High Power RF Overview & Progress

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SLAC NATIONAL ACCELERATOR LABORATORY

BERKELEY LAB Lawrence Berkeley National Laboratory

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U.S. DEPARTMENT OF ENERGY Office of Science

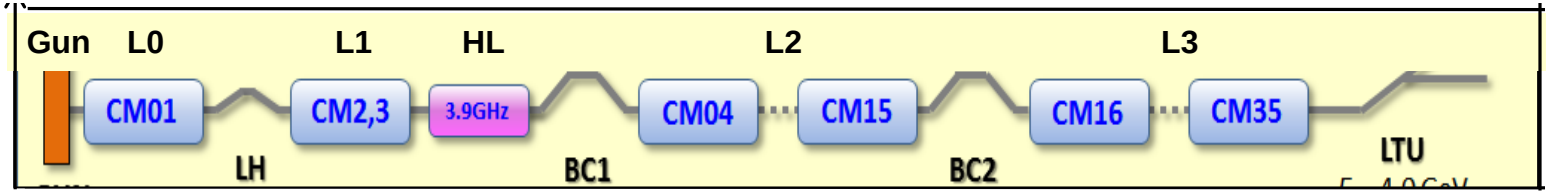
Introduction

- LCLS-II Bird's Eye View
- HPRF on LCLS II
  - SSAs
  - Waveguide Systems
  - NIRP
- Summary

LCLS II – Second Linac Coherent Light Source at SLAC

- A second Generation CW X-ray free electron laser facility, based on a 1.3 GHz, continuous-wave (CW) superconducting linear accelerator.
- Using first kilometer of existing SLAC Gallery and Tunnel
- 4 GeV 100 μa CW to be delivered to the undulator hall (possible future High Energy upgrade to 8 GeV)
- X-ray energies from 0.25 to 5 keV (2.5 Å), at 1 MHz. (12 to 20 keV with HE upgrade)

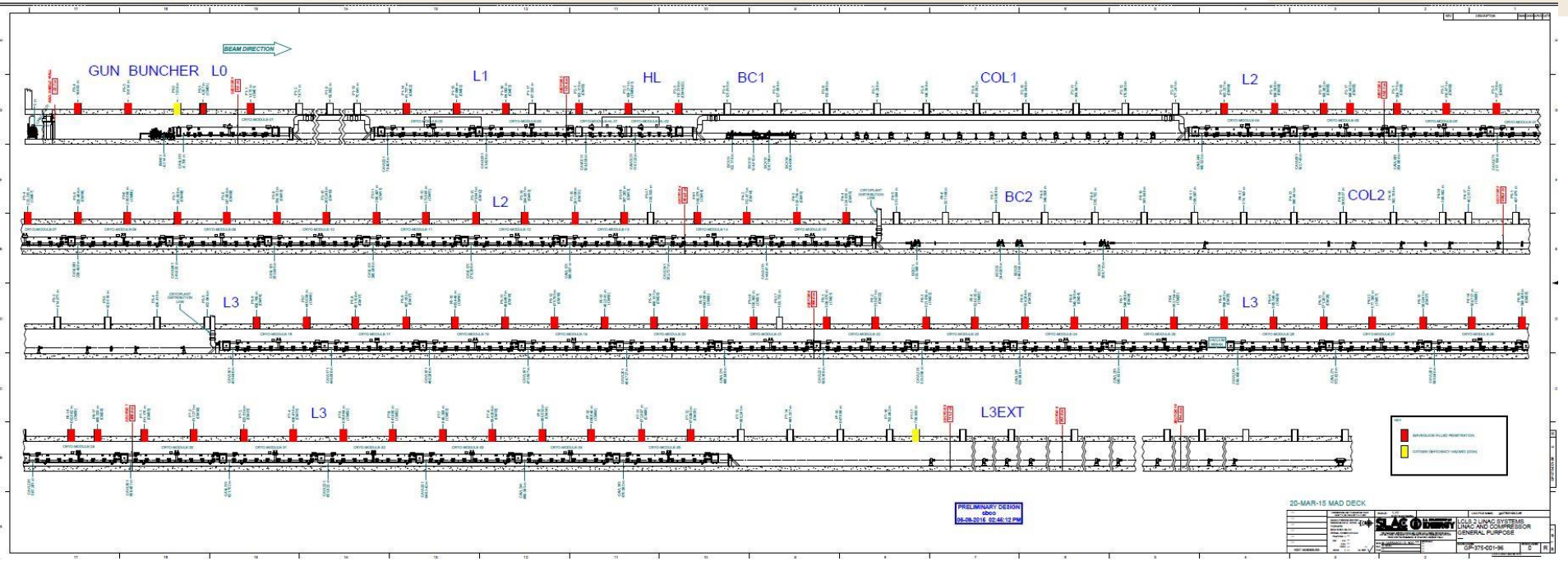
High Power RF (HPRF) Systems on LCLS II



- Gun, Buncher and Cryogenic Cavities in L0, L1, HL, L2, L3
  - 284* 3.8 kW, 1.3 GHz Solid State Amplifiers (SSA)
    - 280 for L0, L1, L2, L3
    - 4 for buncher after gun (not shown on drawing

    * note one of these is 4.6 kW
  - 16 1 kW, 3.9 GHz Sources for Harmonic Linac, HL
  - 2 60 KW, 185.7 MHz Sources for Gun (LBNL scope)

SLAC Gallery to Tunnel Penetration Allocations HPRF in Red



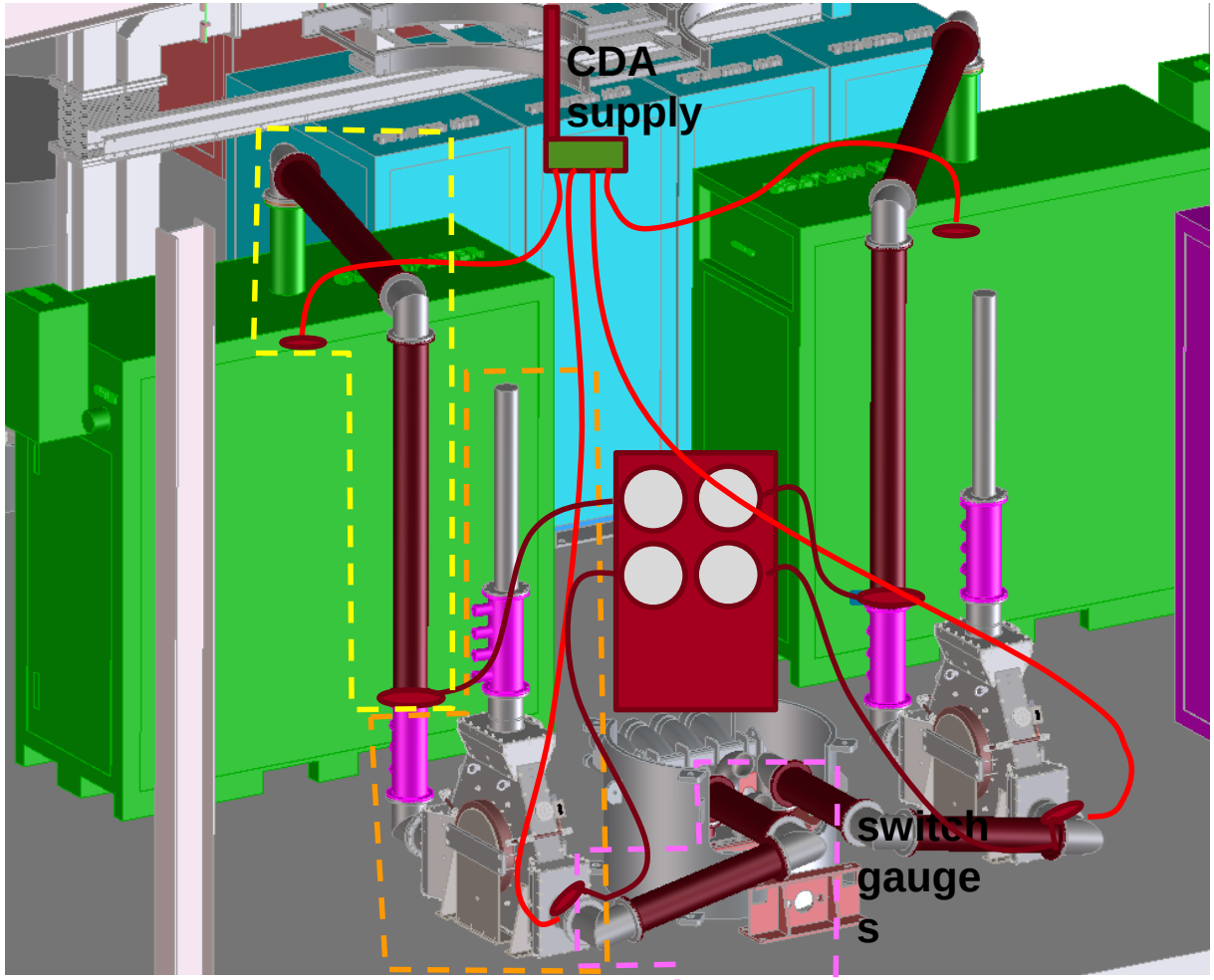
- **Total of 74 HPRF penetrations**
  - **1 for the RF Gun (187.5 MHz, 60 kW)**
  - **1 for the Buncher (1.3 GHz, 3.8 kW but need only 2.5 kW)**
  - **70 for main linac (1.3 GHz, 3.8 kW)**
  - **2 for Harmonic Linac (3.9 GHz, 1 kW energy linearizer)**

GUN HPRF System (LBNL Scope) Delivered and in Installatin process

SSAs made by R&K Company.

Circulators made by FERRITE

- SSAs
- Coax Transmission
- Circulator and load
- Dual Directional couplers
- Non Ionizing Radiation protection system.



3.9 GHz Harmonic Linac power system
Energy Linearizer pre Bunch Compressor 1

Critical RF Source Components

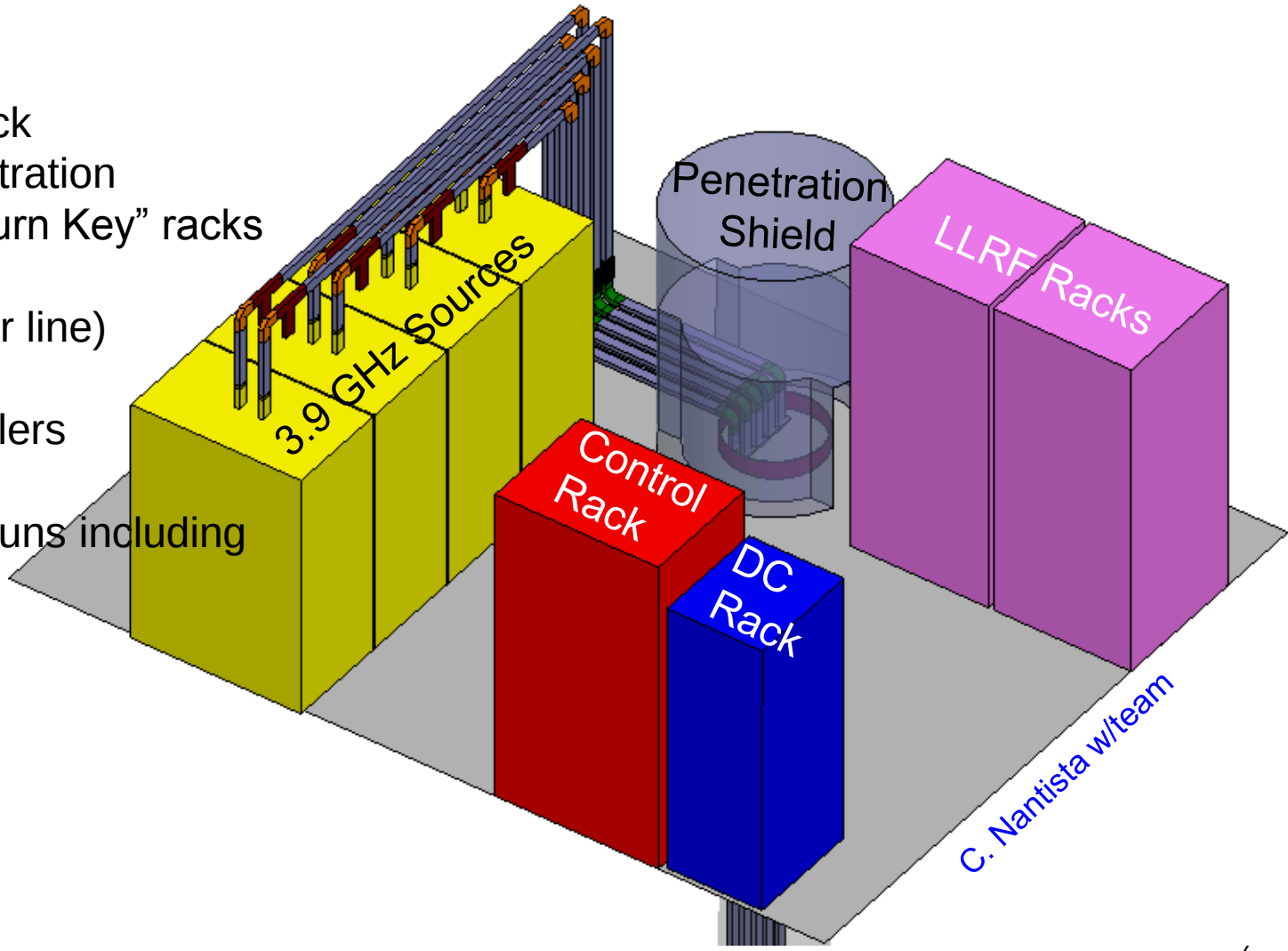
- 16 HPRF sources
  - 2 sources per rack
  - 4 racks per penetration
  - Self contained “turn Key” racks

- 16 Isolators (one per line)

- 16 Directional Couplers

- 16 RF waveguide Runs including
  - E & H Bends
  - Straights
  - Flex guides
  - Purge spacers
  - Gaskets

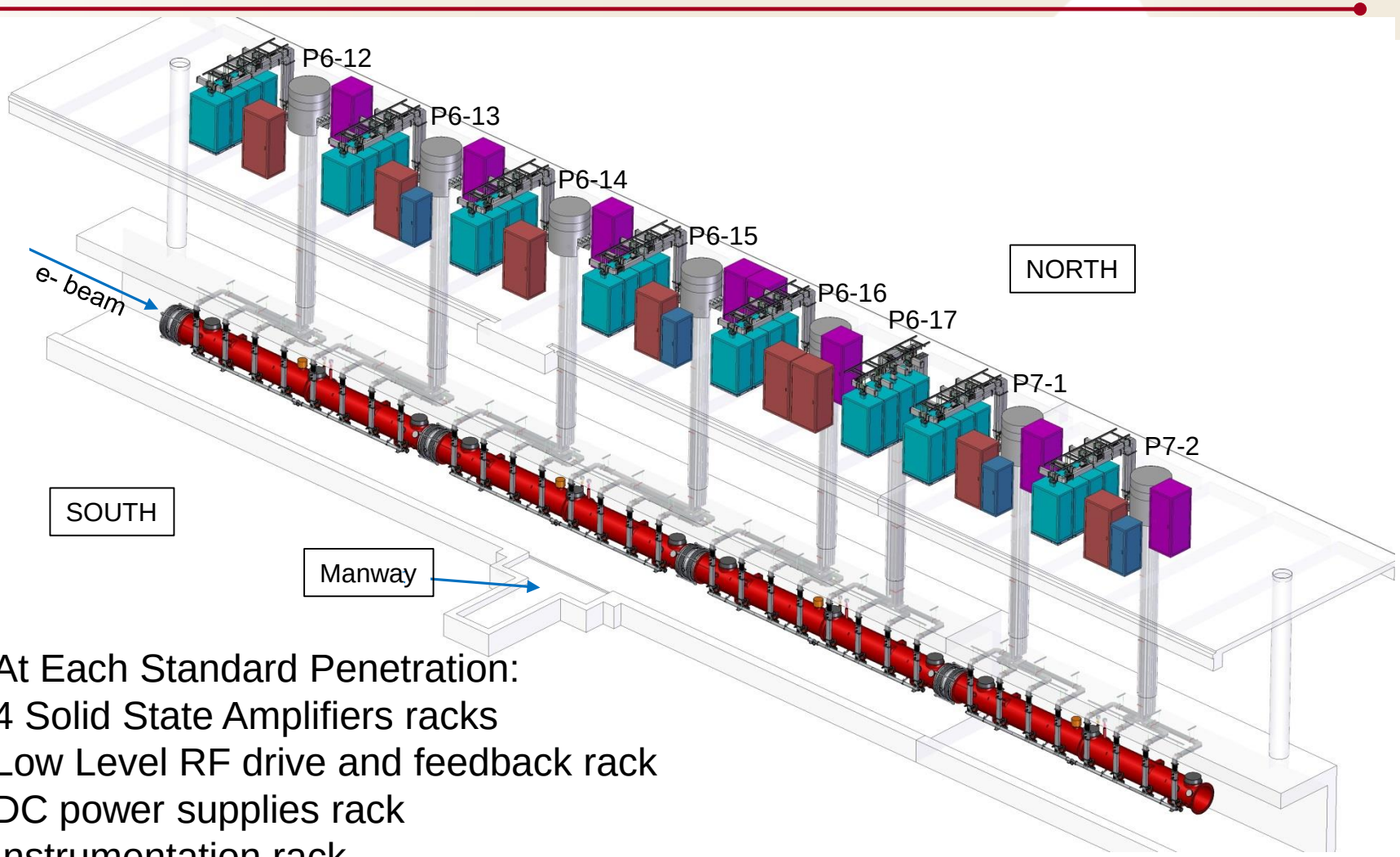
Two Such Penetrations



LCLS II 3.9 GHz SSA Basic RF Specifications 8 Racks with 2 Sources Each Shipped by R&K

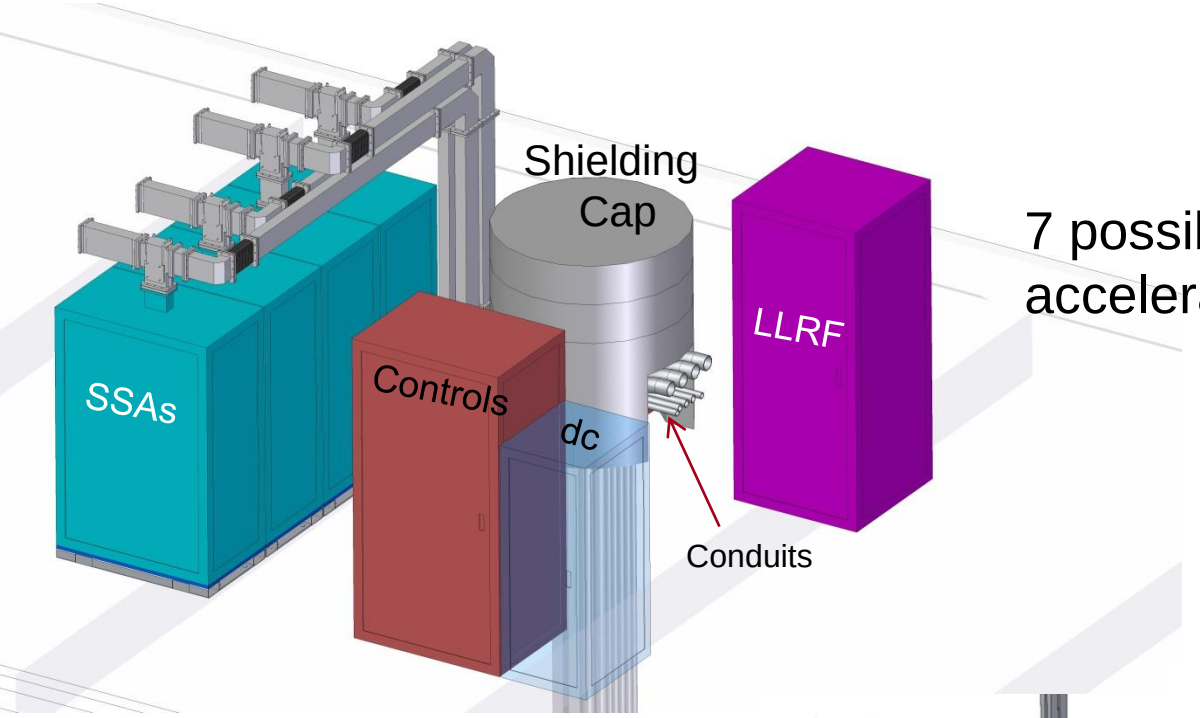
Requirement	
Frequency	3.9 GHz
Power (< 1 dB Compression)	900 W with < 10 dBm input
Bandwidth (1 dB)	> 2 MHz centered about 3.9 GHz
Open Loop RF Stability	< 0.1 % amplitude, < 0.1 deg on a one second time scale
Small Signal Delay	< 300 ns
Phase Variation (0.1 to 1 kW)	< 10 Degrees
Noise Figure	< 10 dB
Harmonic Content	<- 30 dBc
Spurious Content	< -60 dBc
Drain Voltage Operation Range	30%-100%, user adjustable
Efficiency at 1 kW (< 1 dB Compression)	> 25%
Reliability/Maintainability	> 15,000 hr MTBF (for items that disable system)
Cooling	Low Conductivity Water (LCW) 4 GPM at 30^{O} C plus internal air heat exchanger (Air temp < 45 degC)

Layout at Eight HPRF Penetrations in L3 Includes all Variations of the LCLS II 1.3 GHz

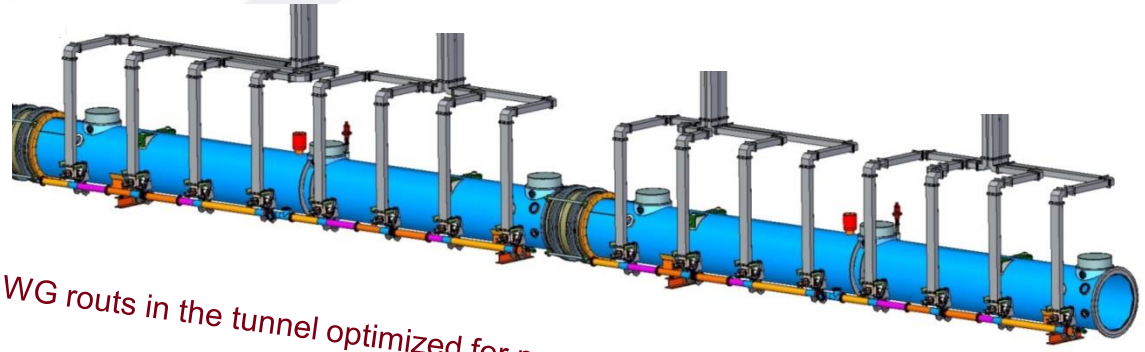


At Each Standard Penetration:
4 Solid State Amplifiers racks
Low Level RF drive and feedback rack
DC power supplies rack
Instrumentation rack
Shielding

Basic Layout at a typical LCLS-II 1.3 GHz HPRF Penetration Includes Buncher, L0, L1, L2, L3



7 possible variations at the accelerator housing ceiling.



WG routs in the tunnel optimized for proximity of penetration to the Cryomodule.

LCLS II 1.3 GHz SSA Basic Specifications
279 1.3 GHz Delivered by R&K Company

Requirement	
Frequency	1.3 GHz
Power (< 1 dB Compression)	3.8 kW with < 10 dBm input
Bandwidth (1 dB)	> 1 MHz centered about 1.3 GHz
Open Loop RF Stability	< 0.1 % amplitude, < 0.1 deg on one second time scale
Small Signal Delay	< 300 ns
Phase Variation (1 to 3.8 kW)	< 10 Degrees
Noise Figure	< 10 dB
Harmonic Content	< 30 dBc
Spurious Content	< 60 dBc
Drain Voltage Operation Range	30%-100%, user adjustable
Efficiency at 3.8 kW (< 1 dB Compression)	> 40%
Power Factor	≥0.9
Reliability/Maintainability	< 3 % transistors fail/year (but can still run with 1 failure)
	> 30,000 hr MTBF (for items that disable system)
Cooling	Low Conductivity Water (LCW) 4 GPM at 30^{O} C plus internal air heat exchanger (air temp < 45 degC)

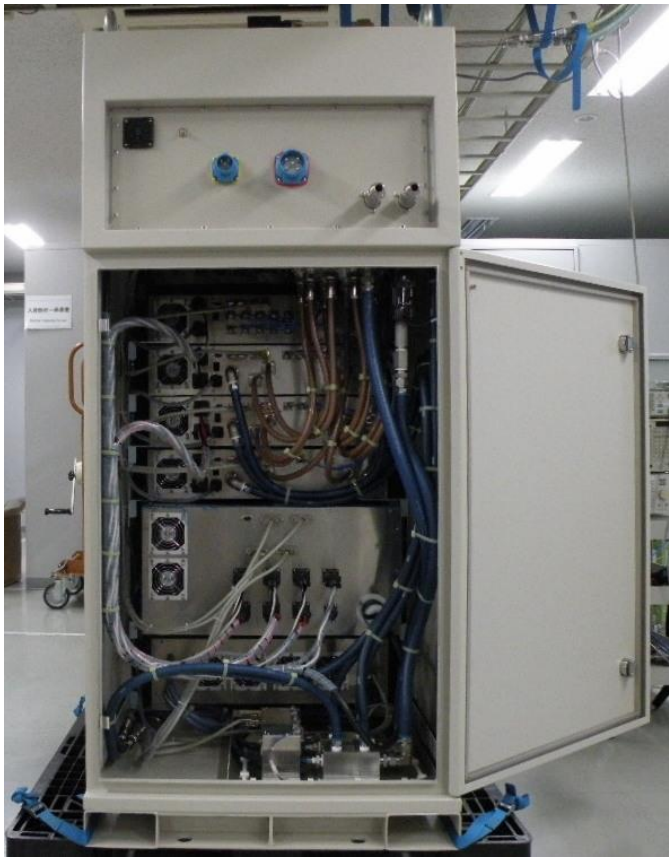
LCLS II SSA unit is self sustained and self protected

Basic SSA Units include

- Control Module
- Power supplies
- Heat Exchanger
- Amplifier Modules
- Power combiner
- Internal Isolator Directional Coupler
- Rectangualr Wave guide output at a specified location

Front and Side

Back

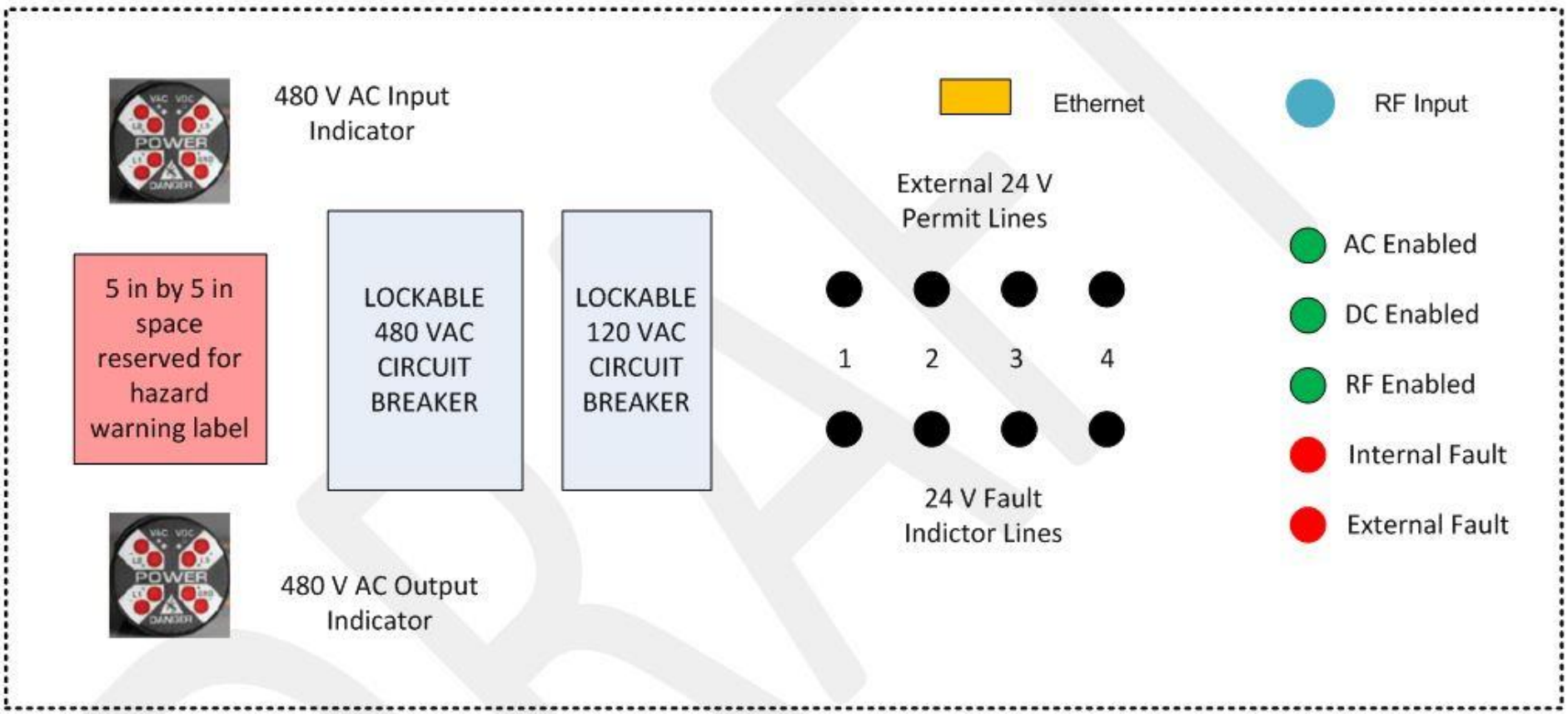


The R&K 1.3 GHz SSA Rack for LCLS II

LCLS II Modular Nature of LCLS II SSAs

- The Modular Nature of the SSAs facilitates
  - Repairs with minimal impact on operation.
  - Possible upgrade to higher power if transistor technology improves considerably to improve efficiency.
  - Already an upgrade from 3.8 to 4.6 kW that fits in the same rack has been designed and one sample delivered by R&K.

The SSA Control Panel Defined by SLAC and Incorporated by R&K



The Control System has the following Features.

- Control Unit front panel has the following features –
  - RF and Ethernet input
  - AC, DC, RF enable lights,
  - 120 and 480 VAC status lights,
  - Internal and external fault lights
  - and 24 V Input and output permits via BNC.

- Self protecting - SSA will trip on internal Fault and remove all output 24 V permits to alert the LLRF system if
  - external or internal reflected power exceeds threshold
  - Input water temperature is not in range
  - Input water flow is not in range

- Trip on command due to External faults - other problems on the Machine can require the SSA to trip
  - 4 external enable signals (24 V) let the SSA know all is OK
    - One will be dedicated to Non Ionizing Radiation Protection diagnostics
    - Other three can be used for any other system on the machine to command the SSA to trip or if more than two then those signals will go into a sum box.

LCLS II SSA Factory Acceptance Tests

- Each and Every SSA undergoes the following Rigorous tests and more at the factory:
  - Electrical Equipment Inspection Plan (EEIP)
  - Output power (w/1dB compression) vs. input power for various drain voltages.
  - Δ Phase (Output – Input) vs. input power for various drain voltages.
  - Efficiency vs. input power for various drain voltages.
  - Gain curves at each Amplifier state and for the entire system.
  - Output Power and Phase vs. Frequency at 3.8kW and 1.5 kw
  - Spurious and Harmonic Spectrum Analysis
  - Operate unit in 45^{O}C environment for 24 hrs. at 3.8 KW and 2 hrs. at 1.5 KW and record (~ per min.)
    - Output power
    - Reflected power back to the SSA
    - Δ Phase (Output – Input)
    - rms power variation (over a ~ 1 second interval)
    - rms phase variation (over a ~ 1 second interval)
    - Cooling water temperature
    - Inside-the-rack air temperature
    - Outside-the-rack air temperature

    Unit should operate without a fault during this test
- Long term tests at Vendor site or at SLAC and of course at the Partner Labs.

Minimizing Chance for a Blow UP!

- **All SSAs have undergone riggourous Factory Acceptance Tests at R&k Including in California hot weather conditions.**
- **All SSAs have passed thorough Electrical Equipment Inspection Plan.**

LCLS II SSA Electrical Equipment Inspection Plan

- Each and Every SSA must pass the following EEIP inspection at the factory or at delivery location.
  - Rack as a whole –
    - ground bonding of all the walls
    - are all terminals >50 V covered and touch safe?,
    - All wire harnesses,
      - wire size,
      - is insulation in tact?
      - Routing - do all the 480V wires have bend radii ≥6 times radius,
      - Colored according to Code (important for safety of maintenance techs)
      - lugs of distribution lines,
  - Open every single chassis
      - check for the same things as above inside the chassis
      - Are fans easy to remove and install safely?

SSA Installation at SLAC in Progress)

LCLS II: 10 1.3 GHz SSAs AT FNAL, 25 at JLAB for Cryo Module Tests Will be Returned for Final Installation at SLAC.

At FNAL

At JLAB

Documentations left at FNAL and JLAB

R&K provided a complete set of hard copy and electronic documentation including

- Operation manual,
- Drawings and schematics
- Factory Acceptance Test Data,
- Source codes (electronic only),
- R&K's Modbus interface (electronic only),
- R&K's software for changing IP address and instructions (electronic only)

LCLS II - SSA Reliability Specifications

The SSA reliability is Specified in the Engineering Specification Document for the 1.3 GHz SSAs and will be also for the 3.9 GHz sources.

- Less than 1% of the transistor pallets fail per 2000 hours

- System continues to operate with one transistor failed.

- Systems that inhibit operation that take more than 1 hour to repair do not occur more than once on average per 30,000 hours

- An internal interlock system shuts off the SSA under various failure conditions (water flow, overheating, large rf reflection, etc)

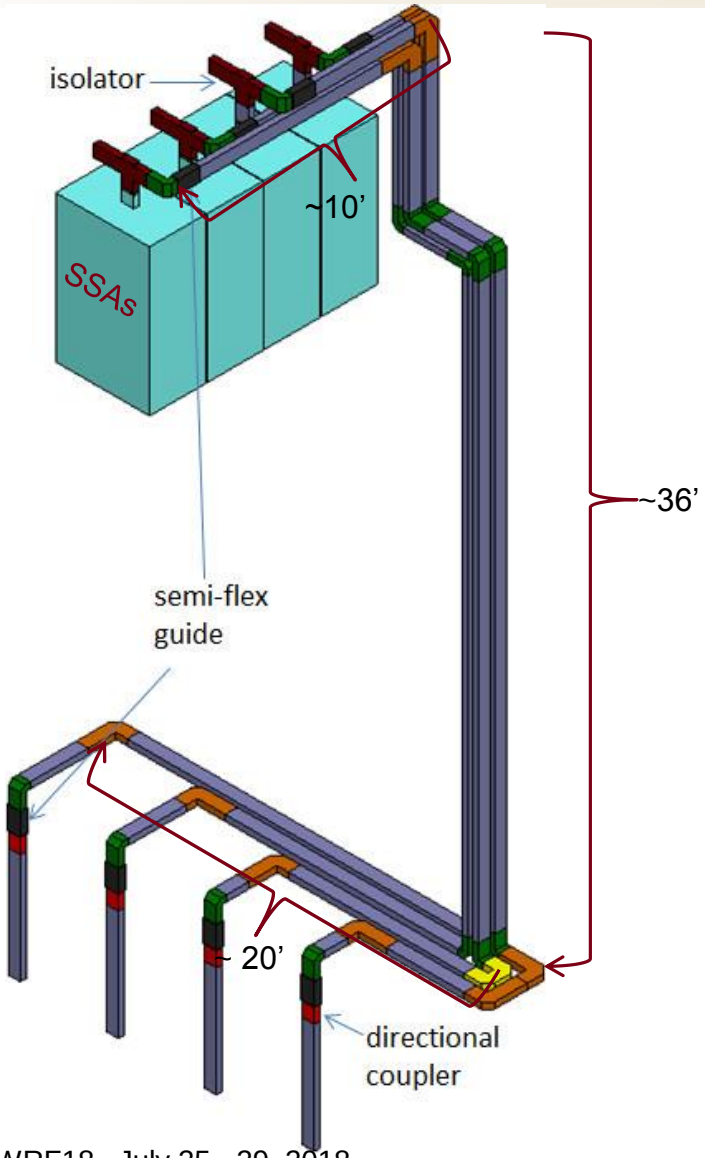
1.3 GHz SSA Availability – Not a Limiting Factor for LCLS II

Failure	MTBF (khr.) (R&K units)	Average Number of Failed Units (12 hr. repair period)
Main Amplifier (Can run with 6 failed)	68.5	0.05
Pre Amplifiers	273	0.01
Main Power Supply (Can run w/ 2 out of 6 failed)	88	0.04
Controller	79.2	0.04
Heat Exchanger Fans	244	0.01
Flow Meter	66.9	0.05
TOTAL PER SSA RACK	**17.4**	**0.21**

With an average of 0.21 failed, probability of exceeding 6 failures = 2.6×10^{-9}

Thus Uptime for LCLS II SSA System is 99.99999974% C. Adolphsen

On to Basic LCLS-II Waveguide System



- Waveguide system consists of
  - Isolator immediately after the SSA output
  - Straights
  - E, H and U bends
  - 2 Flex Guides (downstream of Isolator and final E-bend in the housing
  - Directional Coupler after second flex guide
- Identical layouts for
  - SSA to cryomodule (slight support variations possible)
  - in penetration
  - cryomodule to accelerator housing ceiling
- Accelerator Housing Ceiling one of 5 Variations mentioned above
- The bottom of the penetration is sealed with a plate and calking to prevent tunnel air in case of an accident He_2 to escape into the gallery.

Isolator Specifications for 1.3 GHz (3.9 GHz)
16 3.9 GHz and 120 1.3 GHz delivered by FERRITE
More on the Way

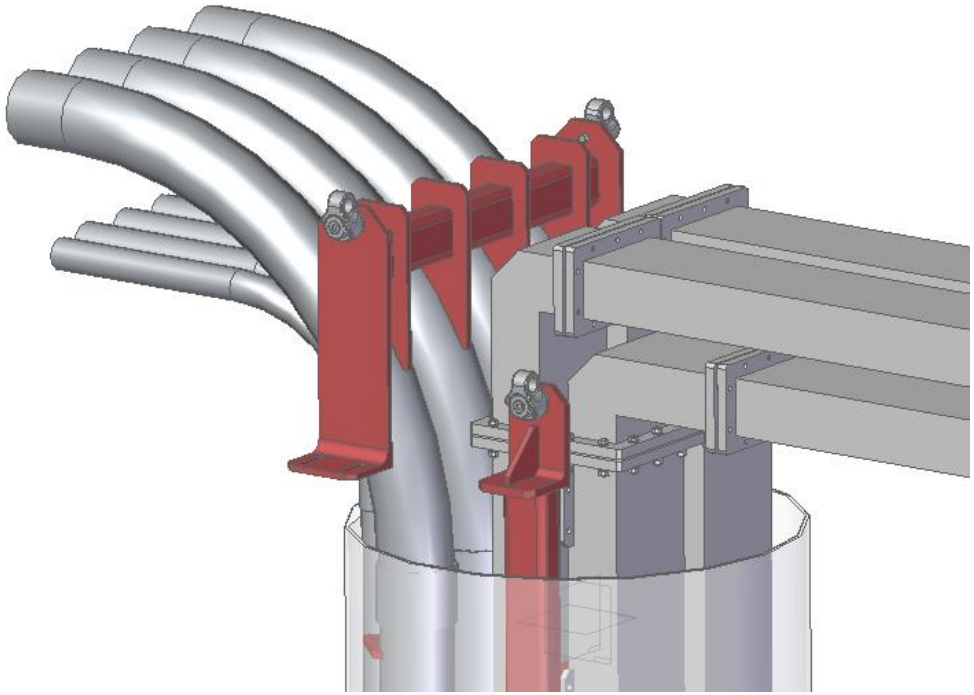
PARAMETER	SPECIFICATION
operating center frequency (f_0)	1,300 MHz (3,900 MHz)
bandwidth (BW)	10 MHz (30 MHz)
RF source operating power range	0–4 kW or 0–7 kW (0–1 kW) CW, w/ up to full reflection @ any phase
additional beam induced RF into the output port	≤ 430 W or 3.75 kW (≤ 190 W or 1.7 kW)
isolation ($-S_{12}$)	≥ 25 dB across BW
return loss (S_{11} & S_{22})	≤ -27 dB across BW; VSWR < 1.094)
insertion loss ($-S_{21}$)	≤ 0.15 dB (≤ 0.3 dB) across BW
RF body leakage	< -50 dB
waveguide	WR650 (WR284), corrosion resistant
flange type	WR650 (WR284) standard, flat, smooth to few mil level
angle between input and ouput ports	90°
cooling	low conductivity water cooled
pressurizability	airtight and performance stable to 4 psig
proximity	must work at 30” (12”) spacing w/o magnetic interference

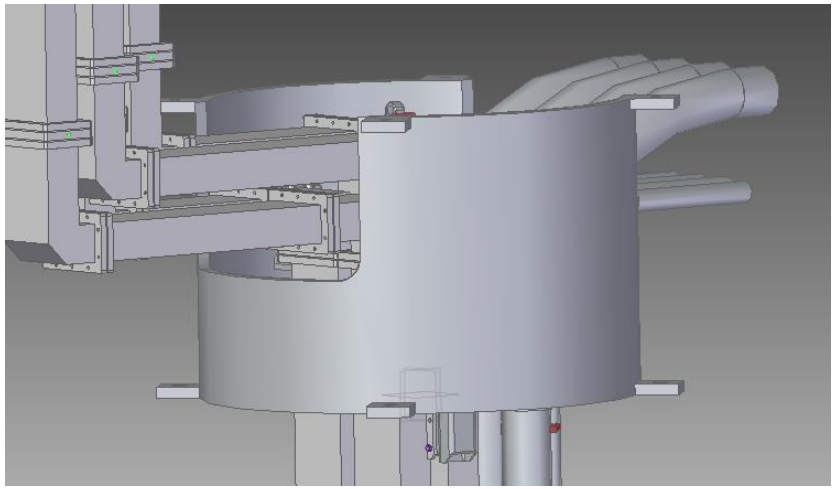
Directional Coupler Electrical Specifications for 1.3 GHz (3.9 GHz) 16 3. GHz and 284 1.3 GHz Delivered by MEGA

PARAMETER	SPECIFICATION
operating center frequency (f_0)	1,300 MHz (3,900 MHz)
bandwidth (BW)	10 MHz (30 MHz)
operating power range	0–7 kW (0–2 kW) CW, w/ up to full reflection @ any phase
coupling (@ f_0)	-50 dB (-40 dB) ± 0.5 dB (forward & reverse, w/ factory cal.'s labeled)
coupling flatness	0.1 dB across 200 kHz (600 kHz) around f_0, 0.3 dB across BW
directivity	> 40 dB across BW
return loss (S_{11} & S_{22})	< -40 dB across BW; VSWR < 1.02
insertion loss ($-S_{21}$)	< 0.01 dB (< 0.02 dB) across BW
coupling ports	dual broad wall (same side) loop couplers
RF body leakage	< -50 dB
waveguide	WR650, corrosion resistant
flange type	WR650 standard, flat, smooth to few mil level
connectors	non-Teflon, precision Type N female, 50 Ω
pressurizability	gas tight and performance stable to 4 psig
radiation	radiation resistant materials (e.g. Rexolite windows, non-Teflon connectors)
length	12″

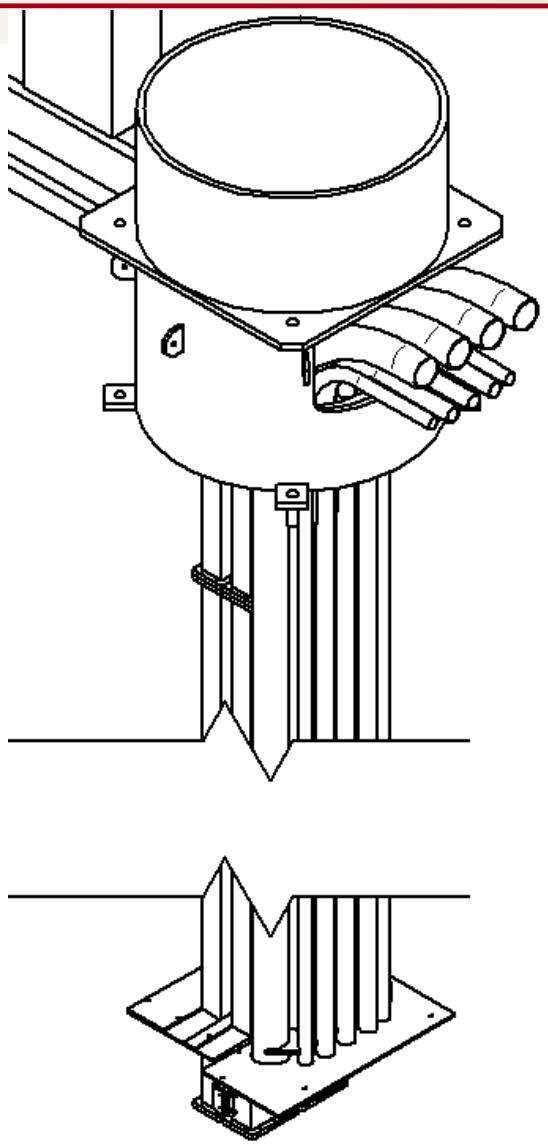
HPRF Penetration Configuration

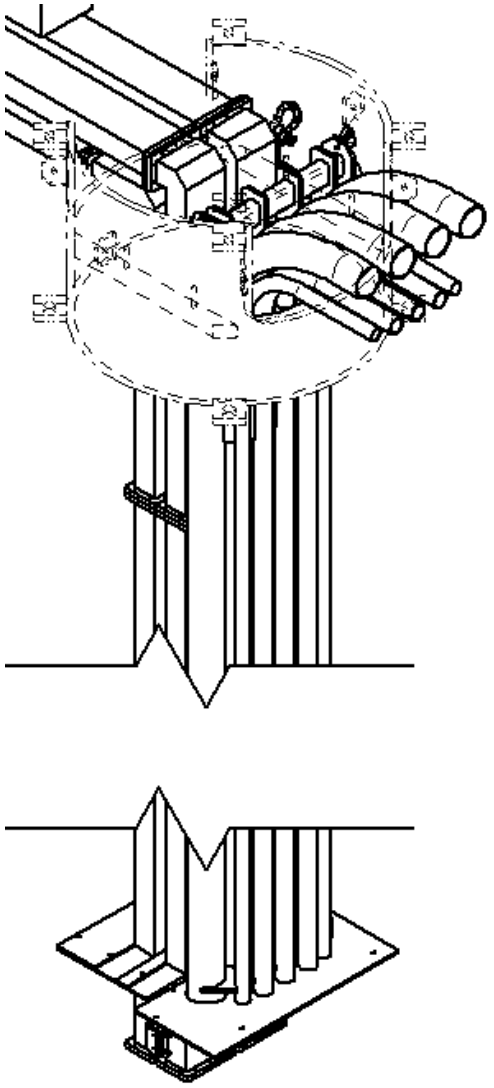
- Each L-band HPRF penetration to contain 4 waveguides, 9 conduits (ranging in size from 1.5 to 4”),
- Where as for S-band each penetration will support 8 waveguides.



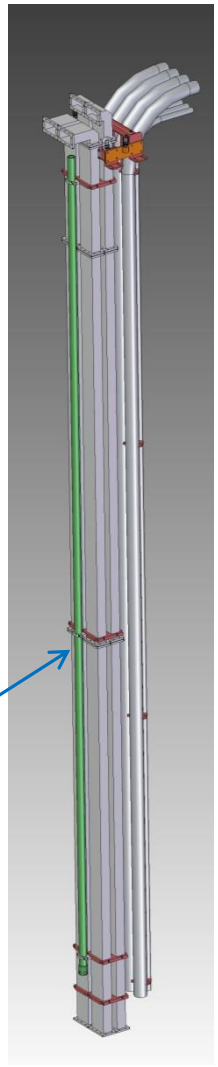


Penetration Waveguide and Conduit Bundles Inside Shielding Cap





Installation Scenarios in Discussion Already Waveguide Bundles share Penetration with Conduit Bundles.

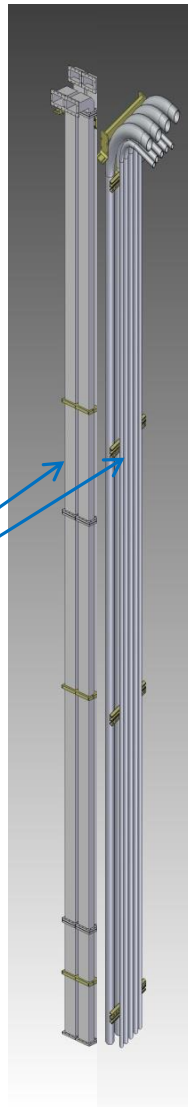


28.5 ft.

Air cooling pipe in case needed

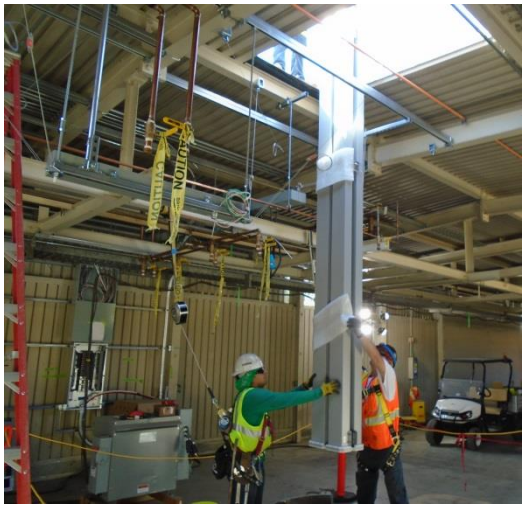
Waveguide and conduits in penetration

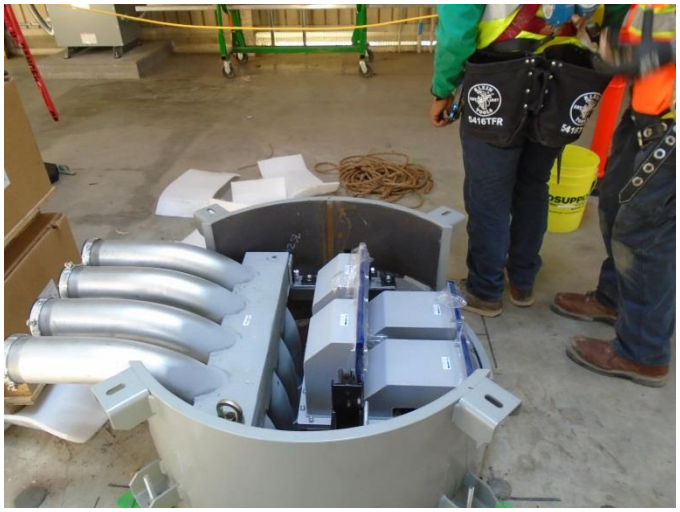
- Installed in bundles from the roof
  - First the Conduit bundles
  - Then the WG bundles.
- Waveguide supports designed for the weight and lever Arms associated with the waveguide system
- Vibration damping to practically elliminate WG effect on microphonics



Guards to hold each bundle together

Penetration L-band WG & Conduit Bundles. 100% Installed





- ~25 foot bundles of 9 Conduits are lowered into the penetration from the gallery roof opening
- Then a bundle of 4 waveguides (no flanges in the penetration) are lowered from the roof into the penetration
- The shield base serves also as a support for anchoring the bundles.

Installation Photos: Gallery Buncher Penetration (P0-03)

- SSAs, Isolators on top, WG runs, and supports installed in the gallery for buncher.

Installation Photos: Waveguide Installation in the Housing

- Waveguides have been installed in the accelerator tunnel and the progress continues at a steady rate. .

HPRF Penetration Heat Loads

For G=16 MV/m, Q_L= 4.1e7 and WR650 loss =0 .00839 dB/m

I_b = 0

Pforward = 2.62 kW, Preflected = 2.56 kW, Ptot = 5.18 kW
Heat per WG: 9.99 W/m

I_b = 100 μA

Pforward = 3.67 kW, Preflected = 1.93 kW, Ptot = 5.60 kW
Heat per WG: 10.8 W/m

I_b = 300 μA

Pforward = 6.48 kW, Preflected = 1.46 kW, Ptot = 7.94 kW
Heat per WG: 15.3 W/m

Approximate length in the penetration: 25 ft. = 7.62 m
From 4 waveguides, the total heat in the penetration load is:

I_b = 0:	40.0 W/m	or	304.8 W	+	30W Conduit
I_b = 100 μA:	43.2 W/m	or	329.2 W	+	30W Conduit
I_b = 300 μA:	61.2 W/m	or	466.3 W	+	30W Conduit

C. Nantista

HPRF Penetration Temperature

Conditions:

Gallery ambient T = 40^{O}C

Accelerator housing ambient T = 25^{O}C

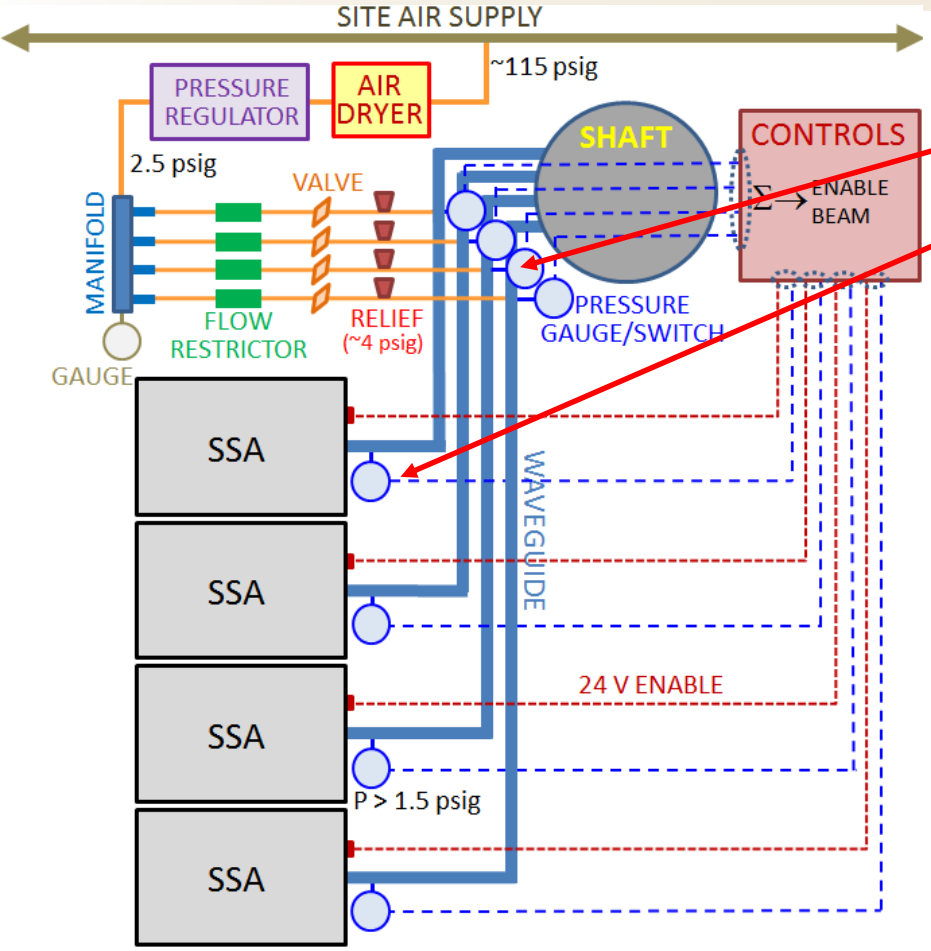
No Cooling With Bottom of Penetration Covered.

Case	100μA	300 μA
Calculated WG T	74^{O}C	91^{O}C
Calculated Conduit T	71 - 73^{O}C	86-88C

- **A passive air cooling pipe installed in the space between the WG and conduit bundle is expected to reduce the temperature of the conduit carrying the phase signal cable to 60^{O}C for the 100 μA operation. If needed we can also blow air into it.**

- **Conduit bundle in the penetration for the phase signal lines will have 3 thermocouples installed at the bottom, middle and top to monitor its temperature.**

LCLS-II: On to NIRP Scenario

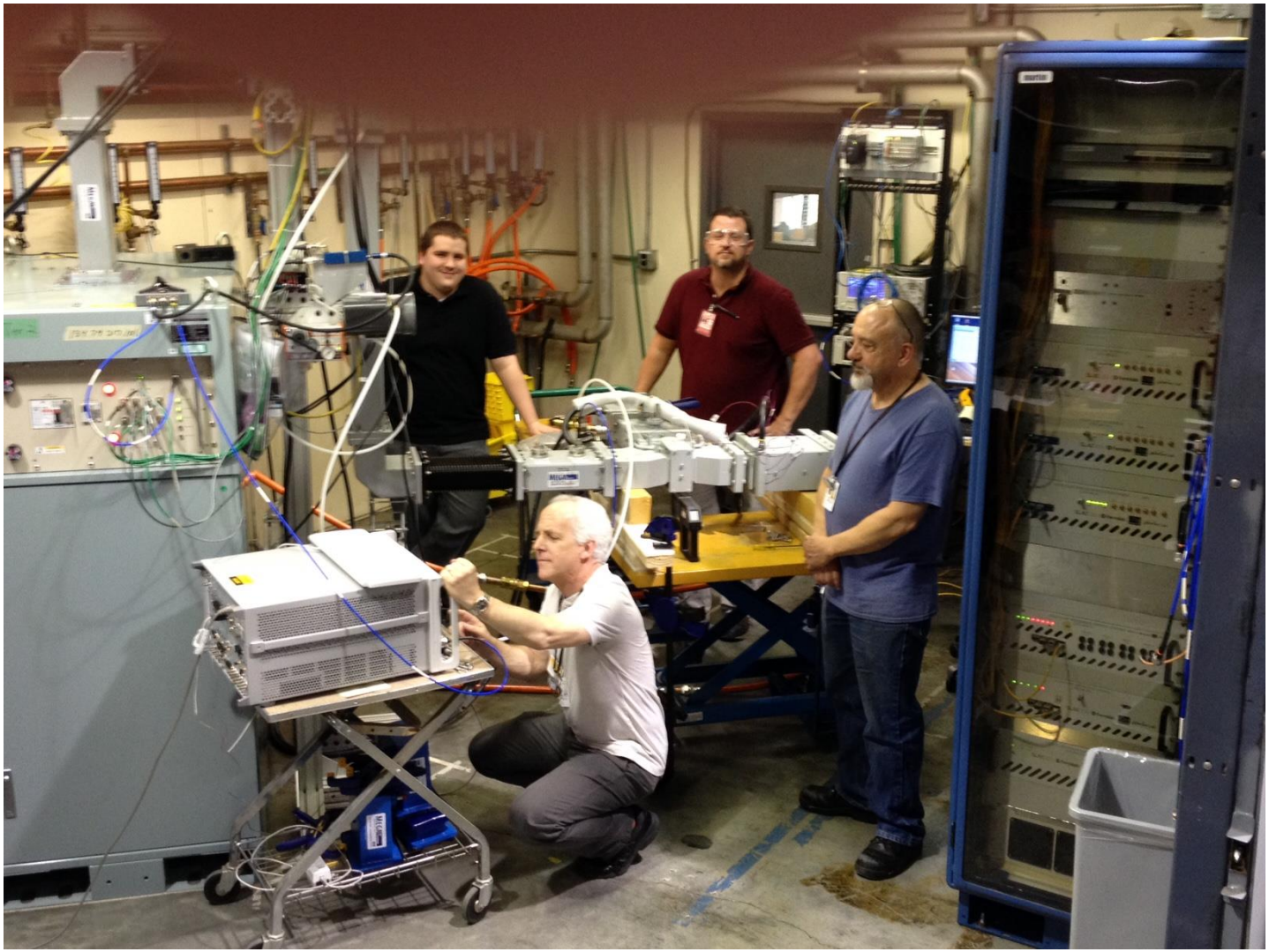


- Each RF run has two gauges
  - On the WG run
  - At the SSA
- When one gauge reads a fault that SSA is turned off.
- If both gauges read a fault both that SSA and Beam are turned off
- If SSA needs to be removed for an extend period
  - SSA Pressure Gauge is removed with it
  - RF Shorting Plate added to the Waveguide
  - Waveguide re-pressurized

An RF Test Stand at SLAC for Risk Mitigation and to Discover as many Blow Ups as Early as Possible

- The test stand to accommodate 3 SSA stations is complete and used to
  - Qualify SSAs under long term operation
  - Test SSA control software
  - Qualify Waveguide components
    - Isolators
    - Directional couplers
    - Straights, bends and flexes
  - Test Non Ionizing Radiation Plan scenarios.
  - Provide experience for operations.
  - Maybe learn about Blowups (hopefully non) and make corrections to apply on LCLS II

Prototype Isolator High Power Tests at the HPRF Test Stand in Building 15



LCLS II HPRF Summary

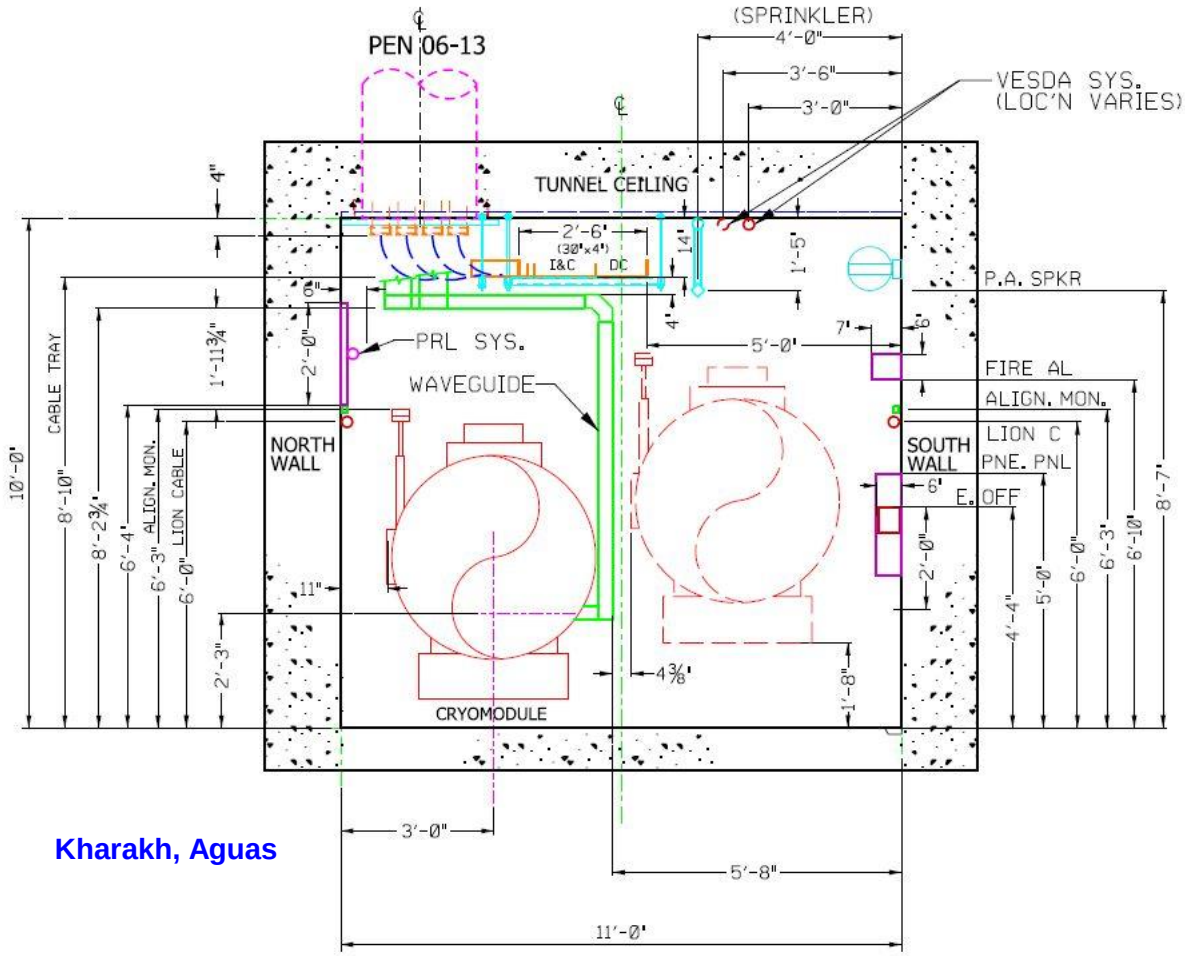
- RF component specification are very detailed not only about RF performance but quality as well. We hope to avoid blow ups.
- All ordered 1.3 GHz SSAs delivered at SLAC, FNAL and JLAB for installation and Cryo Module tests. .
- A HPRF Tests stand at SLAC is used daily for various HPRF tests.
- All Gun HPRF systems delivered and installation nearly complete.
- All Directional Couplers delivered.
- Half of the 1.3 GHz and all of the 3.9 GHz isolators in delivered. More on the way.
- All 1.3 GHz WG components delivered and in installation.
- 3.9 GHz WG components will be delivered in September in time for installation.
- NIRP designed, parts procured, Installation in progress.
- HPRF Test Stand is very useulf
- No blow us to report at this time. Maybe in 2020. Hopefully not.

End
Backup Slides below

SLAC NATIONAL ACCELERATOR LABORATORY
BERKELEY LAB Lawrence Berkeley National Laboratory
Argonne NATIONAL LABORATORY
CORNELL UNIVERSITY FOUNDED A.D. 1865
Fermilab
Jefferson Lab

U.S. DEPARTMENT OF ENERGY
Office of Science

Tunnel Cross Section Near HPRF Penetrations Interferences with other systems Resolved



Kharakh, Aguas

ACCELERATOR TUNNEL

(TYP. CRYO-WAVEGUIDE & TRAY AT PENETRATION)

Tunnel Cross Section Near HPRF Penetrations in L0 Interferences with other systems Resolved