Status of the LCLS-II Project

Andrew Burrill (on behalf of the LCLS-II Collaboration)

Outline

- Project Overview
  - Key Performance Parameters
  - Schedule & Status
- The SRF Linac
  - SRF Cavities
  - Cryomodule Assembly and Testing
  - Issues & Mitigation
- Conclusions

Project Collaboration: SLAC couldn't do this without…

European XFEL

DESY

cea
DE LA RECHERCHE À L'INDUSTRIE

LAL
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE


Remove SLAC Linac from Sectors 0-10
New Injector and New Superconducting Linac
LCLS-II

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New Injector and New Superconducting Linac
New Cryoplant
LCLS-II


Remove SLAC
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New Injector and
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LCLS-II
New Cryoplant
Existing Bypass Line
New Transport Line


Remove SLAC Linac from Sectors 0-10
New Injector and New Superconducting Linac
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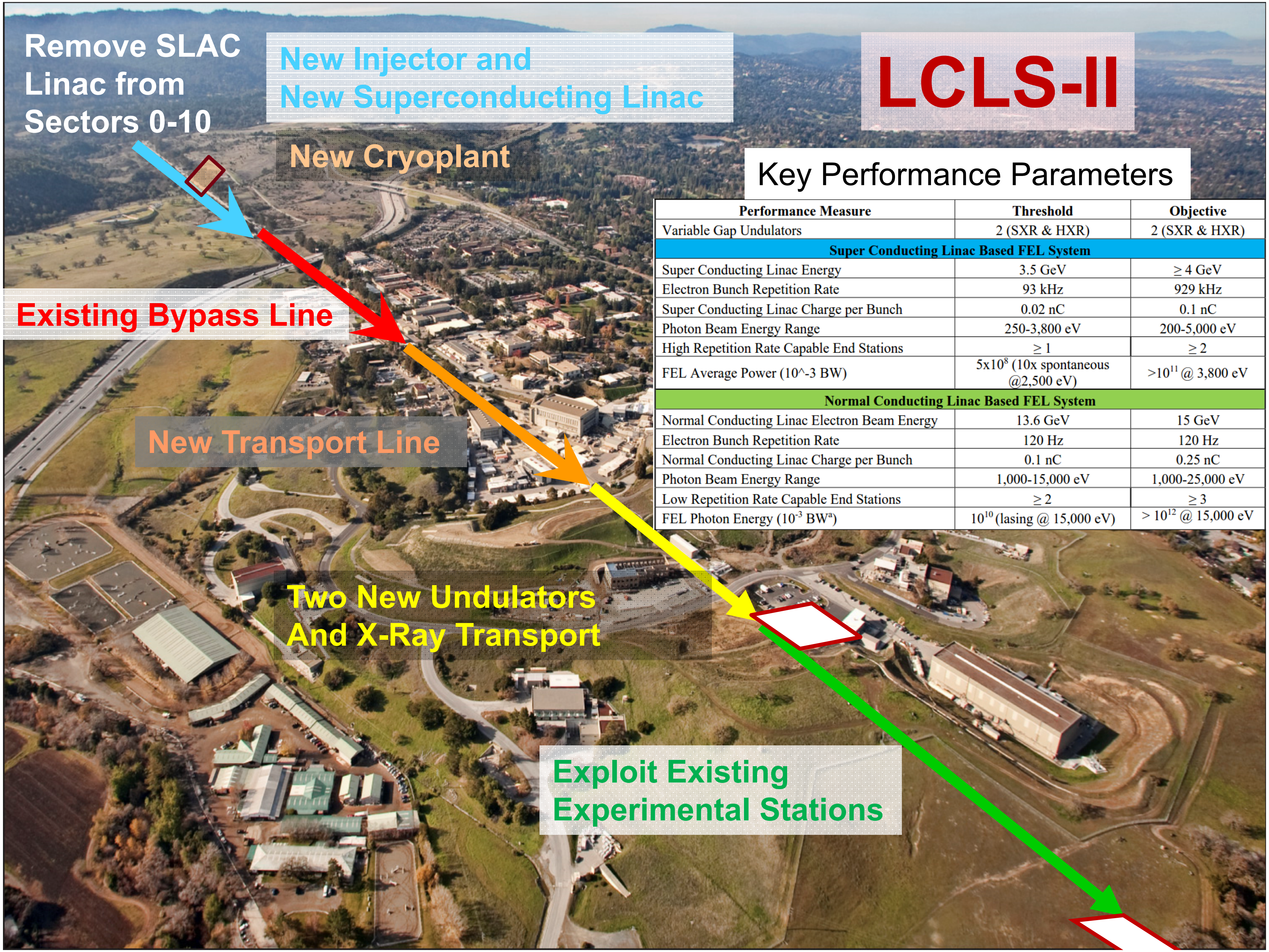
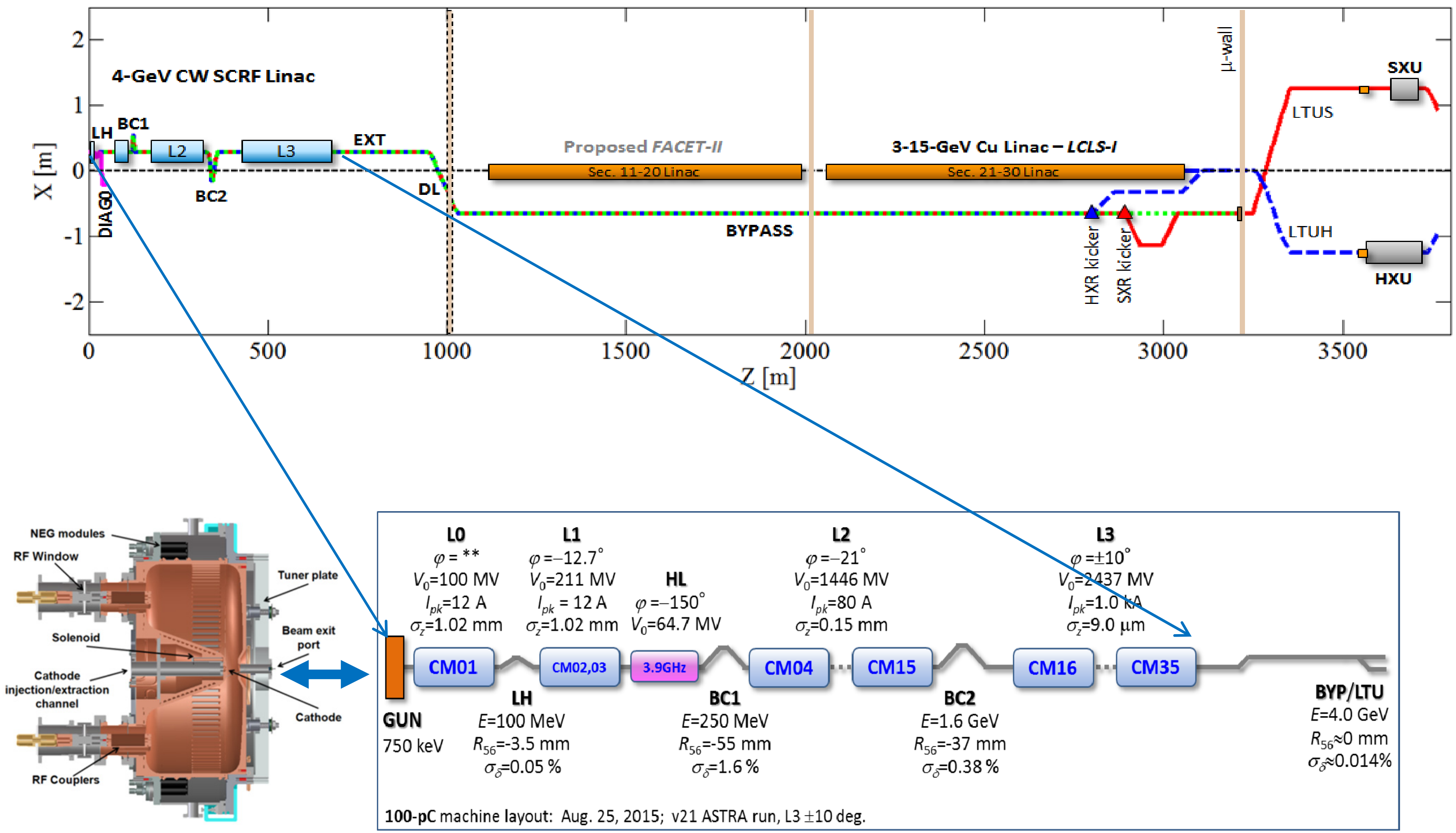
New Cryoplant
Existing Bypass Line
New Transport Line
Two New Undulators And X-Ray Transport
Exploit Existing Experimental Stations



Key Performance Parameters

Performance Measure	Threshold	Objective
Variable Gap Undulators	2 (SXR & HXR)	2 (SXR & HXR)
Super Conducting Linac Based FEL System		
Super Conducting Linac Energy	3.5 GeV	≥ 4 GeV
Electron Bunch Repetition Rate	93 kHz	929 kHz
Super Conducting Linac Charge per Bunch	0.02 nC	0.1 nC
Photon Beam Energy Range	250-3,800 eV	200-5,000 eV
High Repetition Rate Capable End Stations	≥ 1	≥ 2
FEL Average Power (10^-3 BW)	5×10^{8} (10x spontaneous @2,500 eV)	>10^{11} @ 3,800 eV
Normal Conducting Linac Based FEL System		
Normal Conducting Linac Electron Beam Energy	13.6 GeV	15 GeV
Electron Bunch Repetition Rate	120 Hz	120 Hz
Normal Conducting Linac Charge per Bunch	0.1 nC	0.25 nC
Photon Beam Energy Range	1,000-15,000 eV	1,000-25,000 eV
Low Repetition Rate Capable End Stations	≥ 2	≥ 3
FEL Photon Energy (10^{-3} BW[a])	10^{10} (lasing @ 15,000 eV)	> 10^{12} @ 15,000 eV

Linac Layout

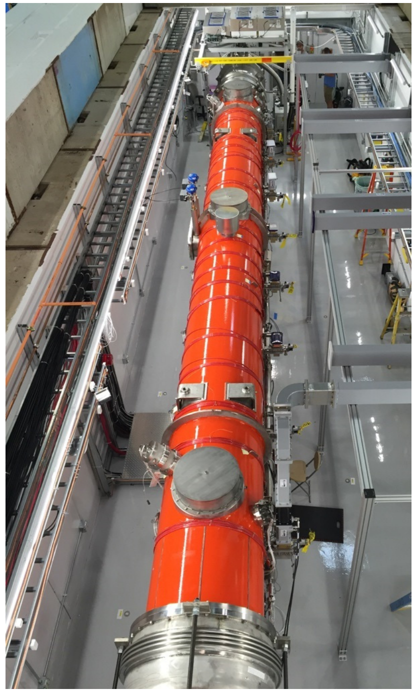


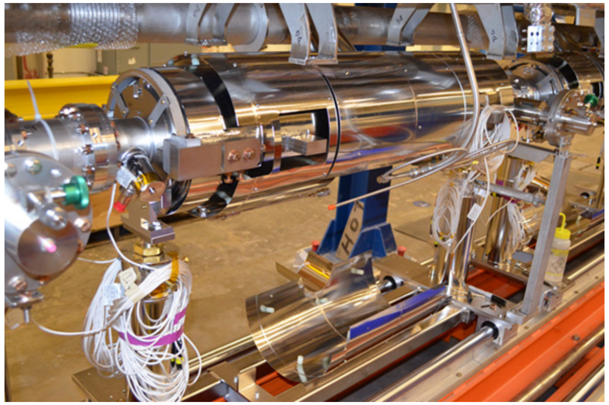
Cryogenic Systems Scope:

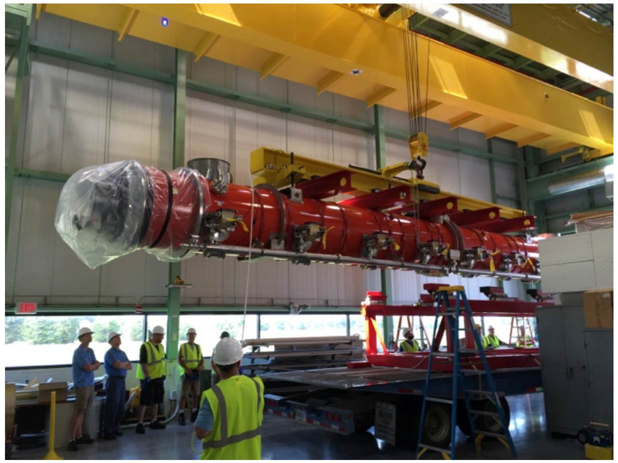
Component	Count	Parameters
Linac Cryomodules	1.3GHz - 35 ea 3.9 GHz - 2 ea	Linac – 4 cold sections 8 cavities per cryomodule (1.3 & 3.9 GHz)
1.3 GHz Cryomodule (CM)	8 cavities/CM	13 m long. Cavities + SC Magnet package + BPM
3.9 GHz Cryomodule	8 cavities/CM	6.2 m long. Cavities + BPM
Additional Cryomodules	1.3 GHz: 4 production + 1 spare 3.9 GHz: 1 spare	
1.3 GHz 9-cell cavity	320 each	16 MV/m; Q_0 ~ 2.7e10 (avg); 2.0 K; gradient reach to 19 MV/m (No Q-spec); bulk niobium sheet - metal
3.9 GHz 9-cell cavity	24 each	13.4 MV/m; Q_0~2.0e9
Cryoplant (CP1/CP2)	2 each	4.5 K / 2.0 K cold boxes; 4 kW @ 2.0 K; 18 kW @ 4.5 K; 3.7 kW nom. tot. load
Spare compressors	2 Warm He Comp. 1 spare Cold Comp.	
Cryogenic Distribution System (CDS)	210 m vacuum-jacketed line, 2 each distribution boxes, 6 each feedcap / 2 each endcap	

LCLS-II Cavity and CM Statistics

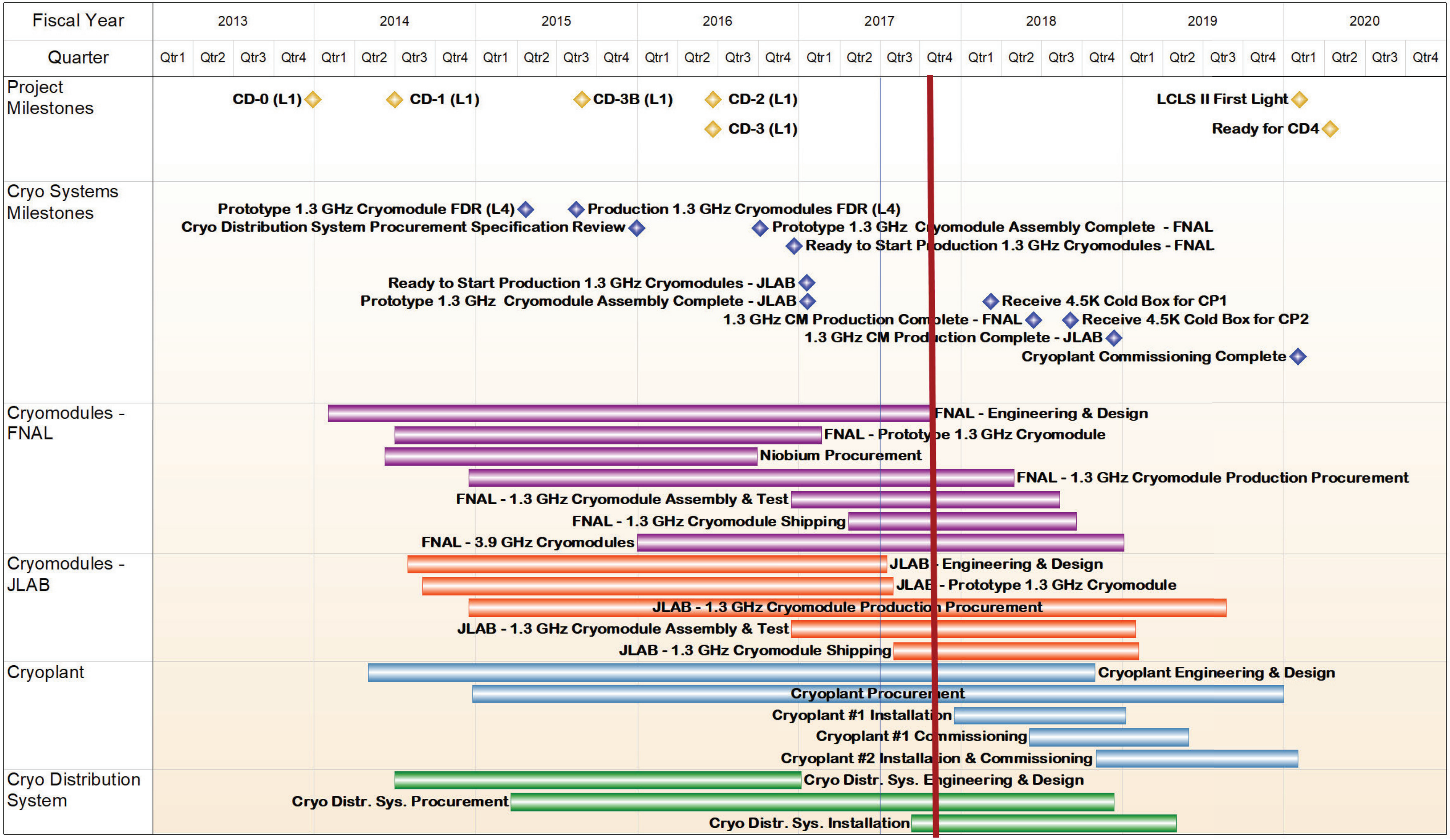
- 280 1.3 GHz Cavities required
  - 266 from Vendors, 16 from ILC R&D program
- 143 of 280 cavities tested so far.
- 4 of 35 1.3 GHz cryomodules tested.
- 9 cryomodules currently being assembled



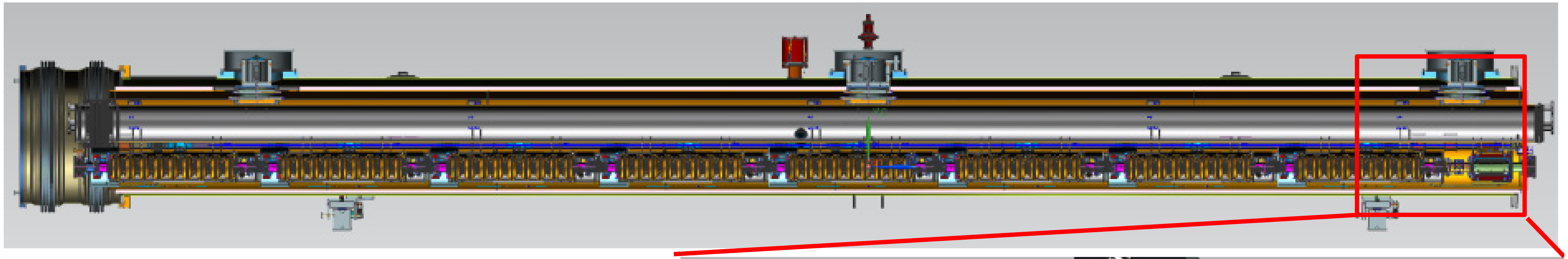




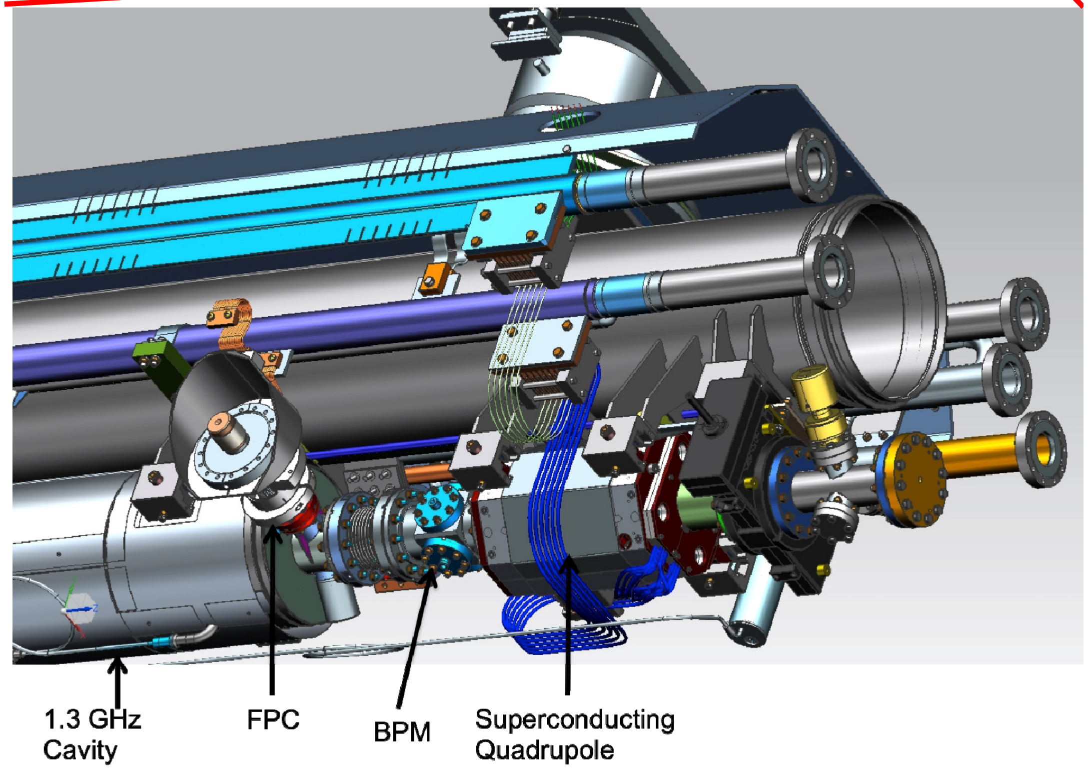
1.04 – Cryogenic Systems - Summary Schedule



The 1.3 GHz Cryomodule

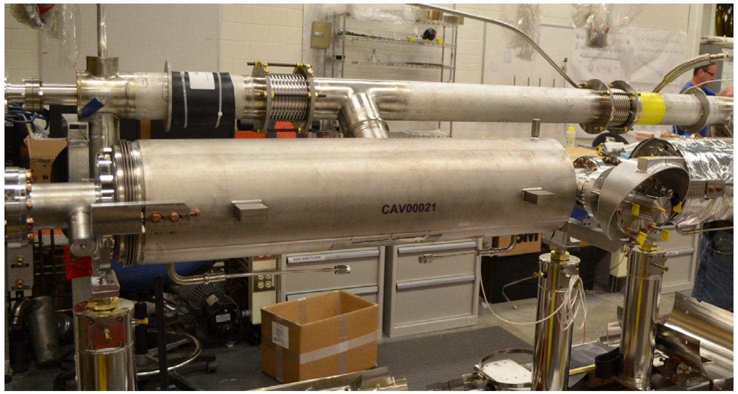


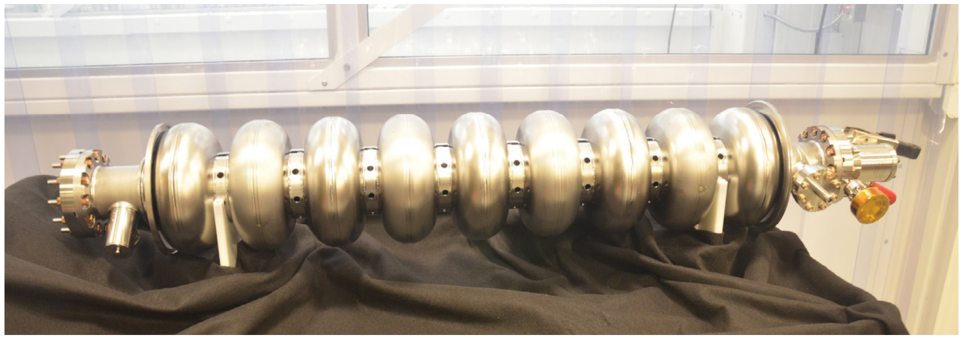
XFEL Style Cryomodule
8 – 1.3 GHz Tesla style cavities
1- Button beam position monitor
1- Conduction cooled quadrupole Magnet
5K Thermal Intercept (no 5K shield)
50K Intercept and Shield



Cavity Requirements and Recipe

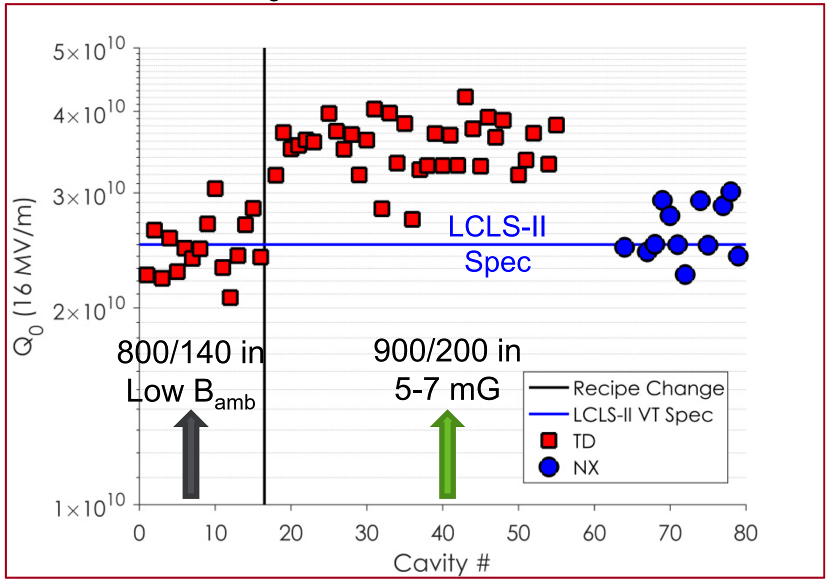
- LCLS-II cavity VTA test requirements:
  - $Q_0 \geq 2.5e10$ at 2 K and 16 MV/m
  - Must reach gradient of 19 MV/m
- Nitrogen doping was implemented to improve Q_o
- Initial cavity recipe called for H_2 degassing at 800 C and 140 μm bulk EP; changed to 900 C and 200 μm after the first articles to improve Q_o



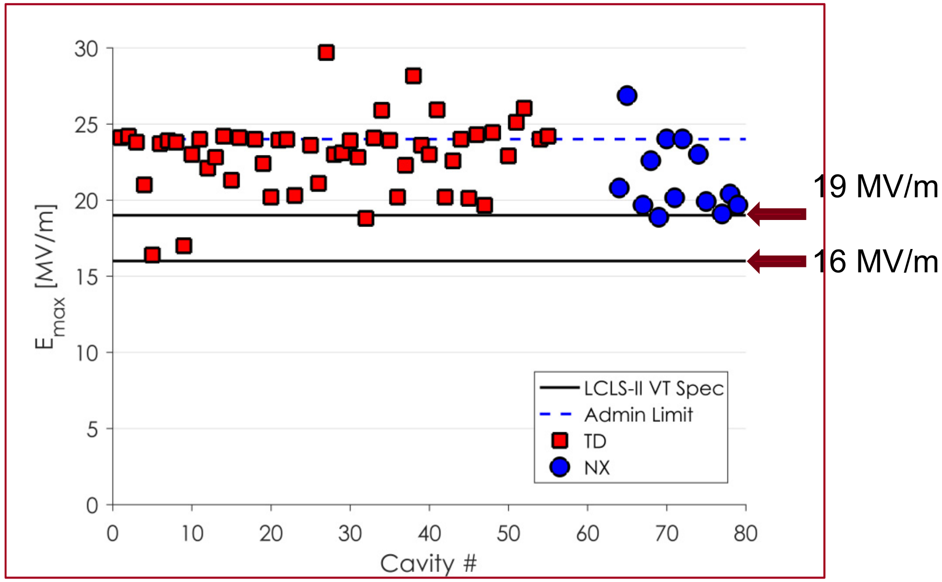


The technology has shown significant capabilities beyond our initial consideration.

Cavity Q_0 Performance in VT



Cavity Gradient Reach in VT



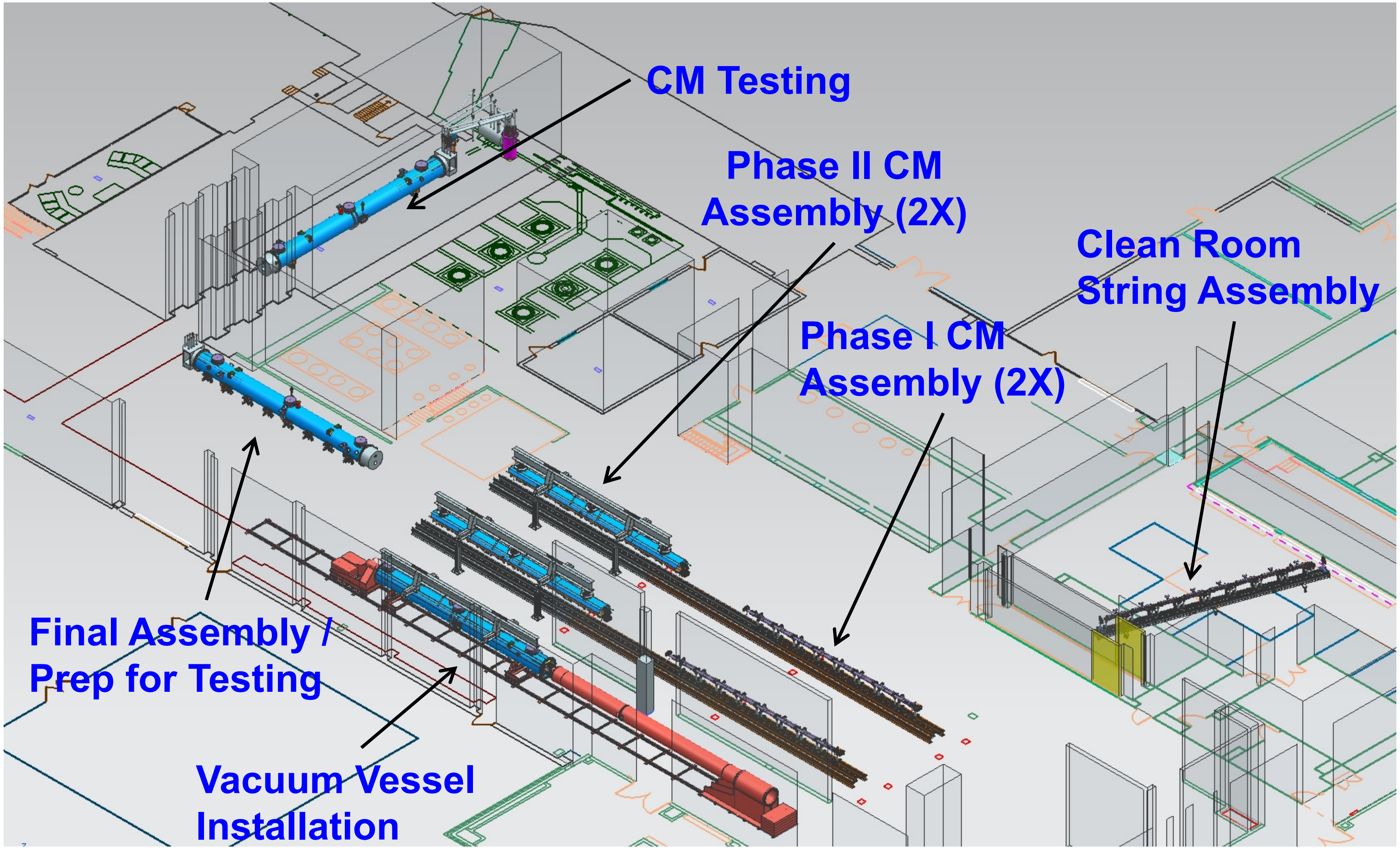
- Highest performance cavities are manufactured with Tokyo-Denkai (TD) niobium.
- Cavities manufactured from Ningxia (NX) material do not perform as well as TD at **900 C.**
  - Further temperature increases are being implemented for NX and look promising.
- **All Material meets spec – N_2 doping is sensitive to parameters beyond what was specified.**
- Additional material has been ordered to replace cavities that do not meet spec.

=> Average Q_0 and gradient reach may decrease

Cryomodule Assembly Strategy at FNAL and JLab

- **Identical Production Designs** - utilize as much of the DESY/XFEL design as practical to reduce schedule risk and overall cost
  - FNAL produces 18 CMs (16 –1.3 GHz, 2 –3.9 GHz); JLab produces 17 CMs
- **Identical Parts Received** at Partner Labs
  - Well-developed drawing packages, clear requirements and specifications
  - Procurement activities split between labs
- **Identical Tooling Interfaces**
  - Avoid adding custom features to CM
  - Adapt non-CM hardware interfaces to Lab-specific tooling
- **Equivalent Processes yielding Equivalent Performance**
  - Recognize that some tools are different at each lab (e.g. HPR, vertical testing systems, vacuum leak checking equipment, etc.)
  - Monitor key process variables in consistent fashion

JLab Layout for LCLS-II CM Production



CM Testing Criteria

	Criteria	F1.3-01	J1.3-01	F1.3-02
1	Cavity beamline vacuum Cold (2K) $1x10^{-10}$ Torr Warm (room temperature) $1x10^{-8}$ Torr	✔	✔	✔
2	Center Frequency 1.300000 GHz +/- 20kHz	✔	✔	✔
3	Individual cavities reach at least 16 MV/m	✔	✔	✔
4	Field emission onset ≥ 14 MV/m for each cavity individually	✔	✔	✔
5	BPM Verification	✔	✔	✔
6	Average CM $Q_0 \geq 2.5x10^{10}$ at 16 MV/m as measured after at least 10 hours c.w. operation or until the FPC window temperature reaches equilibrium	✔		✖
7	HOM $Q_{ext} \geq 5x10^{11}$, maximum power measured out of a single HOM is 1.5 W at nominal gradient of 16 MV/m with the forward power set to 2.5 kW for at least 10 hours or Thermal equilibrium	✔	✔	✔
8	Tuner range –slow 450 kHZ, fast 0-500 Hz	✔	✔	✔
9	The magnet package is verified electrically to be without shorts or opens and can be operated at a current of at least 20 A without quenching	✔	✔	✔
10	Nominal FPC $Q_{ext} = 4x10^7$ with range verified from $1x10^7$ to $6x10^7$	✔	✔	✔
11	Measure total static heat load on the CM with all cavities operating at 16 MV/m and document for comparison with the LCLS-II Cryogenic Heat Load table developed by Tom Peterson. A summary of these values is listed below for reference assuming a $Q_0 = 2.5x10^{10}$ and all 8 cavities are operating. Dynamic 2K = 92 W; Dynamic 5K = 8 W; Dynamic 45K =92W Static 2K = 7 W; Static 5K = 17 W; Static 45K = 123 W Total 2K = 99 W; Total 5K = 25 W; Total 45K = 215 W	✔	✔	✖

Performance Expectation for the first 11 cryomodules

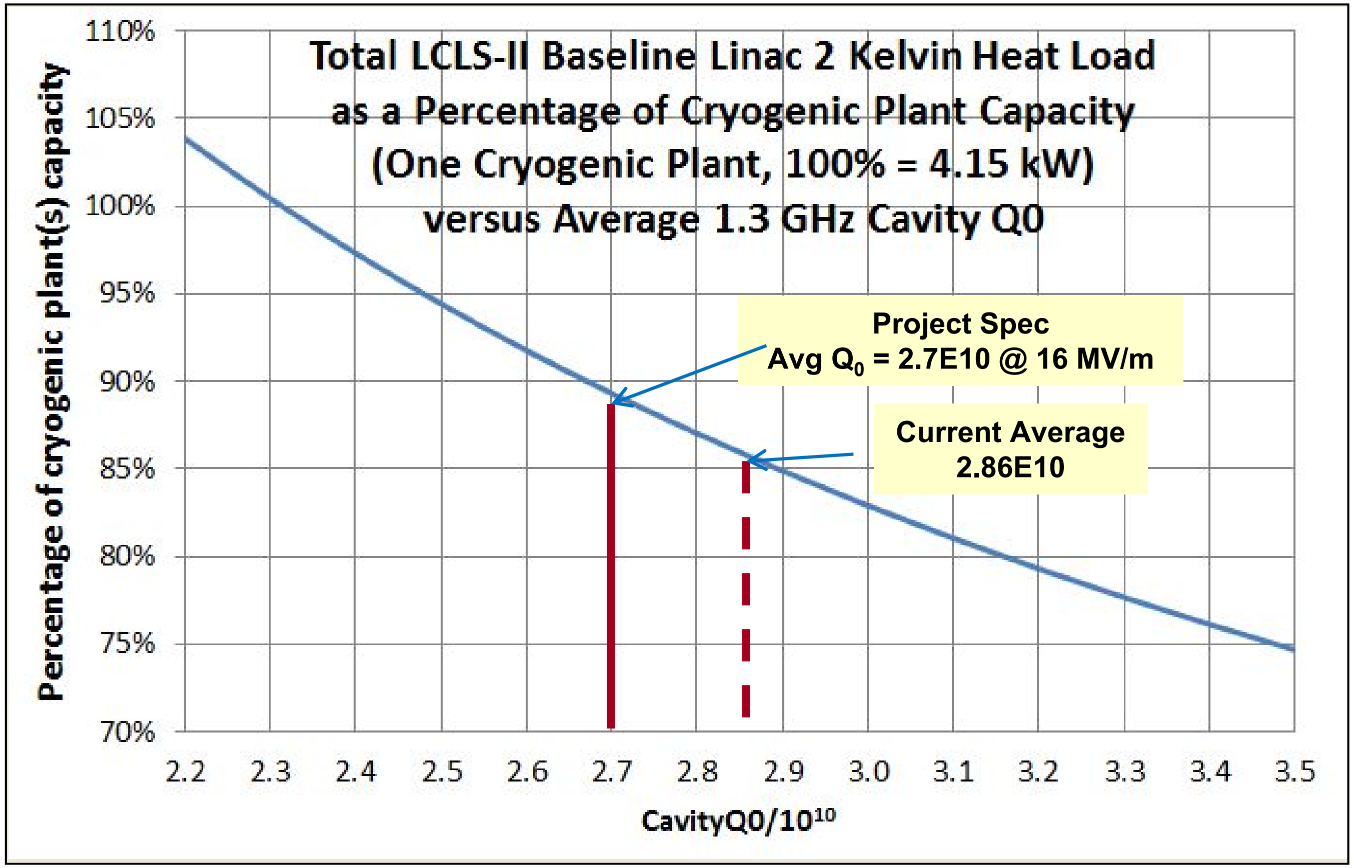
	Cryomodule	Data Source	Average Q	Avg Gradient VT [MV/m]	Avg Usable Gradient CM (FE < 50 mR/hr)	Cavities at Admin Limit (21MV/m)
pCMs	F1.3-1 (pCM)	CM Test	3.0×10^{10}	22.0	18.2	1
	J1.3-1 (pCM)	VT/CM Test	2.7×10^{10}*	20.6	19.4	1
800 C bake	F1.3-2	CM Test	2.1×10^{10}	23.4	20.0	4
	J1.3-2	Vertical Test	2.1×10^{10}	21.5		
900 C bake	F1.3-3	CM Test	3.31×10^{10}**	23.2	17.6/19 w/HOM fix	6
	J1.3-3	Vertical Test	3.61×10^{10}**	22.2		
	F1.3-4	Vertical Test	3.33×10^{10}**	23.0		
	J1.3-4	Vertical Test	3.62×10^{10}**	23.9		
	F1.3-5	Vertical Test	3.01×10^{10}**	21.6		
	J1.3-5	Vertical Test	2.69×10^{10}**	22.7		
	F1.3-6	Vertical Test	2.82×10^{10}**	22.2		
	Totals		**2.86×10^{10}**	**21.9**	**18.8/19.2**	

* JLab CM testing still underway (Q from VT)

*** VT Q scaled based upon measured field in the first 2 CMs.

Q_0 Spec = 2.7×10^{10}

LCLS-II can commission the linac at 4 GeV with one cryoplant.



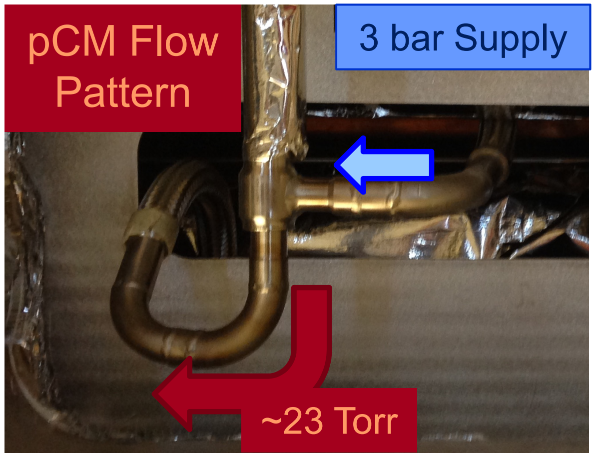
➢ *Our goal is to build a 4GeV linac operable by one cryoplant.*

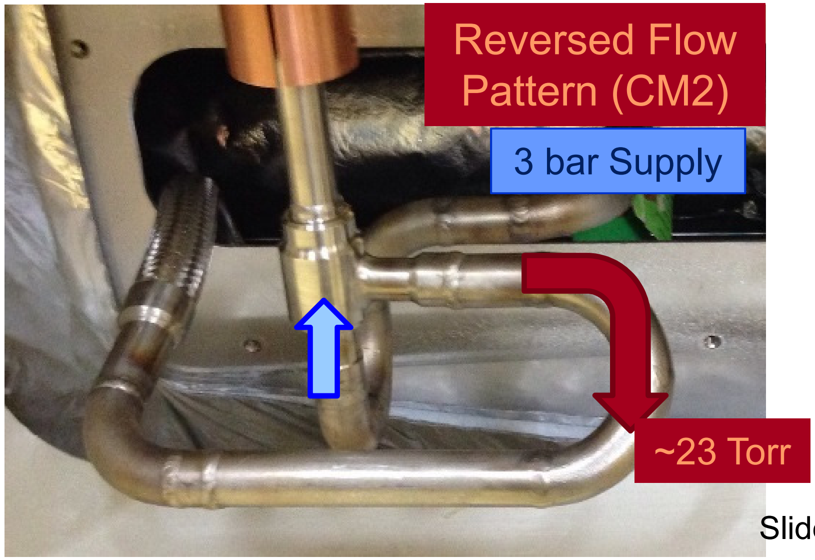
Issues

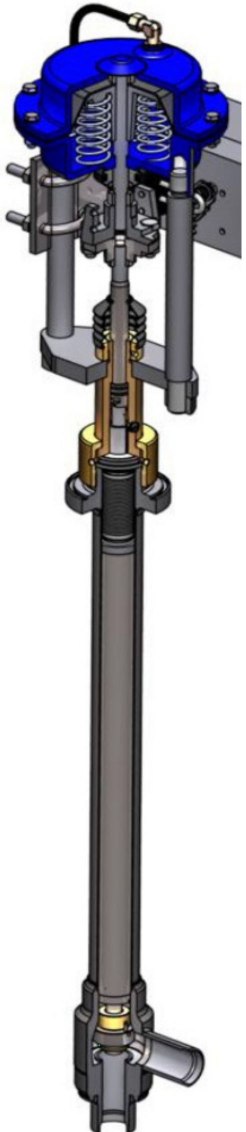
- Microphonics
  - Worse than anticipated
  - Testing time did not account for extra work to mitigate
  - Significant improvements seen in the lasts few months.
- CM Cool down rate
  - Single cavity horizontal test used to establish baseline for cooldown rate
  - CM testing indicates higher flow rates are required to eliminate flux trapping
  - Cooldown rate required varies based on cavity material and heat treatment recipe!

Mitigation Steps in Cryomodule Design – Supply Valves

- Test results show valve reversal (lower press in stem) significantly reduces/eliminate TAOs there
  - F1.3-01 configuration has valve stem at supply pressure (~3 bar)
  - Reversing flow will lower this pressure to sub-atmospheric, requiring guard gas to prevent contamination
  - All cryomodules will have guard gas, reversed valves
- Additional effort to mitigate TAOs in cryogenic distribution system should improve inlet temperature at test stand



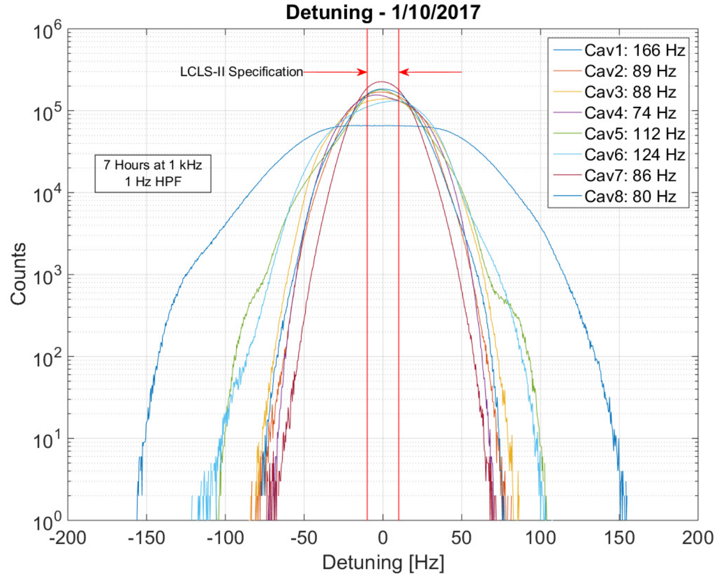




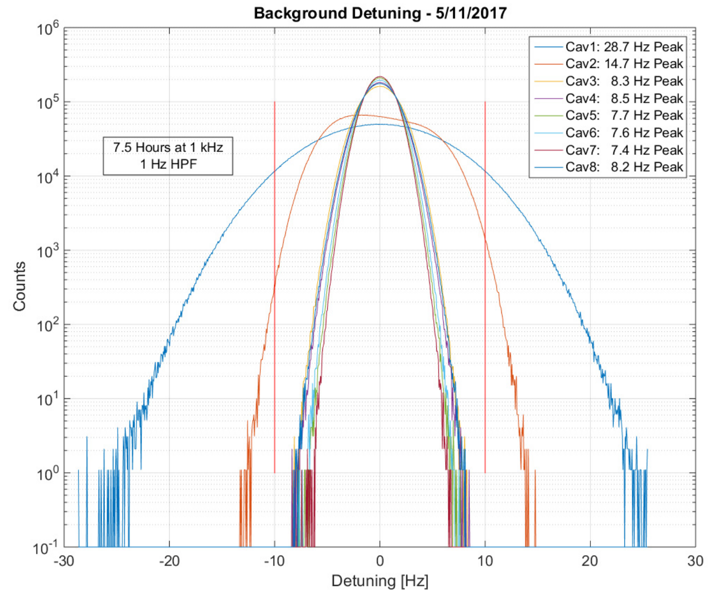
Slides from J. Holzbauer

Progress to Date

- The microphonics environment in the F1.3-02 is a factor of ~10 improved over pCM.
- Significant improvements in stability of the system, leading to a far more predictable detuning environment



pCM As Cooled Down

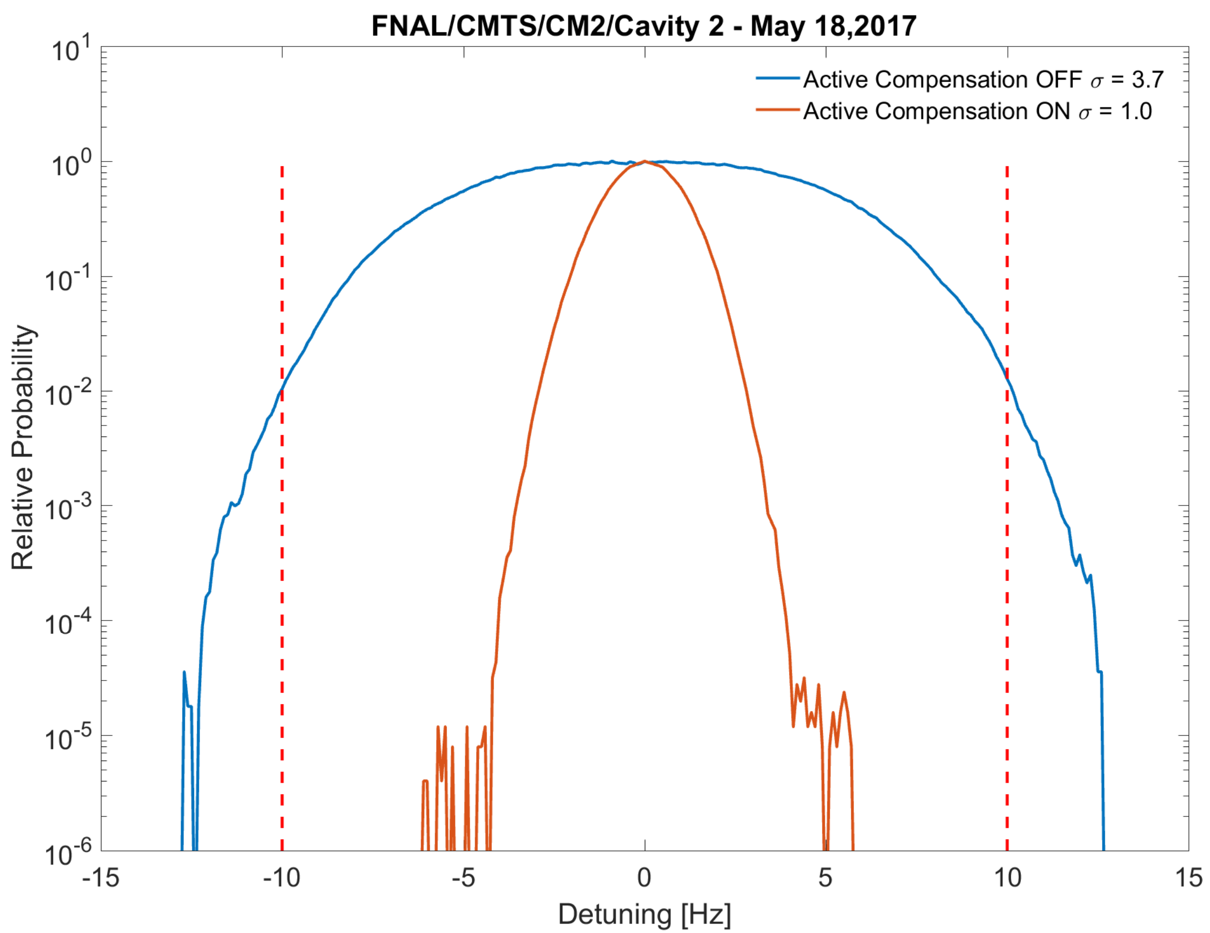


F1.3-02
After Improvements

Slides from J. Holzbauer

Active Compensation Implementation (first pass)

- Bank of band-pass filters will be used for active compensation
- Data shown for four filters with manually tuned coefficients
- RMS detuning reduced by factor of 3.7, over the factor of 3 specified
- Stability and optimization studies under way



Slides from J. Holzbauer

F1.3-01 Q_0 under Different Cool Down Mass Flow

Temperature difference from top of the cavities and bottom of cavities

Mass Flow	80 g/s	47 g/s	25 g/s	Slow Cool Down
Cavity	∆ T(K)	∆ T(K)	∆ T(K)	∆ T(K)
CAV1	4.1	3.3	2.6	≤0.08
CAV4	4.9	4.7	4.4	≤0.08
CAV5	7.0	7.1	7	≤0.08
CAV8	5.6	5.6	2.89	≤0.08
Average Q_0	2.99e10	~2.46e10	~2.26e10	2.06e10

Q_0 spec 2.7e10

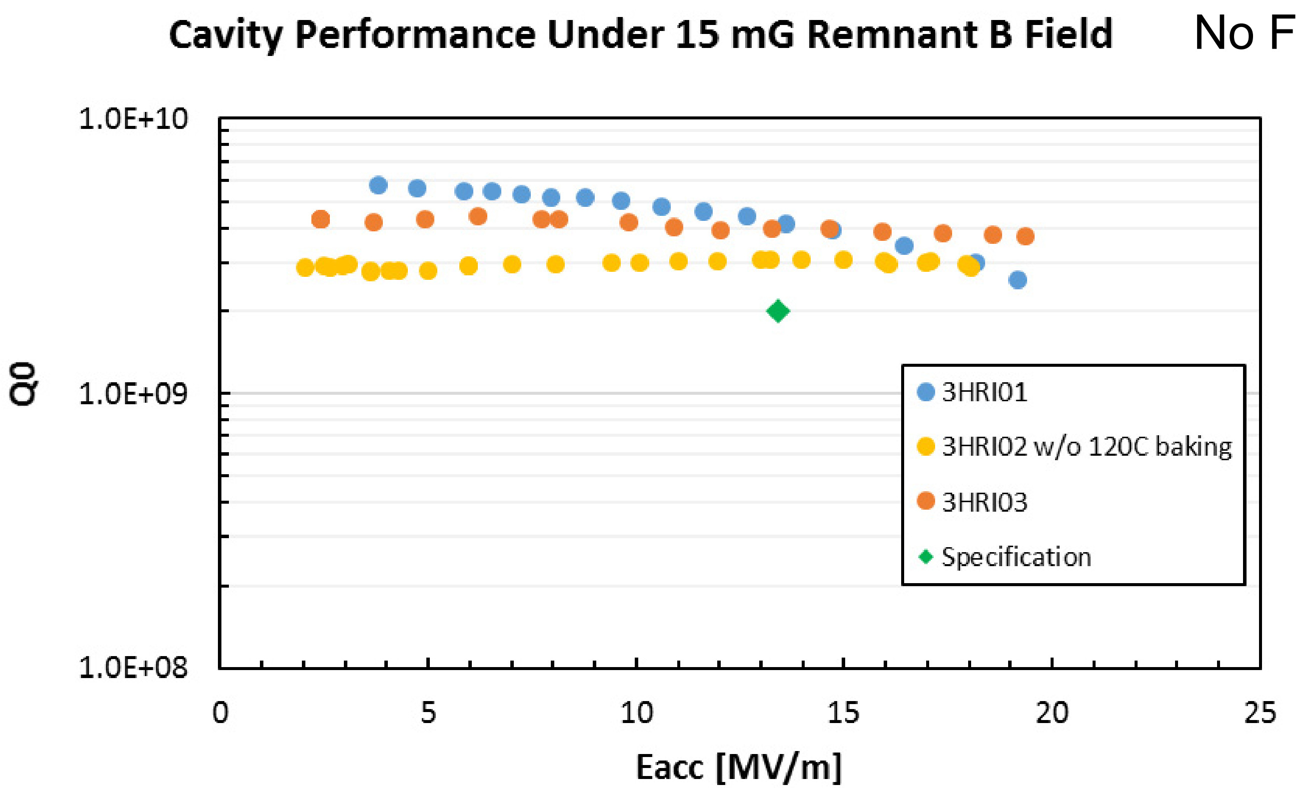
Performance of cavities produced with different recipes or base material will be different

Fast cool down with sufficient mass flow can achieve effective flux expulsion

Data from Genfa Wu

LCLS-II 3.9 GHz Cavity Gradient and Q_0 Measurement (Bare)

No Field Emission



Cavity Q_0 Exceeds Specification in a Cryomodule like remnant field

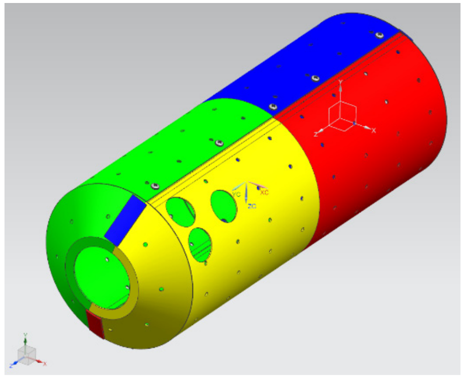
VTS acceptance Eacc > 18 MV/m

VTS Acceptance Q > 2.0e9 @13.4 MV/m, >1.5e9@15 MV/m

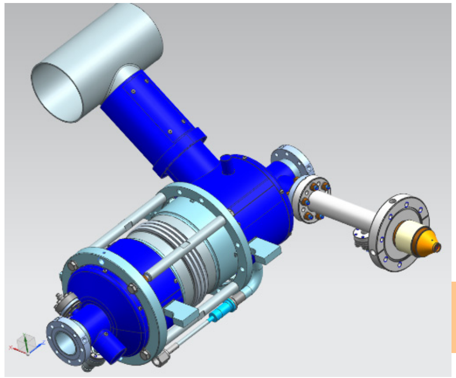
Data from S. Aderhold

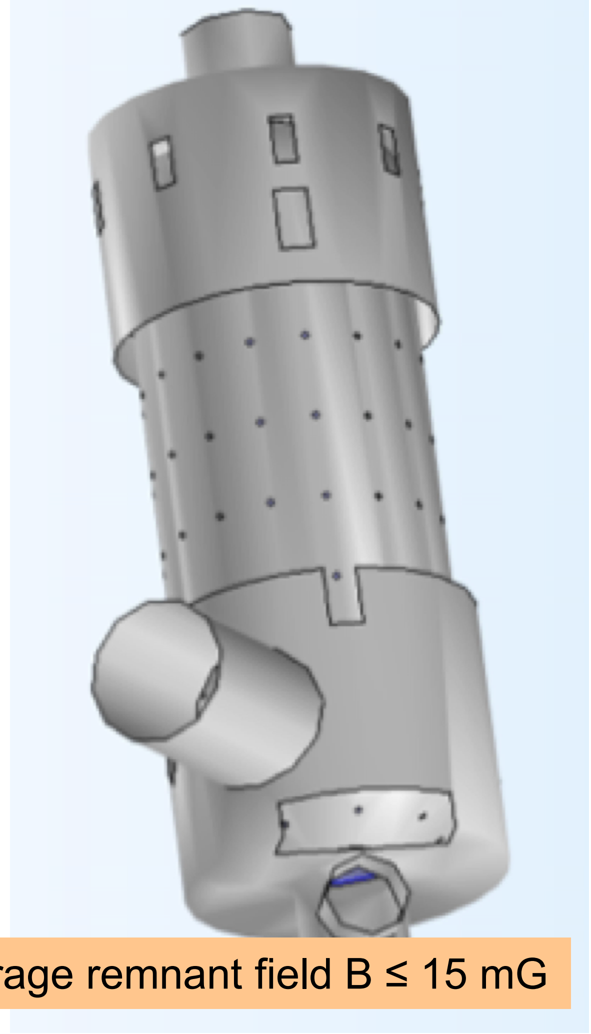
3.9 GHz Cavity Internal and External Magnetic Shields

- Internal shield
  - With R = 1.5 mm holes, 18 circumferential, 8 rows at irises
  - With three R = 12 mm chimney openings
- External shields
  - Openings for cavity lugs, invar rod post, coupler flanges, pick up probe
    - HOM shall be covered by a separate can
- Prototype received and warm test completed



Burrill - SRF 2017

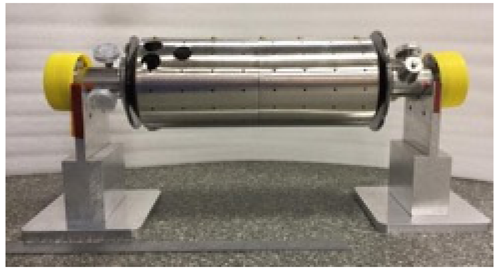




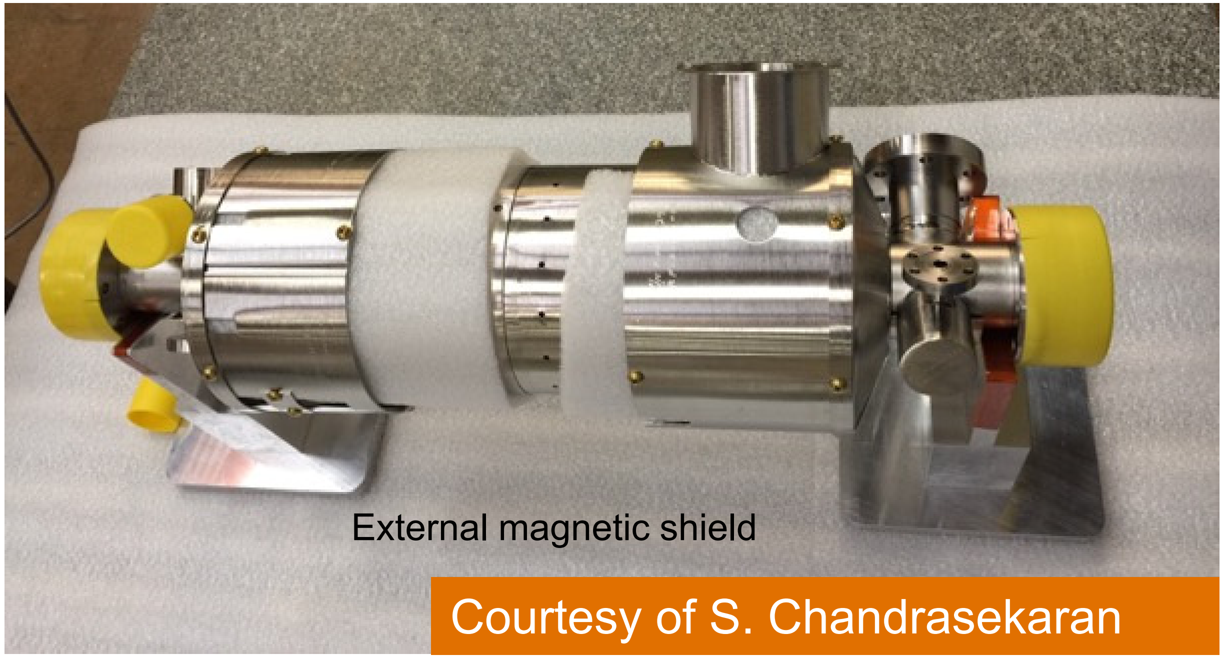
Data from S. Aderhold

Design Verification Status – Magnetic Shield/Dressing

- Internal magnetic shield fits OK
- External magnetic shield mostly fits
- Fields meet spec (15mG) at room Temp.
- Two cavities were dressed with internal shields



Internal magnetic shield



External magnetic shield

Courtesy of S. Chandrasekaran

Summary

- High Q_0 recipe will allow for LCLS-II to operate with average Q_0 ≥2.7×10^{10} @ 16 MV/m
  - **130 MV Energy gain CW per CM = 80 W to 2K**
- A few issues have been identified but solutions exist
- Prototype cavity performance was excellent, exceeded spec
- Production cavity performance is very good, will get better
- Initial results are very encouraging

Could not be done alone.

The Collaboration and help from XFEL is essential for this project to succeed.

Acknowledgements

Many many thanks to everyone at JLab, FNAL and SLAC for making this project possible & for material for this talk.

Thanks to the DOE Office of Basic Energy Science for funding us to do this fun work.

Thanks to XFEL for the support, guidance and many technical discussions.

The End

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BERKELEY LAB

Argonne NATIONAL LABORATORY

Fermilab

Jefferson Lab