SRF Linac for LCLS-II:
Design Approaches, R&D, and First Test Results

Marc Ross (SLAC LCLS-II)

SRF2015 Whistler, BC

14 September 2015

Introduction

For your consideration:

Three elements for technical advancement:

1. Science →

   Motivation

2. Technical development →

   Tools that enable

3. Industrial and Infrastructure backbone →

   Practical Capability and Cost

Outline

1. Introduction
2. Free Electron Laser based on SRF
3. Linac requirements
4. CW Linac based on TESLA/ILC/E-XFEL Technology
5. R&D
6. Initial Results
7. Production Plan
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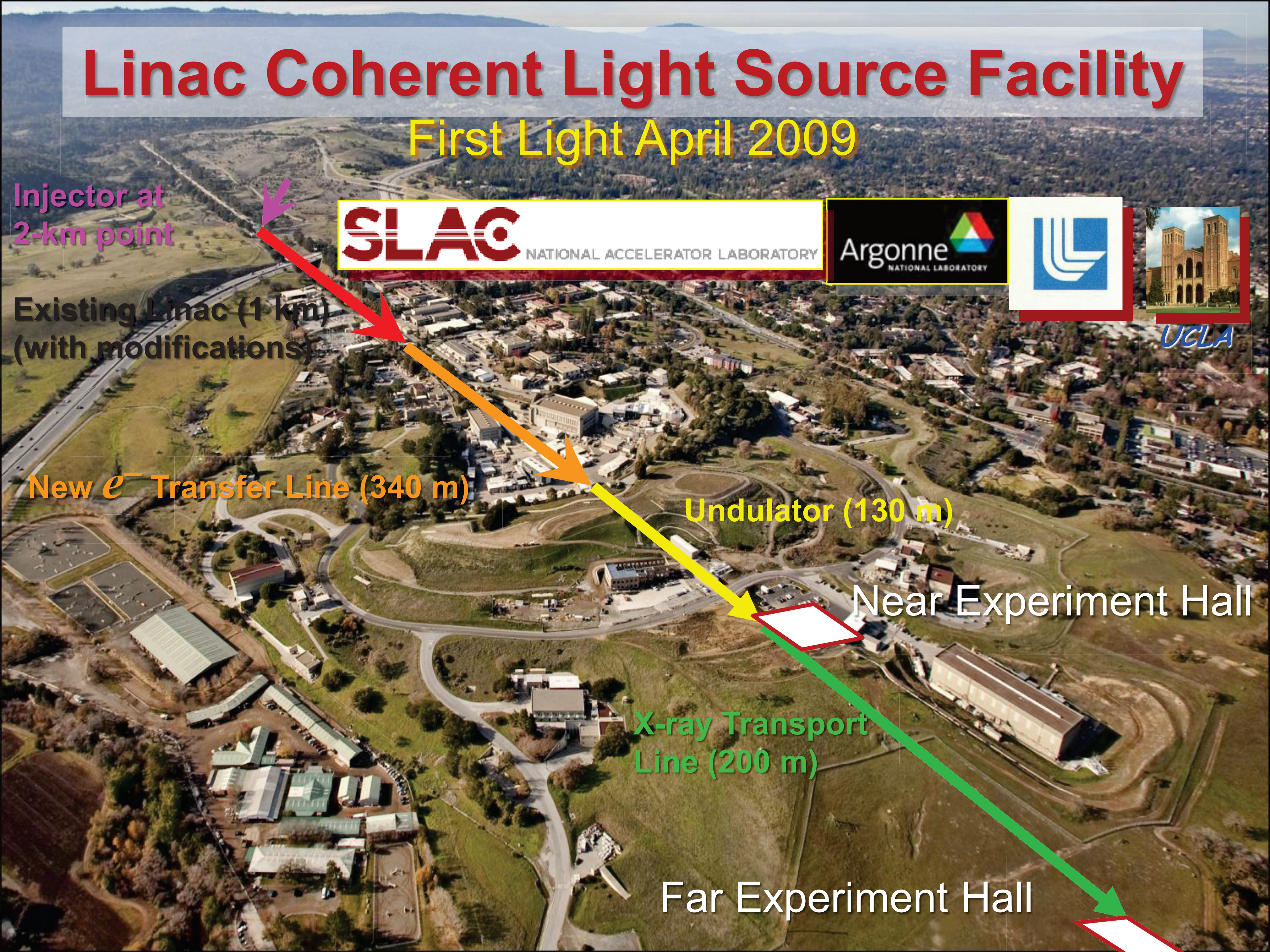
Linac Coherent Light Source Facility

First Light April 2009



2009: Success of LCLS at SLAC

→ Remarkable facility for remarkable *photon science* ←

What's next for photon science in the US? How to develop this valuable tool?

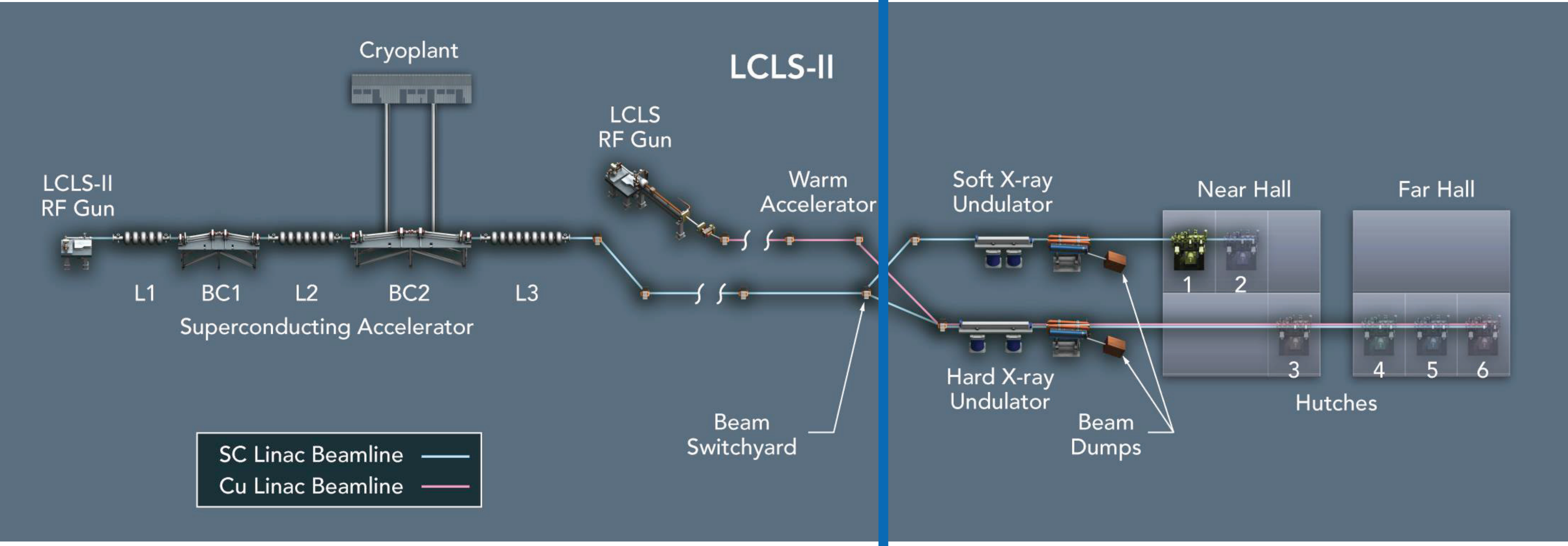
Extraordinary convergence (2010 – 2013):

1) LCLS Success
2) Technical Development and Industrialization of a core linac technology →

   Superconducting Radio-Frequency (SCRF)

Old / new technique to be deployed together for LCLS-II

LCLS-II Hybrid Free Electron Laser at SLAC:



DOE Partner Labs bring the expertise

Fermilab
- 50% of cryomodules: 1.3 GHz
- Cryomodules: 3.9 GHz
- Cryomodule engineering/design
- Helium distribution
- Processing for high Q (FNAL-invented gas doping)

Design Lead

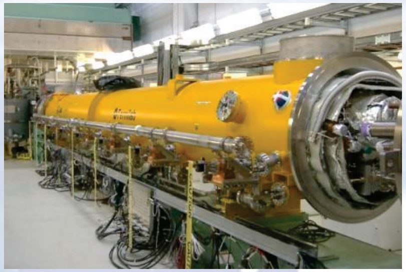
Jefferson Lab — Exploring the Nature of Matter
- 50% of cryomodules: 1.3 GHz
- Cryoplant selection/design
- Processing for high Q

Berkeley Lab
- Undulators
- e^- gun & associated injector systems

Argonne National Laboratory
- Undulator Vacuum Chamber
- Also supports FNAL w/ SCRF cleaning facility
- Undulator R&D: vertical polarization

Cornell University — Founded A.D. 1865
- R&D planning, prototype support
- processing for high-Q (high Q gas doping)
- e^- gun option

Nick Walker

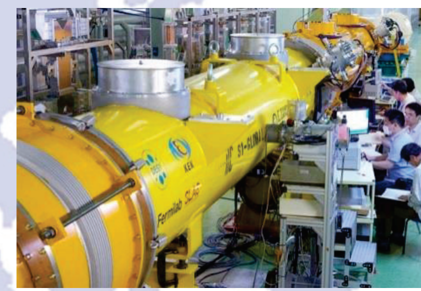


Largest deployment of this technology to date
- 100 cryomodules
- 800 cavities
- 17.5 GeV (pulsed)

Kitakami
proposed ILC site

FNAL/ANL
SLAC
Cornell
JLab
LAL/
Saclay
DESY
INFN Milan
IHEP
KEK

US infrastructure for
- 35 cryomodules
- 280 cavities
- 4 GeV (CW)



International Partner Labs lend their expertise

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LCLS-II SRF Linac

Closely based on the ***European XFEL / ILC / TESLA*** Design

- Under development ~ 20 years with ***> 1000 cavities*** by 2016

Uses ***CEBAF-12 GeV Upgrade Cryoplant*** Design

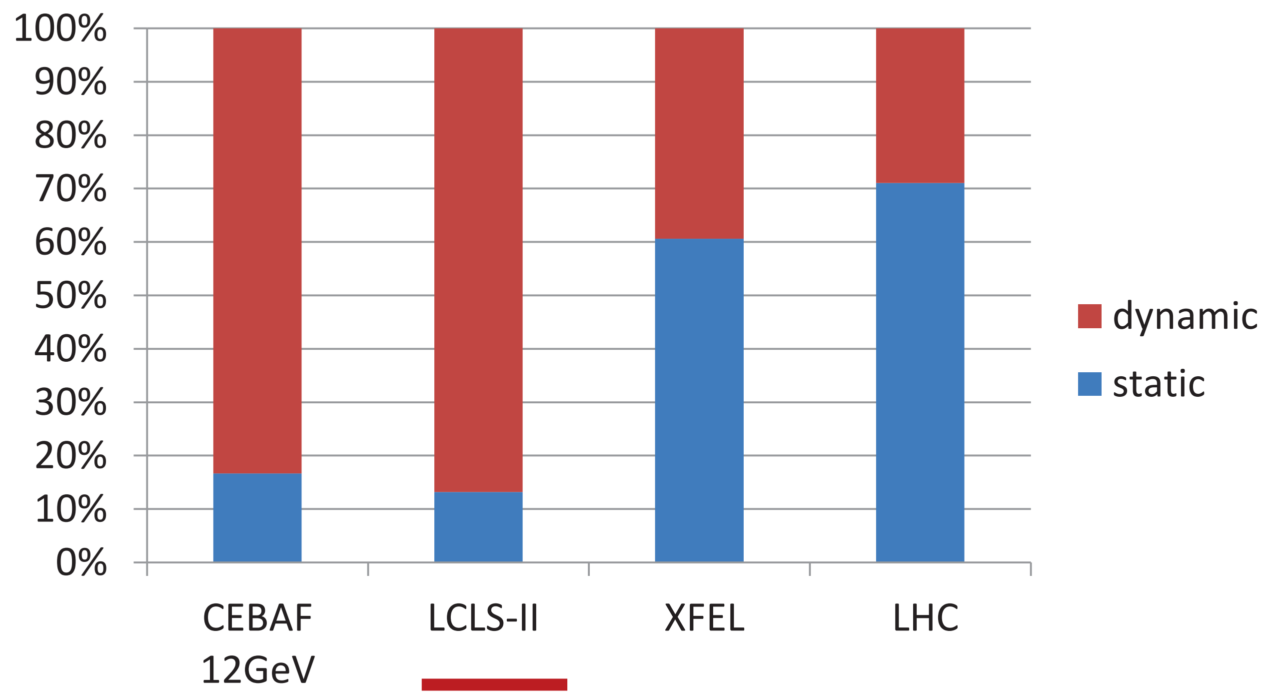
LCLS-II Linac consists of:

Component	Count	Parameters
Linac	4 cold - segments	35 each 8 cavity Cryomodules (1.3 GHz) 2 each 8 cavity Cryomodules (3.9 GHz)
1.3 GHz Cryomodule	8 cavities/CM	13 m long. Cavities + SC Magnet package + BPM
1.3 GHz 9-cell cavity	280 each	16 MV/m; Q_0 ~ 2.7e10 (avg); 2 deg. K; bulk niobium sheet - metal
Cavity Auxiliary	per each cavity	Coaxial Input Coupler; 2 each HOM extraction coupler; lever-type tuner
Cryoplant	2 each	4.5 K / 2.0 K cold box system; 18 kW @ 4.5 K equivalent (x two)

2 Kelvin Heat Load – Dynamic vs Static

1.3 GHz cavity Q0			2.70E10
E [MV/m]			16.0
Linac heat-loads (kW)	HTTS (80K)	LTTI (8K)	2.0 K
Cryomodule static	4.05	0.82	0.28
Cryomodule dynamic	5.28	0.63	3.01
Distribution system	3.28	0.19	0.15
Estimated TOTAL	**12.61**	**1.64**	**3.44**

Comparison: Dynamic vs Static 2 K Heat load



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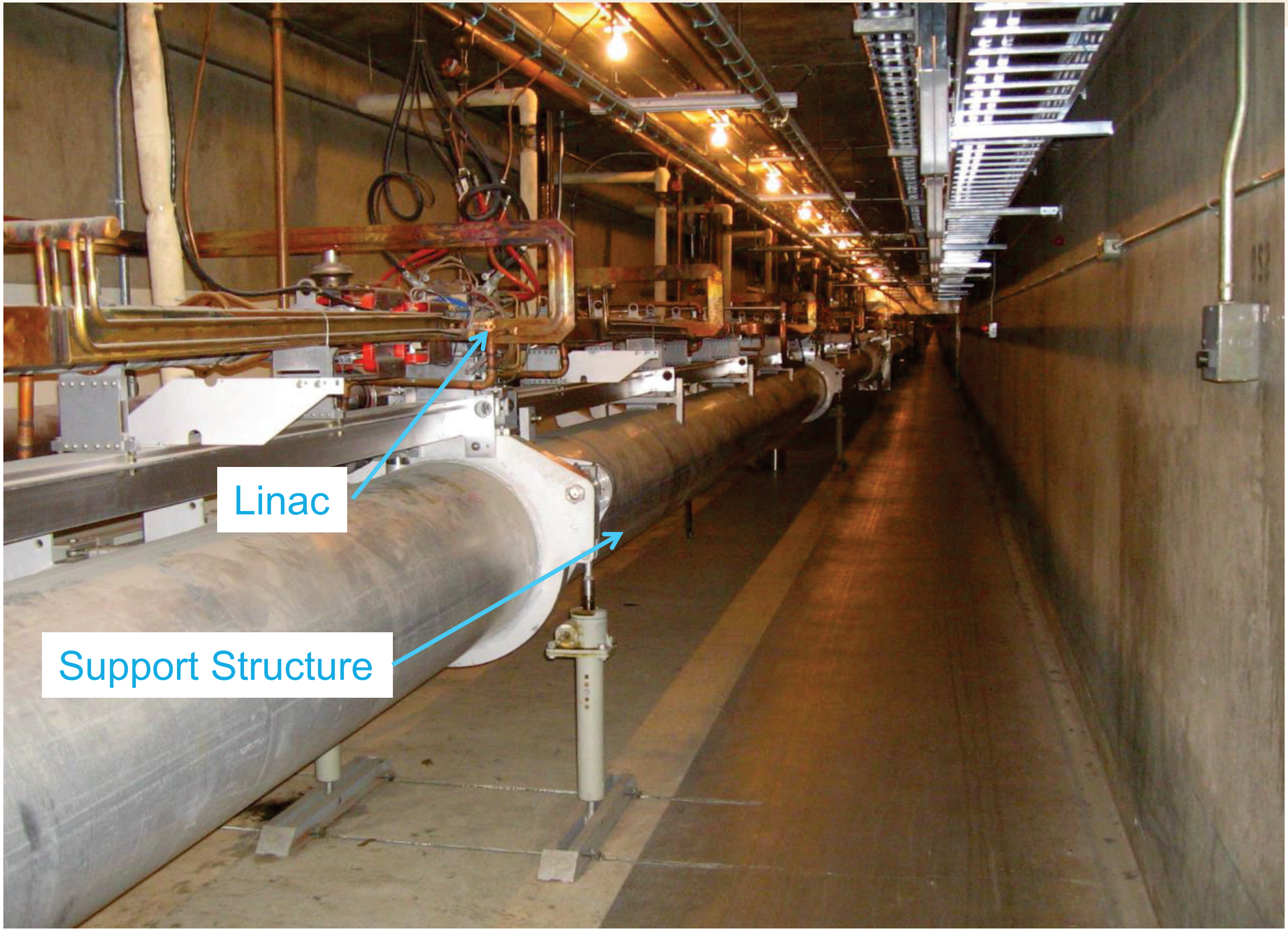
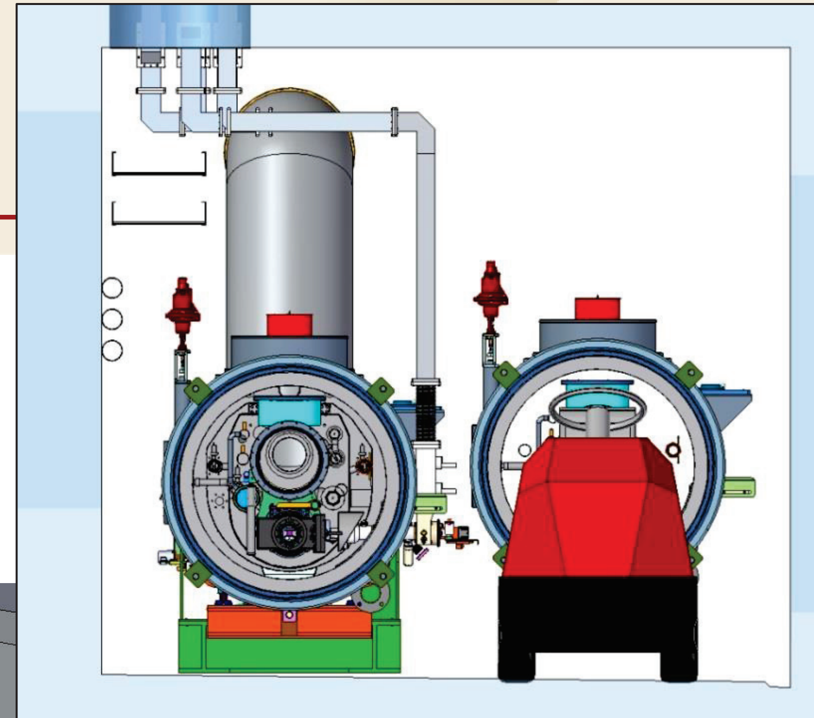
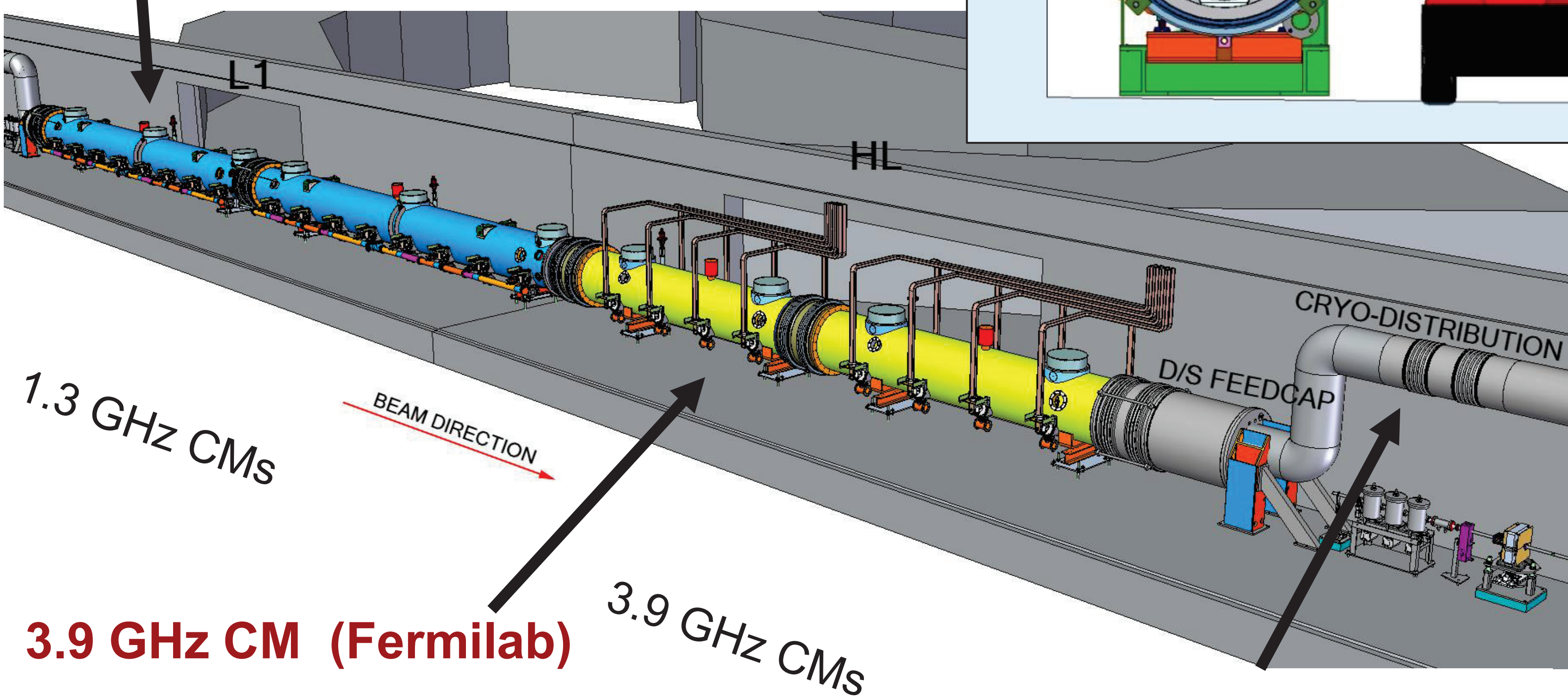
Existing SLAC Linac in its Tunnel (~1966 to present day)



Tunnel Layout and Cross-section



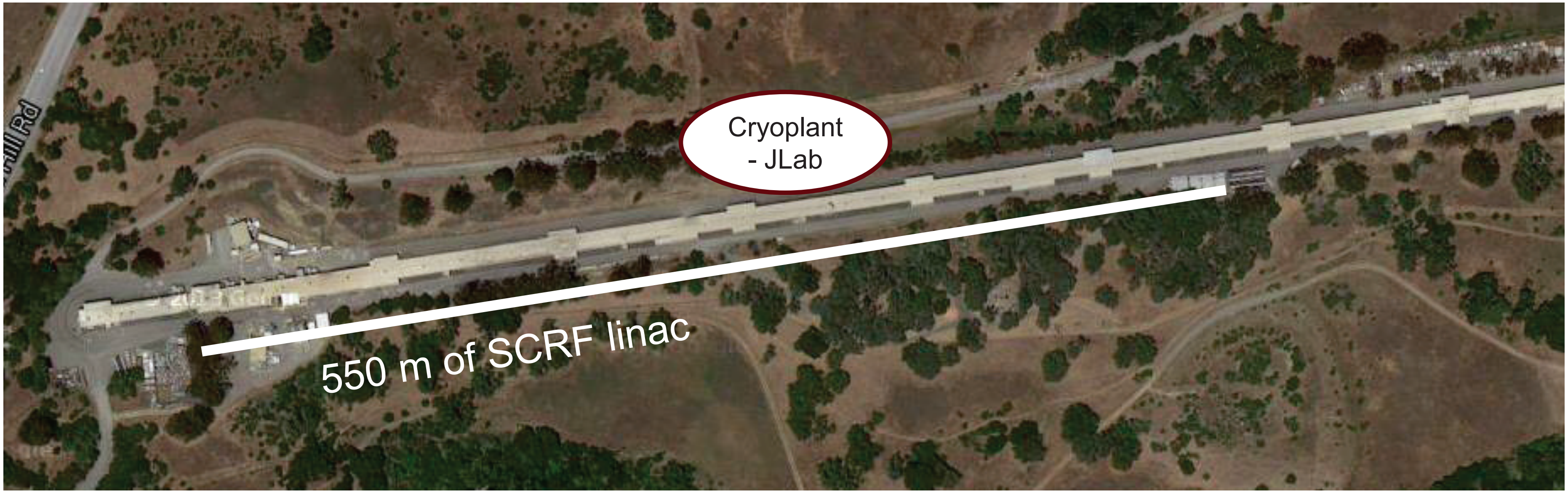
1.3 GHz Modules (Fermilab/JLab)



3.9 GHz CM (Fermilab)

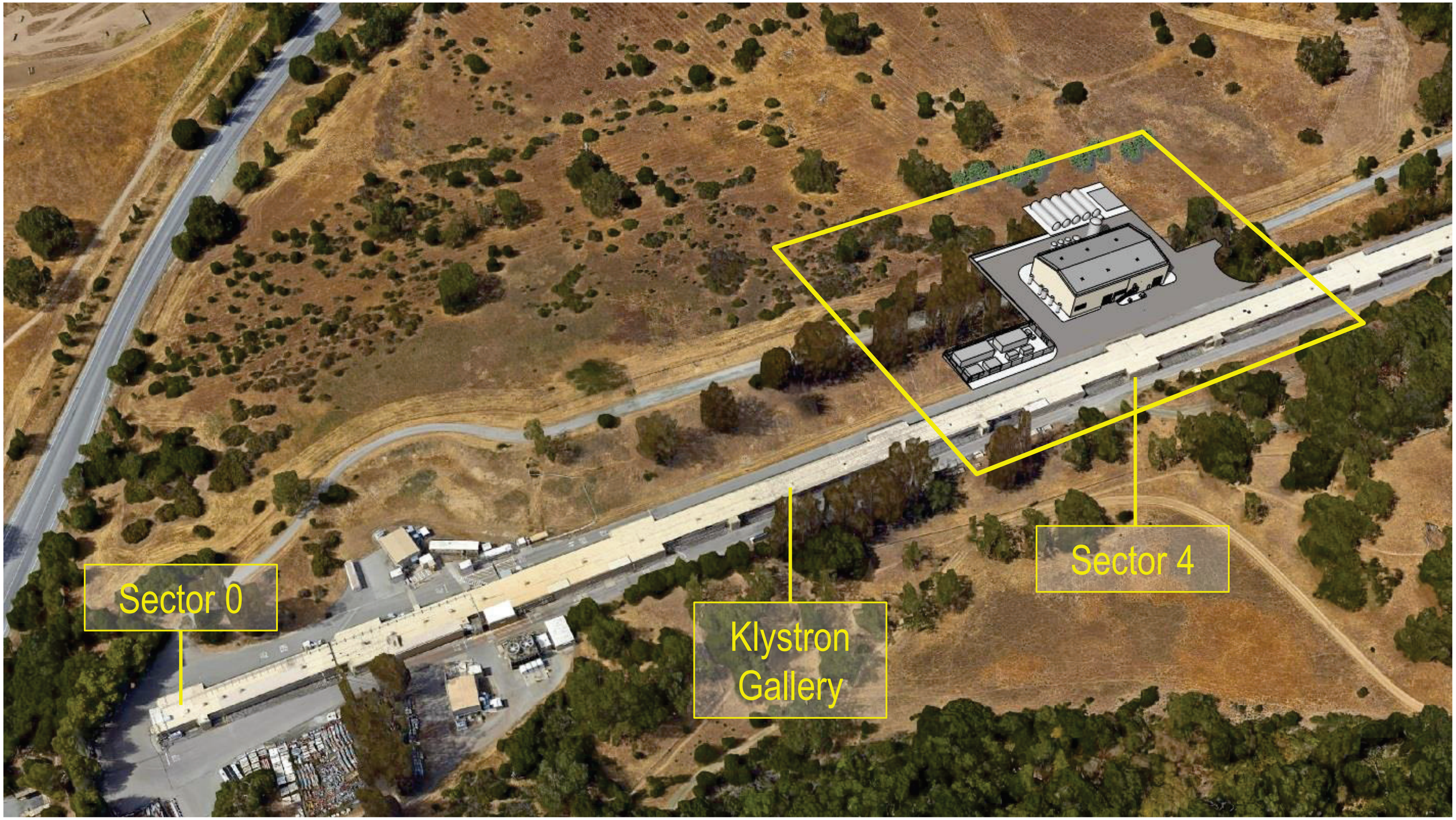
CDS (Fermilab)

First 800 m of SLAC linac (1964):

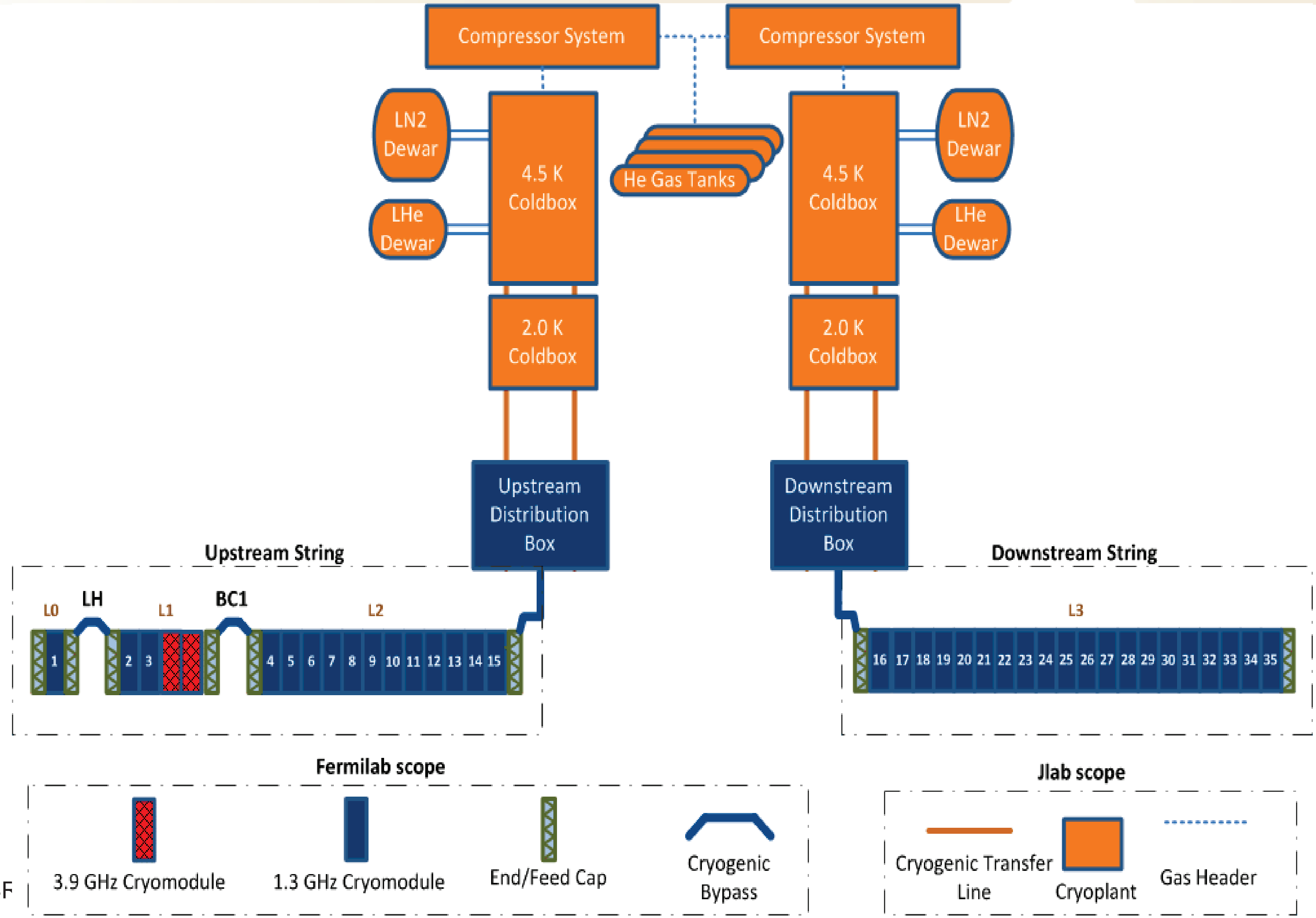


35 +2 cryomodules to replace
~500 m of S-band linac

Cryogenic Plant Building Site



Cryogenic System Schematic



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CW Linac based on TESLA/ILC/E-XFEL
Design Approach and R&D Plan

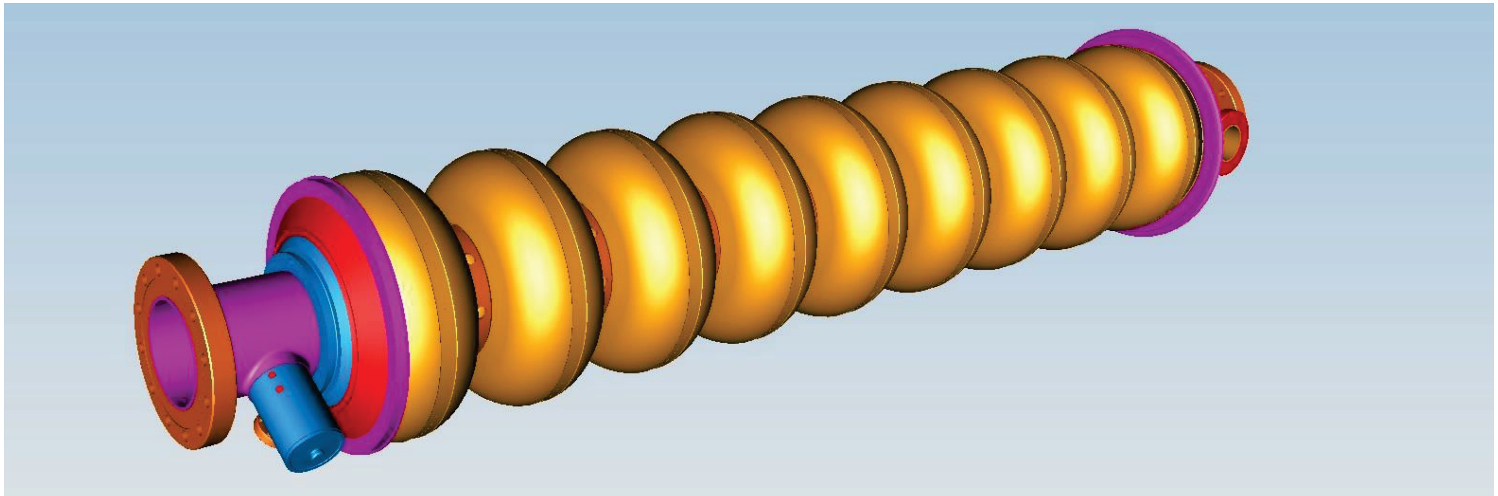
SLAC

- Proof of principle
  - Low cryogenic-loss performance – *Vertical Test*
    - Magnetic shielding
    - Cool-down protocol
- Design validation
  - Cryogenic performance – *Horizontal Test*
  - High average power Coupler
  - High-performance tuner
  - Conduction-cooled quadrupole
  - Solid-state high-power single-cavity RF source
  - Radiation
- Integration

A standard 1.3 GHz 9-cell cavity:

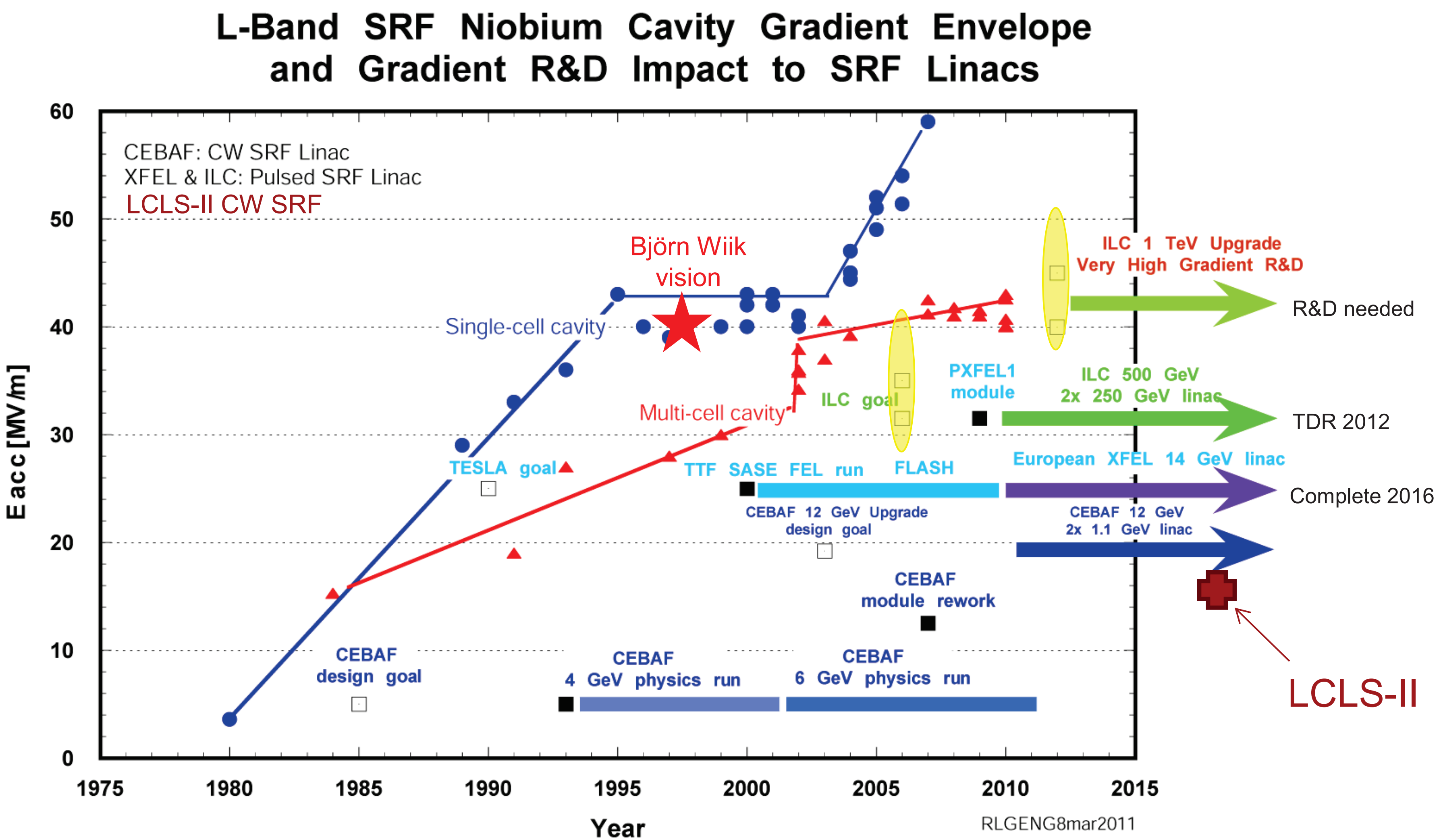
LCLS-II CW operation: 16 MV/m; <Q0>~2.7e10 → 10 watts@2.0 K

- <Eacc_max> 18 MV/m
- 280 each
- 16 from ILC-GDE SRF (2009-2011); ← Provided by Fermilab (short)
- 264 dressed cavities to be made by industry following XFEL-style production scheme



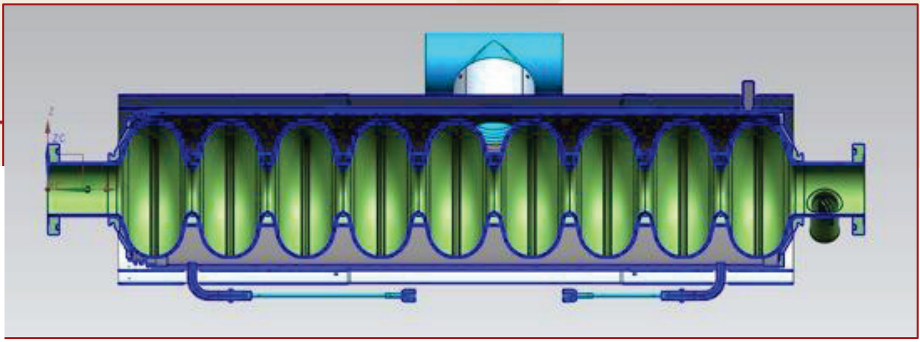
RongLi Geng

SRF Cavity Gradient Progress



Steady progress in SRF cavity gradient makes SRF an enabling technology
SRF based electron linacs (CW & pulsed) have track record of successful operations

Cavity dressed in its titanium helium vessel with power coupler



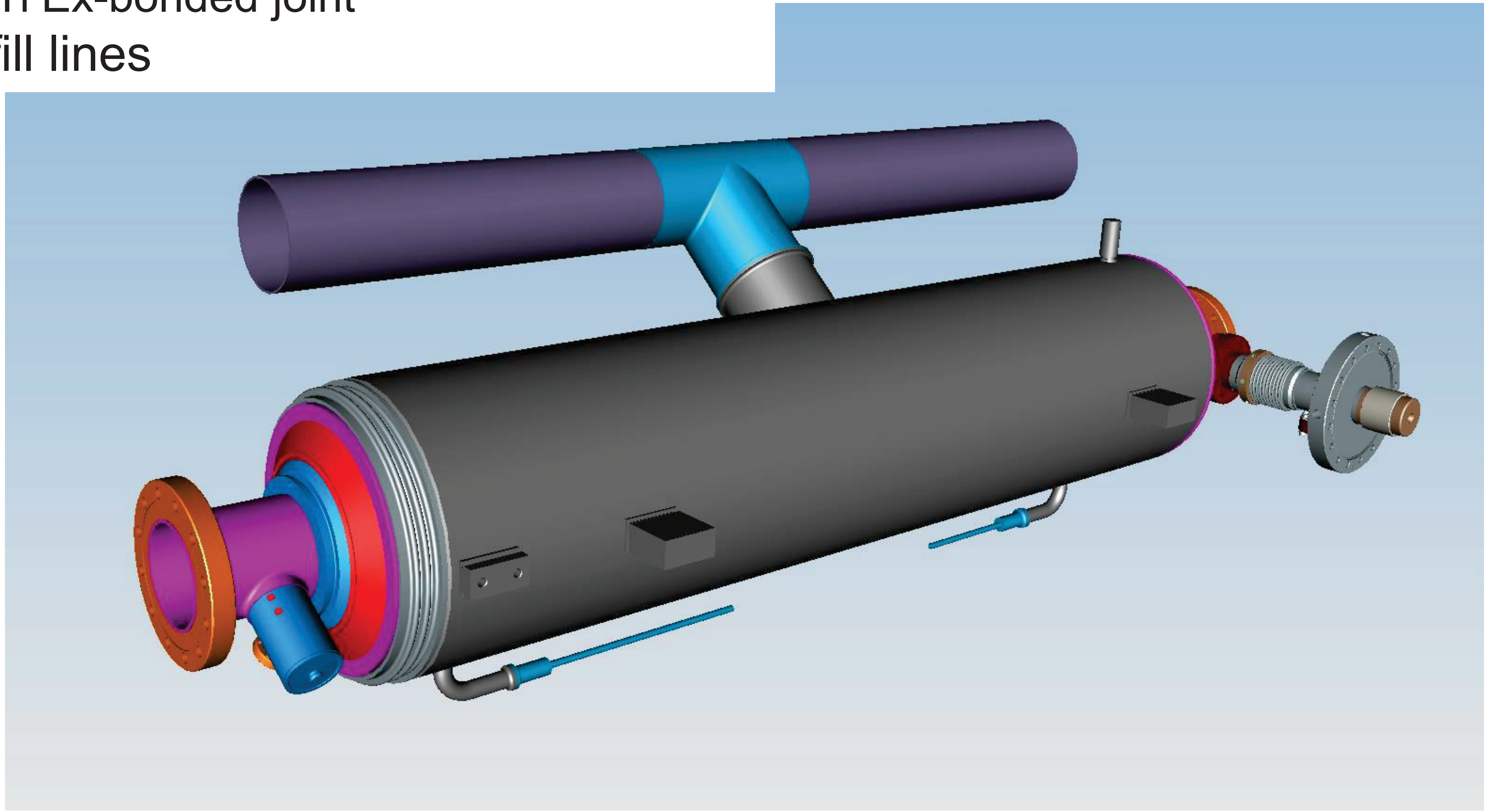
- 27 LHe liters @ 2.0K/0.029 bar

10x greater heat load than XFEL/ILC

95 mm 'chimney'

- ~centrally located
- SS-Ti Ex-bonded joint

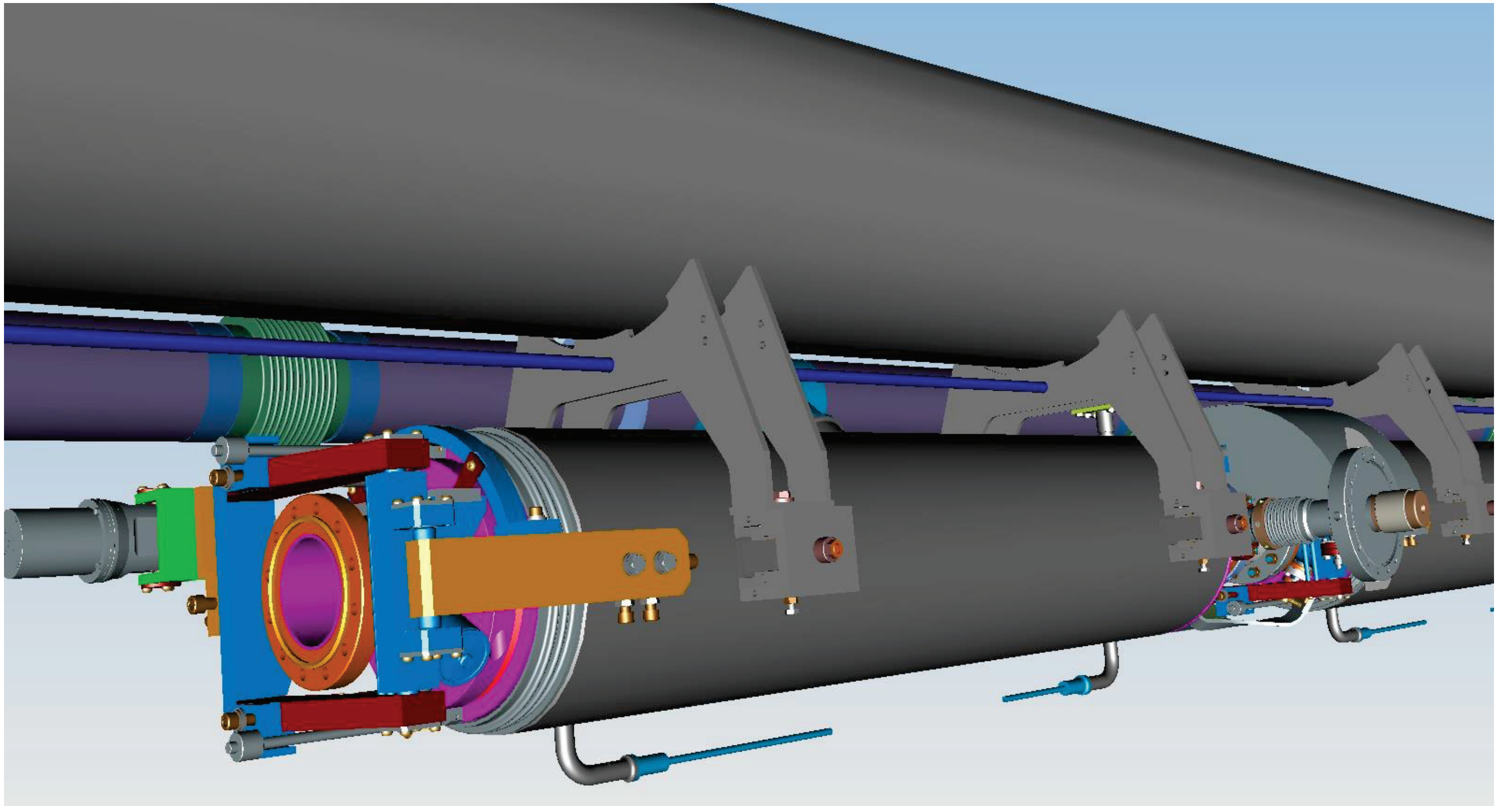
Two fill lines



Cavity / helium vessel suspended from low-pressure cold-gas return pipe

Cryomodule backbone: 300 mm diameter pipe

- Scissor tuner compatible with short inter-cavity spacing



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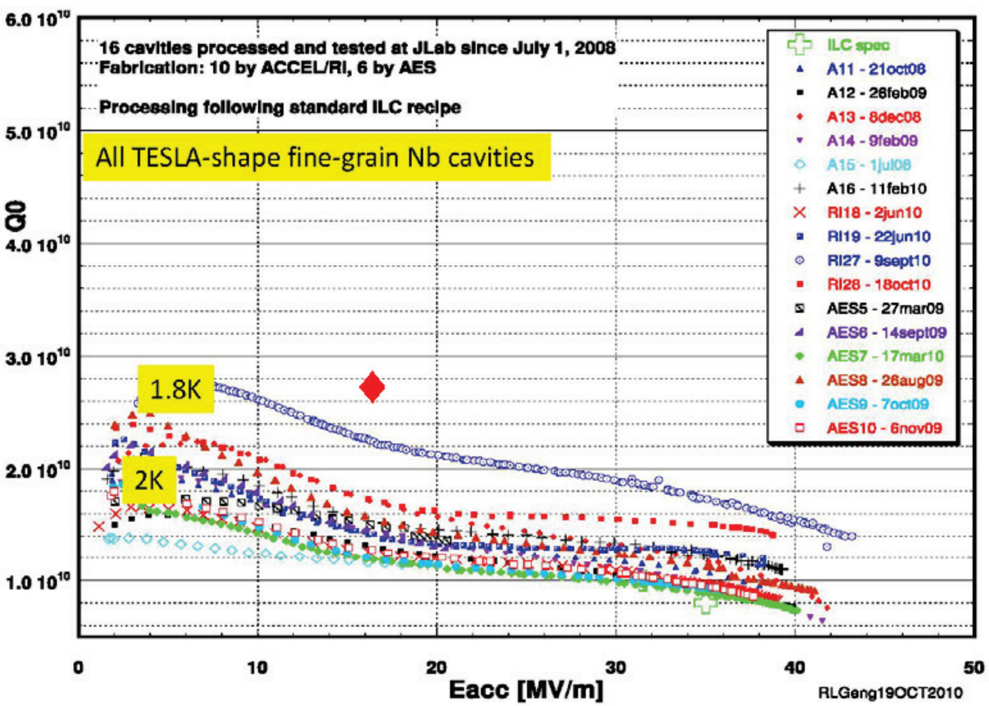
Motivation for High Q_0 R&D

High Q0 doping developed by Fermilab

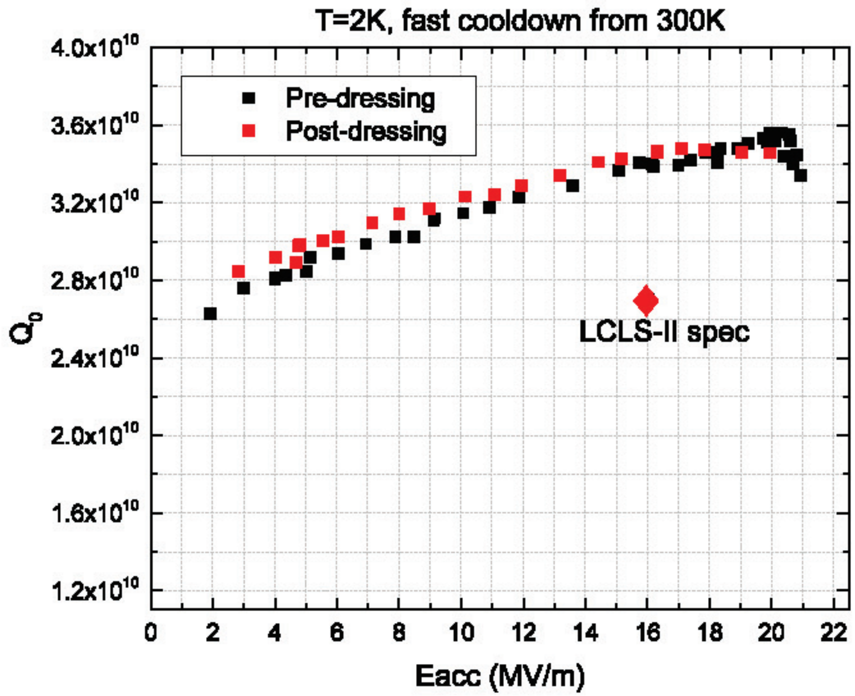


"The best cavities of 2010"

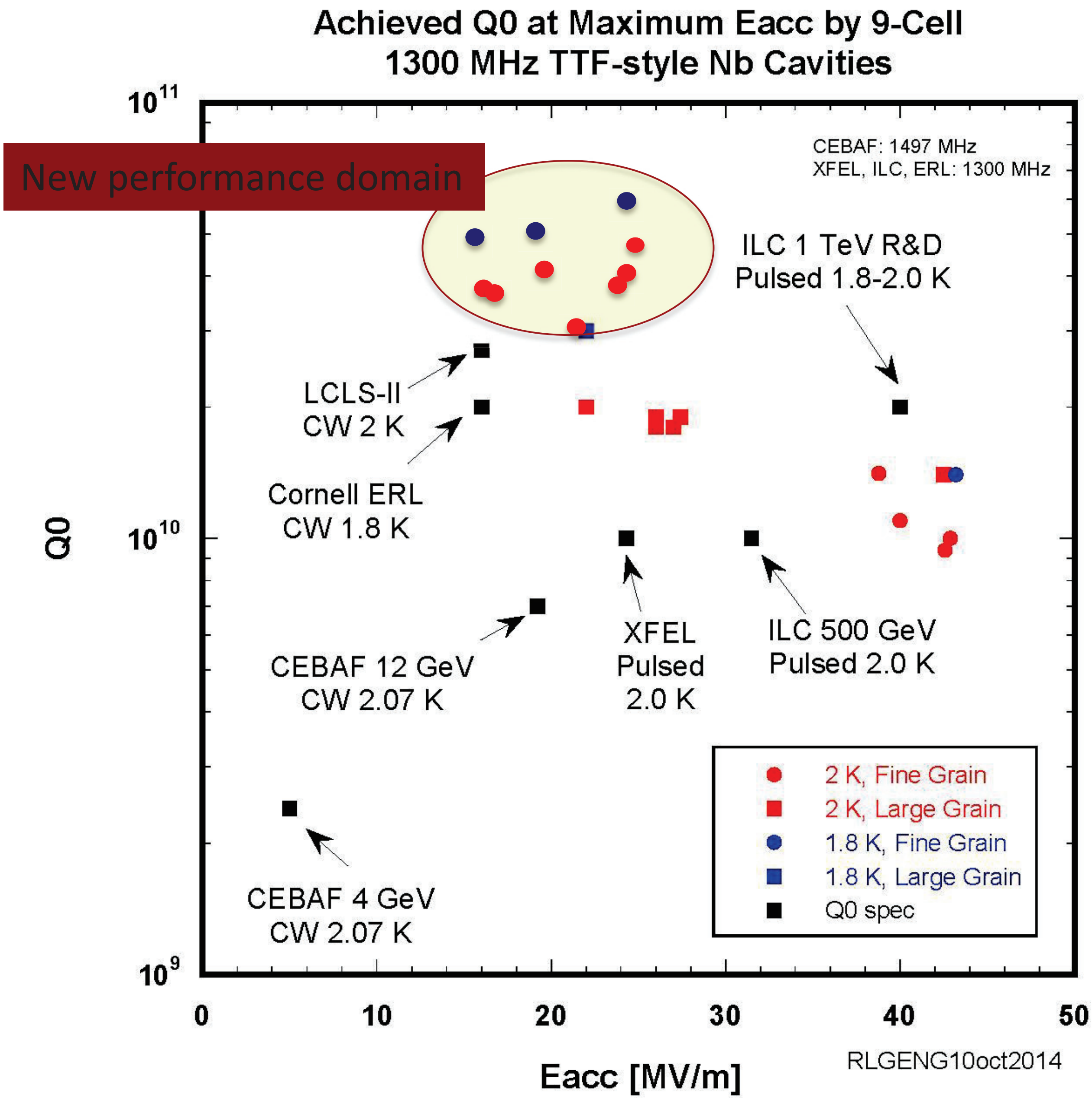
The SRF world is changing

"The best dressed cavity of 2014" (so far)

TB9AES011



FNAL IB4 Vacuum Oven:
High Q Nb surface doping done here



C. Reece

The door has opened to new opportunities.

New interesting challenges have appeared for exploiting these opportunities with high Q_0.

SRF2015 1409 (M. Ross, SLAC)

Three-lab High Q0 Studies schedule (2014):

1. Use single-cell cavities to optimize and define protocol
2. Apply to nine-cell cavities for vertical test
3. and for horizontal (cryomodule-like) cryostat test

HIGH Q0 SCHEDULE
2014-01-20
M. Ross, SLAC

15 tests completed September 1, 2014

		Y	2014																						
		M	J	J	F	F	M	M	A	A	M	M	J	J	J	J	J	A	A	S	S	O	O	N	N
		D	13	27	10	24	10	24	07	21	05	19	02	16	30	14	28	11	25	08	22	06	20	03	17
Fermilab		Num. Tests																							
1.	N-treatment process optimization with single-cell cavities	8				3					6			8	◊										
2.	9-cell cavity treatments and vertical tests	8						1	2			3	4			5	6	7	8	◊					
3.	Dress 9 cell cavities for HTS complete																			◊					
4.	HTS tests (Fermilab)	3															1			2		3	◊		
5.	**Final FY 2014 report submitted**																							◊	
Jlab		Num. Tests / Cavities																							
1.	Begin single cell cavity fab	6	◊																						
2.	Cavity set complete						◊																		
3.	Single cell parametric study	18						3	6	9	12	15	18	◊											
4.	Production protocol ready for application to 9-cells														◊										
5.	Nine cell production processing	6															1	2	3	4	5	6	◊		
6.	**Final report submitted**																							◊	
Cornell		Num. Tests																							
1.	Single cell tests - initial	10							2	4	6	8	10	◊											
2.	Single cell tests - final	8															3		5		8	◊			
3.	Nine cell - initial process	4											2					4							
4.	Nine cell - secondary process	2																							2
5.	HTC Tests (Cornell)	3															1			2			3		
6.	**Final report submitted**																								◊

What Has Been Learned toward High Q_0?

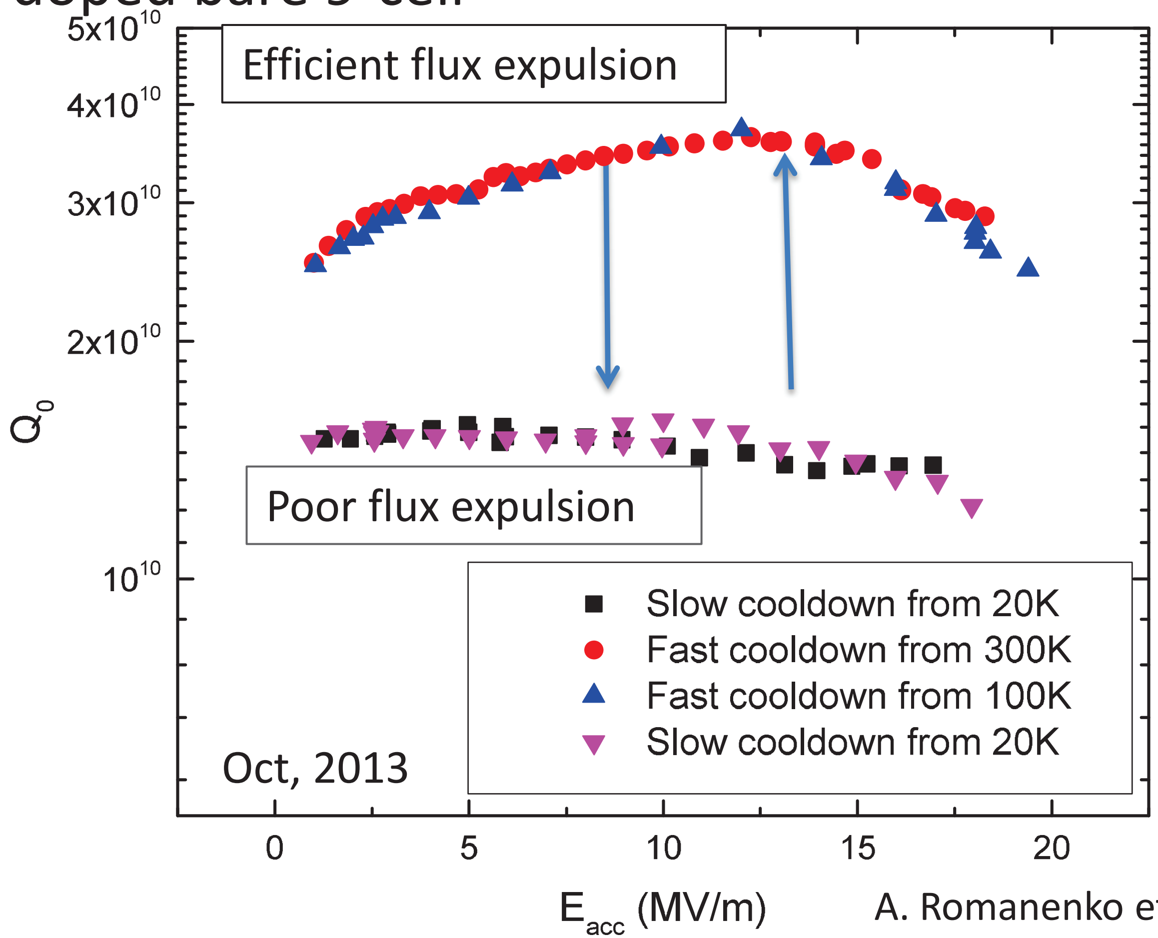
C. Reece

- Subtle near-surface material details matter a lot
  - High temperature diffusion doping can lower $R_{residual}$ and $R_{“BCS”}$
  - The best surfaces show decreasing R_s to ~**5 nohms** @80 mT, 2 K, 1.3 GHz
- Magnetic flux must be carefully managed
  - Cavity Q performance is easily limited by extrinsic effects that yield frozen-in flux that
- “Magnetic hygiene” standards must improve or be actively corrected
  - Fixture hardware, instrumentation connectors, etc. non-magnetic, low permeability
- Temperature gradient across cavity during T_c transition is very helpful for expelling residual flux. (“Fast” is but a means of creating gradient.)
- Asymmetric temperature gradient across cavity assembly with dissimilar metals during T_c transition may generate currents, large *B*-field, and frozen flux.
- Cavity quench presents opportunity for flux entry – and Q degradation
- N-doped material appears to trap available flux more readily than non-doped material.
- Higher doping appears correlated with lower cavity quench fields.

What Has Been Learned toward High Q_0?

- Temperature gradient across cavity during T_c transition is very helpful for expelling residual flux. ("Fast" is a means) **FNAL VTS tests**

N-doped bare 9-cell



A. Romanenko et al. J. Appl. Phys. 115, 184903 (2014)

Slow cooling leads to strong deterioration of Q_0

Meissner effect flux expulsion is sensitive to the cooling conditions through T_c

Trapped flux adds R_s

Detailed characterization is underway

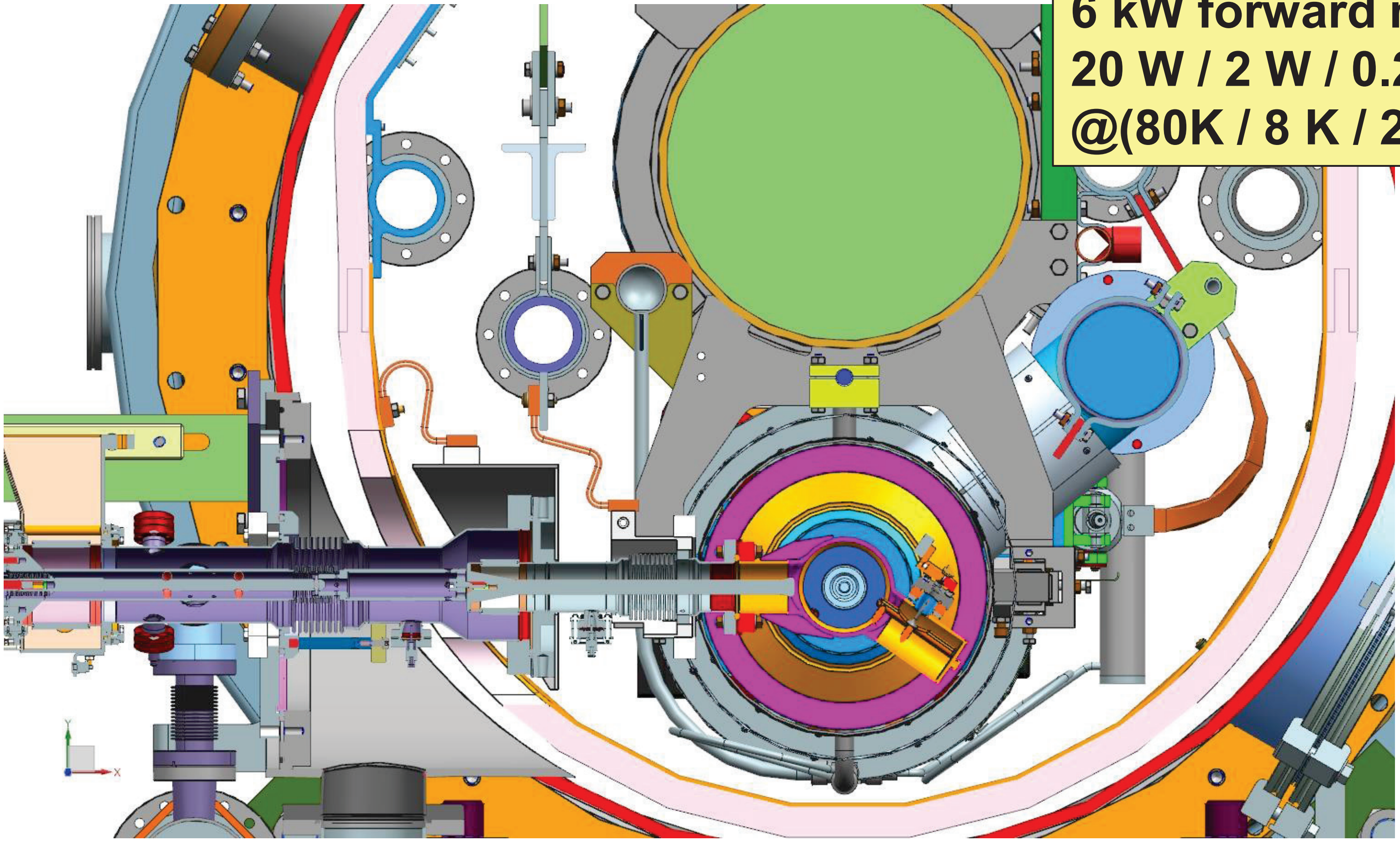
LCLS-II Linac System Design:

1. ***High average power input coupler***; high heat in a cryomodule
2. ***High Q loaded*** (4e7); sensitive to tuning and ***microphonics*** (few 10's Hz)
3. ***Conduction-Cooled Magnet Package***
4. ***RF Power source***; cost and flexibility
5. ***Radiation*** from 'dark-current' self-captured electrons

Power Coupler Design and Integration

Thermal interfaces to cryomodule

6 kW forward max
20 W / 2 W / 0.2 W
@(80K / 8 K / 2.0 K)



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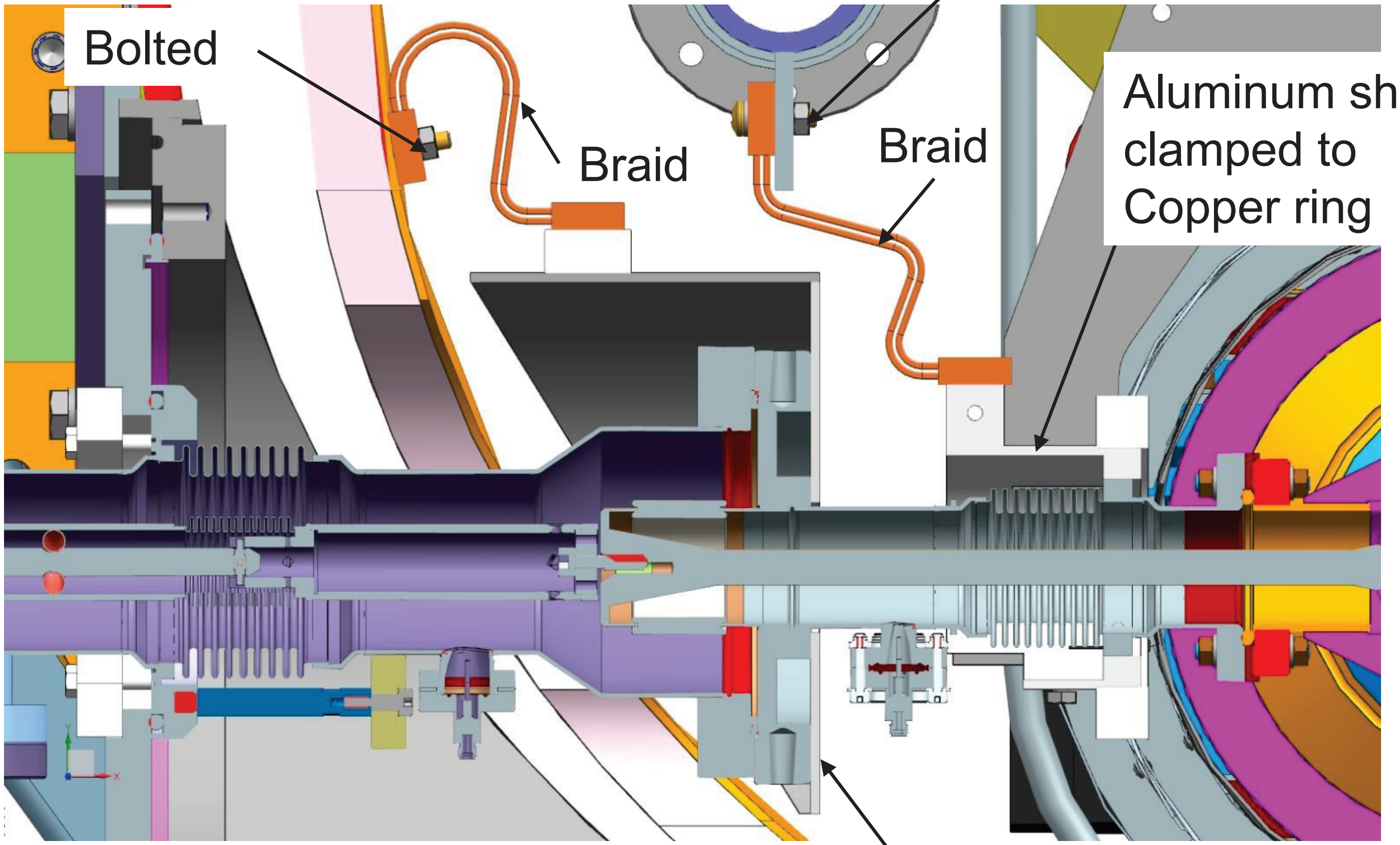
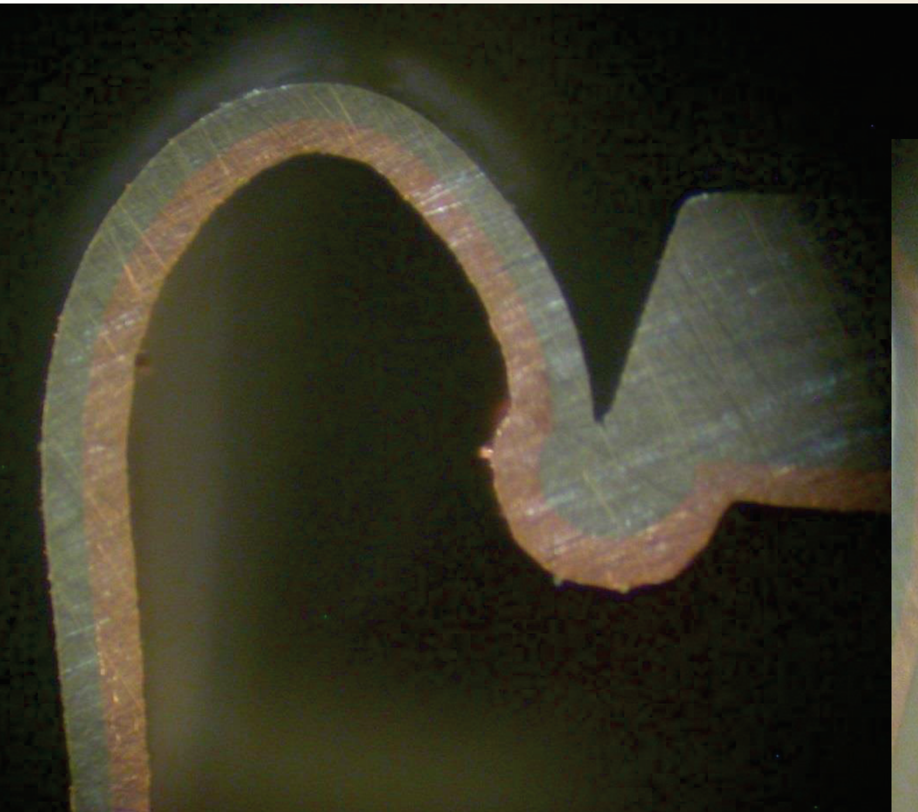


Thick (150 micron) Copper-plated SUS bellows:



SRF2015 1409 (M. Ross, SLAC)

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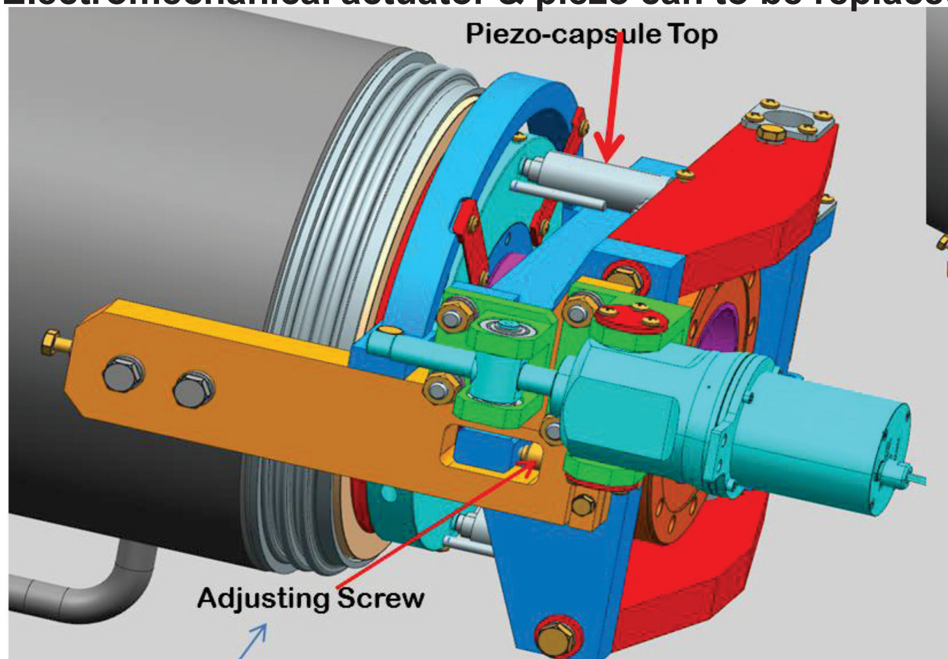
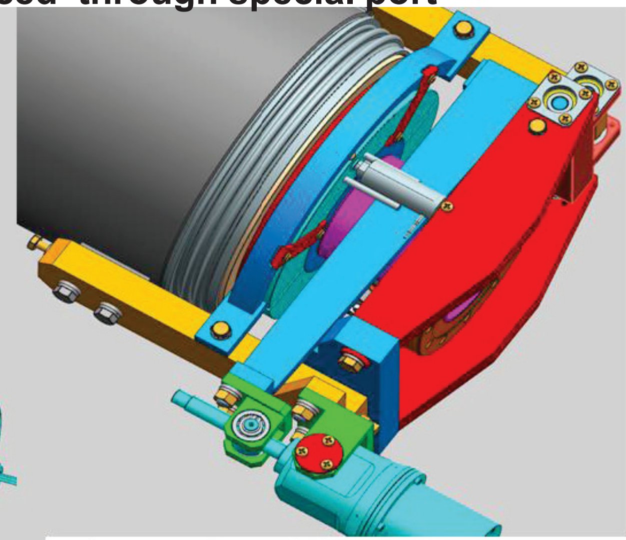
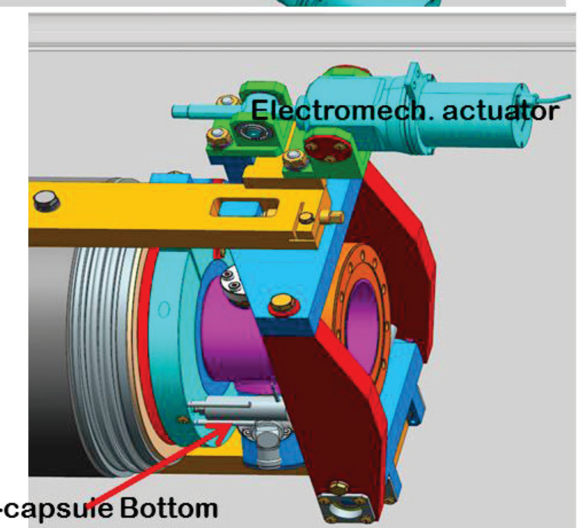
LCLS II Tuner – parameters and accessibility

Electromechanical actuator & piezo can to be replaced through special port

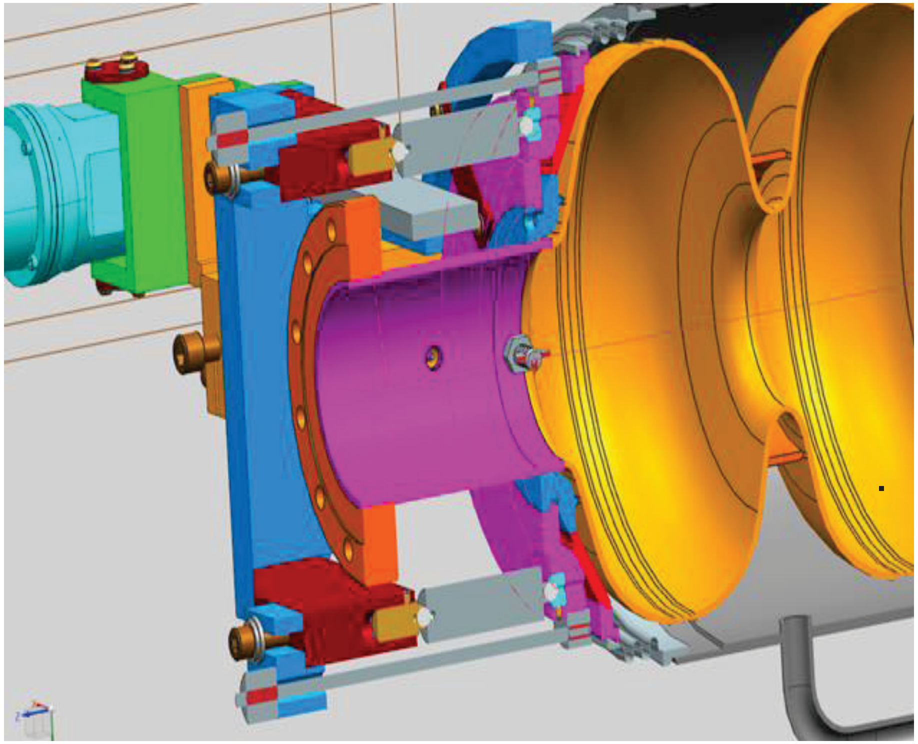


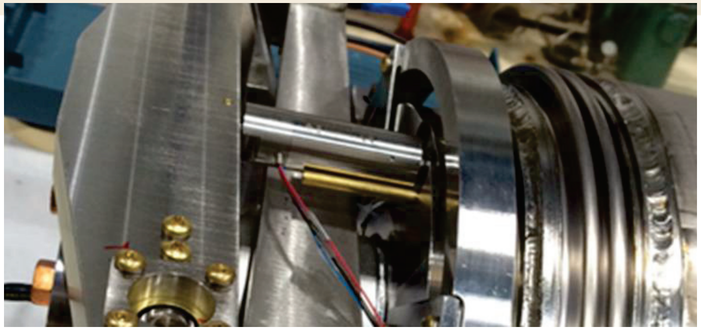


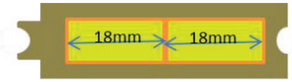


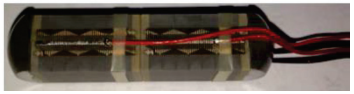
Tuner parameters	*specifications*	*measured*
Coarse Tuner ration	20	21.5
Coarse Tuner frequency max. range	450kHz	>600kHz
Coarse Tuner resolution	1-2 Hz/step	1.3Hz/step
Coarse Tuner short range hysteresis	50Hz	45Hz
Piezo Tuner range(for 4 piezo & 120V)	1kHz	3kHz
Piezo Tuner Resolution	1Hz	0.1Hz

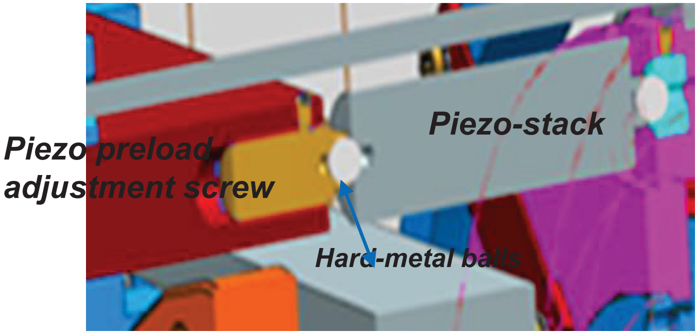
Fast/piezo Tuner Design – Cross Section:











Encapsulated piezo designed and manufactured by Physik Instrumente (PI) per FNAL specifications.

Preloaded Piezo actuator consisting of (2) butted PICMA™ low-voltage multilayer piezo ceramics stacks (18*10*10mm).
Piezo preloaded with 800N.
Each tuner equipped with 4 piezo-stacks, each piezo can be run independently

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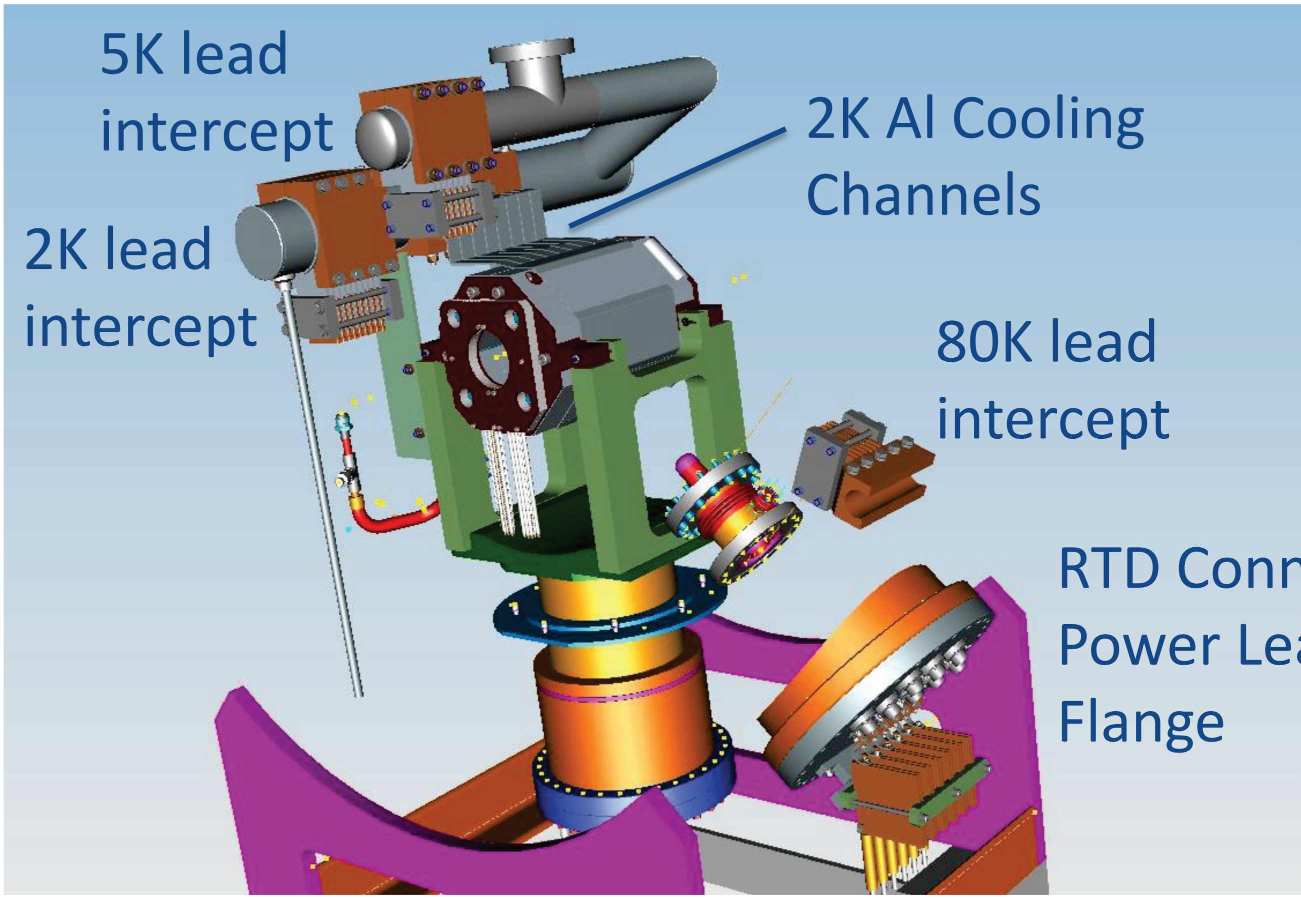
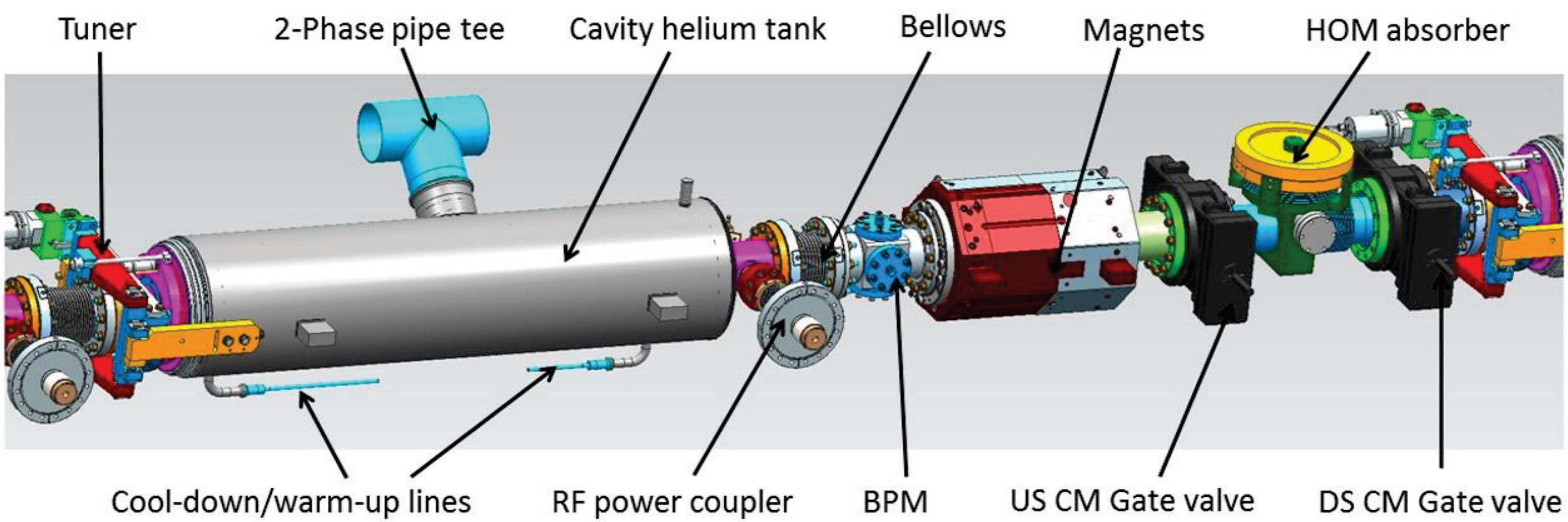
Split Quad Conduction Cooling Test at STC

- 3D Model of Quadrupole and Leads Configuration
  - in Spoke Test Cryostat (STC) at Meson Detector Bldg (MDB)



Summary – Conduction Cooled Magnet Package

- The conduction cooled magnet and current leads showed the stable performance at *20 A peak* specified current for all coils.
- The current ramp rate study confirmed that the magnet could be excited with the ramp rate up to 1 A/s without quench.



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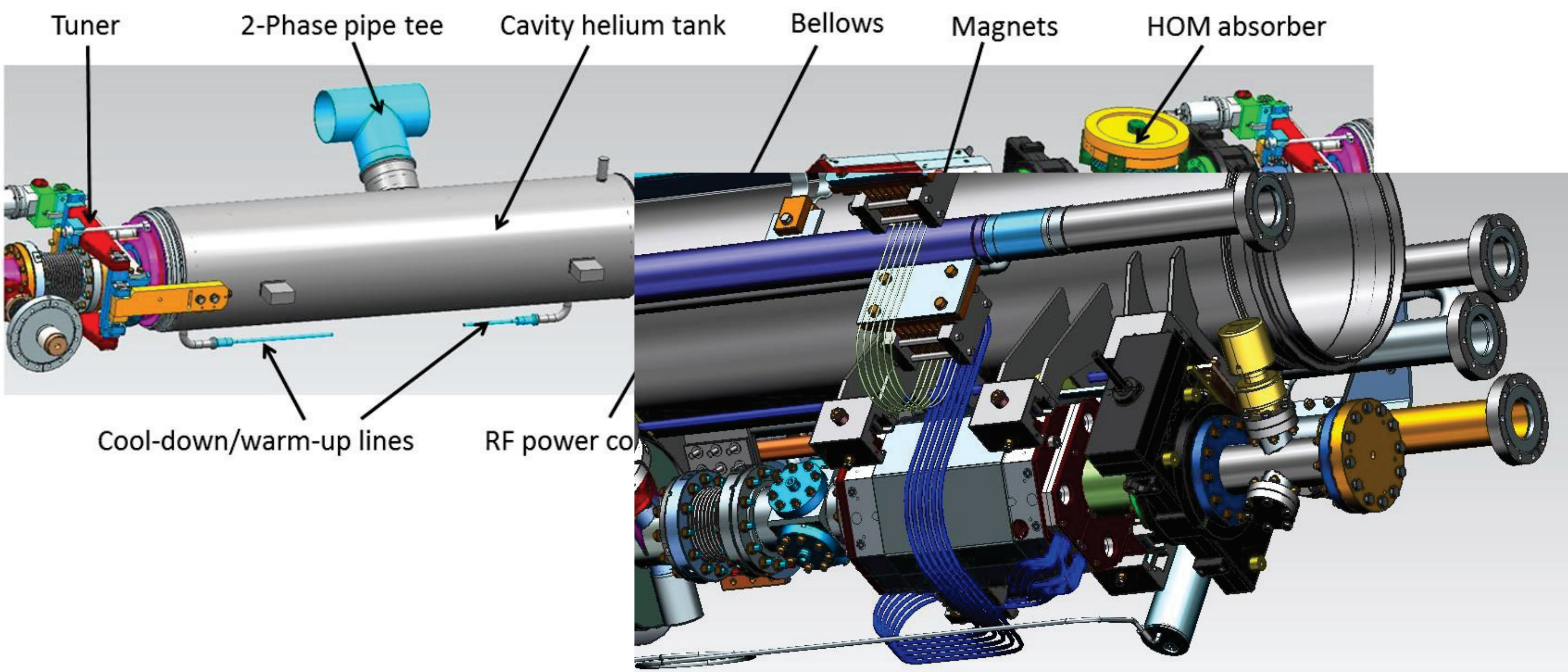

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Solid-State 1.3 GHz Amplifier

HIGH POWER AMPLIFIER

R&K-A1300BW20-6565R

- All Solid-State Power Amplifier
- Frequency Range : 1300MHz±10MHz
- Output Power : 3kW (min.) @Psat (CW)

SPECIFICATIONS @+25℃

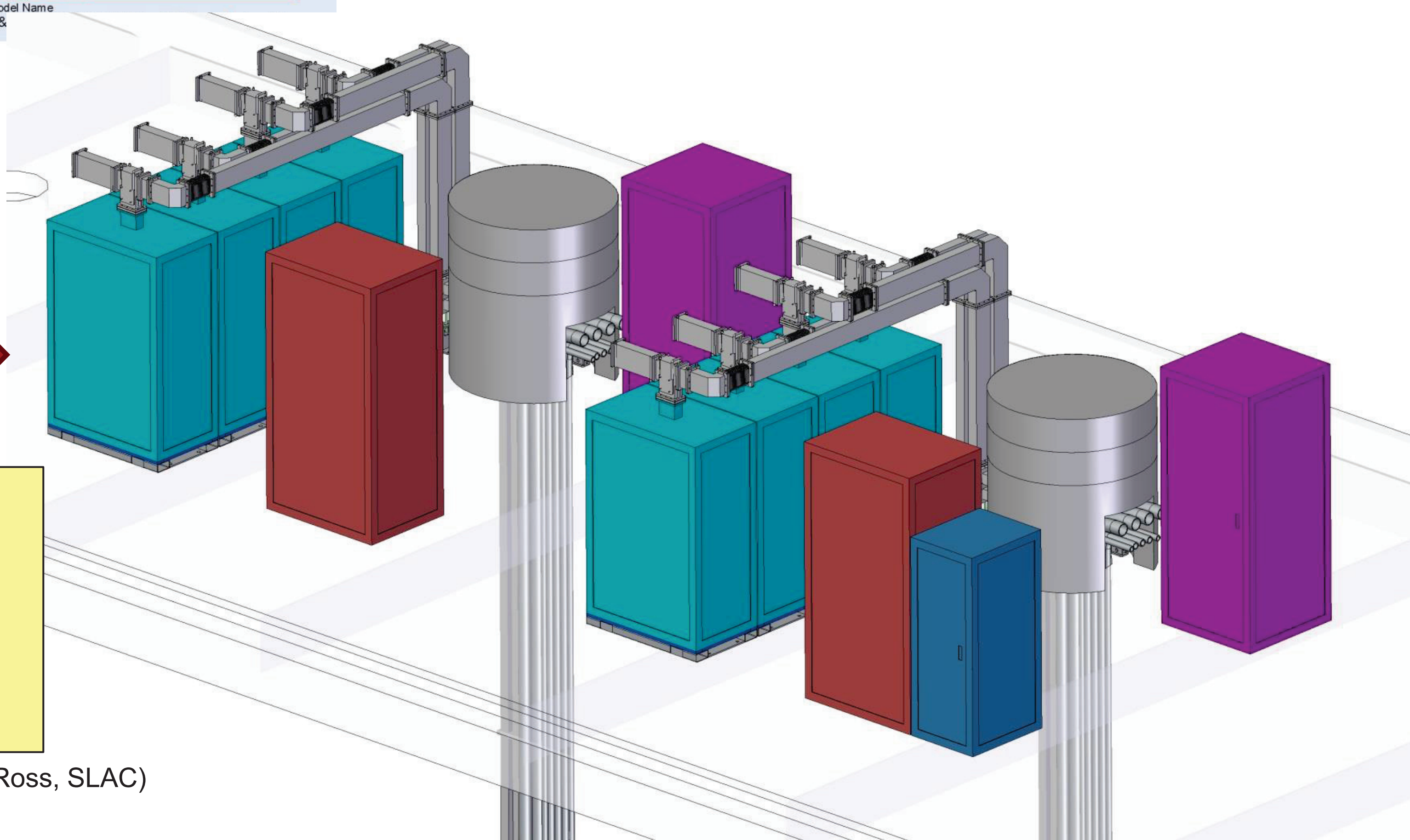
Frequency Range	: 1300MHz±10MHz
Power Gain	: +65.0dB (typ.) @Po=3kW
Gain Flatness	: ±2.0dB (max.)
Output Power	: 3kW (min.) @Psat.
Operation Mode	: Class AB
Harmonics	: −30.0dBc (max.) @Po=3kW
Spurious	: −60.0dBc (max.) @Po=3kW
Impedance	: 50Ω
Input Return Loss	: −15dB (max.)
Maximum RF Input Power	: +3.0dBm
AC Supply Input	: AC200V±15%／3φ, 50／60Hz, 15kVA
Operating Temperature	: +10℃ to +35℃
Storage Temperature	: 0℃ to +55℃
Connectors	: RF - IN N - FEMALE RF - OUT 3 1/8" EIA Flange
Size	: (W)560mm×(D)853mm×(H)804.5mm
Weight	: 200.0kg (max.)
Cooling	: Forced Air Cooling and Water Cooling
Protection Circuits	: Over Temperature Protection Power Supply Voltage Protection Output Over Power Protection Output Over Reflection Power Protection
Metering	: R&K Digital Panel Metering System
Other	: With Output Circulator

HOW TO ORDER

Model Name

R&

'R&K' Amplifier used at KEK Compact ERL



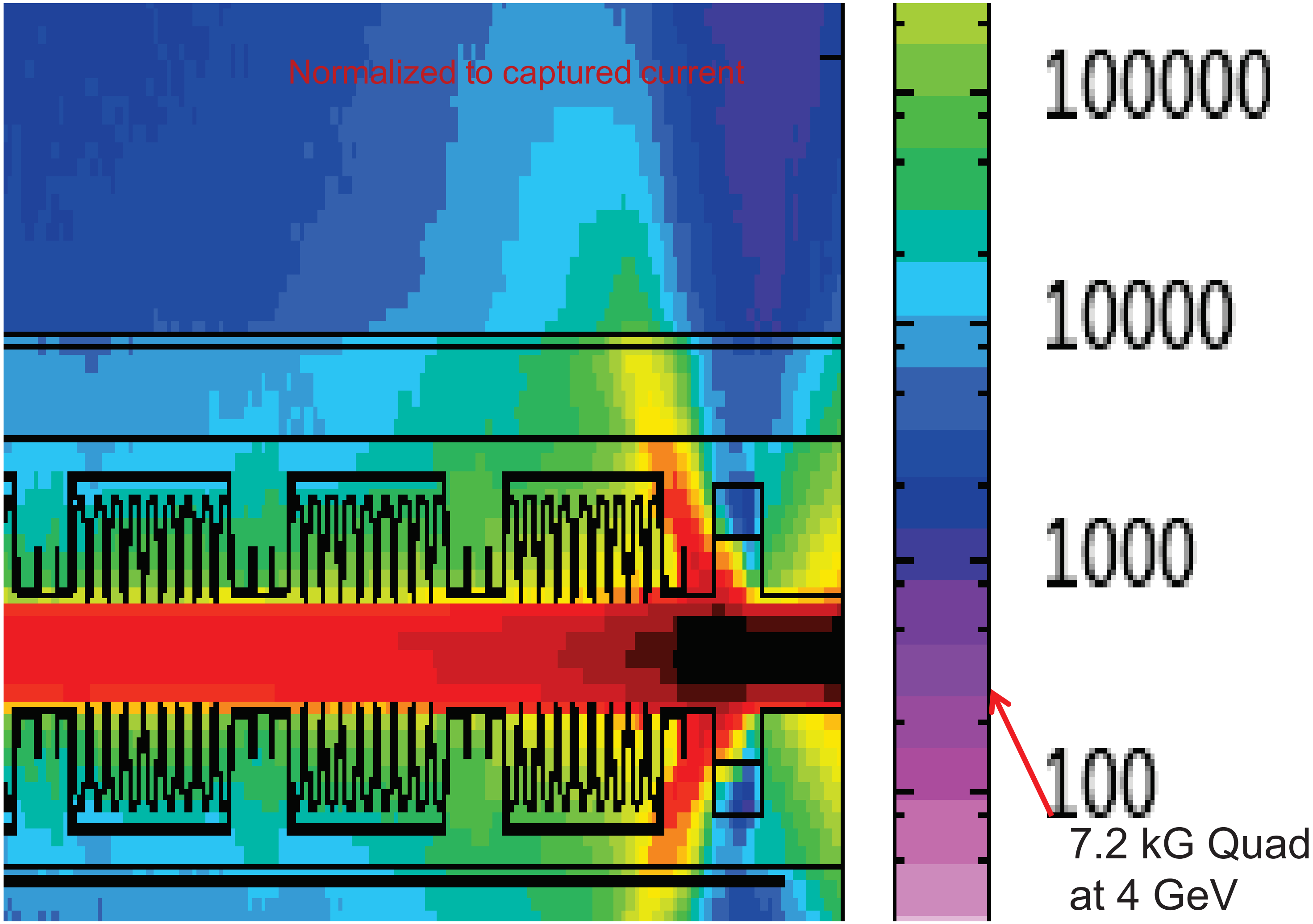
Installation scheme in SLAC Equipment Gallery

SRF2015 1409 (M. Ross, SLAC)

LCLS-II Linac System Design:

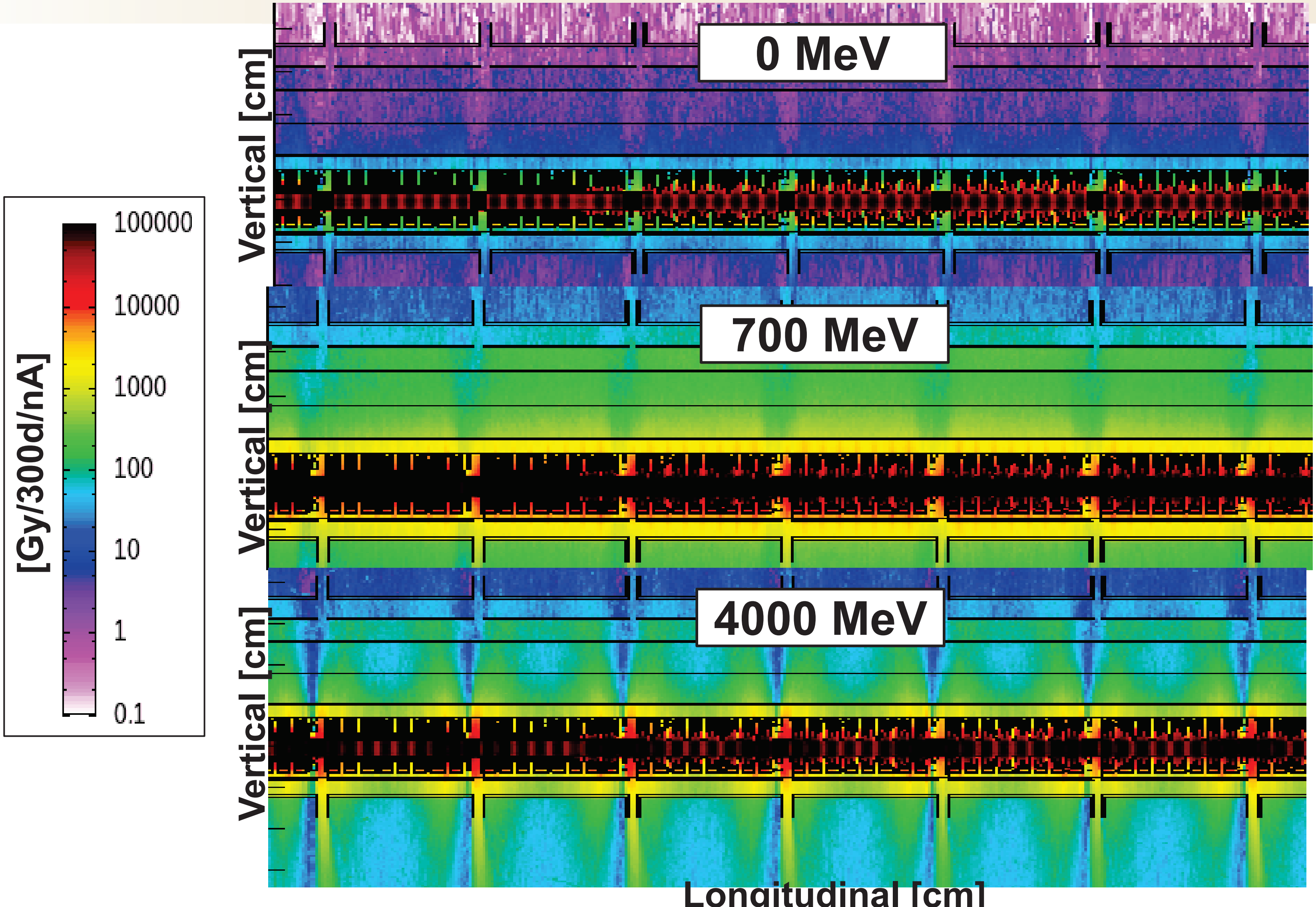
1. ***High average power input coupler***; high heat in a cryomodule
2. ***High Q loaded*** (4e7); sensitive to tuning and ***microphonics*** (few 10's Hz)
3. ***Conduction-Cooled Magnet Package***
4. ***RF Power source***; cost and flexibility
5. ***Radiation*** from 'dark-current' self-captured electrons

Computed Dose In and Around a CM

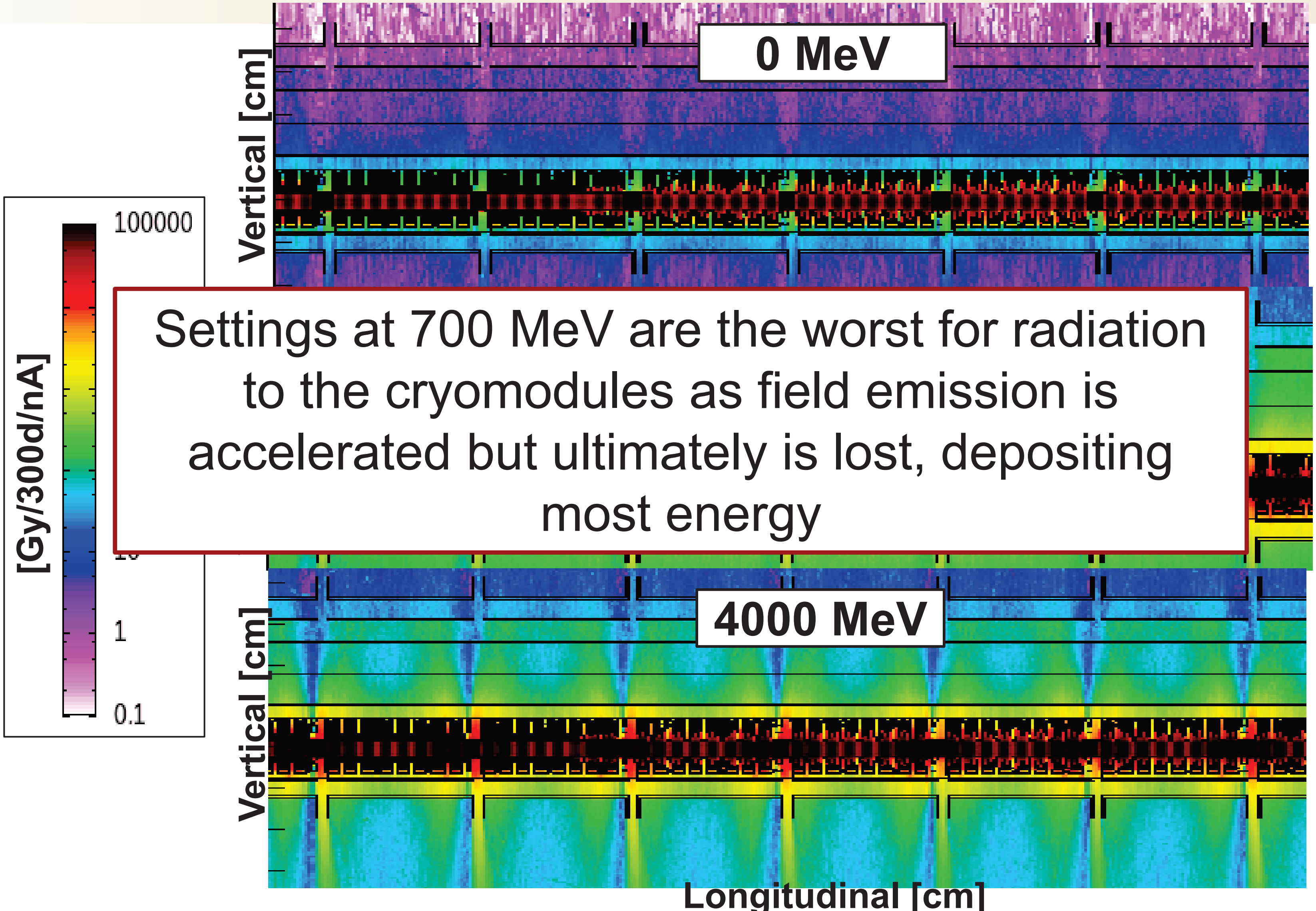


Dark Blue ~ 100 mRad / hour / nA, Red ~ 1 kRrad / hour / nA

Effect of quad settings on radiation fields: 8 cryomodule-model

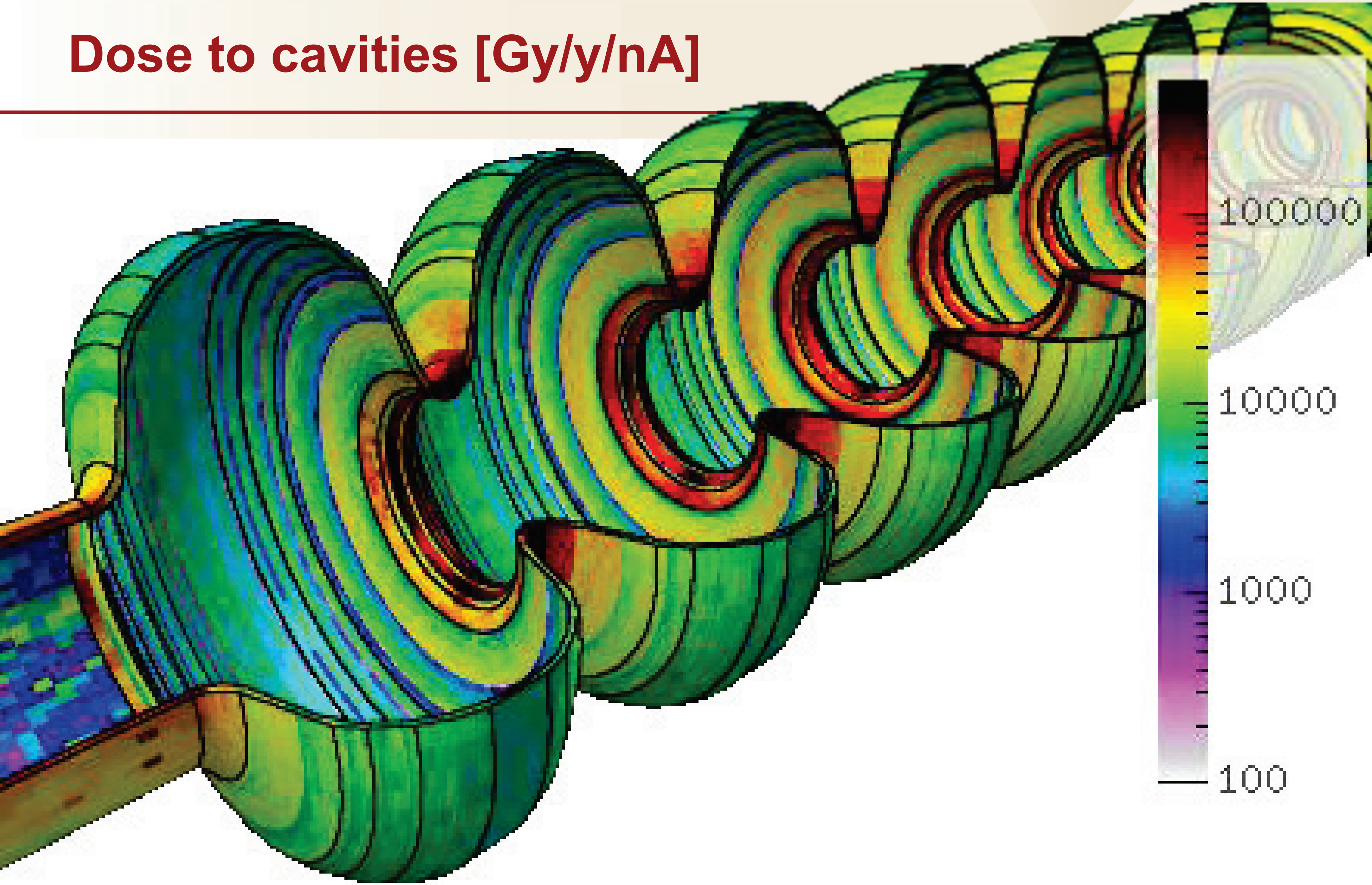


Effect of quad settings on radiation fields

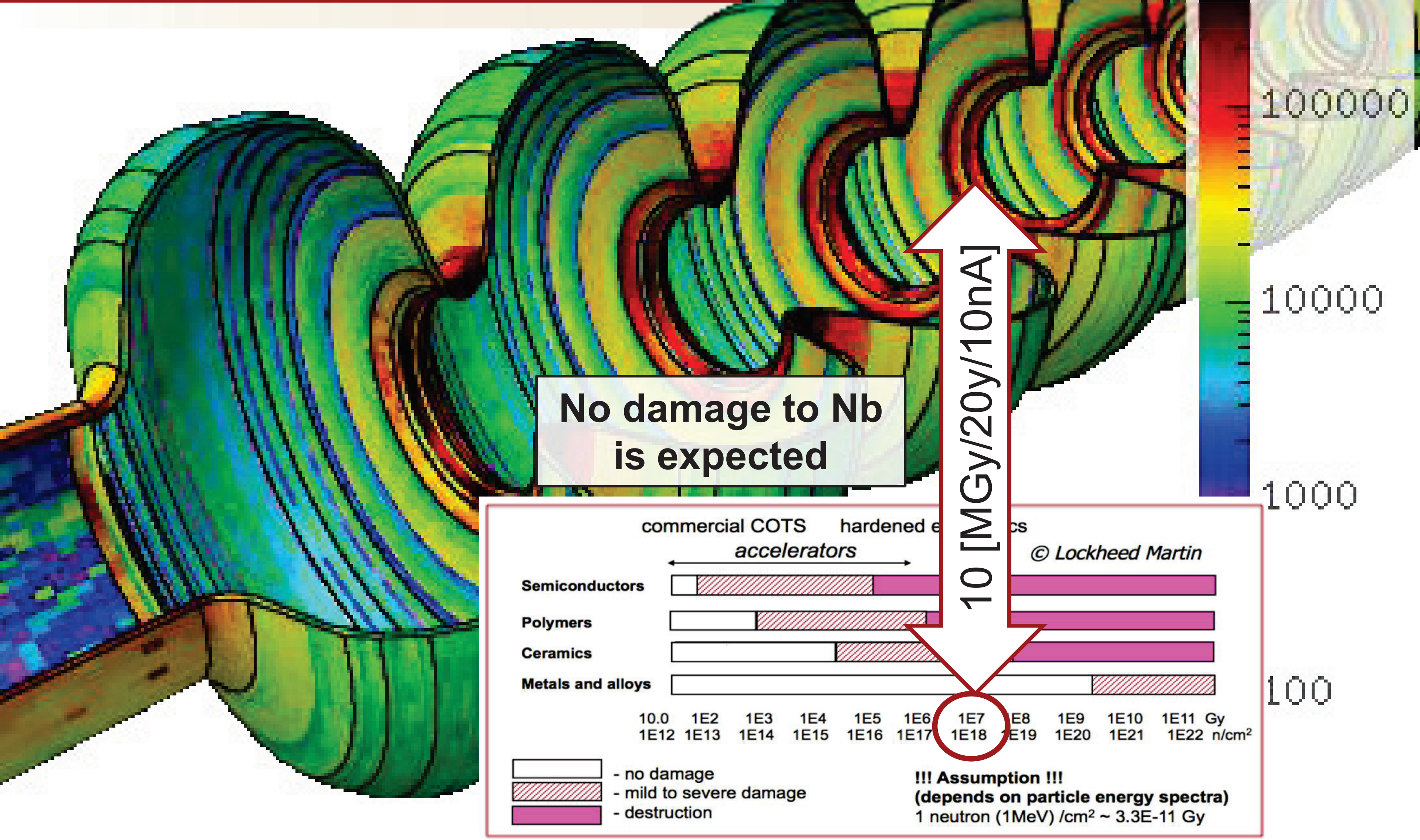


Settings at 700 MeV are the worst for radiation to the cryomodules as field emission is accelerated but ultimately is lost, depositing most energy

Dose to cavities [Gy/y/nA]



Dose to cavities [Gy/y/nA]



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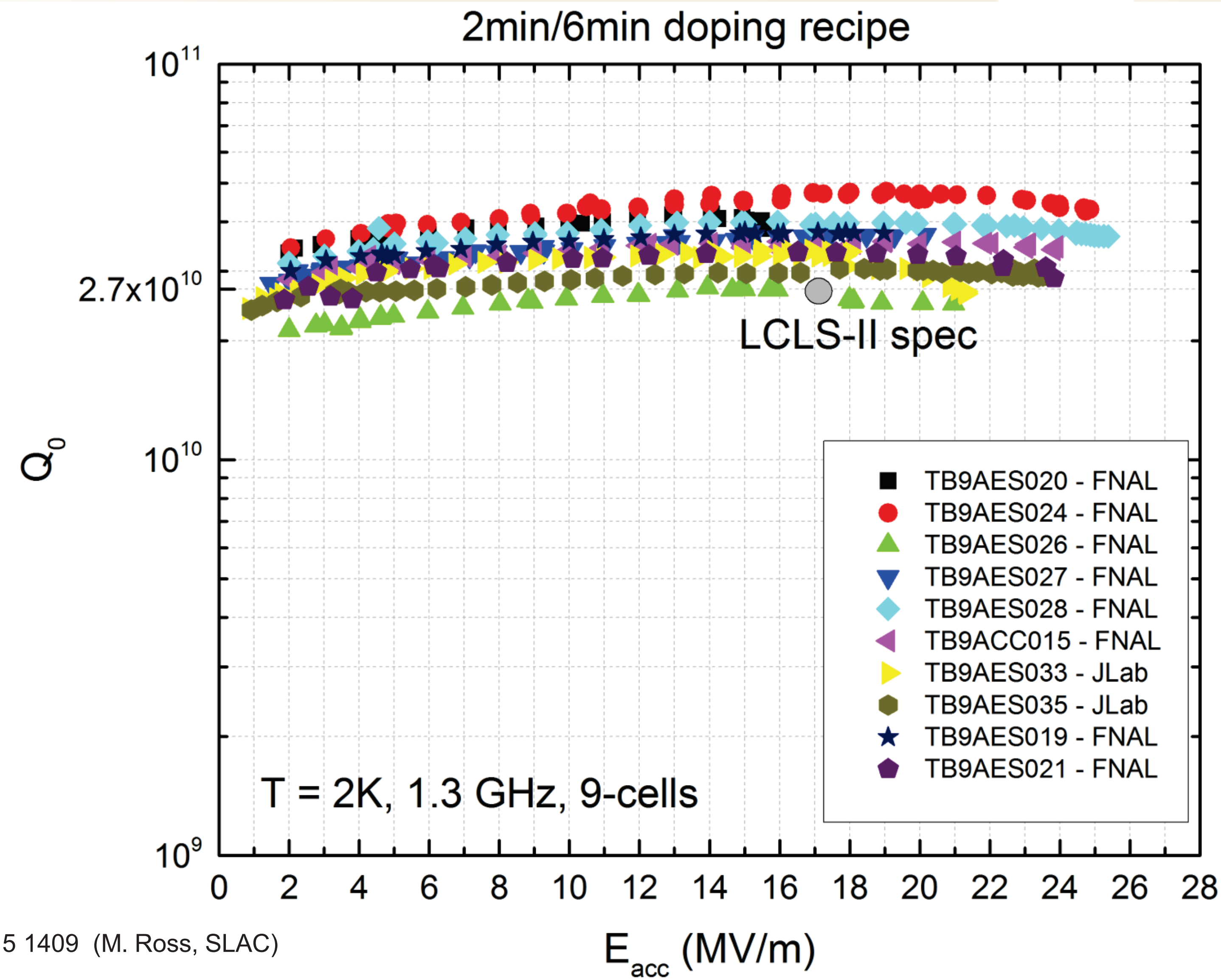
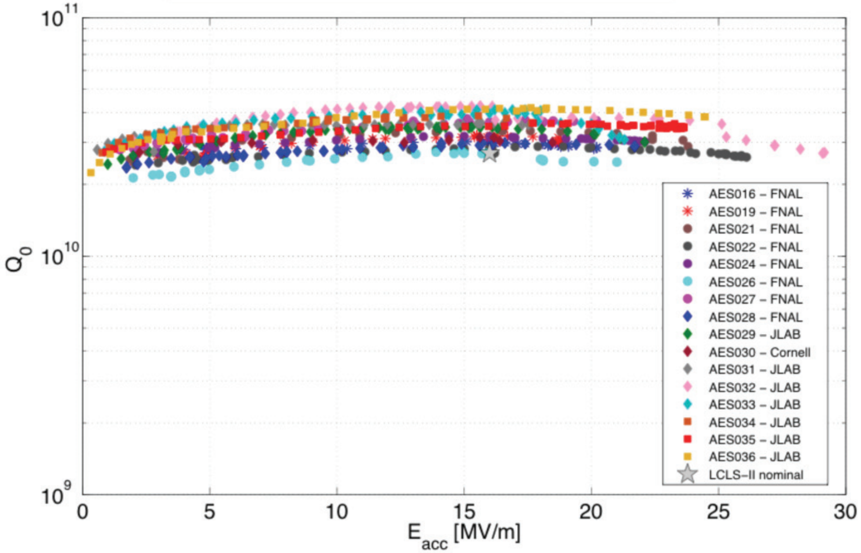
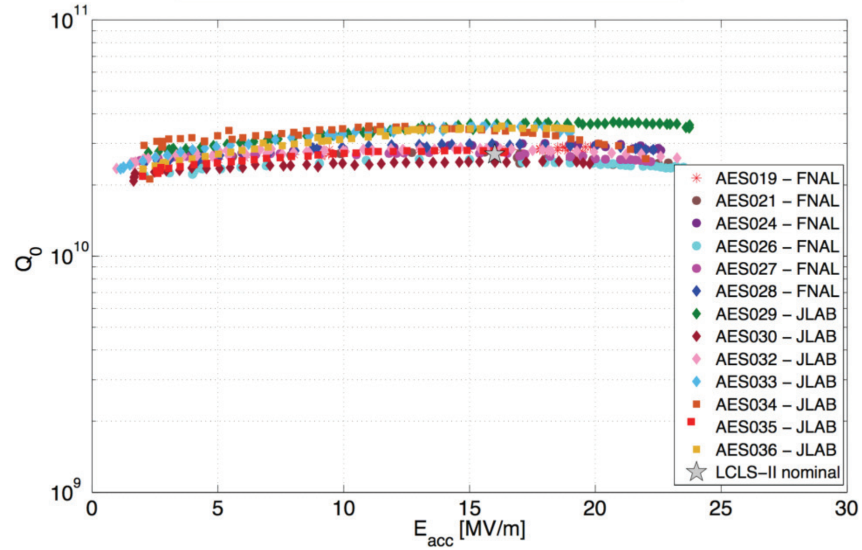
FNAL + Jlab Nine Cell 2.0K Results, N-doping recipe



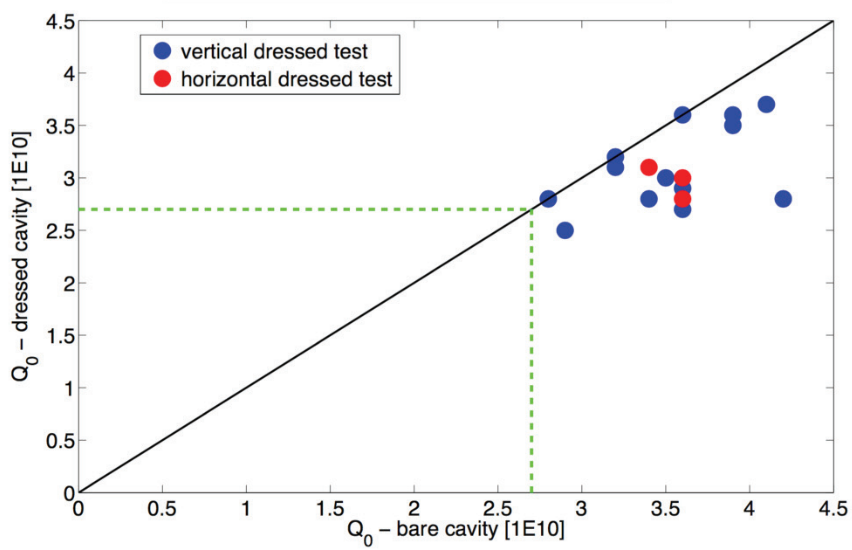
2K Bare Cavity Performance in Vertical Test



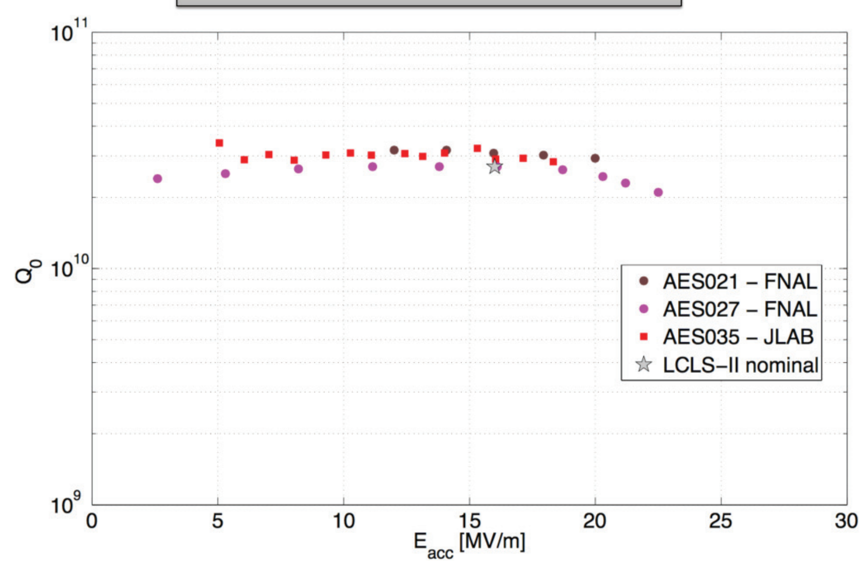
2K Dressed Cavity Performance in Vertical Test



2K Dressed vs Bare Cavity Q_0 Comparison



2K Dressed Cavity Performance in Horizontal Test



Cavity ID #	Qo - VT bare	Qo - VT dressed	Qo - Horizontal tests	Max gradient
AES	E10	E10	E10	MV/m
Fermilab				
16	3.0	pending, 9/21		20.2
19	3.2	3.1		18.8
21	3.4	2.8	3.1	23.0
22	3.1	pending, 9/21		26.2
24	3.2	3.2		22.0
26	2.8	2.8		21.4
27	3.6	2.7	2.8	22.8
28	3.5	3.0		22.0
ACC015	3.5			24.0
JLab				
35	3.6	2.87	3.0	23.6
33	3.9	3.55	pending, 9/18	21.3
31	3.5	pending,9/16		19.4
34	3.9	3.08		19.6
32	4.2	2.8		29
36	4.1	3.7		25
29	3.6	3.21		22
30	3.4	2.48		20

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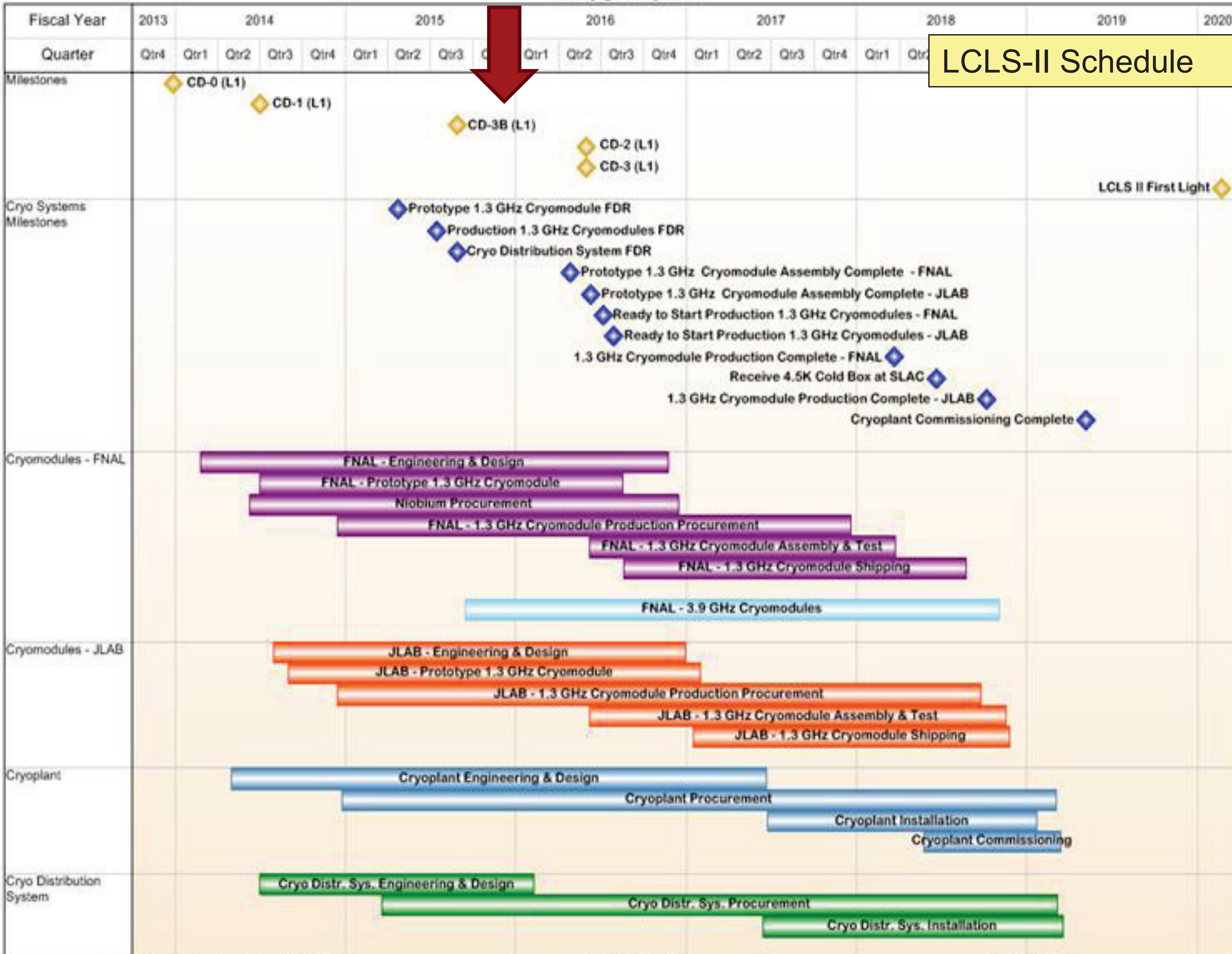
Cryomodule Production

- Follow as closely as possible XFEL industrialized path
  - Saclay (CEA) now assembling one cryomodule every four days
  - ***Both Fermilab and Jlab will have Saclay – style production line***
  - ***Substantially lower rate***
  - Guidance for touch-labor (cost) estimate

- Production-line development between three labs (and DESY)
  - (work-station development, tooling, touch-labor analysis collaborative effort)

- Desy, Saclay, and Orsay (LAL) are special partners to LCLS-II

LCLS-II Schedule



LCLS-II Strategy – One Design, Two Production Lines operating in parallel

- Designs for Prototype and Production CMs (aim to satisfy PR and CM FRS)
- **Identical Prototypes** - utilize as much existing hardware as possible to reduce schedule risk and reduce overall cost while achieving the same performance as the production CMs
- **Identical Production Designs** - utilize as much of the DESY/XFEL design as practically possible to reduce schedule risk and reduce overall cost
  - **FNAL produces 16 CMs; JLab produces 17 CMs**
- **Identical Parts Received** at Partner Labs
  - Well-developed drawing packages, clear requirements and specifications
  - Concurrent reviews within LCLS-II project
  - Procurement activities – lead technical contacts at Jlab/FNAL/SLAC work together during all phases
- **Identical Tooling Interfaces**
  - Interfaces between CM hardware and tooling are identical
    - 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 (e.g. samples to verify etch rates)

Fermilab SRF Overview

25 years experience with ILC / TESLA design

- FNAL has been building SRF Program since 2006
  - Extensive infrastructure – can be used for LCLS II
    - Inspection, EP, tumbling, HPR, VTS, HTS, assembly, CMTS…
    - Ongoing SRF Program supports facility maintenance
  - Cavity & cryomodule design and fabrication (low β and 1.3 GHz)
  - Originally focused on ILC (XFEL CM design, starting point for LCLS II)
    - Now focused on CW applications (PIP II) => complements LCLS II
  - Material & Cavity Processing R&D – now pursuing High Q_0 R&D
- Built three cryomodules of "LCLS II type" (pulsed operation)
  - CM1 successfully tested
  - CM2 currently being tested (most cavities reached 31.5 MV/m)
  - 3.9 GHz (successfully being operated in FLASH)
  - PIP II designs build off this experience

Jlab SRF Overview

~1990, Jefferson Lab (Jlab) SRF Division was created to build the CEBAF accelerator

- **43 cw cryomodules** housing 346 1500 MHz cavities
- 42 standard 8 cavity cryomodules and 1 unique 2 cavity injector cryomodule
- Peak production rate of **2 cryomodules per month**
- Cryomodules/cavities exceeded specifications (~ factor of 2 in gradient and Q_0)

~1995, Jlab FEL

- **4 cw high current** cryomodules, (3 ea 8 cavity and 1 ea 2 cavity)
- Based on the CEBAF design
- New HOM Damping and thermal management
- Higher power RF power couplers, 8 and 50 kW (final 100 kW)

25 years experience
81 Cryomodules

~2000, Spallation Neutron Source (ORNL)

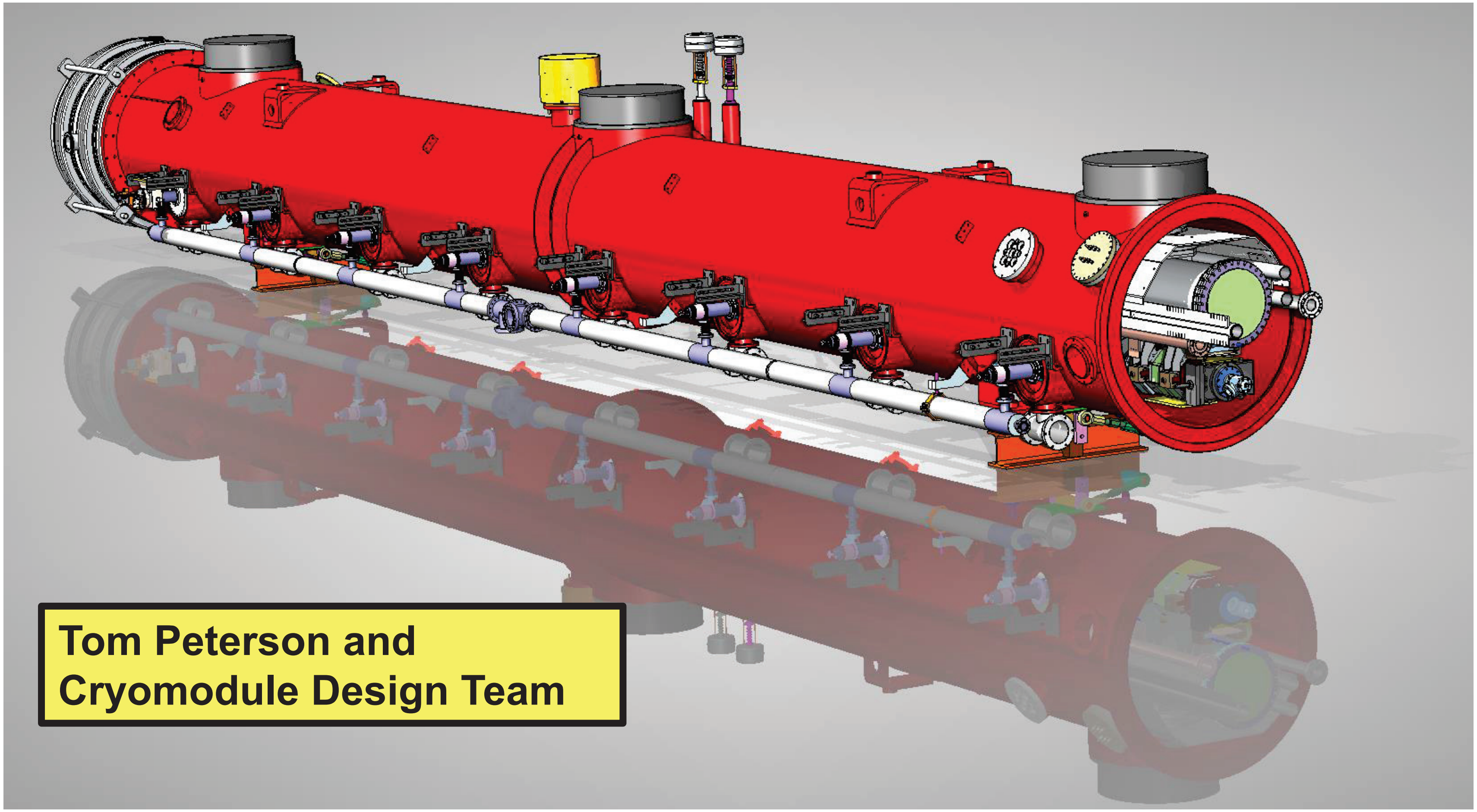
- **24 ea** 3 or 4 cavity cryomodules, 23 production and 1 prototype cryomodule
- Pulsed high power proton machine
- 2 blank sheet cavity and cryomodule designs, medium and high beta
- 18 months from start to first prototype cryomodule tested

~2010, Jlab 12 GeV energy upgrade, C100 cryomodule

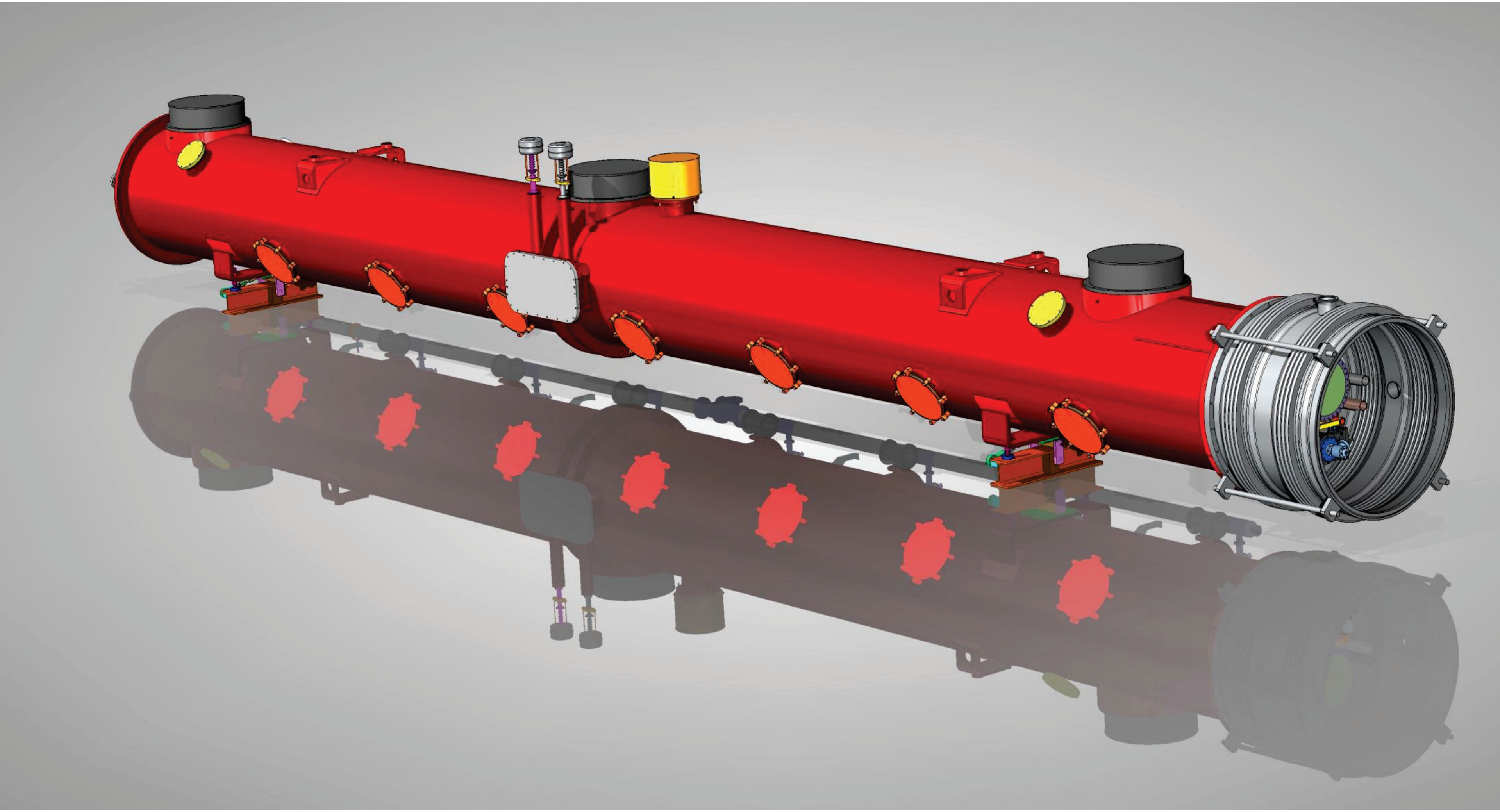
- Blank sheet design
- 1500 MHz, 7 cell, Low Loss type (operating at ~20 MV/m) cavities
- Same footprint of old cryomodules resulting in a 40% increase in active length fraction
- **10 ea cryomodules built (80 cavities)**, tested and installed in CEBAF → similarities w E-XFEL

LCLS-II Cryomodule - Front

SLAC



LCLS-II Cryomodule - Back



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SRF: ILC ↔ LCLS-II ↔ ILC

Before: TESLA Collaboration, XFEL, SRF R&D

2013: ILC TDR International Review (Feb)

Performance Demonstrations, Industrialization, Cost

2013: LCLS-II CW SRF Linac proposed to DoE – SC(BES)

CD-0 (Aug), CD-1 (Aug 2014), CD-2/3 (2QFY16)

2014: High Q0 Process development

Fermilab (lead), JLab, Cornell; (Cavities from FNAL)

2018: LCLS-II Cryomodule Construction Complete (Aug)

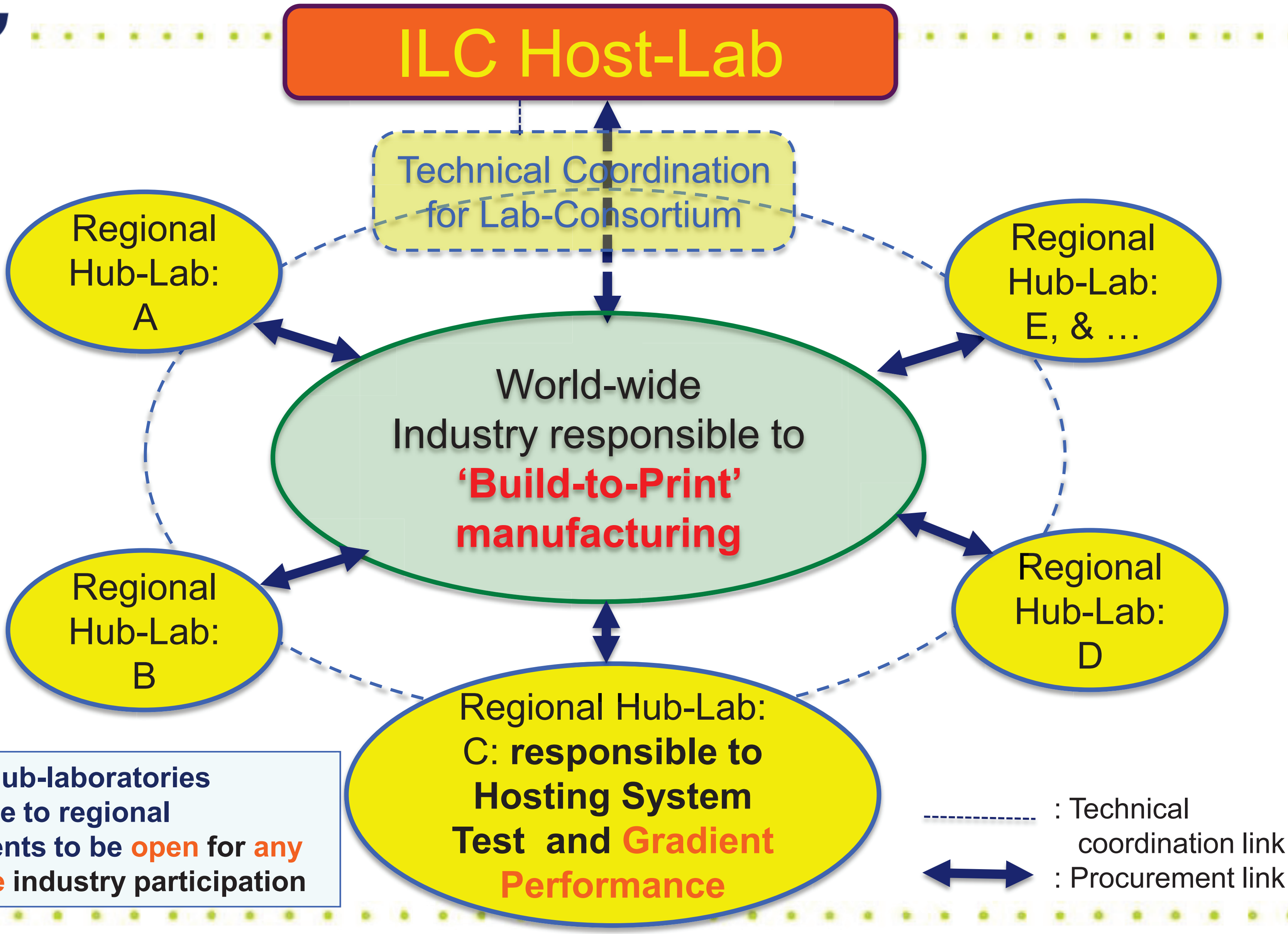
→ *First light at end of FY2019*

2018: US Infrastructure Qualified and Demonstrated

→ *ready for ILC or future SRF application*

SRF Cost Reduction / Risk Reduction through application

SCRF Procurement/Manufacturing Model



Regional hub-laboratories responsible to regional procurements to be open for any world-wide industry participation

SRF Summary

Cavity / Cryomodule:

- Cost Validation : ***few percent scale***
- Cost Reduction
  - Applied production v/v continued R&D
  - From C100 to EXFEL: ***factor 2 cavity cost reduction***
- Technical Risk Mitigation
  - ***Demonstrate construction and performance*** of TESLA/ILC-type cryomodules for science in the US

For US, the work on LCLS II has brought together SRF programs in a way that maximizes collaboration, efficient sharing of IP, and facilities giving the most "bang for the buck".