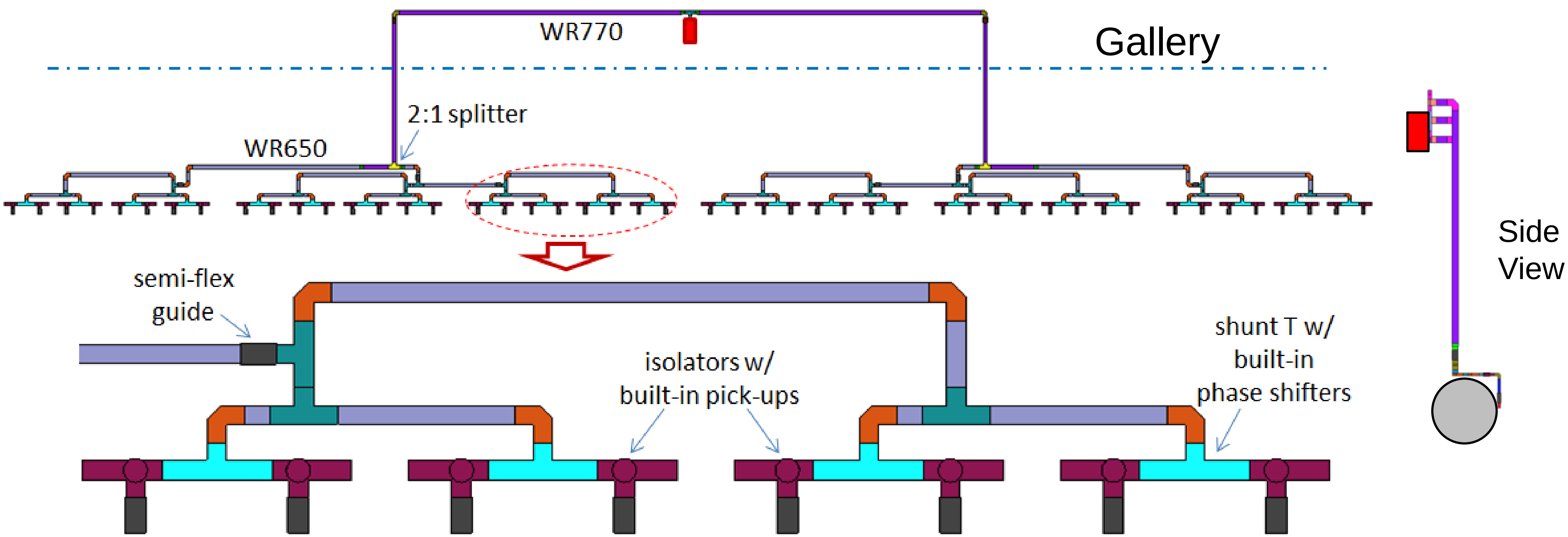
PEPII HVPS: Max 90 kV, 2.5 MW, SCR Controlled (Baseline)

Parameters	Conditions	Values	Units
Topology		12	Pulse
Dc Output Power	Max	2.5	MW
Output Current	Max	23	A
Output Voltage	Tap	-34	kV
(continuous adjust)		-53	kV
		-77	kV
		-90	kV
Ripple	0 Degree	< 0.2%	RMS
Voltage regulation	@ -90 kV	< 0.1%	
Output Protection	< 5 Joules	SCR Crossbar	
Configuration	Free Stand Outdoor use		

- Each supply will power two 300 kW klystrons. Total of 4 HVPS's are required, which includes one spare
- 15 units available, SSRL recently upgraded using one unit



Klystron Waveguide System



1.3 GHz Waveguide Components

Example of air-filled waveguide components used at DESY to bring power to the cavities

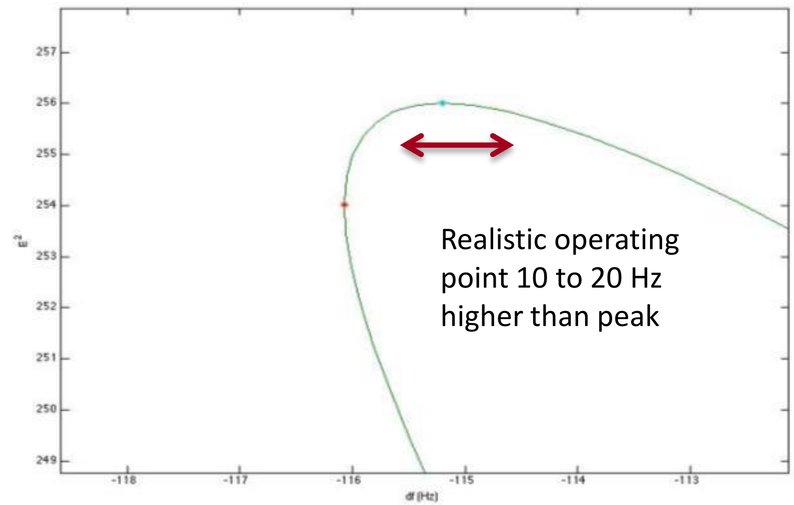
Parts bought commercially

Open Loop Cavity Stability Range

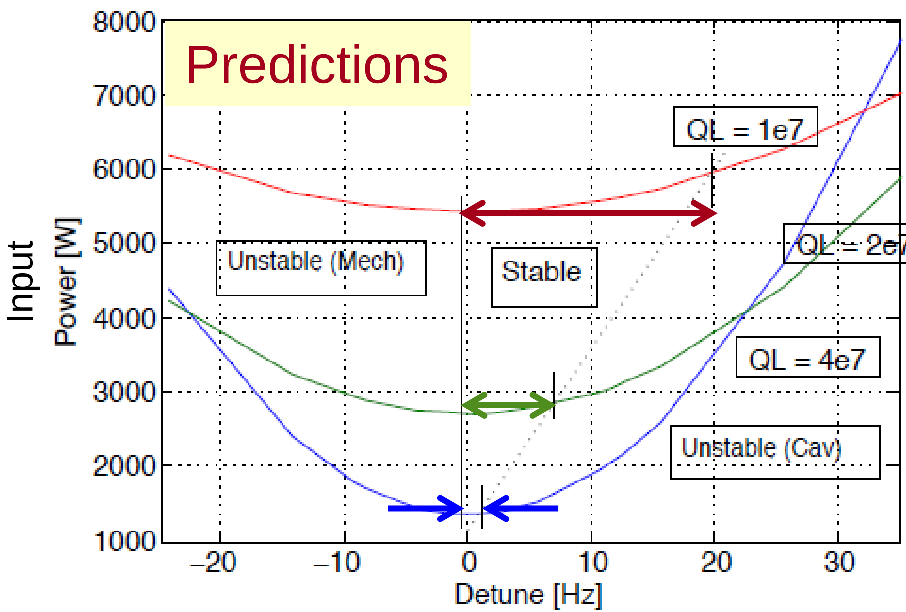
Klystron approach costs half as much per cavity than using SSAs.

However open loop (no FB) operation can be unstable due to Lorentz force distortion of the Lorentzian cavity frequency response.

Will test whether piezo-actuator feedback eliminates instabilities as rf feedback does.



Gradient Squared vs Detuning



Power vs detuning for $Q_L = 1, 2, 4e7$

$Q_L = 1e7$

Stable for $\Delta\omega = -0.35, .., 20.66$ Hz

$Q_L = 2e7$

Stable for $\Delta\omega = -0.35, .., 4.66$ Hz

$Q_L = 4e7$

Stable for $\Delta\omega = -0.35, .., 1.66$ Hz

Summary

Commercial rf sources and waveguides are available that will meet the power needs of the LCLS-II cavities, whether fed singly or in groups.

Balancing cost, performance and risk to find the best approach to power the cavities.

Coupler Specs, Modifications and Risks

Chris Adolphsen

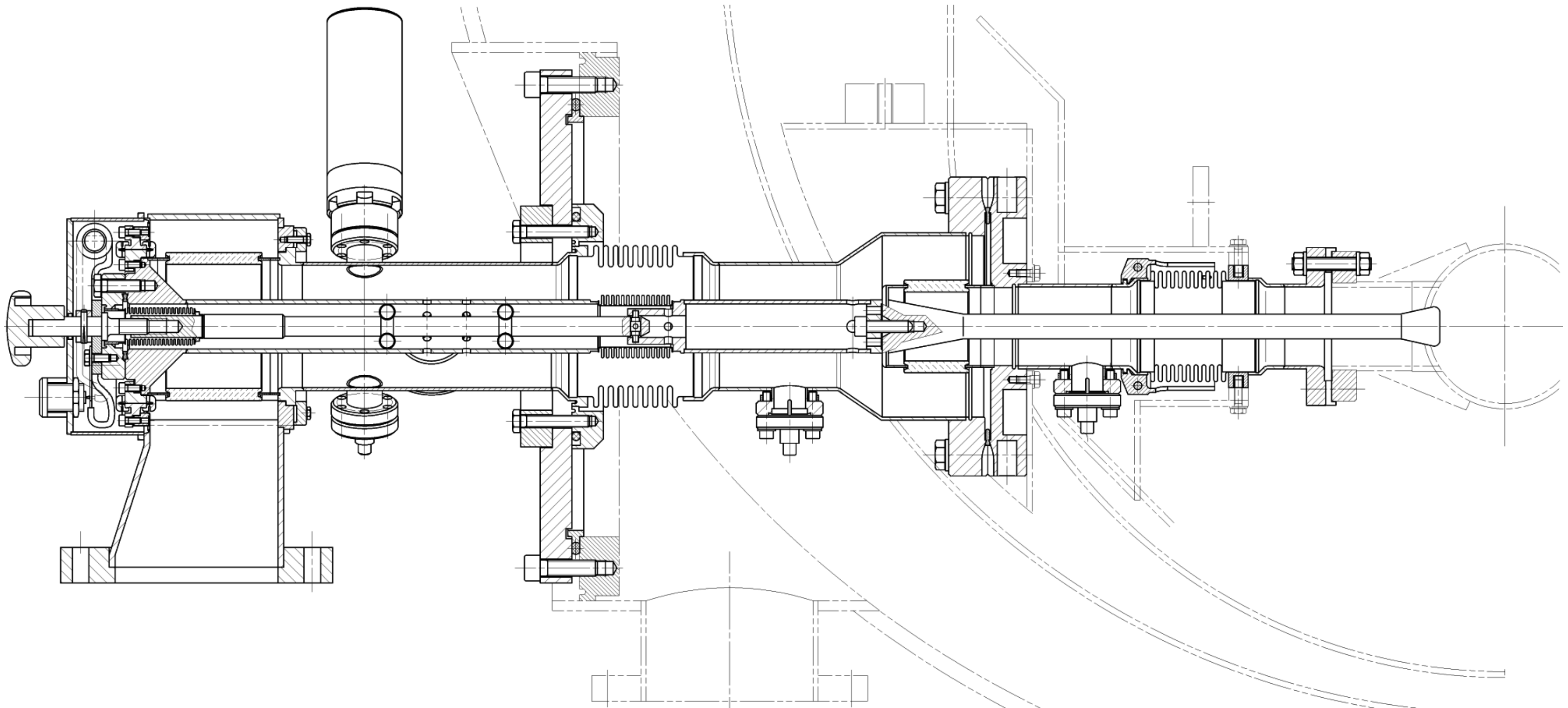
Coupler FDR

8/28/14

Cavity Power Coupler

Use basic DESY 2006 TTF3 design, but

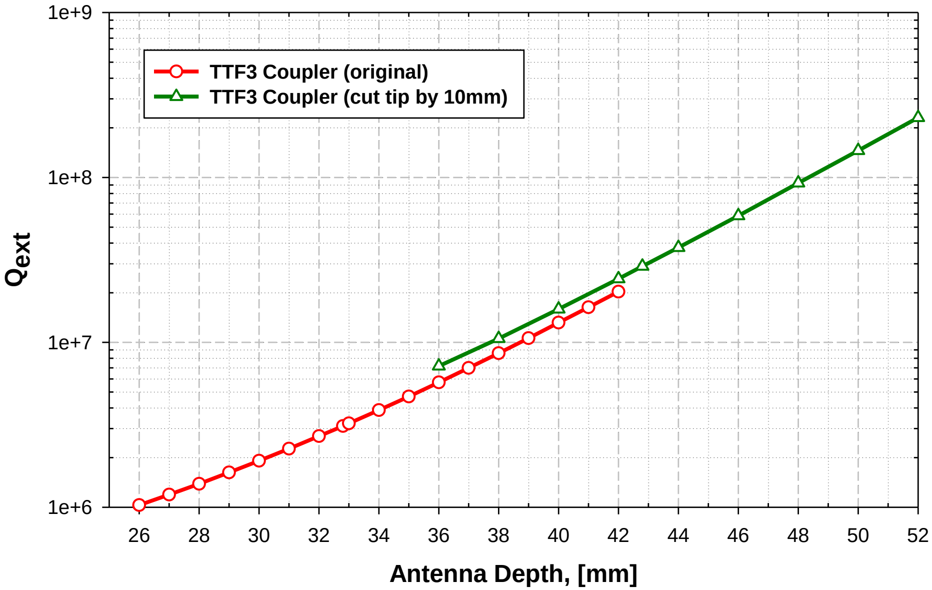
- Shift Qext range higher
- Improve cooling of warm section so can run at 7 kW with full reflection
- Modify waveguide assembly (use flex rings, perhaps an aluminum WG box and push-pull antenna position tuner with exterior coarse/fine control manual control)



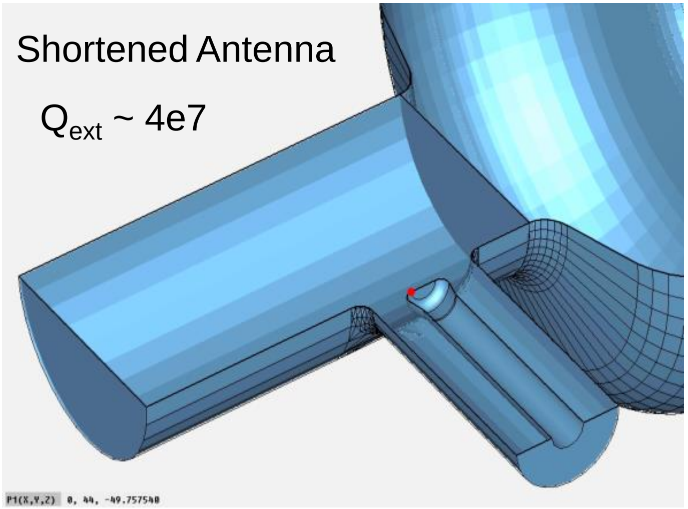
LCLS-II Coupler Technical Specs

Item	Spec	Comment
Design	DESY TTF3	Defined by SLAC drawings
Max Input Power	7 kW CW	
Max Reflected Power from Cavity	7 kW CW	Assume would run with full reflection
Minimum Qext Foreseen	1e7	Allows 16 MV/m with no beam and 6.6 kW input, and allows 6 MW beams with 33 kW input
Maximum Qext Foreseen	5e7	Match for 0.3 mA beams at 16 MV/m, 26 Hz BW
Reduction in Antenna Length	8.5 mm	Maintain 3 mm rounding
Range of Antenna Travel	+/- 7.5 mm	Range measured
Predicted Qext Min Range	3.6e6 – 4.7e6 – 7.5e6	Assuming +/- 5 mm transverse offsets
Predicted Qext Max Range	1.0e8 – 1.1e8 – 1.5e8	Assuming +/- 5 mm transverse offsets
Warm Section Outer Cond Plating	10 um +/- 5 um, RRR = 10-100	Nominal EuXFEL
Warm Section Inner Cond Plating	150 um +/- 10 um, RRR = 10-100	Modified to limit temp rise < 150 degC for 14 kW
Cold Section Outer Cond Plating	10 um +/- 5 um, RRR = 30-80	Nominal EuXFEL
Center Conductor HV Bias	Optional	Use flex copper rings that can be replaced with existing capacitor rings if HV bias needed
Warm and Cold e-Probe Ports	Yes	But do not expect multipacting at low power
Warm Light Port	Yes	But do not expect arcs at low power
Motorized Antenna	No	Unlikely we will need to adjust after first set
Cold Test and RF Processing	No	With 7 kW input, low fields and no multipacting bands – will instead process in-situ

Shorter Coupler Antenna

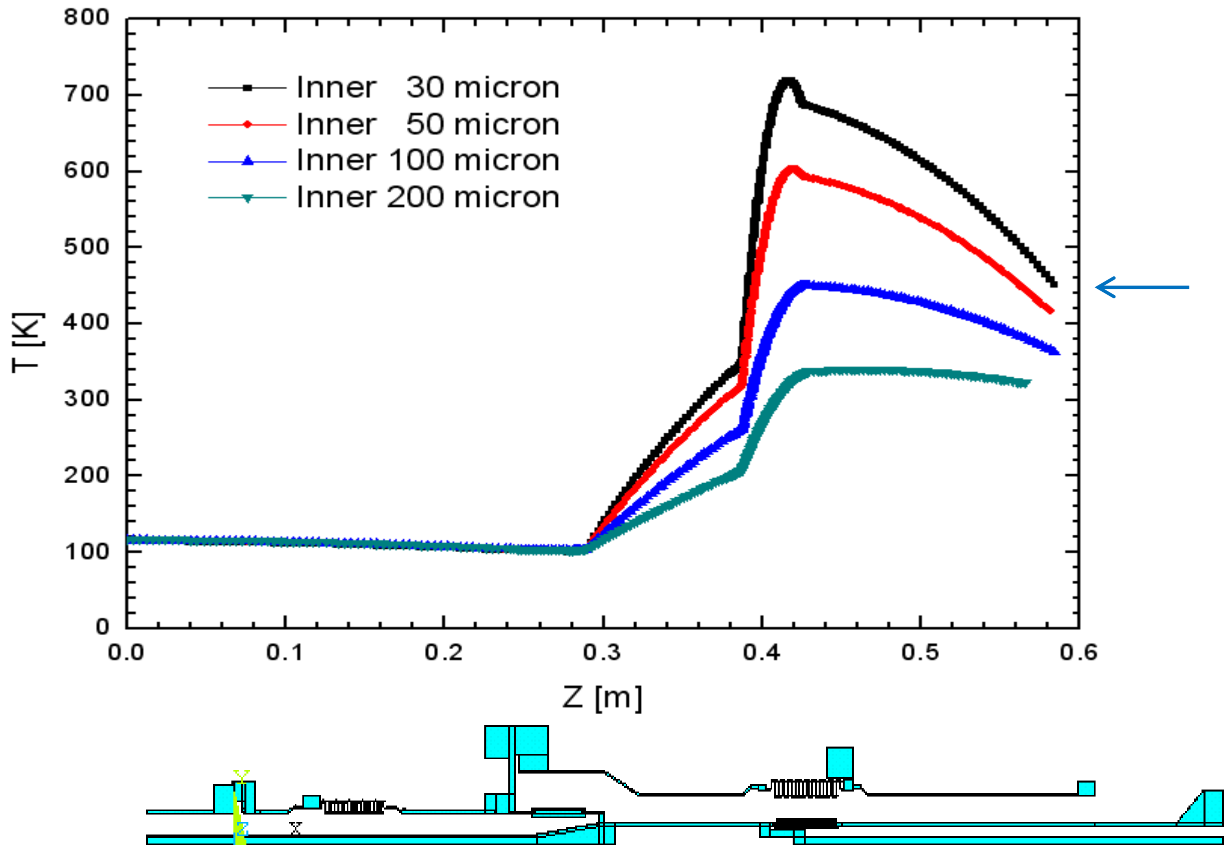


	Q_{min}	Q_{mid}	Q_{max}
Original coupler*	1E6	4.0E6	2.0E7
Tip cut by 10 mm	8E6	4.0E7	2.0E8
Tip cut by 8.5 mm	6E6	2.5E7	1.4E8



Coupler Heating

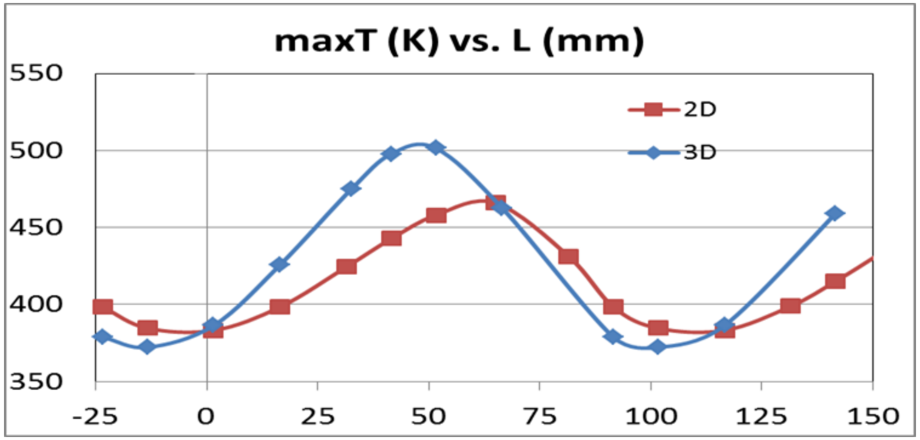
Inner conductor temperature for 15 kW TW operation for various thicknesses of the warm section inner conductor copper plating



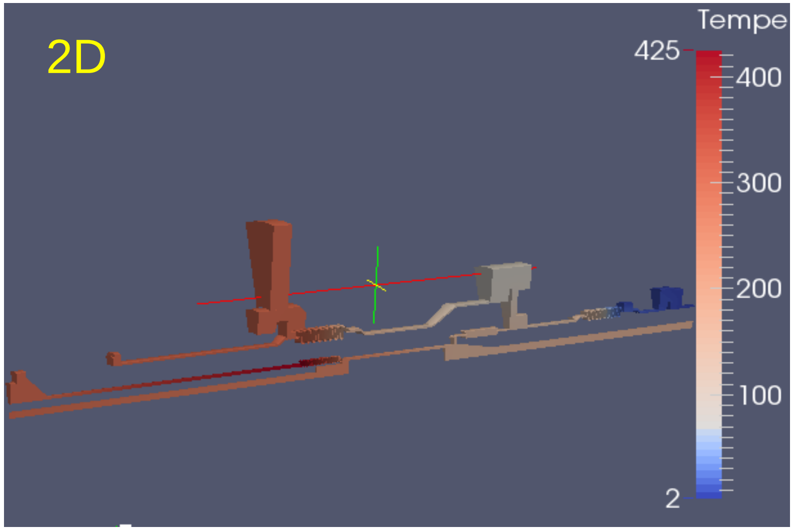
Limit to 450 K (bake temp)

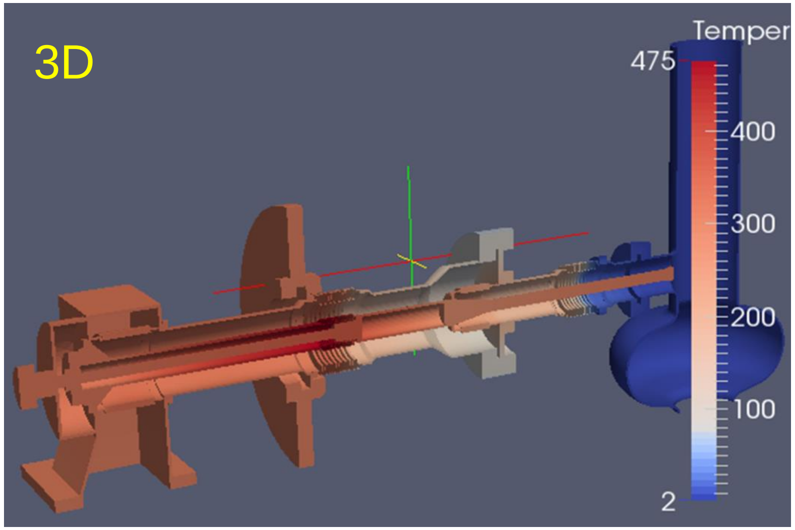
7 kW Full Reflection Simulations

- Simulations assume 100 um inner conductor plating and no resistivity increase with plating roughness
- 3D case includes heating in the warm window
- Location = 33 mm corresponds to on-resonance operation (no beam)



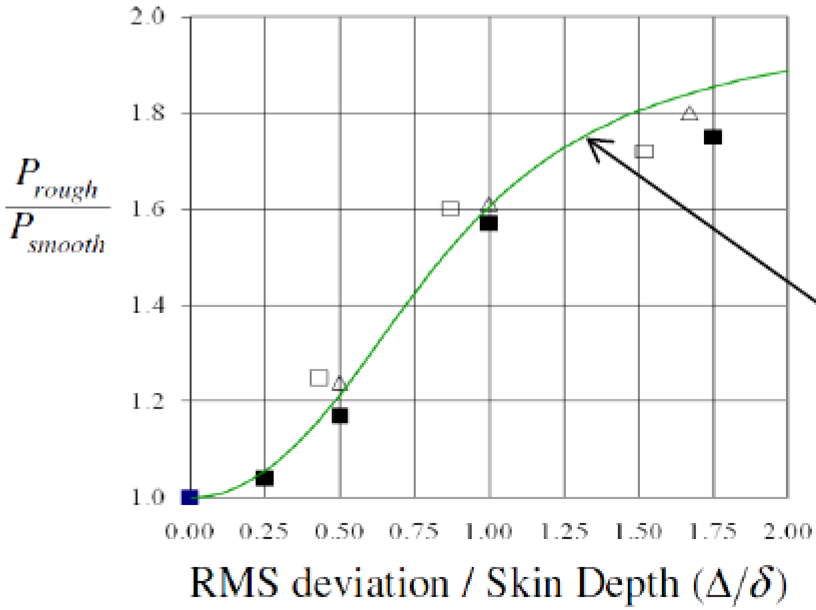
Effective location of the short (mm)





Effect of Copper Roughness on Resistivity

Rs = Rs_ideal (T,RRR) * Ksr (roughness, skin depth(Rs_ideal(T,RRR)))



Hammerstad's correction coefficient

Wrong

$$K_{sr} = 1 + \left(\frac{2}{\pi} \cdot \arctan\left[1.4 \left(\frac{\Delta}{\delta_s} \right)^2 \right] \right)$$

Empirical, Max = 2

1.3 GHz Skin Depth (um)	RRR = 10	RRR = 100
T = 300 K	1.8	1.8
T = 70 K	0.8	0.6
T < 20 K	0.6	0.2

Theoretical Approach at SLAC

Developing better theory that depends on feature height to separation ratio – expect this ratio to be << 1, which plot below shows will have a minor effect on heating

Assume the sin profile of the surface

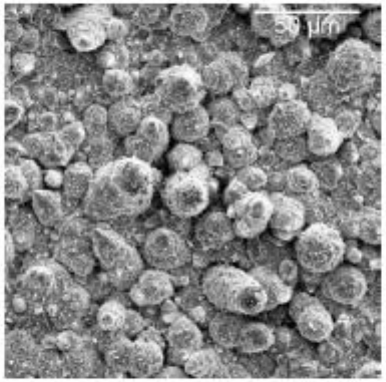
$$y_0(x) = h\cos\left(\frac{2\pi x}{\lambda}\right)$$

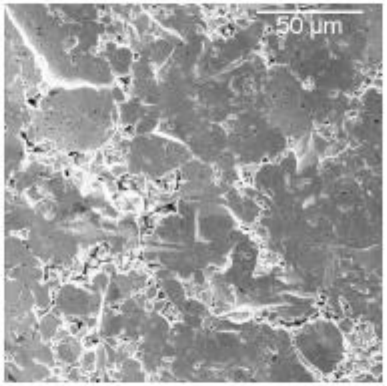
Assume small skin depth, $\delta \ll h, \lambda/2\pi$. The boundary condition for the magnetic field on the surface is

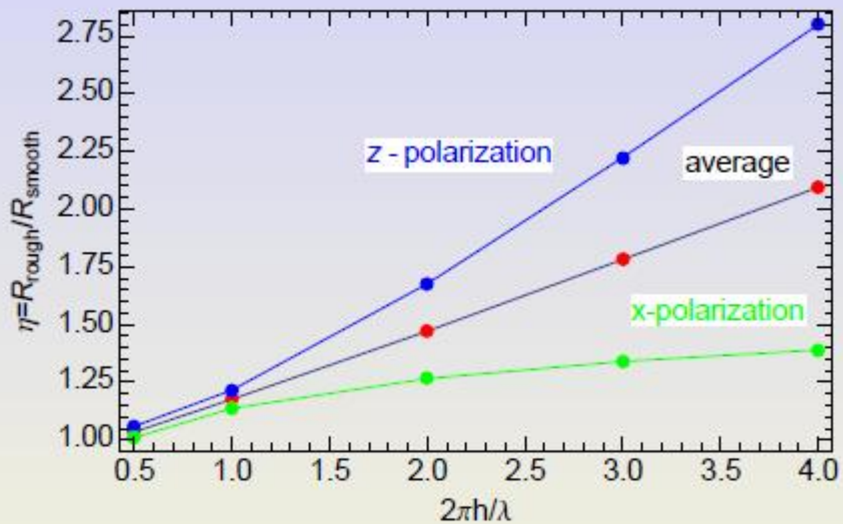
$$H_n|_{\mathrm{surface}} = 0$$

Resistivity increase factor

$$\eta = \frac{\int_{\mathrm{period}} H_t^2 \, ds}{H_0^2 \lambda}$$





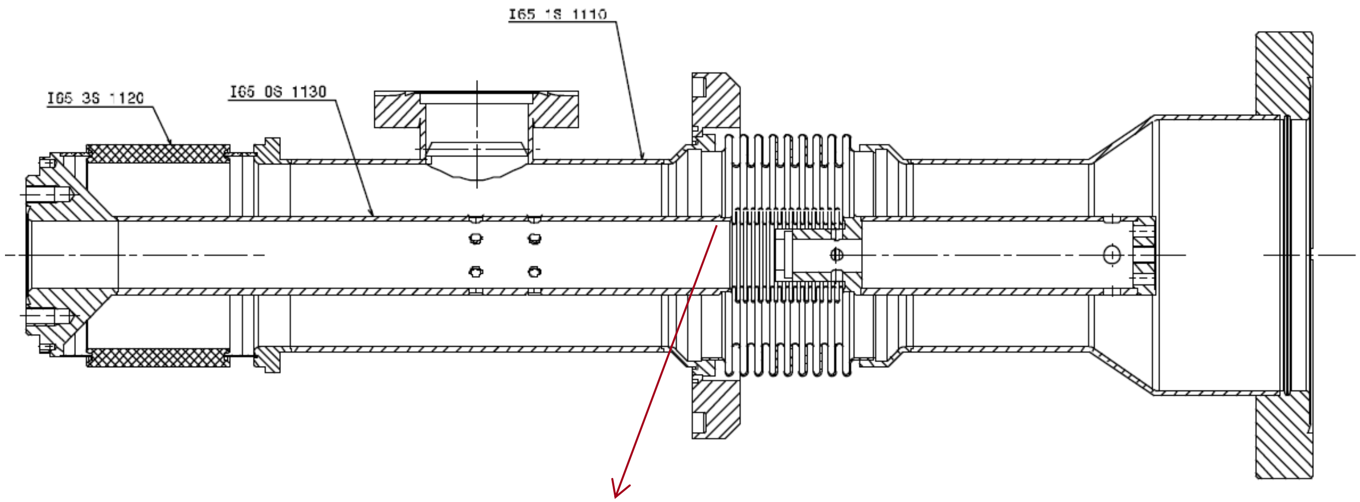


G. Stupakov

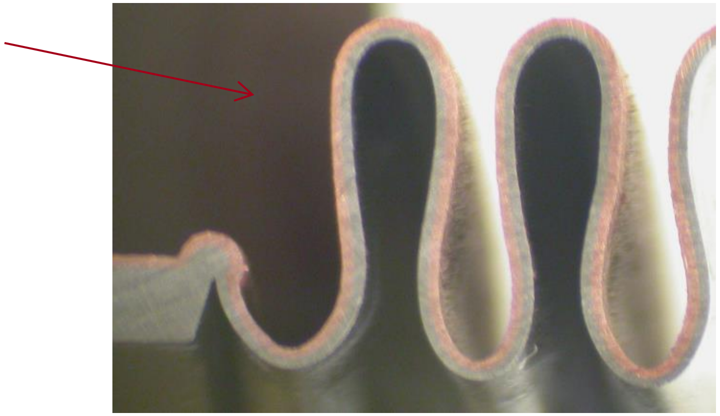
Thicker Copper Plating Qualification

Increase copper plating thickness on warm section inner conductor from 30 um to 150 um

Recently had 3 ILC sections modified in this way – two will be used in HTS tests at FNAL



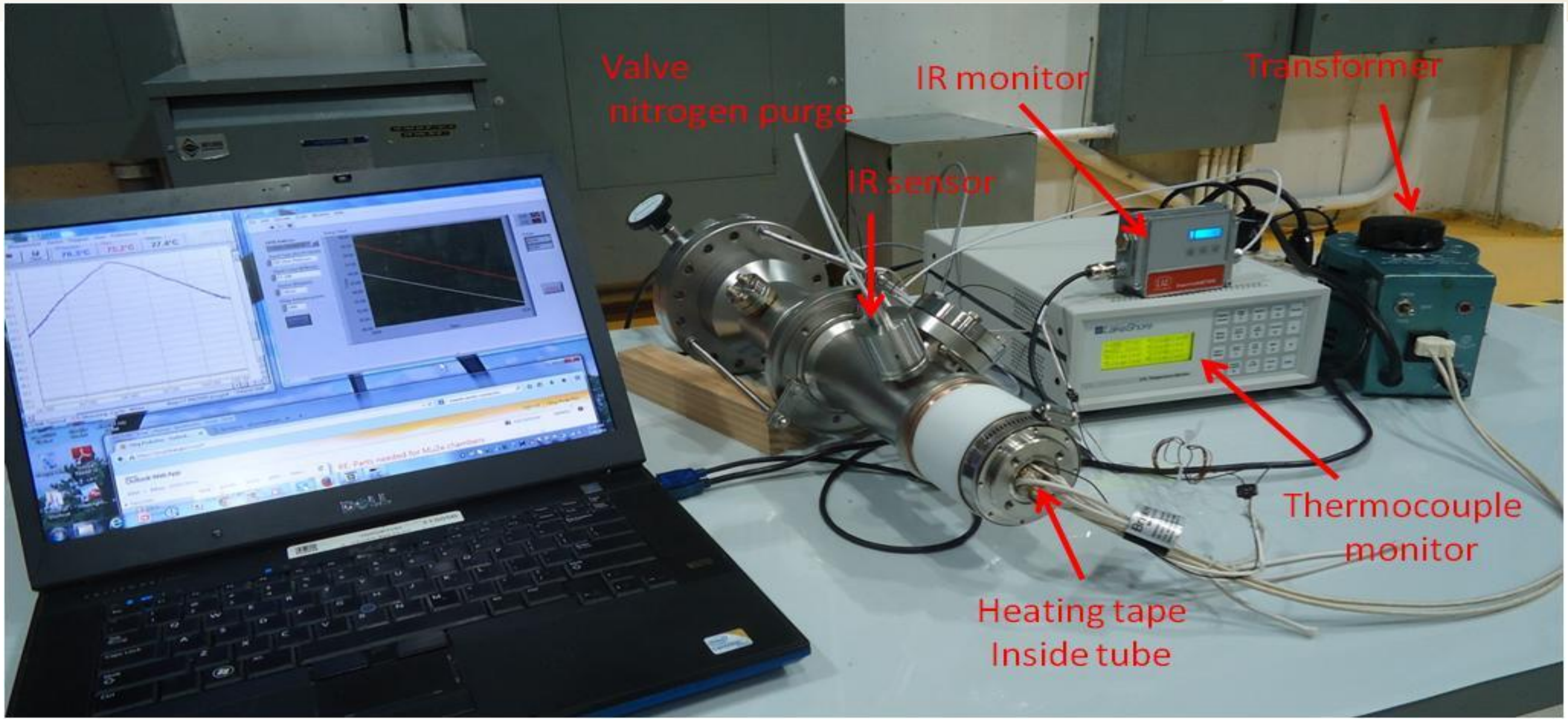
Cross section of inner conductor bellow in a test section: measure 120-180 um copper thickness variation

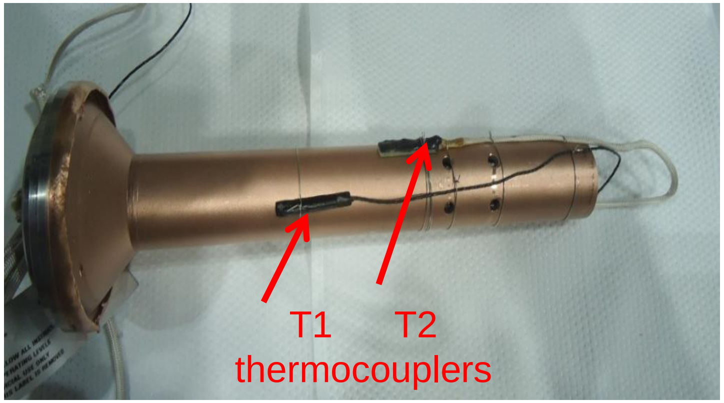


FNAL HTS Test Schedule

#	Test, goal	Start 2014	Cav. type	Helium Vessel	HOM antenna	Coupler (cold)	Coupler (warm)	Magn shield	Tuner	RF
1	HTS commissioning XFEL feedthroughs test	June	ILC RI26	ILC	XFEL	variable	None	1-layer +coil	None	SSA 200W
2	High-Q0 cavity (AES011)	Aug	high-Q#1	ILC	None	variable	None	1L+coil	None	SSA 200W
3	FPC cold modified JLAB feedthru test µ-phonics study	Sept	high-Q#1	ILC	JLAB	FPC modif	FPC He cooled	1L+coil	blade	IOT 10kW
4	FPC#1 modified; µ-phonics study	Sept	high-Q#1	ILC	JLAB	FPC modif	FPC#1 modif	1L+coil	blade	IOT 10kW
5	High-Q cav. #2 FPC#2 modified; HV	Oct.	High-Q#2	LCLS-II	XFEL	FPC modif	FPC#2 modif	1L+coil	None	IOT 10kW
6	High-Q#3 integrated test Tuner; 2L-magn.shield	Oct	High-Q#3	LCLS-II	JLAB	FPC modif	FPC#1 modif	2-layer	Lever tuner1	IOT 15kW
7	high-Q#2 integrated test Tuner reliability	Nov.	High-Q#2	LCLS-II	XFEL	FPC modif	FPC#2 modif	2-layer	lever tuner2	IOT 10kW

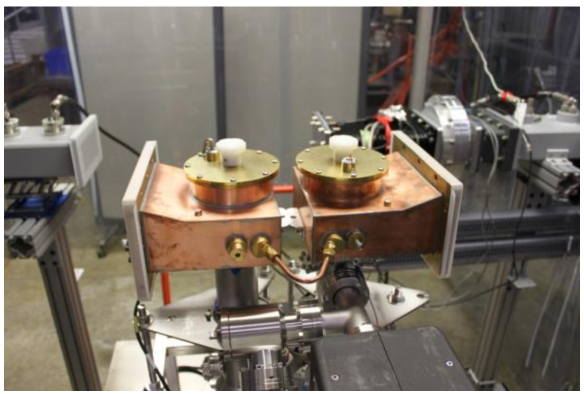
Calibration of IR sensor on Warm Section at FNAL

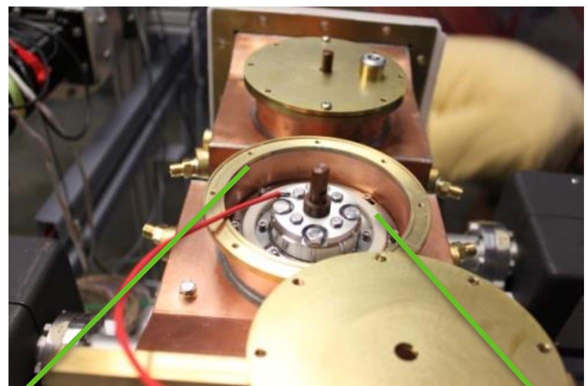


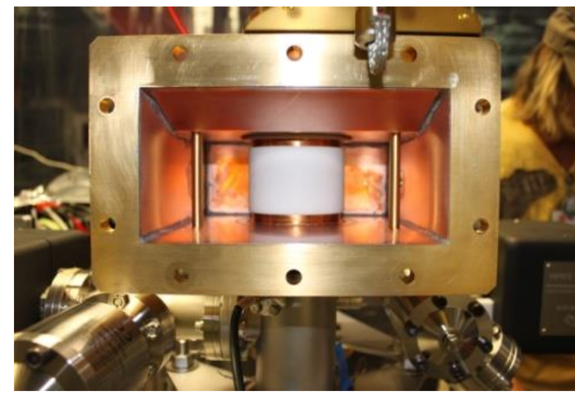


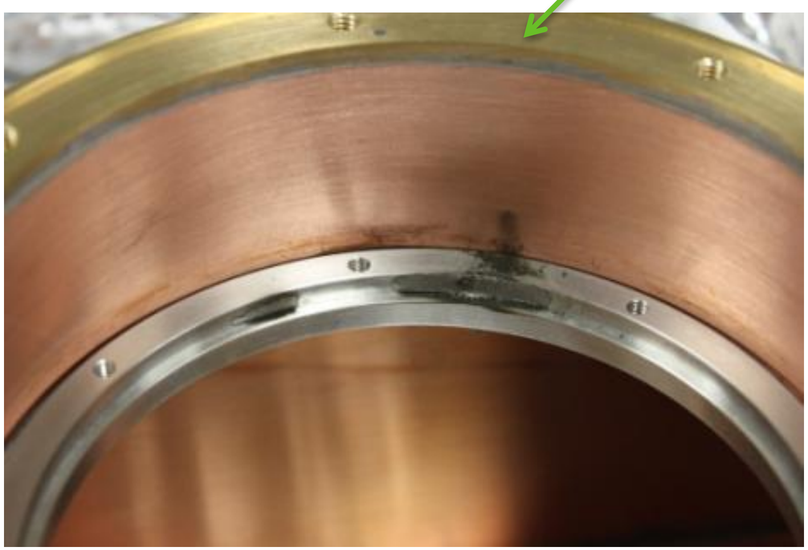
Arcing at Waveguide Contact

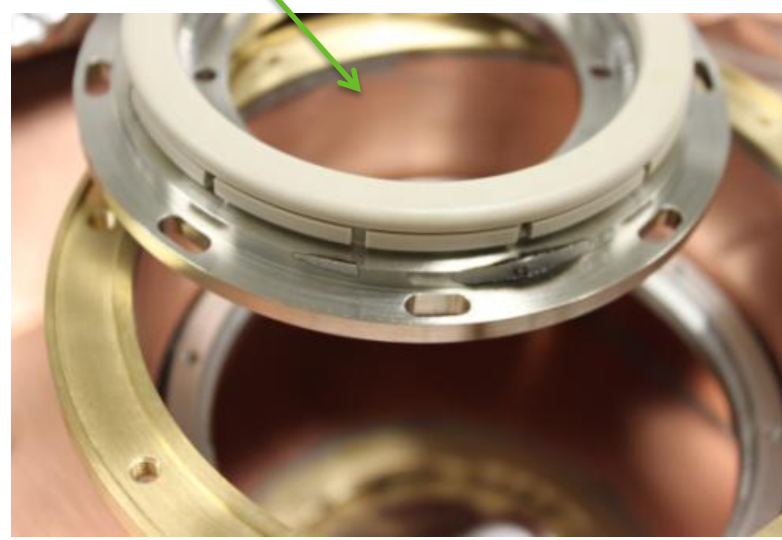
When processing ILC couplers, discovered that the waveguide ‘capacitor’ mating surface had arced in some of the warm sections





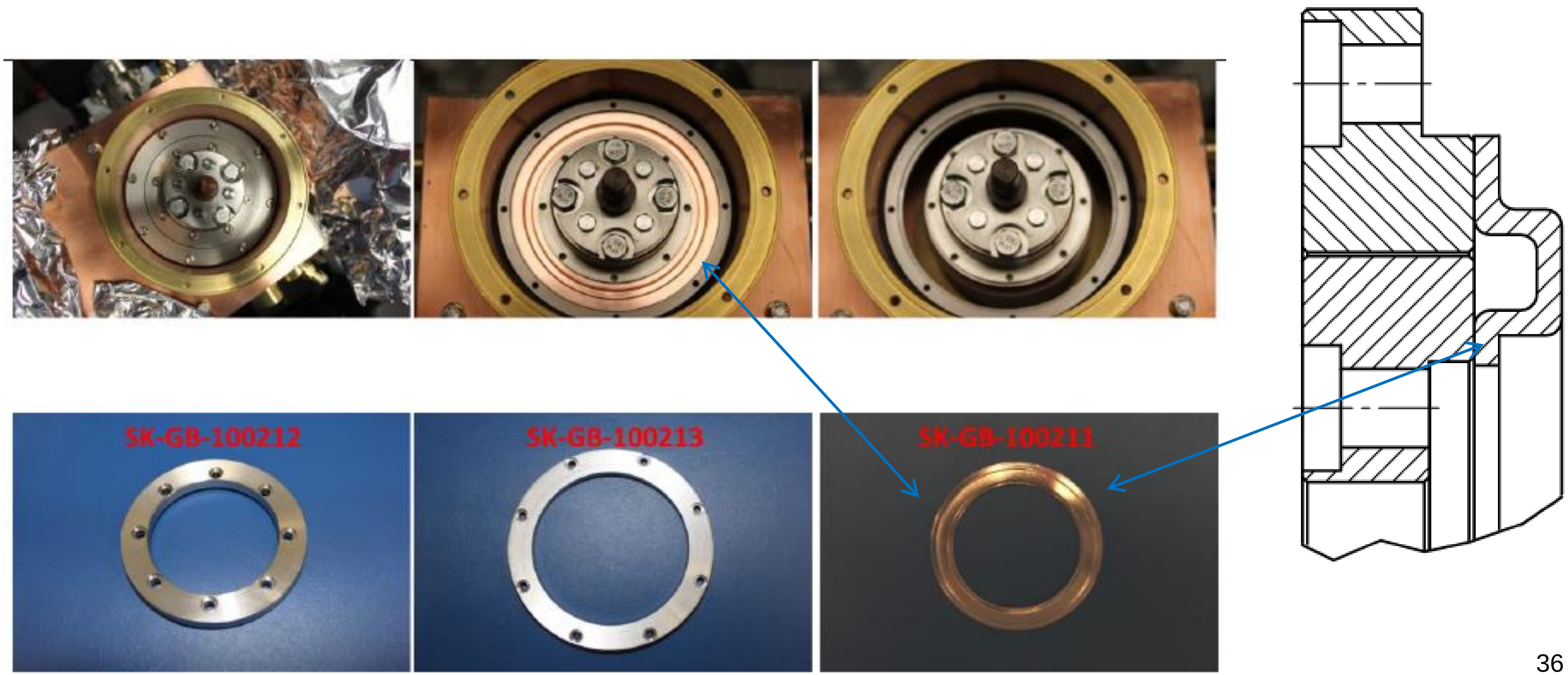






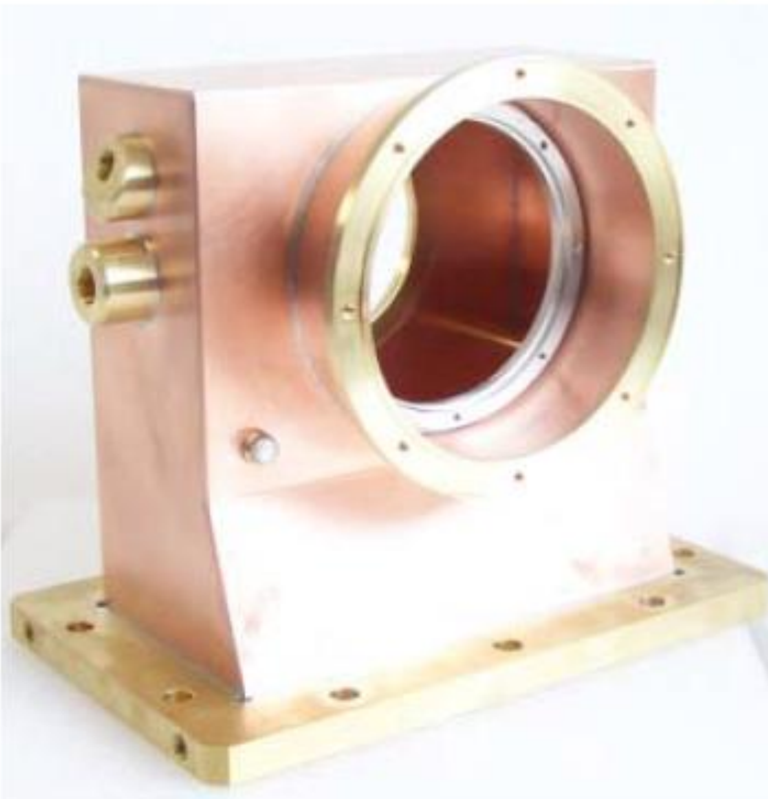
Copper Flex Rings

- Made plug-compatible copper flex rings to replace non-flexible HV capacitance rings to get better WG-to-Window contact
- Adopted by EuXFEL



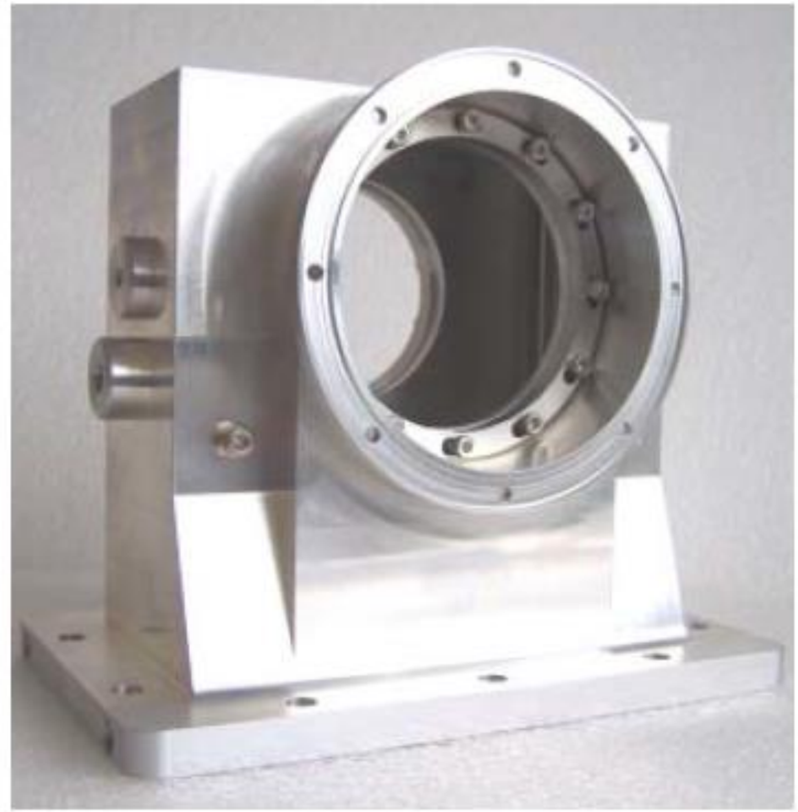
Aluminum Waveguide Box (not in baseline)

The most expensive part of the coupler !



Copper + stainless steel + brass: 13 parts

brazed and soldered

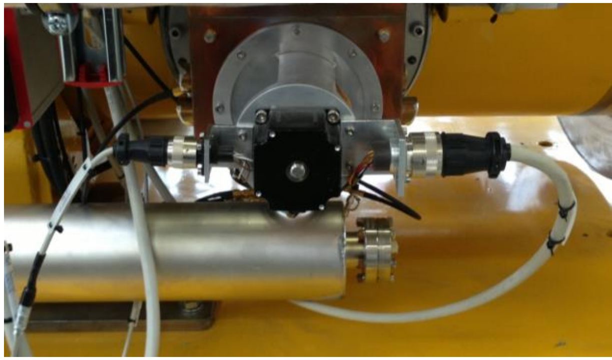


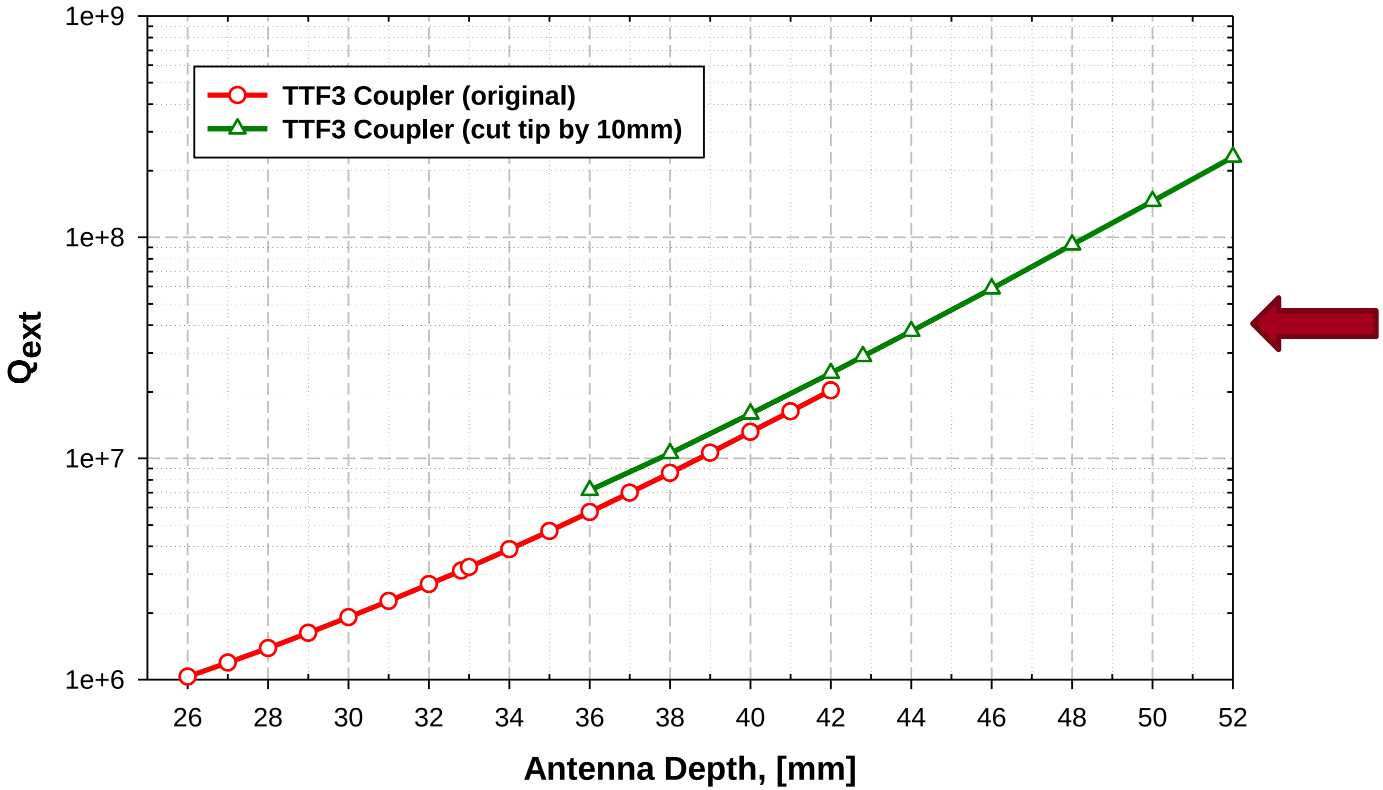
Al alloy: 1 single part

- Prototypes: machined from single block
- Mass production: casting

Setting Qext

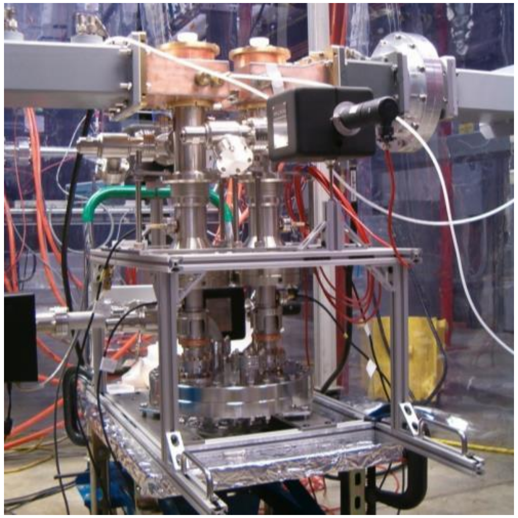
- Will use manual knob, not motor to move antenna
- Need to set antenna to 0.5 mm accuracy to get Qext in the 4.0-4.5e7 range
- Probably send people into SLAC tunnel to iterate on Qext during commissioning (i.e. can't rely on mechanical tolerances)

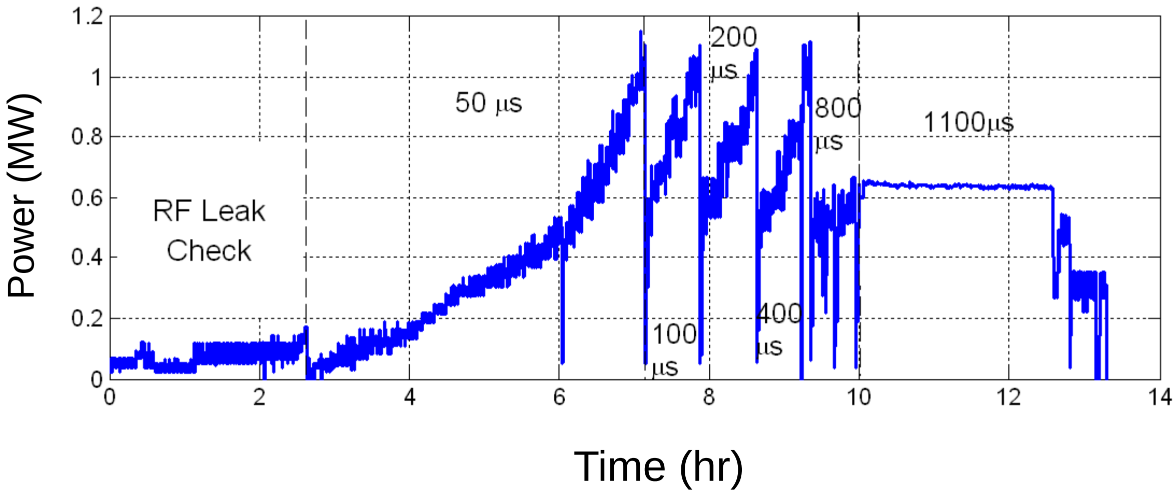




Production Coupler RF Processing and Instrumentation

- Will not low-power test couplers
- Will not pulse power process the couplers
- Will not CW process the couplers
- Will not instrument e-probe ports
- Will not instrument light port
- Will monitor current of the pump on the 8-cavity coupler vacuum manifold





Summary

- Making fairly minor modifications to DESY TTF3 coupler design for CW operation at LCLS-II
- Cavity high power tests at FNAL HTS are critical for demonstrating coupler performance