Technical Developments in Support of Accelerator-based Science at SLAC

Marc Ross (SLAC LCLS-II)

International Beam Instrumentation Conference

September 15, 2014

Technical Developments for Accelerator-based Science

Basic Energy Science Advisory Committee (BESAC) and Particle Physics Project Prioritization Panel (P5)

1. *BESAC recommends FEL construction:*
   - SLAC proposed LCLS-II, now accepted,
   - a new 4 GeV CW superconducting linac
   - LCLS-II involves several US partner-labs
   - now in full-swing.
2. *P5 strongly supports International Linear Collider (ILC) development,*
   - directed toward construction in Japan.

Both rely on L-band superconducting RF (SRF) technology in development for 25 years.

SRF Development for particle physics deployment phase:

SRF technology was developed for use in high-energy physics accelerators.

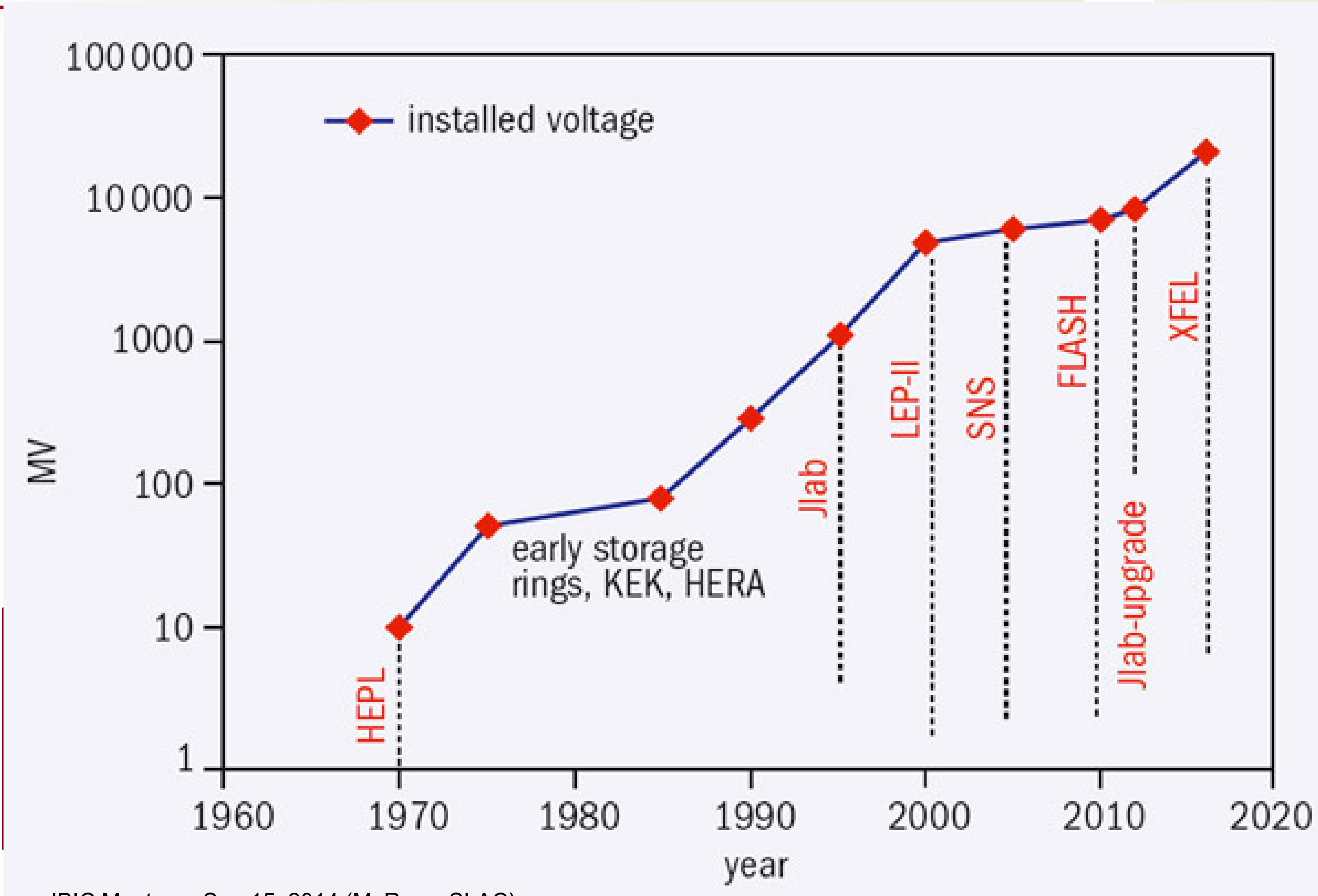
Pioneers: e+/e- collider storage rings at DESY (Petra), Cornell (CESR), KEK (Tristan), and Cern (LEP)

Goal: cost-effective, high-gradient, reliable SRF for next generation e+/e- colliders: storage-ring 'factories' and linear colliders.

TESLA collaboration: increasing the practical SRF accelerating gradient to propose a multi-kilometer pulsed SRF linac.

1. <u>increase industrial involvement,</u>
2. <u>reduce static cryogenic-loss,</u>
3. <u>improve packing-factor</u>

SRF Development for particle physics deployment phase:



SRF for the International Linear Collider (2005 – present)

2012: **International Linear Collider (ILC) Technical Design Report**

- ILC Technical Design:
  - standardized, industrialized, production recipe for 1.3 GHz bulk-niobium SRF cavities
  - Performance demonstration, production capability, cost estimate

European XFEL project, (DESY host), with roughly 100 (800 SRF resonator cavities) cryomodules using exactly this technology (2016)

LCLS-II project, (SLAC host), 300 cavities using the CW adaptation of this technology

Outline

1. Industrialization of 1.3 GHz SRF technology
   - 1990's to present
   - TESLA, E-XFEL, and ILC (also CEBAF 12 GeV)
2. LCLS-II
   - Free Electron Laser at SLAC – based on ILC / E-XFEL SRF
3. SRF for LCLS-II
   - Low cryogenic-loss cavities: 'N_2 doping' process developed by Fermilab
   - Multi-lab partnership
4. Implications for ILC

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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 (3QFY15)

2014: High Q0 Process development (Apr – Sep)

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 ?*

SRF Cost Reduction / Risk Reduction through application

LCLS-II SCRF linac basic building block: 9-cell sheet-metal cavity

Figure 1.2-1: A TESLA nine-cell 1.3 GHz superconducting niobium cavity.

~ 70 parts electron-beam welded at high vacuum

- ~ 1.25 m^2 x 3mm thick sheet metal

pure niobium and niobium/titanium alloy

- niobium cost similar to silver

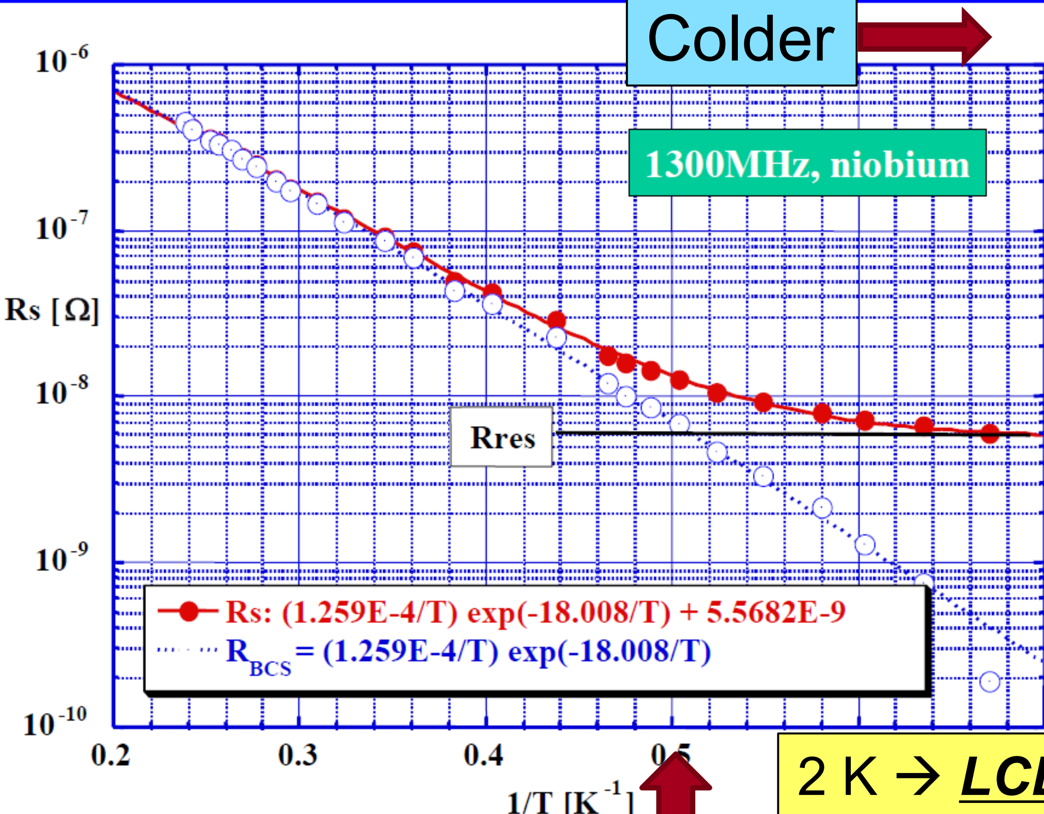
weight ~ 70 lbs

6 flanges

SCRF vs temperature

Colder is better – to a point

Measurement of the Surface resistance



2 K → ***LCLS-II temp***.

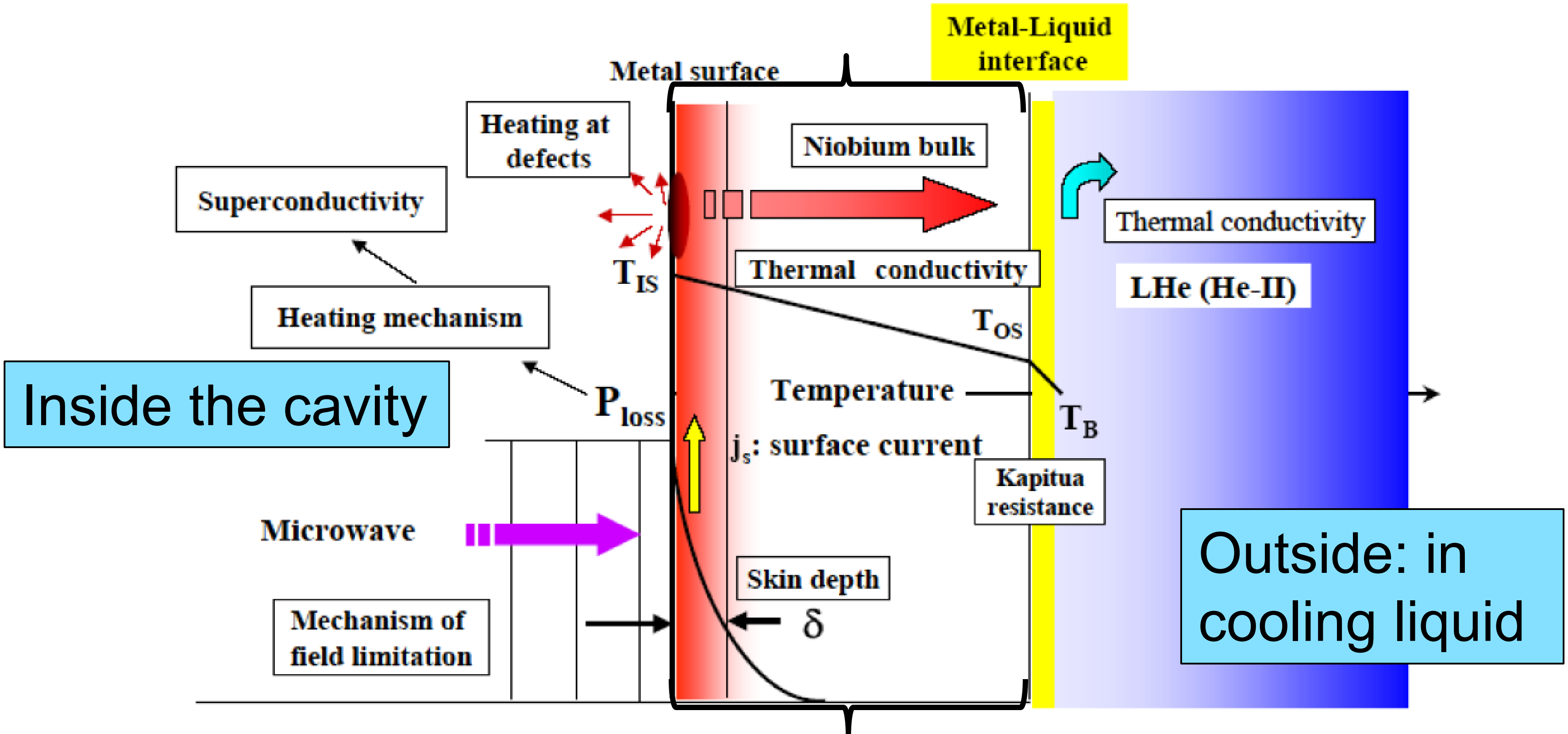
R_{BCS} ~ 8nΩ,
理論と良く合っている。

Real surface resistance : $R_S = R_{BCS}(T) + Rres$

東大物理大学院集中講義2007 Kenji Saito, MSU

SRF Specifics and Constrains

What happens when microwave is input a cavity?



Surface resistance is very very small.

➡ Cavity performance strongly depends on the surface.

Thermal conductivity @ superconducting state is very small.

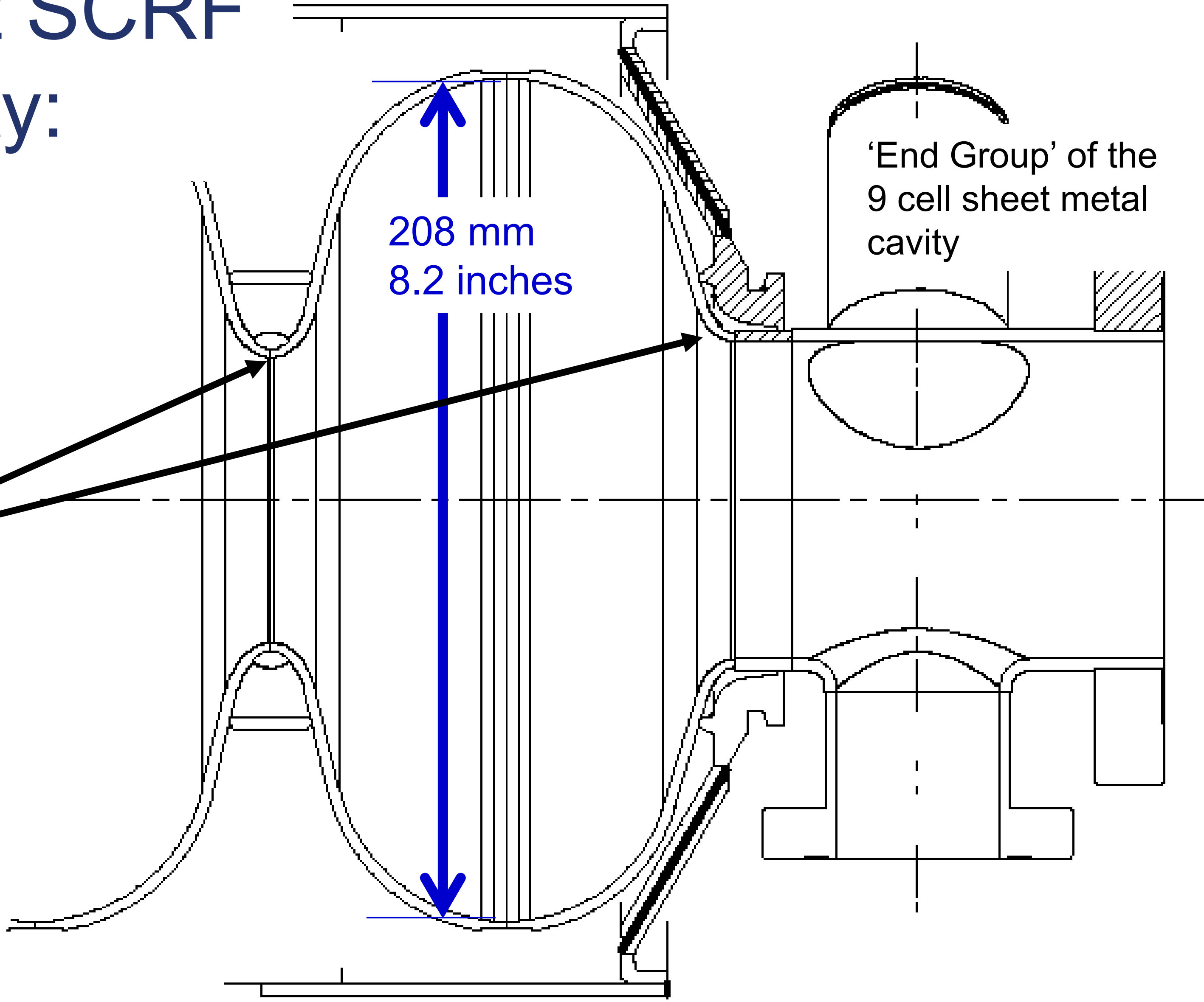
➡ *High thermal conductivity* is very important.

Kenji Saito, MSU

1300 MHz SCRF Cavity:

1.7 million volts acceleration between adjacent irises.

Electric current in the SCRF resonator is entirely in a thin film close to the internal surface



IBIC Monterey Sep 15, 2014 (M. Ross, SLAC)

1300 MHz SCRF Cavity:

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Electric cu
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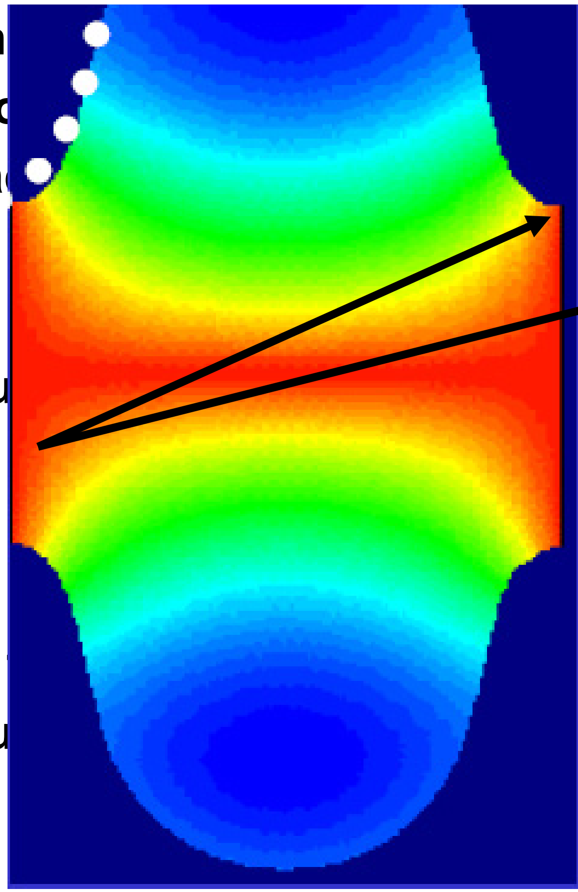

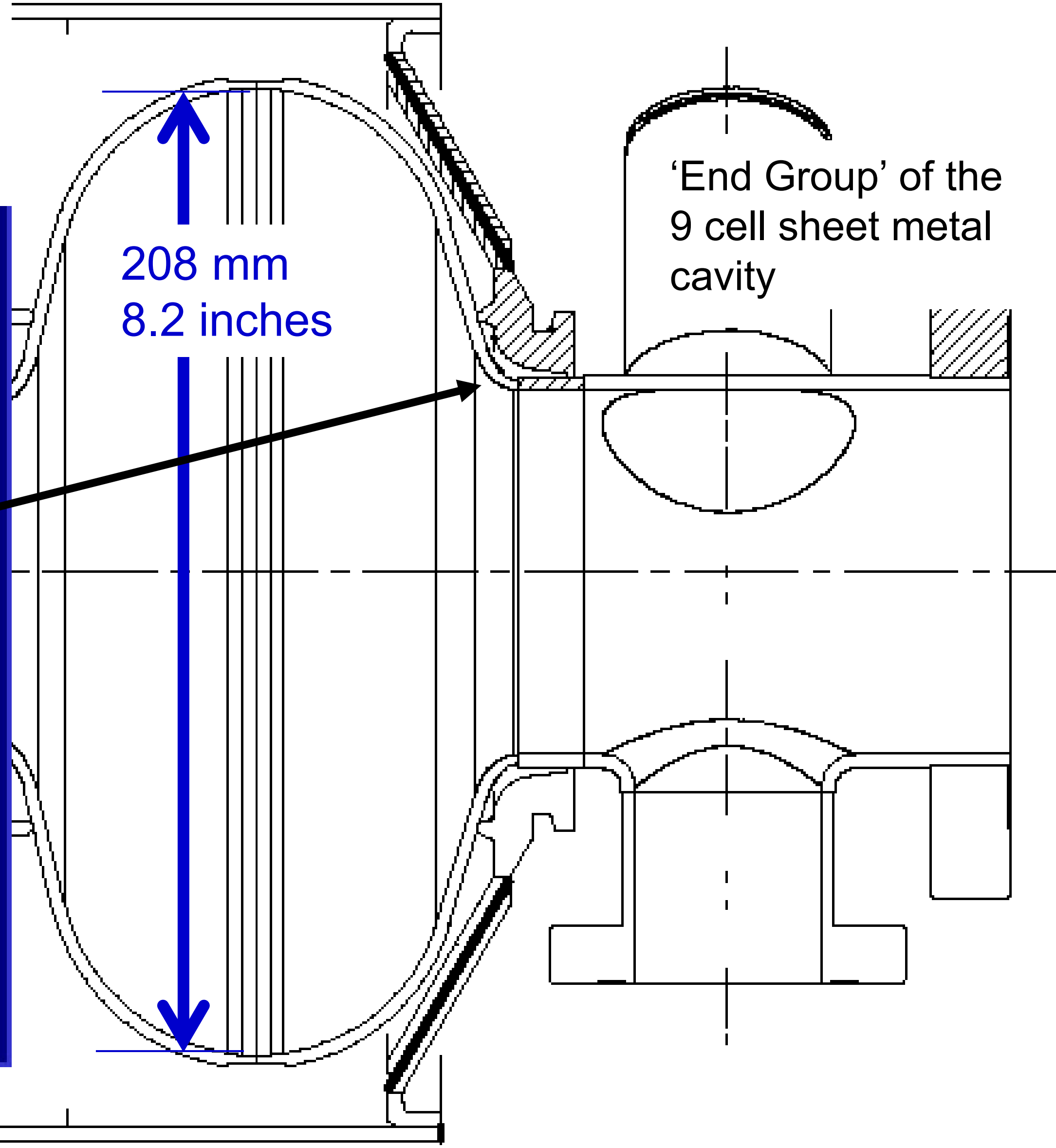

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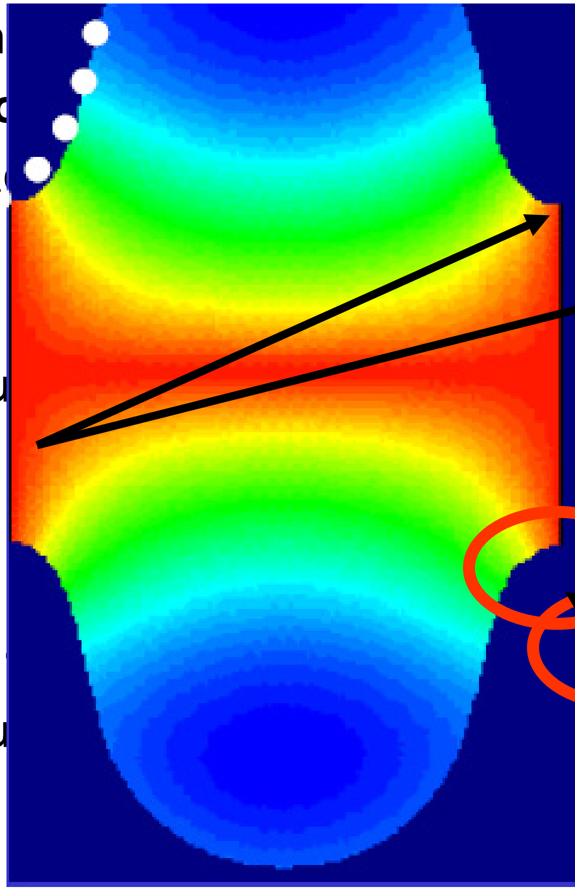
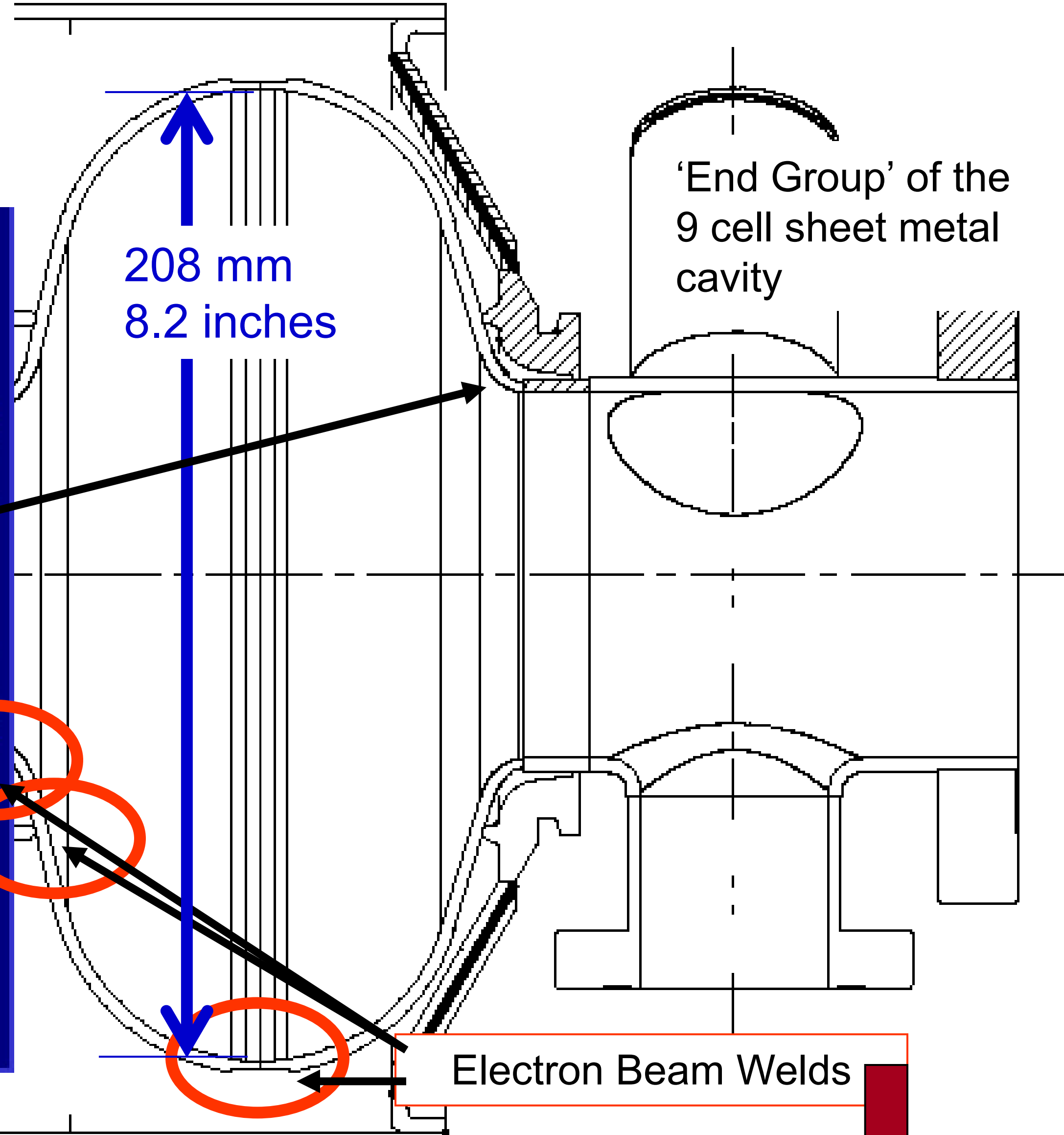
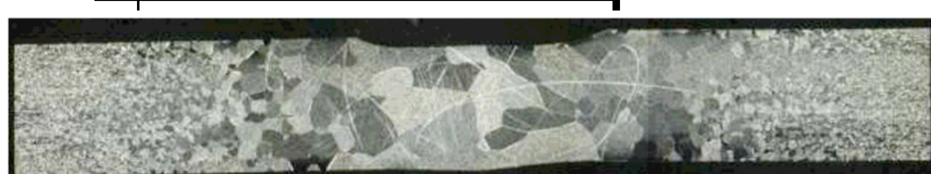


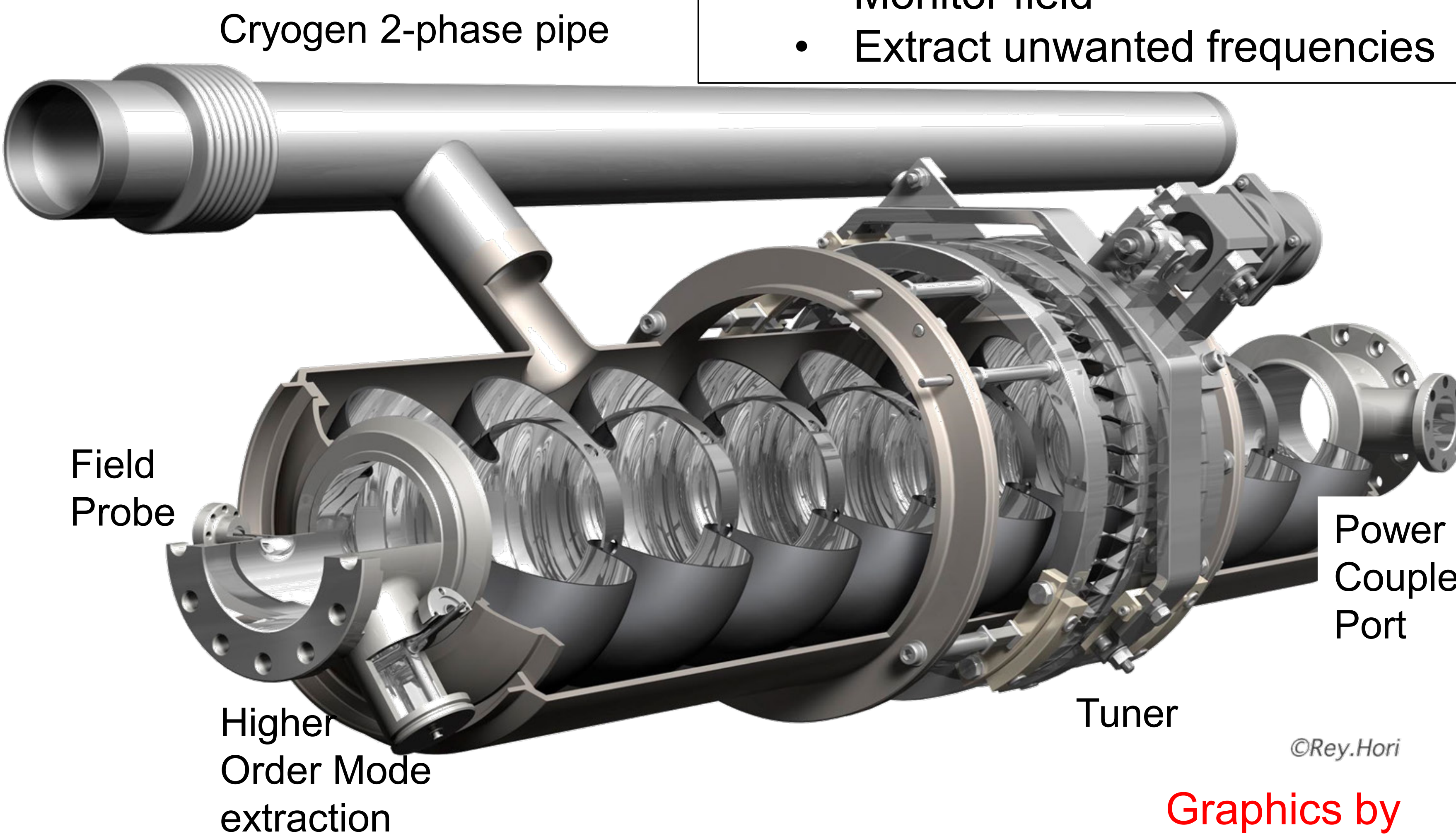




IBIC Monterey Sep 15, 2014 (M. Ross, SLAC)

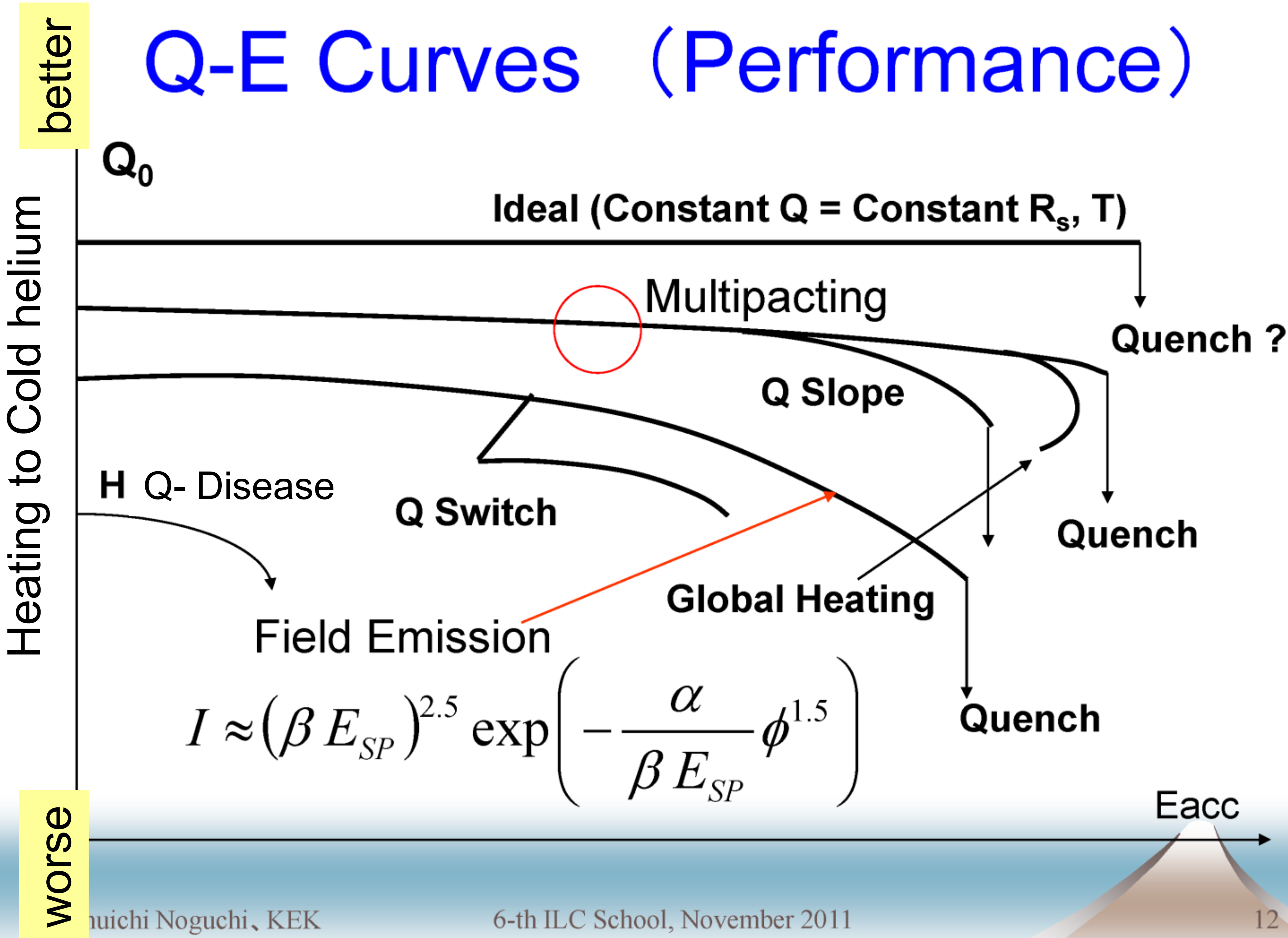
1300 MHz SCRF Cavity
inside its liquid-filled tank

- 9 cell resonator cavity
- Ports:
  - Beam in /out
  - Bring in power
  - Monitor field
  - Extract unwanted frequencies



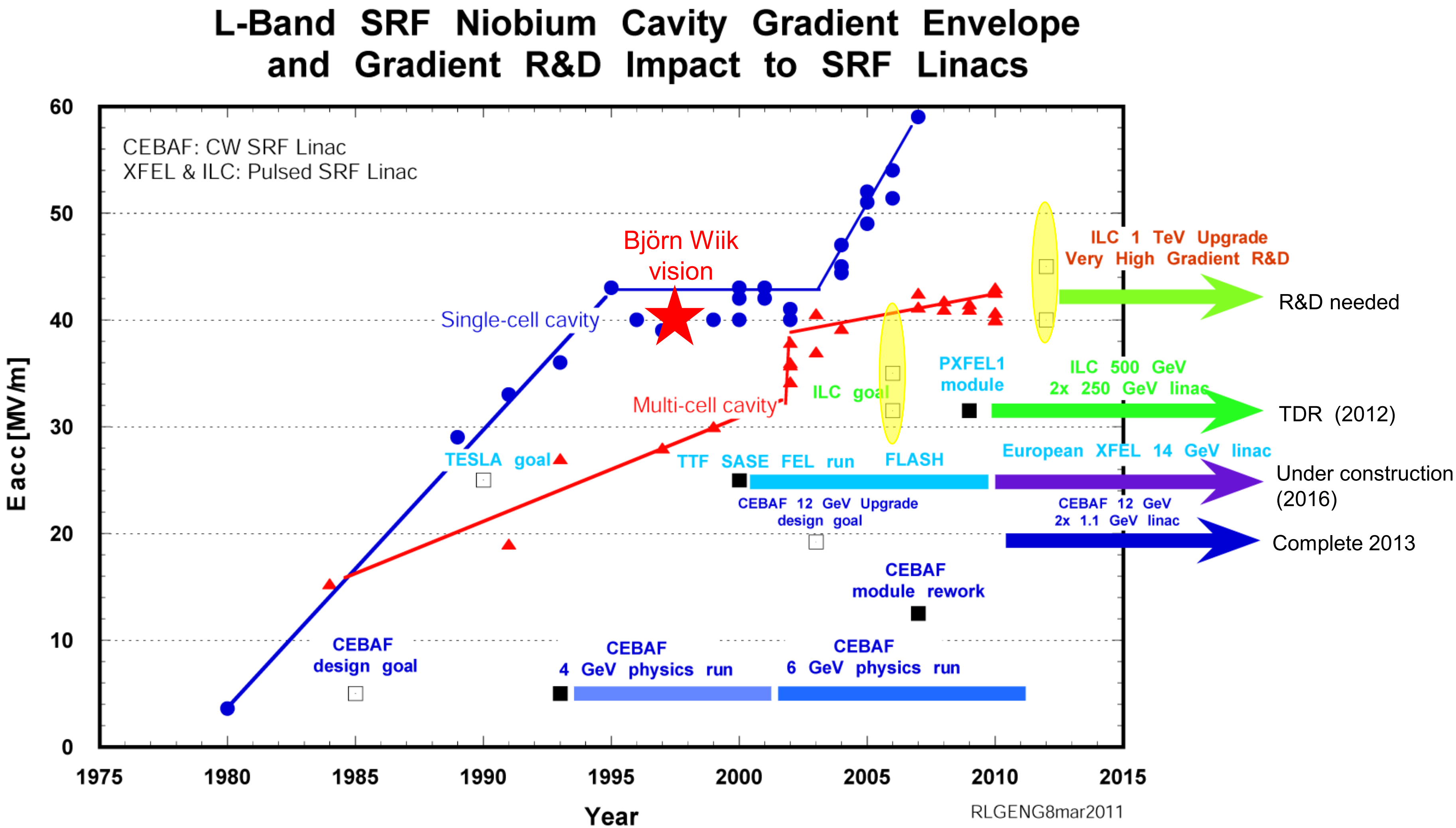
Graphics by Rey. Hori

Q-E Curves (Performance)



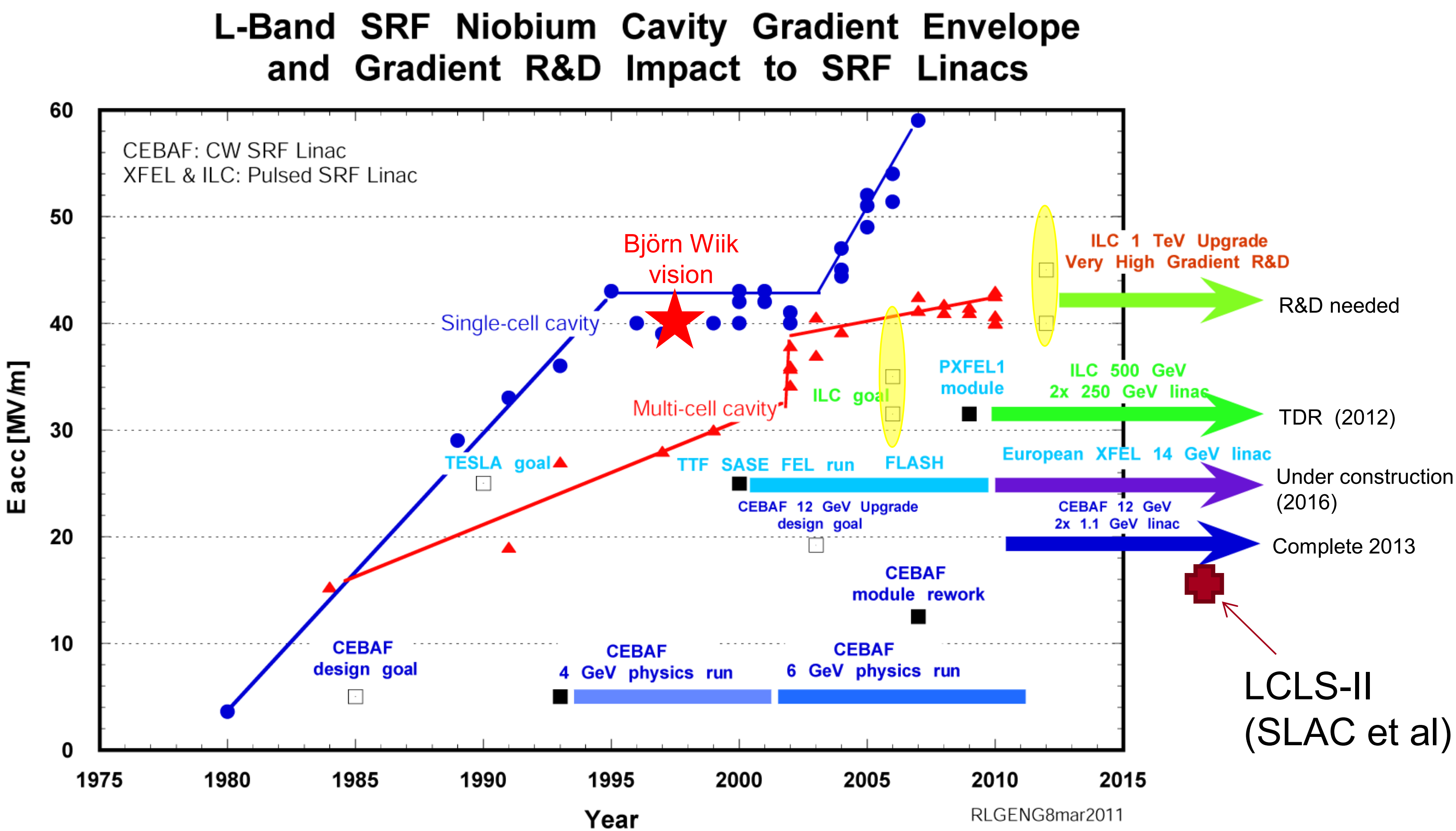
$$I \approx (\beta E_{SP})^{2.5} \exp\left(-\frac{\alpha}{\beta E_{SP}} \phi^{1.5} \right)$$

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

SRF Cavity Gradient Progress



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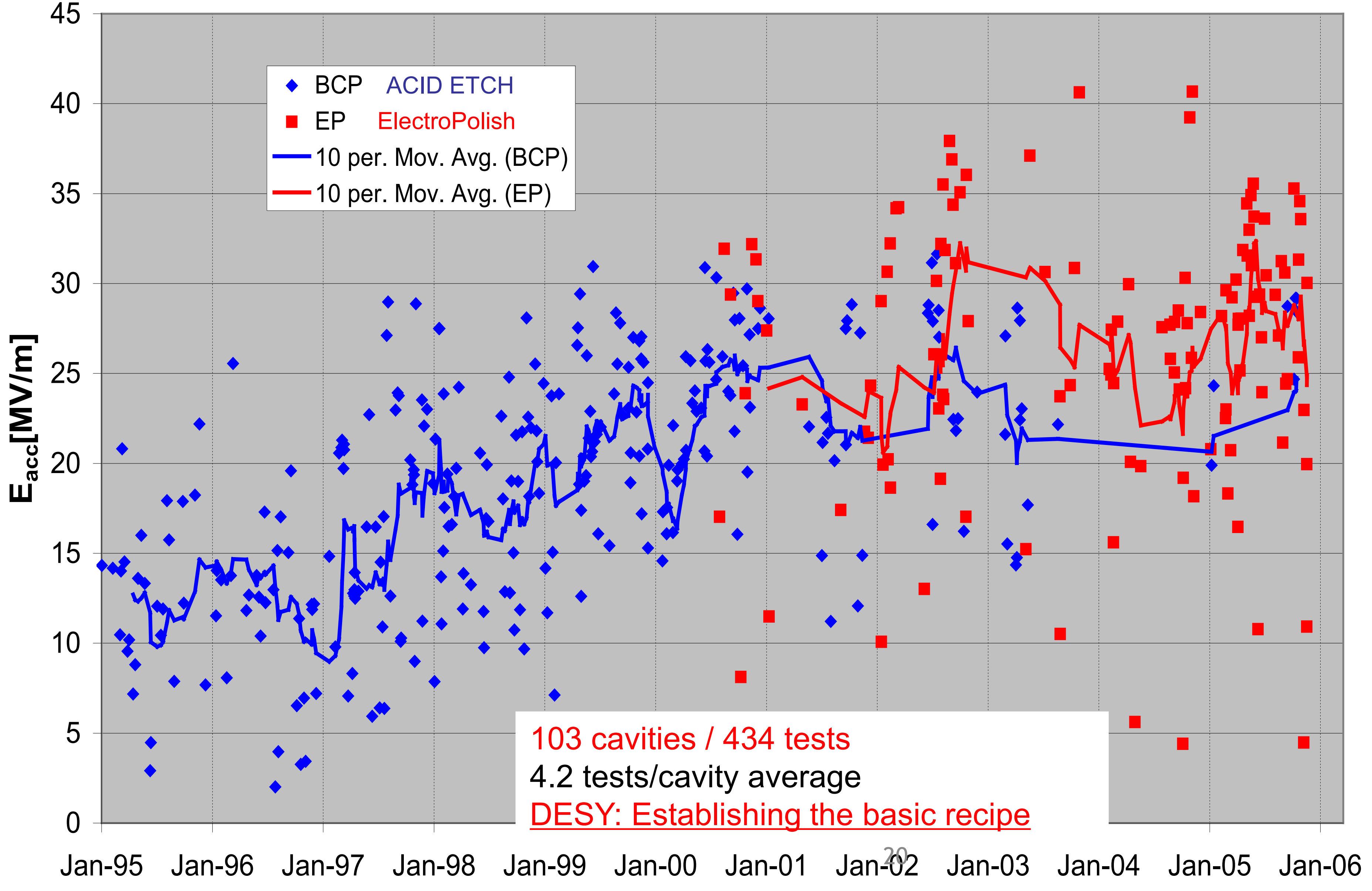
SRF based electron linacs (CW & pulsed) have track record of successful operations

A Model for Cavity and CM Production and Qualification Process

Step hosted	Industry	Industry/Laboratory	Hub-laboratory	ILC Host-laboratory
Regional constraint	no	yes or no	yes	yes
Sub-comp/material - Production/Procurement	Nb, Ti, specific comp. …		Procurement	
9-cell Cavity - Manufacturing	9-cell-cavity, Process, He-Jacketing		Procurement	
9-cell Cavity - Performance Test			Cold, gradient test	
Cryomodule component - Manufacturing	V. vessel, cold-mass ...		Procurement	
Cryomodule/Cavity - Assembly		Cav-string/ CM-assembly		
SCRF Cryomodule - Perofrmance Test			Cold, gradient test	
Accelerator integration, Commissioning				Accelerator sys. Integ.

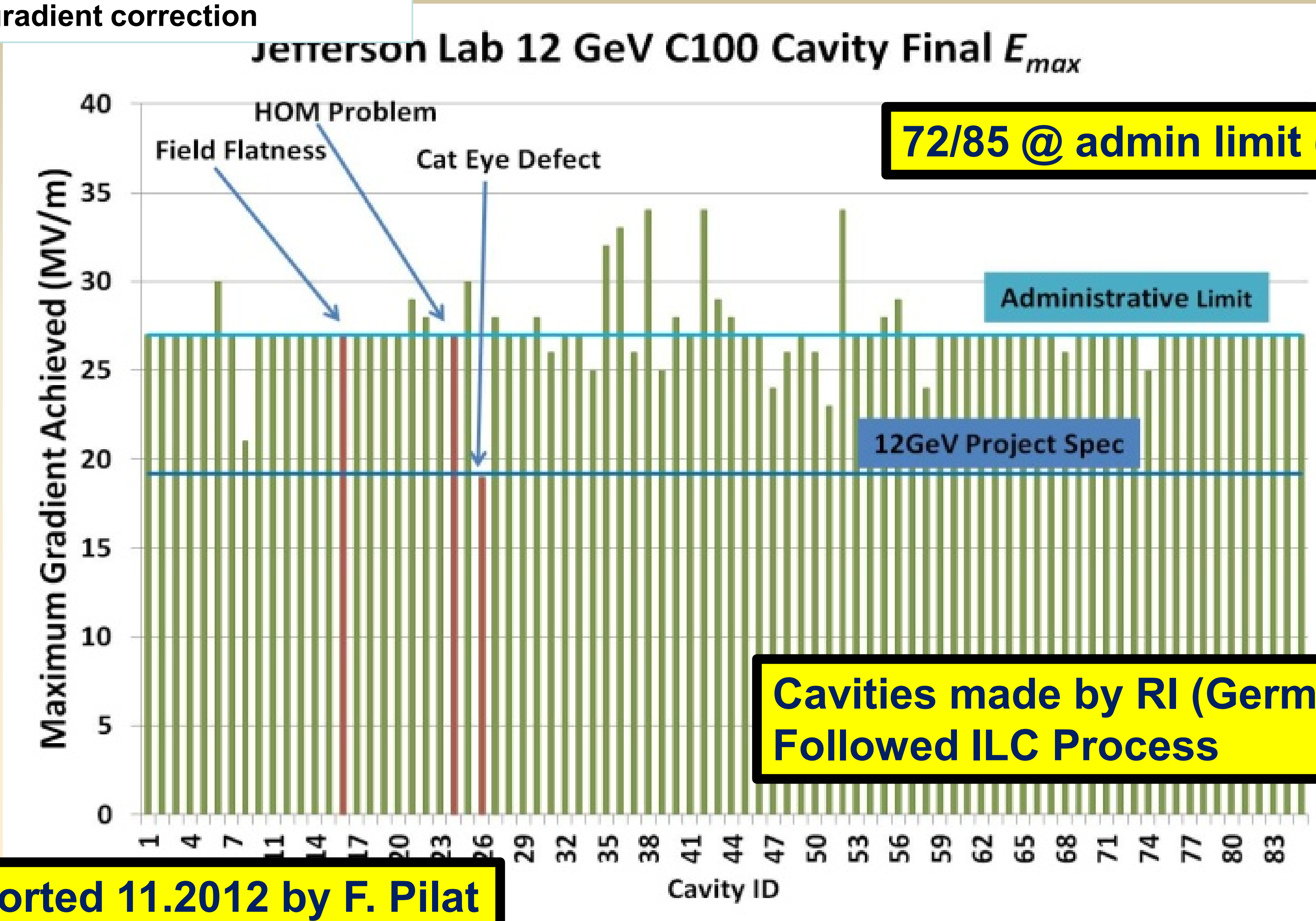
Vertical Cavity Test Results at DESY: 1995-2006



CEBAF 12 GeV upgrade

12 GeV cavities: overall performance

Vertical Test; 1500 MHz 7 cell; 10% gradient correction



72/85 @ admin limit (85%)

Cavities made by RI (Germany); Followed ILC Process

Reported 11.2012 by F. Pilat

E.ZANON S.p.A.

research instruments

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3 Americas

4 Asia

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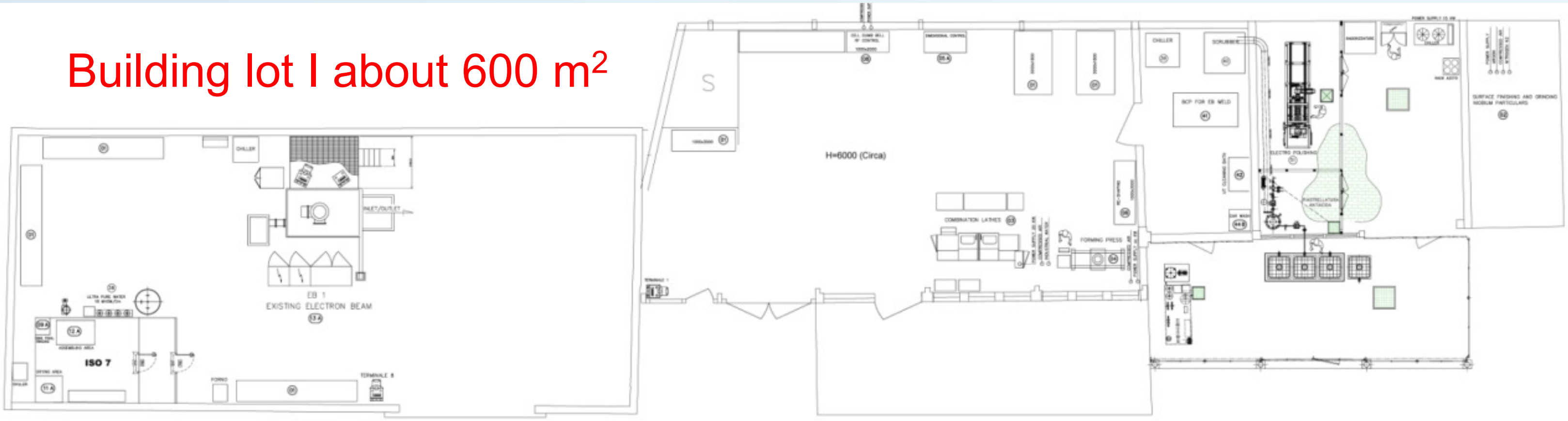
NINGXIA ORIENT TANTALUM INDUSTRY CO.,LTD.

* (or soon to be)

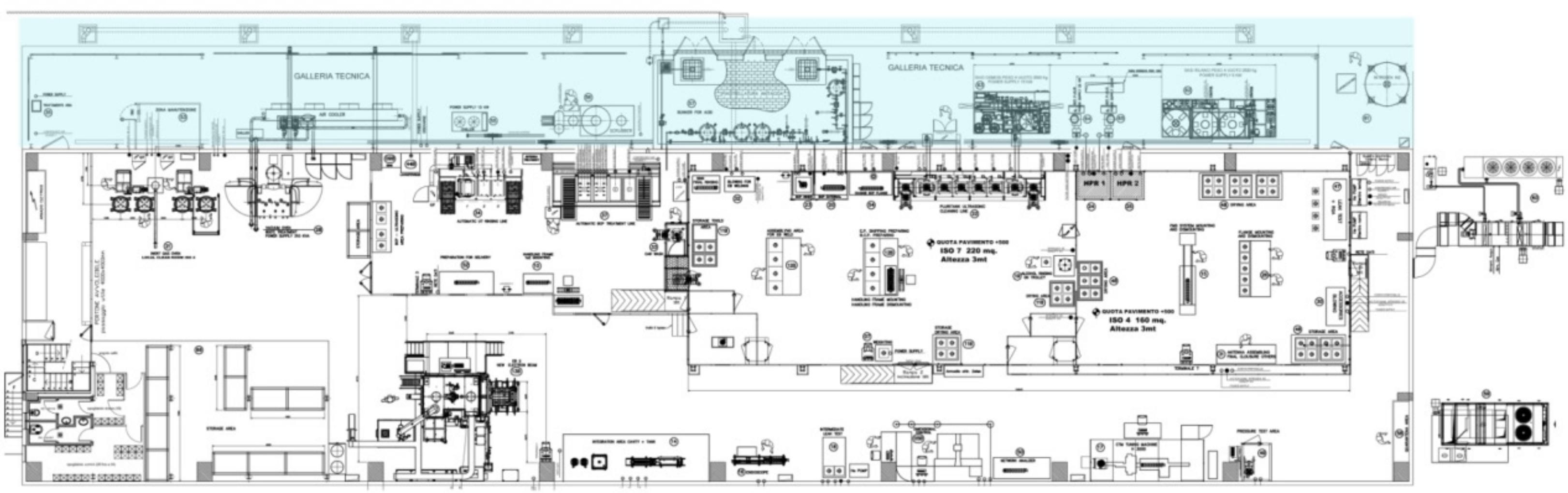
Infrastructure for SC cavities production (D)

Cavity's production lay-out

Building lot I about 600 m^2



Building lot IV 1200 m^2 (plus 600 m^2 for services)



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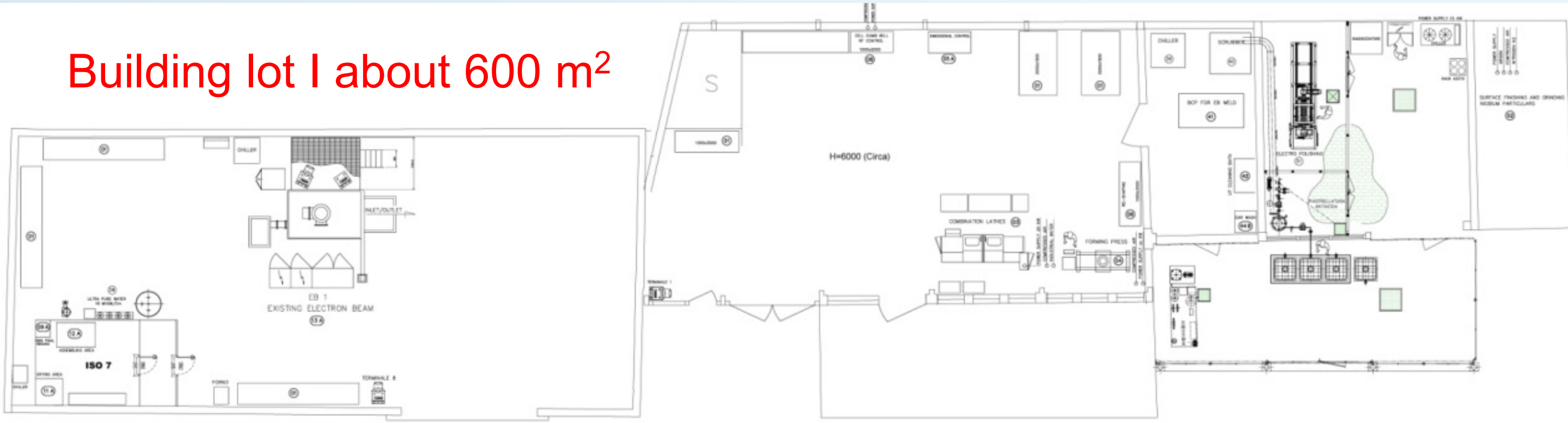

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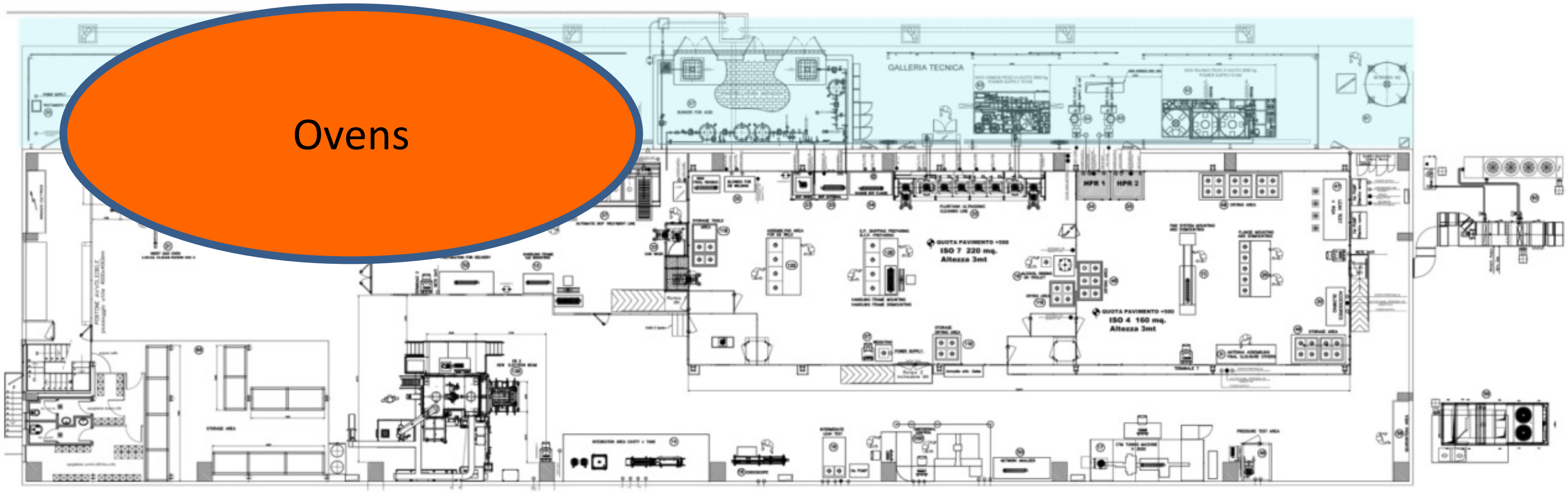

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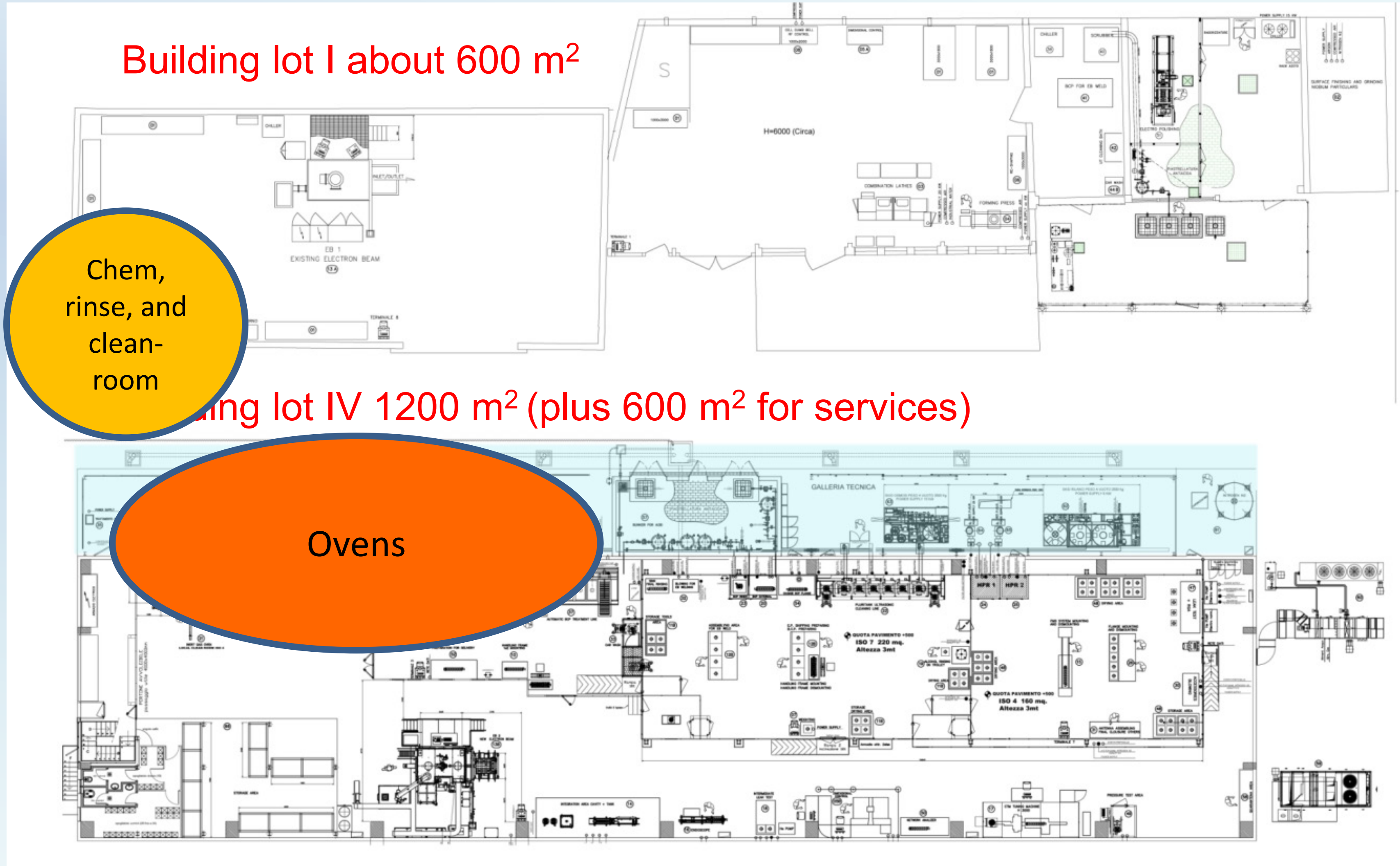

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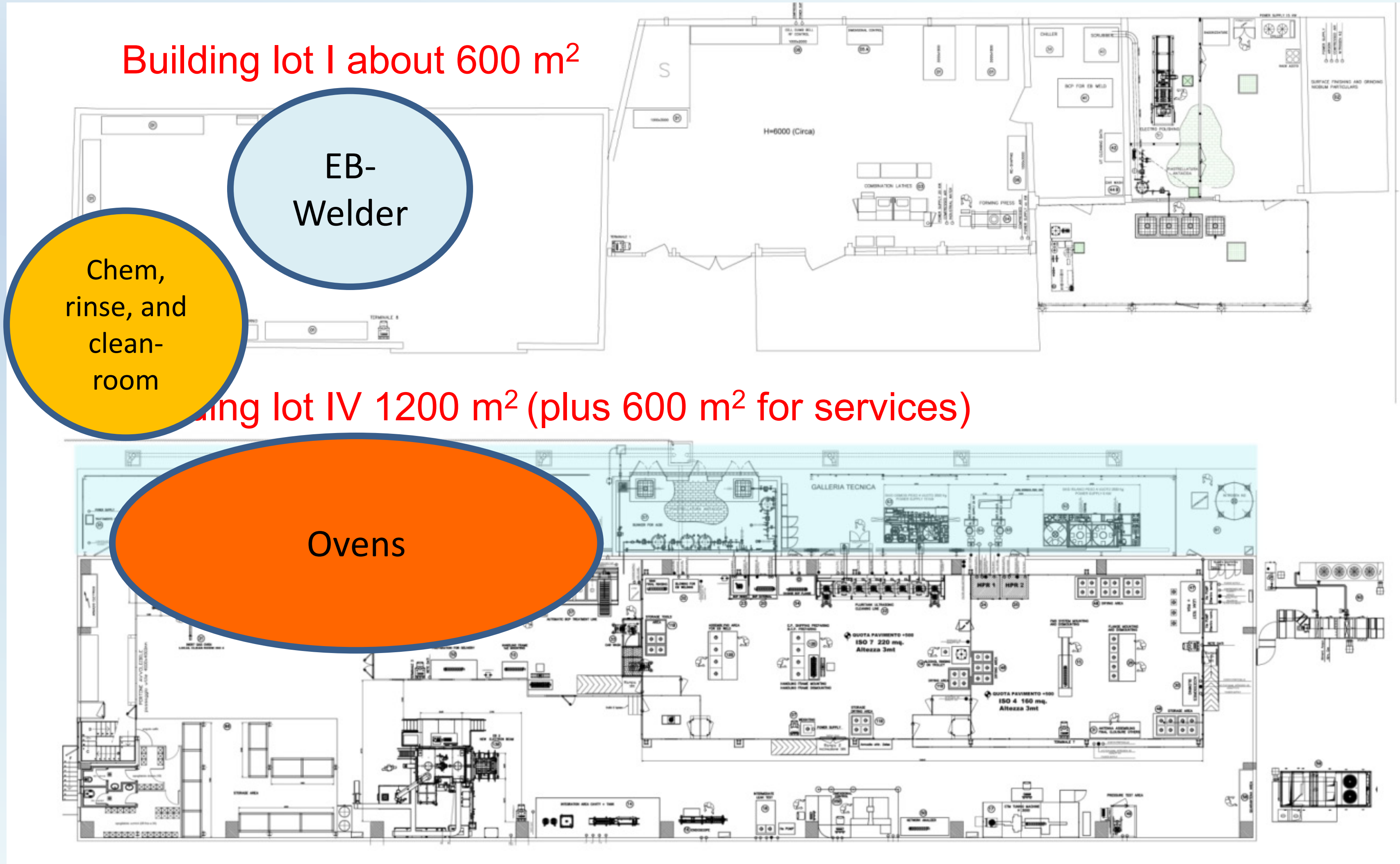

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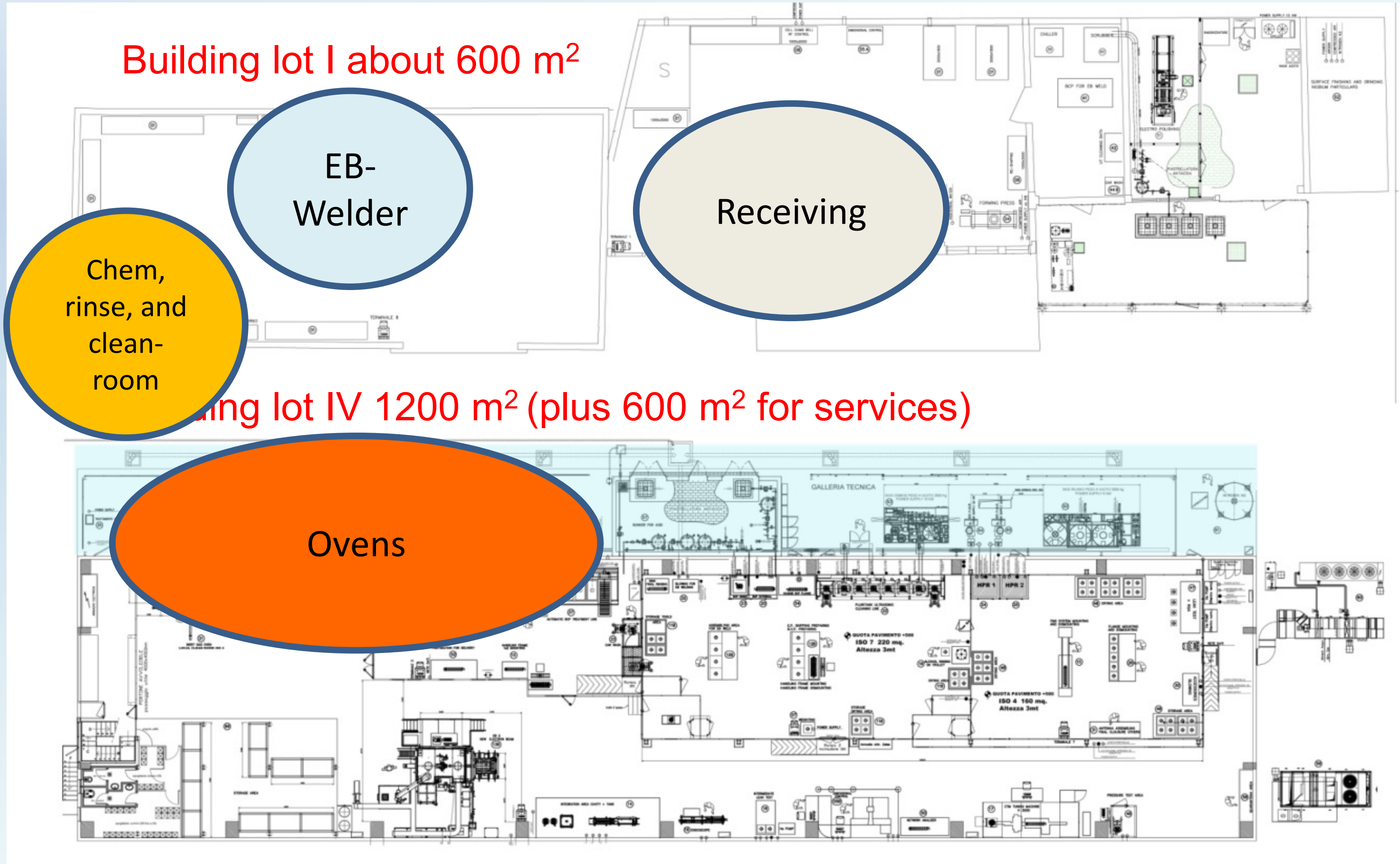

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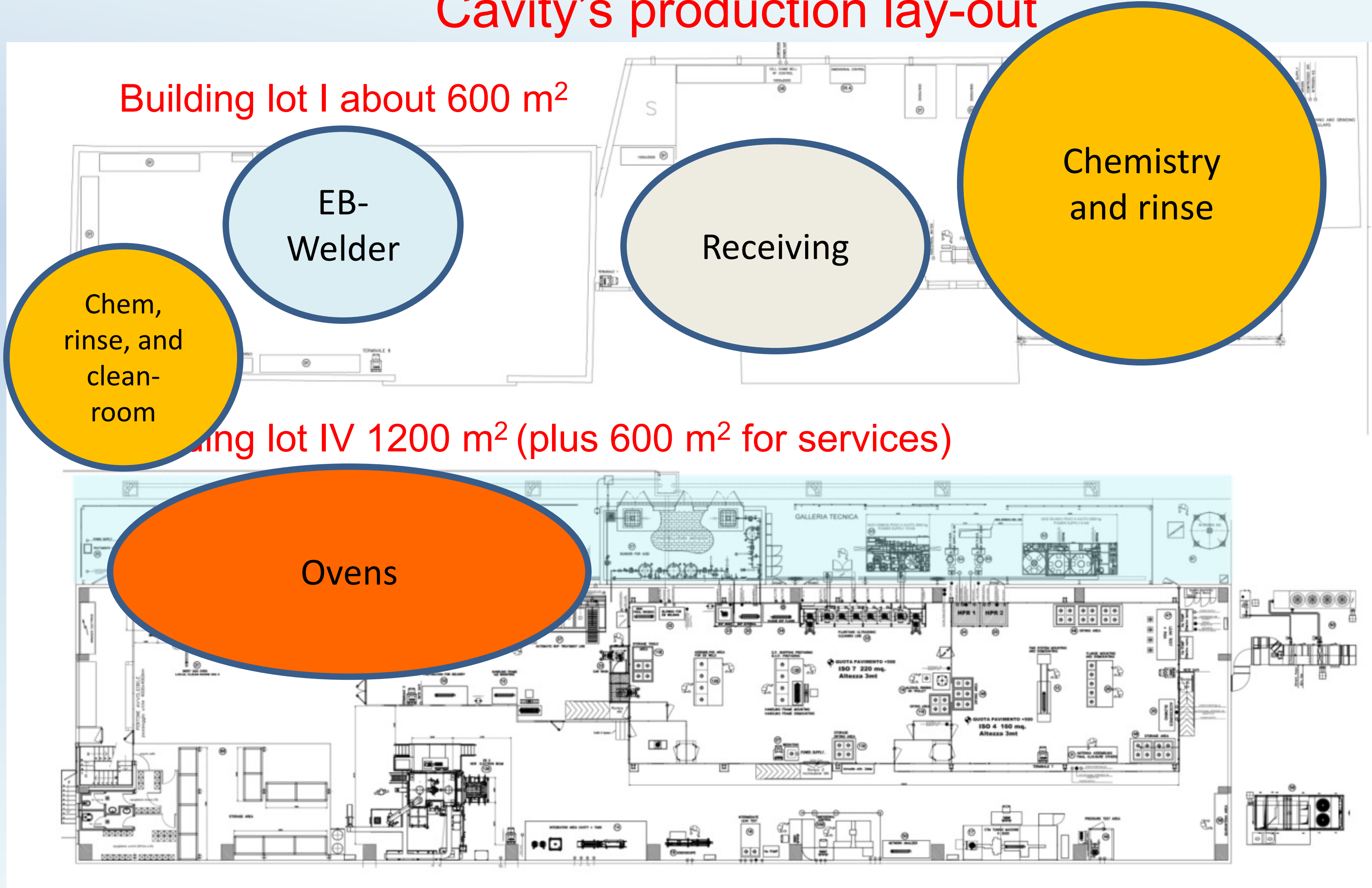

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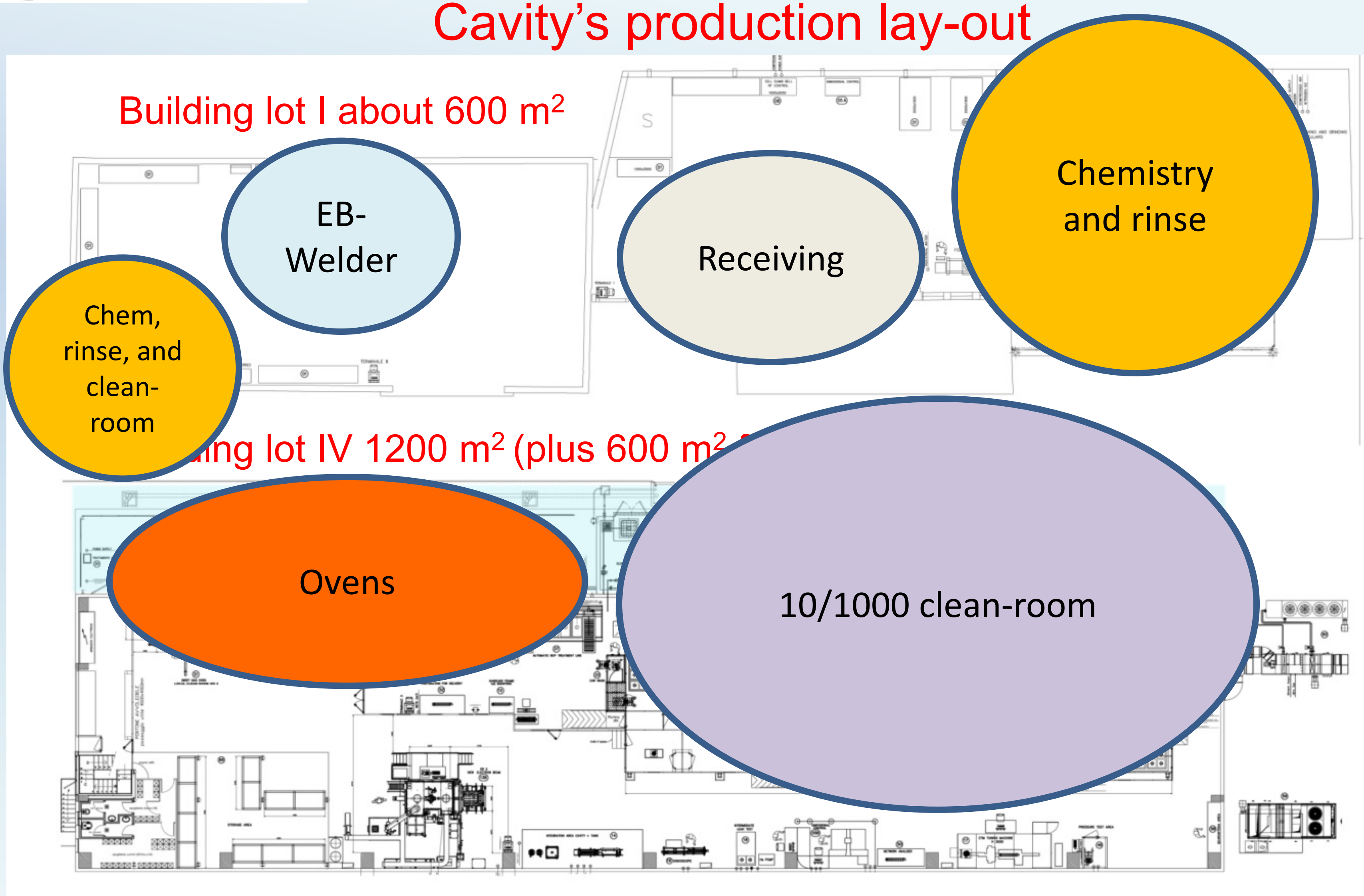

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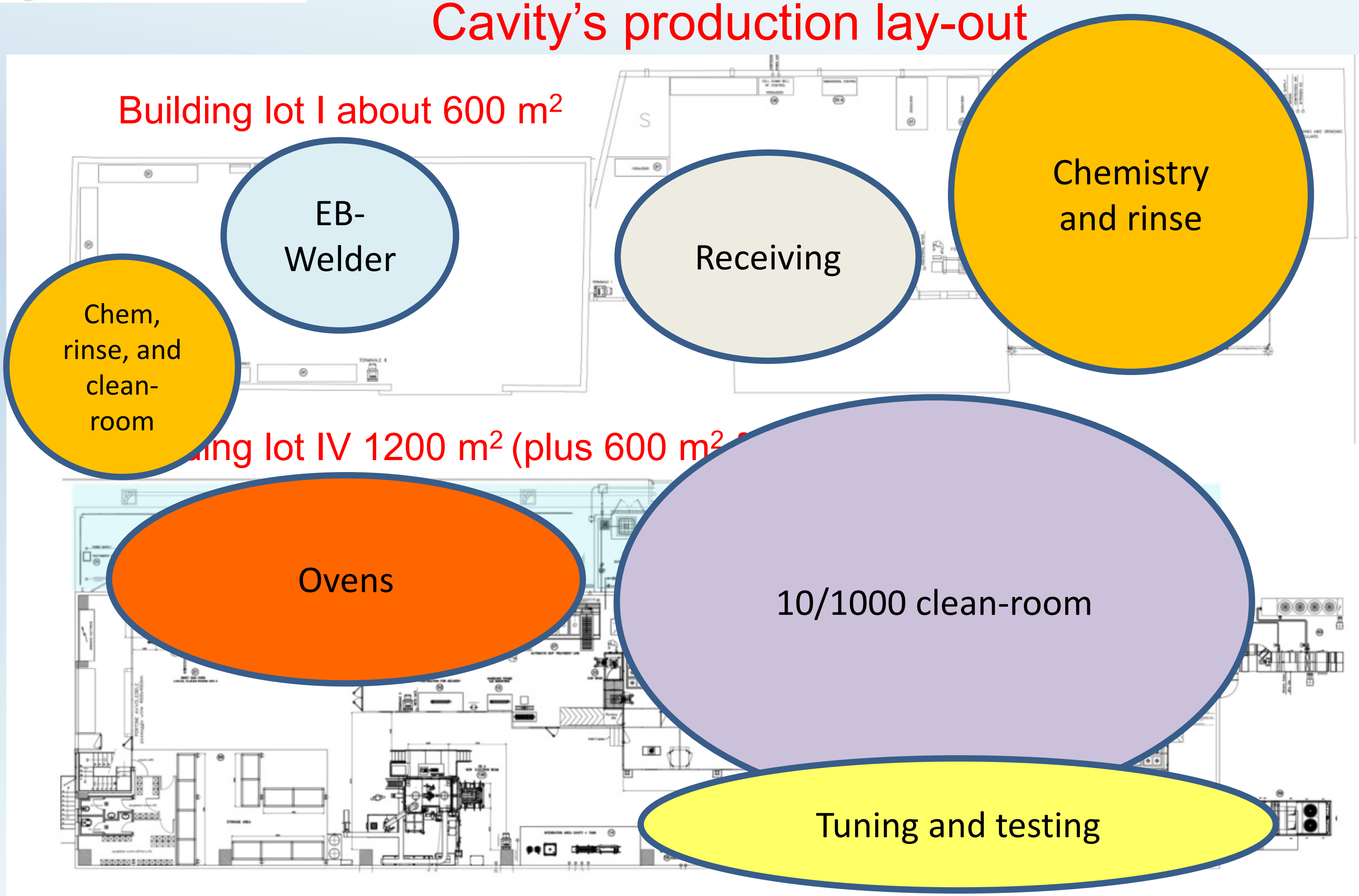

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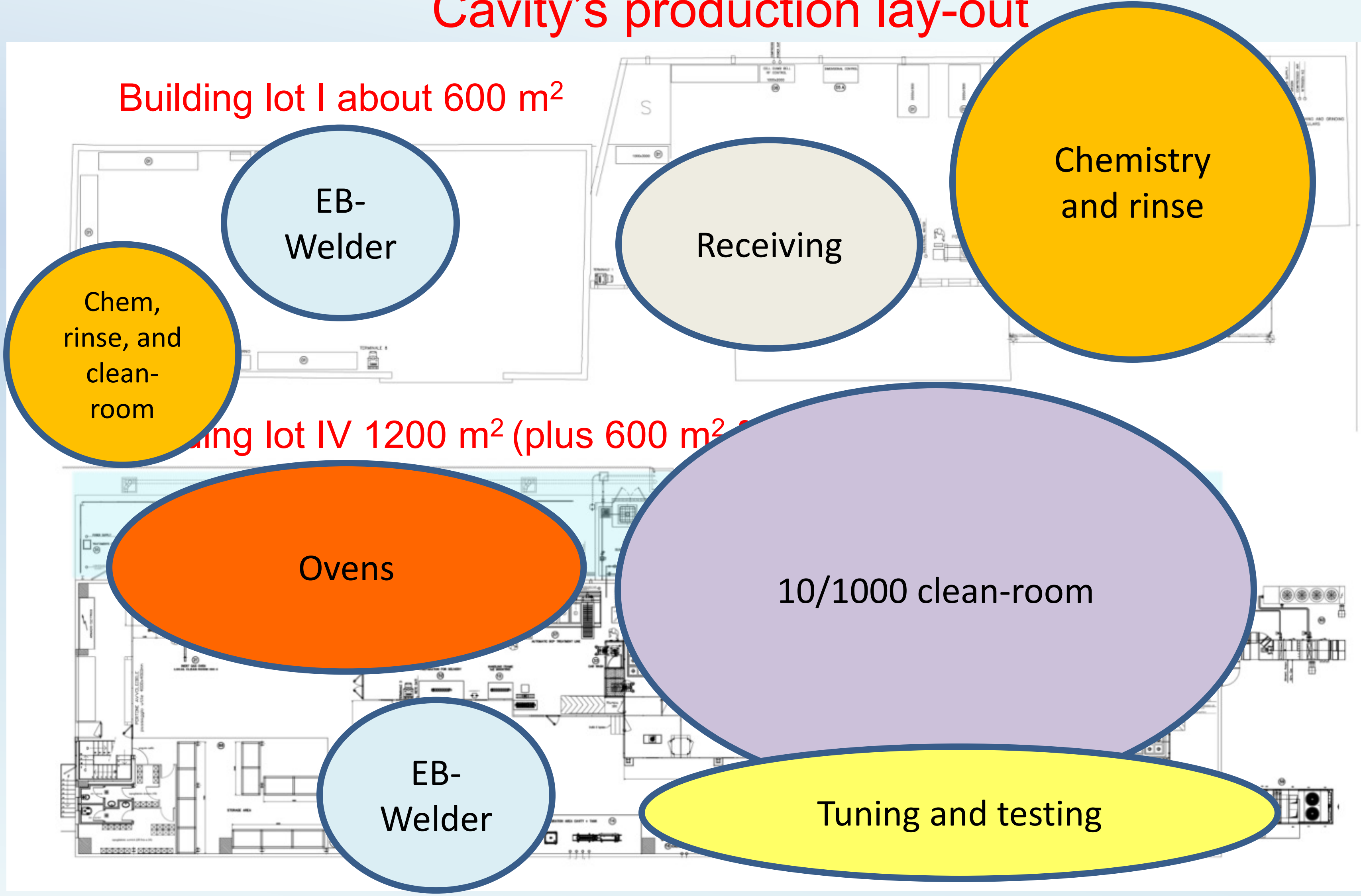
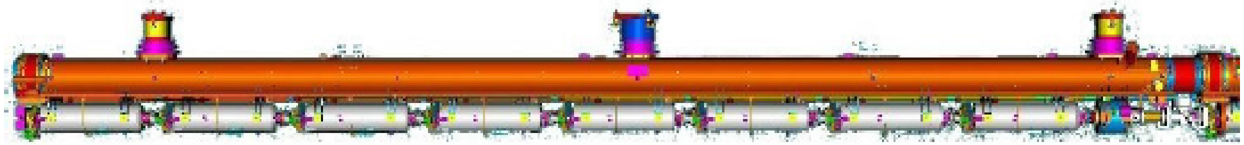


IPAC14: Courtesy: H. Weise

An Accelerator Complex for 17.5 GeV

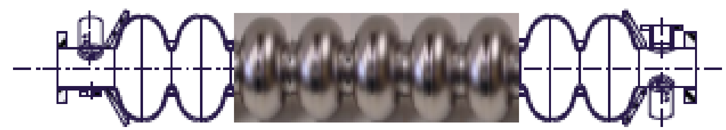
100 accelerator modules



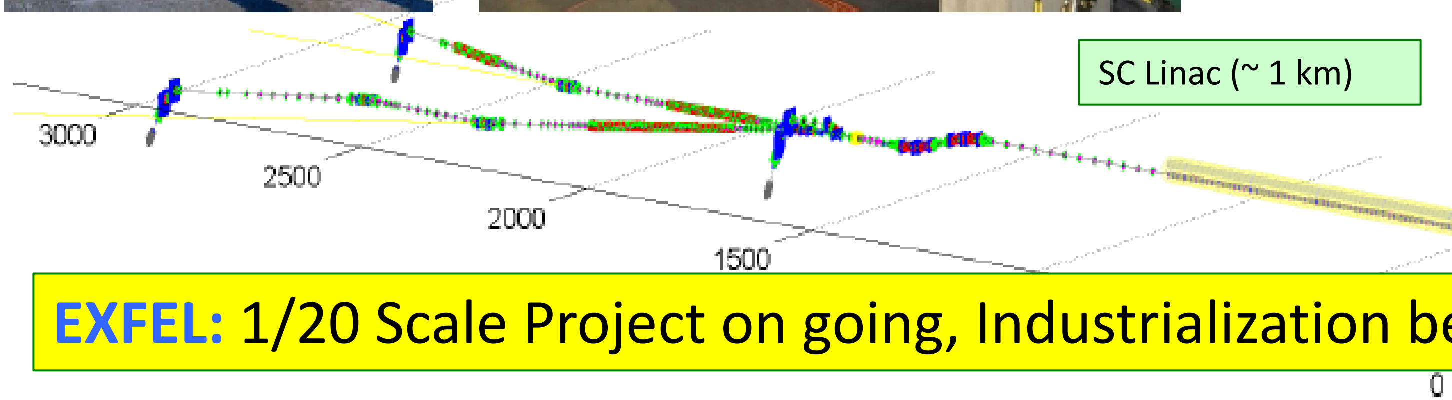
Some specifications

- Photon energy 0.3 - 24 keV
- Pulse duration ~ 10 - 100 fs
- Pulse energy few mJ
- Superconducting linac. 17.5 GeV
- 10 Hz (27 000 b/s)

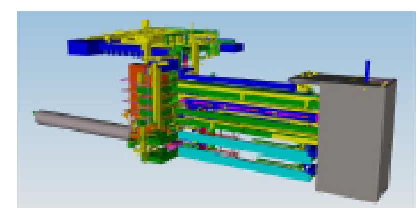
800 accelerating cavities
1.3 GHz / 23.6 MV/m



25 RF stations
5.2 MW each

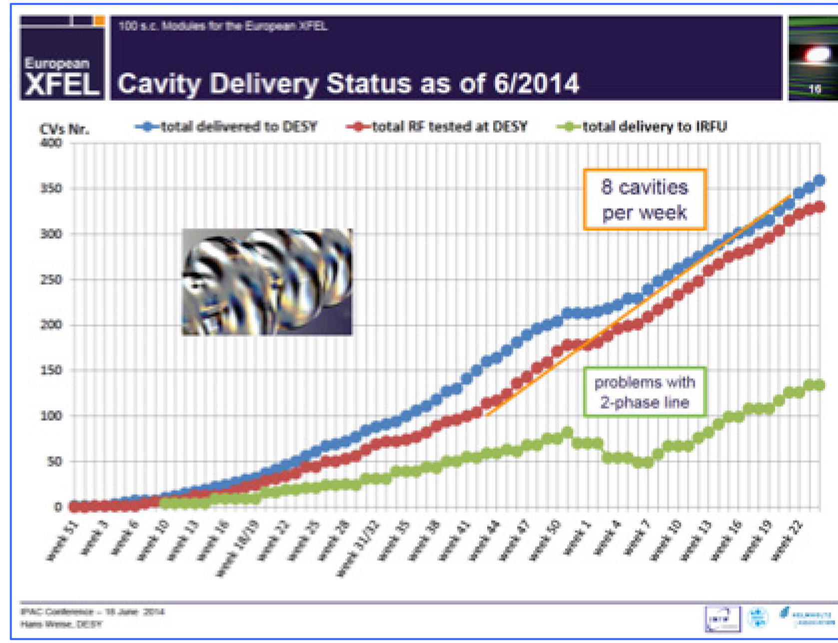


SC Linac (~ 1 km)



EXFEL: 1/20 Scale Project on going, Industrialization being verified !!

SCRF Cavity Production



- **Gradients** in average above specification (almost 300 cavities tested)
  - Average usable gradient after delivery (26.8 ± 7.1) MV/m
  - 2/3 of cavities can be used w/o further treatment
  - 1/3 is getting additional treatm. -> usable grad. increased to (29.6 ± 5.1) MV/m

2014.6: # cavities produced > 300. Usable Gradient: ~ < 30 > MV/m

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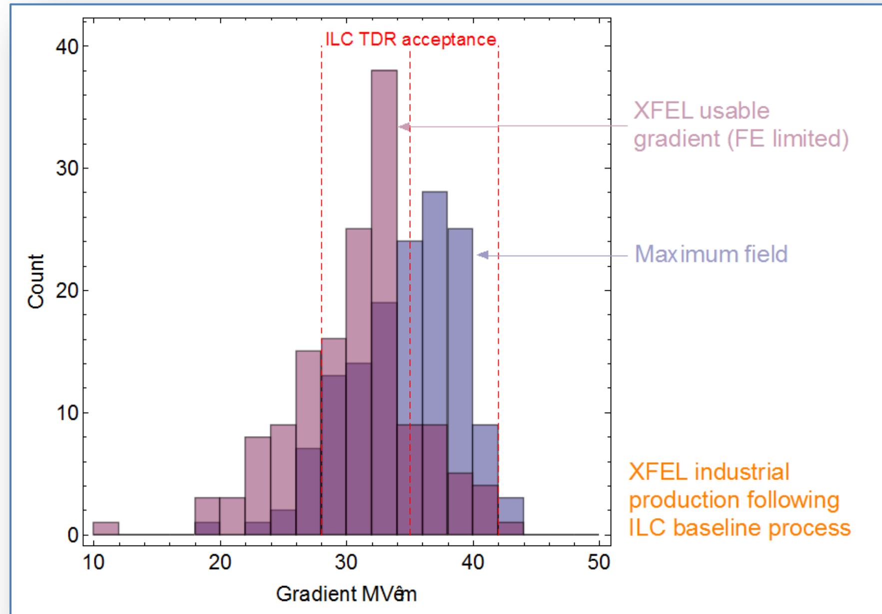

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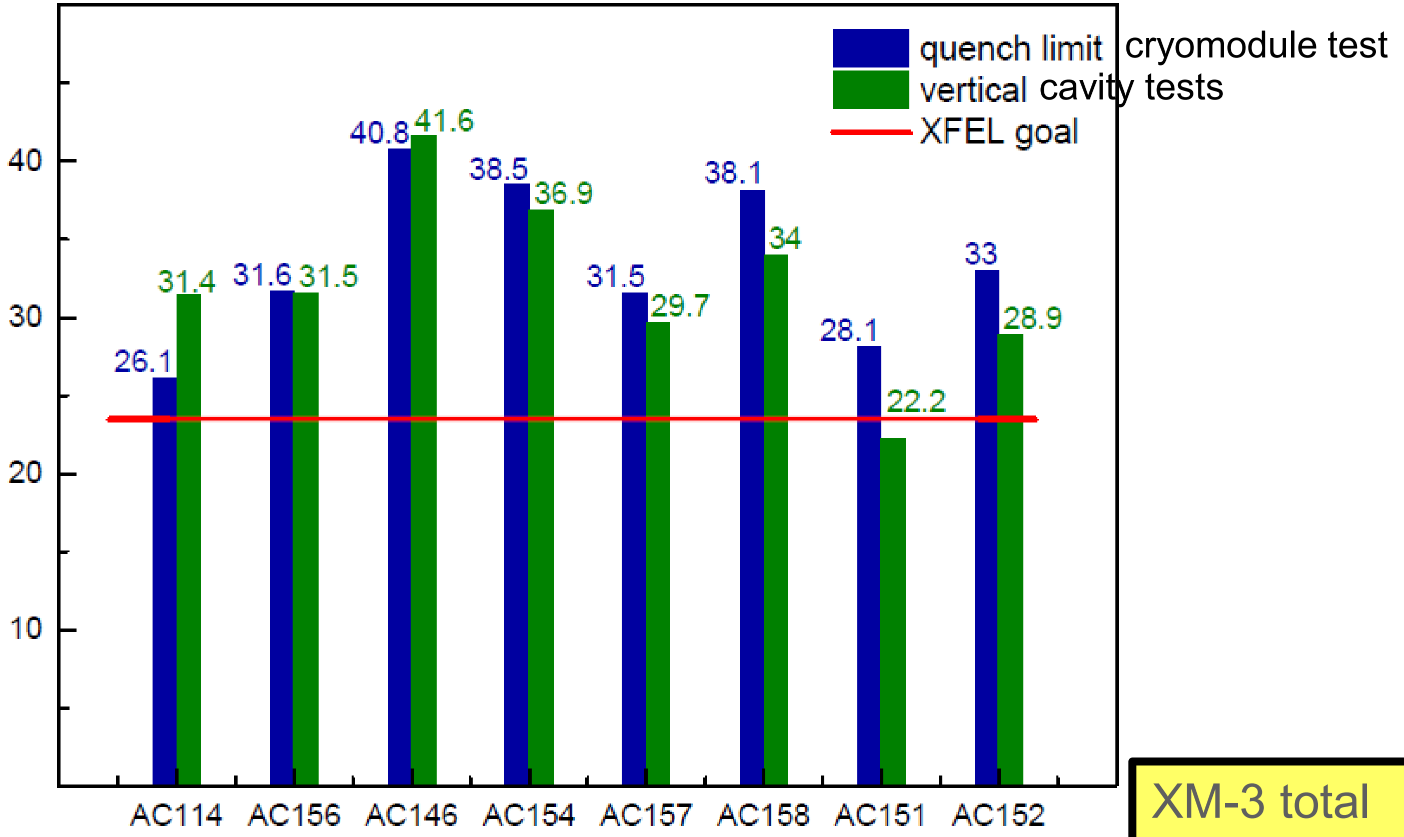
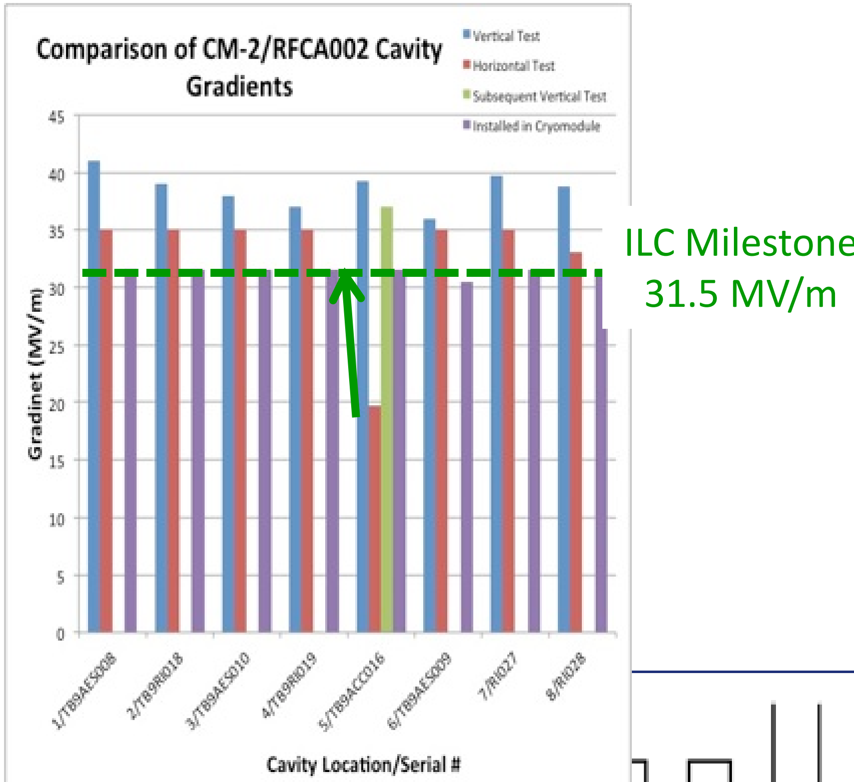
XM-3 RF Test Results

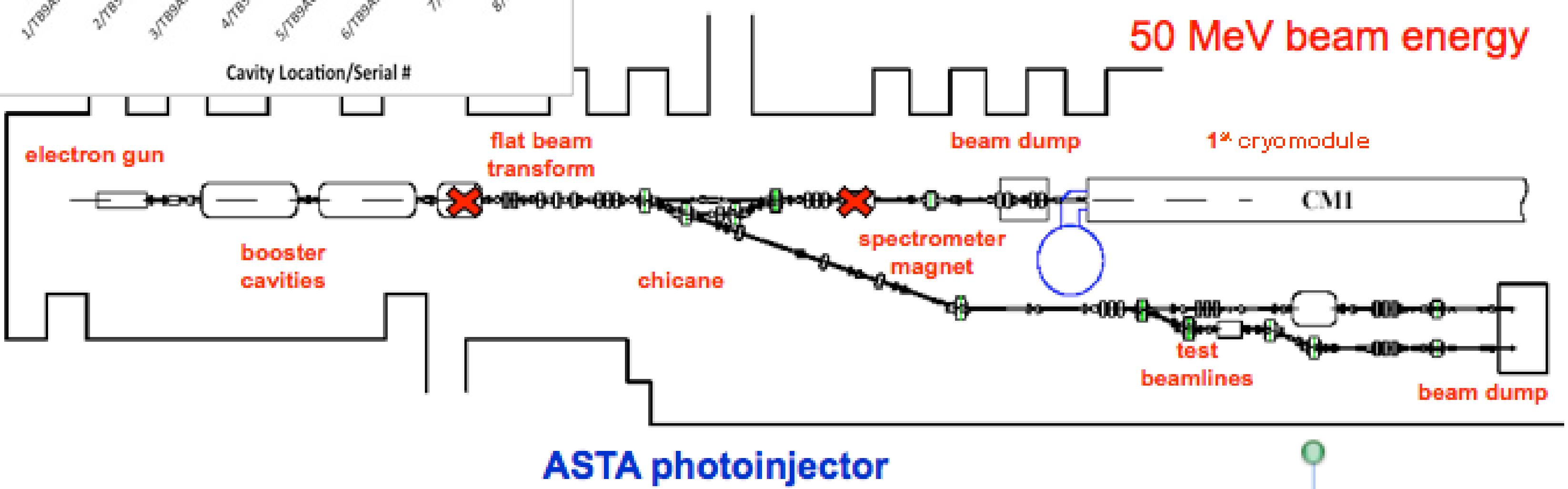


Gate valve	CV 1	CV2	CV3	CV4	CV5	CV6	CV7	CV8	BQU		
	AC114	AC156	AC146	AC154	AC157	AC158	AC151	AC152			
Eacc (VT)	31,4	31,5	41,5	36,9	29,7	38,8	22,2	28,9			
Fe limit (VT)	31,4	31,5	41	36,9	29,7	38,8	16,8	20		**229,6**	**MV**
CMTB	23,2	31,4	40,8	38,5	31,5	38,1	22,7	33		**231,8**	**MV**
										29,0	MV/m

XM-3 total gradient compared with VT

Will it work ? System Tests - Fermilab





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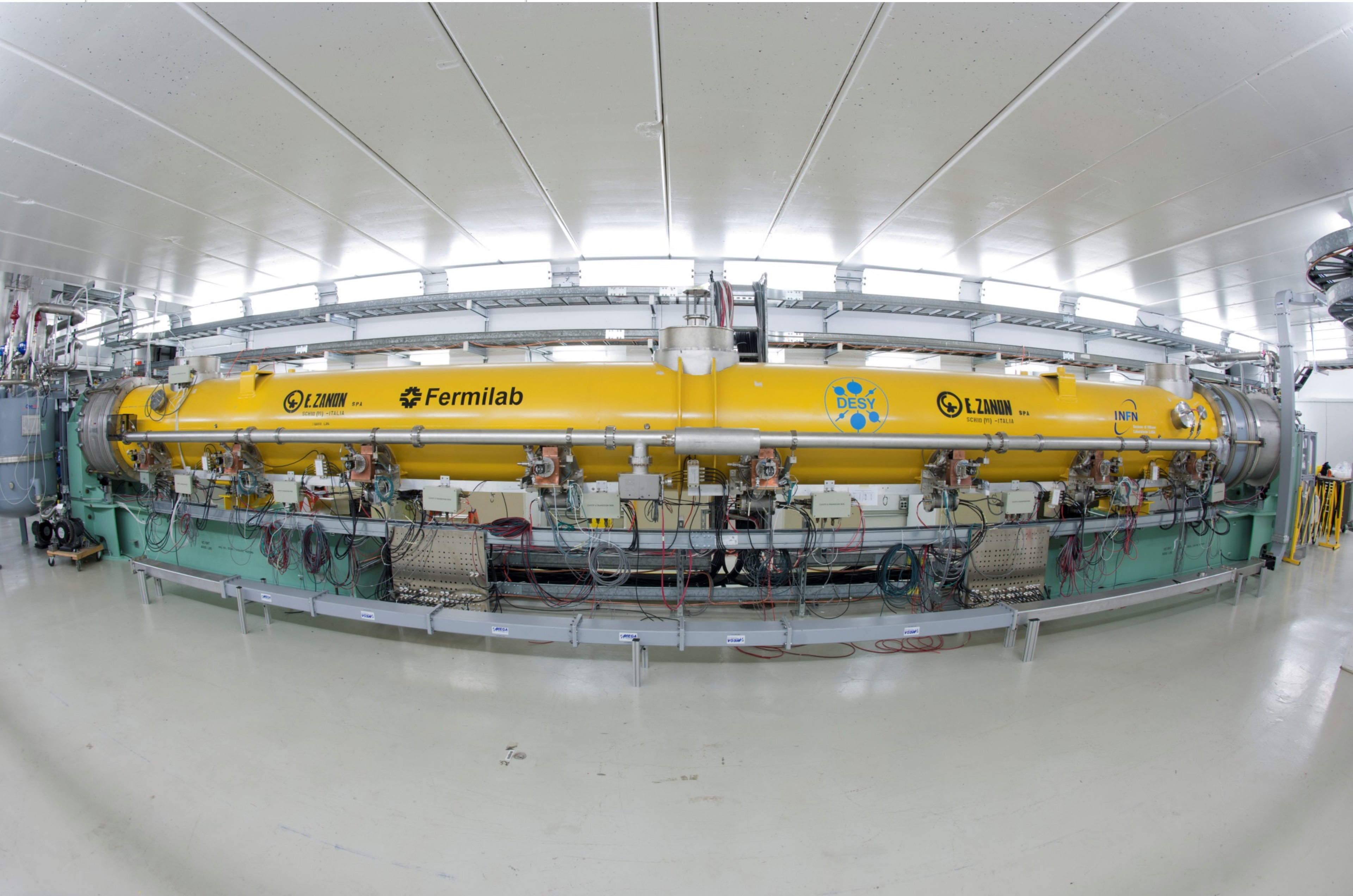

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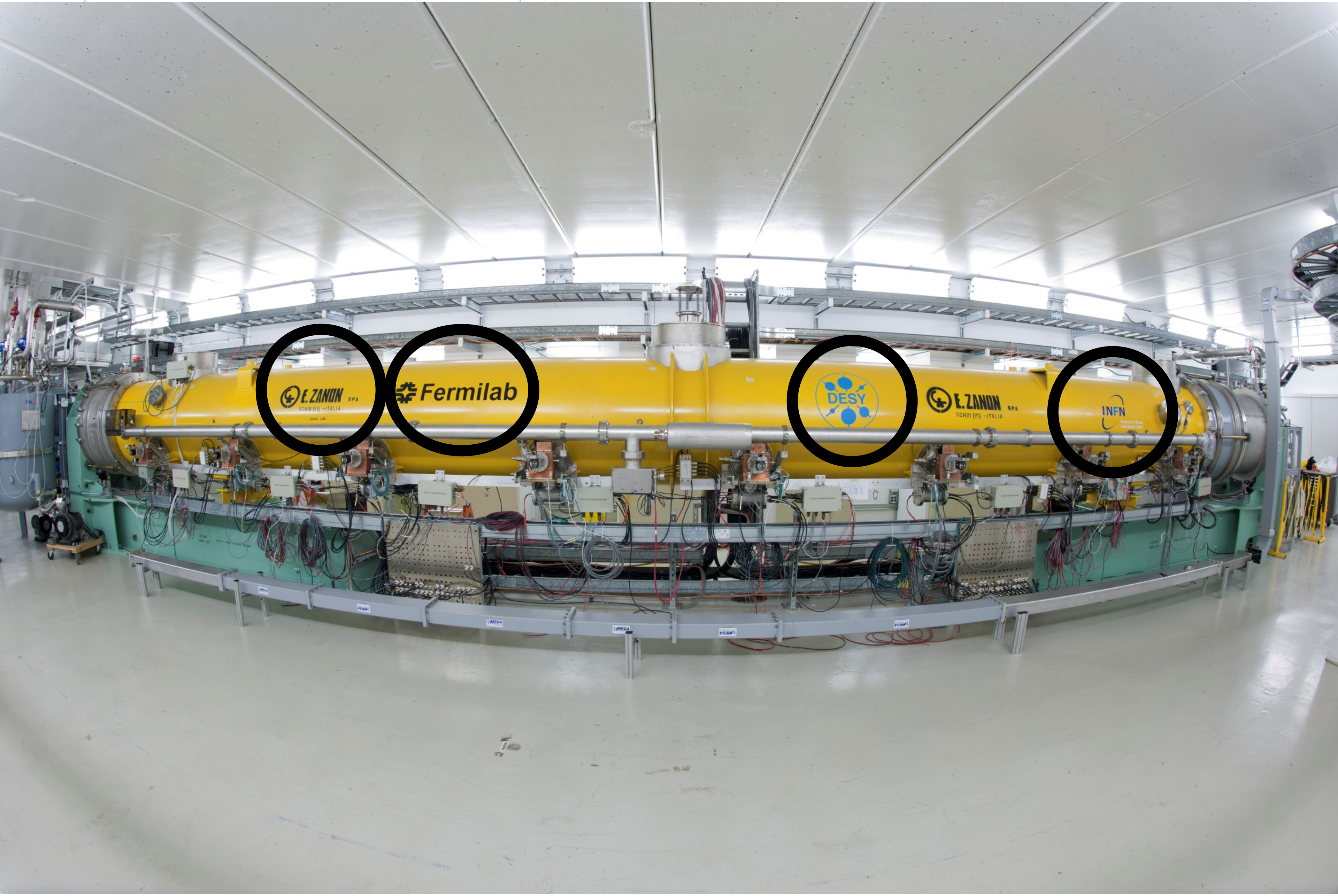

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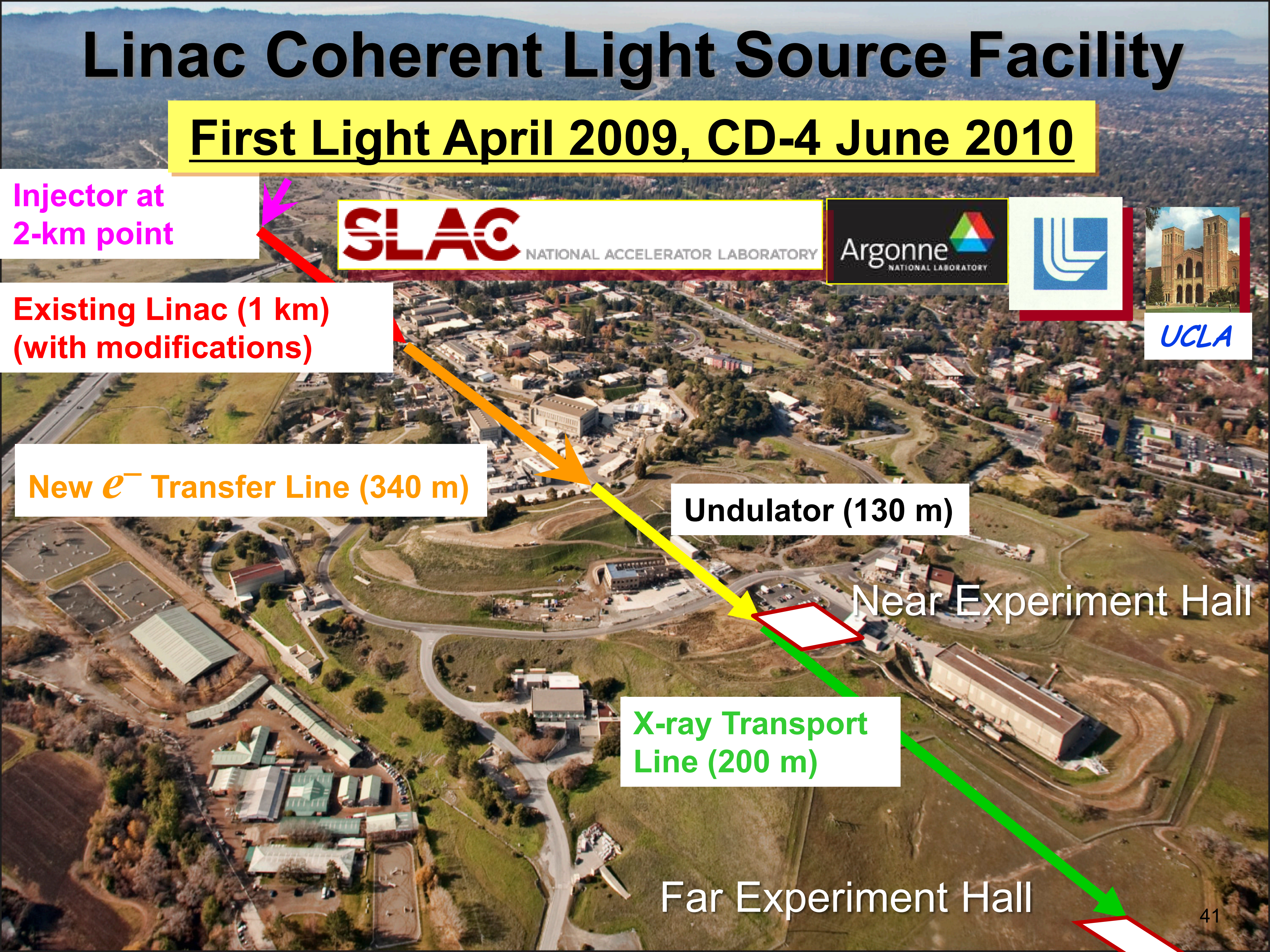
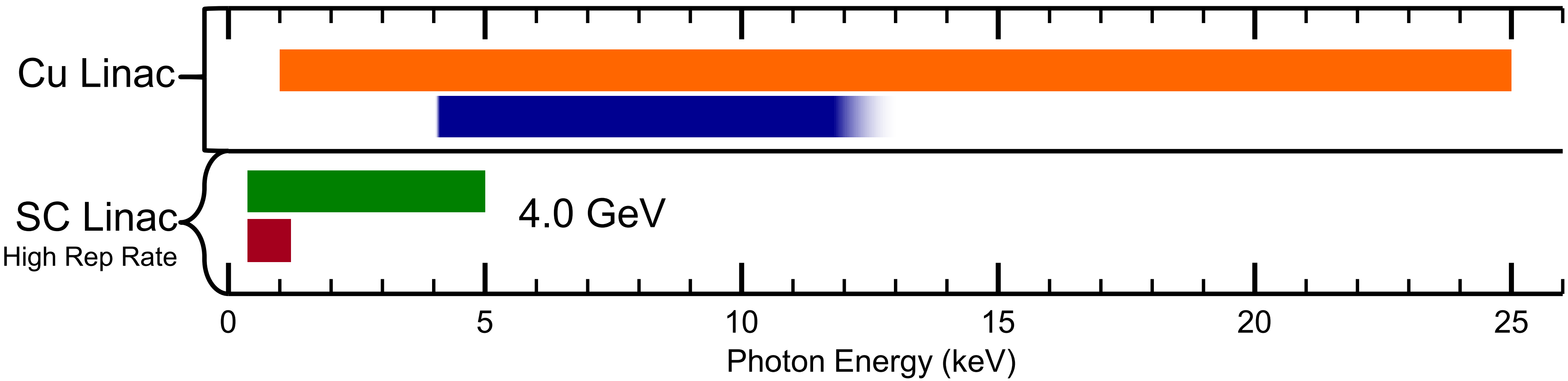
Linac Coherent Light Source Facility

First Light April 2009, CD-4 June 2010



Photons for Basic Energy Science
(Material, Condensed Matter, Biology, Chemistry…)

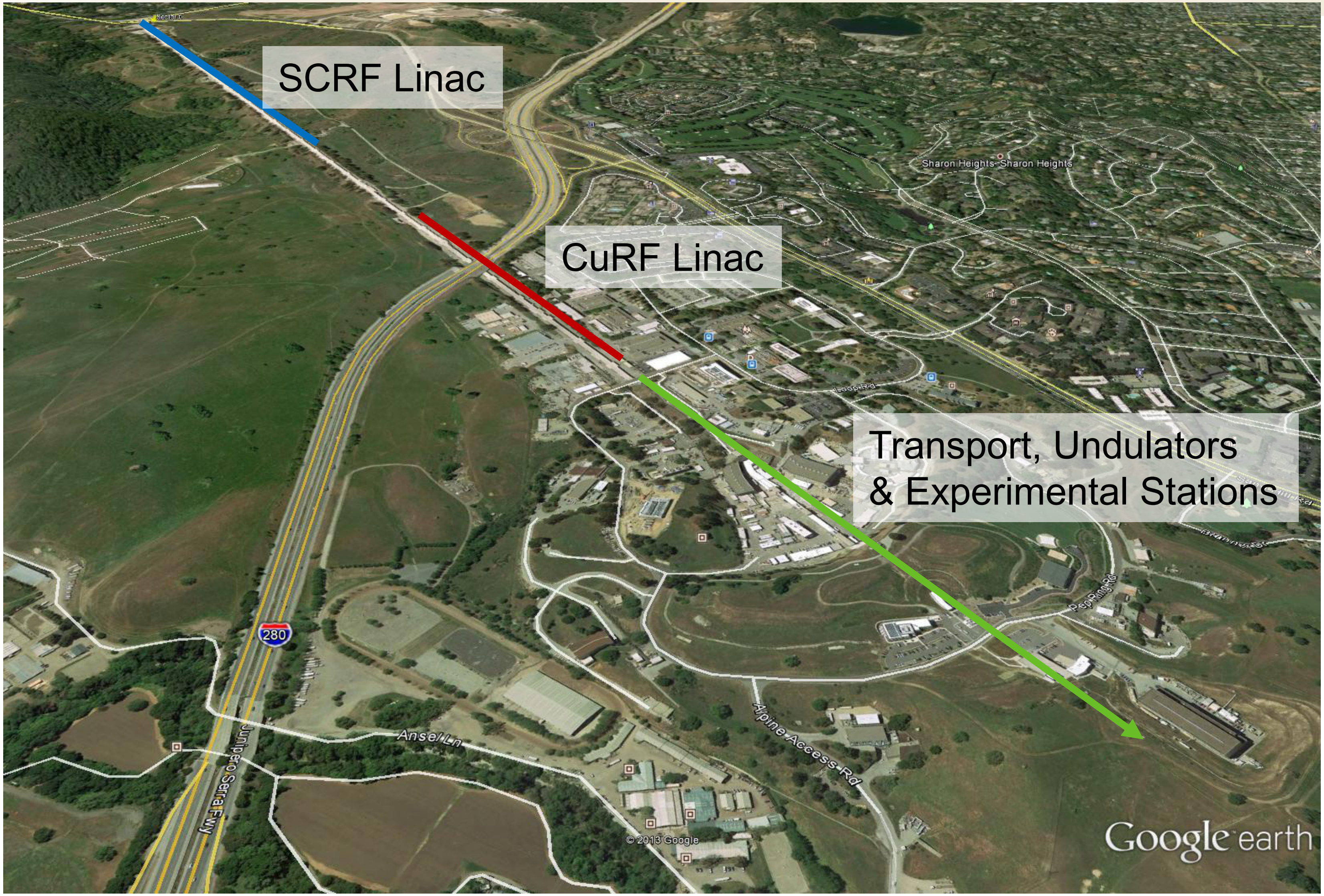


Legend

- Cu SASE
- Cu Self Seeded
- High Rep Rate SASE
- Self Seeded (Grating)

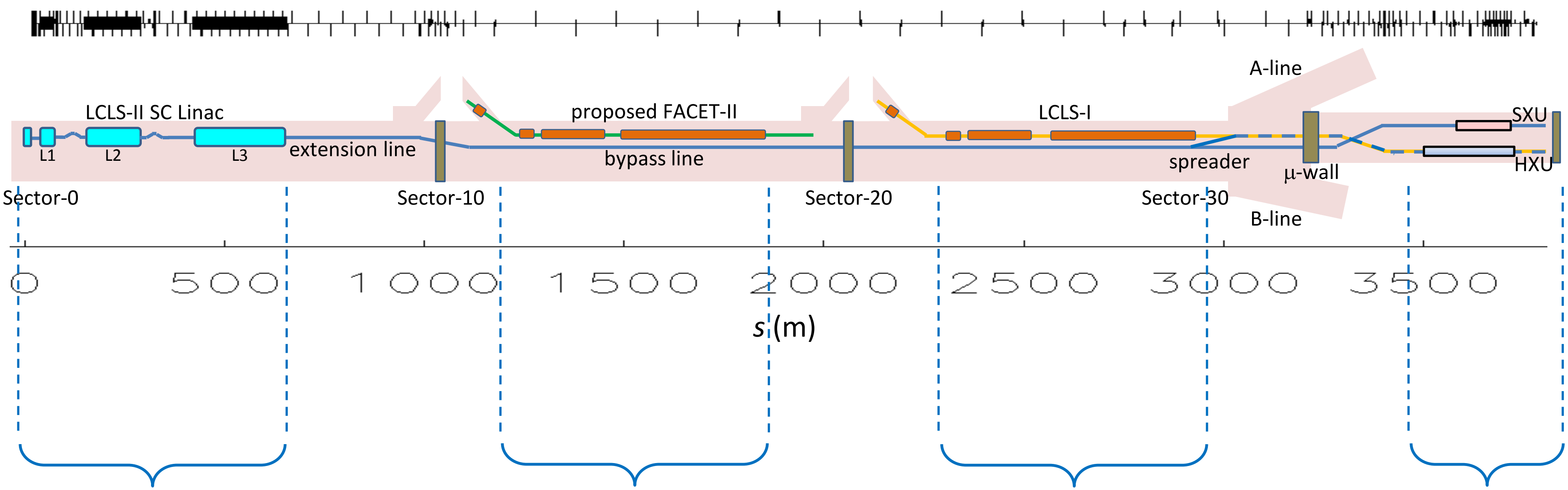
- Hard X-Ray Source:
  - 1-5 keV w/ new 4 GeV SC linac
  - Up to 25 keV with LCLS Cu Linac
- Soft X-Ray Source:
  - 250 eV-1.2 keV w/ 4 GeV linac
- ***Both linacs feed HXR undulator***

LCLS-II Concept
Use 1st km of SLAC linac for CW SCRF linac



LCLS Layout in SLAC Linac Tunnel

(only approximately to scale)



New SCRF Linac (4 GeV)

Proposed FACET-II and Bypass Line

Existing LCLS-I Linac

Undulators (LCLS-I & -II)

LCLS-II Objectives:

- Build 4 GeV (up to 300 micro-Amp) CW superconducting linac based on TESLA / ILC / E-XFEL 1.3 GHz technology
- Develop cavity process for high-Q0 production
- Develop CW cryomodule design and operations scheme for 110 W @ 2K / CM (or better) based on high-Q0 cavity process
- Use industrial capability for 1) dressed-processed-cavity, 2) coupler, and 3) vacuum-vessel/cold-mass production
- Adapt JLab ‘CHL-2’ (12 GeV Upgrade) Cryoplant for SLAC

LCLS-II Cavity Control

10 to 100x lower current than ILC / XFEL

- (LCLS-II 60 micro Amp / EXFEL - ILC 6 mA)
- → Matched LCLS-II loaded Q_L ~ 3e8; effective resonance width very narrow; BW few Hz
- Difficult with today's state-of-the-art cavity controls

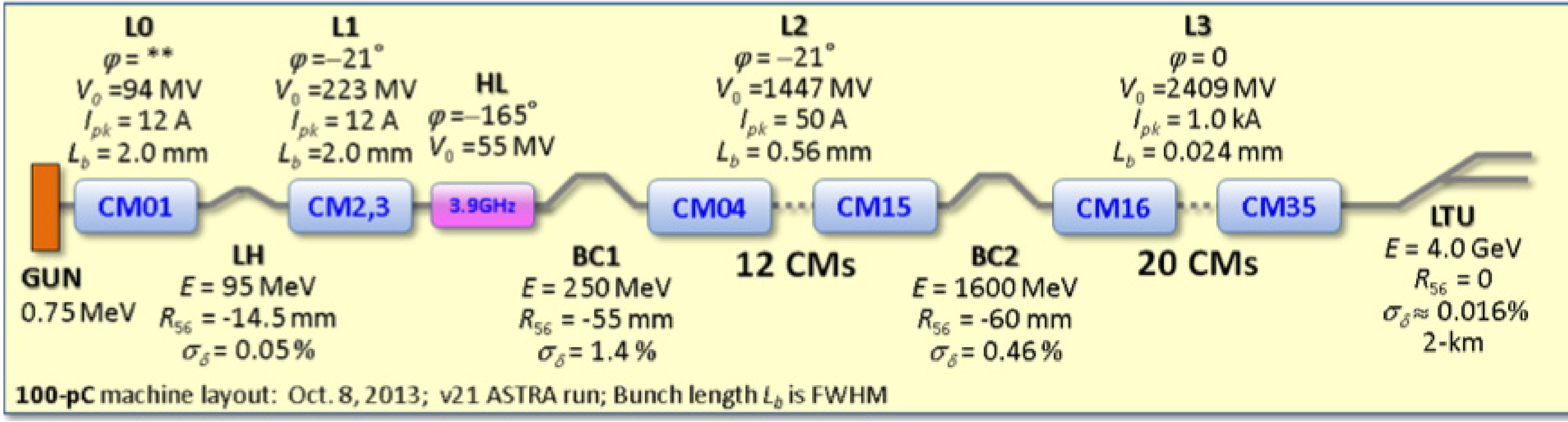
LCLS-II: 6e6 < Q_L < 1e8; nominal 4e7 BW 50 Hz

ILC / XFEL: 1e6 < Q_L < 1.4e7

Microphonics / cavity resonance control → key R&D topics for low current CW linacs

- Also useful for ILC

LCLS-II Linac



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

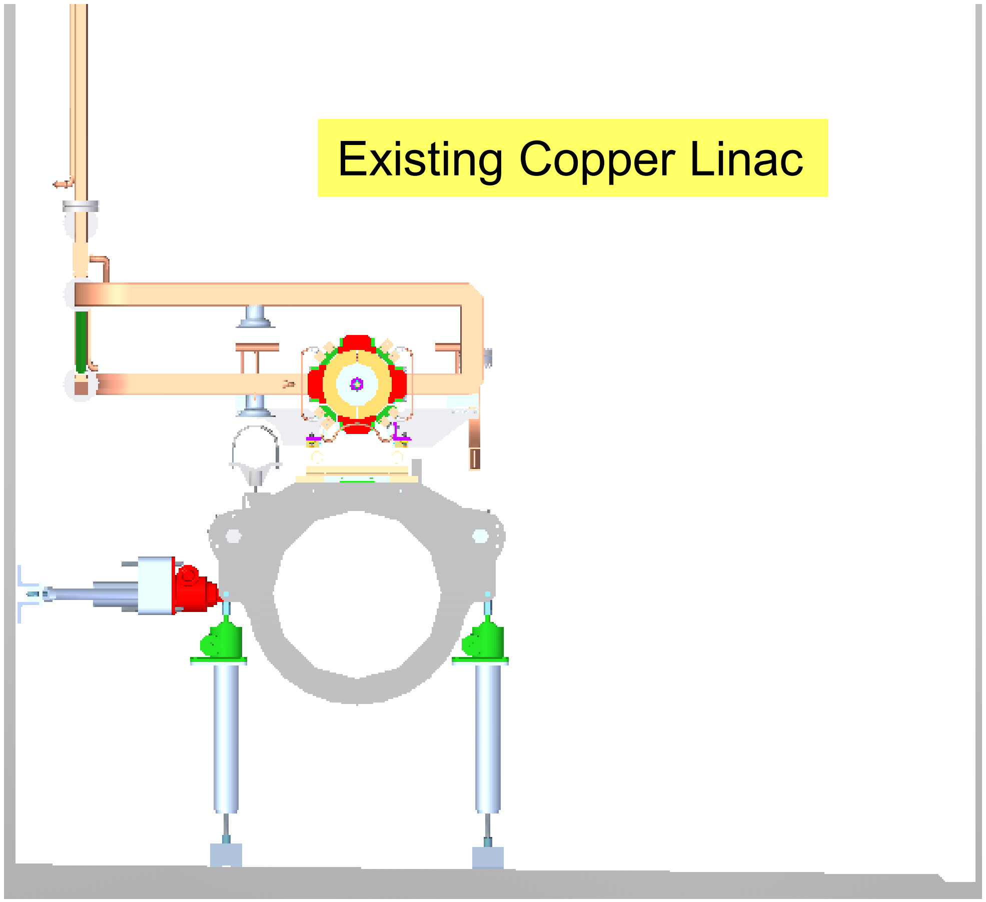
Under development ~ 20 years with ***> 1000 cavities*** to be made and tested (inc. 800 for E-XFEL – completed 2016)

- Thirty-five **1.3 GHz 8-cavity cryomodules**
- Two **3.9 GHz 8-cavity cryomodules**
- Four cold segments (L0, L1, L2 and L3) which are separated by warm beamline sections.
- 280 1.3 GHz cavities
- 16 3.9 GHz cavities

Re-purposing the SLAC Tunnel

SLAC Linac Tunnel: 11 wide x 10 feet high

It will be a tight fit!



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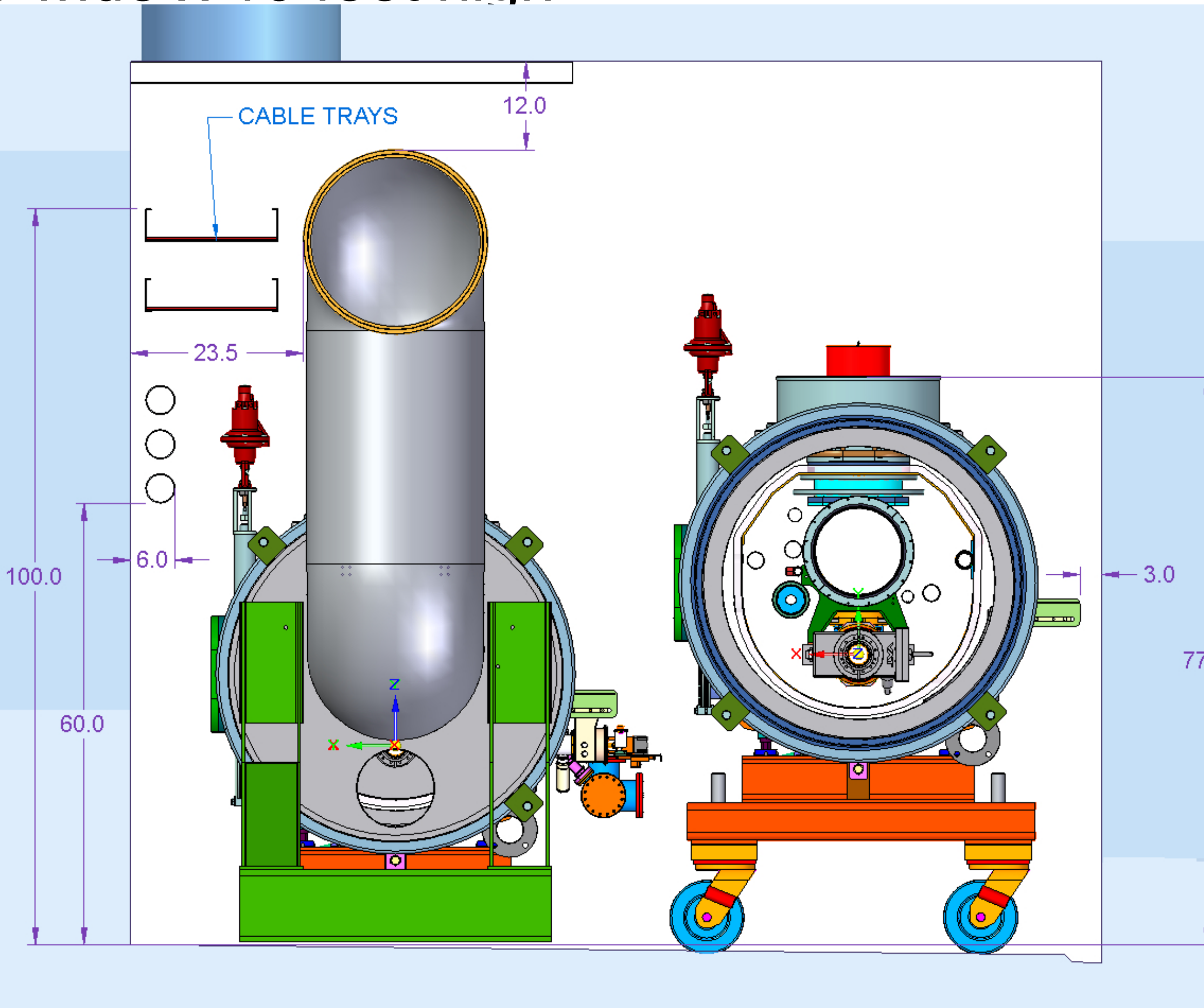
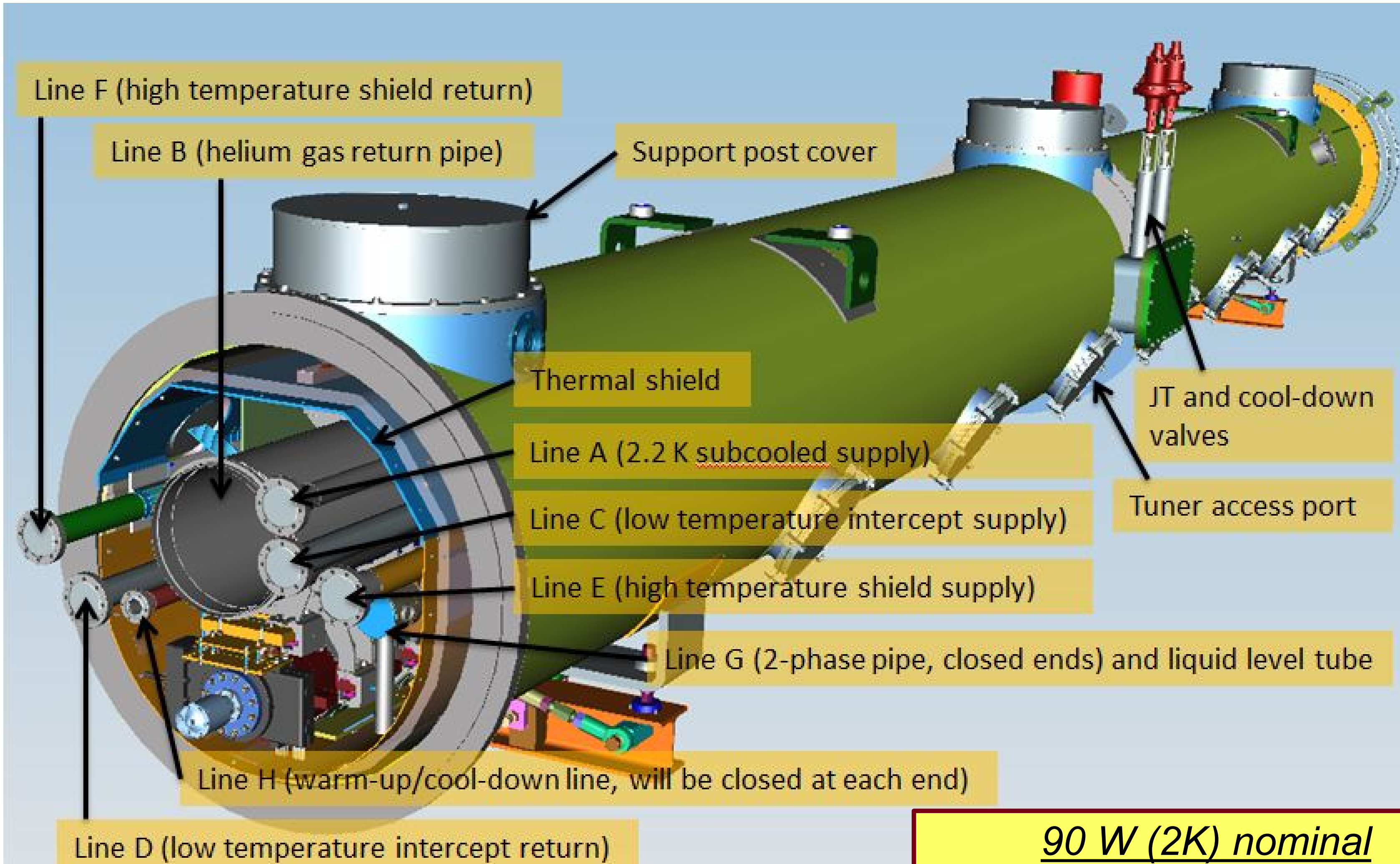
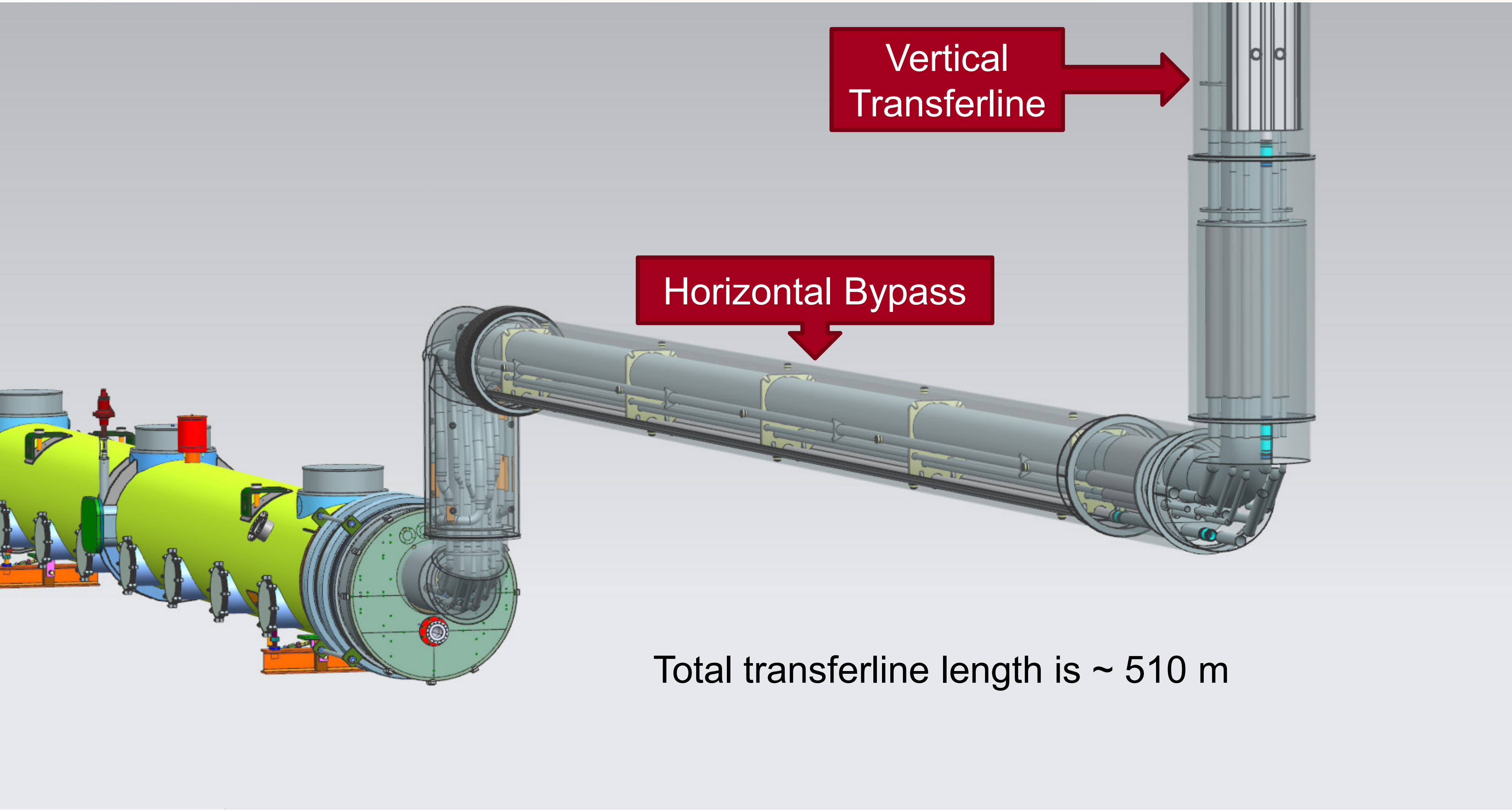


LCLS-II Cryomodule in 3-D



90 W (2K) nominal
Functional Requirements:
LCLSII-2.5-FR-0053

CM, Feed Cap and Bypass and Vertical Transferline

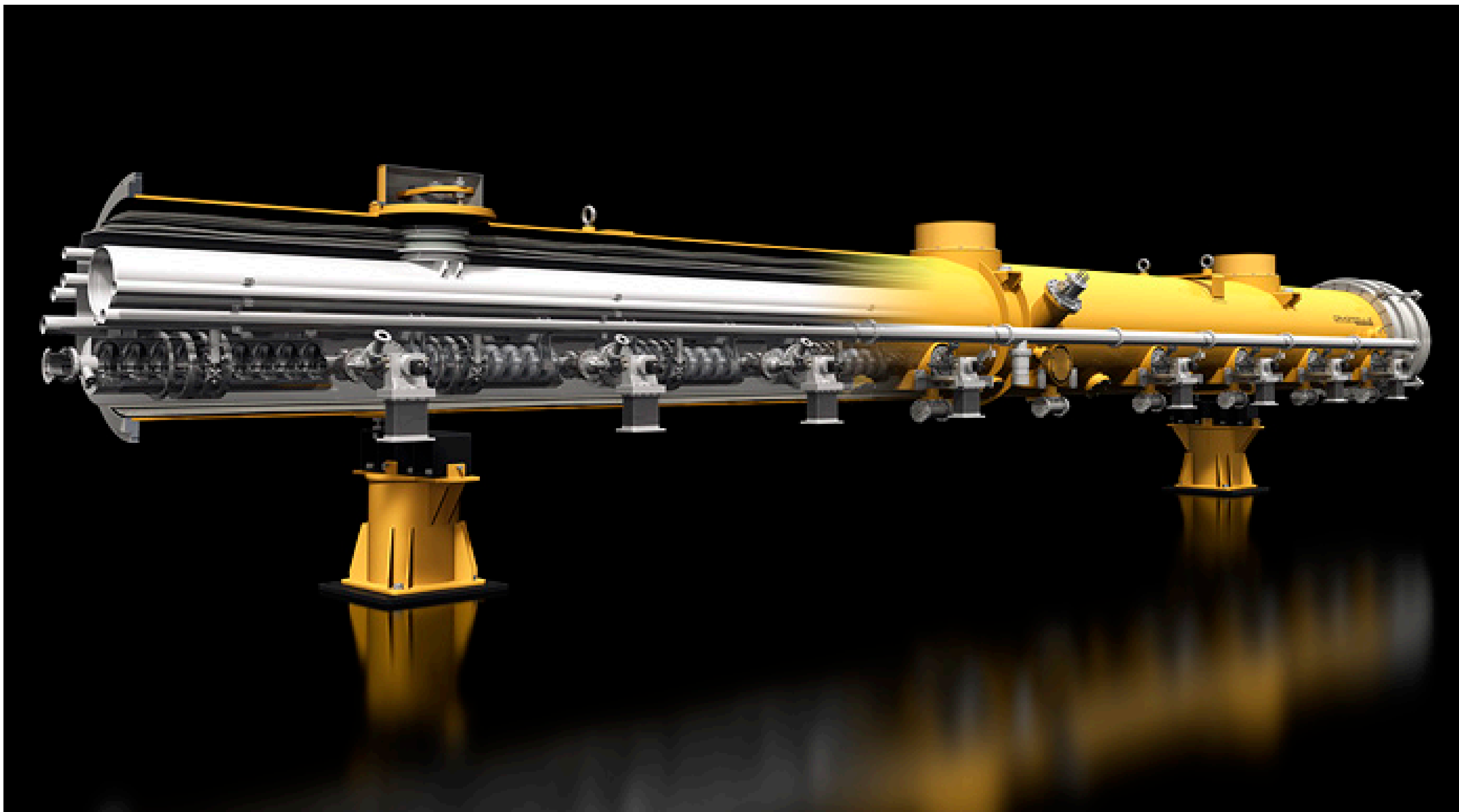


Total transferline length is ~ 510 m

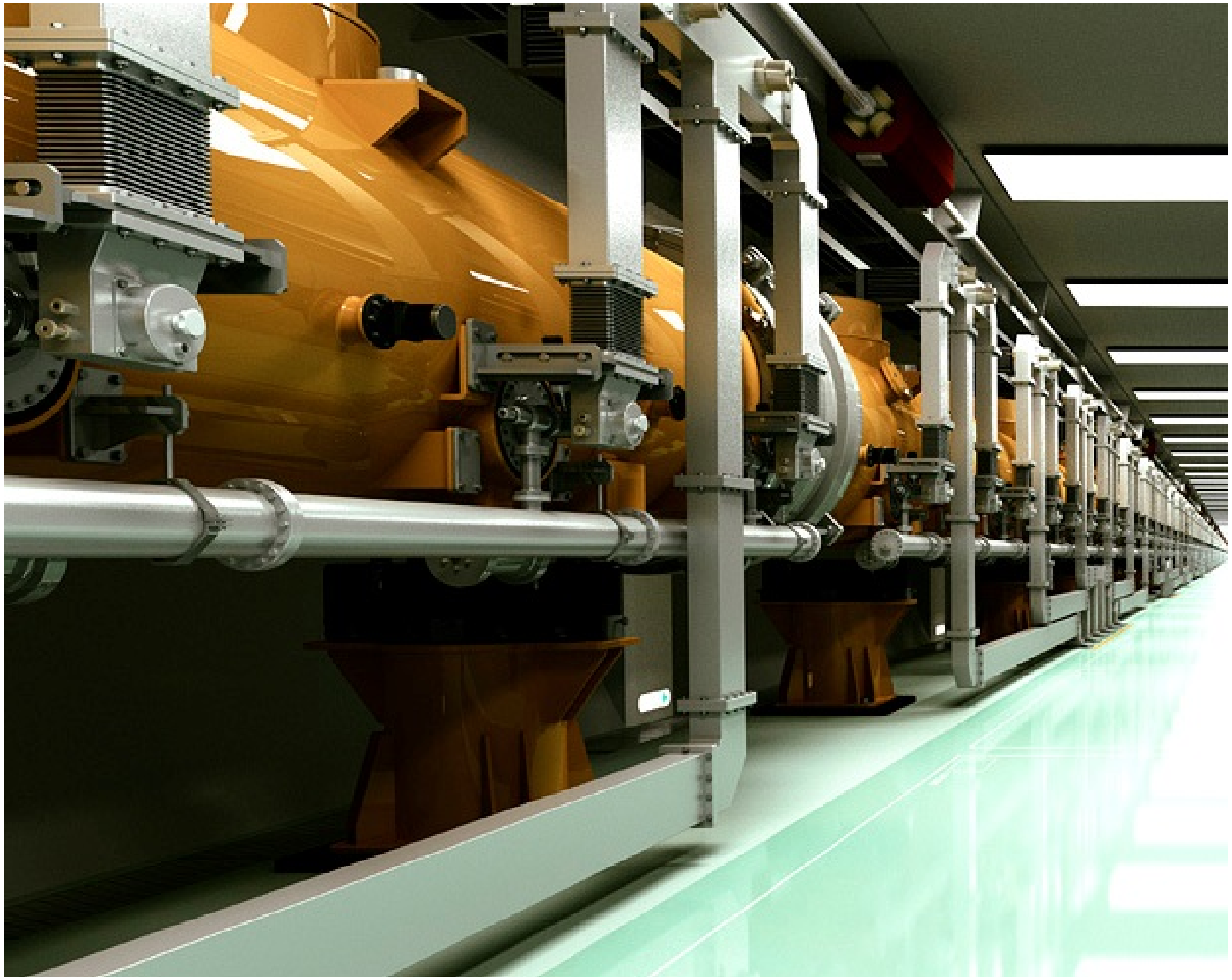
Cryomodule from the side:

12.6 m long; 1 m diameter

- (Similar to LHC dipole)
- 8 cavities w / superconducting quad magnet



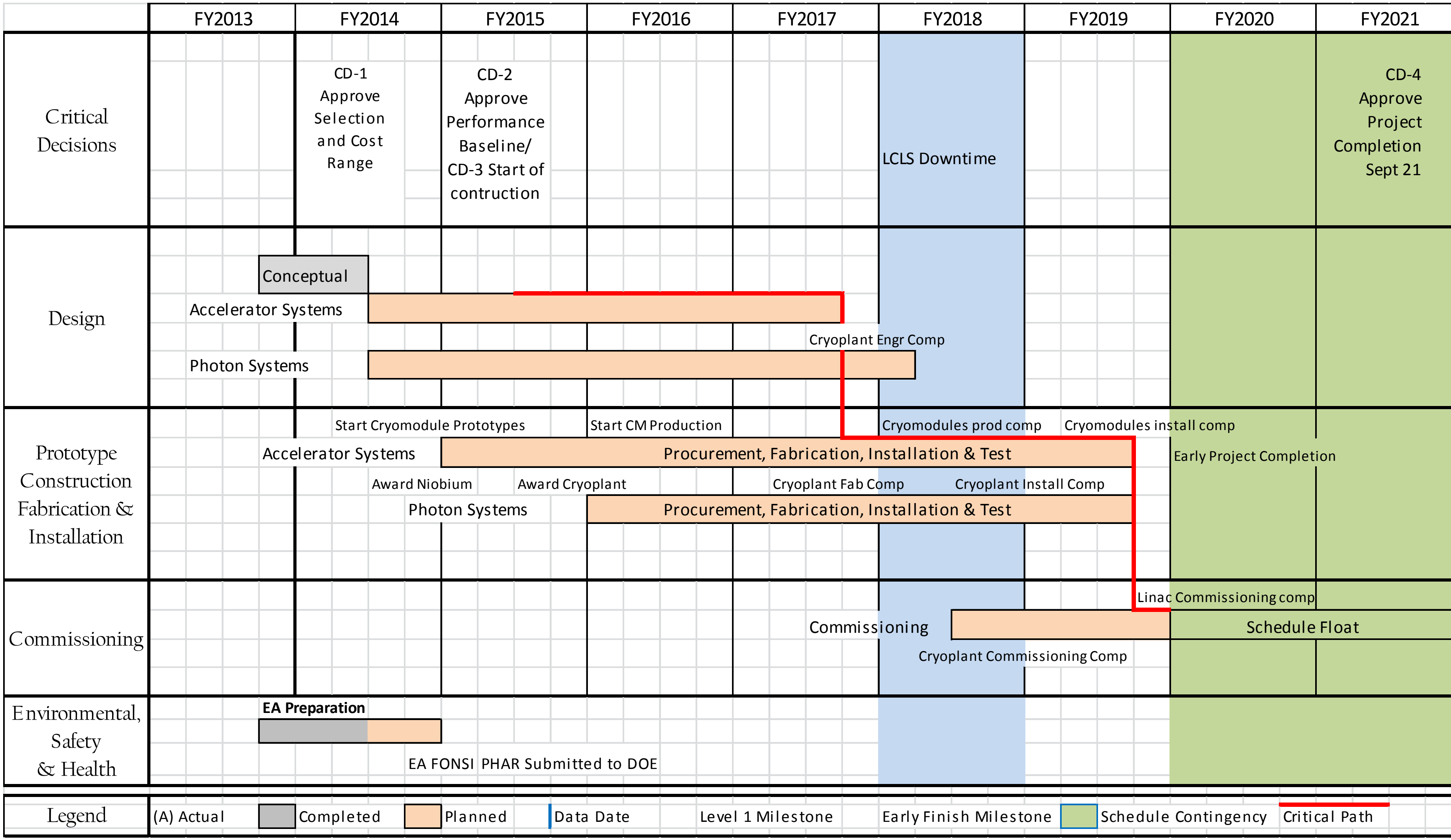
Future view along linac –
after LCLS-II SCRF linac installation:



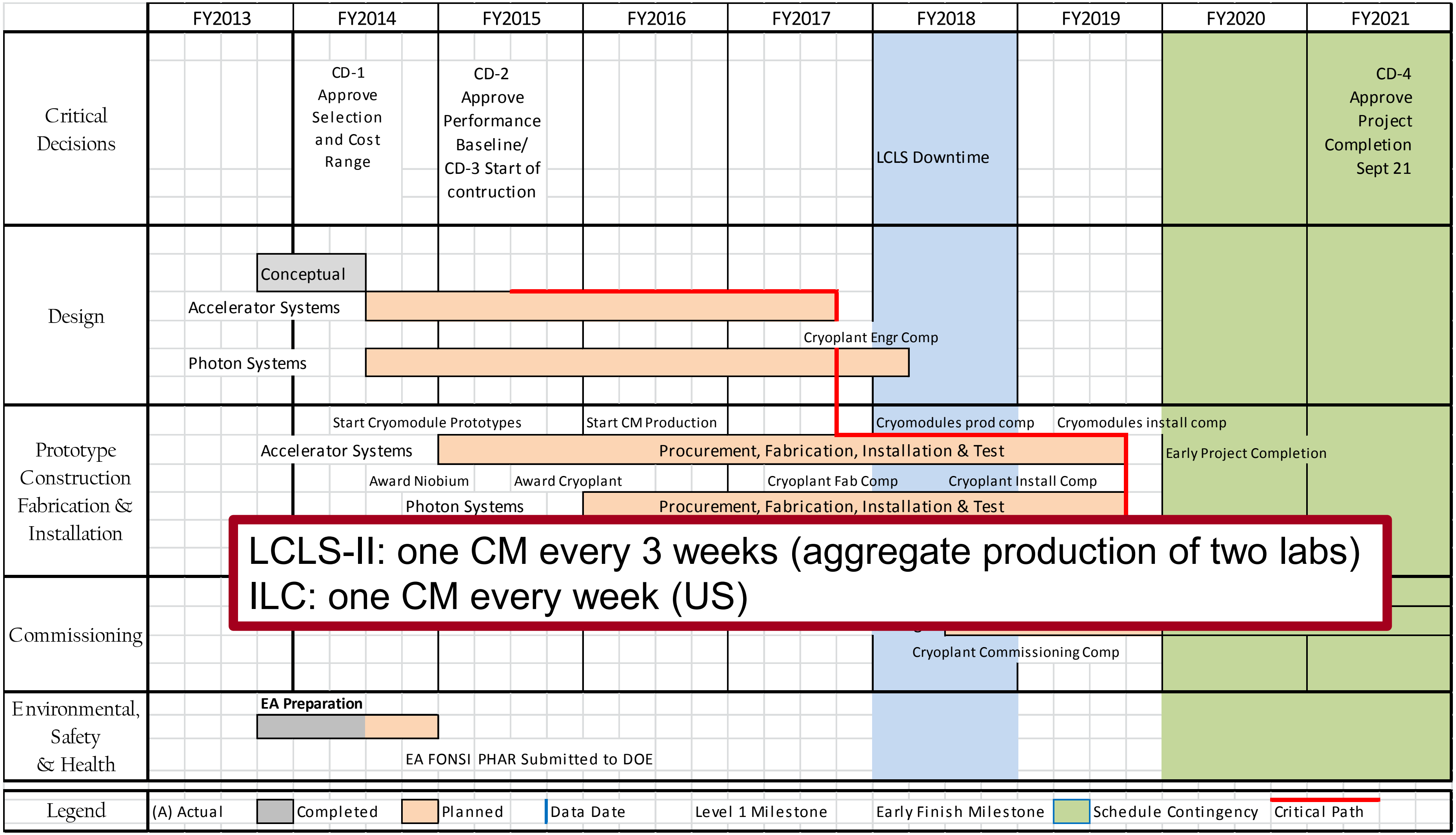
Project Collaboration: SLAC couldn't do this without…

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

Summary Schedule



Summary Schedule



LCLS-II: one CM every 3 weeks (aggregate production of two labs)
ILC: one CM every week (US)

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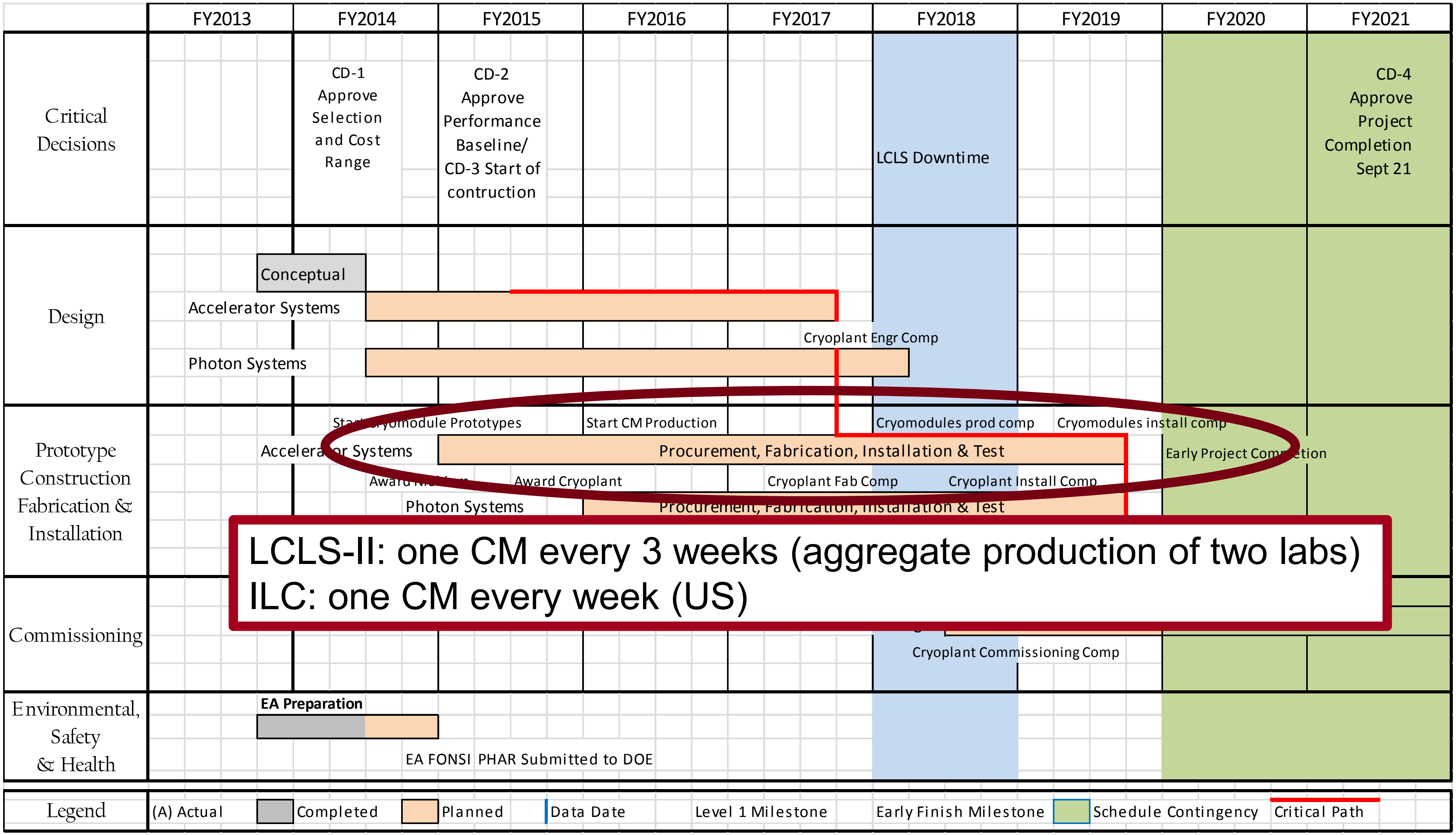

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Outline

1. Industrialization of 1.3 GHz SRF technology
   - 1990's to present
   - TESLA, E-XFEL, and ILC (also CEBAF 12 GeV)
2. LCLS-II
   - Free Electron Laser at SLAC – based on ILC / E-XFEL SRF
3. SRF for LCLS-II
   - Historic shift – very high performance resonators with Q0 ~ 1e11
   - Low cryogenic-loss cavities: 'N_2 doping' process developed by Fermilab
   - Three-lab (Fermilab, JLab and Cornell) development and demonstration
   - Multi-lab partnership
4. Implications for ILC

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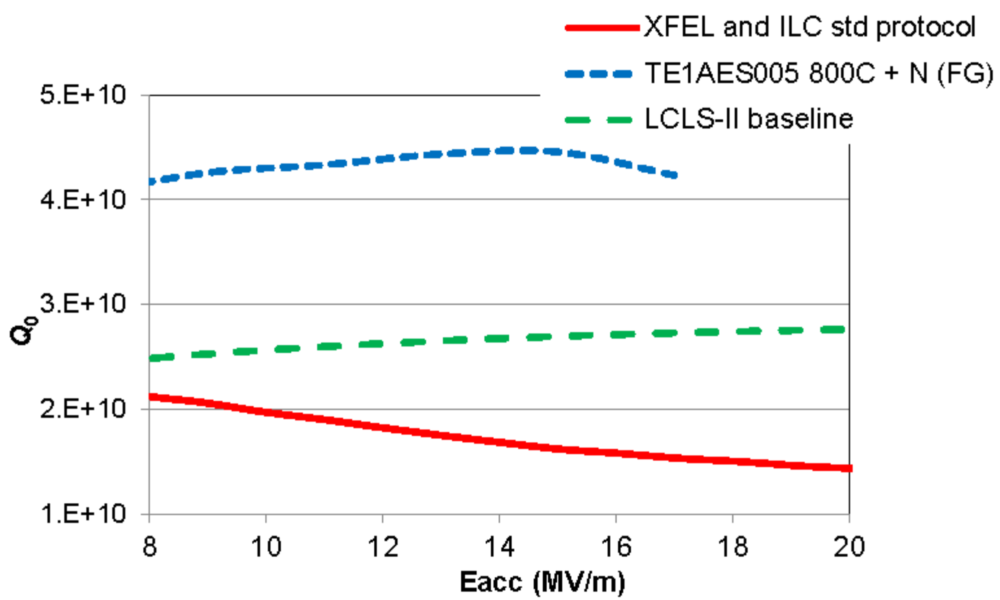
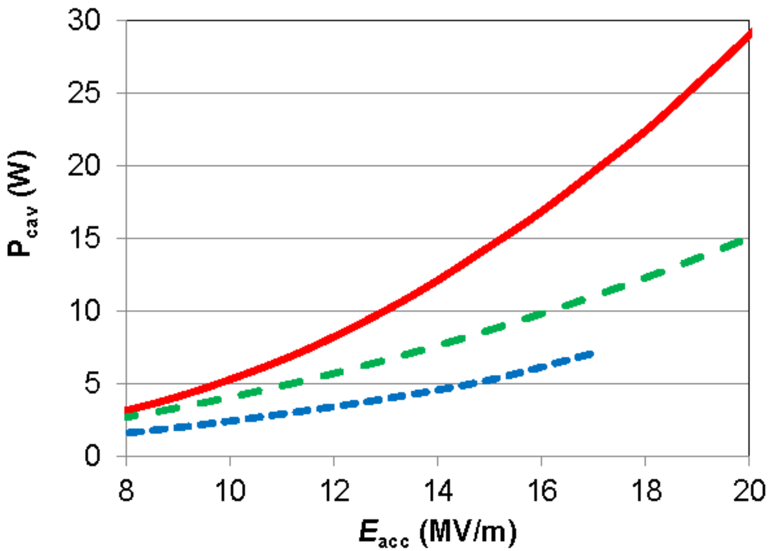
Motivation for High Q_0 R&D

High Q0 doping developed by Fermilab

- High Q_0 is a surrogate for low rf losses = low dynamic cryo heat load
- New Nb surface doping phenomenon with significantly lowered $R_{s\text{-BCS}}$ and $R_{s\text{-residual}}$ discovered 2012-2013
- Our mission: expedite development for use in LCLS-II





Fermilab-developed ‘gas-doping’ process →

Fermilab has developed a cavity processing recipe that results in ***high quality factors (>3E10)*** at operating gradients between 10 and 20 MV/m.

In 2014 Fermilab led a Q0 program in collaboration with Cornell and JLab.

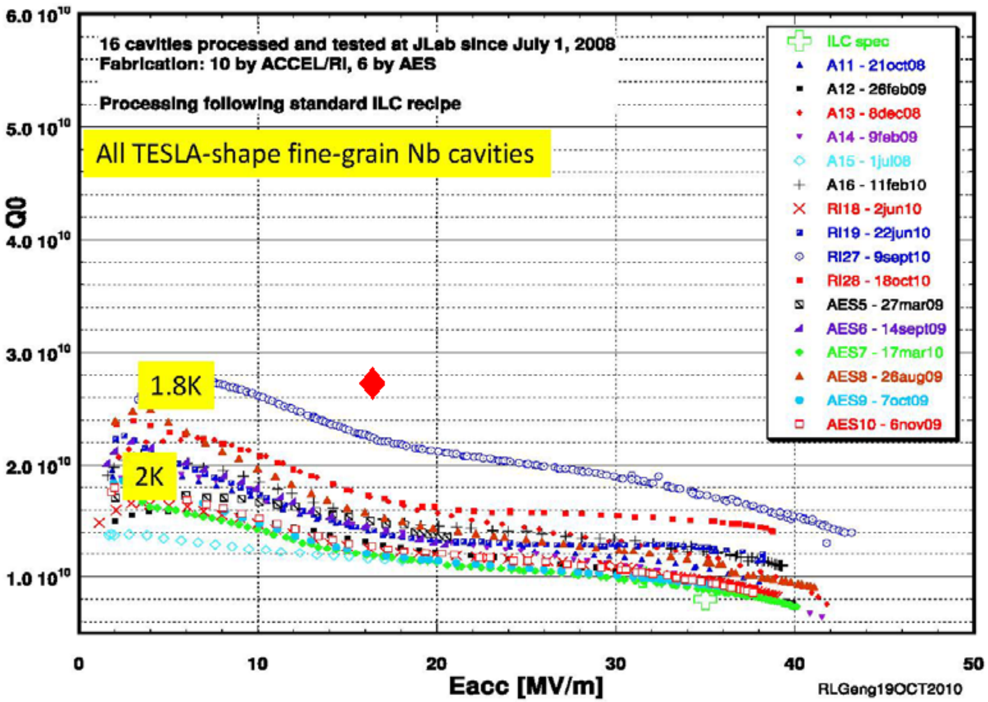
The primary goal is to develop a reliable and industrially compatible processing recipe to achieve an average Q0 of 2.7E10 at 16 MV/m in a practical cryomodule; minimum 1.5E10.

To reach this goal, the collaborating institutions processed and tested single-cell and 9-cell 1.3 GHz cavities in a successive optimization cycle.

The deliverable is industrial capability and cost-effective production yield.

- Supporting the cryoplant design choices

Motivation for High Q_0 R&D

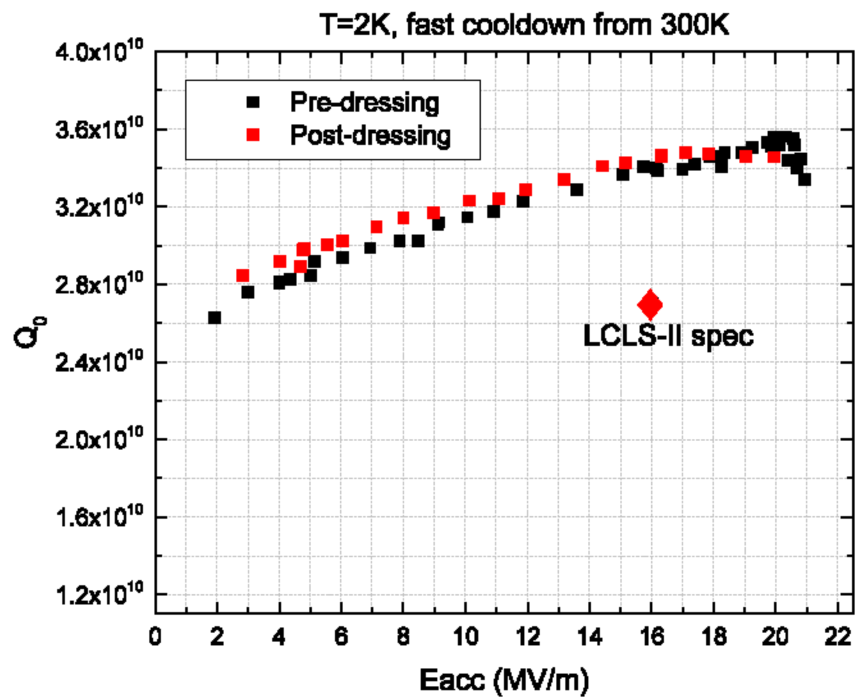


"The best cavities of 2010"

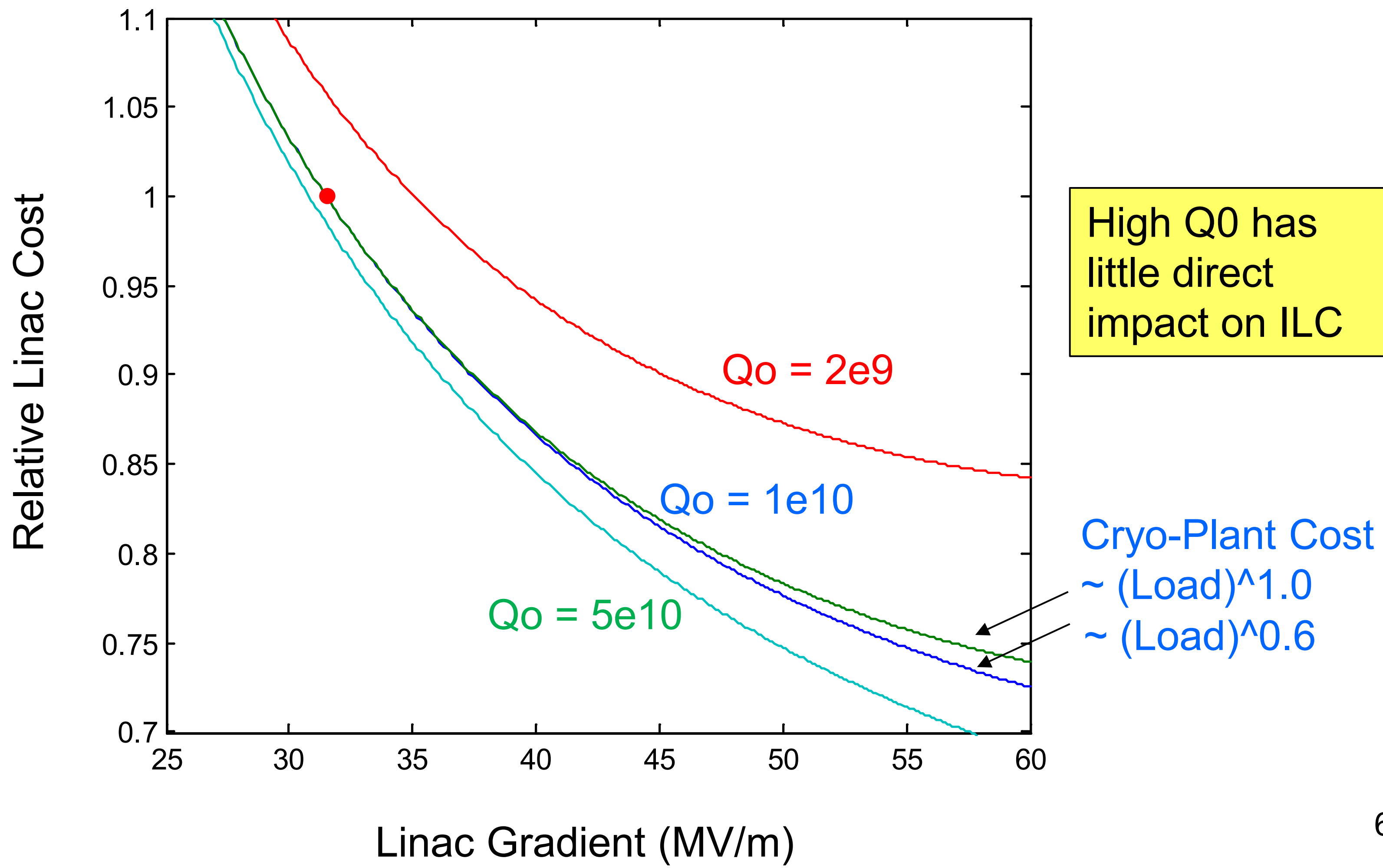
The SRF world is changing

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

TB9AES011

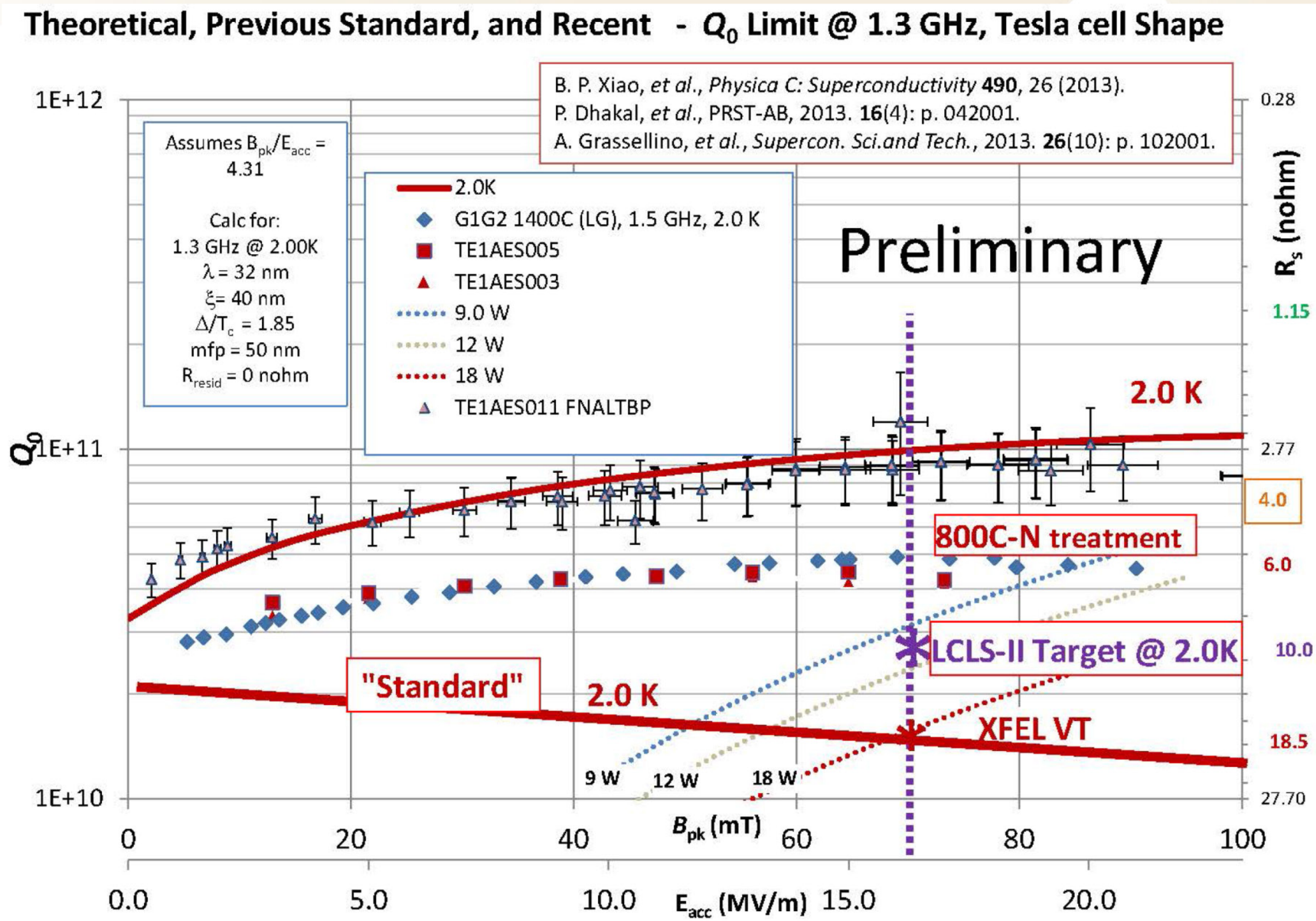


Americas ILC Linac Cost Versus Cavity Gradient and Qo



High Q0 has little direct impact on ILC

Q_0 picture still looks good for LCLS-II, but new discipline will be required



FNAL IB4 Vacuum Oven

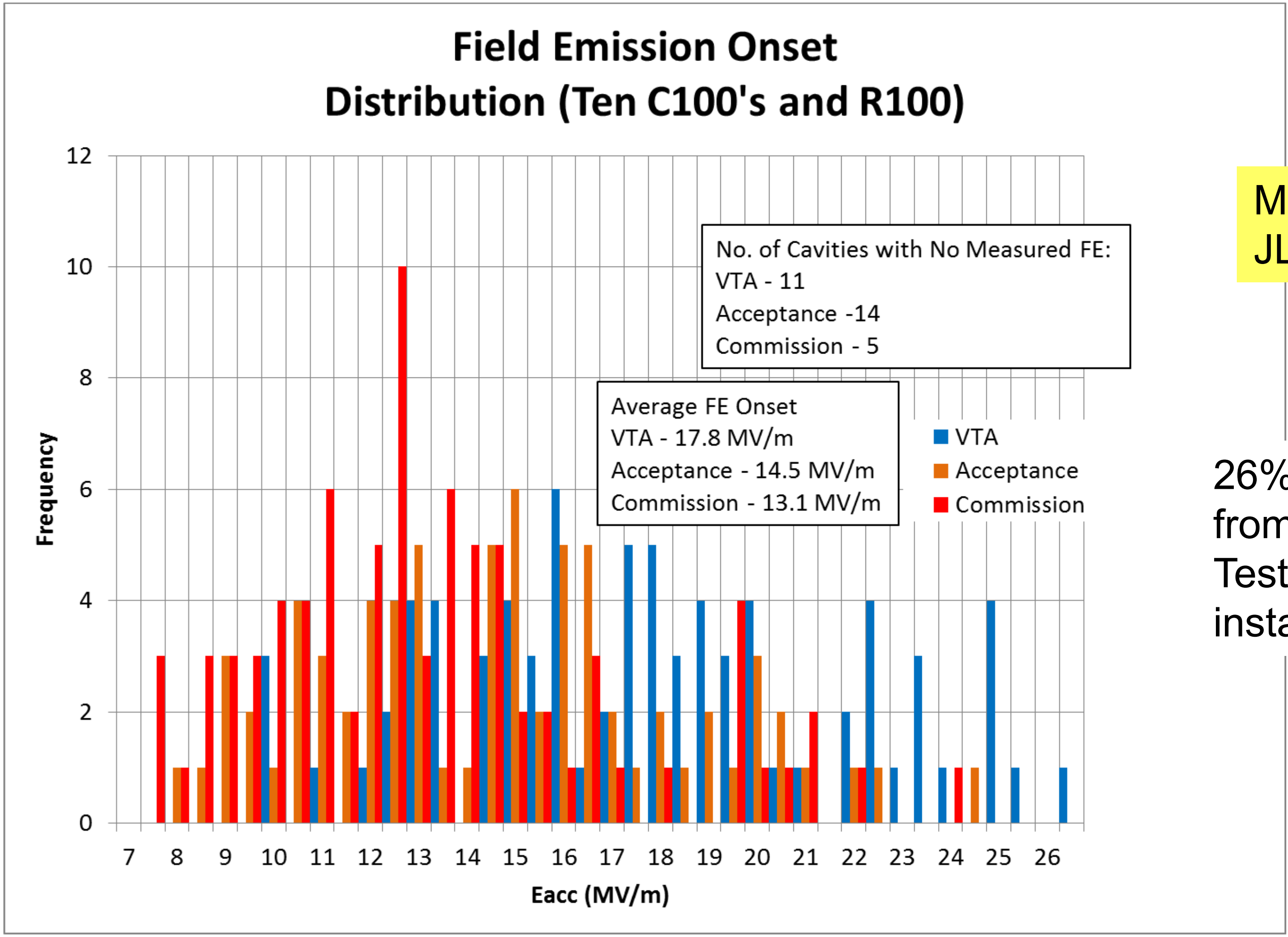
LCLS-II High Q0 R&D Program – Preliminary Nine-Cell VT Results

High Q0 testing done at 3 labs: Fermilab (from 2012); JLab and Cornell (2014)

High Q0 Program 9 cell results			
	Q0	E_acc (MV/m)	
Average	3.5E+10	19.0	
Yield	100% (avg. 2.7e10)	47% (18 MV/m)	88%(16 MV/m)
Number of cavities tested; some multi-pass			
17 (3 Cornell; 5 Jlab; 9 Fermilab)			

Initial results meet LCLS-II VTS High Q0 criteria: 30% margin

Field Emission Onset



Mike Drury, JLab

26% reduction from Vertical Test to CM installation

Effect of cool-down *speed-through-transition*

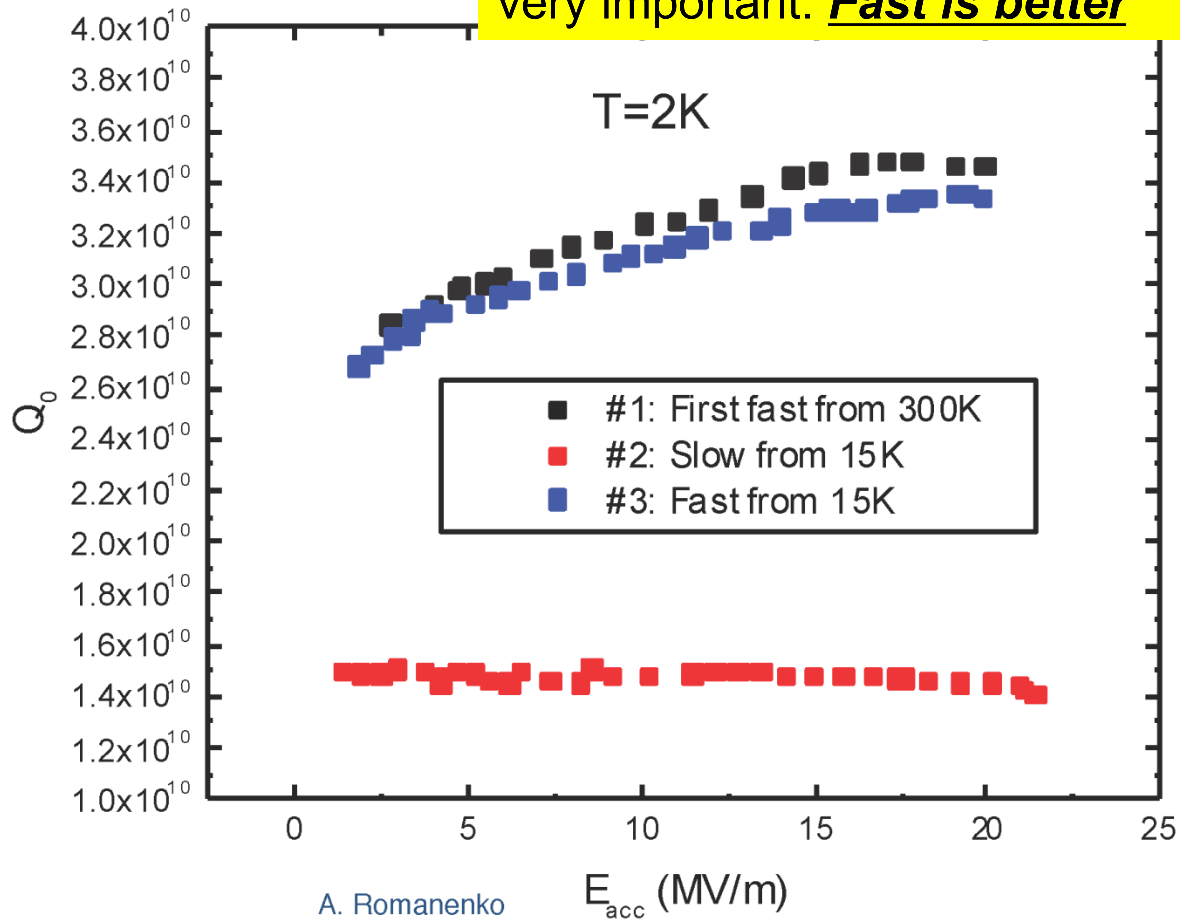
Cool-down speed appears to be very important: ***Fast is better***

"Dressed" cavity results under different cooling regimes.

- Thermogradient-generated fields have no impact on Q in VT, slow cooling through T_c has dramatic effect.

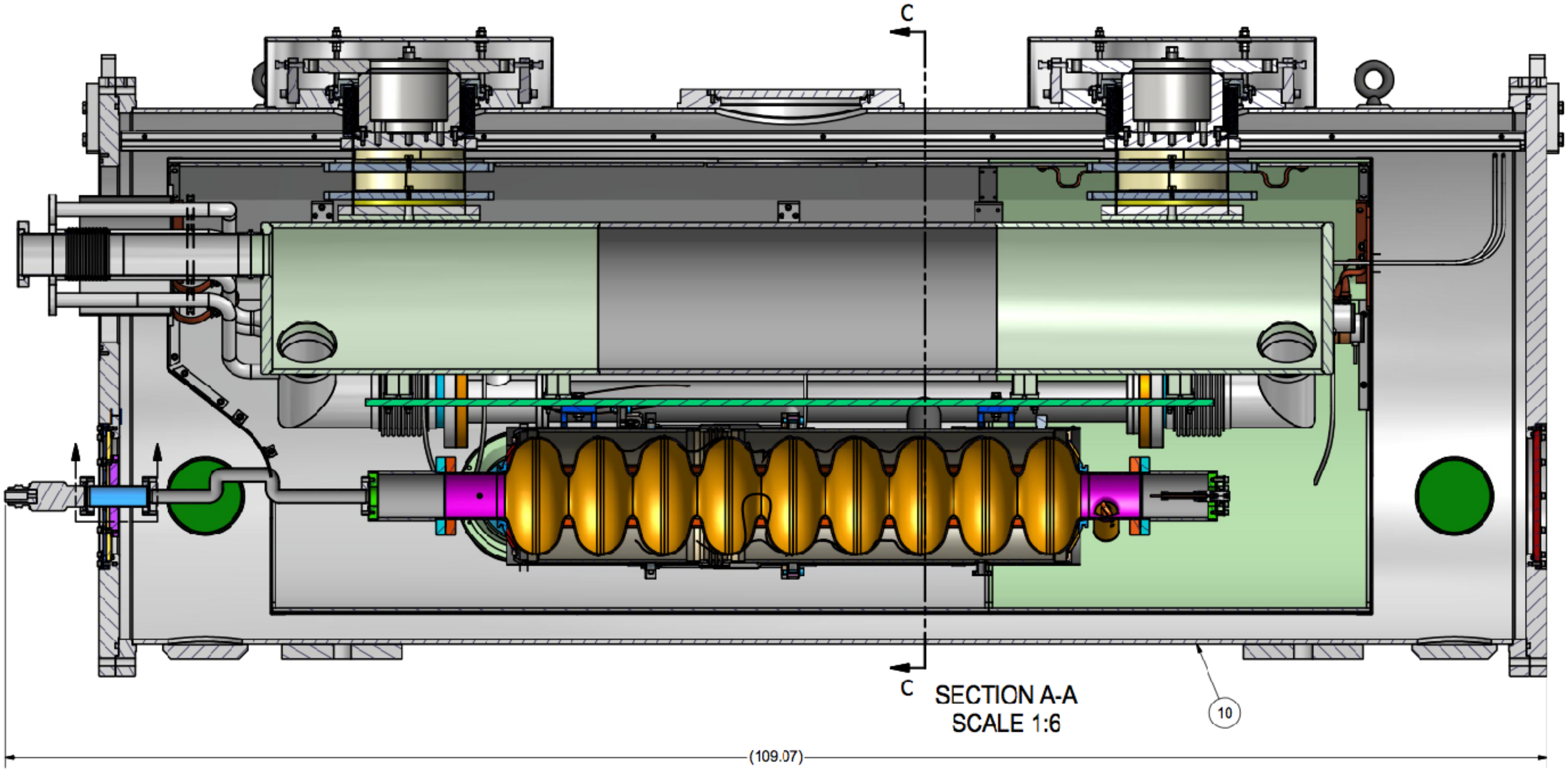
  [fast ~1.8K/min; slow ~0.3K/min through 9.2K]

- Precautions will have to be taken in CM to obtain fast cooling through transition.

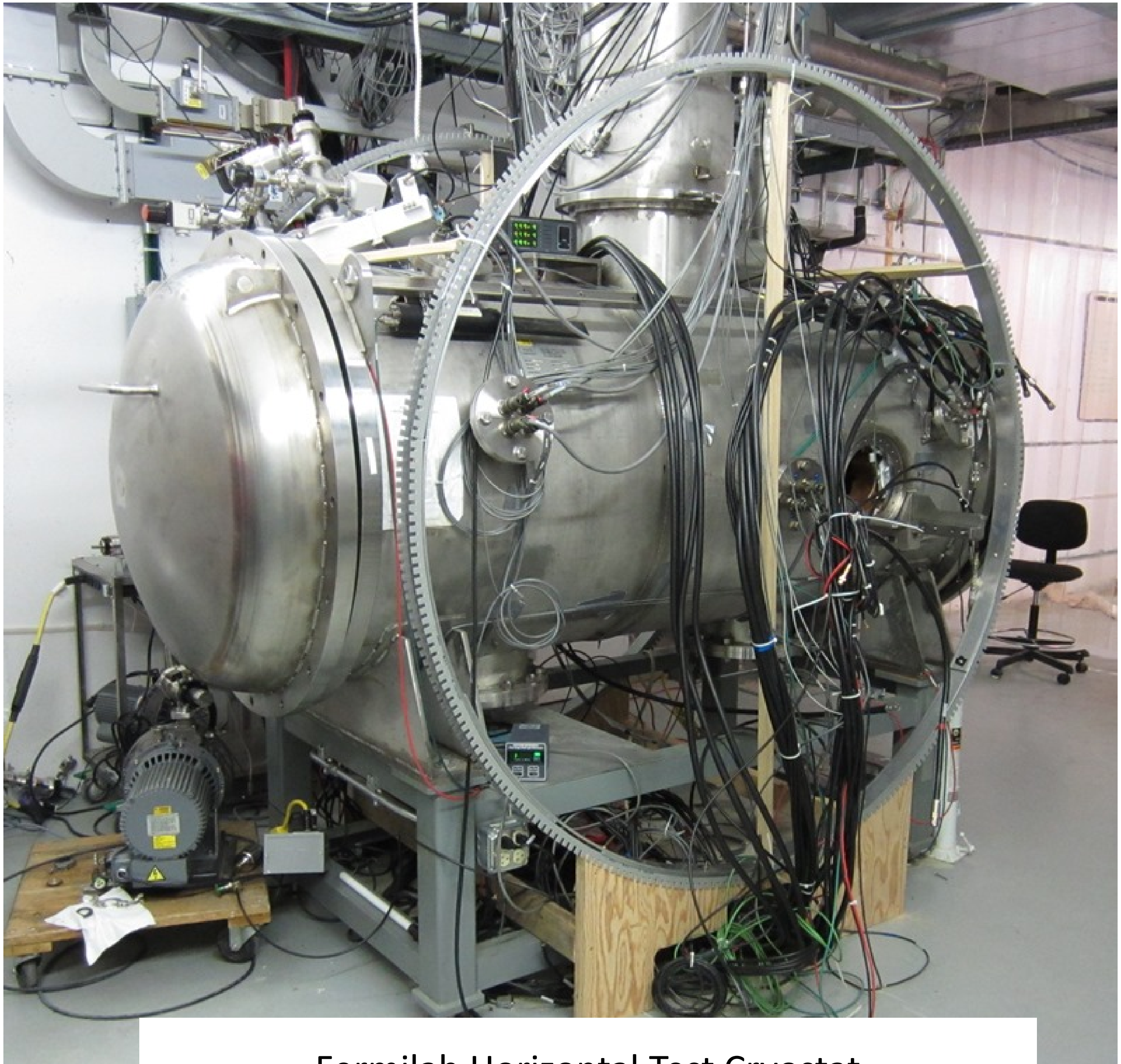


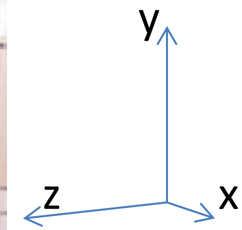
A. Romanenko

LCLSII Cavity Tests in the Cornell one-cavity Horizontal-Test-Cryomodule (HTC)



- Small modifications were needed to host a 9-cell cavity (changes to 2-phase line, cavity support).





Fermilab Horizontal Test Cryostat
With Three Axis Magnetic Cancellation

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For ILC: Summary

Cavity / Cryomodule:

- Cost Validation : ***few percent scale***
- Cost Reduction
  - Applied production v/v continued R&D
  - (tooling, infrastructure, and experience)
  - From C100 to EXFEL: ***factor 2 cavity cost reduction***
  - (Hasan's target)
- Technical Risk Mitigation
  - ***Demonstrate construction and performance*** of ILC-type cryomodules for science in the US

For US, the work on ILC and now 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".