Industrial Session
Regional Report - North America

Camille M Ginsburg
FNAL LCLS-II deputy team lead & cryomodule CAM

LCWS18 Arlington, Texas
24 October 2018

Presentation goal

- Activities relevant to the ILC
  - in the North American region
    - in the accelerator regime
      - of interest to industrial partners

The ILC is a global project

- Industry equally must be distributed around the world
- Multiple vendors for high-tech components necessary

Outline

- Summary of recent ILC-related R&D progress with impact on industrial partners
- LCLS-II cryomodules: ILC production on a (much) smaller ~1/30 scale
- Path forward toward ILC realization

North American region ILC-related R&D: N2 infusion

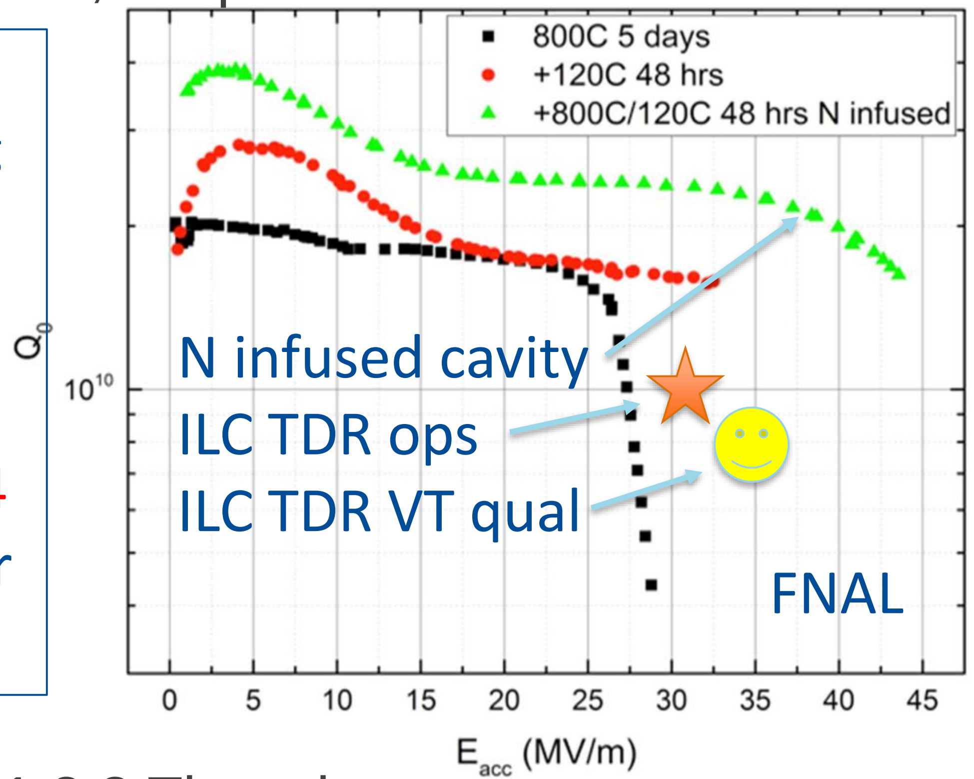
- ILC-related cavity R&D for cost savings
  - Could require lower cryogenic capacity (high Q0) and fewer cavities (high gradients) simultaneously
  - Materials, surface treatments, shapes

➢ Nitrogen infusion process

- Very high Q0 at 2 K for accelerating fields >35 MV/m
- Very high accelerating gradients ~45 MV/m repeatedly reached

➢ Grassellino et al., Supercond. Sci. Technol. 30 (2017) 094004

➢ Process is reproduced at other laboratories

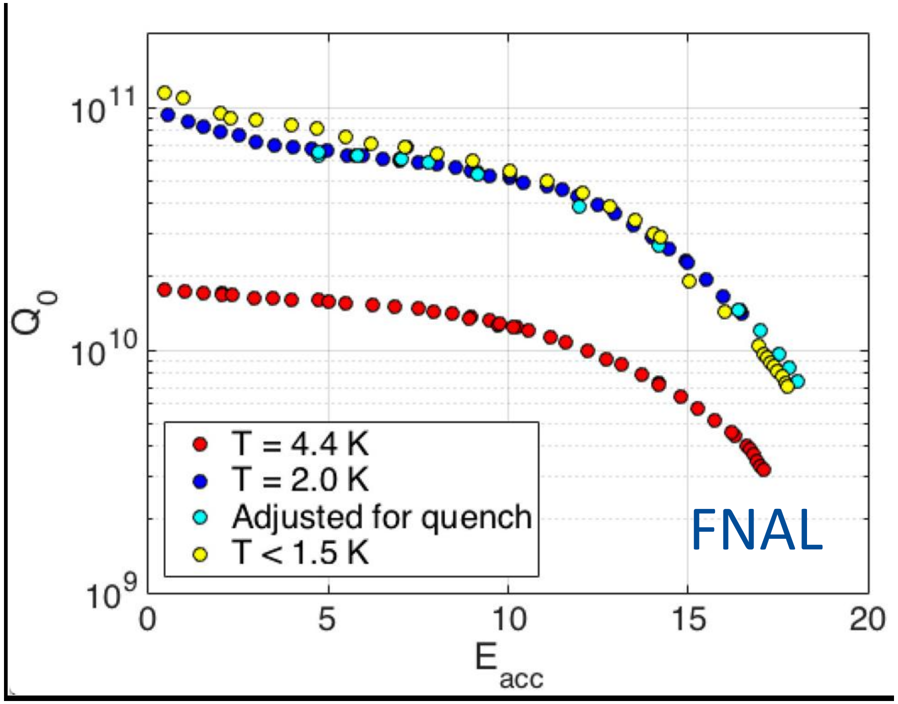


➢ See presentations in SRF1,2,3 Thursday

North American region ILC-related R&D: Nb3Sn

Nb3Sn coated niobium cavities using vapor deposition

Cavities could be operated at higher temps, e.g., 4K, with cryo savings



S. Posen et al., doi:10.18429/JACoW-IPAC2018-WEPML016

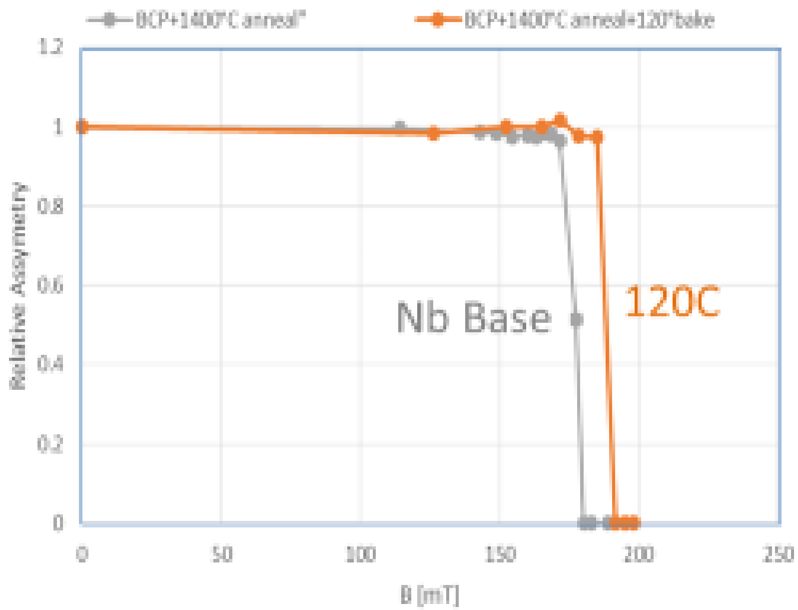
- See presentation in SRF Thursday

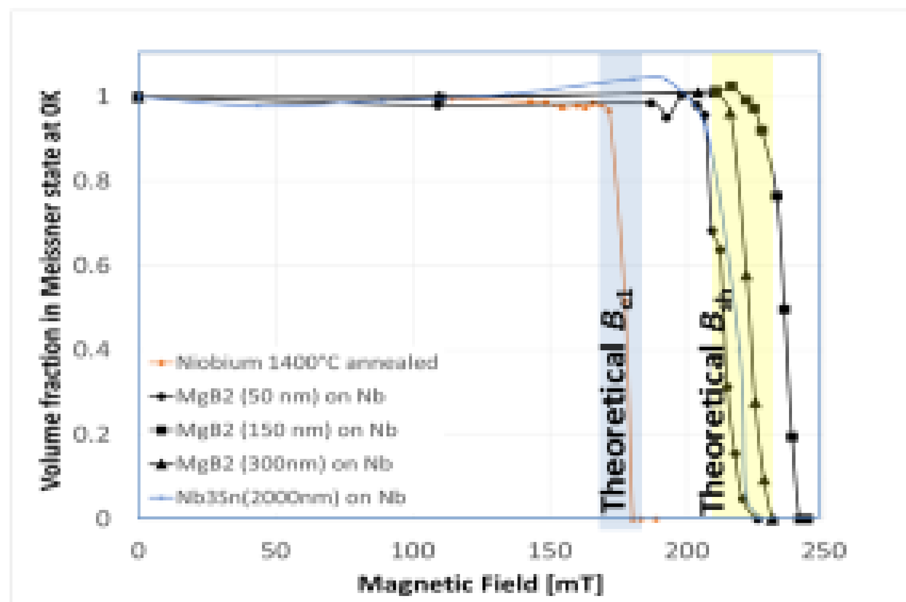
North American region ILC-related R&D

TRIUMF — Flux entry on layered system

muSR Findings (TRIUMF): *Baking at 120C (high K) enhances the field of first flux entry; A layer of a high K and Tc material on niobium enhances the field of first entry by about 40% .*

- Consistent with `dirty layer' hypothesis.

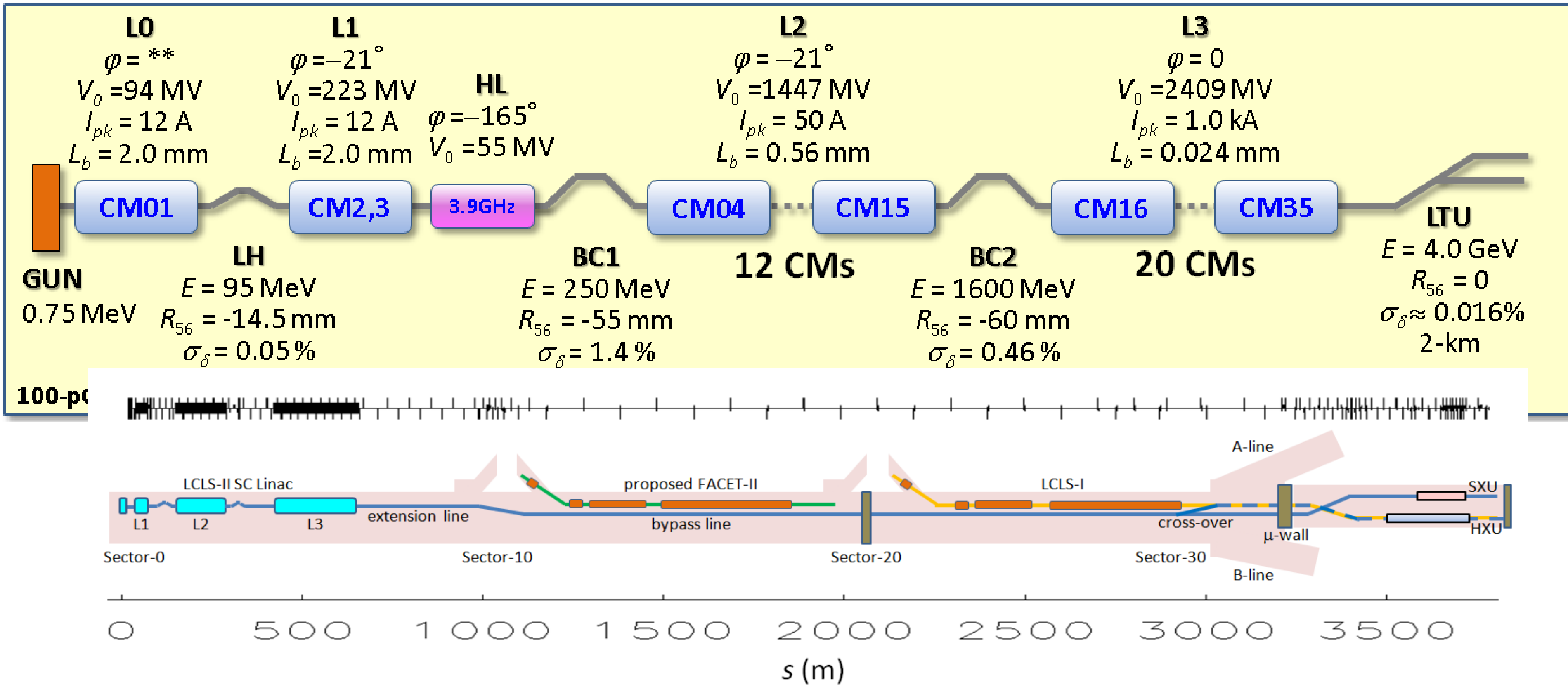




T. Junginger, R. Laxdal, W. Wasserman, *Superheating in coated niobium*, SUST, DOI: 10.1088/1361-6668/aa8e3a, 2017

4

LCLS-II



– Light source located at SLAC; an upgrade to the existing LCLS-I
  - Adds two new X-ray laser beams and space for additional new instruments, greatly increasing the number of experiments
– 4 GeV superconducting CW electron linac based on EuXFEL/ILC SRF
– 35 1.3 GHz cryomodules; 2 3.9 GHz cryomodules
– From the technology perspective, a 1/30 scale model for ILC linac

LCLS-II project collaboration for cryogenic systems

Fermilab

- Cryomodule engineering/design
- 50% 1.3 GHz, 100% 3.9 GHz cryomodules
- Cryogenic distribution system
- High Q0 (FNAL-invented N2 gas doping)

Jefferson Lab – EXPLORING THE NATURE OF MATTER

- 50% of cryomodules: 1.3 GHz
- Cryoplant selection/design
- High Q0

Argonne NATIONAL LABORATORY

- FNAL/ANL SCRF cleaning facility
- Cryomodule design support

CORNELL UNIVERSITY FOUNDED A.D. 1865

- High Q0

LCLS-II fast timescale with funding agency (DOE)

Level 1 Baseline Milestones	Schedule
CD-0 - Approve Mission Need	4/22/2010 (Actual)
Mission Need Statement (Update)	9/27/2013 (Actual)
CD-1 - Approve Alt. Select. & Cost Range	10/14/2011 (Actual)
CD-3a(1) - Approve Long Lead Procurement (LLP)	3/14/2012 (Actual)
CD-1 - Approve Alt. Select. & Cost Range (Update)	8/26/2014 (Actual)
Advanced Procurement of Niobium Material	8/26/2014 (Actual)
CD-3b(2)- Approve LLP	5/28/2015 (Actual)
CD-2 – Approve Performance Baseline	**3/21/2016(Actual)**
CD-3 – Approve Construction Start	**3/21/2016(Actual)**
CD-4 - Project Complete/Start of Operations	**June 30 2022**

In less than a year, from September 2013 until August 2014, project developed an initial scope, schedule and budget for CD-1 review

LCLS-II cryomodule design and production model

- Use existing designs and procedures to the extent possible to optimize cost and schedule
  - LCLS-II SRF linac closely based on *TESLA / ILC / EuXFEL* design
  - Under development ~20 years with *> 1000 1.3 GHz cavities* fabricated and tested (>800 for EuXFEL)
  - ➢ Just add CW operation! And High Q0 cavities!
- FNAL responsible for LCLS-II CM design, working closely with JLab & SLAC
- FNAL/JLab split CM assembly, and test prior to shipment
  - Equivalent processes
  - Approximately one CM complete every 4 weeks at each lab

➢ Cooperation & assistance from EuXFEL necessary to realize design, production and test of LCLS-II CM's

- ➢ DESY, CEA Saclay, CNRS Orsay, INFN Milan/LASA

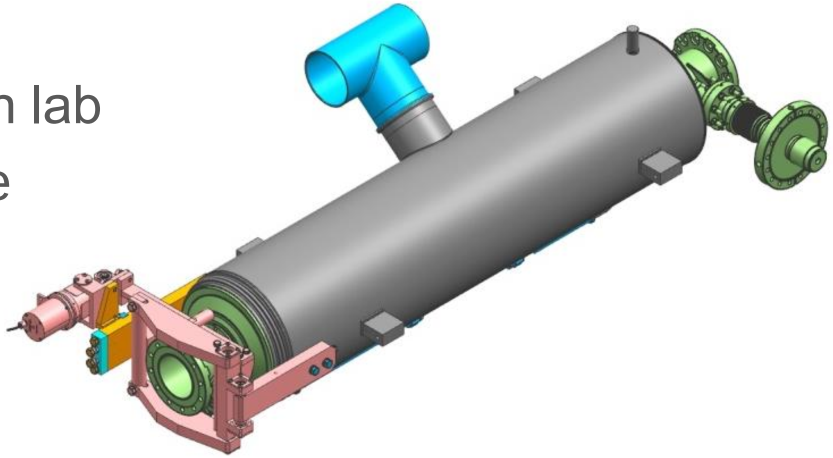
LCLS-II CM strategy: one design, two production lines

- **Identical CM 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
- **Two Identical Fast 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 Parts Received** at FNAL and JLab
  - 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
  - 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

LCLS-II prototype 1.3 GHz CM's – design verification

- Purpose of prototypes
  - Test out the design modifications as soon as possible
  - Prove out the JLab infrastructure modifications
  - Develop procedures and travelers, train staff, etc.
- Build two prototype cryomodules, one each at FNAL and JLab
  - Use 16 existing FNAL ILC 9-cell short-short cavities (beam tube lengths)
    - Built by Advanced Energy Systems, Inc
  - Adapt XFEL-style end-lever tuner to short-shorts, and to permit access through ports
  - Otherwise same design as production cryomodules
- Prototype CM's will go in the beamline and must
- perform to specification
- Prototype CM's have been tested at each lab
- No prototype for the 3.9 GHz cryomodule



LCLS-II cryomodule procurement model

Procurement Responsibility Summary			
Component	**FNAL**	**JLAB**	**SLAC**
Niobium	√		
Cavities		√	
HOM/FP Feedthroughs		√	
Cavity Flange Hardware		√	
Helium Vessels		√	
FPC			√
Cavity String Bellows		√	
Cavity String Hardware	√		
Magnet	√		
BPM	√		
HOM Absorber		√	
Gate Valve		√	
2-Phase Pipe Bellows	√		
End Lever Tuner		√	
Magnetic Shielding	√		
GRHP Sub-assembly	√		
Vacuum Vessel	√		
Instrumentation	√		

Procurements split ~between FNAL/JLab

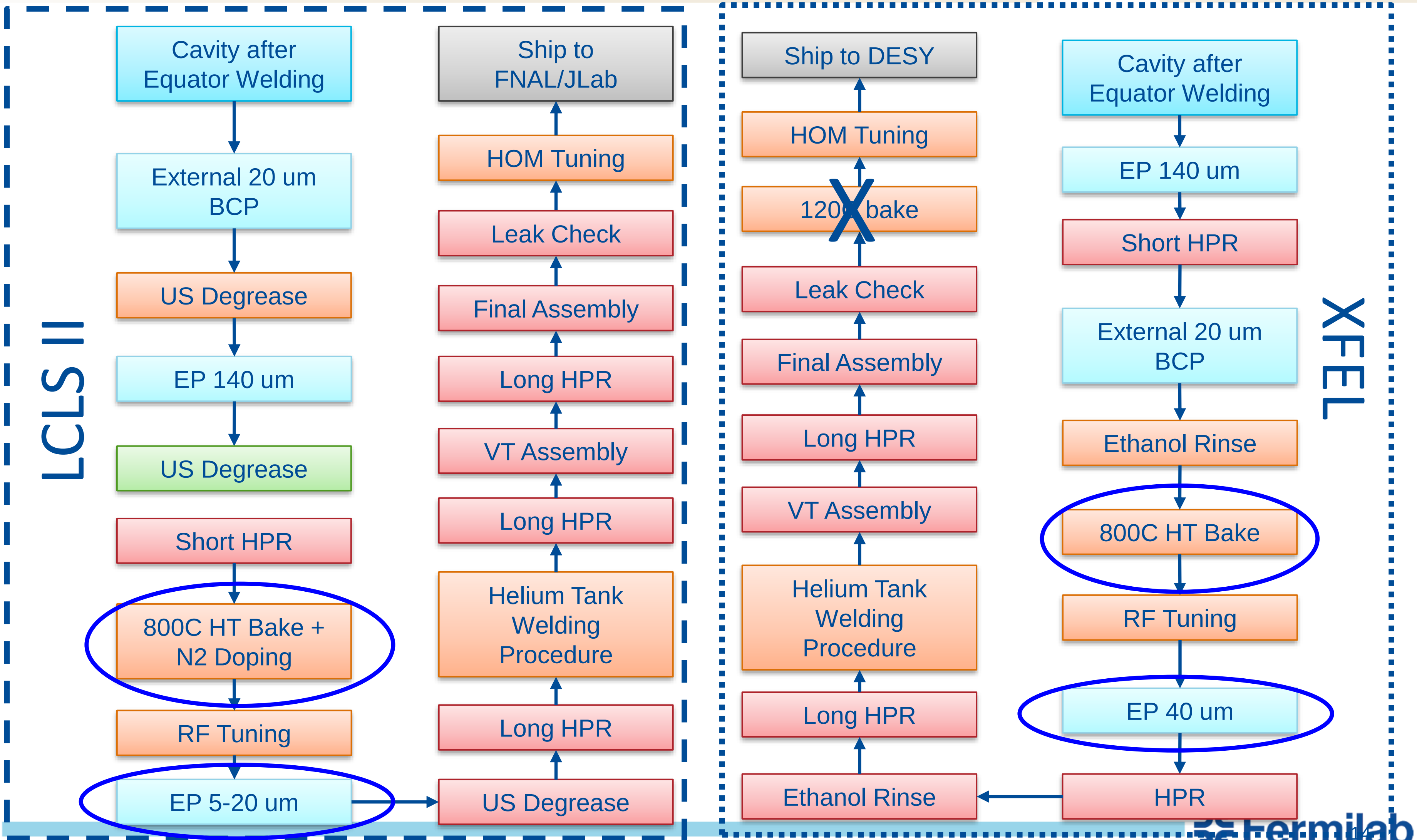
Half of each sent to each lab for CM assy

Example:
FNAL responsible for cavity materials incl QC

JLab responsible for cavity fabrication

LCLS-II vs. EuXFEL industrial cavity processing recipes

Initially expected to be an incremental change to XFEL



Fermilab

LCLS-II industrialization of nitrogen doping (1/2)

- Nitrogen doping discovered in 2013 at FNAL; factor of two or more improvement in Q0 at, e.g., 16 MV/m
  - Effect was well established on single-cell cavities
  - Grassellino et al., SUST 26 (102001) (2013) [Aug 2013]
- Dec 2013 at Director's CD-1 review, LCLS-II project decision to industrialize nitrogen doping as project baseline for cryo cost savings
- Oct 2014 cavity materials contracts placed
- Mar-Sep 2015 Nb sheet material arrives at DESY for QC
- Jun-Nov 2015 Phase I Cavity vendor qualification of nitrogen doping
- Nov 2015 – Jun 2016 Phase II Cavity vendor first articles, followed by full production
- Dec 2015 R&D study shown at the DOE review indicates that different sheet material may expel flux differently, based on different vendor fabrication, and therefore have an intrinsically better or worse cavity Q0
  - First indications of this problem: Posen et al., SRF 2015, MOPB104 [Sep 2015]

LCLS-II industrialization of nitrogen doping (2/2)

- Jun 2016 Flux trapping identified as a major issue on production cavities
  - Nb sheet variability meant that previous vendor qualification tests were not sufficient to determine cavity performance based on cavity surface treatment
  - All Nb sheets delivered to vendors passed DESY QC
  - Production quality was even better than for EuXFEL
- Jul-Dec 2016 Modifications to heat treatment temperatures started, cavity performance showed variability depending on Nb sheet vendor/lot
- Oct 2016-Jun 2017 Development of surface treatment recipes for different Nb sheet vendor/lot
- Jan 2019 Final cavity delivery

Gonnella et al., NIMA833 (2018) 143-150

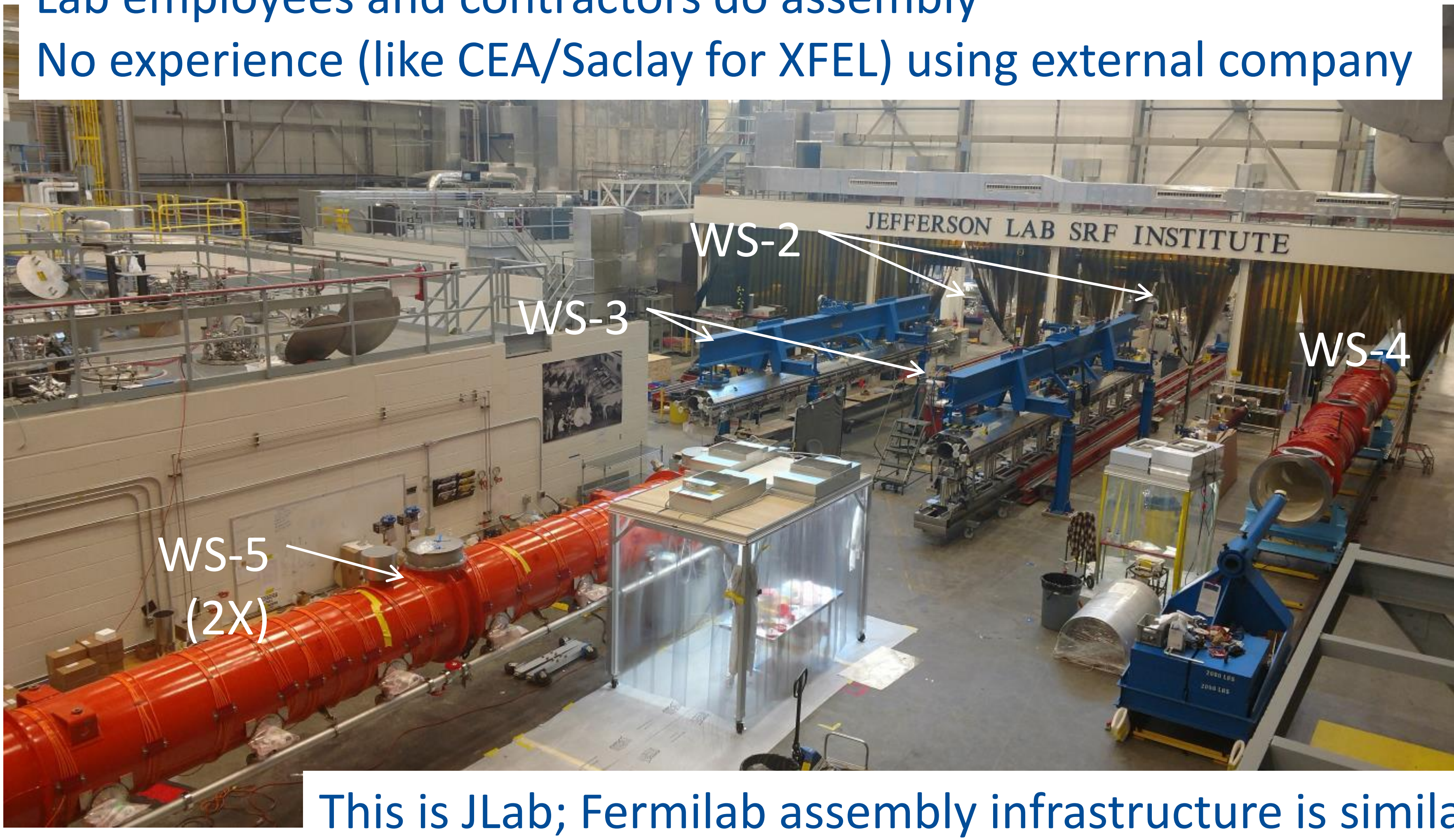
LCLS-II lessons learned for high-Q0 cavity operation

- We can only wreck performance relative to a good vertical test Q0 in zero H field
- Every nano-Ohm of residual resistance matters
- Fast cooldown - reduce Rs from thermal currents
- Minimizing “trapped magnetic flux” is the requirement rather than low “remanent magnetic field” to optimize cavity performance
- Some Nb sheet material traps flux more – no new spec yet
- Magnetic shielding - reduce Rs from trapped flux
  - Use Metglass to cover any gaps, a labor-intensive effort
- Magnetic hygiene
  - Avoid magnetic components if possible => cost & schedule
  - Demagnetize even 316L steel, a labor-intensive effort

LCLS-II cryomodule assembly

Lab employees and contractors do assembly

No experience (like CEA/Saclay for XFEL) using external company



This is JLab; Fermilab assembly infrastructure is similar

FNAL Prototype 1.3 GHz CM Performance

	pCM after RF_Conditioning			
Cavity	Max Gradient**	Usable Gradient* [MV/m]	FE onset [MV/m]	Q0 @16MV/m 2K
TB9AES021	21.2	18.2	14.6	2.6E+10
TB9AES019	19	18.8	15.6	3.1E+10
TB9AES026	19.8	19.8	19.8	3.6E+10
TB9AES024	21	20.5	21	3.1E+10
TB9AES028	14.9	14.2	13.9	2.6E+10***
TB9AES016	17.1	16.9	14.5	3.3E+10
TB9AES022	20	19.4	12.7	3.3E+10
TB9AES027	20	17.5	20	2.3E+10
Average	**19.1**	**18.2**	**16.5**	**3.0E+10**
Total Voltage	**153**	**145.3**		

Acceptance = 128 MV

all results with cavities at 2 K

*Usable Gradient: demonstrated to stably run CW, FE < 50 mR/h, no dark current

**Also limited by administrative limit ~20MV/m

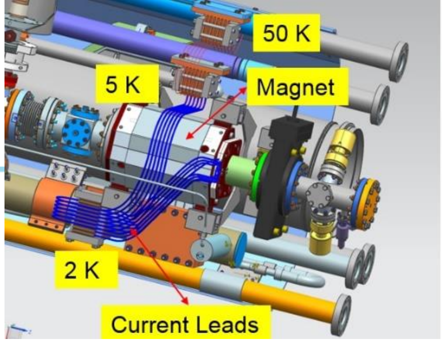
***Measured at 14 MV/m

JLab achieves similar results

SRF cavity manufacturing in North America

- Advanced Energy Systems was qualified to produce cavities of ILC performance requirement; went out of business in 2016
- Niowave, PAVAC, Roark are North American companies manufacturing SRF cavities for other projects
- Fermilab, JLab and Cornell worked with AES for about 5 years to reach ILC-needed quality, prior to current advances
  - This is intensive and NOT fast
  - 16 AES cavities procured for ILC R&D went into the first two cryomodules for LCLS-II, exceeding performance requirements
- Production cavity contracts for LCLS-II went to EZ and RI in Europe
  - These established EuXFEL vendors also had a learning curve for the new LCLS-II requirements, primarily surface preparation
- ILC realization requires substantial effort for cavity fabrication

LCLS-II procurement example: magnet



– Conduction-cooled split quad + dipole-corrector
– Issues with procurement
  • Only one subcontractor world-wide for the high purity aluminum thermal conductors for conduction cooling
  • No vendors offered to do the cold dunk acceptance test
– Magnet fabrication (vendor) complete
– Cold dunk acceptance testing (FNAL) complete – all qualified
  • High precision rotating coil test for field quality, iron and superconductor hysteresis effects, quadrupole and dipole correctors coupling
  • Develop operation procedures for degaussing and standardization for SLAC ops
– Conduction cooling tested in the CM test at CMTS –all qualified
– All magnets either installed in a cryomodule or tested and ready for installation at FNAL or JLab

Challenges of working on a cutting edge project

- Procurements are awarded before development complete
  - Build-to-print is not really build-to-print, because this is not really production yet
  - Costs increase, schedules extend
- Merrow et al., “Understanding the Outcomes of Mega-Projects: A Quantitative Analysis of Very Large Civilian Projects”
  - https://www.rand.org/pubs/reports/R3560.html
  - The schedule will slip by a factor 1.23, and costs increase by a factor 1.34, on average, for large projects built on new technology (new cavity surface treatments!)
  - Regulatory issues (import duties/tariffs! seismic requirements!) exacerbate the problem a factor 1.78 for each regulatory problem faced.

LCLS-II production procurement throughput constraints

Good LCLS-II experience with companies; more qualified companies and/or more throughput would have been helpful

- Cavities, cavity surface processing, clean assembly
- High power couplers
- Copper plating on stainless steel components
- Encapsulated piezos for fast cavity tuning
- High purity aluminum conduction cooling magnet leads
- High purity copper thermal braids for couplers, HOM's etc.
- Clean gate valves and right-angle valves

Conclusions

- R&D highly relevant to ILC is going on at several labs represented at this workshop: ANL, Cornell, FNAL, JLab, SLAC, TRIUMF
- ANL, BNL, FRIB/MSU, ORNL/SNS and several university partners are working on related SRF cavity/cryomodule projects and supporting cavity materials science, also directly or indirectly relevant to ILC
- LCLS-II is a good case study for ILC, with international partnerships and procurements, and smaller scale production cryomodule assembly and testing
- Interesting opportunities would exist for North American labs, universities, and companies for a Japanese ILC

Acknowledgements

I am grateful for discussions and contributions from:

Tug Arkan (FNAL), Ed Daly (JLab), Chuck Grimm (FNAL), Andrew Hutton (JLab), Bob Laxdal (TRIUMF),

Frank Marhauser (JLab), Sam Posen (FNAL),

Kenji Saito (FRIB/MSU), Rich Stanek (FNAL),

Katherine Wilson (JLab), Slava Yakovlev (FNAL)