LCLS-II

The LCLS-II SRF Linac

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

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

Outline

- Project Overview
  - Key Performance Parameters
  - Schedule & Status
- The SRF Linac
  - SRF Cavities
    - High Q_0 Recipe
    - Cavity test results
  - Cryomodule Assembly and Testing
    - JLab and FNAL prototype assembly
    - Initial Results from prototype testing.
- Conclusions

Project Collaboration: SLAC couldn't do this without…

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European XFEL

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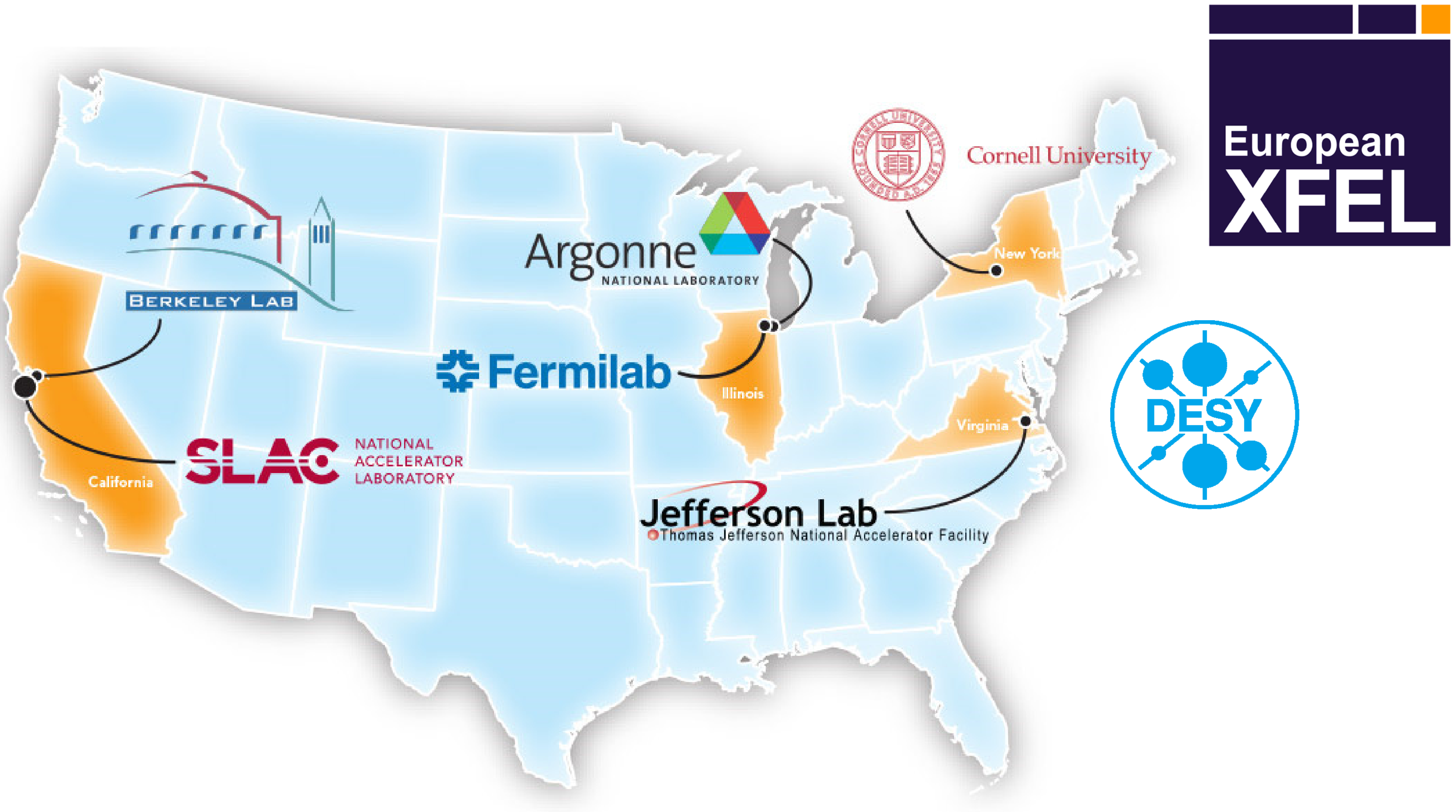

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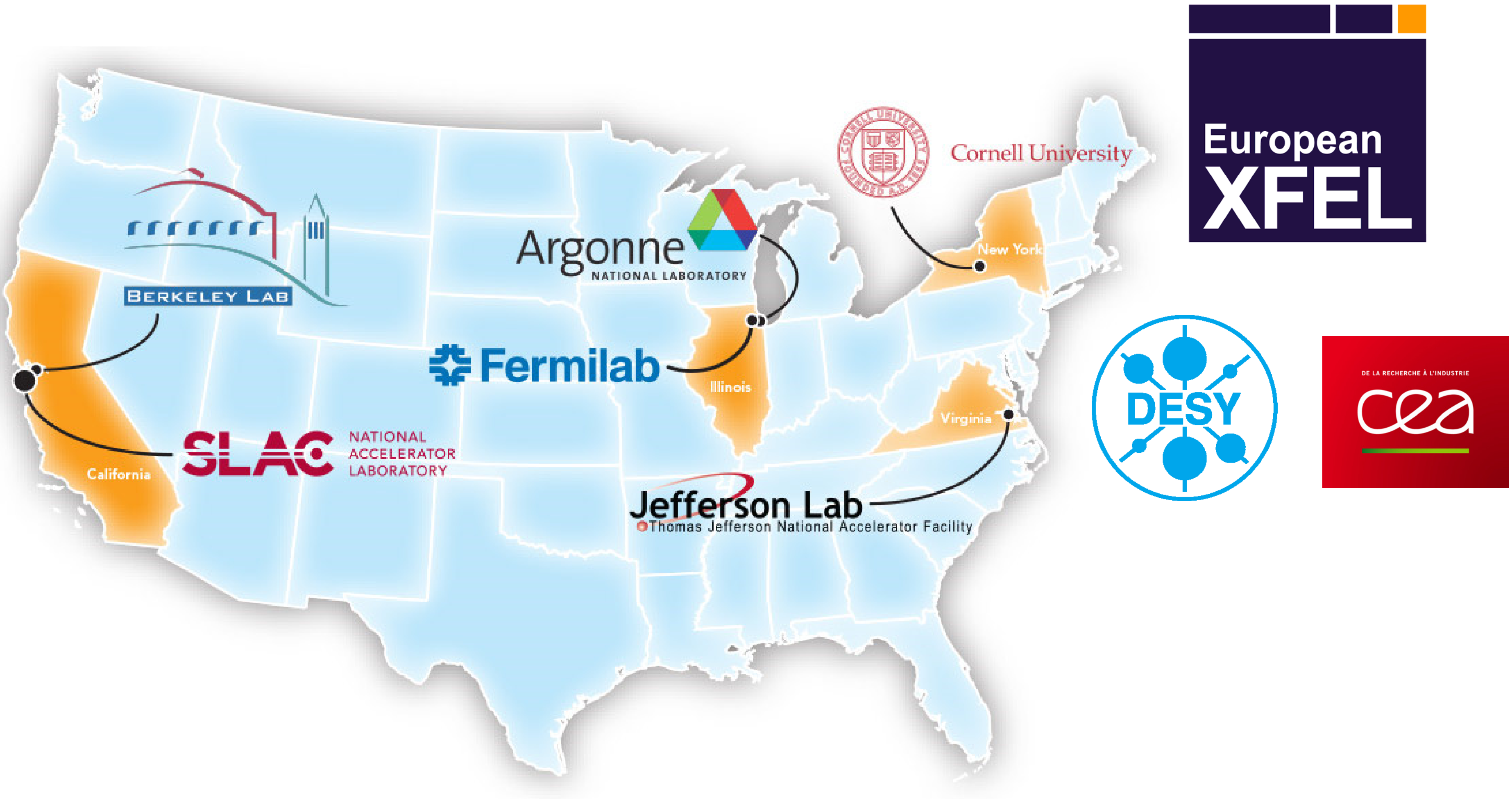

Project Collaboration: SLAC couldn't do this without…

European XFEL

DESY

DE LA RECHERCHE À L'INDUSTRIE
cea

LAL
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Collaborator Responsibilities

Fermilab

- Cryomodule engineering/design
- Manufacture 50% of cryomodules: 1.3 GHz
- Design and manufacture 2 Cryomodules: 3.9 GHz
- Design and acquisition of helium distribution
- Processing for high Q (FNAL-invented gas doping)

Jefferson Lab

- Manufacture 50% of cryomodules: 1.3 GHz
- Design and acquisition of two 4 kW Cryoplants
- Processing for high Q

Berkeley Lab

- Undulators
- e^- gun & associated injector systems

Argonne National Laboratory

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

Cornell University

- R&D planning, prototype support
- processing for high-Q (high Q gas doping)
- e^- gun option


LCLS-II


Remove SLAC
Linac from
Sectors 0-10
LCLS-II

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Two New Undulators And X-Ray Transport

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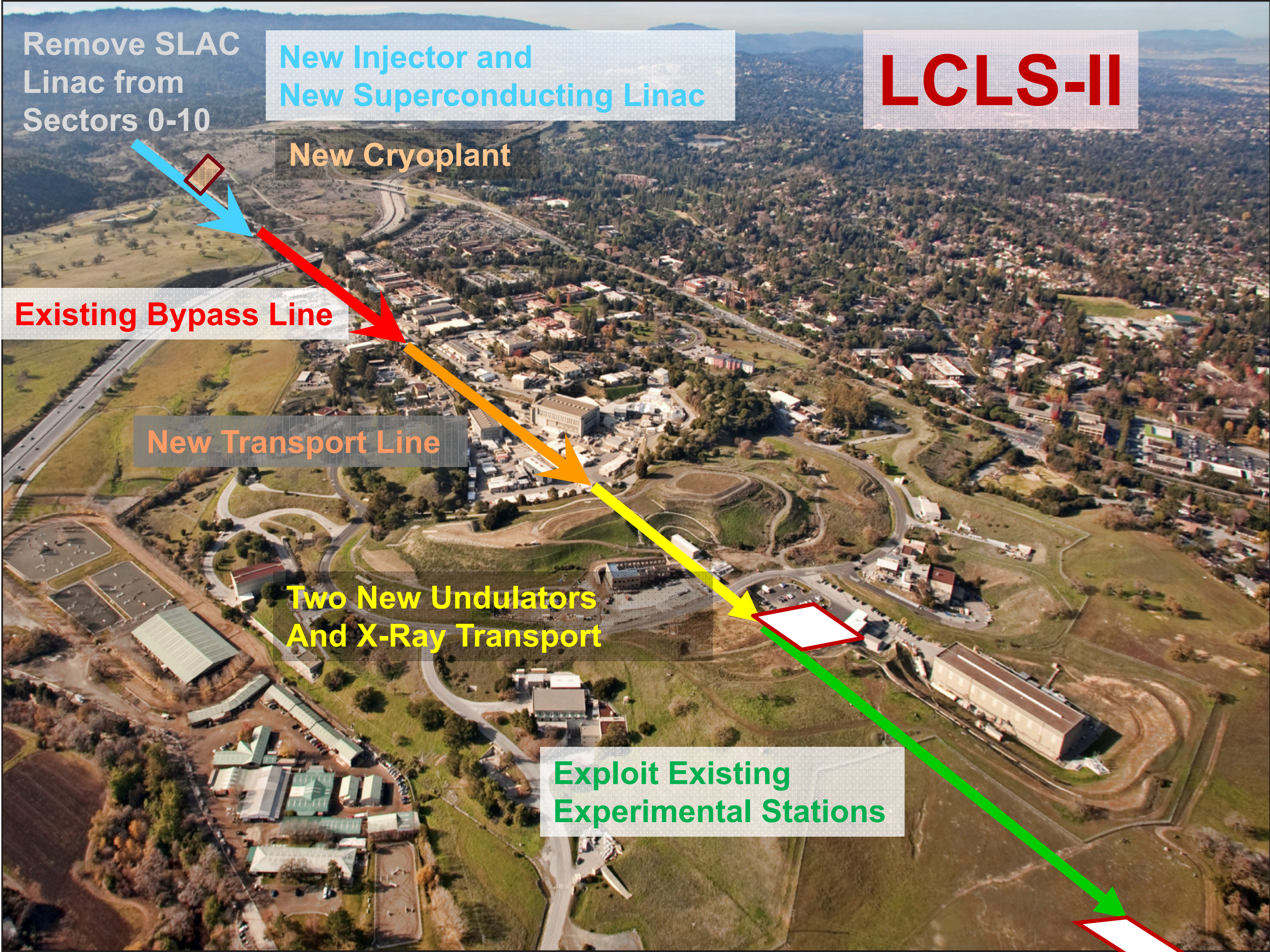
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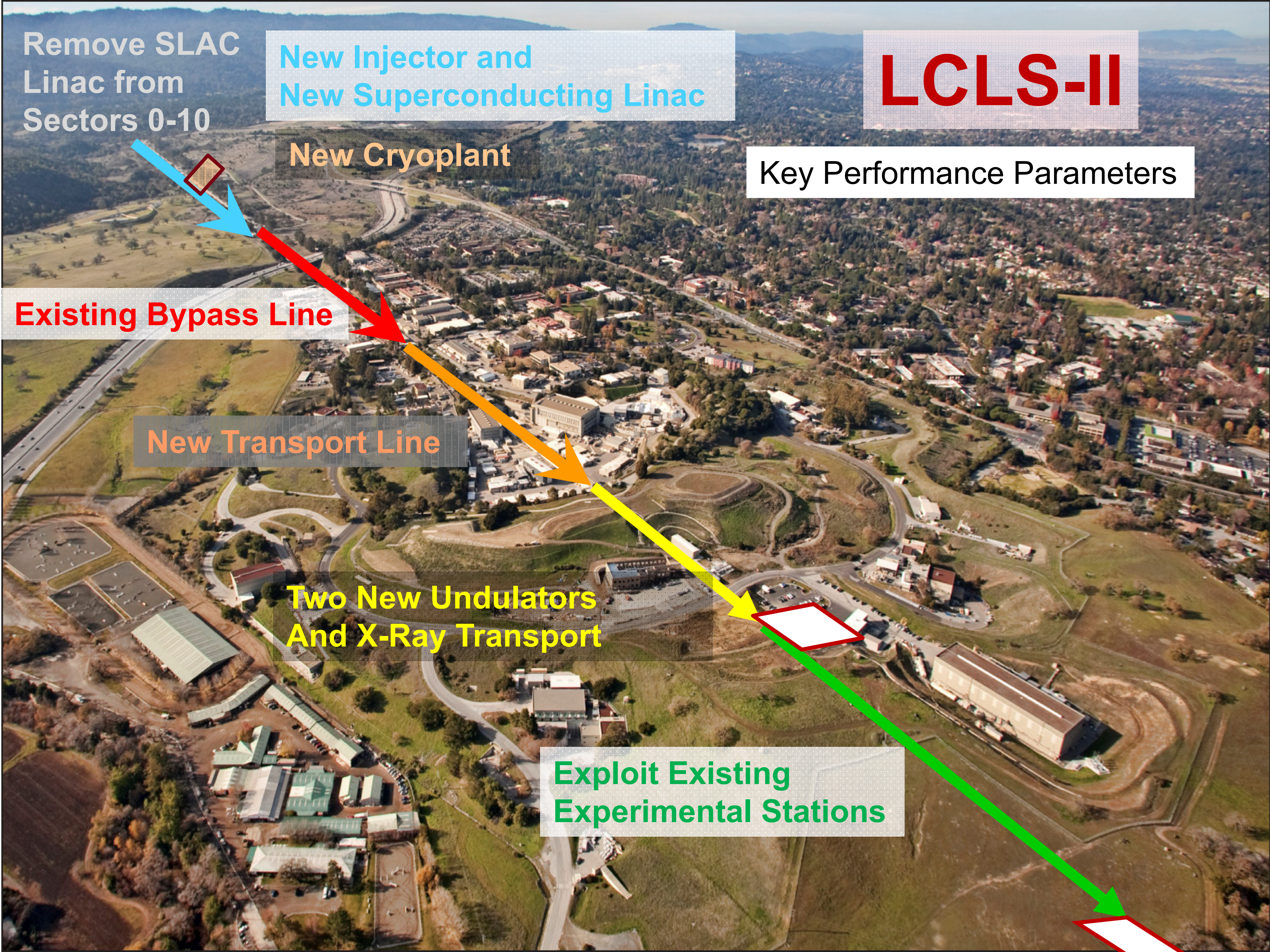
Experimental Stations


LCLS-II
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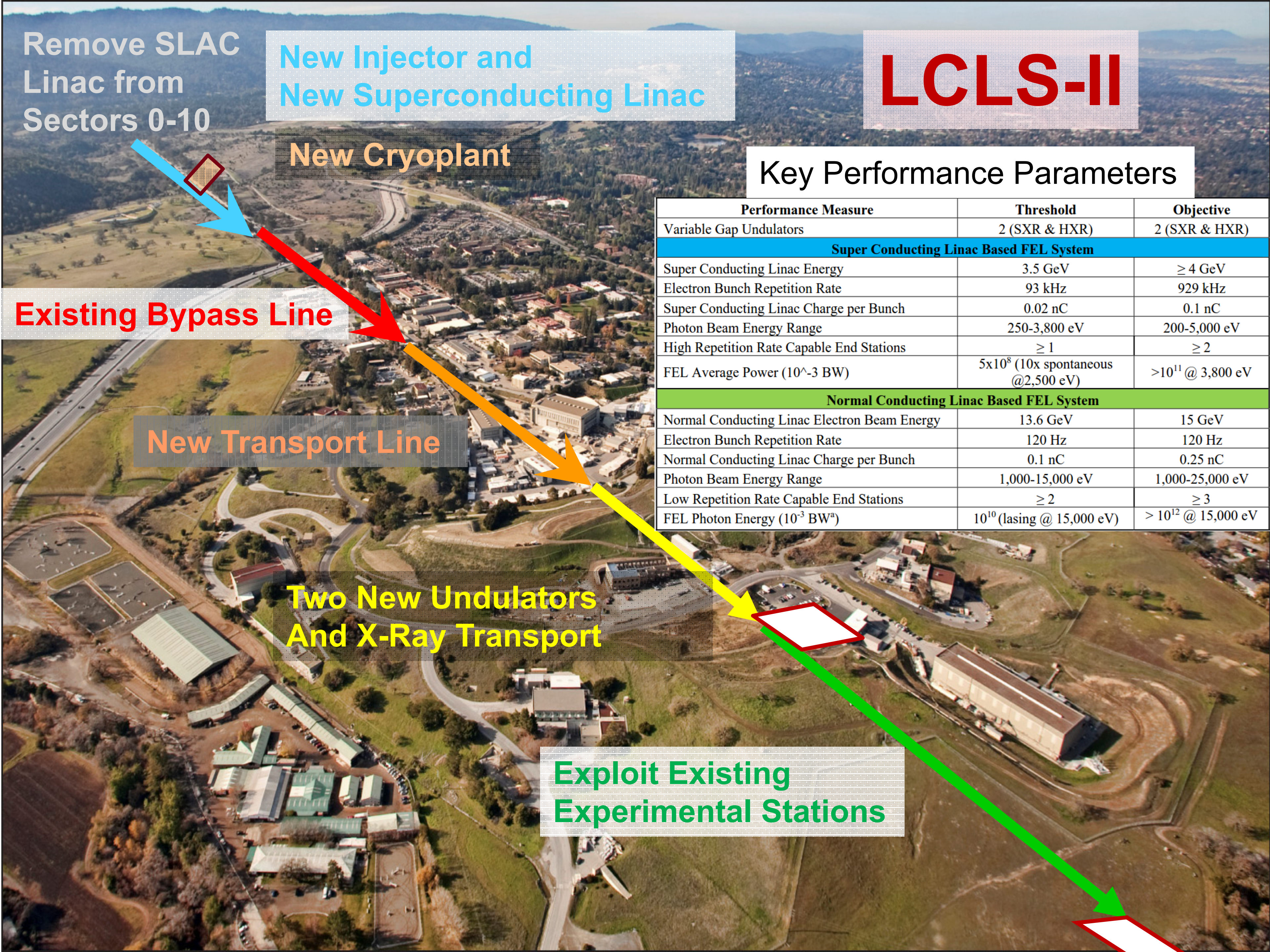
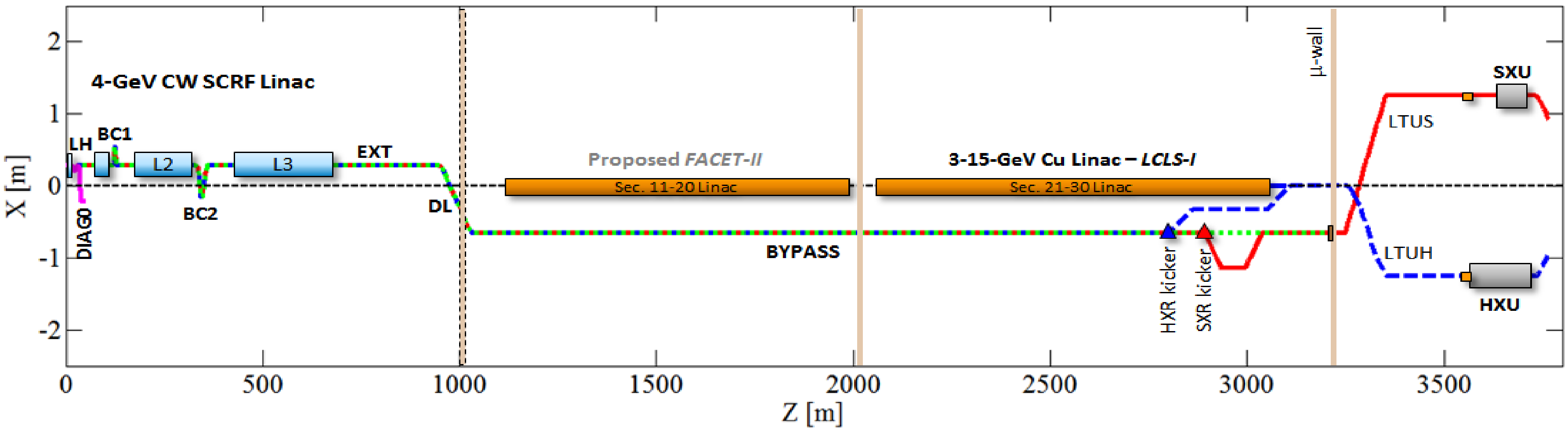
LCLS-II



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)	$5x10^8$ (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



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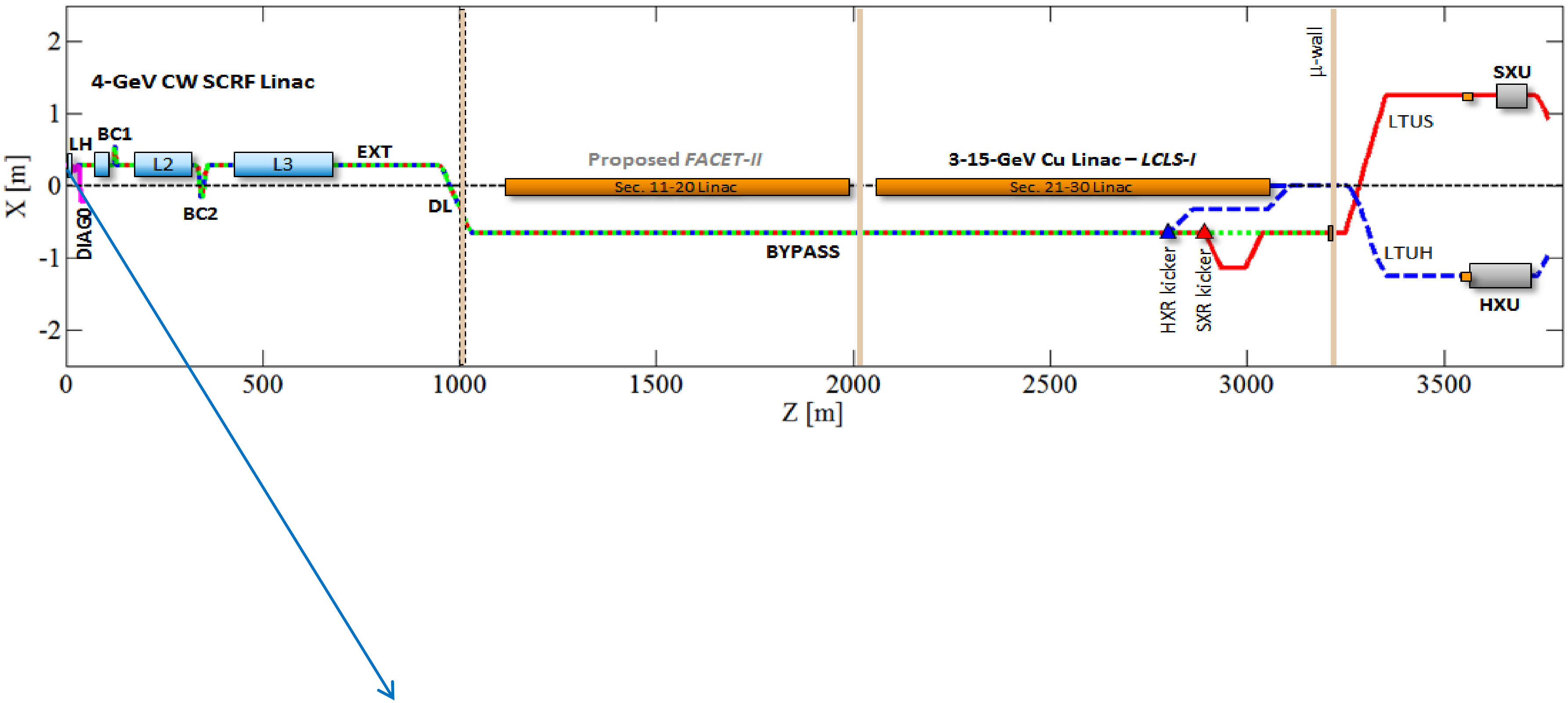

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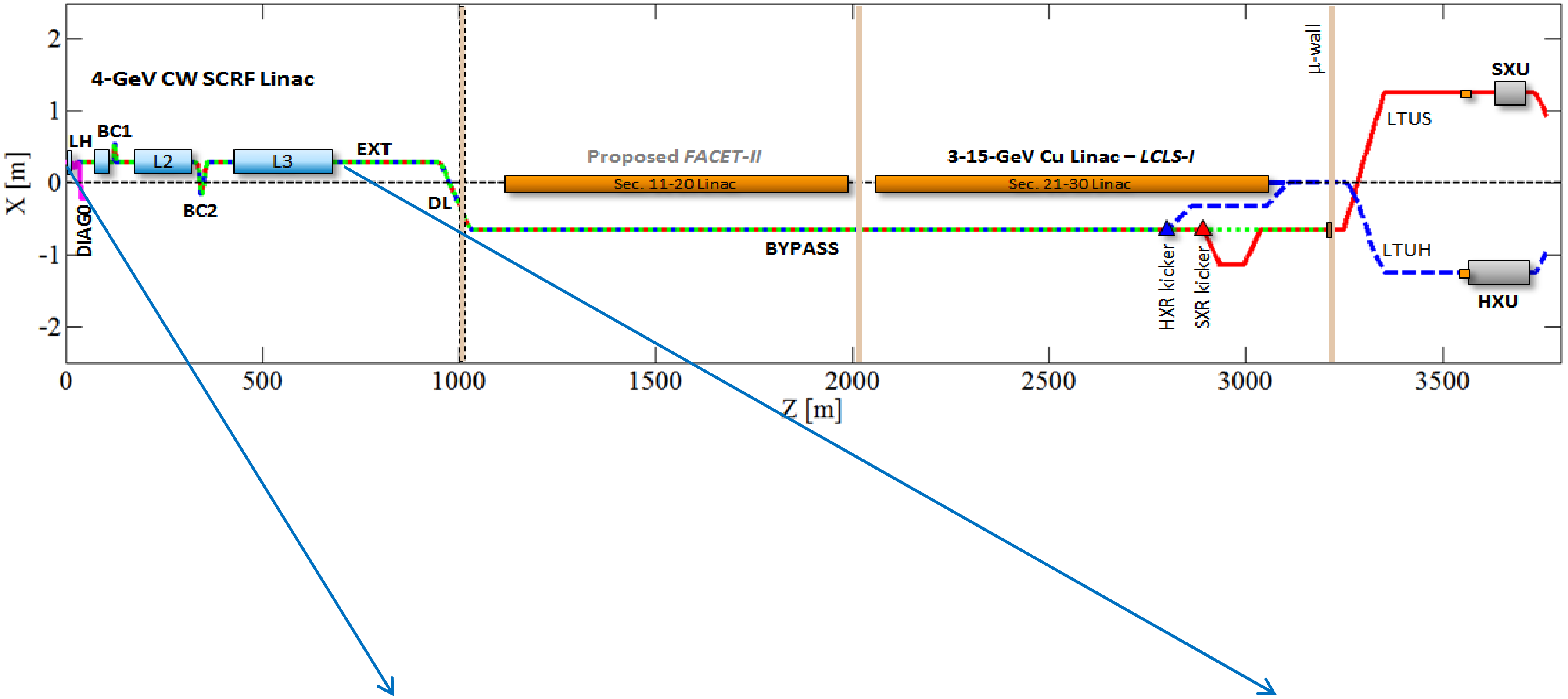

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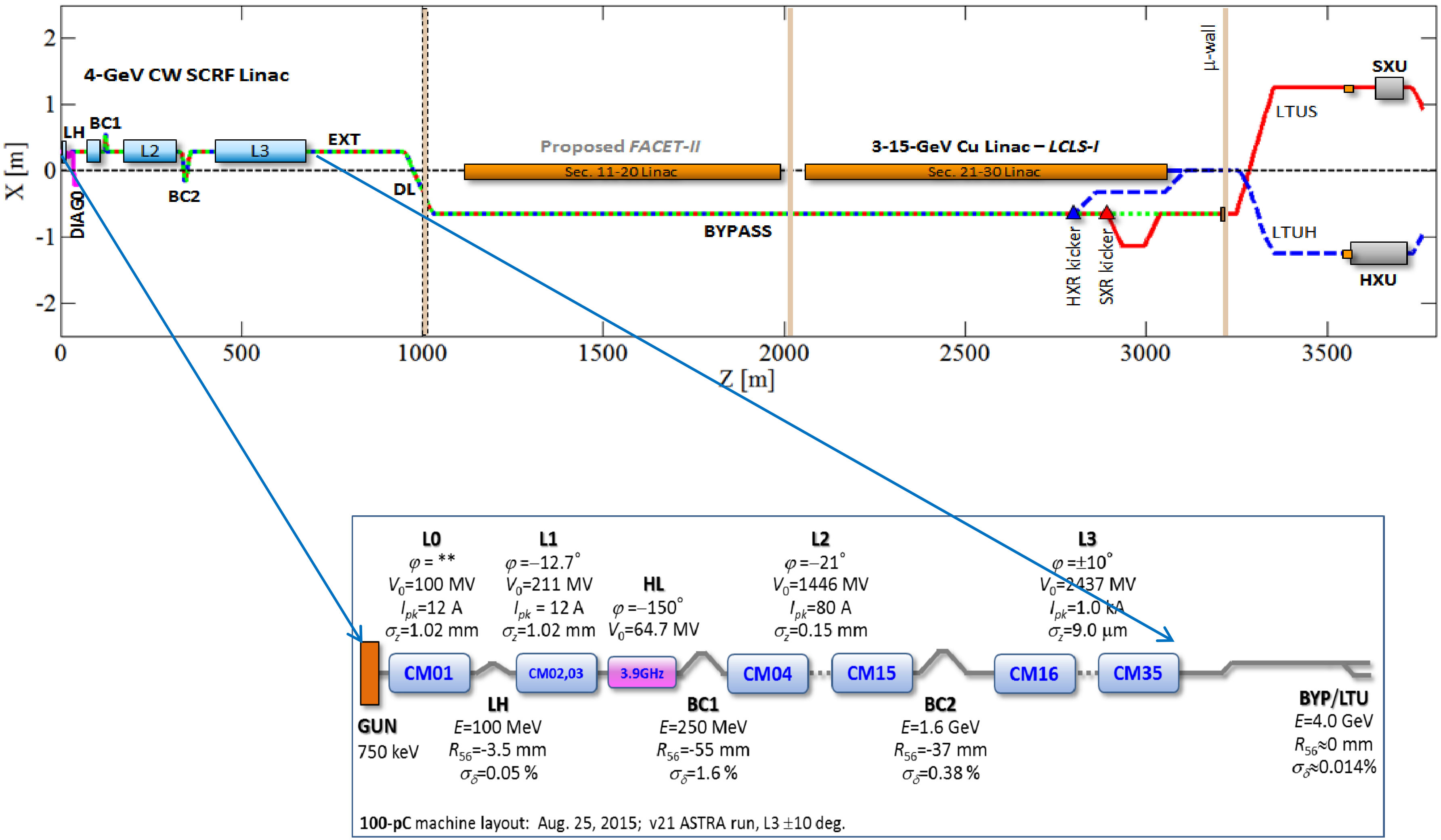

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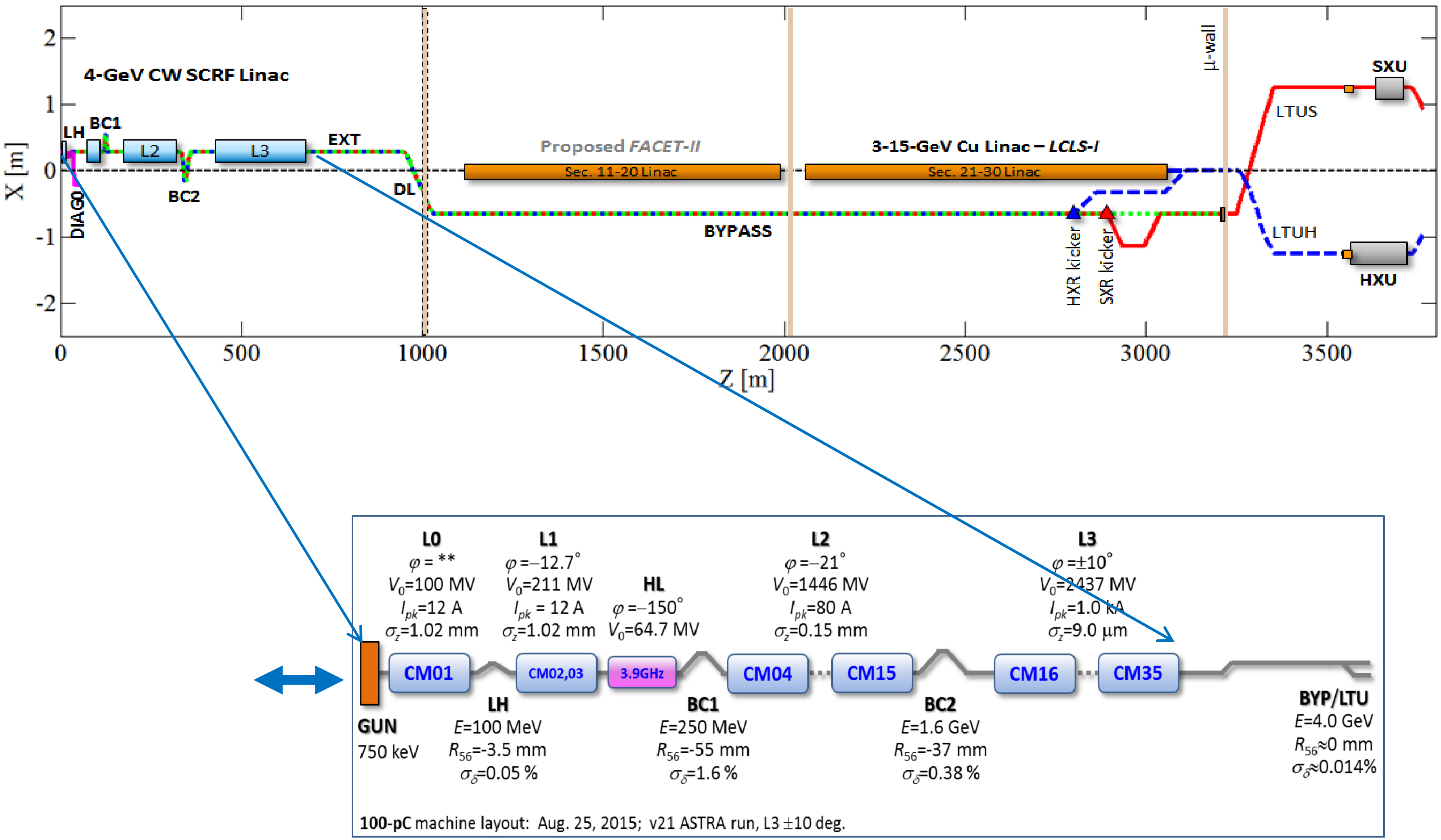

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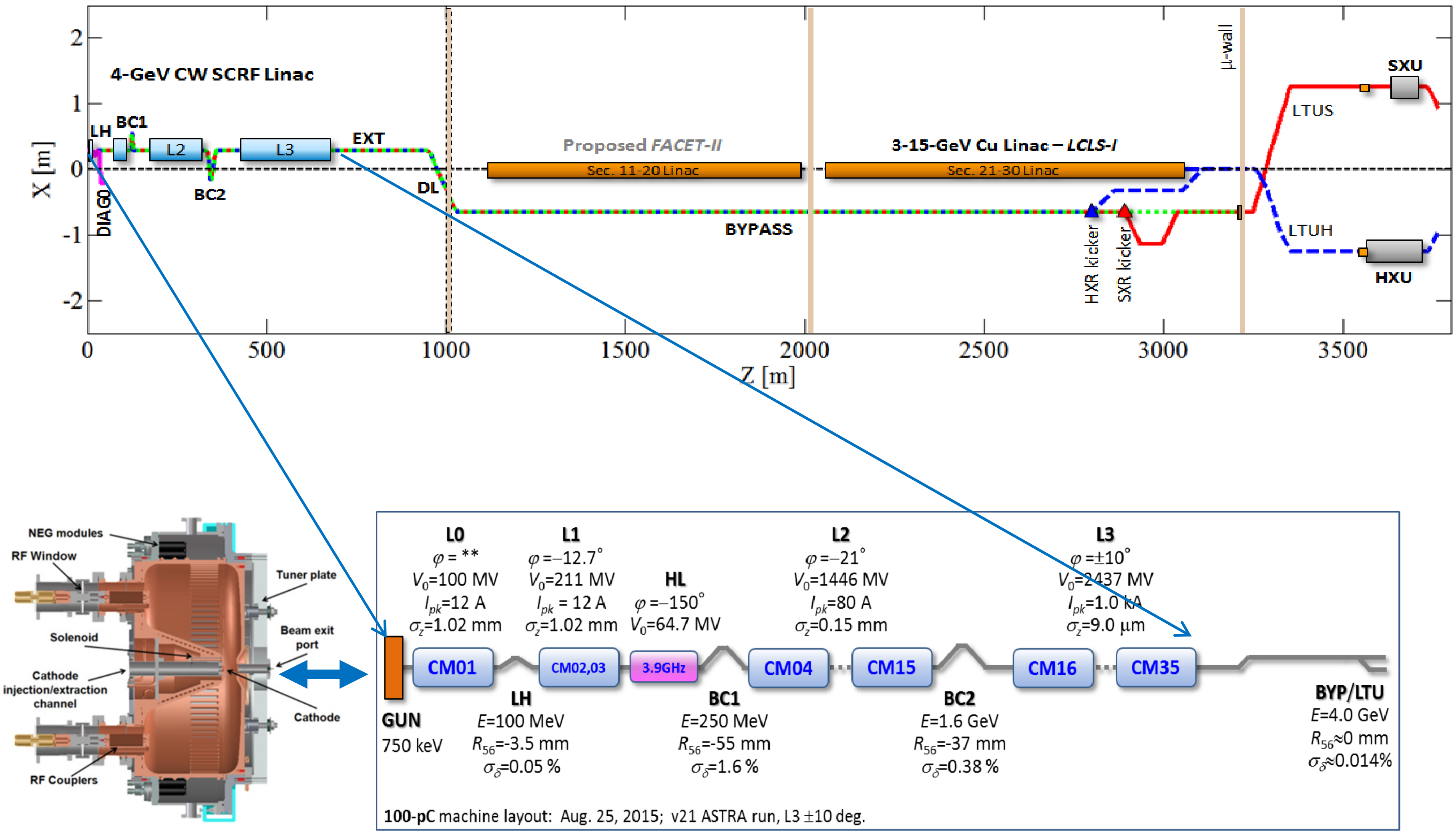
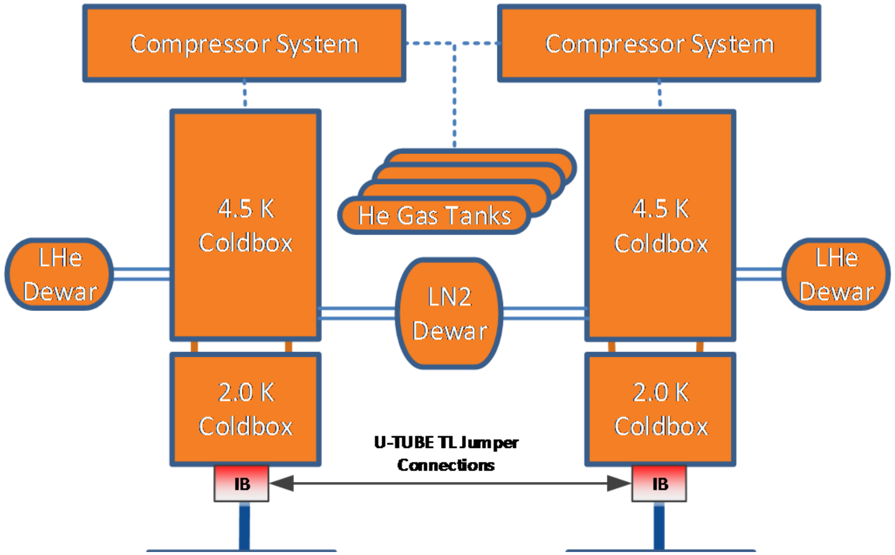
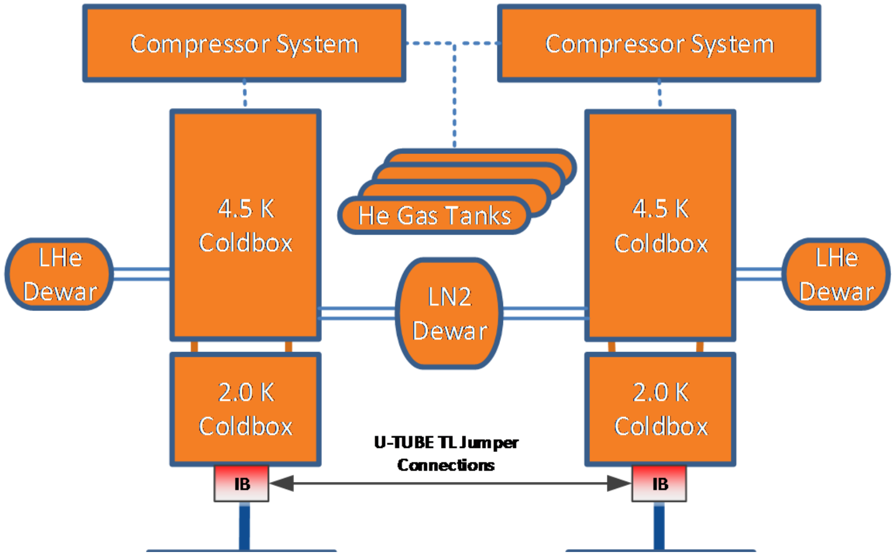


LCLS-II Cryogenic Systems overview:



LCLS-II Cryogenic Systems overview:

Temp Level	Heat Load
35K Shield	30.6 kW
5K Intercept	2.6 kW
2K	8 kW



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Total Cryogenic Capacity

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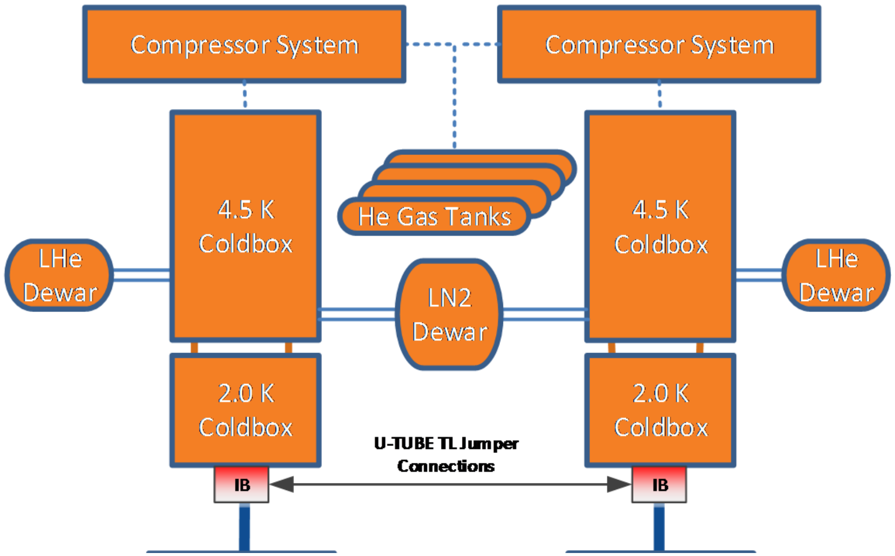

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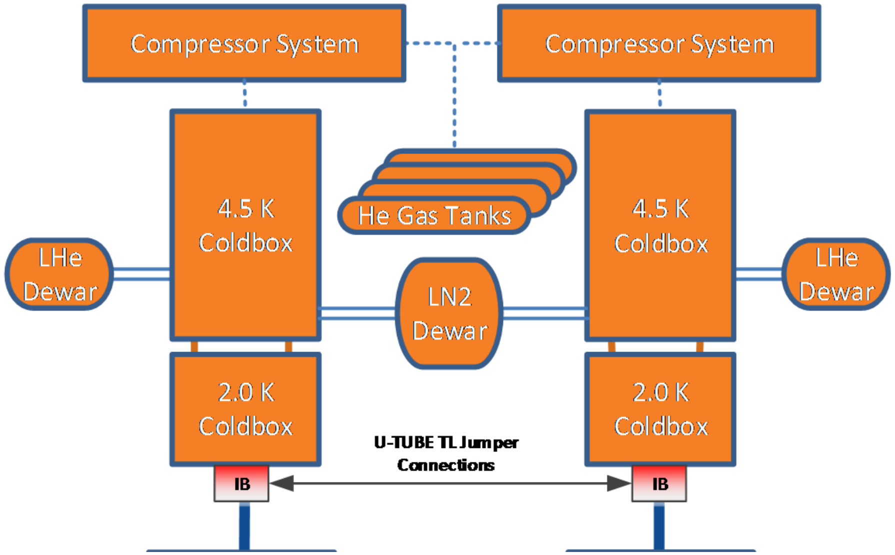


SRF Linac

- 35 – 1.3 GHz CMs
- 2 – 3.9 GHz CMs

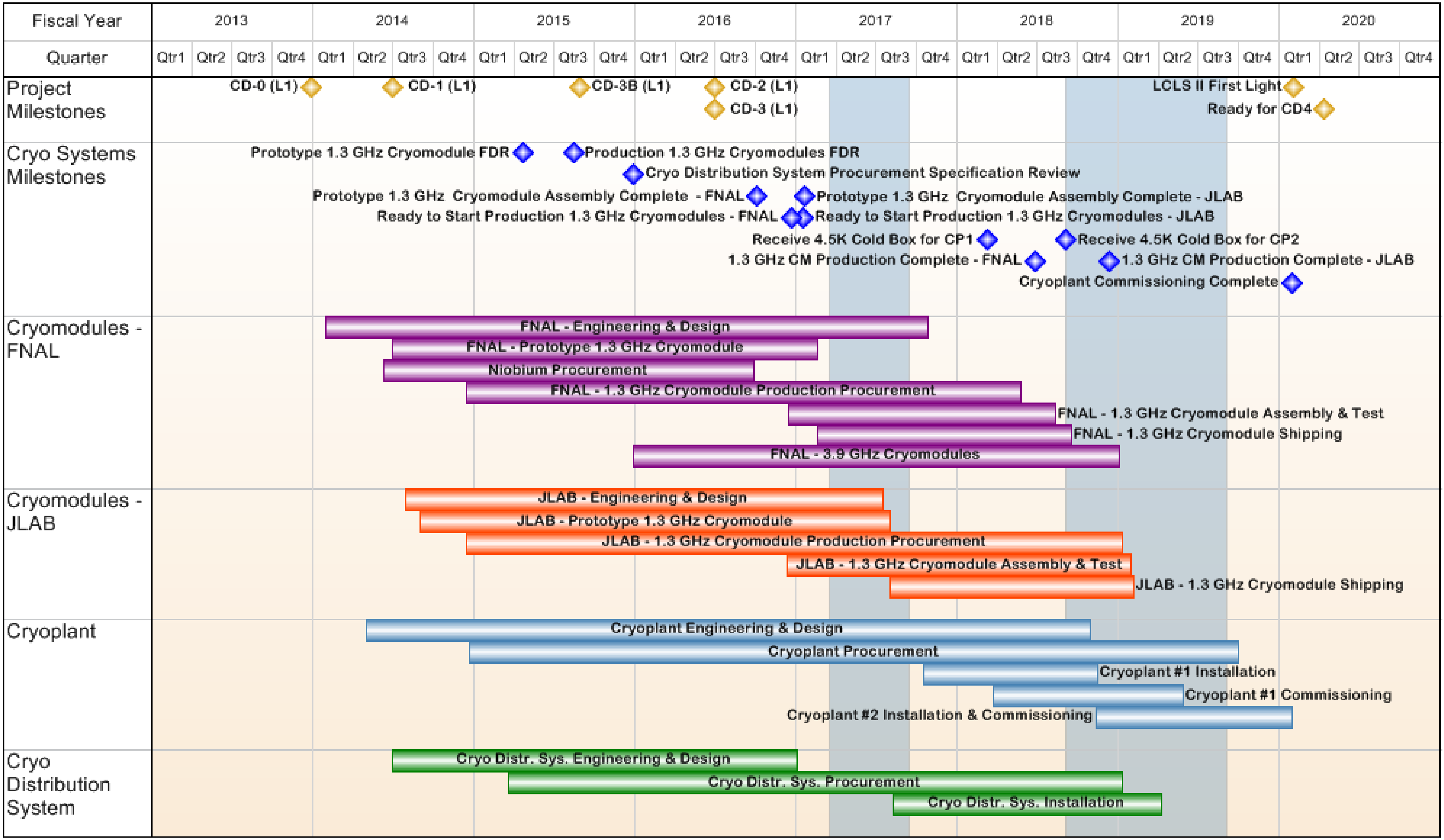
Design loads

35K – 15 kW

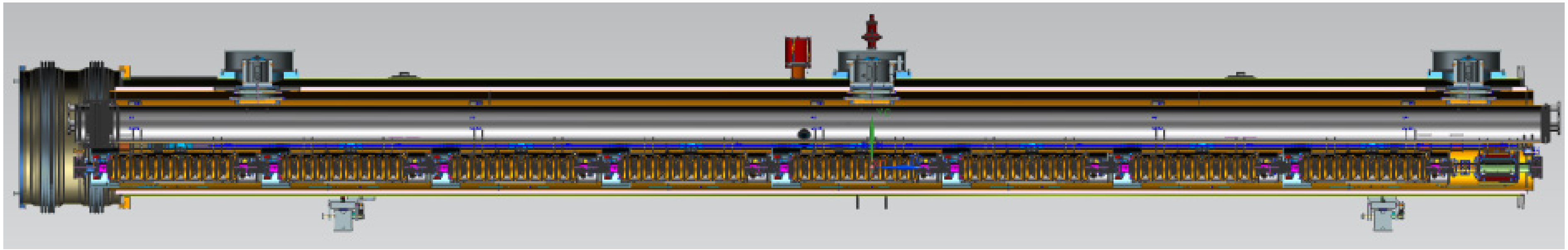
5K - 1.4 kW

2K - 3.7 kW

Cryogenic Systems - Summary Schedule



The 1.3 GHz Cryomodule



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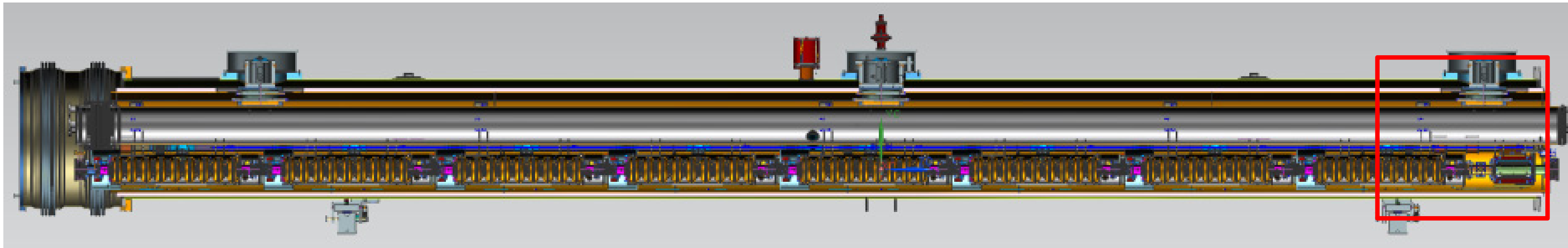

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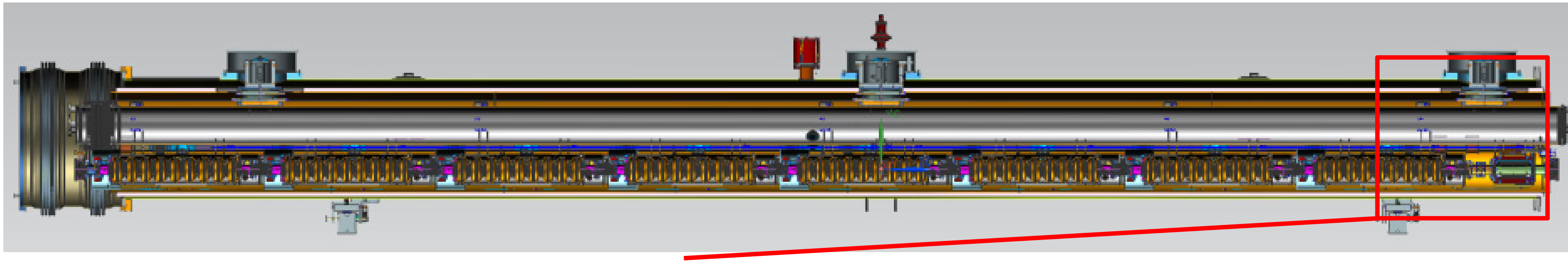

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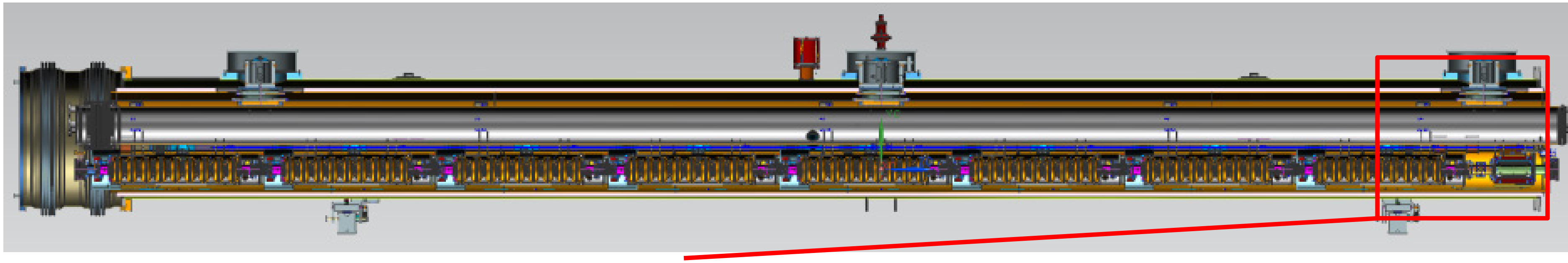

XFEL Style Cryomodule
8 – 1.3 GHz Tesla style cavities
1- Button beam position monitor
1- Conduction cooled quadrupole Magnet
5K Thermal Intercept (no 5K shield)
50K Intercept and Shield

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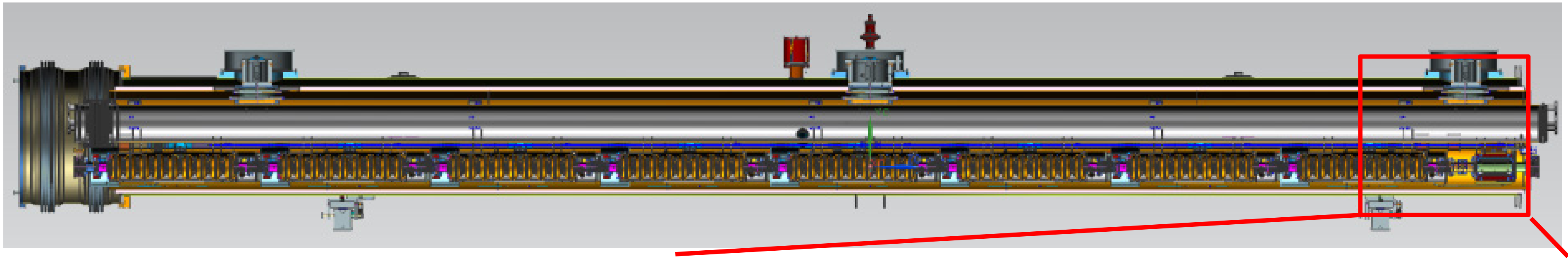

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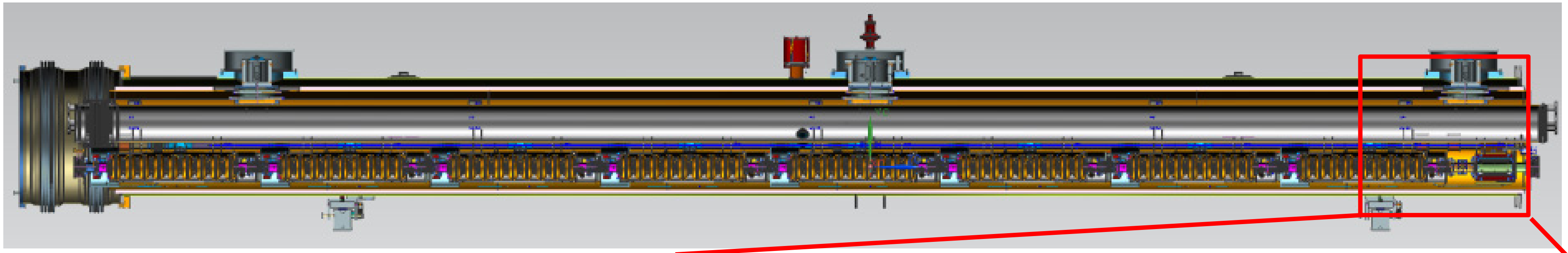

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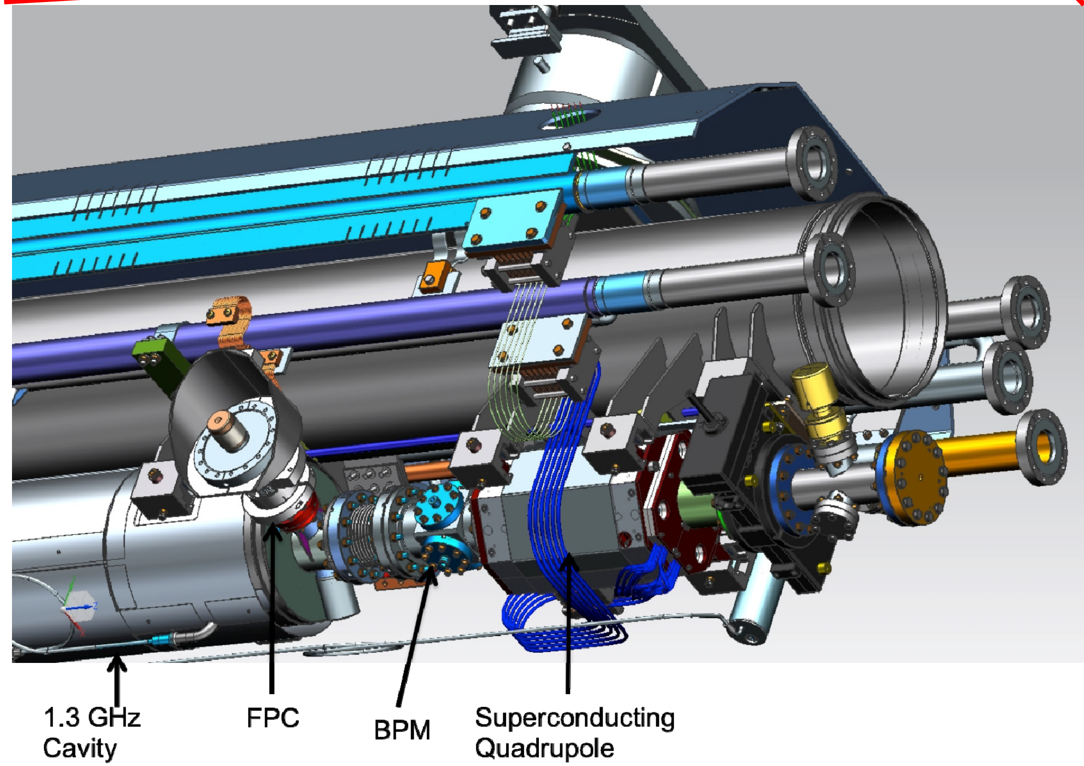

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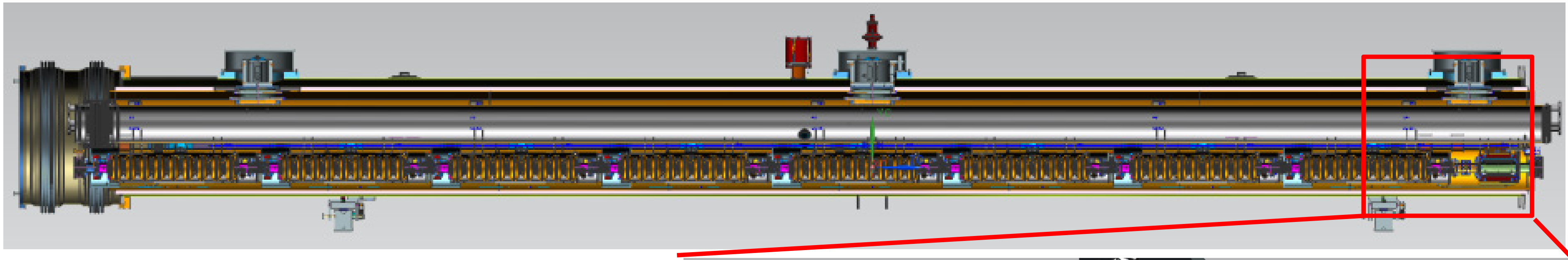

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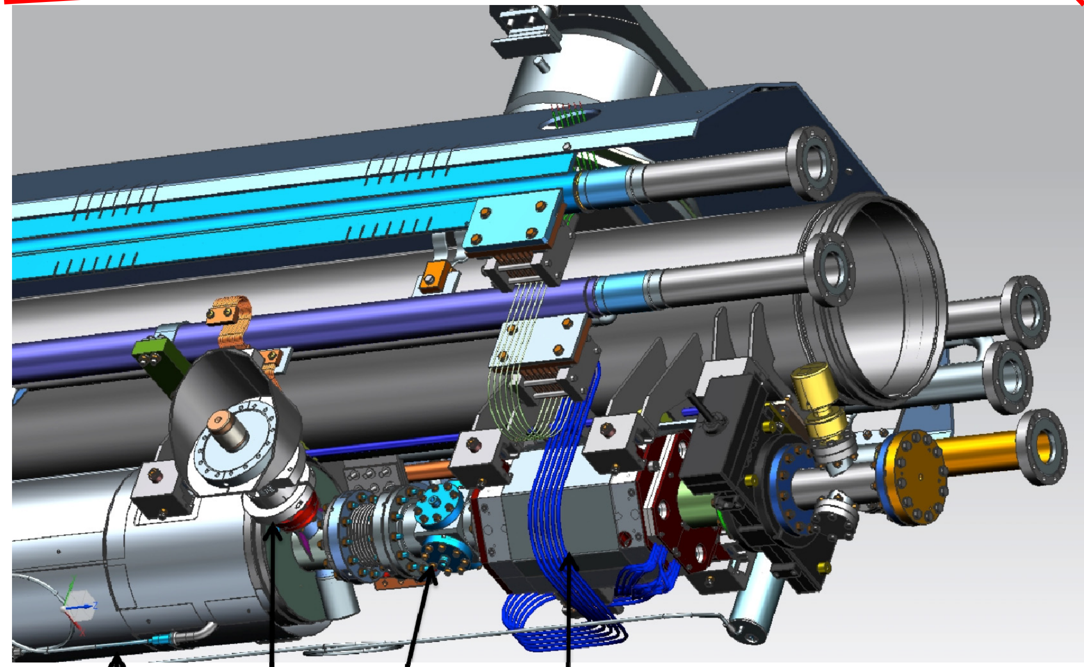

MOPLR006 Monopole HOMs damping in the *LCLS-II* 1.3 GHz Structure
MOPLR029 *LCLS-II* Tuner Assembly for the Prototype Cryomodule at FNAL
THPRC008 Status of the Development and Manufacturing of LCLSII Fundamental Power Couplers
THPRC017 Performance of SRF Cavity Tuners at LCLS II Prototype Cryomodule at FNAL

SRF Cavities

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LCLS-II Specification: **$Q_0 \geq 2.7\text{x}10^{10}$ @ E_{acc} = 16 MV/m** in 5 mG remnant field

- Specification designed to reduce 2K cryogenic load, and thus operating cost of machine.
- Made possible by Nitrogen doping of SRF cavities.
  - Comes with 2 trade-offs.
    - Flux trapping in doped cavities can be up to 3.6 times higher than un-doped cavities
    - Reduction in maximum achievable gradient of cavity – not an issue for LCLS-II
  - Remedied by:
    - Improved magnetic hygiene and shielding
    - Optimized design and cooldown procedures

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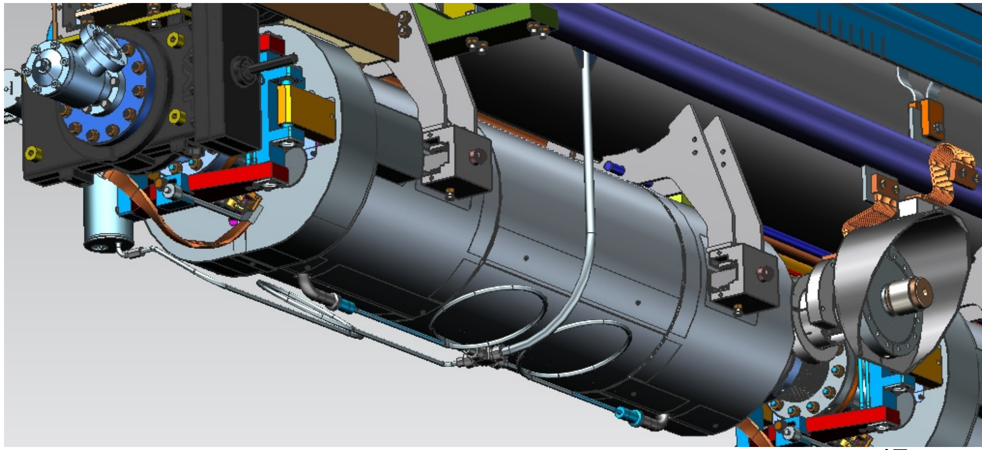

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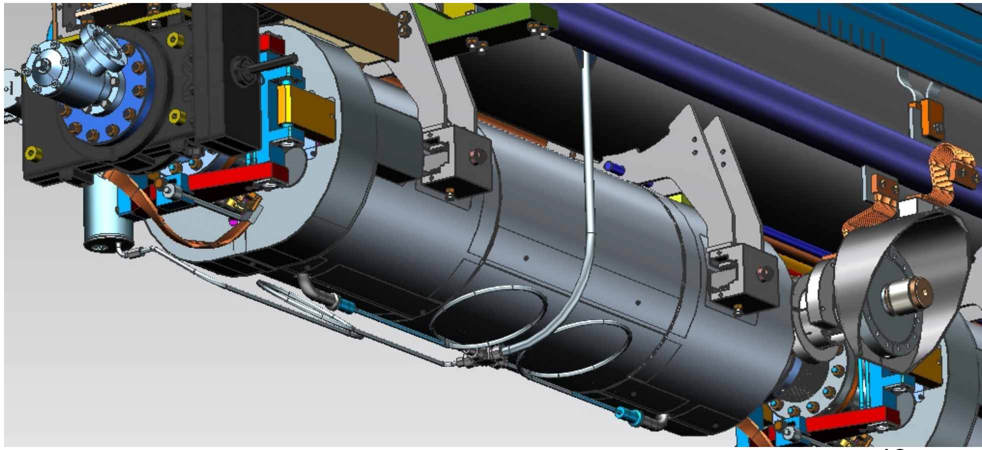
WE2A01 N-Doping: The New Breakthrough Technology for SRF Cavities
TUPLR025 Optimal Nitrogen Doping Level to Reach High Q0



Obtaining and preserving Q ≥ 2.7e10 at 16 MV/m, 2K

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Doping

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Intrinsic
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Doping

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Flux trapping percentage

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Sensitivity to mag field

Flux trapping percentage

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Obtaining and preserving Q ≥ 2.7e10 at 16 MV/m, 2K

$$Q = G/R_s \quad \text{where } R_S = R_{BCS} + R_0 + R_{TF}$$

Doping (R_{BCS})

Intrinsic residual (R_0)

Trapped magnetic flux residual (R_{TF})

$$R_{TF} = s * \eta * B_{amb}$$

Sensitivity to mag field (s)

Flux trapping percentage (η)

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<u>Total Rs budget for Q~ 2.7e10 = 10 nanoOhms</u>

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pCM material:

- R_{BCS} ~ 4.5 nΩ +
- R_0 ~ 1-2 nΩ +
- R_{TF} ~ 1.4*(<0.2)*B =

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Doping (→ R_{BCS})

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---

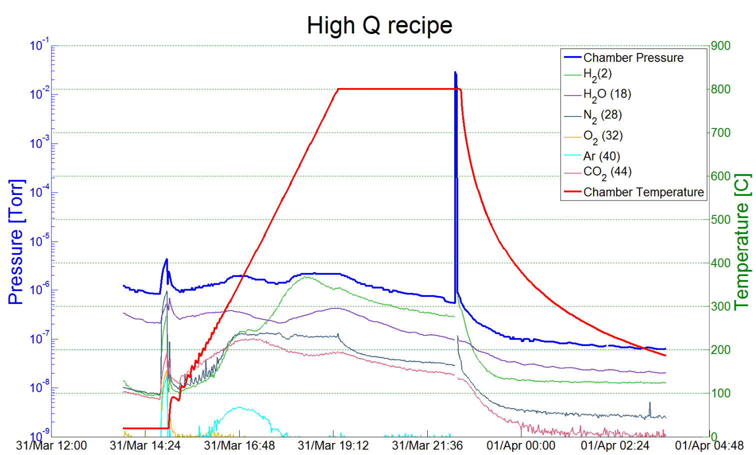
if B ~5 mG = 7.5 nΩ => Q ~3.5e10

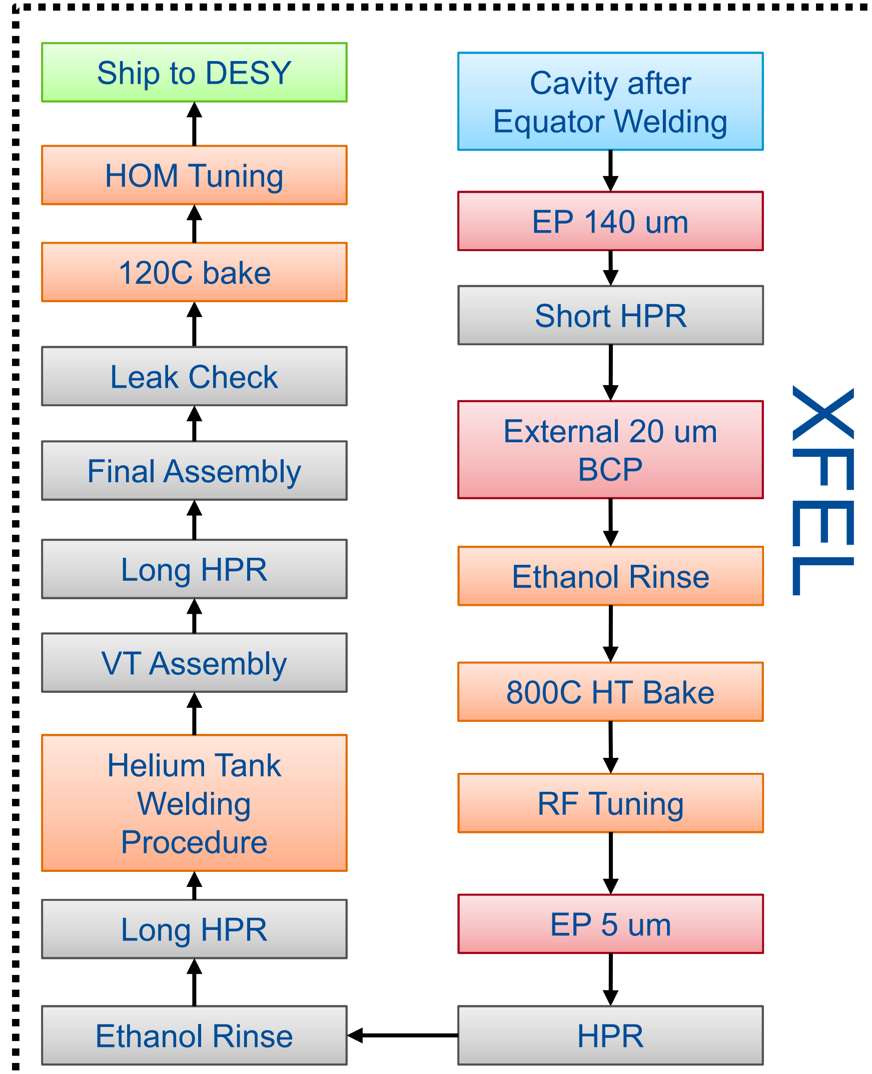
if B ~1 mG = 6.5 nΩ => Q ~4e10

High Q_0 Recipe

Cavity Treatment:

- Bulk EP
- 800 C anneal for 3 hours in vacuum
- 2 minutes @ 800C nitrogen diffusion
- 800 C for 6 minutes in vacuum
- Vacuum cooling
- 5 microns EP





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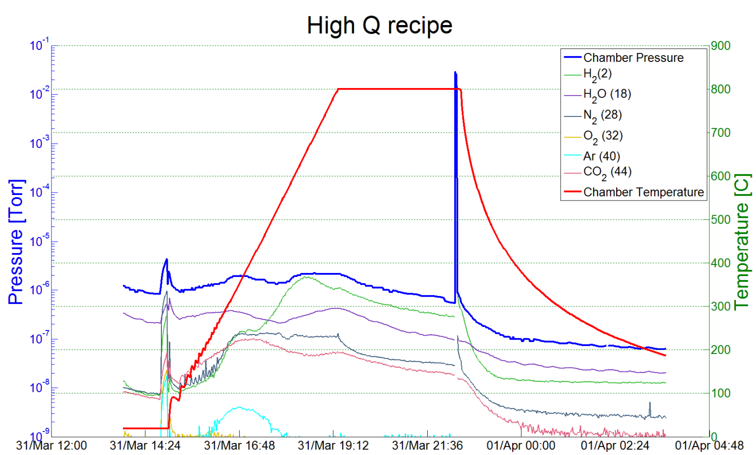

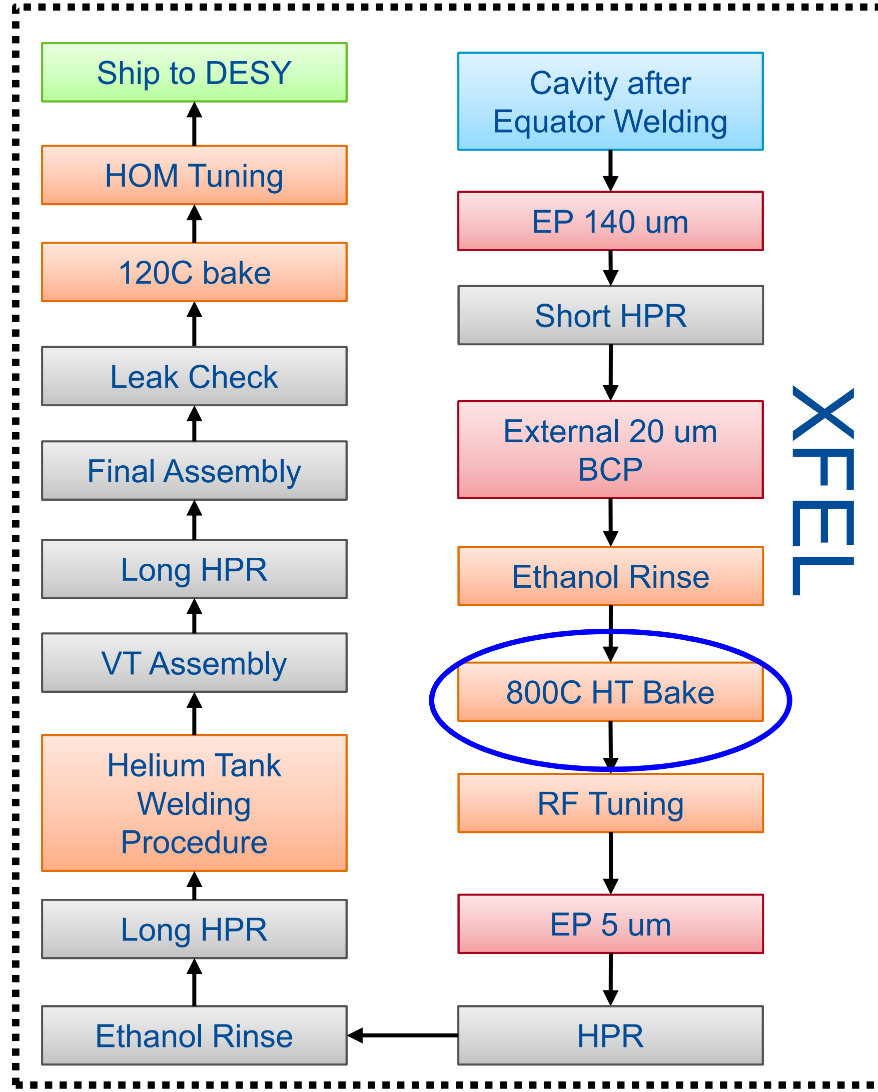

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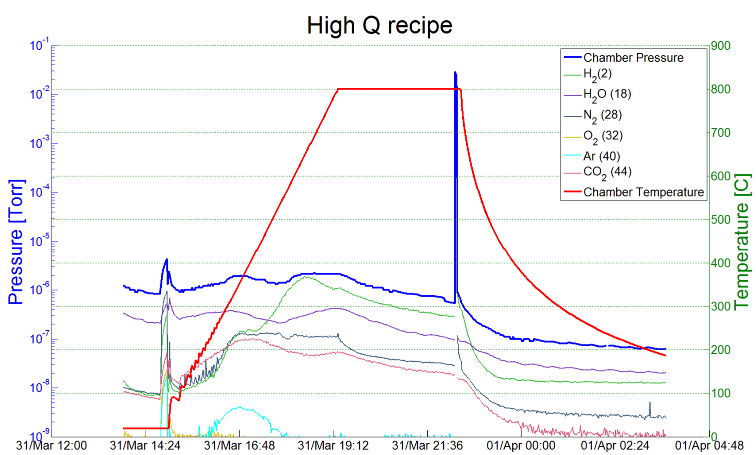

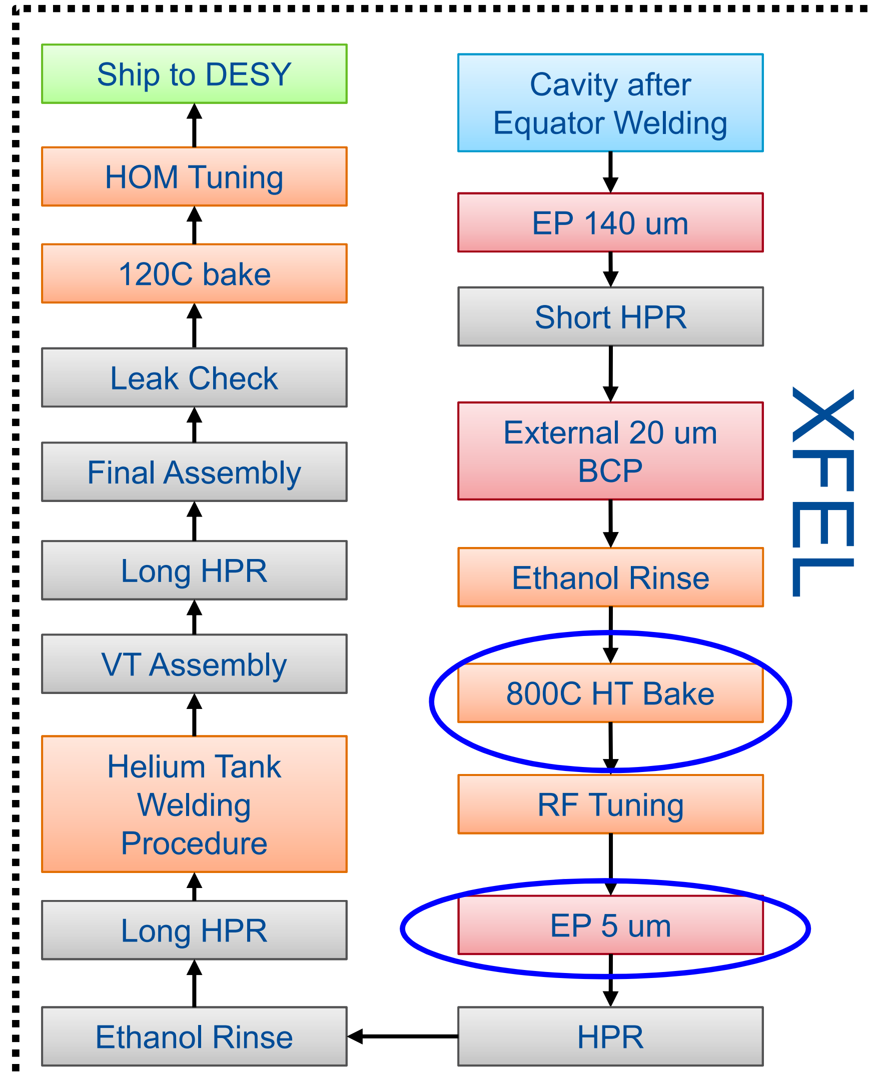

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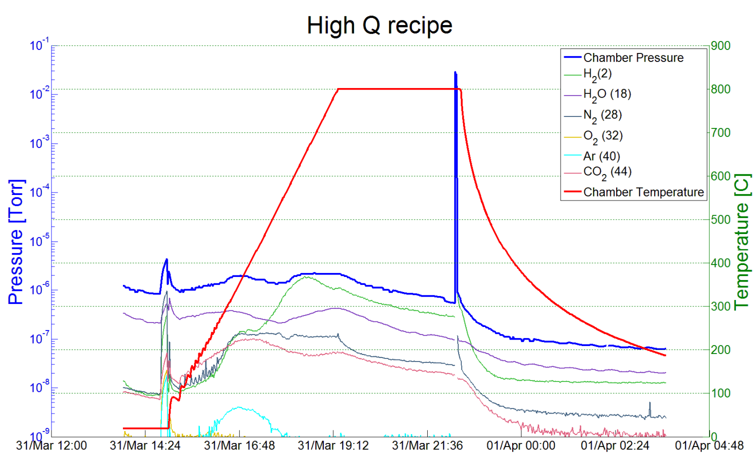
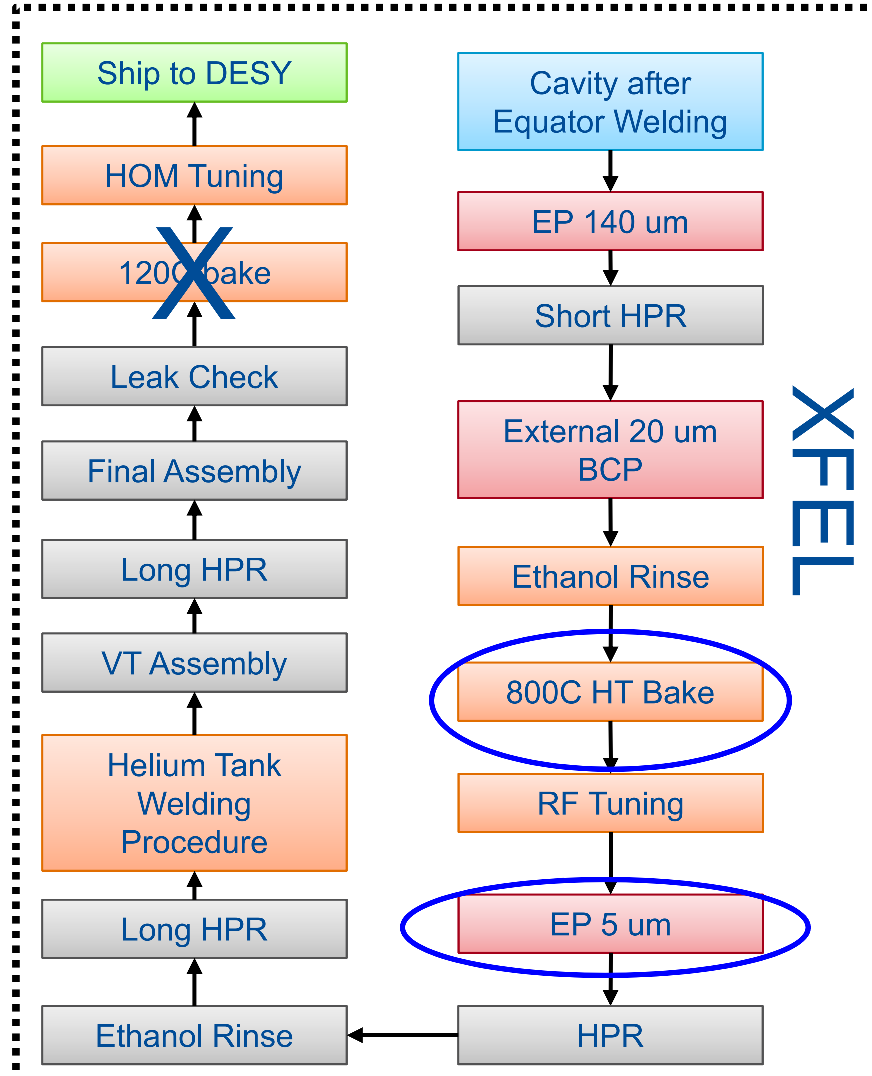
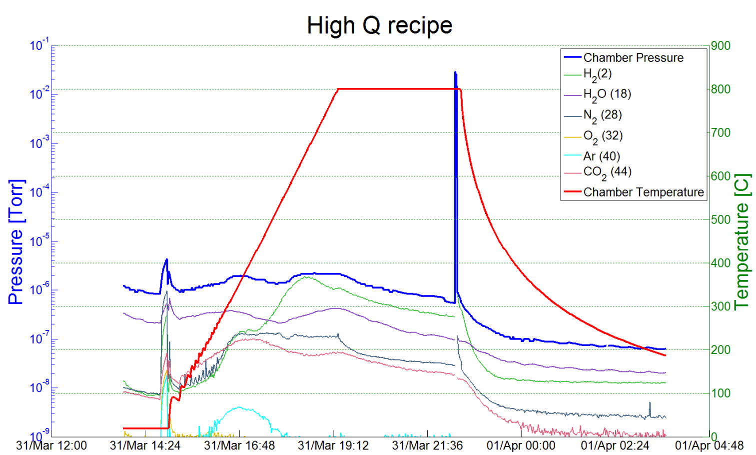


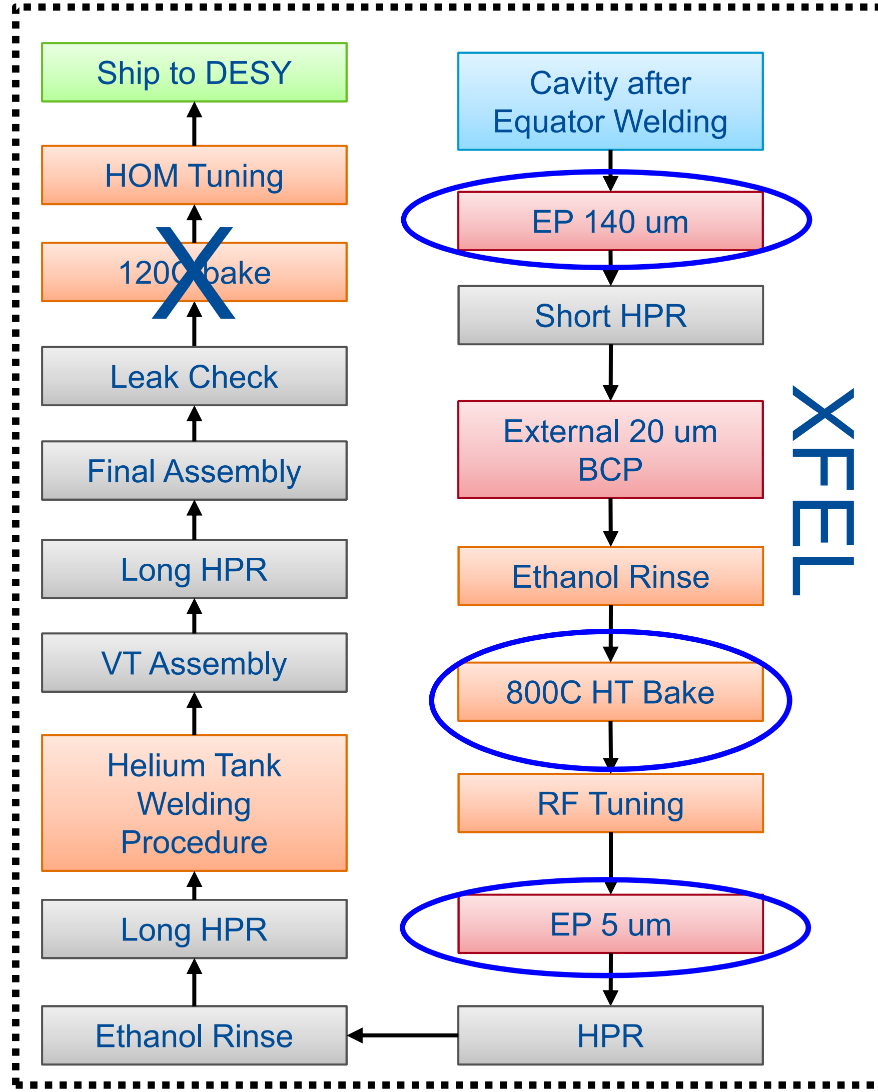


High Q_0 Recipe

Cavity Treatment:

- Bulk EP
- 800 C anneal for 3 hours in vacuum
- 2 minutes @ 800C nitrogen diffusion
- 800 C for 6 minutes in vacuum
- Vacuum cooling
- 5 microns EP





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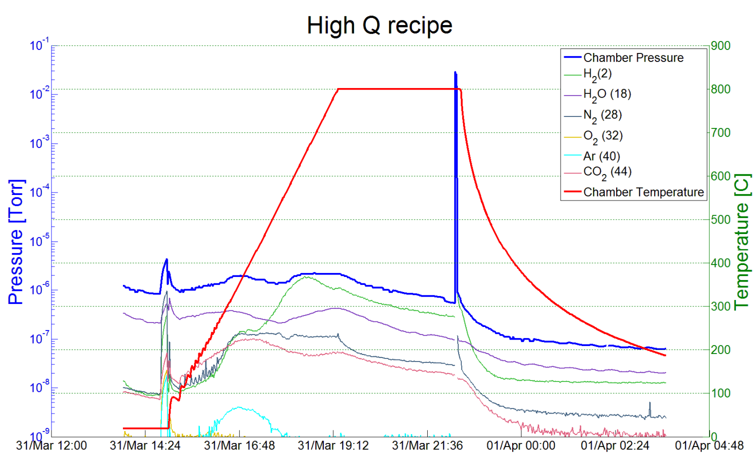
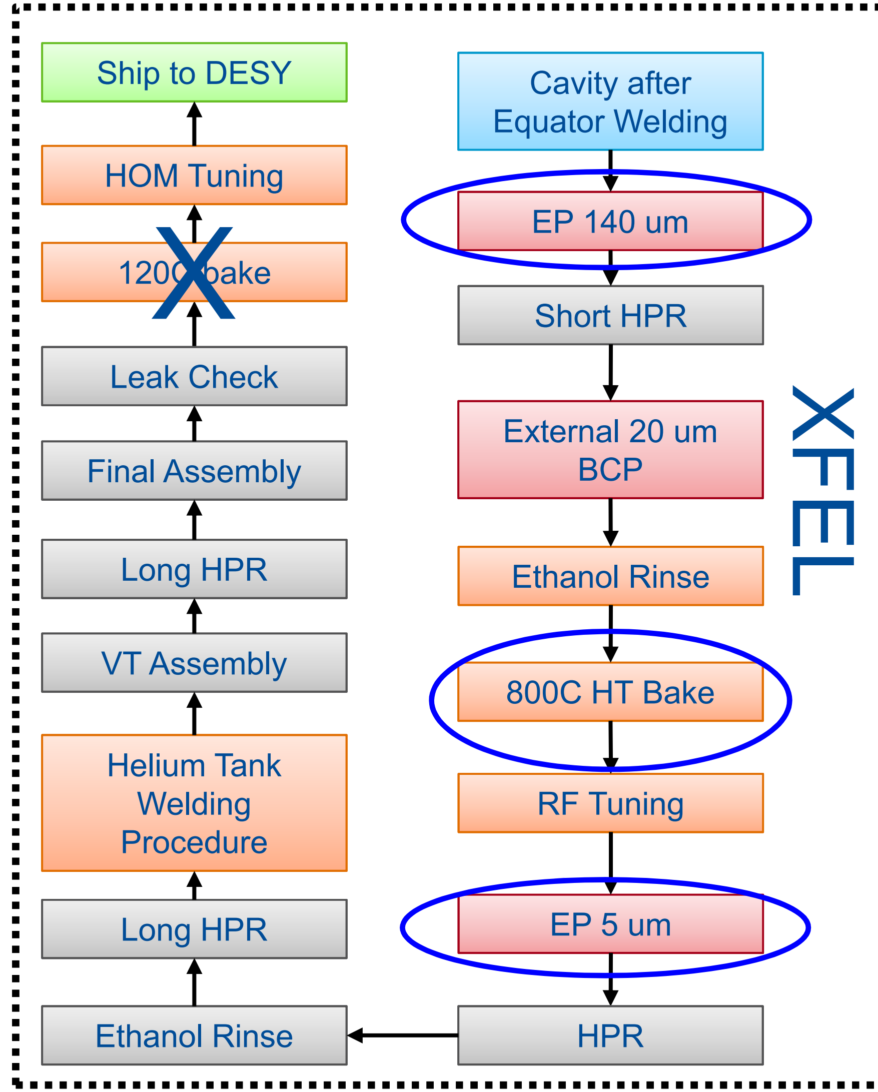
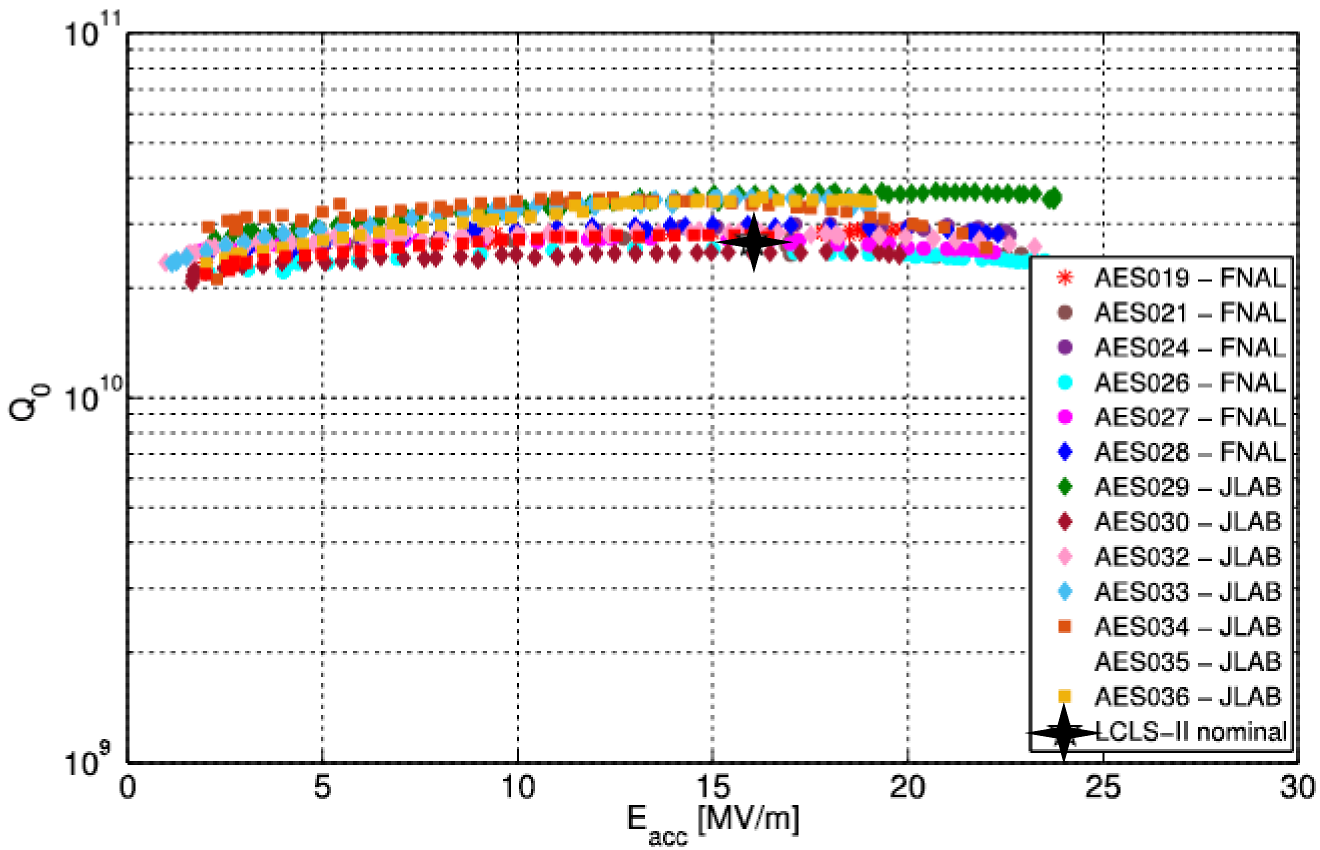


TUPLR021 First Results of High Q Studies in Fermilab LCLS-II Prototype Cryomodule



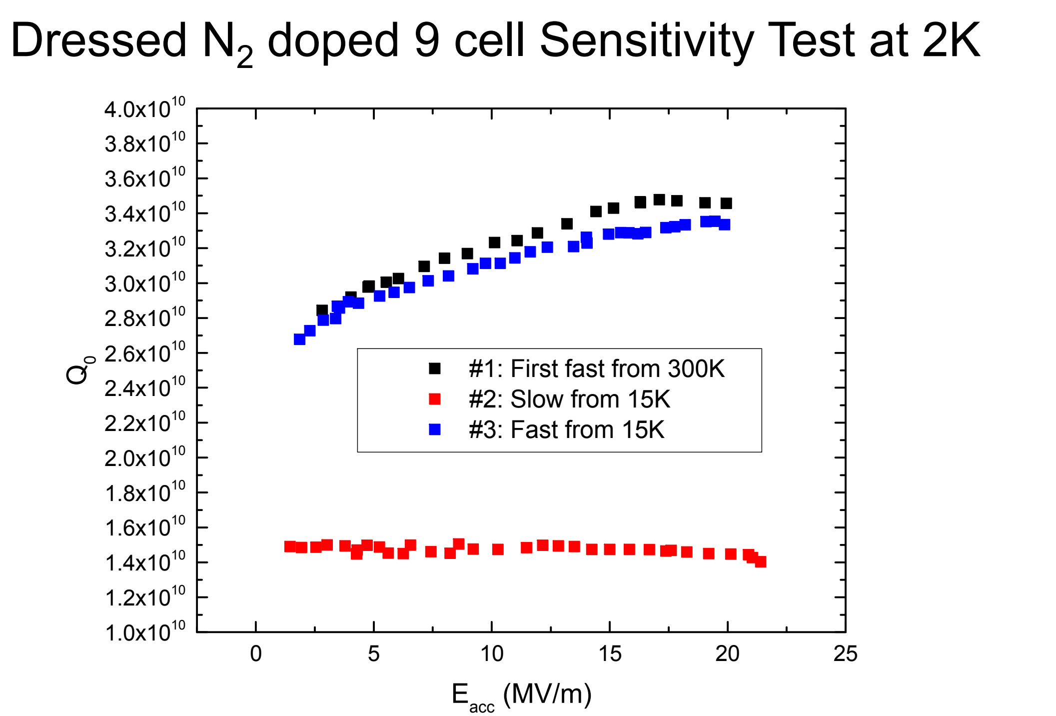
Prototype Vertical Test Results of Dressed Nine Cell Cavities



- pCM cavities material : Wah Chang
- Meet specs Q>2.7e10 even when cooled in vertical dewars with B>5 mGauss

Issues Identified Moving Towards Production

- Cooldown rate affects cavity performance
  - Impact on CM cooldown plan
  - Impact on cavity cooldown plumbing configuration



A. Romanenko, A. Grassellino, O. Melnychuk, D. A. Sergatskov, J. Appl. Phys. ***115****, 184903 (2014)*
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D. Gonnella et al, J. Appl. Phys. ***117****, 023908 (2015)*
M. Martinello, M. Checchin, A. Grassellino, A. Romanenko, A. Crawford, D. A. Sergatskov, O. Melnychuk, J. Appl. Phys. **118**, 044505 (2015)

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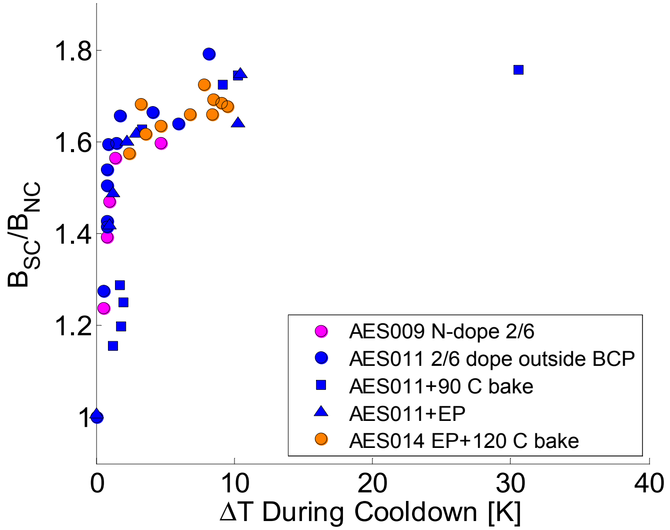

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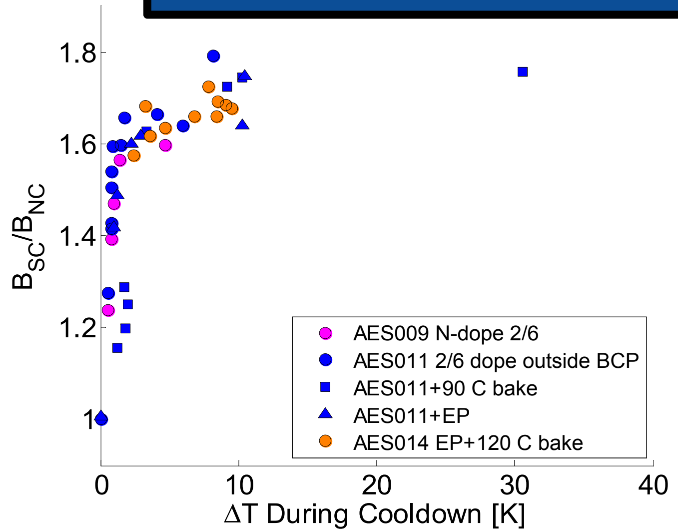

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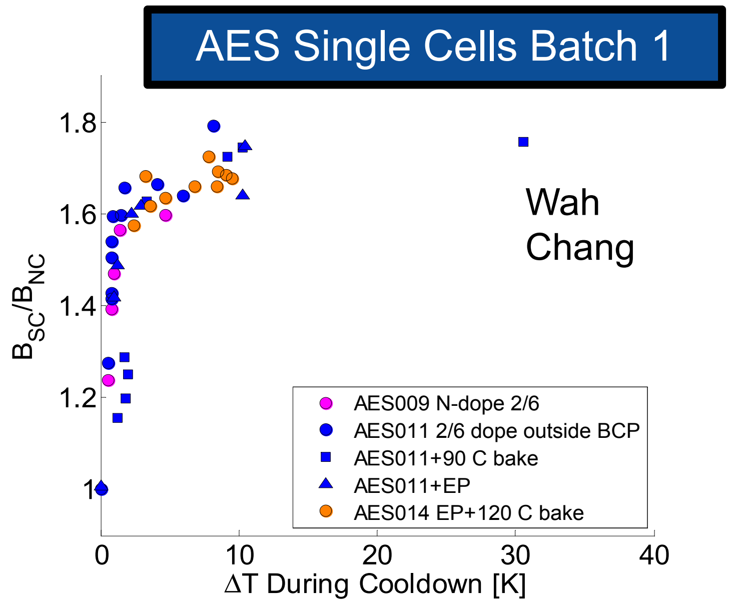

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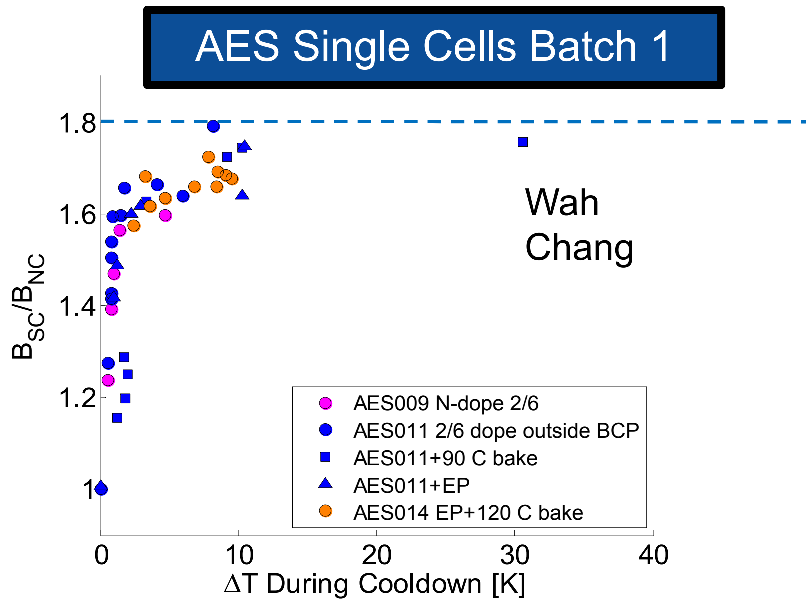

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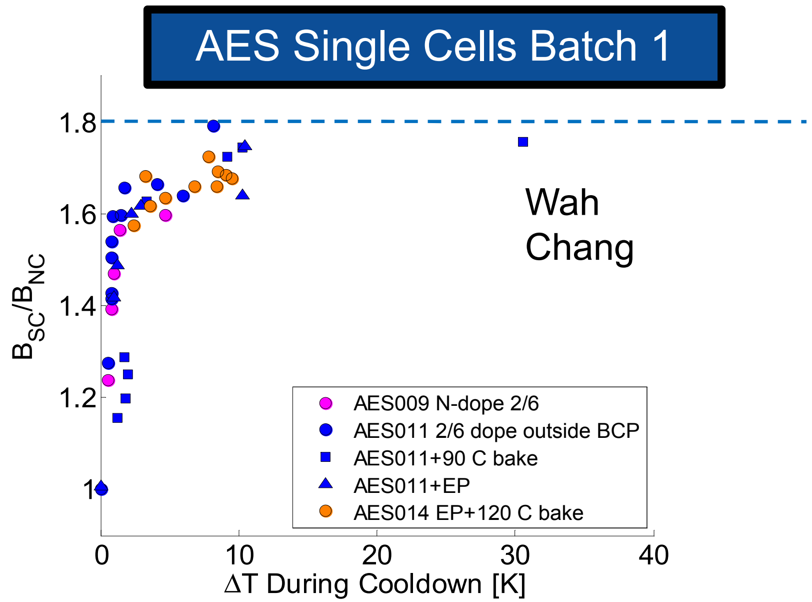

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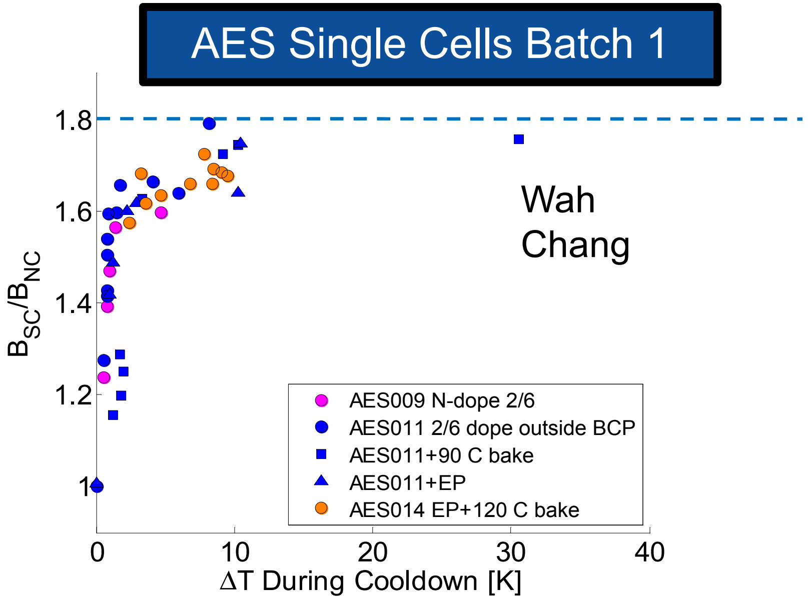
Complete Trapping



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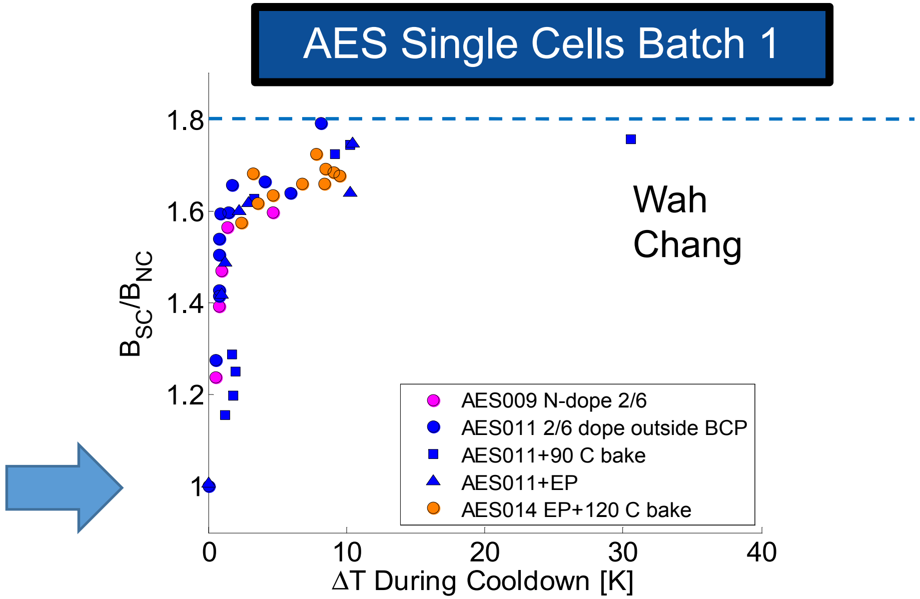

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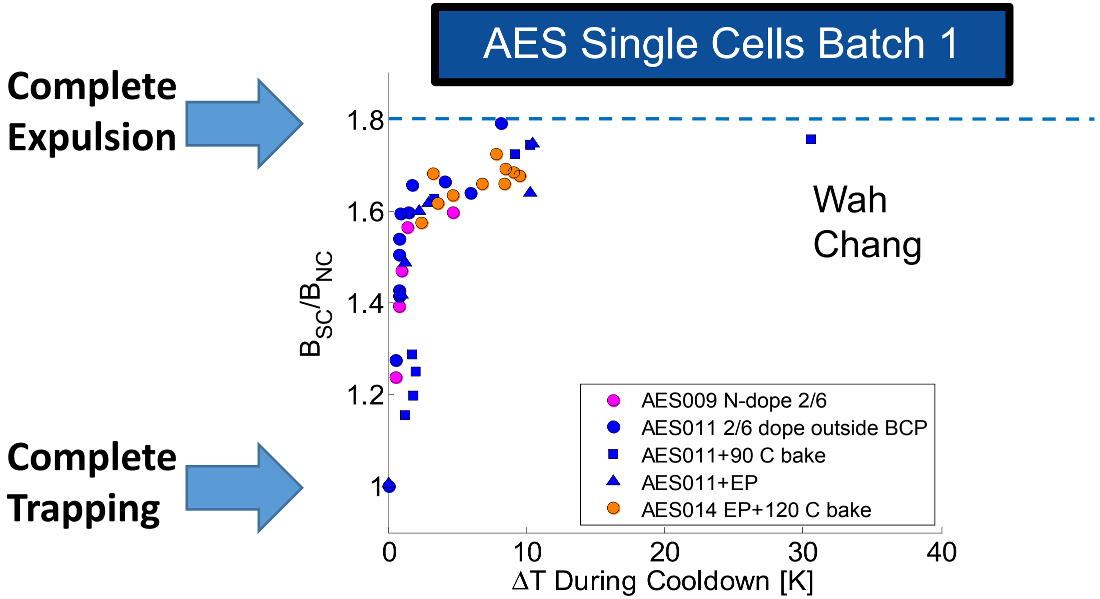

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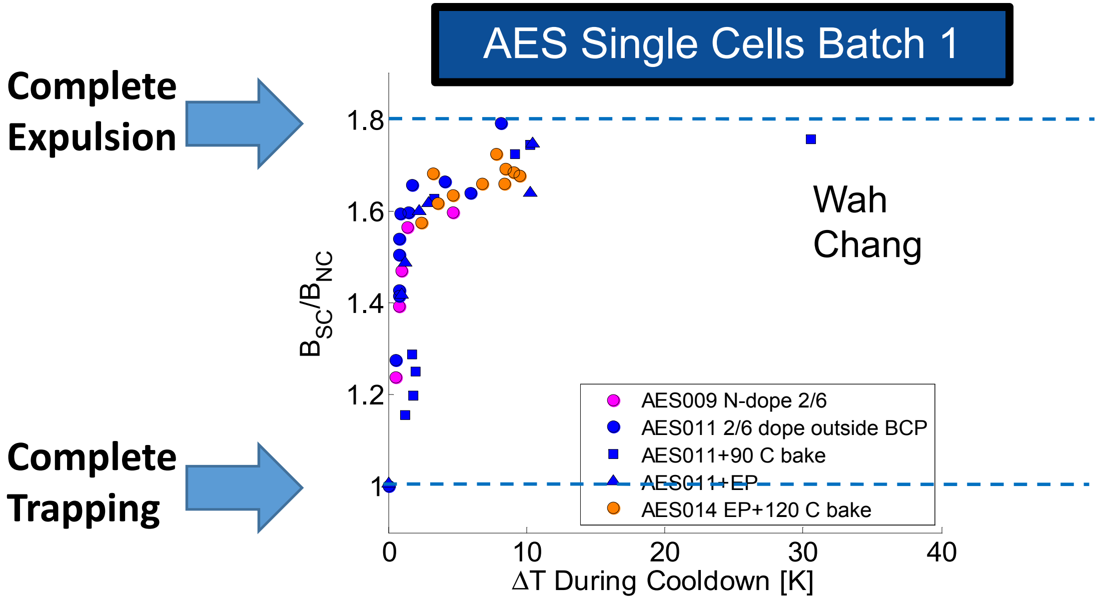

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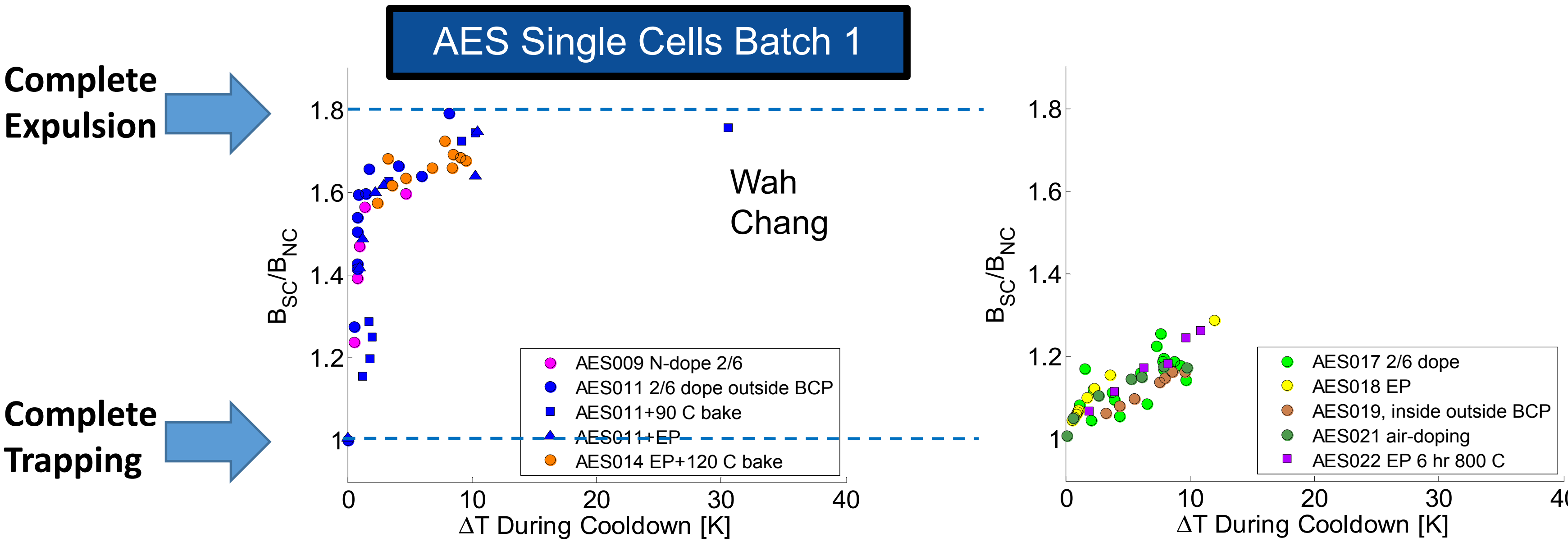

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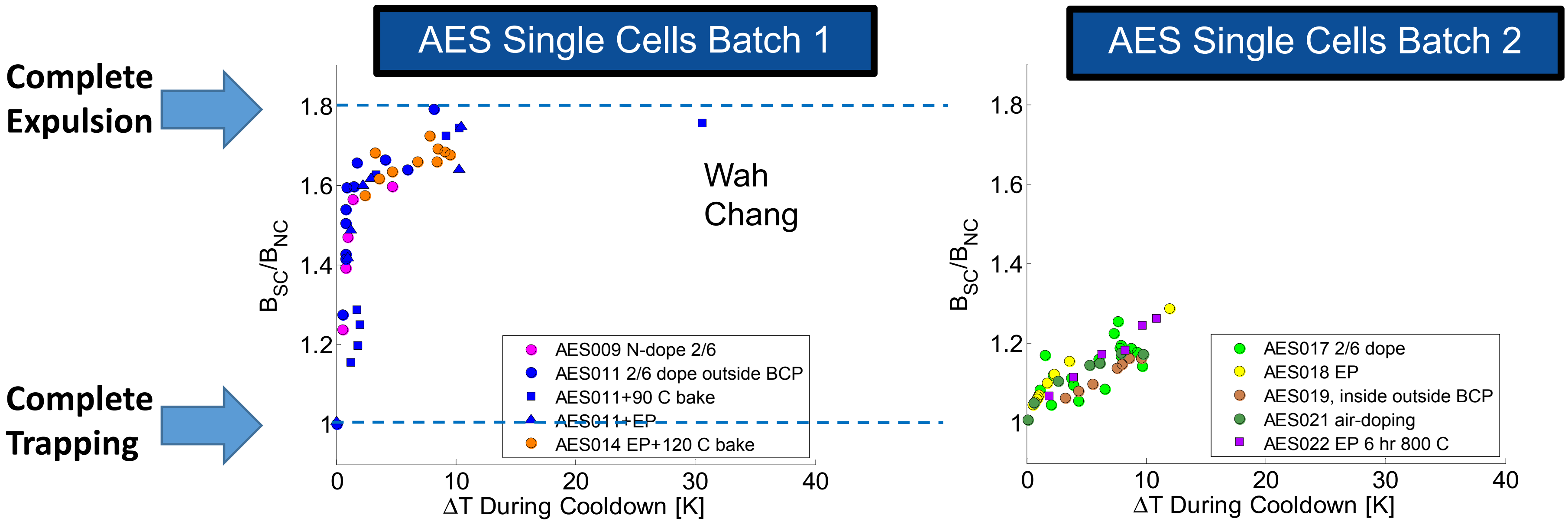

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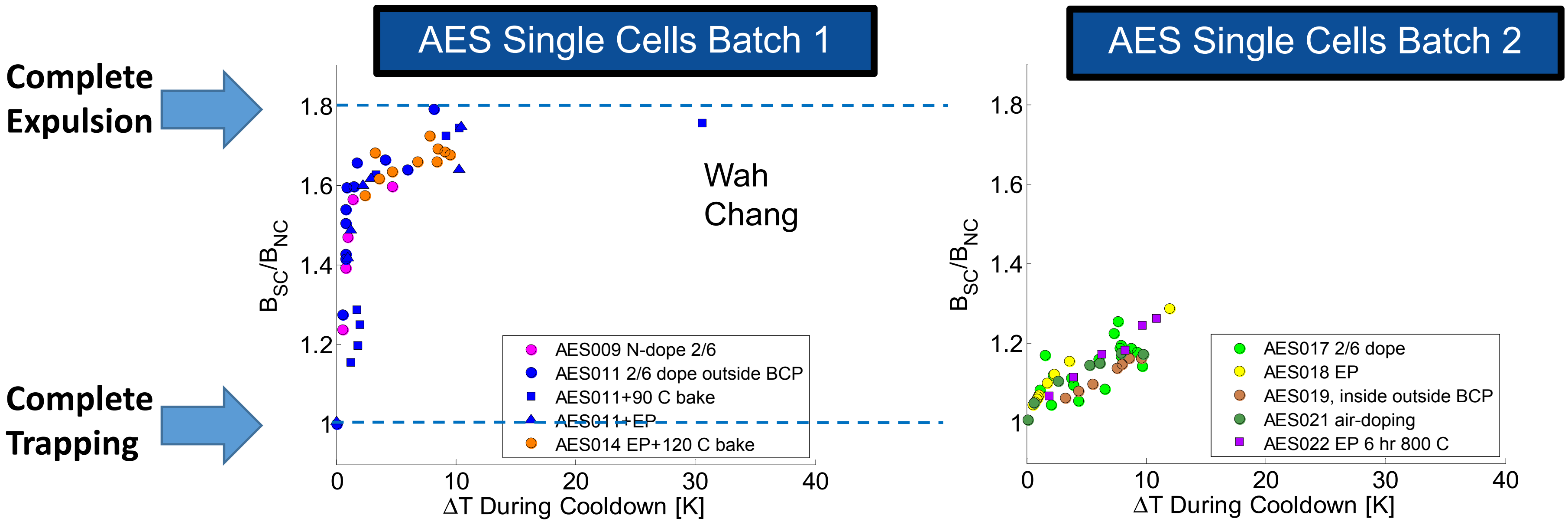

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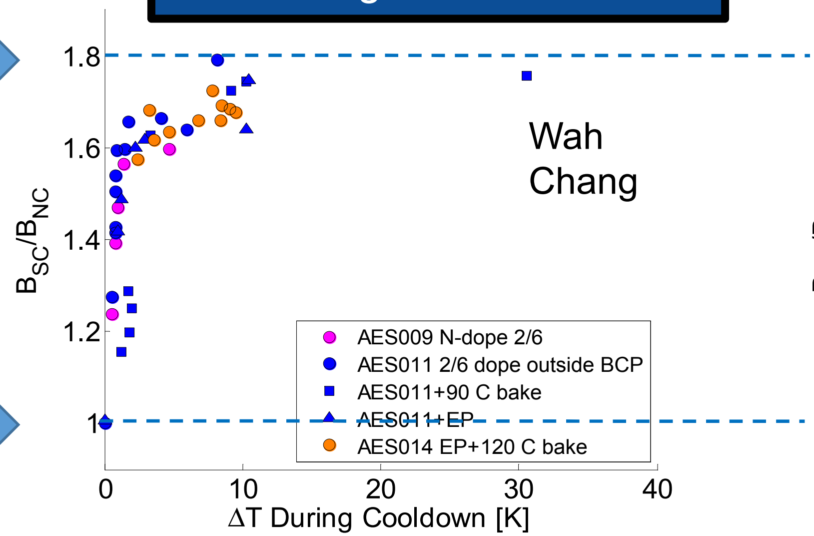
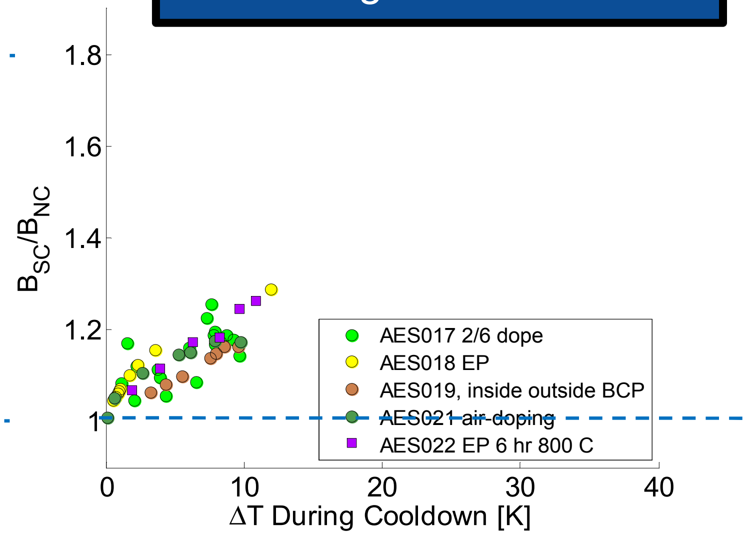


AES Single Cells Batch 2



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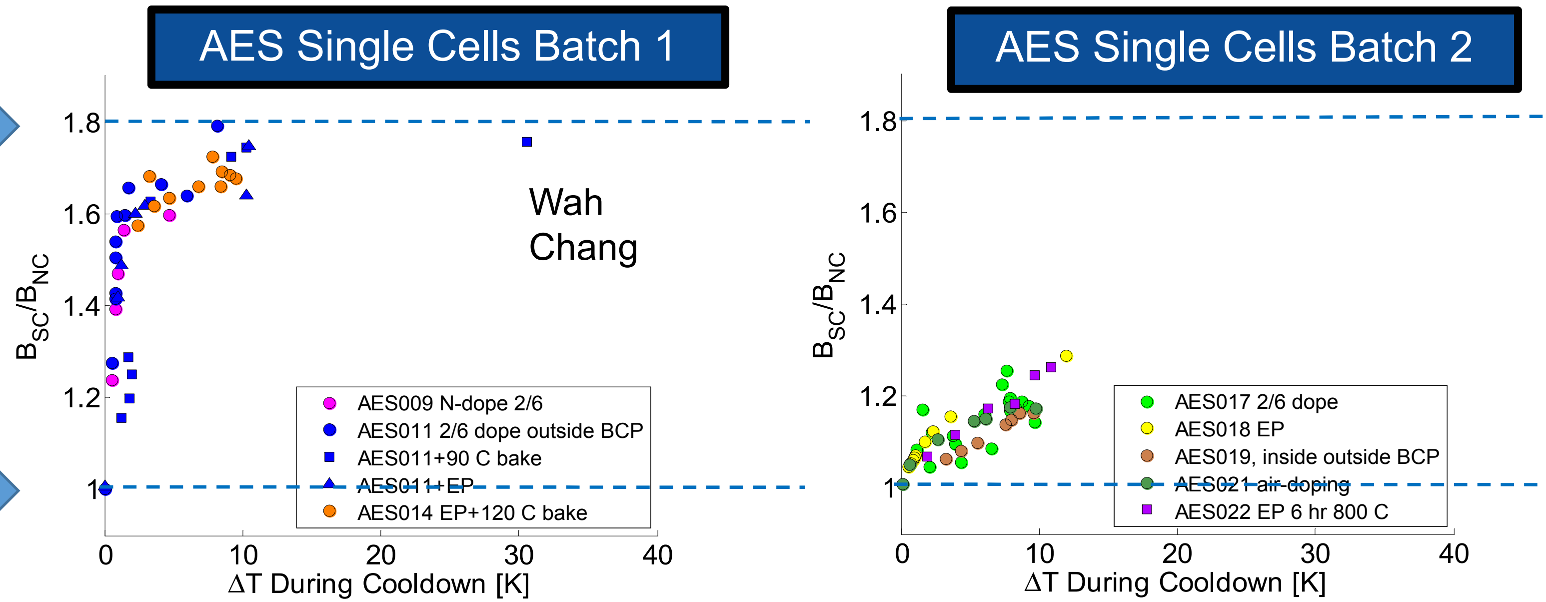

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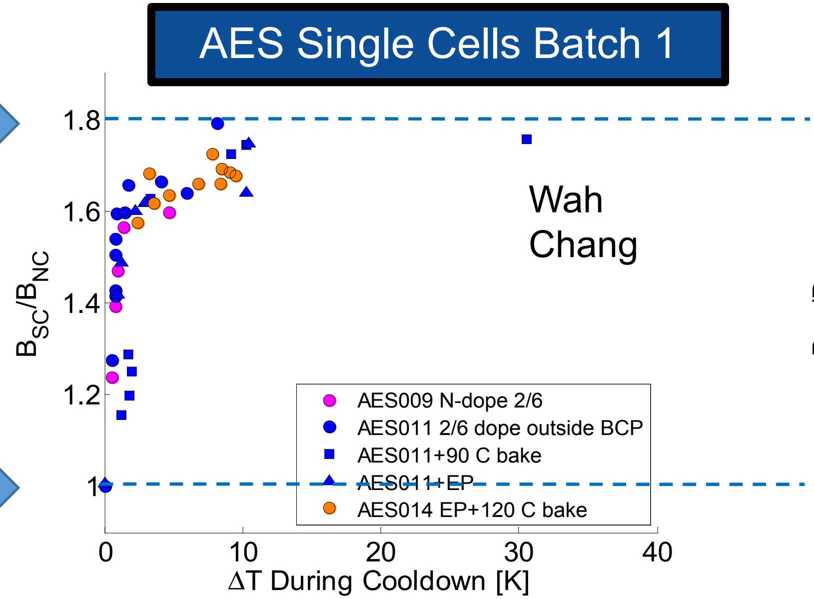

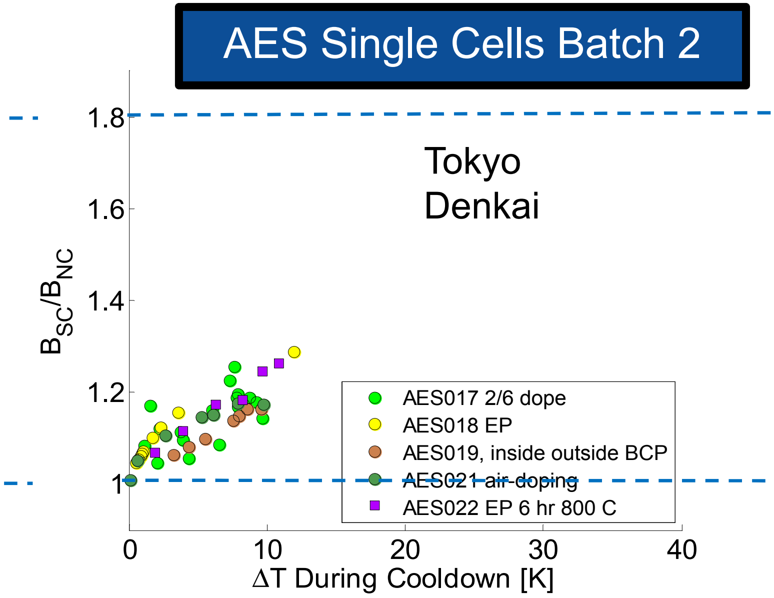

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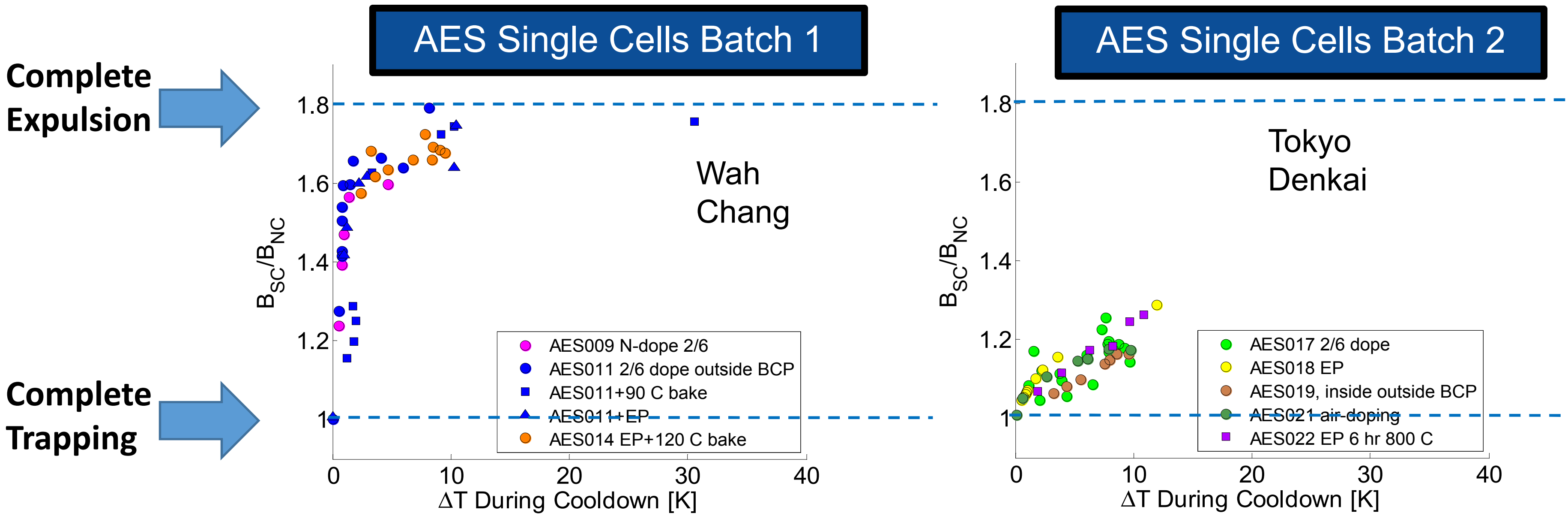

5 K thermogradient: ~95% vs ~20% flux expulsion

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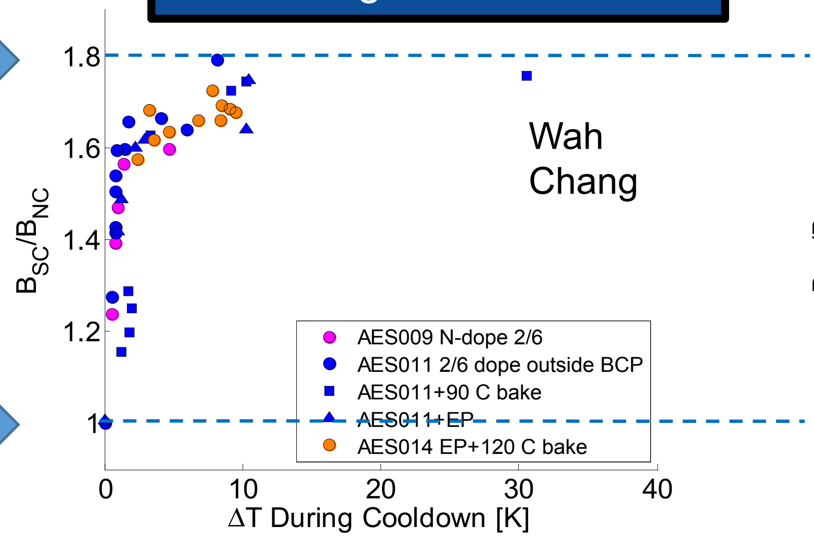

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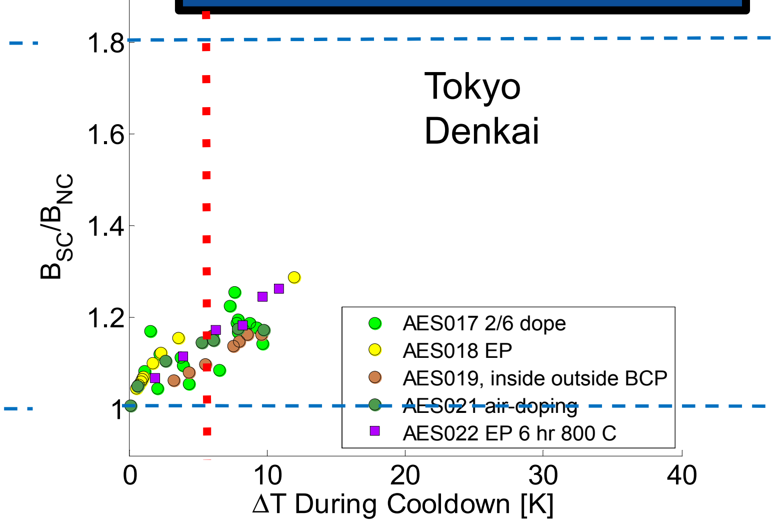

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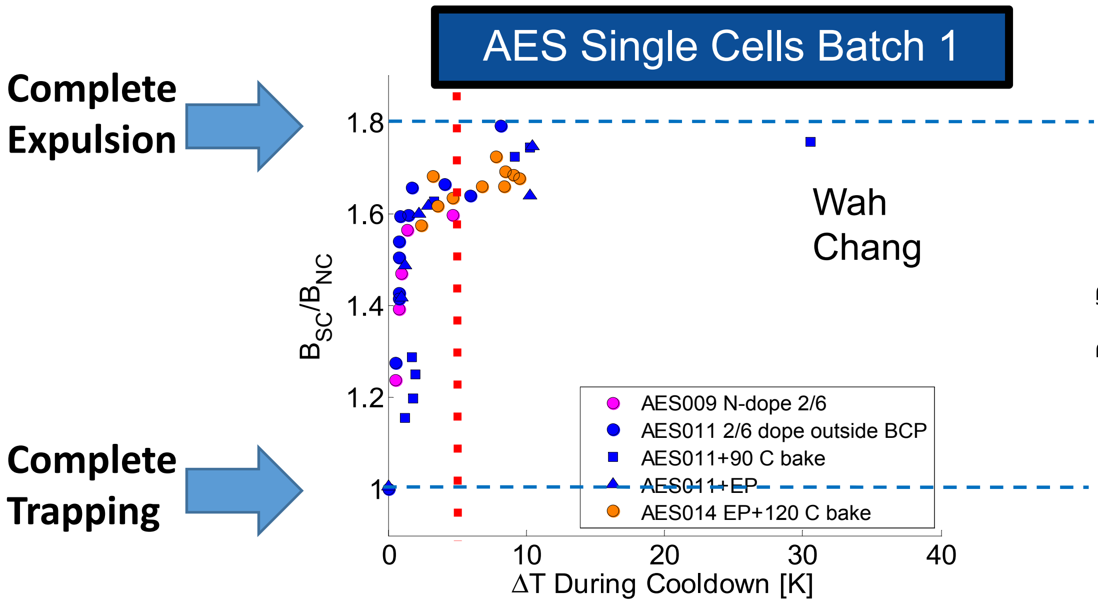

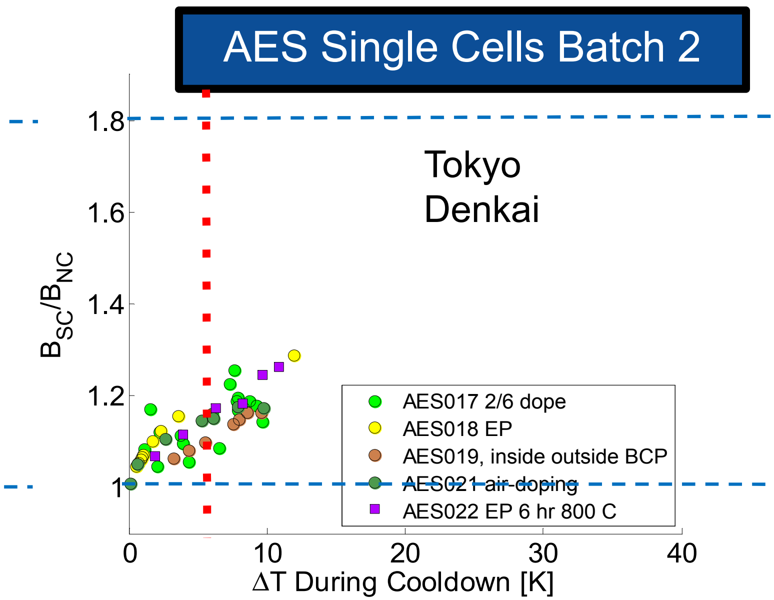

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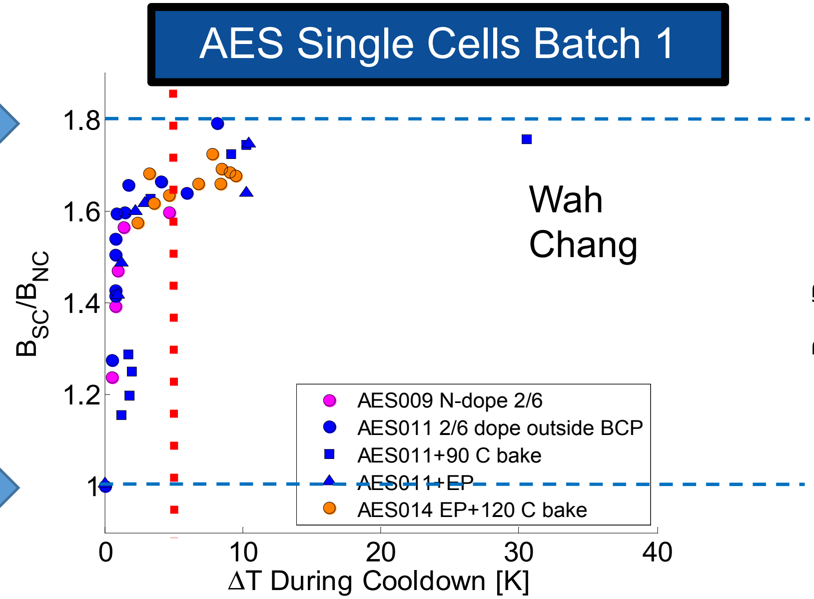

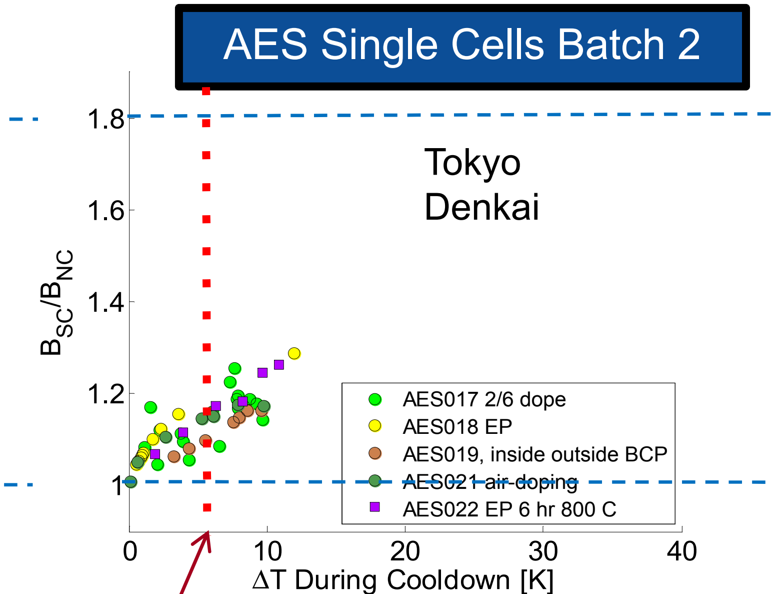

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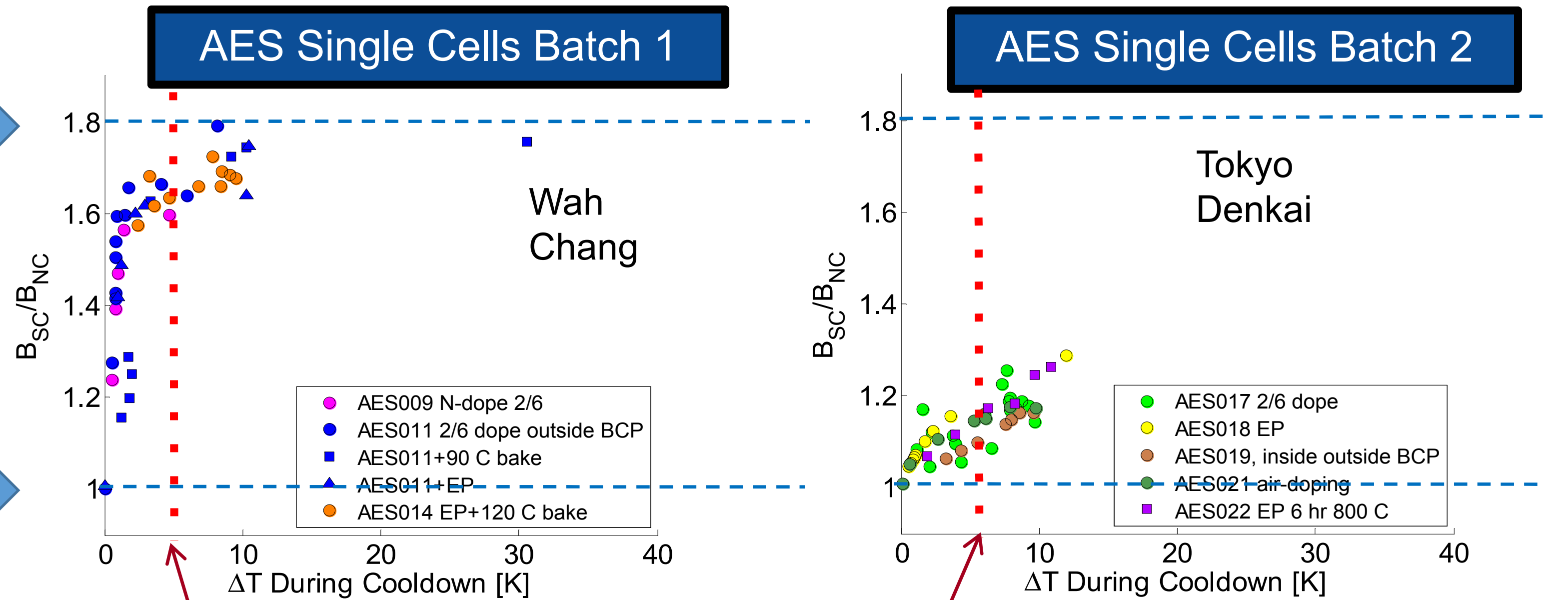

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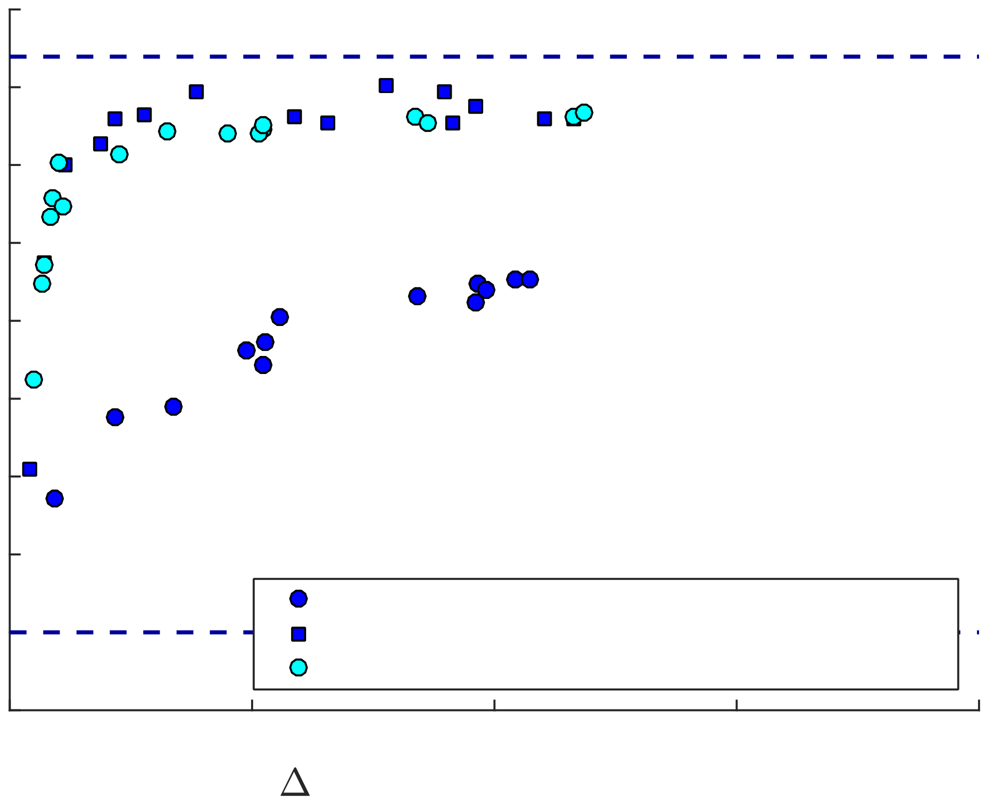

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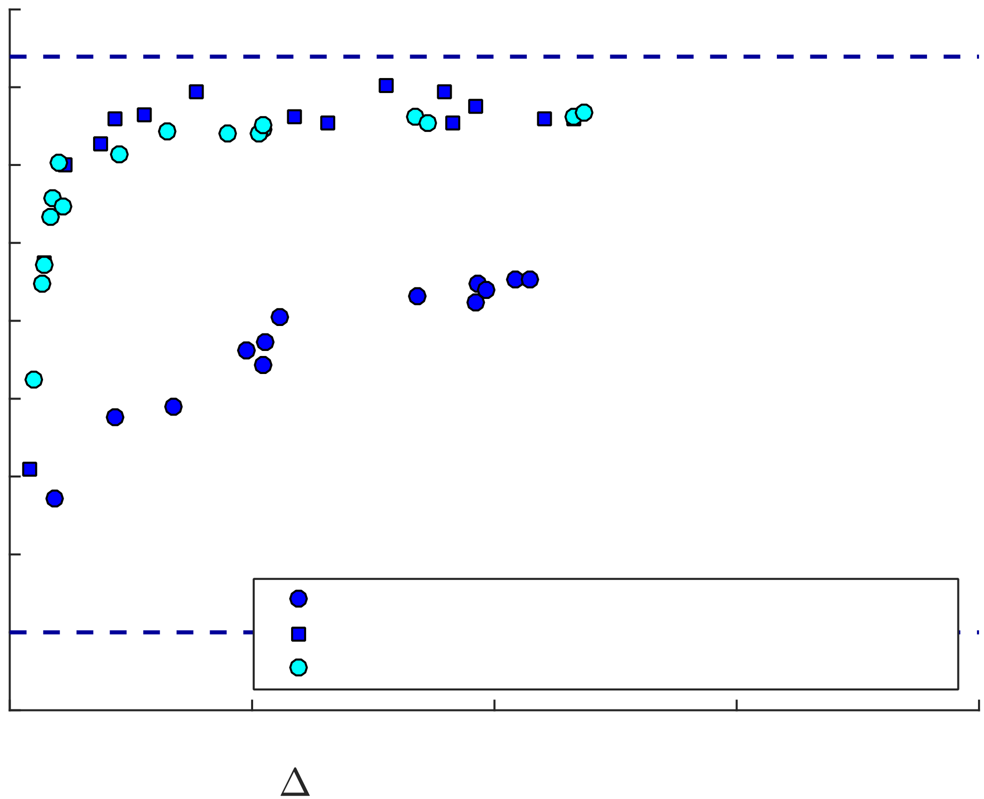

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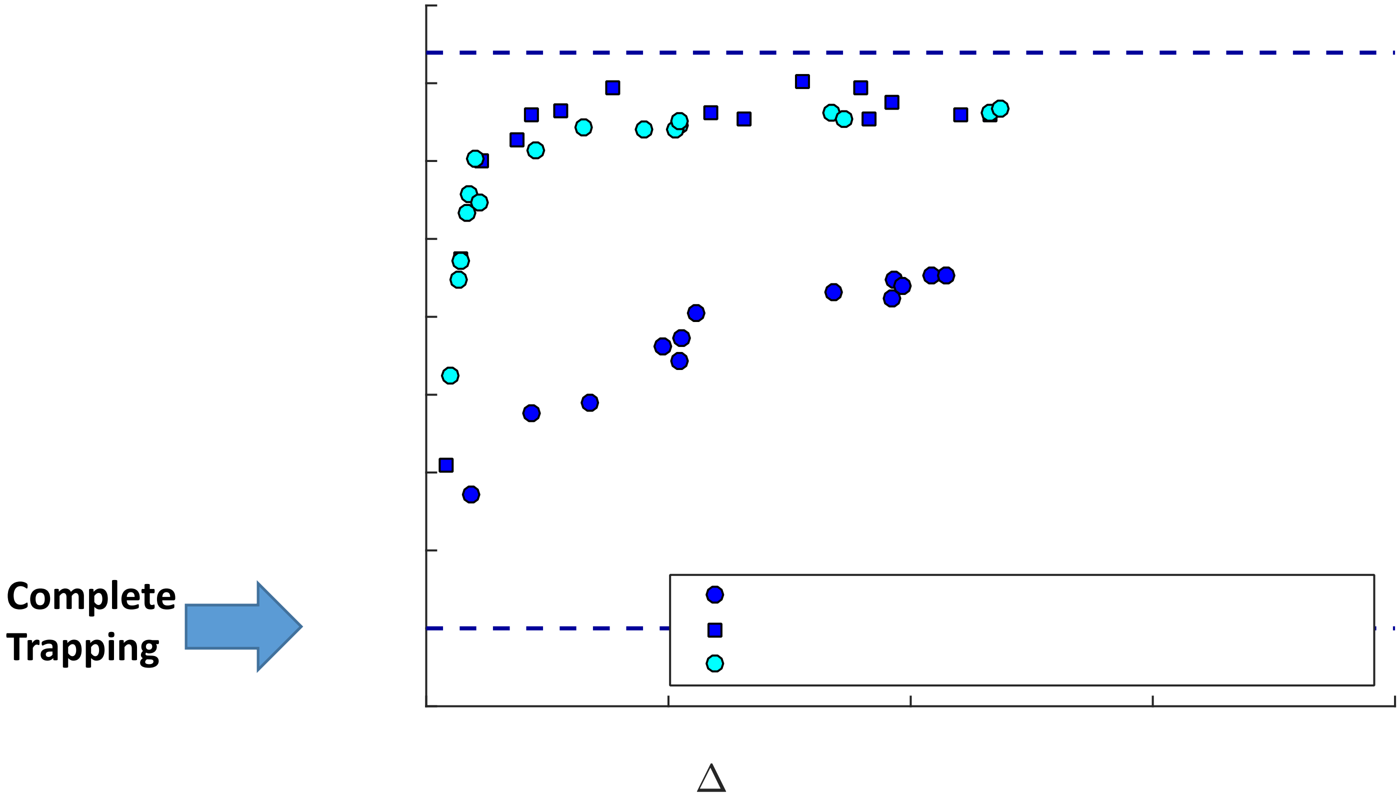

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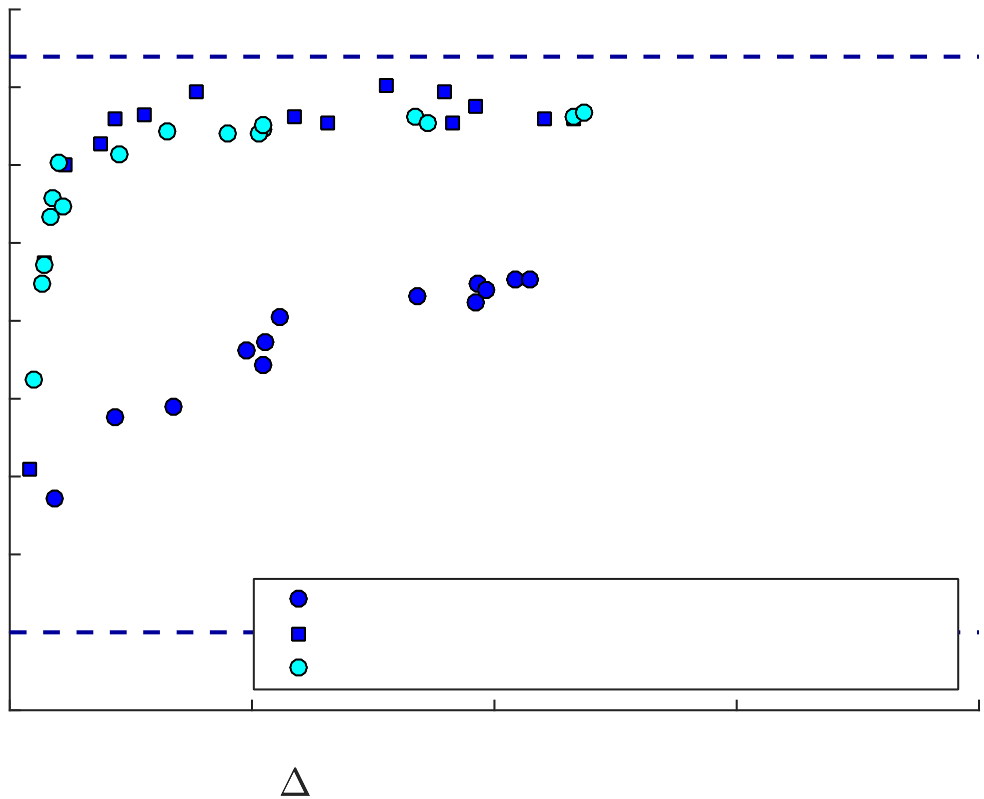

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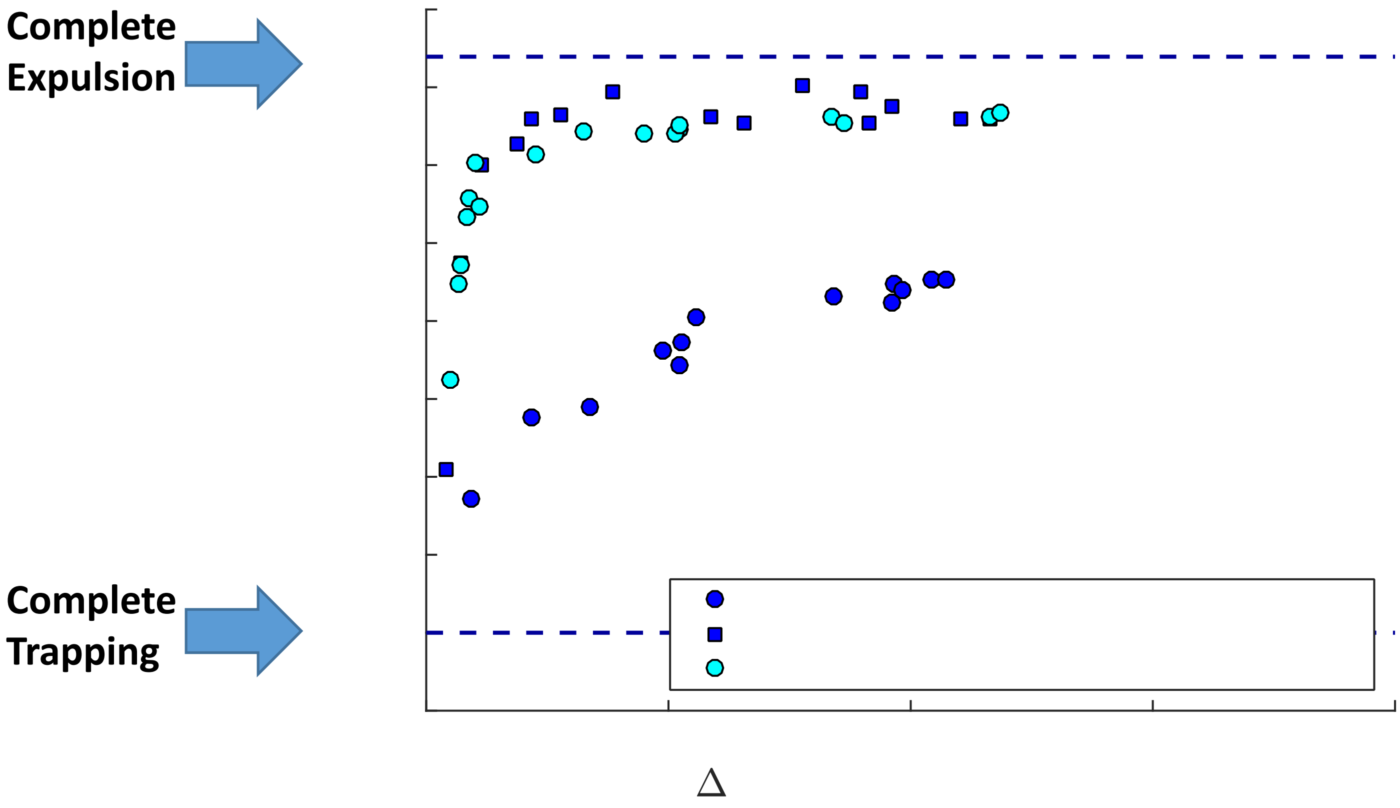

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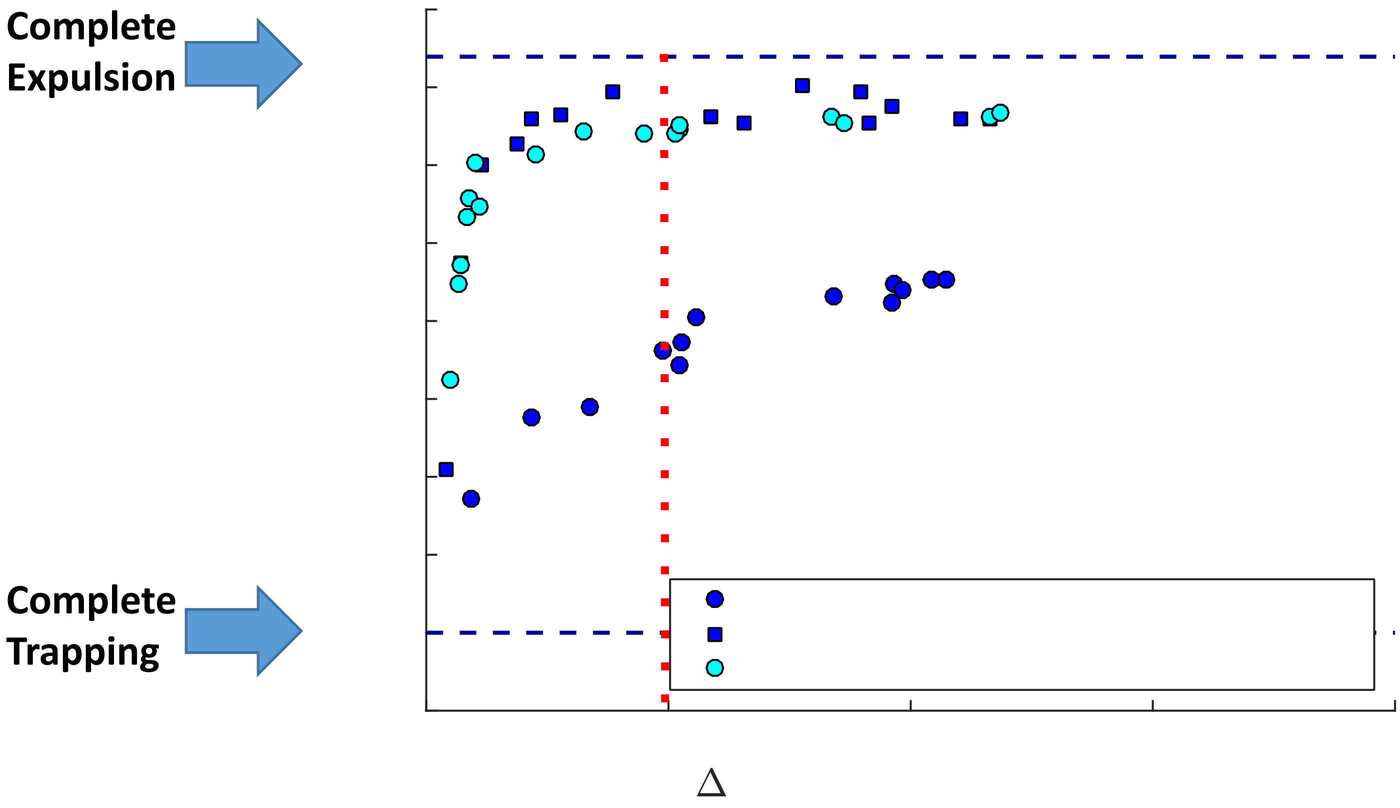

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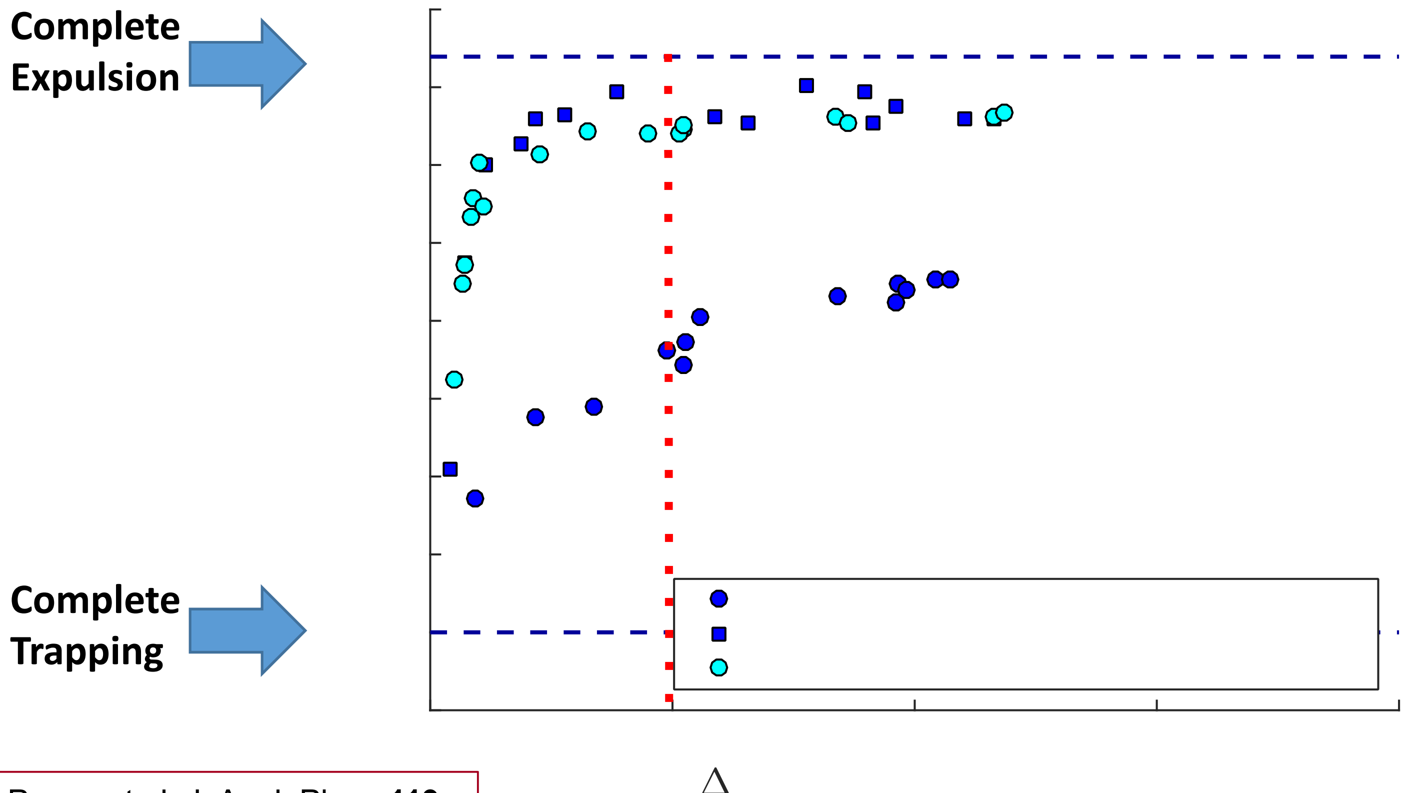

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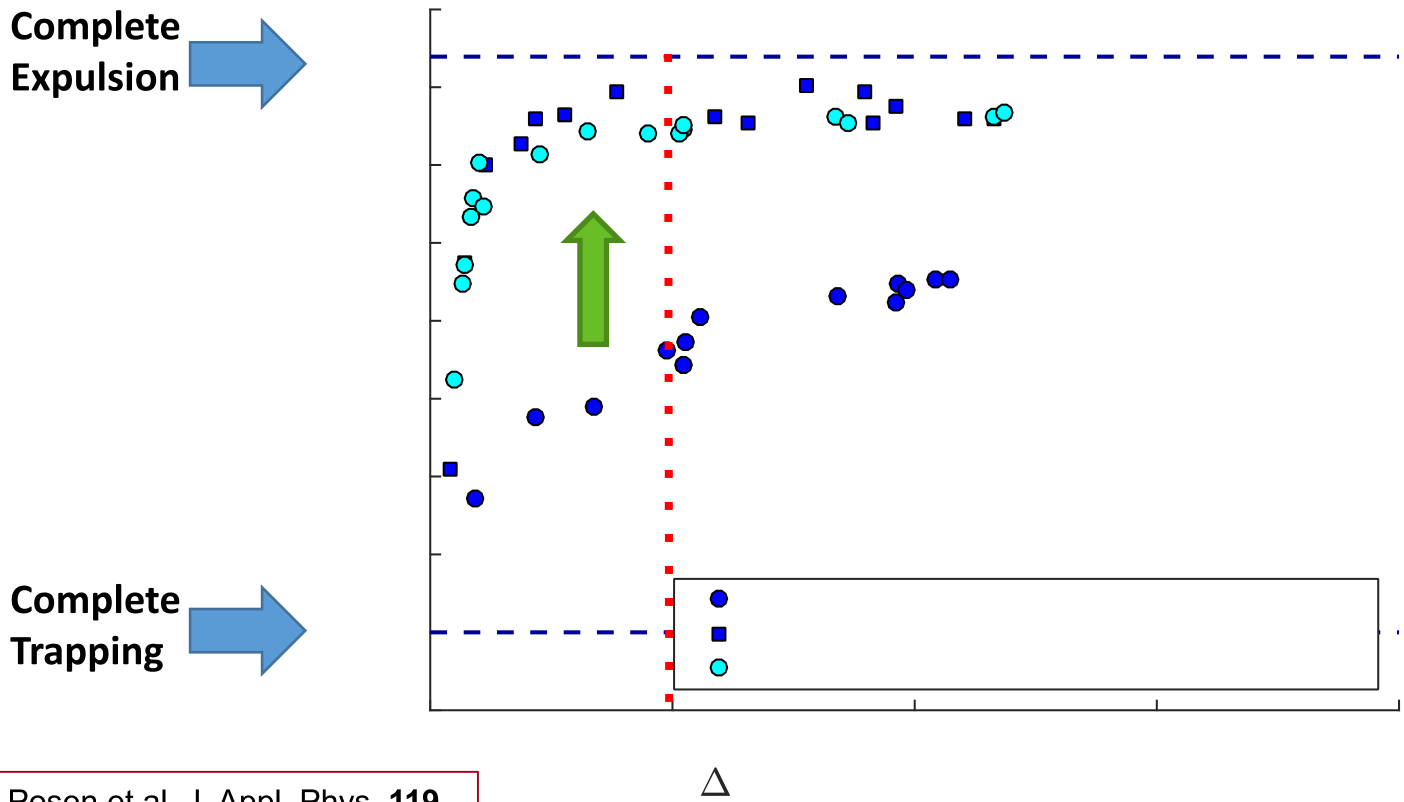

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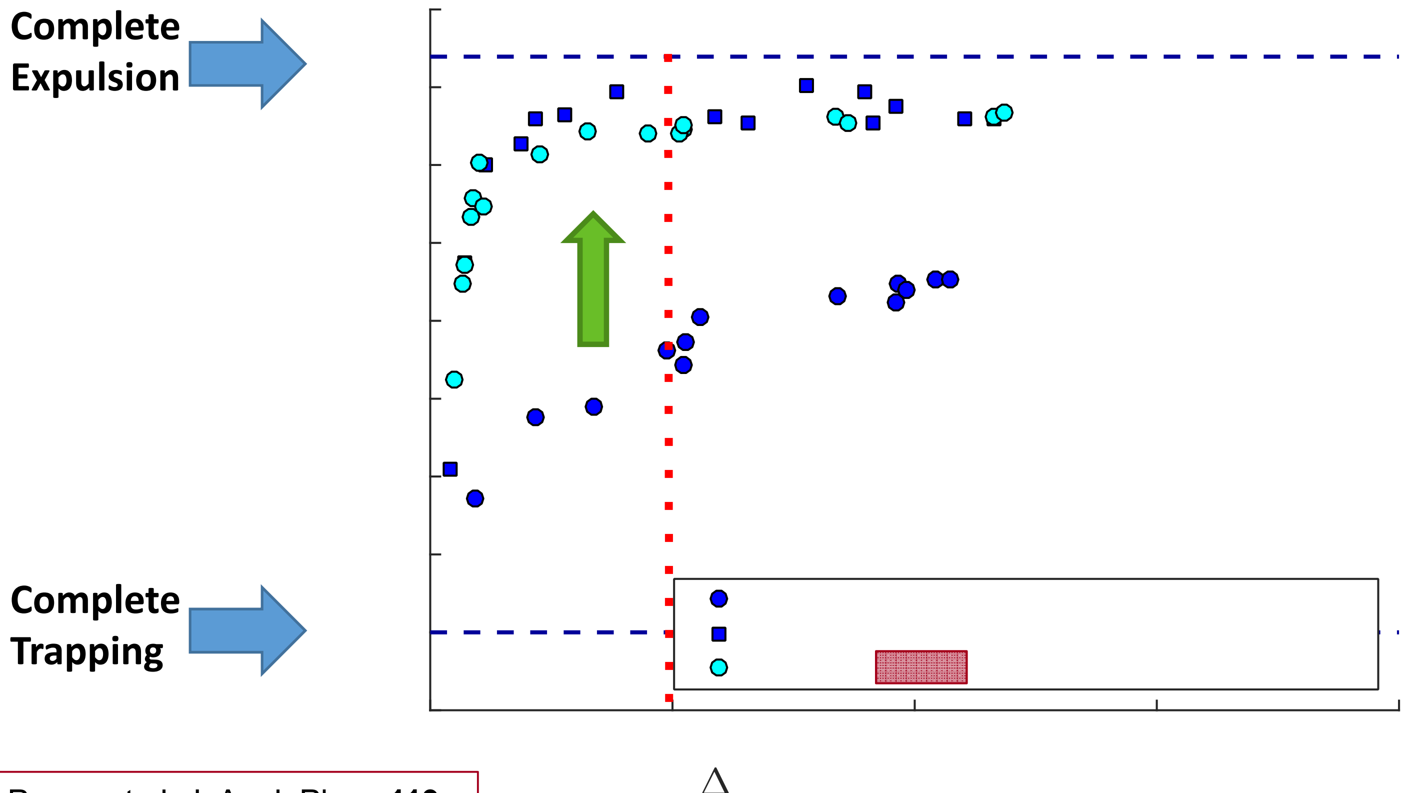

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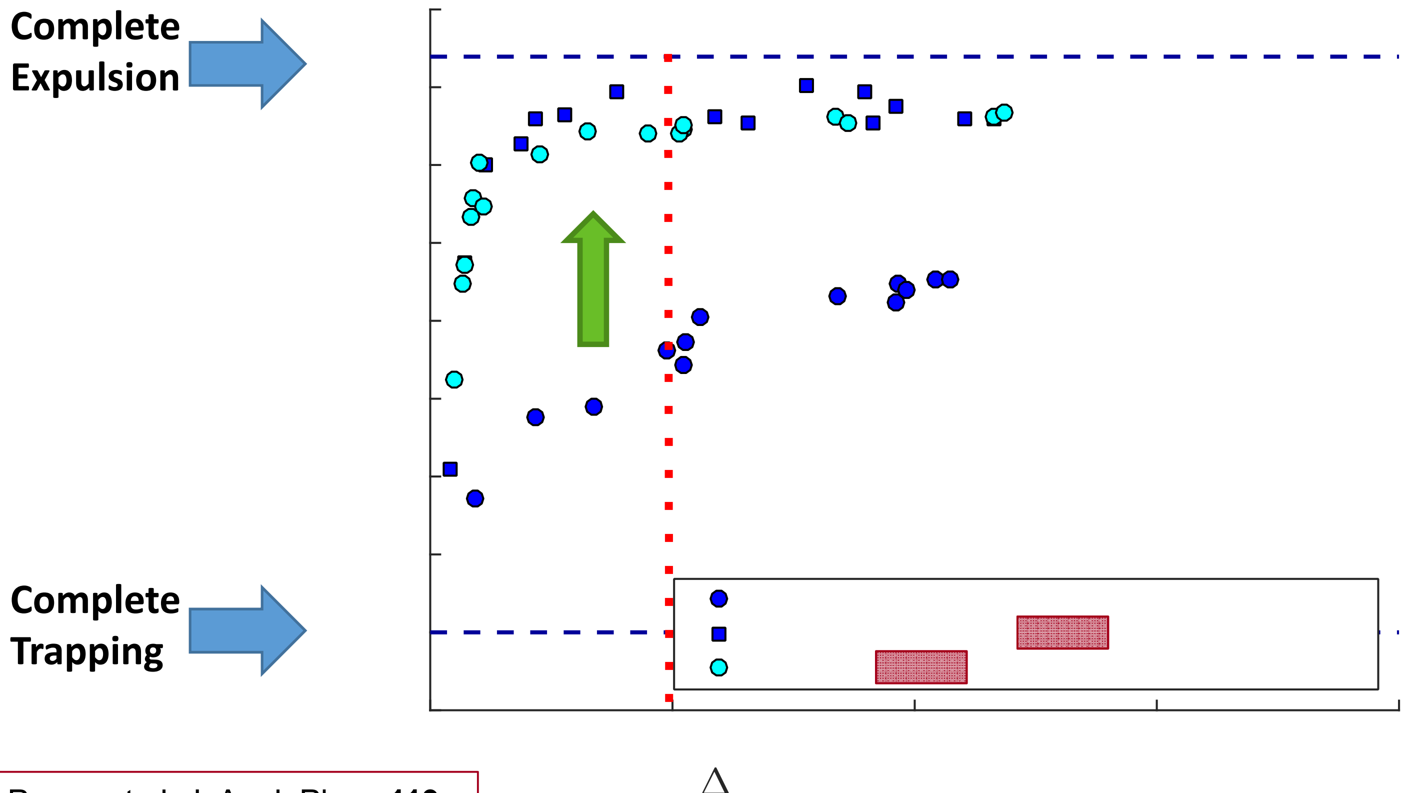

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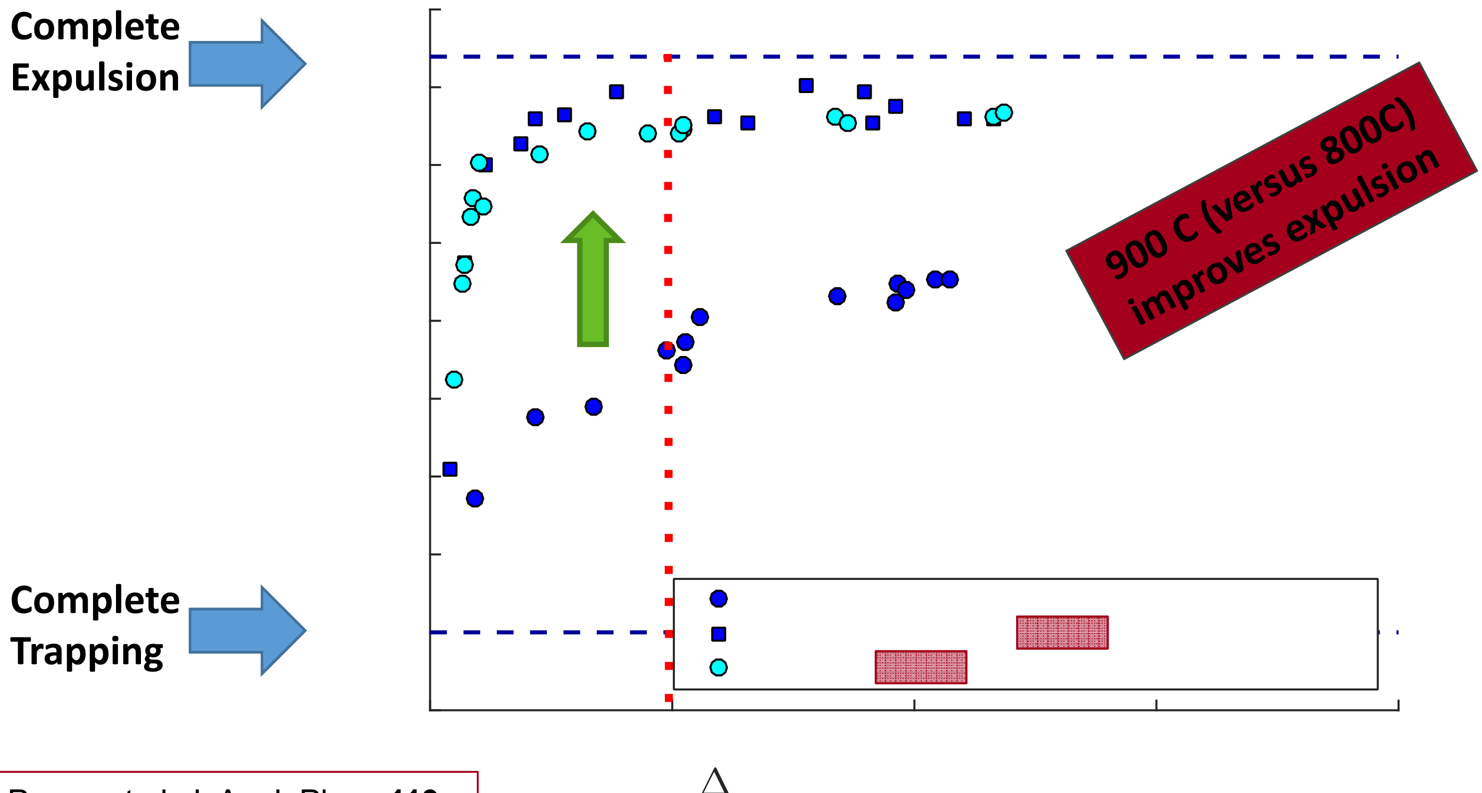

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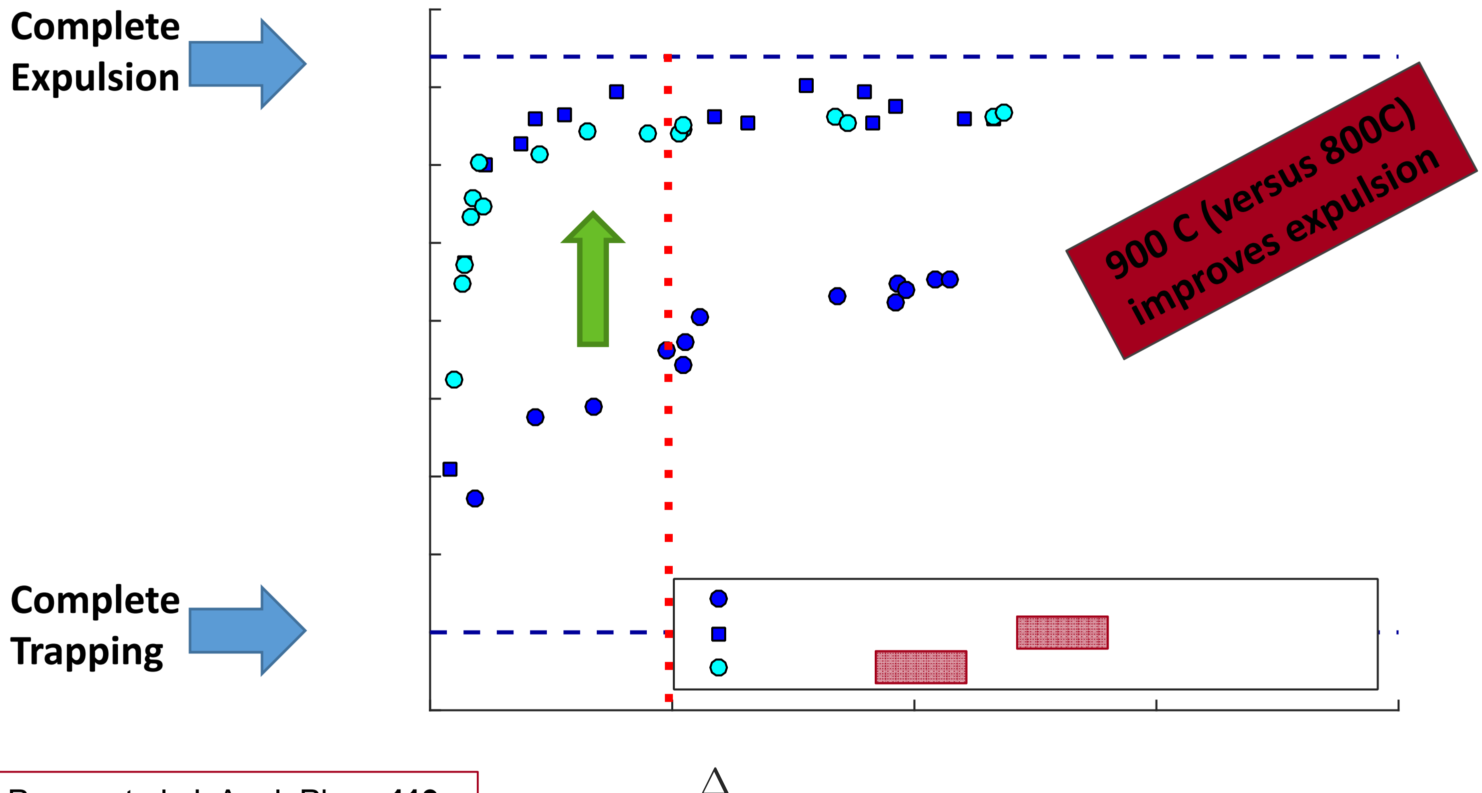

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MOPLR026 Material qualification of LCLS-II production niobium material including RF and flux expulsion measurements on single cell cavities

Production 9 cell Testing

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- Cavities from one vendor have been received and tested.
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  - **Avg Max Gradient = 22.8 MV/m***
    - (11 of 14 Administratively Limited at 24 MV/m)
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Production 9 cell Testing

- Cavities from one vendor have been received and tested.
  - All of these cavities from one material supplier.
- First 16 production cavities have been tested
  - **Avg Q_0 = 2.4x10^{10} at 16 MV/m**
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    - (11 of 14 Administratively Limited at 24 MV/m)
- **Limitation in cavity Q_0 are understood and being addressed**
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Total Rs budget for Q~ 2.7e10 = 10 nanoOhms

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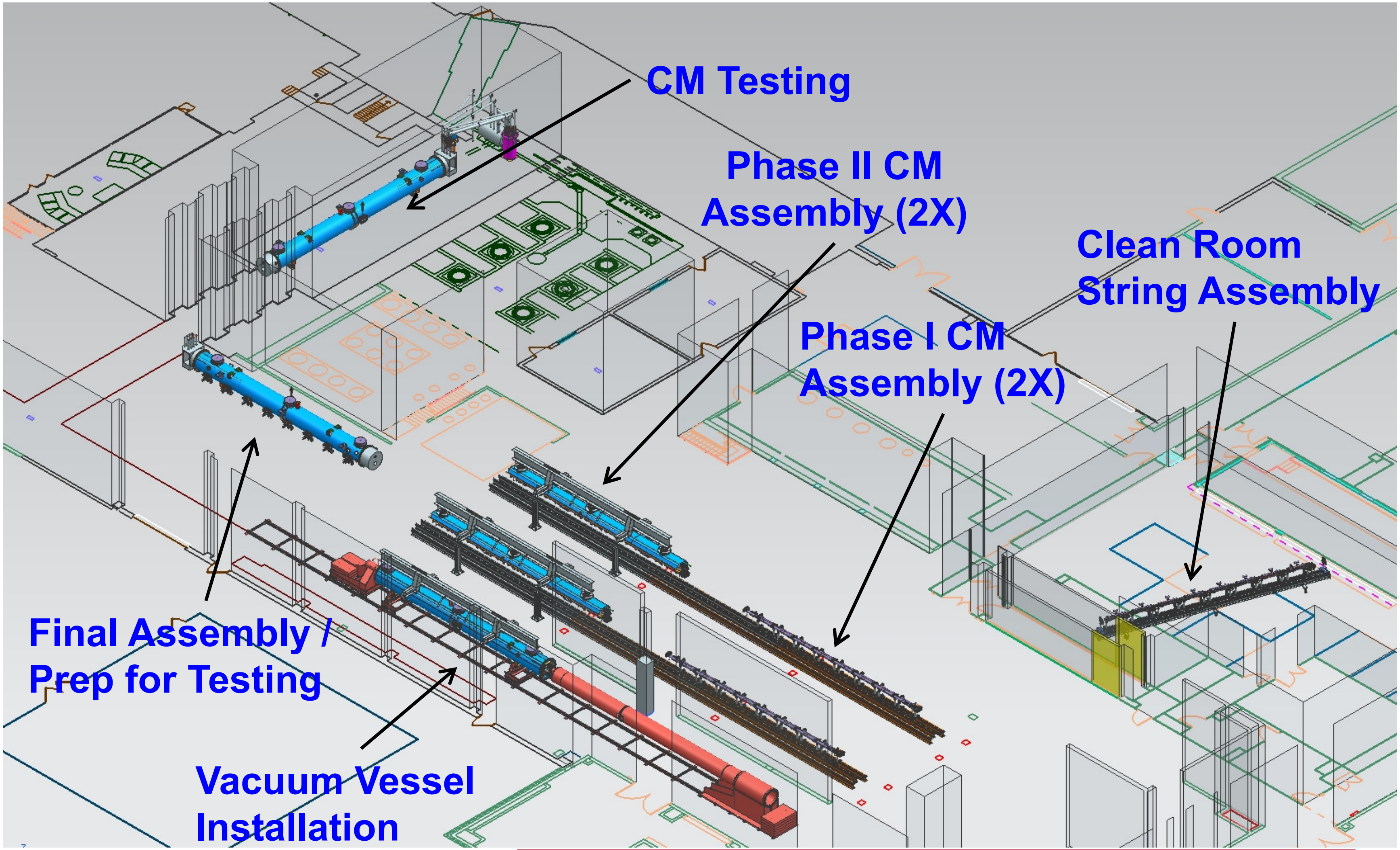
Cryomodule Production and Testing

Cryomodule Assembly Strategy at FNAL and JLab

- **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)

JLab Layout for LCLS-II CM Production



TUPLR022 Particulate Study on Materials for Cleanroom Assembly of SRF Cavities

Cryomodule Testing Infrastructure

Cryomodule Testing Infrastructure

FNAL

- New CMTS ready for testing
- New Cryoplant has been commissioned successfully
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- ~400 Cable connections complete

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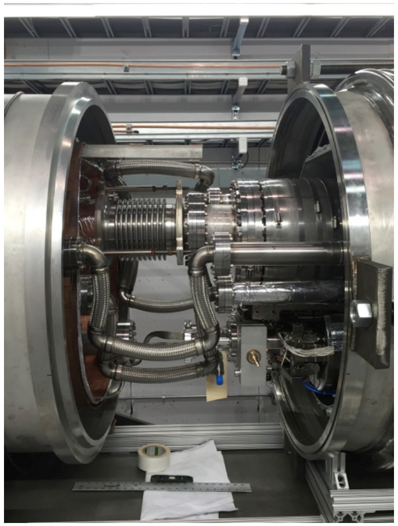

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- New cryo distribution box ready
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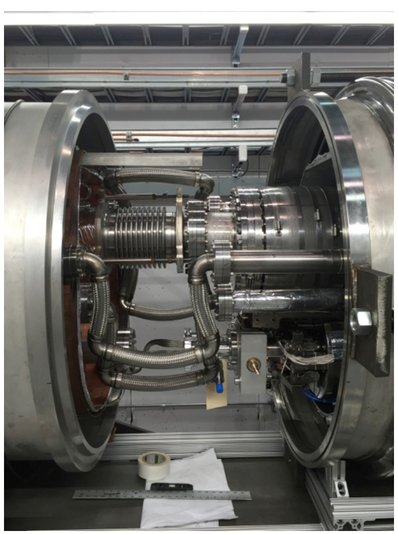

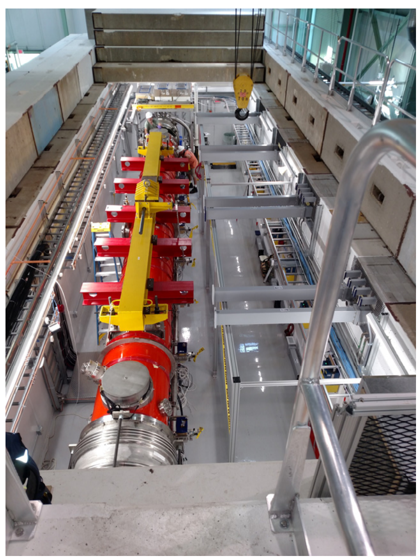

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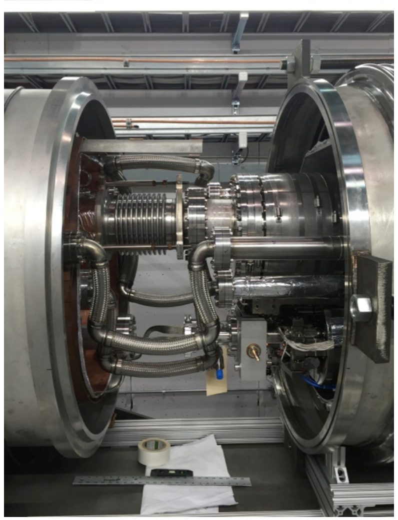

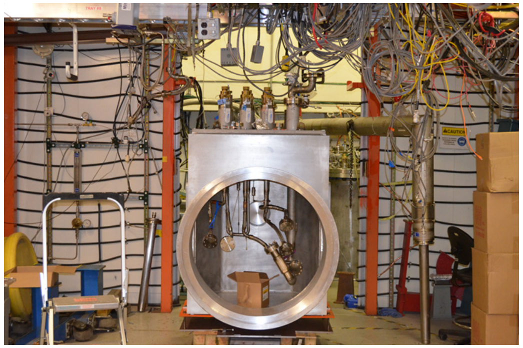

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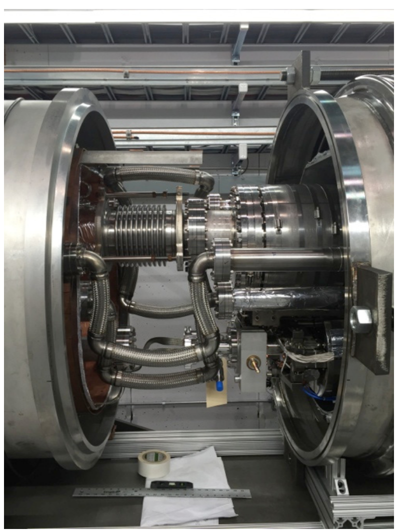

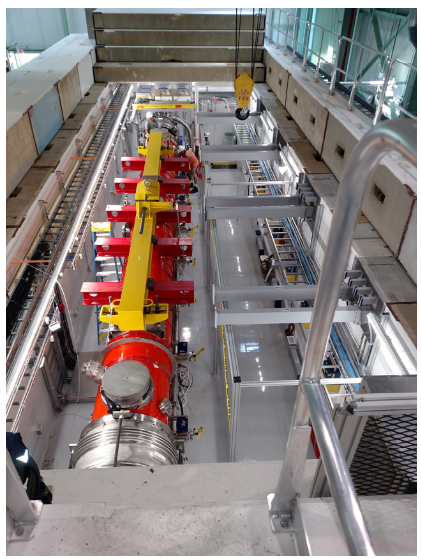

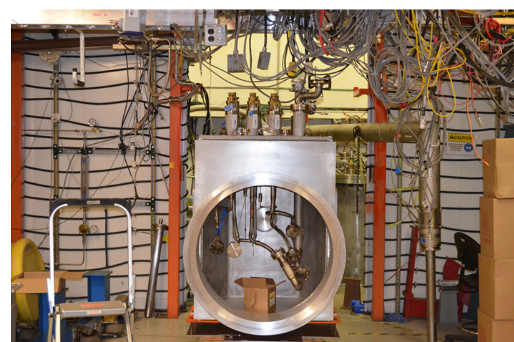

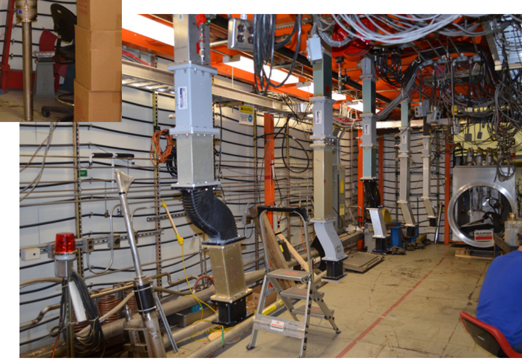

Prototype Cryomodule Status Overview

- Cryomodule Assembly complete at FNAL.
- JLab in Phase II of cryomodule Assembly (~75% complete)
- Testing underway at FNAL
- Testing slated to begin in November at JLab

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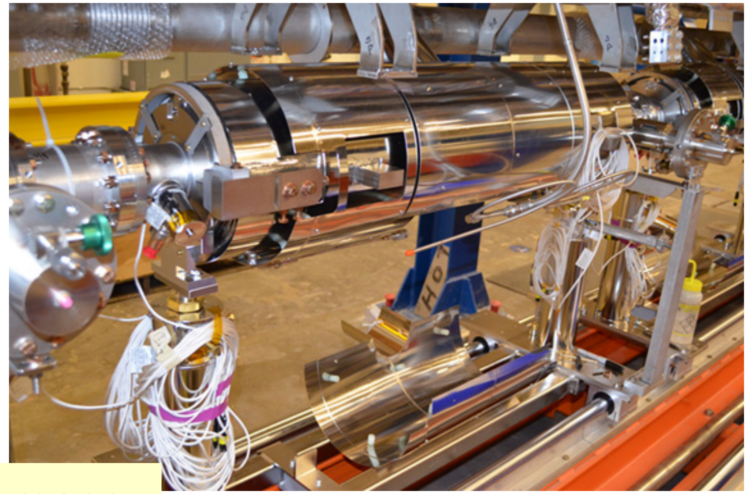
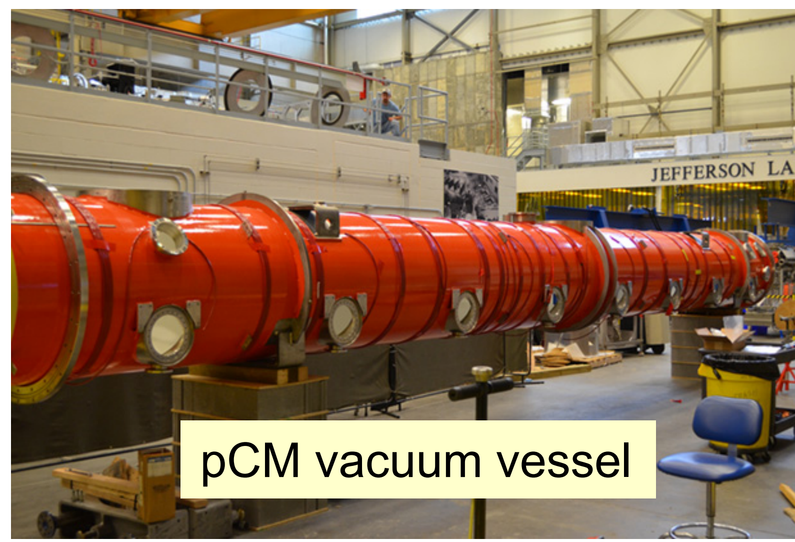
- CM Acceptance criteria are designed to ensure that the CMs delivered to SLAC will meet the requirements for LCLS-II.
  - $Q_0 \geq 2.7x10^{10}$ at 16 MV/m at 2.0K. (XFEL = $1x10^{10}$ at 24 MV/m at 2K)
  - Dark current specification of no more than **10 nA/CM**
  - CM operation within the cryogenic budget

- CM acceptance criteria generated after Cavity & CM testing workshop hosted by FNAL in Oct 2015.
  - https://indico.fnal.gov/conferenceDisplay.py?confId=10553
  - Acceptance criteria chosen for individual cavities and prototype CMs

Prototype CM at JLab:

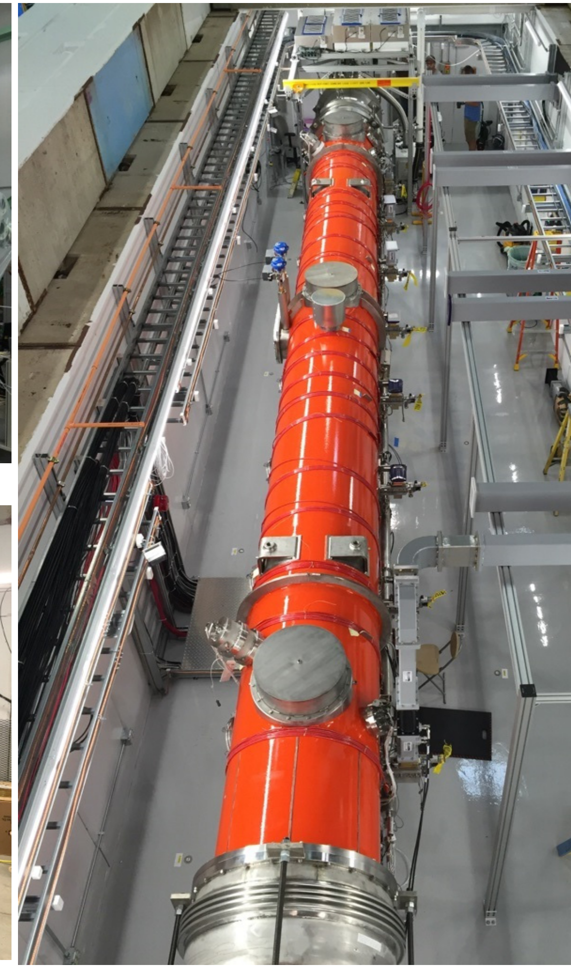


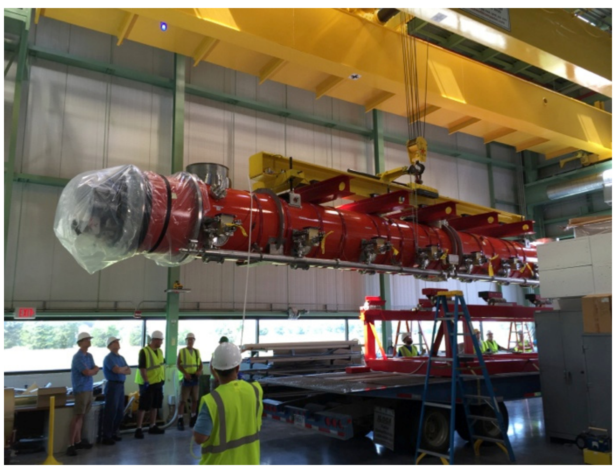
pCM cold mass

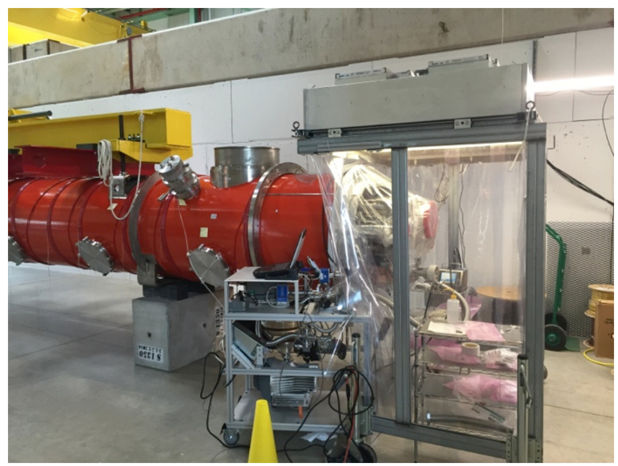


pCM vacuum vessel

Prototype CM at Fermilab:







Transport

Staging Area

pCM in Fermilab Test Area

TUPLR007 LCLS-II Cryomodules Production at Fermilab

Magnetic Hygiene

Magnetic Hygiene

- CM ambient magnetic field specification ≤ 5 mG
- Achieved with strict control of materials, dual layer magnetic shielding, and degaussing and active magnetic compensation on the module.
- Longitudinal fluxgates outside of cavities between two layers of magnetic shields
- 4 Cavities with fluxgates inside the
  helium vessel (cavities 1,4,5,8)
- Magnetic field monitored following installation
  and welding on the CM showed increased readings inside the HV.

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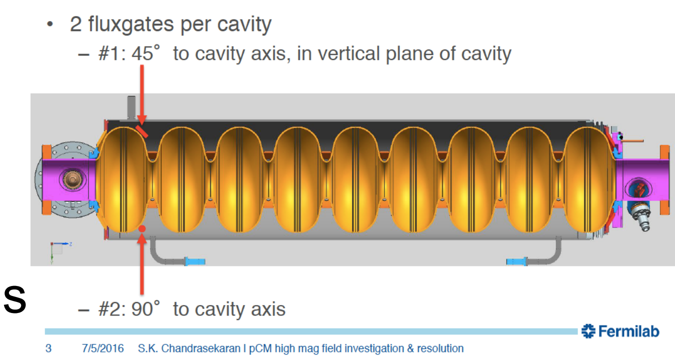

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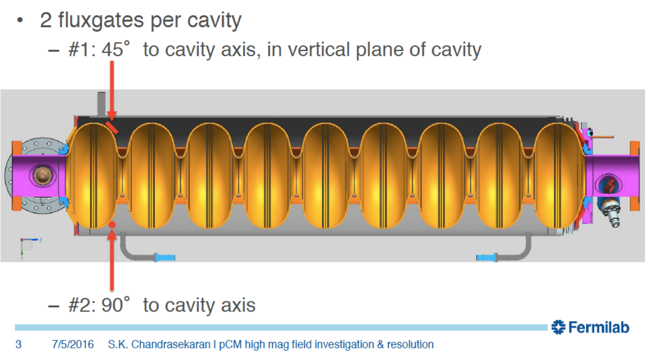

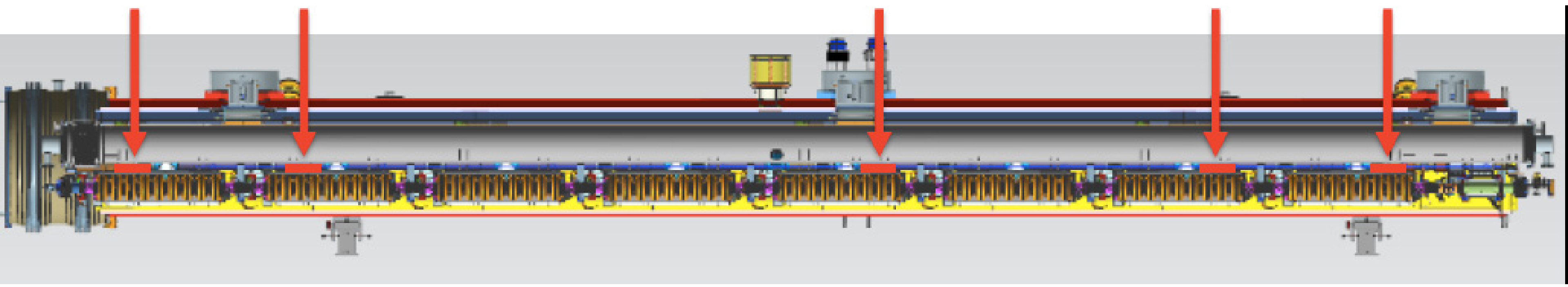

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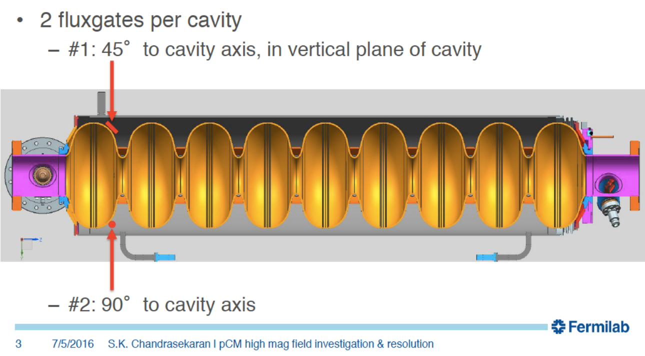

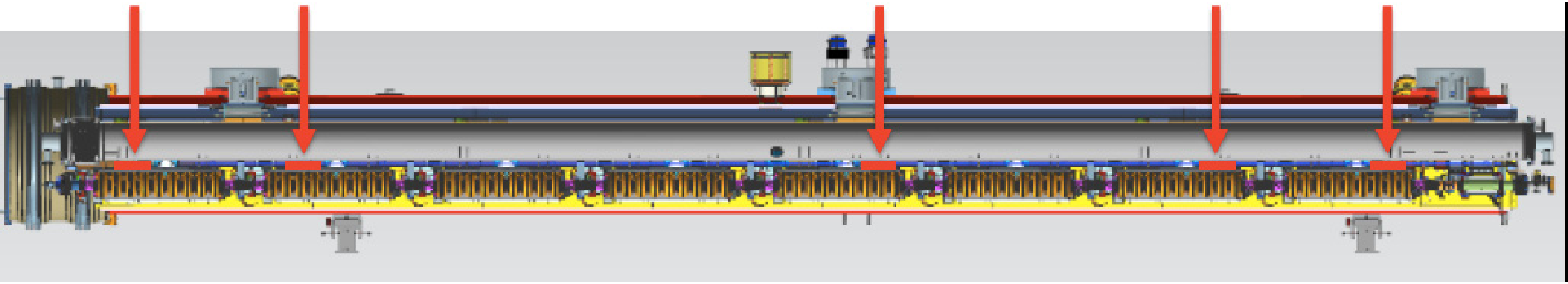

TUPLR027 Magnetic Field Management in LCLS-II 1.3 GHz Cryomodules

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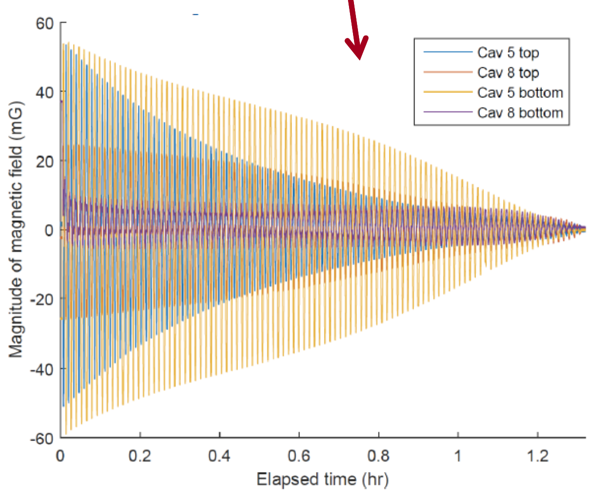

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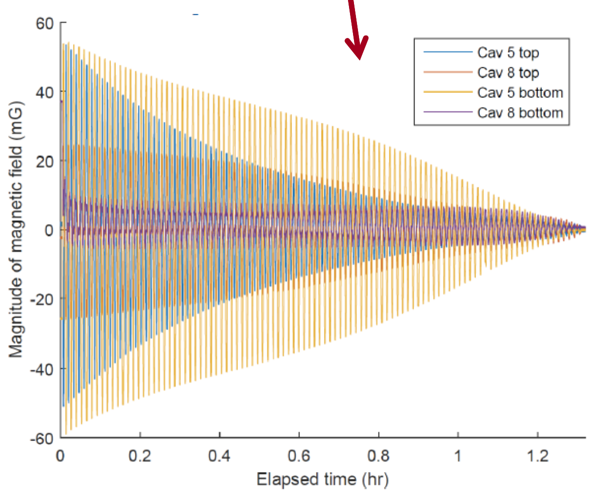

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Demonstration of demagnetization of a fully assembled CM

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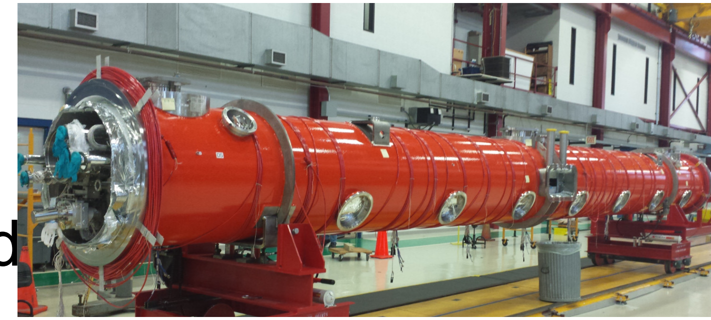

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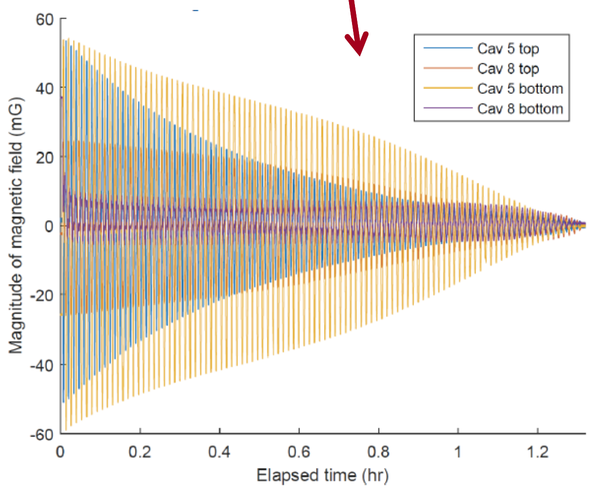
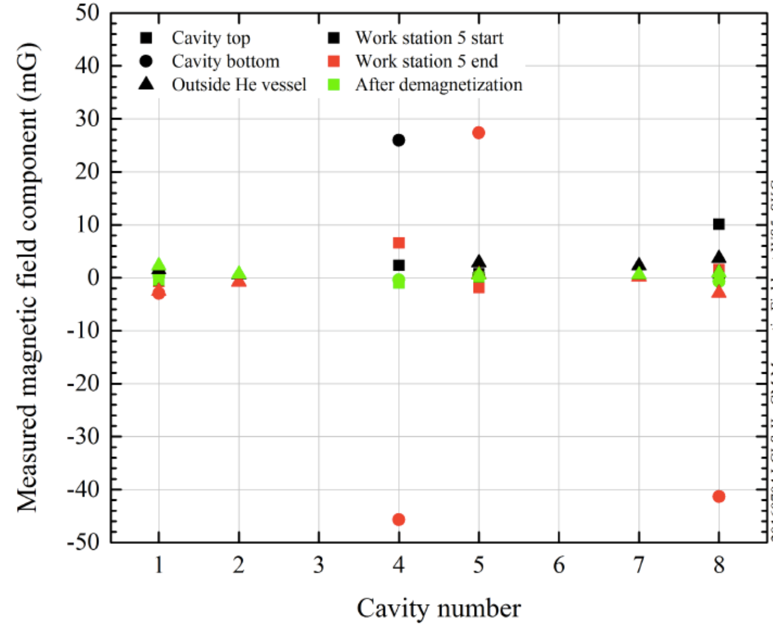


Demagnetization of pCM



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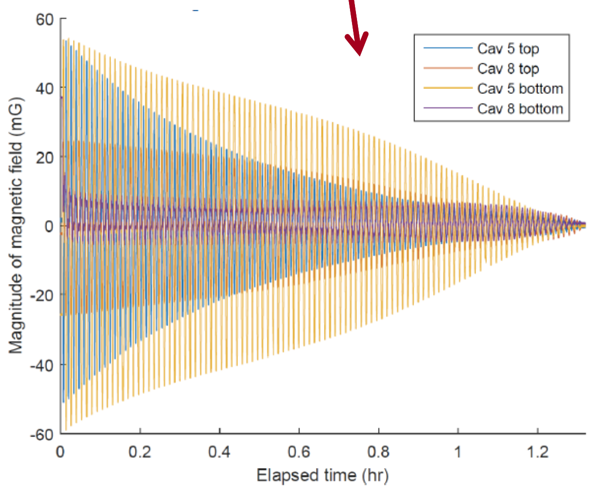

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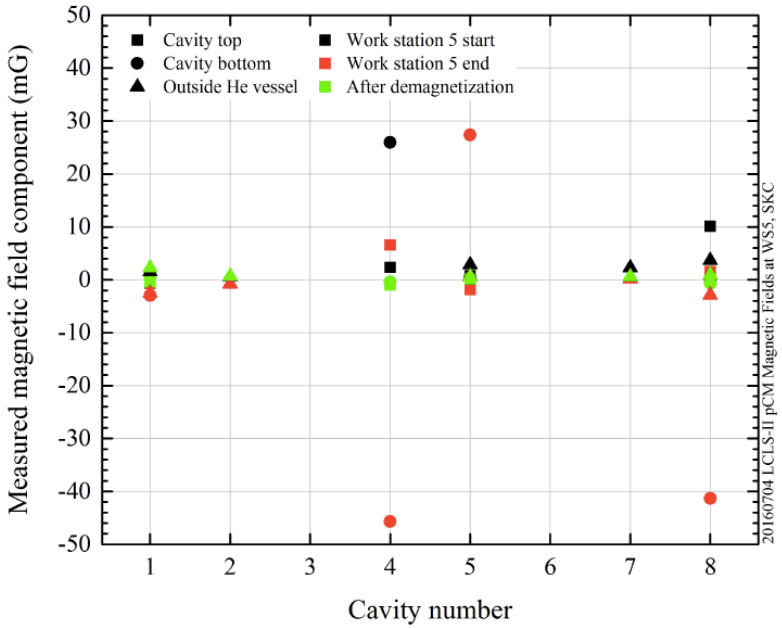

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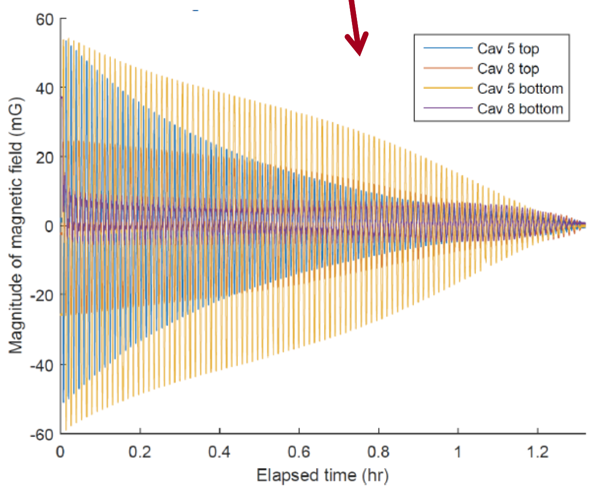

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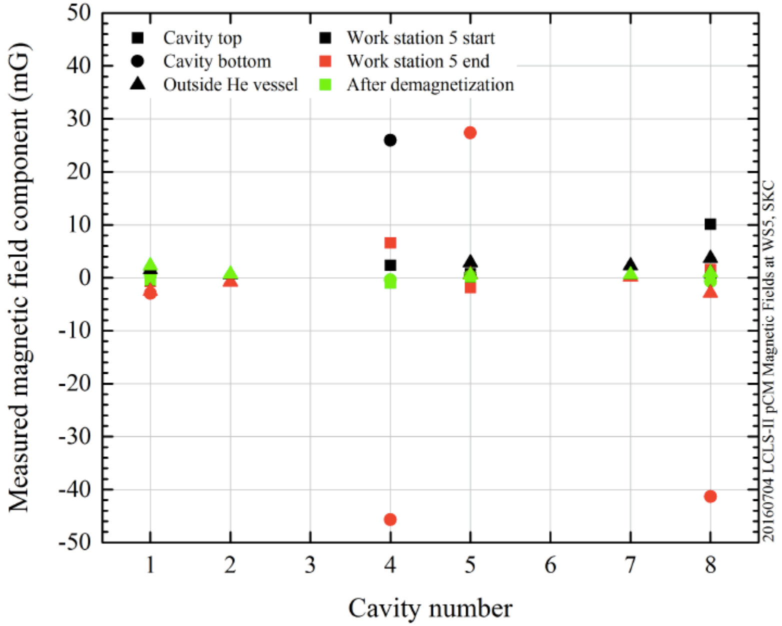

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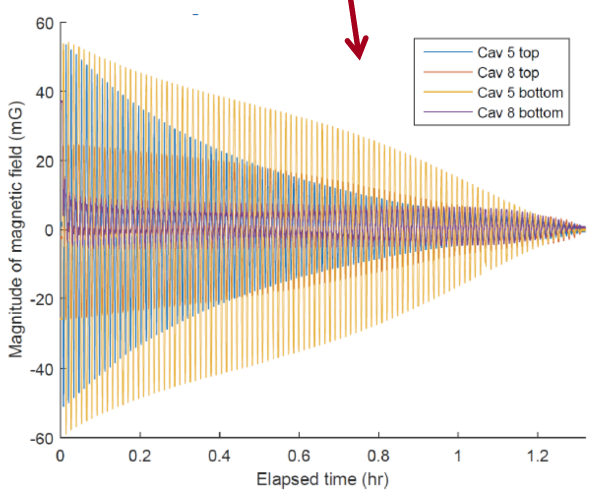

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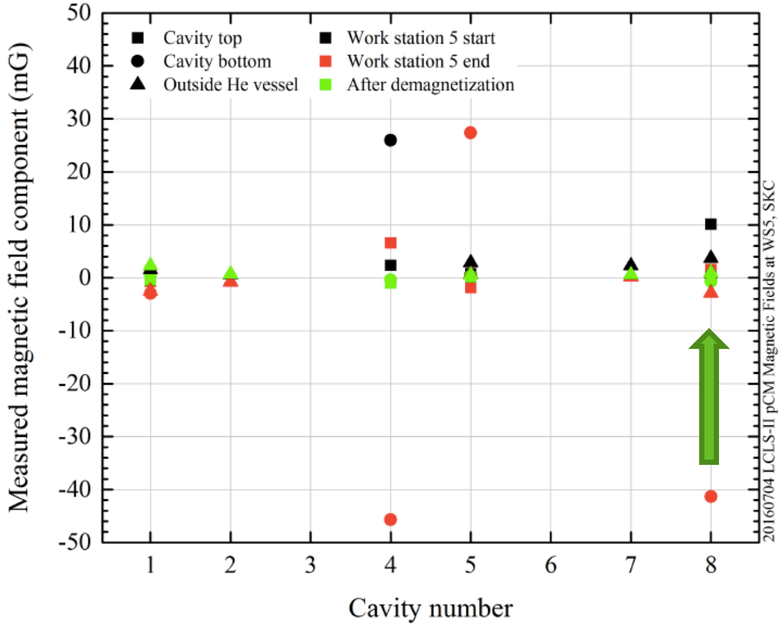

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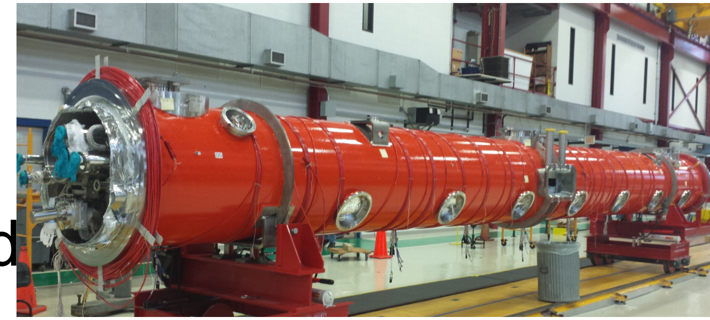

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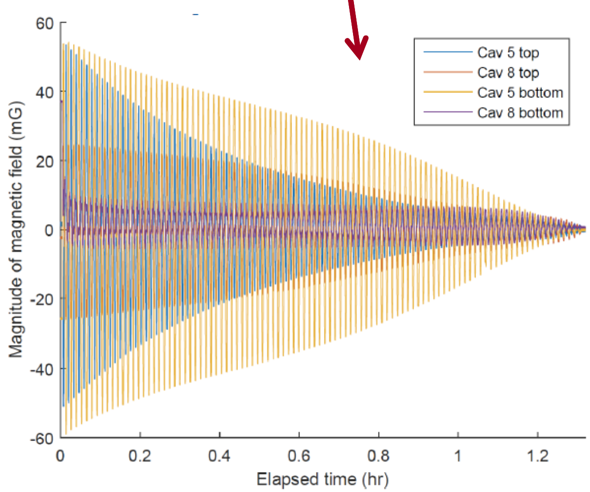

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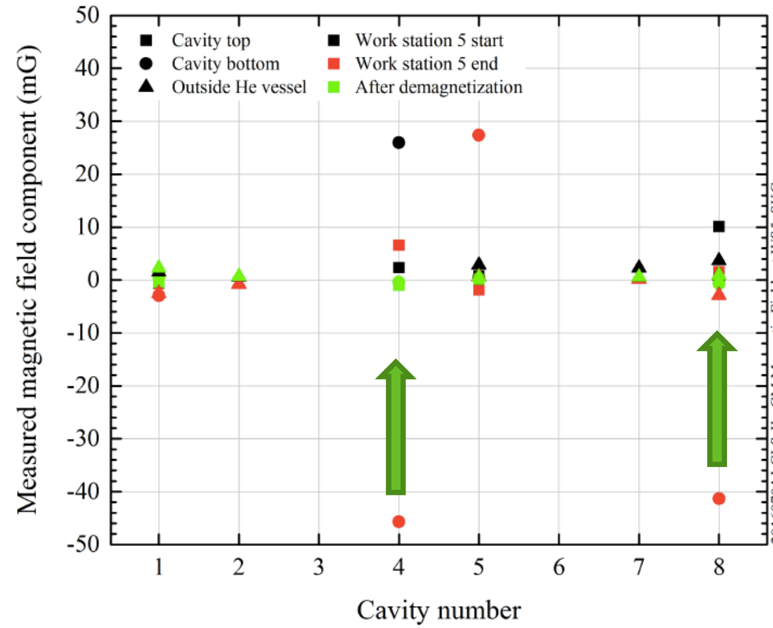

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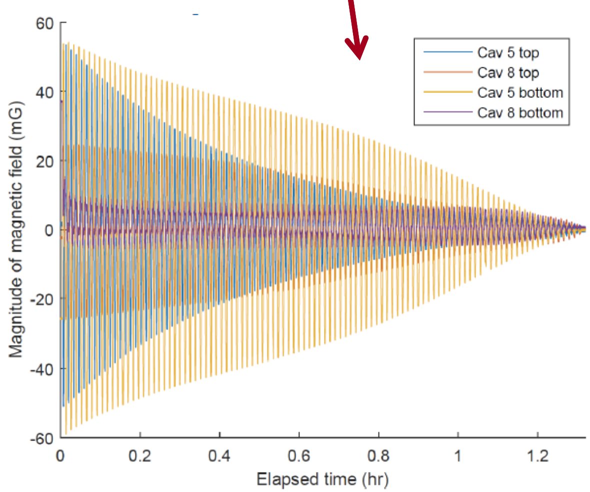

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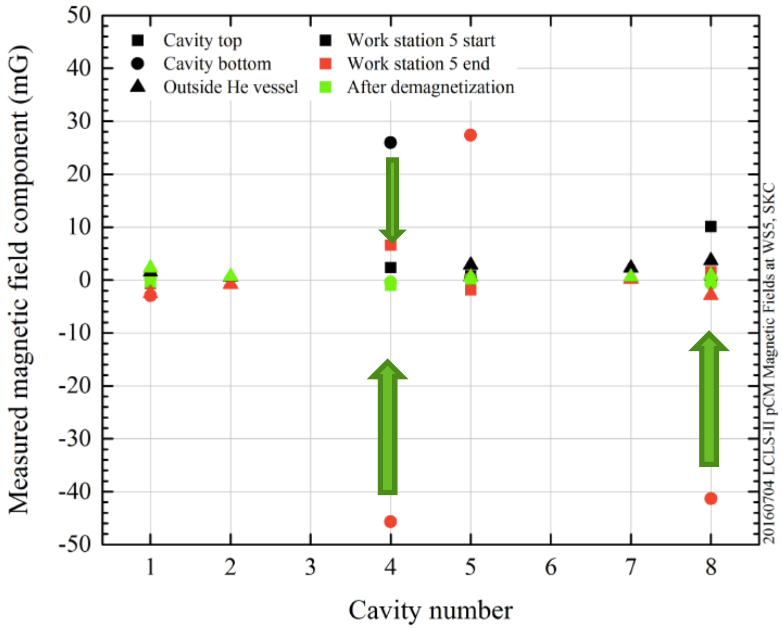

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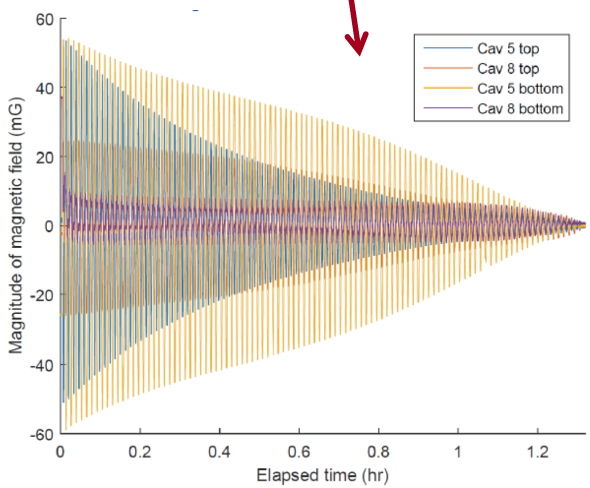
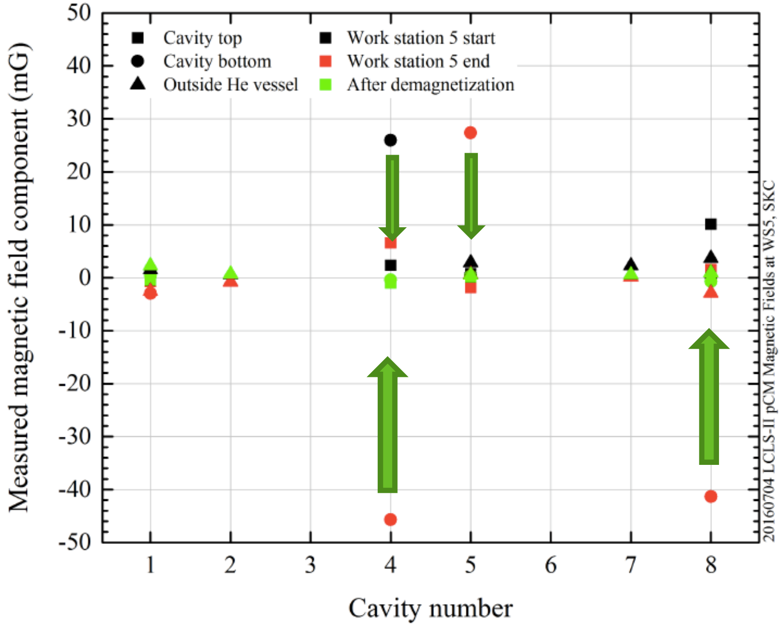


Demagnetization of pCM



It Works!!

Demonstration of demagnetization of a fully assembled CM

Work led by S. Chandrasekaran

Fermilab Prototype Cryomodule First Results

Fermilab Prototype Cryomodule First Results

- CM cooled down to 2.1K – cooldown to 2K this week
- Tuner motors and piezo all check out fine
  - Tuner motor temperature increase only 3K after continuous running
- BPM checked out – ok
- Magnet coils have been powered to 20 A – ok
- All FPCs warm conditioned up to 4 kW
  - No electron activity
  - No vacuum incidences
  - Q_{ext} set to 4.1×10^7
- **All 8 cavities brought up to 16 MV/m**
  - 6 with very little or no field emission
  - 2 require further processing

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MOPLR022 Commissioning and First Results from the Fermilab Cryomodule Test Stand

Summary

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- High Q_0 recipe will allow for LCLS-II to operate with average $Q_0 \geq 2.7 \times 10^{10}$ @ 16 MV/m
  - **130 MV Energy gain CW per CM = 80 W to 2K**
- A few issues have been identified in the R&D phase with production Nb sheet material
  - Solutions exist for these issues, being implemented by vendors
- Prototype cavity performance was excellent, exceeded spec
- Production cavity performance is very good, will get better
- Prototype CM assembly completed successfully at FNAL and nearing completion at JLab
- Initial results from FNAL are very encouraging

Could not be done alone.

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

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Acknowledgements

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.

LCLS-II

The End

SLAC NATIONAL ACCELERATOR LABORATORY

BERKELEY LAB Lawrence Berkeley National Laboratory

Argonne NATIONAL LABORATORY

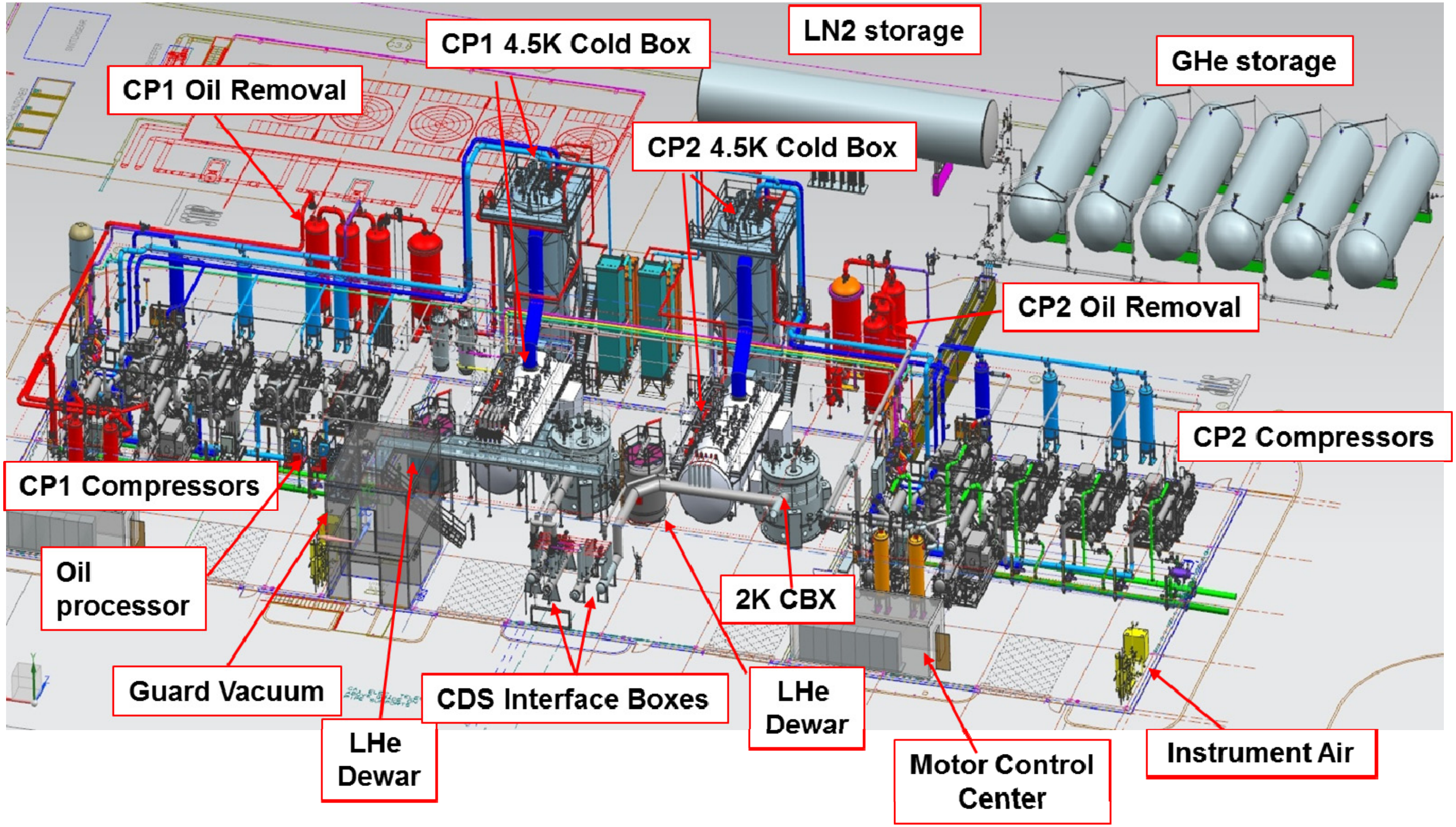
CORNELL UNIVERSITY FOUNDED A.D. 1865

Fermilab

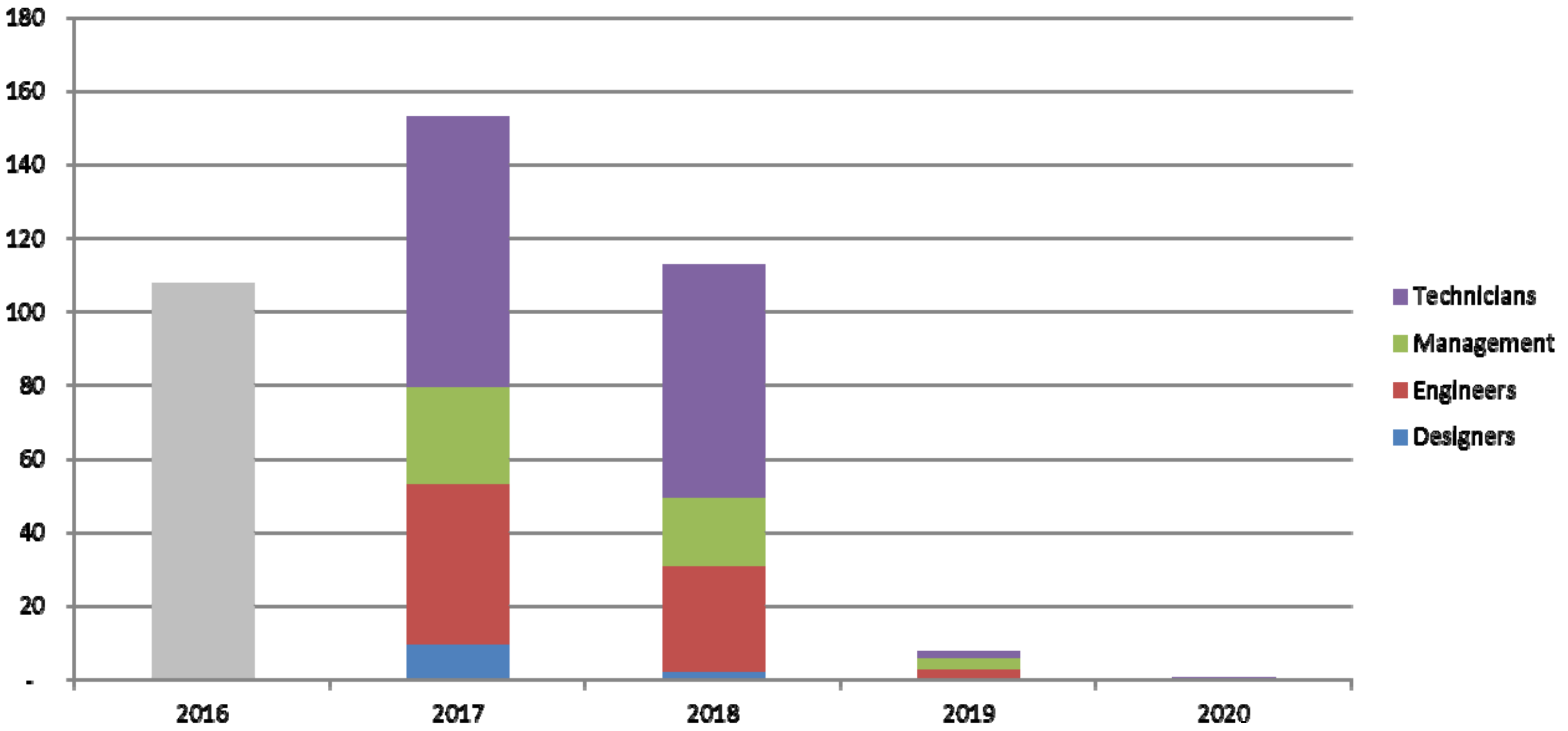
Jefferson Lab

Backup

Cryogenic Cooling Facilities: 2 x 4kW @2 K



1.04 – Cryogenics Systems – Staffing (FTEs)



Thru month end June 2016 averaging 96.7 FTE