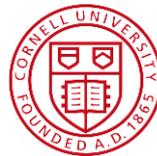# RF System Conceptual Design for the LCLS-II CW, SCRF Linac

Chris Adolphsen, SLAC

5/13/2014
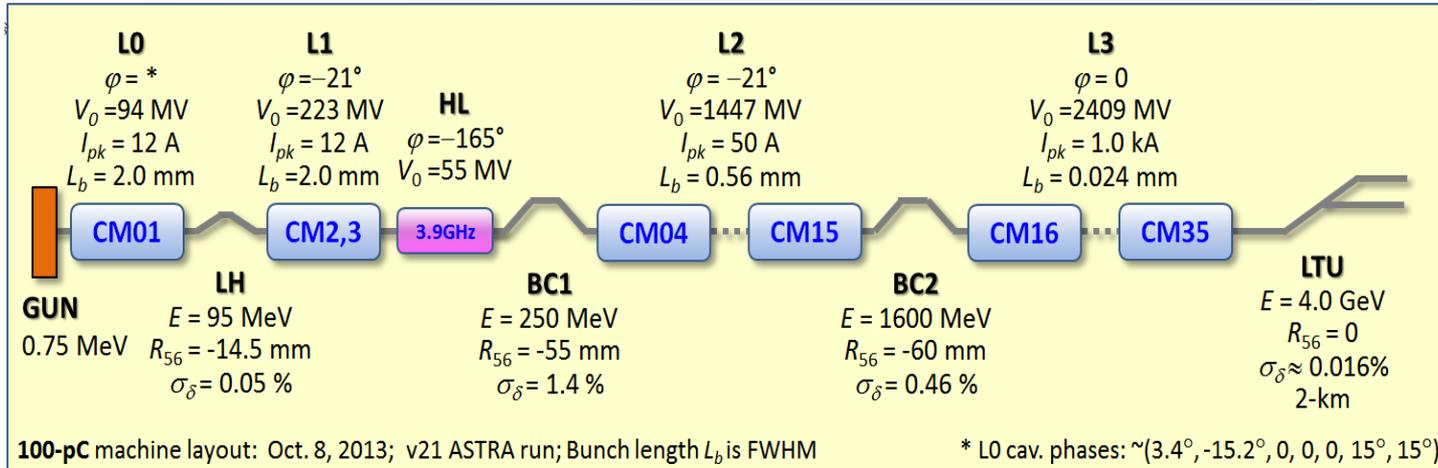
Chris Adolphsen, SLAC

Outline

- 1.3 GHz Requirements
- Choice of RF Sources
  - Single and Multiple Cavity Drive Options and Relative Costs
- Solid State Amplifiers
  - Specs, Experience, Layout
- High Power Klystrons
  - Specs, Experience, PS's, Layout
- All SSA Approach
- Other RF Sources

4 GeV CW Linac (280, 1.3 GHz Cavities; 16, 3.9 GHz Cavities)

L0
$\varphi = $ *
$V_0 = 94$ MV
$I_{pk} = 12$ A
$L_b = 2.0$ mm

L1
$\varphi = -21°$
$V_0 = 223$ MV
$I_{pk} = 12$ A
$L_b = 2.0$ mm

HL
$\varphi = -165°$
$V_0 = 55$ MV

L2
$\varphi = -21°$
$V_0 = 1447$ MV
$I_{pk} = 50$ A
$L_b = 0.56$ mm

L3
$\varphi = 0$
$V_0 = 2409$ MV
$I_{pk} = 1.0$ kA
$L_b = 0.024$ mm

GUN
0.75 MeV

LH
$E = 95$ MeV
$R_{56} = -14.5$ mm
$\sigma_\delta = 0.05$ %

BC1
$E = 250$ MeV
$R_{56} = -55$ mm
$\sigma_\delta = 1.4$ %

BC2
$E = 1600$ MeV
$R_{56} = -60$ mm
$\sigma_\delta = 0.46$ %

LTU
$E = 4.0$ GeV
$R_{56} = 0$
$\sigma_\delta \approx 0.016$%
2-km

CM01 · CM2,3 · 3.9GHz · CM04 ··· CM15 · CM16 ··· CM35

100-pC machine layout: Oct. 8, 2013; v21 ASTRA run; Bunch length L_b is FWHM   * L0 cav. phases: ~(3.4°, -15.2°, 0, 0, 0, 15°, 15°)

Linac Sec.	V (MV)	φ (deg)	Acc. Grad. (MV/m)	No. Cryo Mod's	No. Avail. Cav's	Spare Cav's	Cavities per Amplifier
L0	94	*	13.2	1	8	1	1
L1	220	−21	14.3	2	16	1	1
HL	−55	−165	14.5	2	16	2	1
L2	1447	−21	15.5	12	96	6	48
L3	2409	0	15.4	20*	160	10	48

One RF Source Per Cavity

One Klystron per 6 CMs

* 2 CMs are powered by one source per cavity

1.3 GHz RF Source Power Requirements

Parameter	Value	Comment
Gradient	16 MV/m	On Crest Reference Gradient
Beam Current	0.3 mA	Maximum
Cavity QL	4.12 e7	Minimizes power for 10 Hz microphonics (MP) offset
Power per Cavity (w MP w/o overhead)	5.72 kW	Power with 10 Hz MP offset – no overhead
Power per Cavity (w MP w overhead)	6.32 kW	With 94% transmission and 4% overhead (10% with spares and actual gradients)
Power for 48 cavities (w MP and w overhead)	303 kW	Either one source per cavity so can track MP locally or one source for 48 cavities
RMS MP offset allowed with a 300 kW source	9 Hz	For Gaussian distributed MP

Other Requirements

- Stability: RF feedback will be used to achieve 0.01% amplitude and 0.01 deg phase stability of sum of cavity voltages associated with each source

  - Addition of beam energy FB loosens these tolerances

- 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 needed to keep cavity gradient stable
  - Use single source per cavity upstream of BC1, and multiple cavities per source downstream if viability demonstrated at high QL
- Single Source (~ 6 kW) per Cavity Options
  - Klystrons + PS about 13 $/W with 43% efficiency (cost increases with efficiency)
  - IOTs have higher efficiency (~ 60 %) but higher cost at such low power
  - Solid State Amplifiers (SSAs) now cost effective (LDMOS Amp + PS around 15 $/W) but have lower efficiency (35%) - however, high availability (modular), and over time, cost likely to decrease and efficiency increase (expect ~ 45% in two years).

Trends in LDMOS Cost vs Performance

No Scale

$ / Watt   Performance

1998   2000   2002   2004   2006   2008   2010
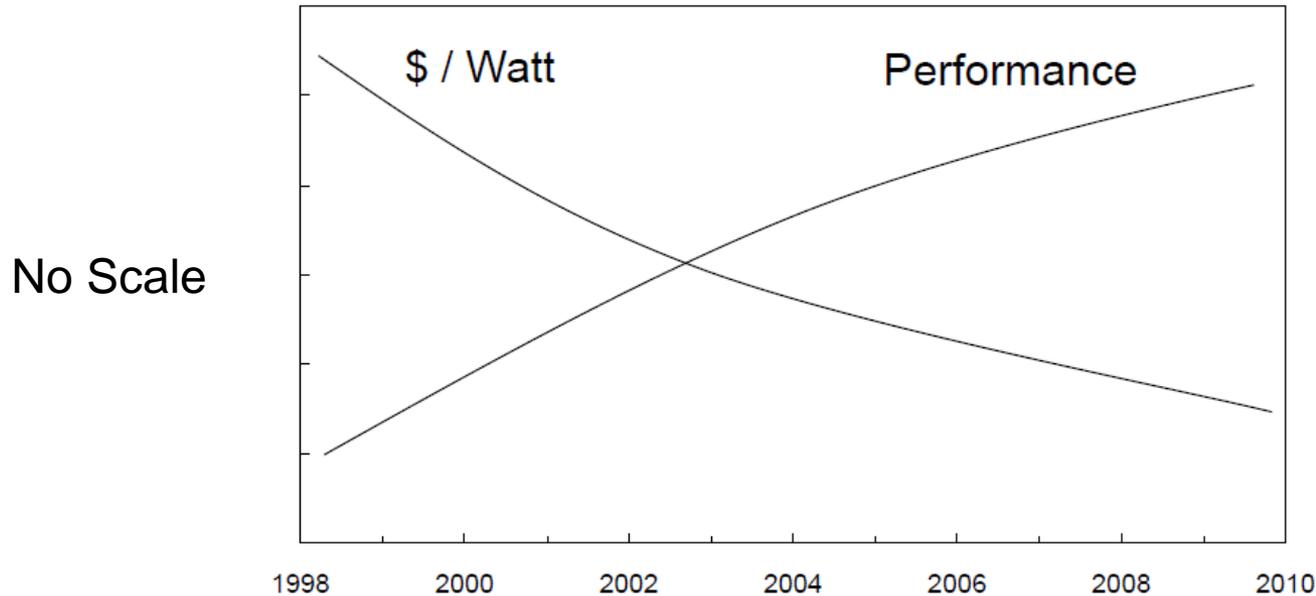
Tao Tang will talk tomorrow about benefits of using GaN Transistors

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

Source Choices

- Use SSAs to drive single cavities

  - Have quotes from several vendors

  - 1.3 GHz units used successfully at ELBE/HZDR and Cornell

- Use 300 kW klystrons to drive 48 cavities (6 cryomodules)

  - 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 (Klystron + PS ~ 6 $/W)

  - No long term operation experience but not pushing limits - CPI and e2V have been selling 110-120 kW tubes

Bruker (Now 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 – no solenoid, HV PS, filament PS nor vacuum pump

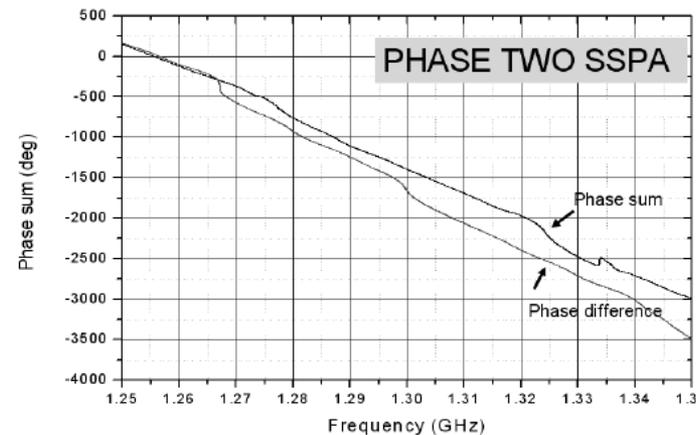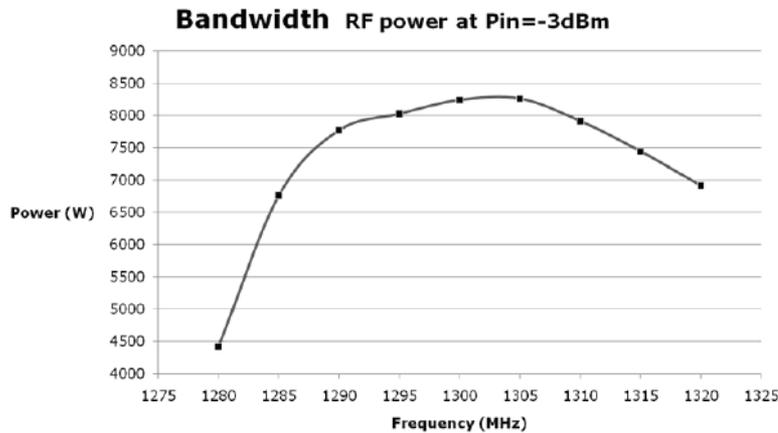Newer units with higher power transistors produce 16 kW in one rack

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

Bruker 10 kW SSA Performance at ELBE*

8.5 kW at 1 dB
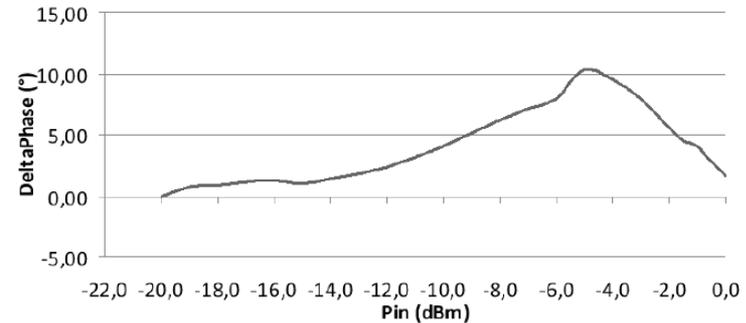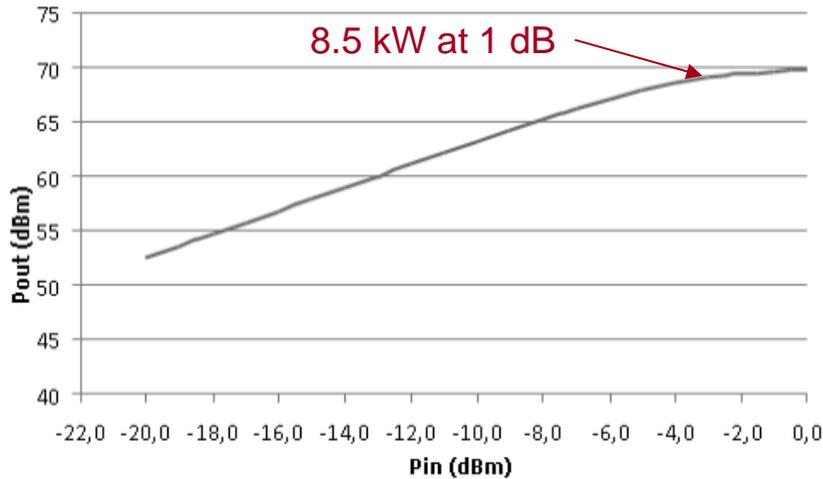
Wide BW – need only few hundred kHz for LCLS-II

Bruker 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	$\pm 0.20\% / °C$
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

Fig.3: NARI01 AC to RF Efficiency vs. Output Power at 650 MHz
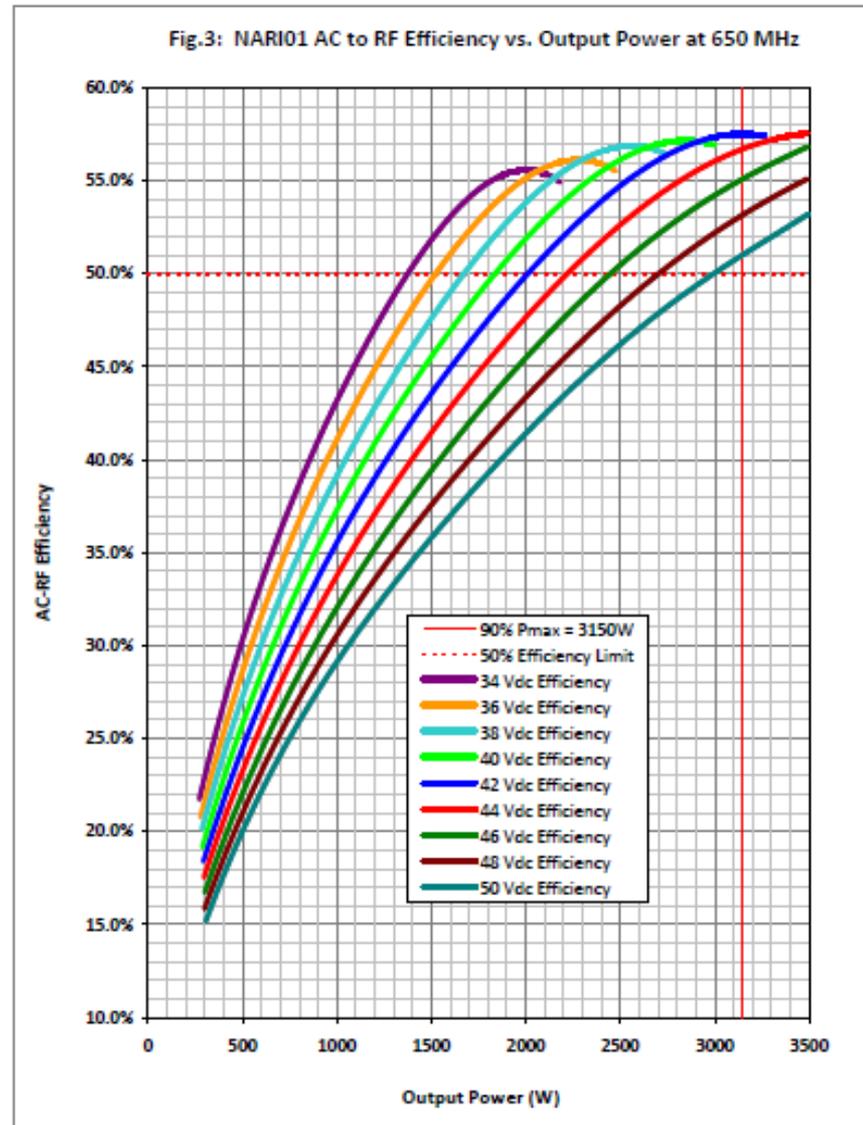
Toshiba E37750 300 kW CW Klystron

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

VKL-7967A

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

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

Klystron Commercial DC Supply:
Thompson 540 kVA, 55 kV PS for NSLS II

PSM - Summed Switching Supplies – 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		

Disconnect Switch

HVPS

15 PEP-II HVPS Units Available

- Installation cost ~ $500k / Unit
  - Disconnect the HVPS
  - Move from Region 6 to Sector 5(?)
  - Klystron Integration
  - Check out and Commissioning

Each supply will power two 300 kW klystrons. Total 4 HVPS's are required, which includes one spare

Open Loop Cavity Stability Range

Main concern with one source driving multiple cavities is the gradient instability during open loop (no FB) operation due to Lorentz force distortion of the Lorentzian cavity frequency response.

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

Realistic operating point 10 to 20 Hz higher than peak
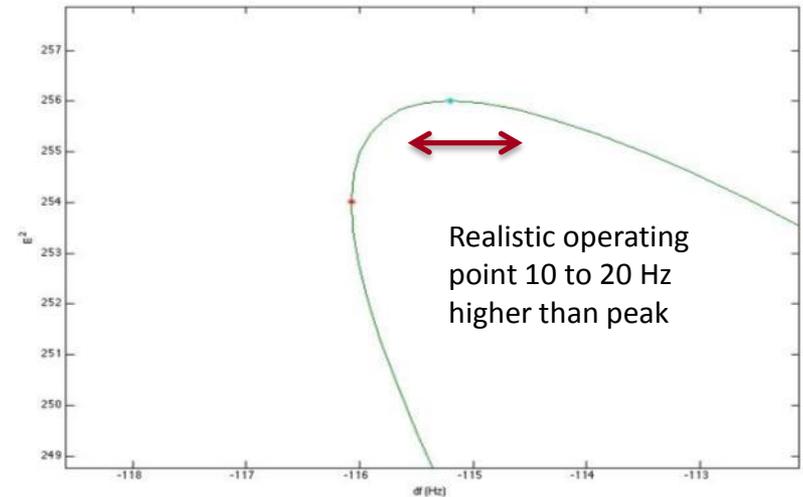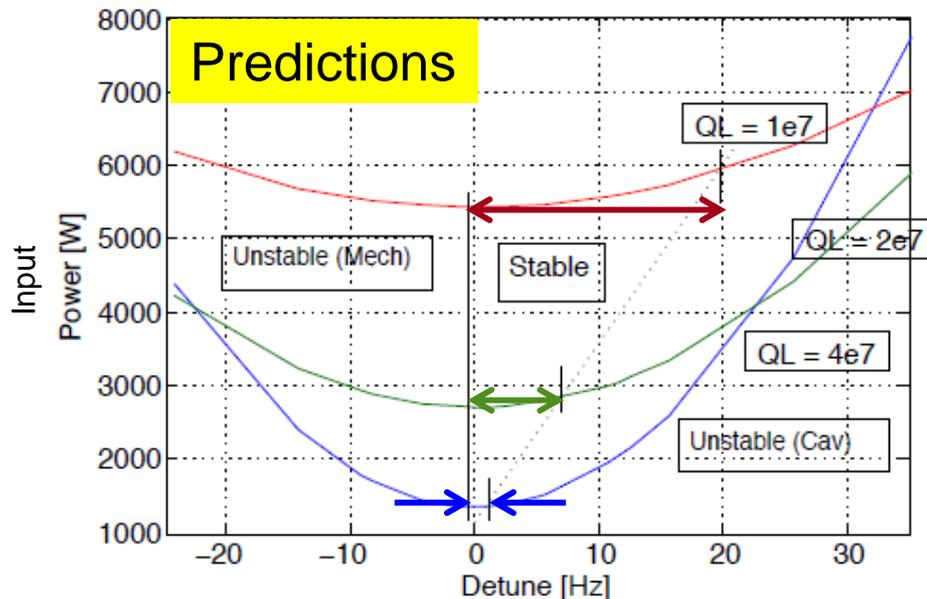
Gradient Squared vs Detuning

Predictions

Input Power [W]

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

C Rivetta

Mitigation: Decrease QL initially

To make the cavity gradients more stable, have plenty of extra power initally. That is,

- Until additional undulators lines are added (not in baseline), beam power limited to about 1/5 of max.
- In this case, can halve QL to 2e7, and with the nominal 6.3 kW/cavity, would have enough rf to double the compensatable detuning to 20 Hz and still have 15% rf overhead.
- RF system relatively easy to upgrade at later date as sources are in the gallery and waveguide is air-filled and can be readily reconfigured.
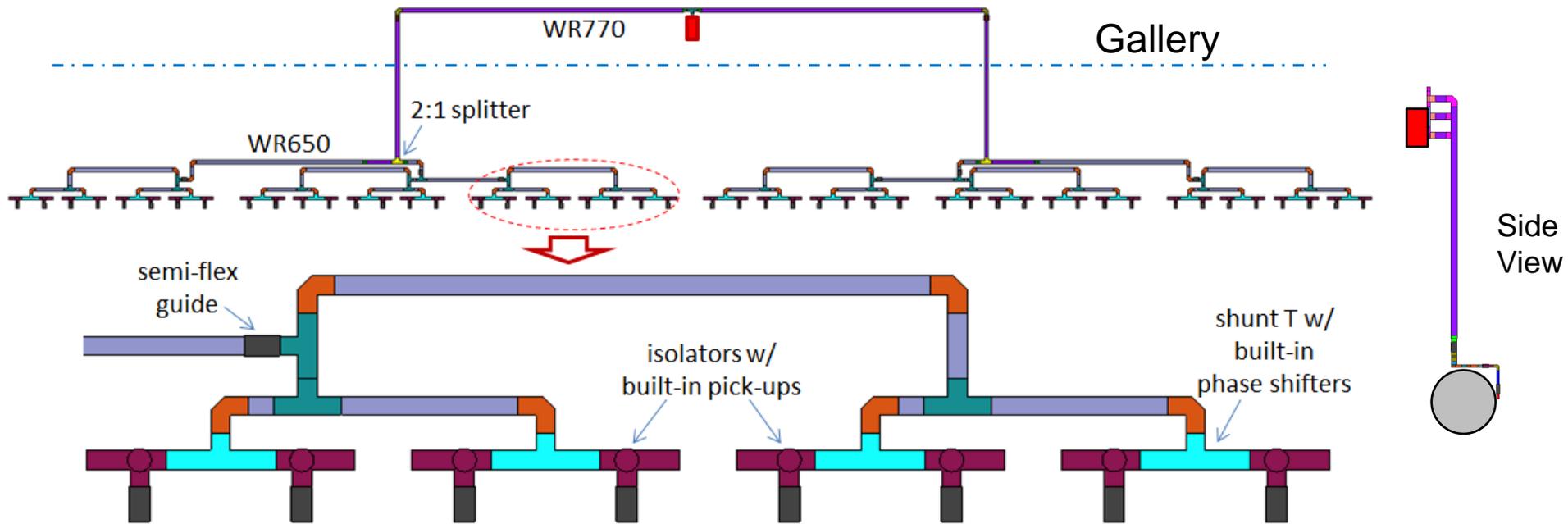
1.3 GHz Waveguide Components

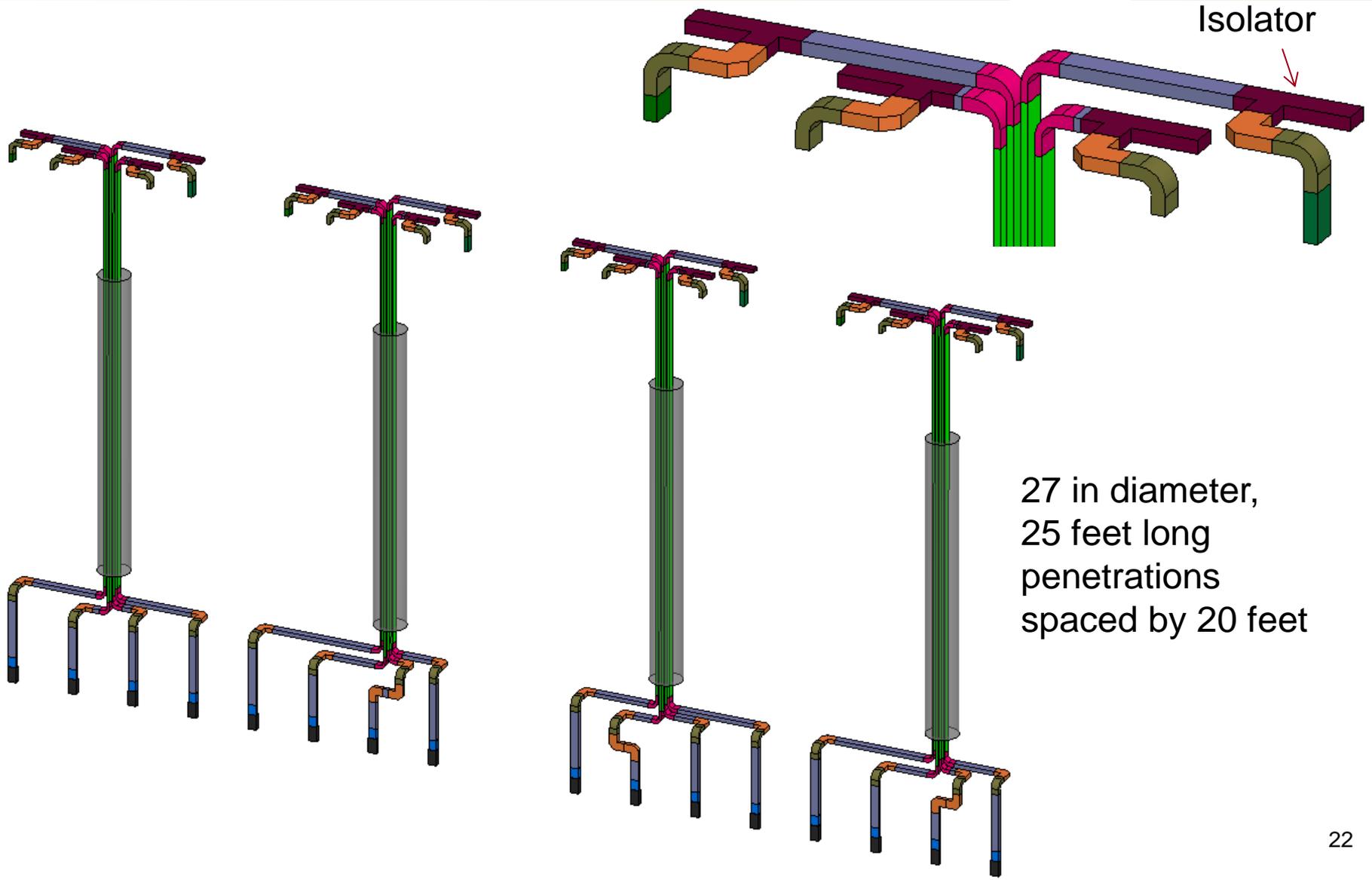Example of air-filled waveguide components used at DESY to bring power to the cavities

Parts bought commercially

Klystron Waveguide System

SSA Waveguide System

Isolator

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

SLAC Klystron Gallery

Yellow = Support system remaining after Gallery preparation

27 Inch Diameter Penetration

Alternate Approach (Not Yet Formally Adopted)

Although the high power klystron approach has lower component costs, there are additional development costs for the LLRF system and the multi-cavity per source approach needs to be demonstrated.

- Developing an all SSA approach but with lower power than the nominal 6.3 kW as the 2 undulator lines can each handle only 120 kW of beam power.

- Current choice is to provide 3.8 kW for 100 uA beams. However, install system that can be upgraded to 6.3 kW by just adding rf modules.
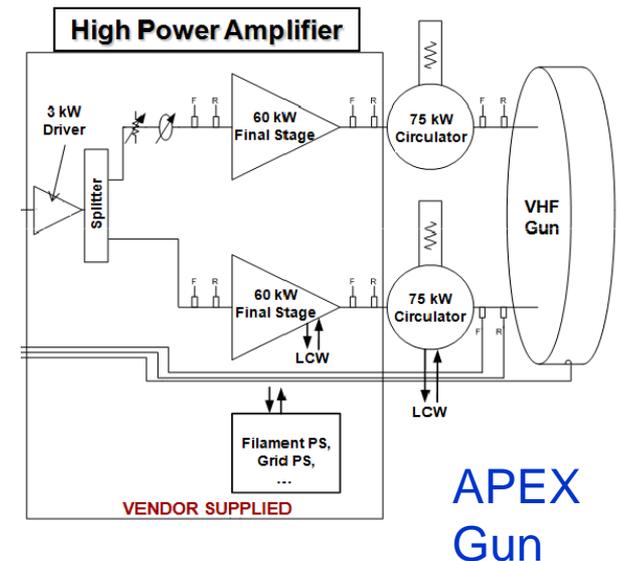
SSA Vendor Qualification

- Have submitted RFIs to refine cost estimate
- Developing 1.3 GHz SSA specs
  - Aim for at least 45% efficiency
  - Tradeoff BW for efficiency
  - Ability to change drain voltage
  - Customize for SLAC (AC voltage, EPICS ready, cooling water pressure, temp sensitivity, back termination, …
- Have two companies build 8 prototypes each for cryomodule testing at FNAL and JLAB as part of larger order

Other RF Sources

- 120 kW, 187 MHz SSA for the NC rf gun

- ~ 1 kW sources for each of 16, 3.9 GHz cavities

- 20 kW, 1.3 GHz source for the buncher (SSA's)

- Klystron Drivers (SSA's)

$$P_g = \frac{V_{cav}^2}{\left(\frac{r}{Q}\right) Q_L} \frac{1}{4} \left(\left[1 + \frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}} \cos \phi_b \right]^2 + \left[\frac{\Delta f}{f_{1/2}} + \frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}} \sin \phi_b \right]^2 \right)$$
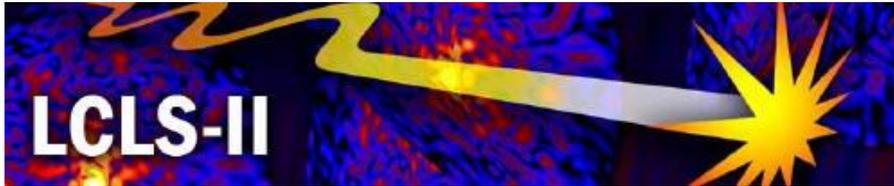
High Power Amplifier

3 kW Driver · Splitter · 60 kW Final Stage · 75 kW Circulator · VHF Gun · 60 kW Final Stage · 75 kW Circulator · LCW · LCW · Filament PS, Grid PS, … · VENDOR SUPPLIED

APEX Gun

3.9 GHz Cavities: R/Q = 750/.346, V = 14.5 MV/m, QL = 2.2e7
Pg = 415 W with Δf so sine term cancelled and beam off
Pg = 1.3 W with Δf so sine term cancelled and beam on at -165 deg

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.