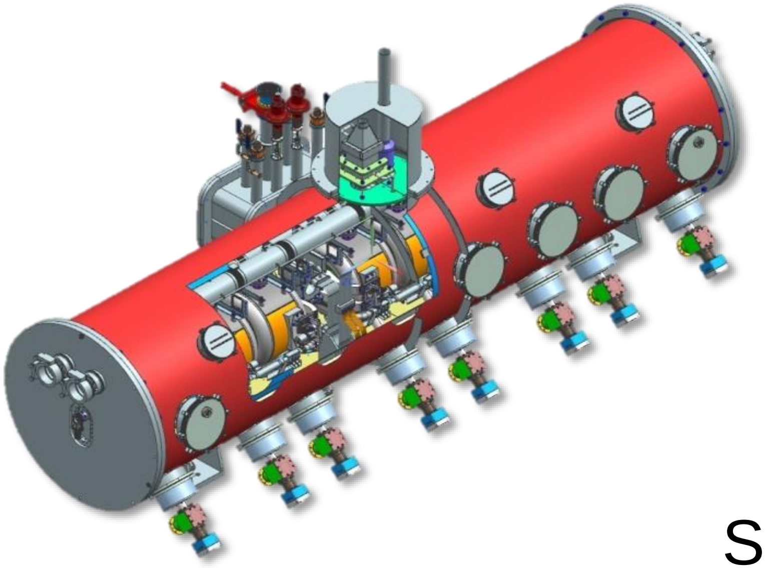
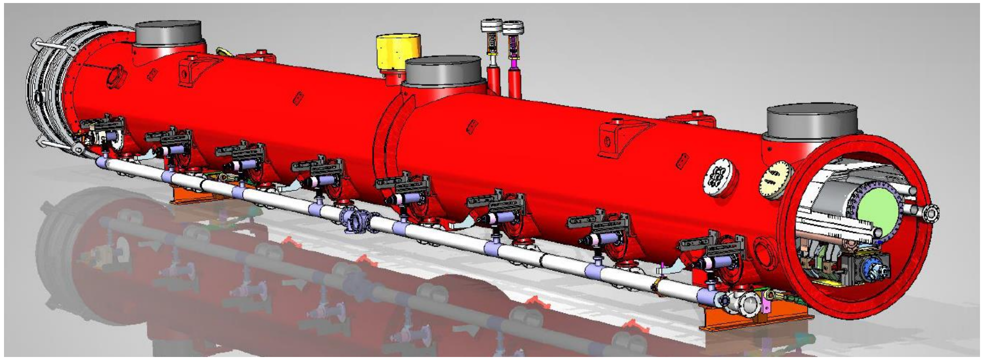
Fermilab

Superconducting RF Development at Fermilab





Sam Posen

Associate Scientist, Technical Division

PASI Workshop

13 November 2015

- Overview of projects – LCLS II and PIP II
- Technical challenges
- Facilities
- Design efforts
- Critical Elements and Subsystems
- Plans and schedule
- Future R&D

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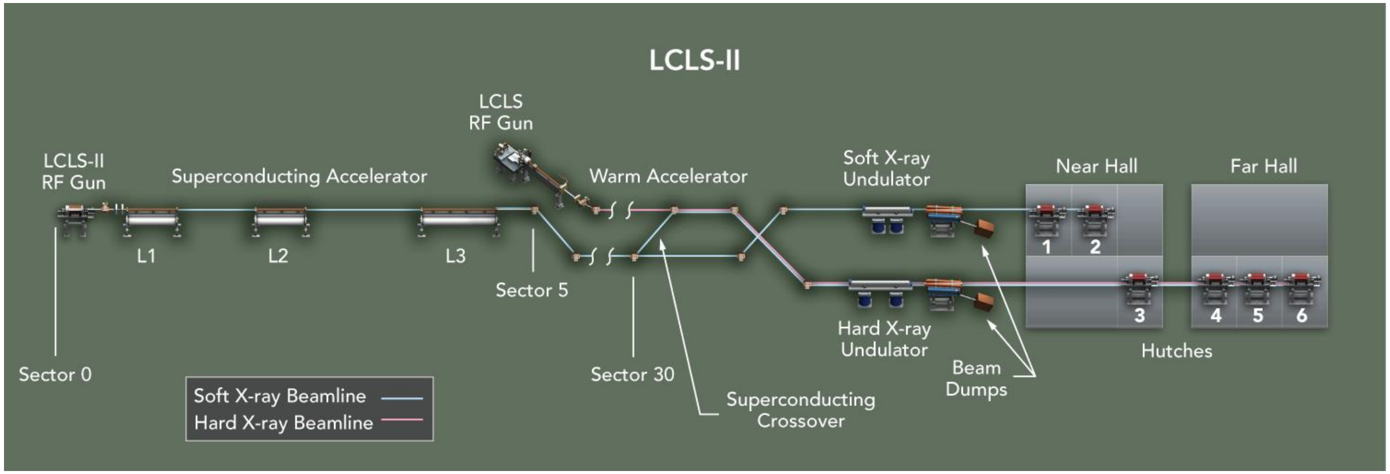
LCLS-II Hybrid FEL at SLAC

- LCLS II: 0.2 - 5 KeV, 1 MHz free electron laser
- Driven by 4 GeV 1.3 GHz CW SRF linac



LCLS II Partner Labs

Fermilab — Design Lead

- 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

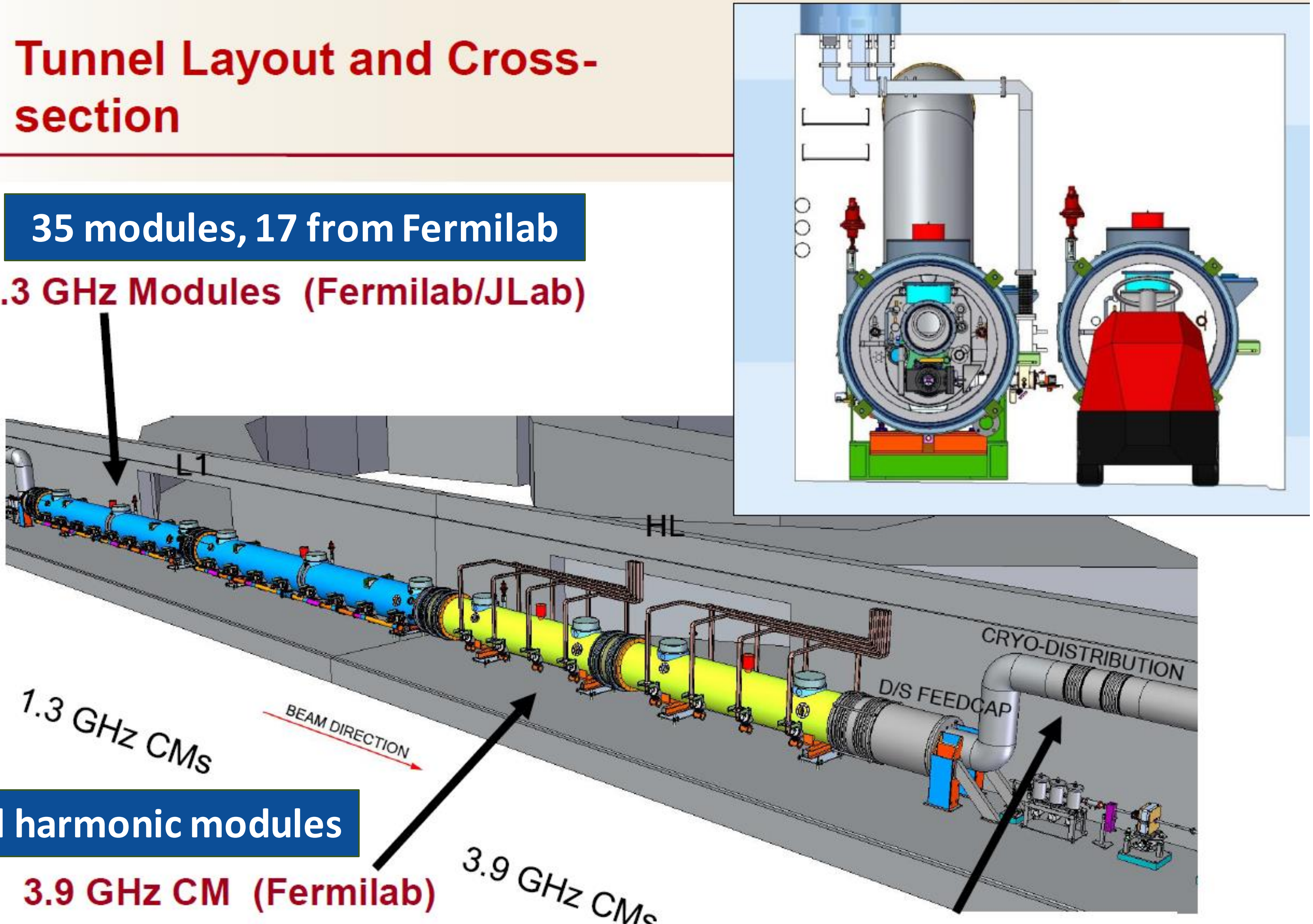
Slide courtesy M. Ross, SLAC

LCLS II SRF Linac

Tunnel Layout and Cross-section

35 modules, 17 from Fermilab

1.3 GHz Modules (Fermilab/JLab)



2 third harmonic modules

3.9 GHz CM (Fermilab)

CDS (Fermilab)

Slide courtesy M. Ross, SLAC

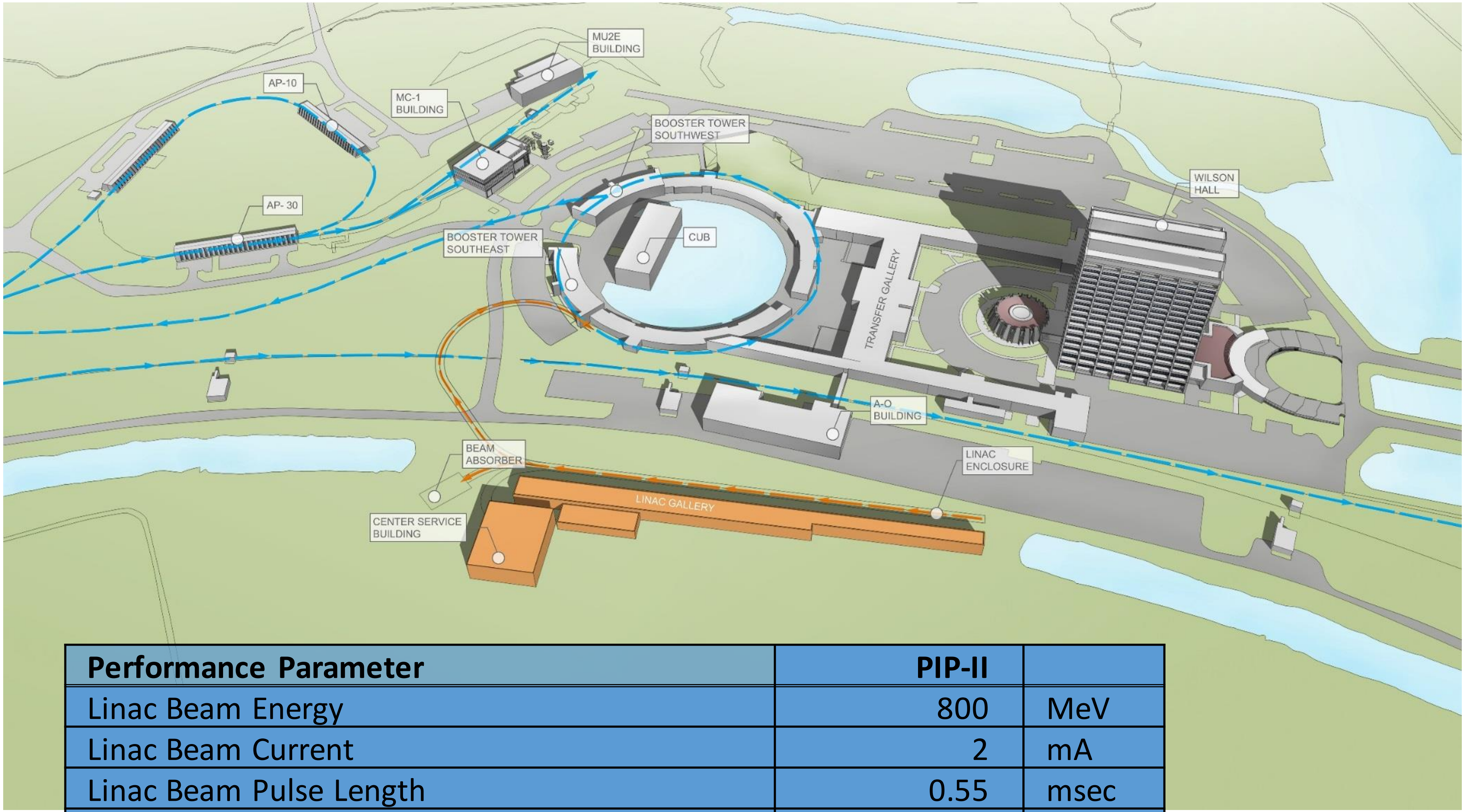
PIP II Mission and Strategy

- **Proton Improvement Plan II (PIP-II):**

The PIP-II goal is to support long-term physics research goals by providing increased beam power to neutrino experiments, while providing a platform for the future.

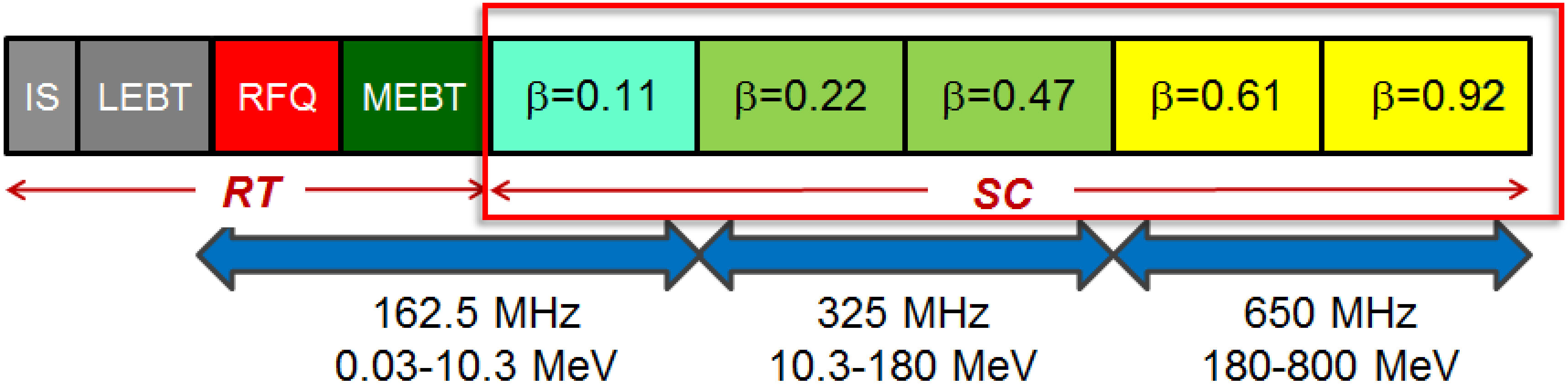
- Design Criteria
  - Deliver >1 MW of proton beam power from the Main Injector over the energy range 60 – 120 GeV, at the start of LBNF operations
  - Support the current 8 GeV program including Mu2e, g-2, and short-baseline neutrinos
  - Provide an upgrade path for Mu2e
  - Provide a platform for extension of beam power to LBNF to >2 MW
  - Provide a platform for extension of capability to high duty factor/higher beam power operations

PIP II SC Linac Requirements



Performance Parameter	PIP-II	
Linac Beam Energy	800	MeV
Linac Beam Current	2	mA
Linac Beam Pulse Length	0.55	msec
Linac Pulse Repetition Rate	20	Hz
Linac Beam Power to Booster	18	kW

PIP II Linac Reference Design



Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-10.3	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	10.3-35	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.47)	325	35-185	35/21/7	SSR, solenoid
LB 650 (β_g=0.61)	650	185-500	33/22/11	5-cell elliptical, doublet*
HB 650 (β_g=0.92)	650	500-800	24/8/4	5-cell elliptical, doublet*

*Warm doublets external to cryomodules

All components CW-capable

9 spoke cavity cryomodules,
15 elliptical cavity cryomodules

PIP II SRF Overview

Name	β	Freq (MHz)	Type of cavity	B_{peak} (mT)	E_{peak} (MV/m)	E_{acc} (MV/m)	ΔE (MeV)
HWR	0.11	162.5	Half wave resonator	48.3	44.9	9.7	2.0
SSR1	0.22	325	Single-spoke resonator	58.1	38.4	10	2.05
SSR2	0.47	325	Single-spoke resonator	64.5	40	11.4	5.0
LB650	0.61	650	Elliptic 5-cell	72	38.5	15.9	11.9
HB650	0.92	650	Elliptic 5-cell	72	38.3	17.8	19.9

- Operating gradients ($E_{peak} \lesssim 40$ MV/m – field emission; $B_{peak} \lesssim 70$ mT);

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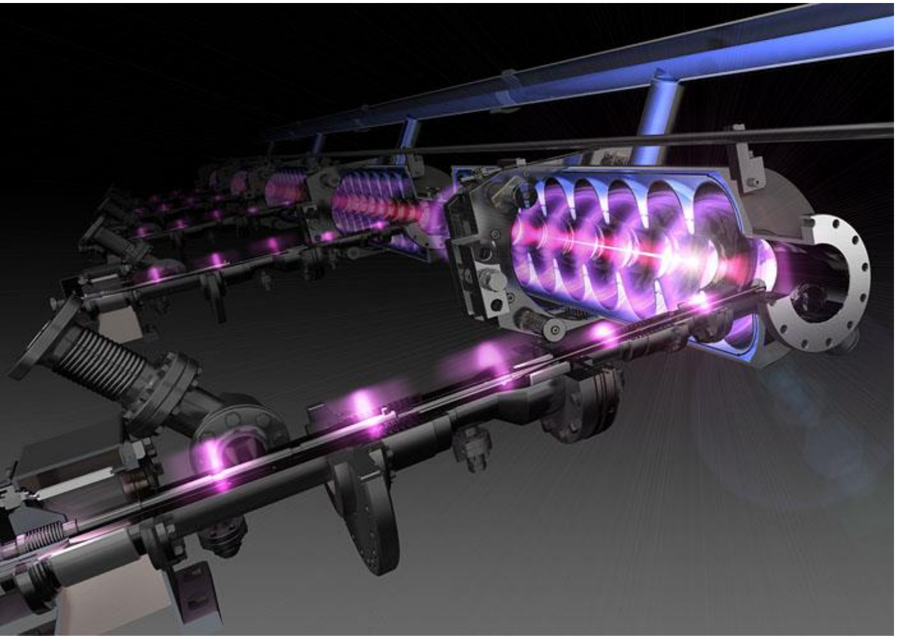
LCLS II SRF Linac

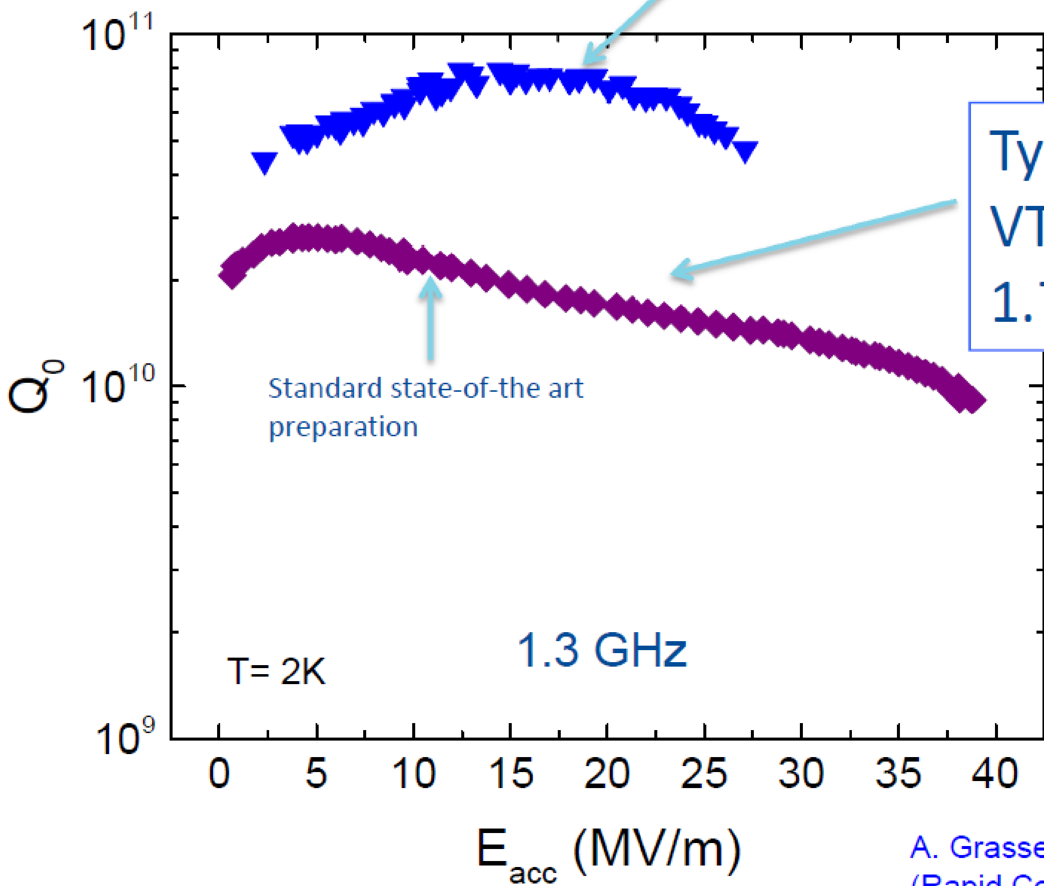
- Linac based on 1.3 GHz SRF cryomodule design: TeSLA / ILC / European XFEL
- 8 cavities per cryomodule at 2 K
- Gradient specification: 16 MV/m
- **Q_0 specification: 2.7×10^{10}**



Images from linearcollider.org

LCLS II High Q_0 R&D

Record after nitrogen doping – up to 4 times higher Q! Average values obtained on nine cell Q(2K, 16MV/m)~ 3.5e10



Typical Q obtained in VTS with 120C bake ~ 1.7e10 at 2K, 16 MV/m

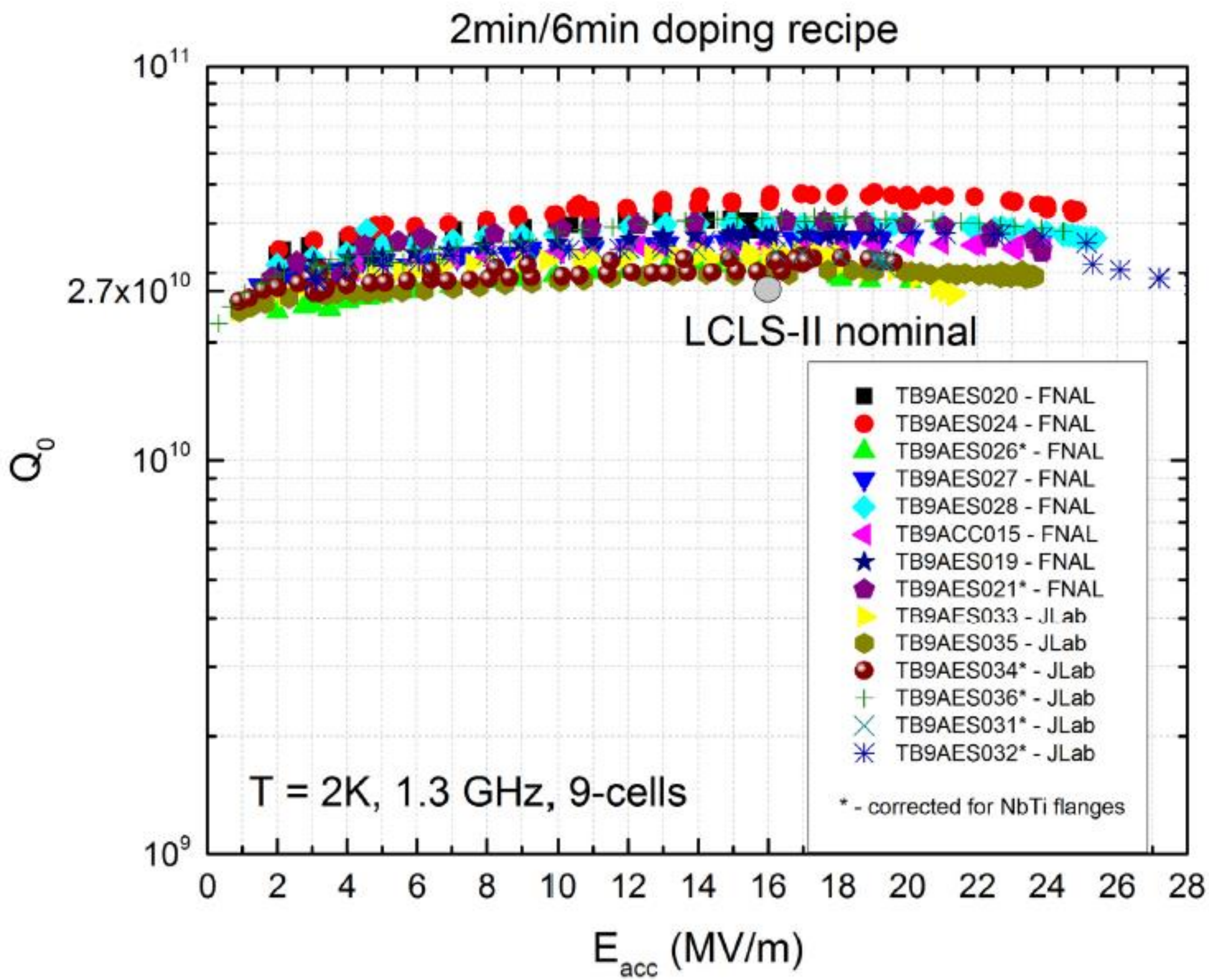
Nitrogen Doping Treatment for LCLS II

- 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

A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication)

Slide courtesy A. Grassellino, FNAL

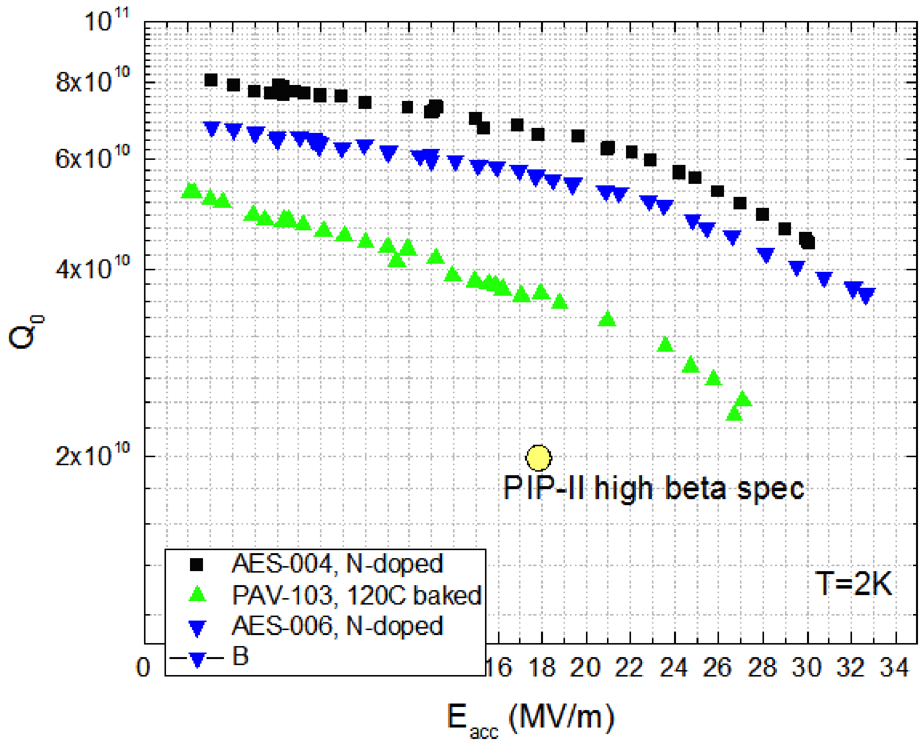
LCLS II High Q_0 R&D



Slide courtesy A. Grassellino, Fermilab

PIP II High Q_0 R&D

- Results – highlights – 120C bake versus N doping
  Q~ 7e10 at 2K, 17 MV/m – world record at this frequency!
- Applying N doping to 650 MHz (beta=0.9) leads to double Q compared to 120C bake (standard surface treatment ILC/XFEL)



Slide courtesy A. Grassellino, Fermilab

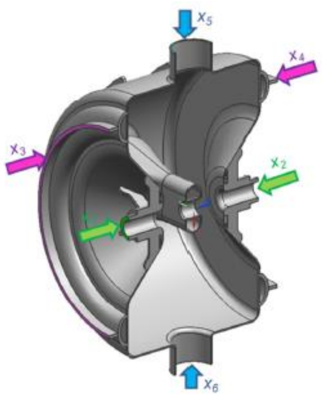
PIP II Technical Challenges

- Low beam loading → narrow bandwidth;
  - Pulsed regime → Lorentz Force Detuning (LFD);
  - CW regime → microphonics;

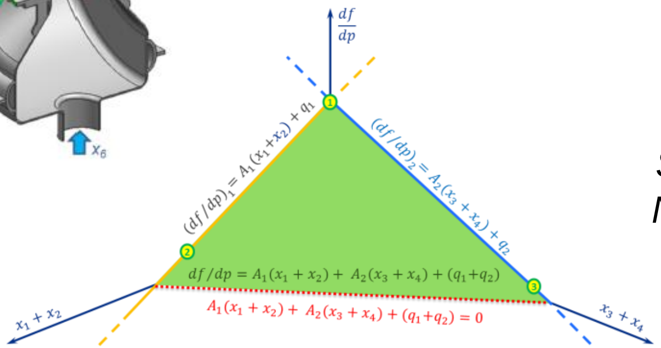
Section	Freq (MHz)	Max detuning (peak, Hz)	LFD at operating gradient (Hz)	Minimal Half Bandwidth (Hz)	Max Required Power (kW)
HWR	162.5	20	-122	33	6.5
SSR1	325	20	-440	43	6.1
SSR2	325	20	-	28	17.0
LB650	650	20	-192	29	38.0
HB650	650	20	-136	29	64.0

PIP II SSR1 Microphonics

Fermilab



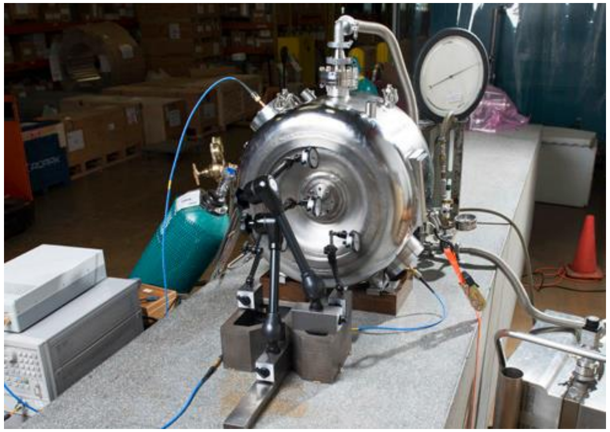
The jacketed SSR1 cavities were designed to have very low sensitivity to helium pressure fluctuations (microphonics).
We physically coupled the Nb cavity and the helium vessel such that we obtain a combination of cavity walls deformations $(x_1 + x_2)$ and $(x_3 + x_4)$ giving a $df/dp = 0$.



Self-compensated system --> Passive compensation
No active control to mitigate the pressure fluctuations

PIP-II requirements: -25 ≤ df/dp ≤ 25 Hz/Torr

	df/dp [Hz/Torr]	S106	S107	S108	S109	S110	S111	S112	S113	S114
Measured	Bare cavity (with transition ring)	-564	-561	-553.5	-555.1	-568.8	-525.8	-524.6	-544.7	-557.2
	With He Vessel (without Tuner)	8	8	-1.2	5.4	7.9	2.7	9.0	6.3	10
	Fully integrated	4*	4	0*	2*	4*	2*	5*	3*	5*

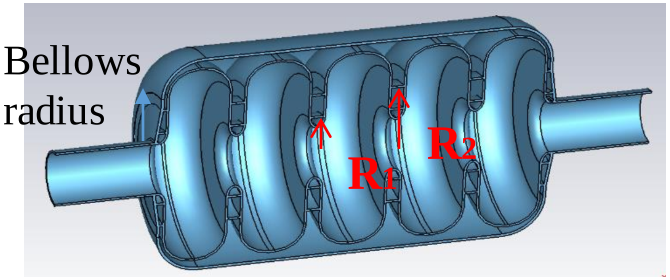


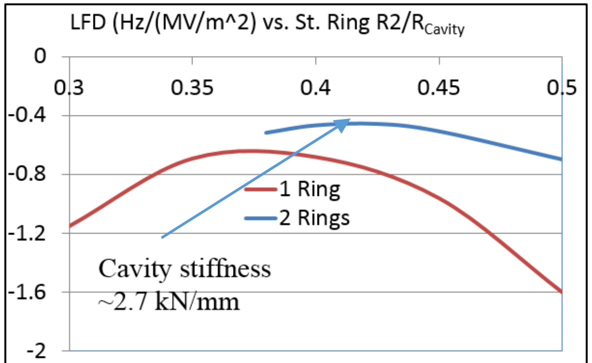
* Not measured yet (best guess)

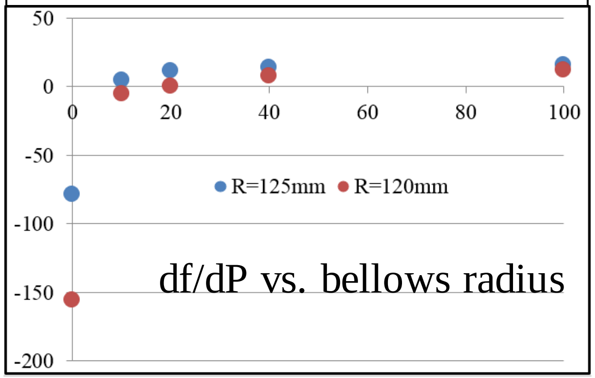
Slide courtesy D. Passarelli, Fermilab

PIP II 650 LFD and df/dp

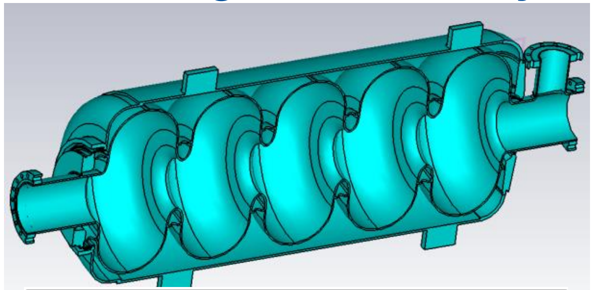
Low-Beta Cavity

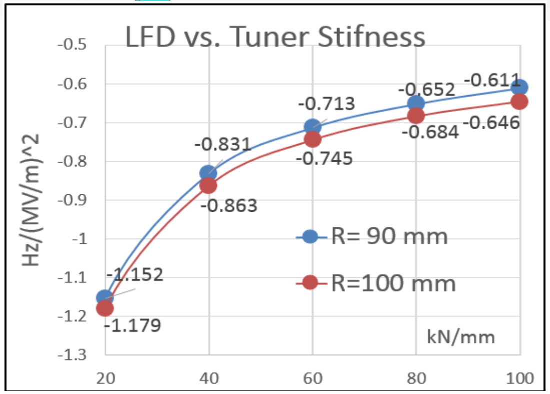


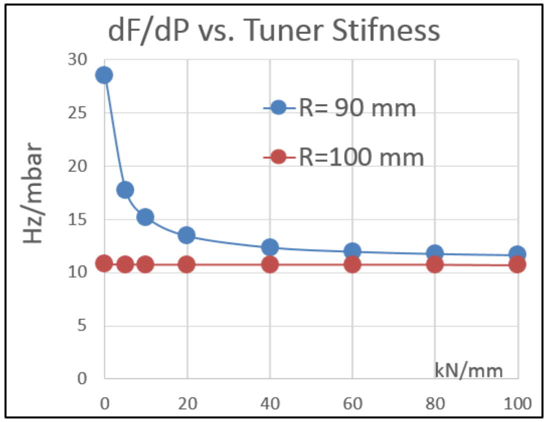




High-Beta Cavity

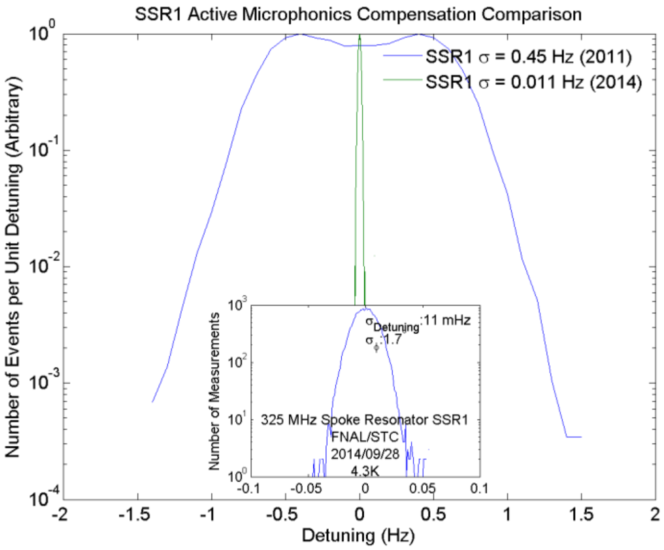


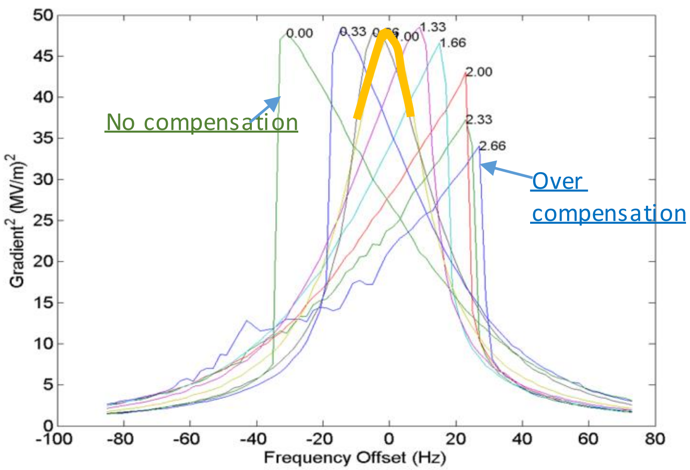




PIP II Resonance Control R&D

- Piezo feedback has successfully stabilized the resonance with high precision in CW to negligible levels (11 mHz RMS)
- Ponderomotive instability has been successfully mitigated using piezo feedforward tied to the square of the gradient during both CW and pulsed operation
- Adaptive feedforward has successfully suppressed detuning from deterministic sources of detuning
- Techniques for fully characterizing the tuner-cavity-waveguide system automatically have been developed and used successfully





Slide courtesy Y. Pischalnikov, Fermilab

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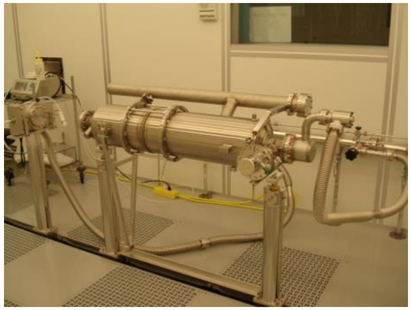
LCLS II Cryomodule Assembly



Receive dressed cavities

↓

Cold coupler assembly

↓

Individual cavities assembled into string

↓

Install string assembly to cold mass

→ Transport from MP9 to ICB →

Install cold mass to fixture

↓

Alignment

↓

Install the cold mass into the vacuum vessel

↓

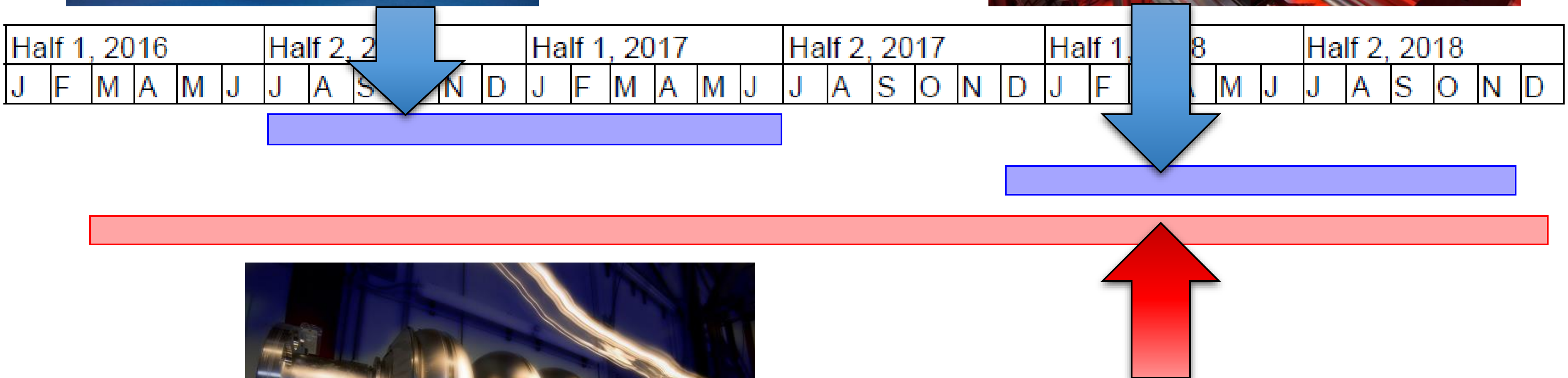
Warm coupler assembly

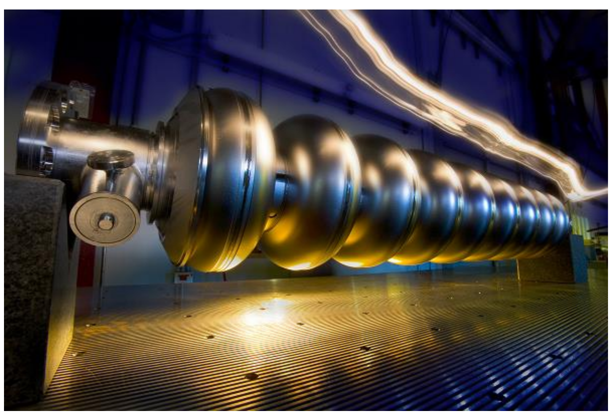
↓

Ship completed cryomodule

Cryomodule Assembly Conflict

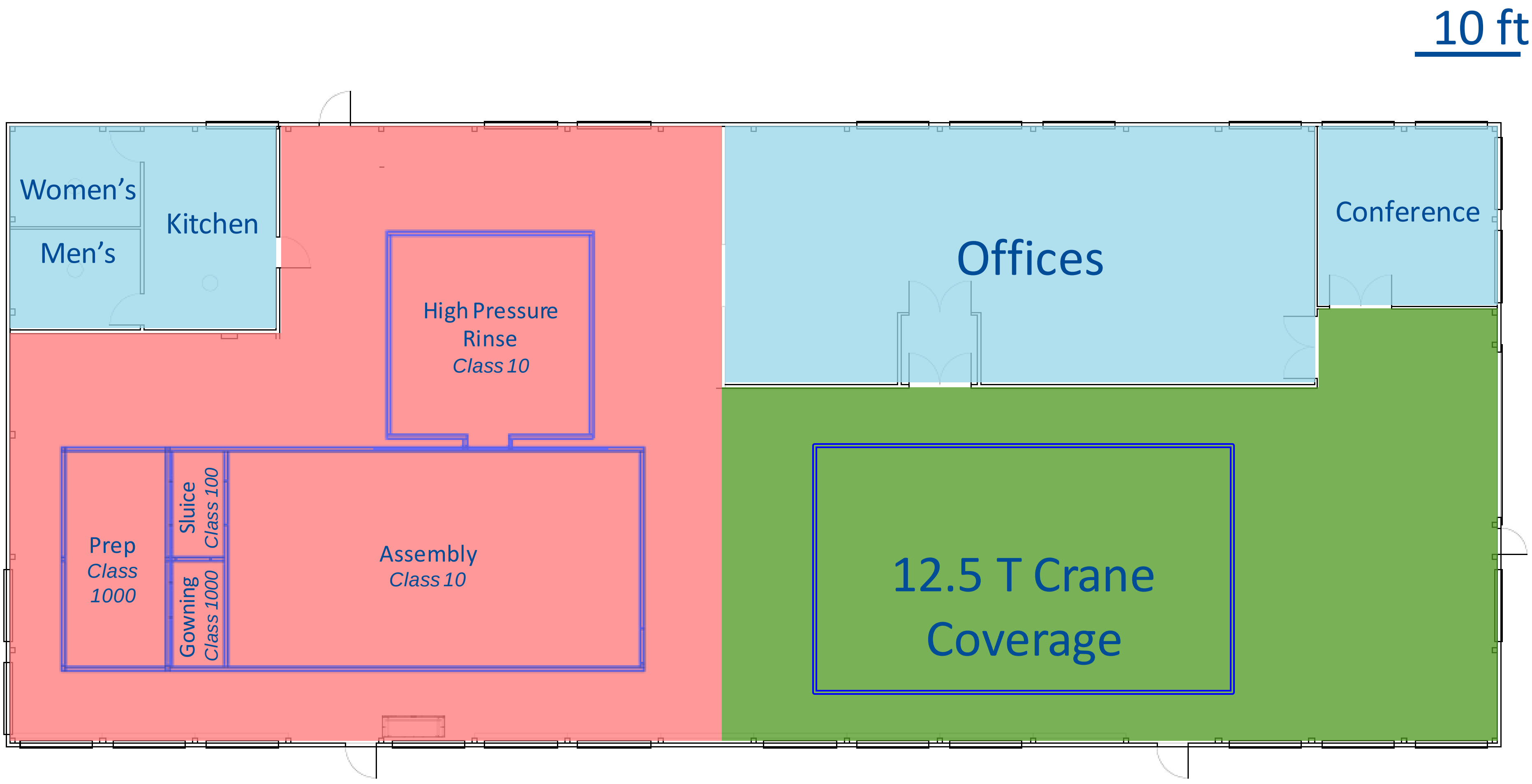
PIP II





LCLS II

PIP II pCM Assembly: Lab 2



PIP II pCM Assembly: Lab 2

Fermilab

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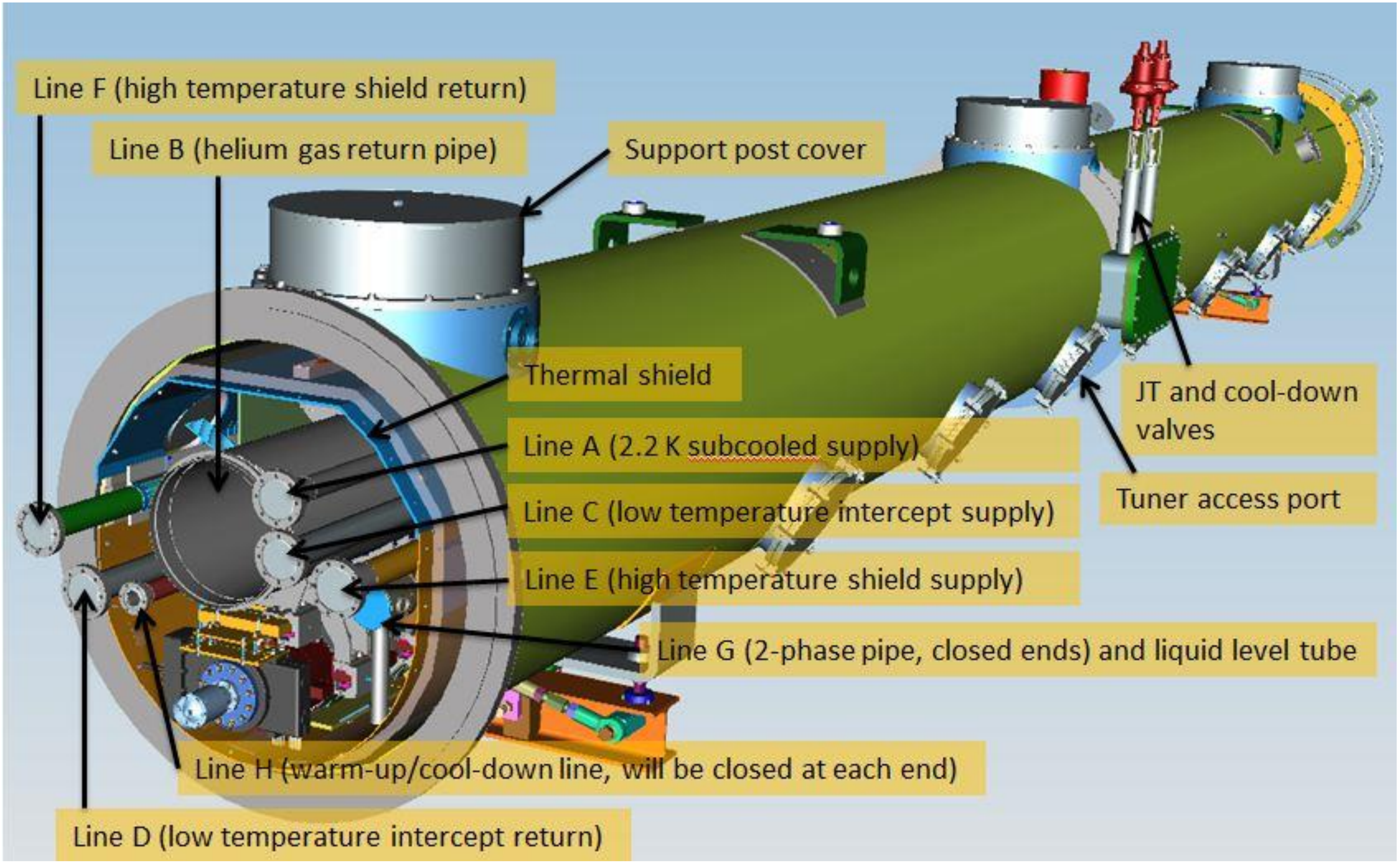
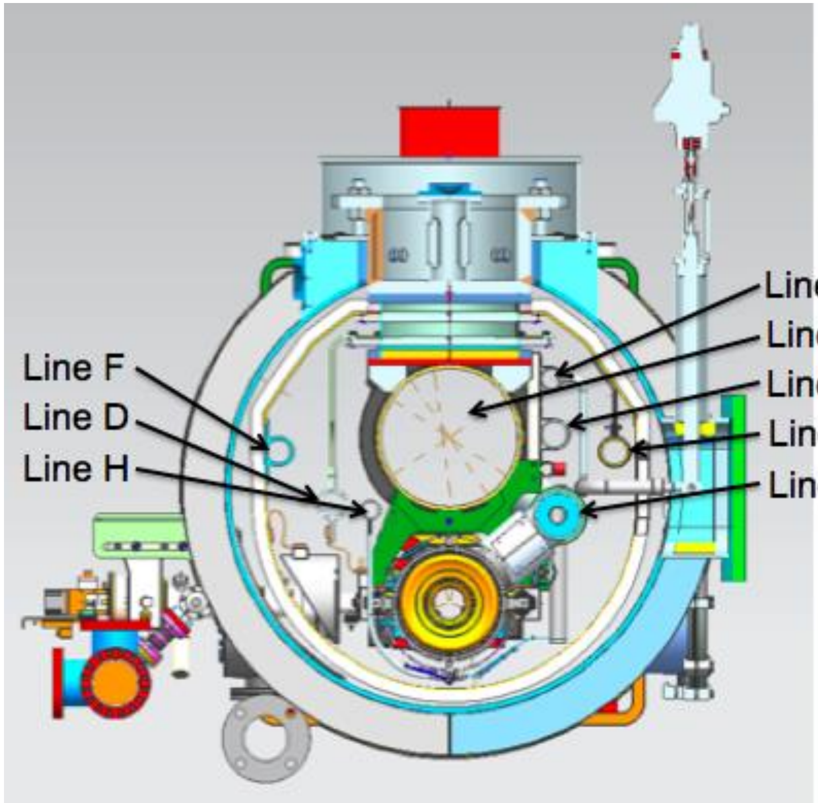
LCLS II Cryomodule



Slide courtesy T. Peterson, Fermilab

LCLS II CM Cryogenic Circuits



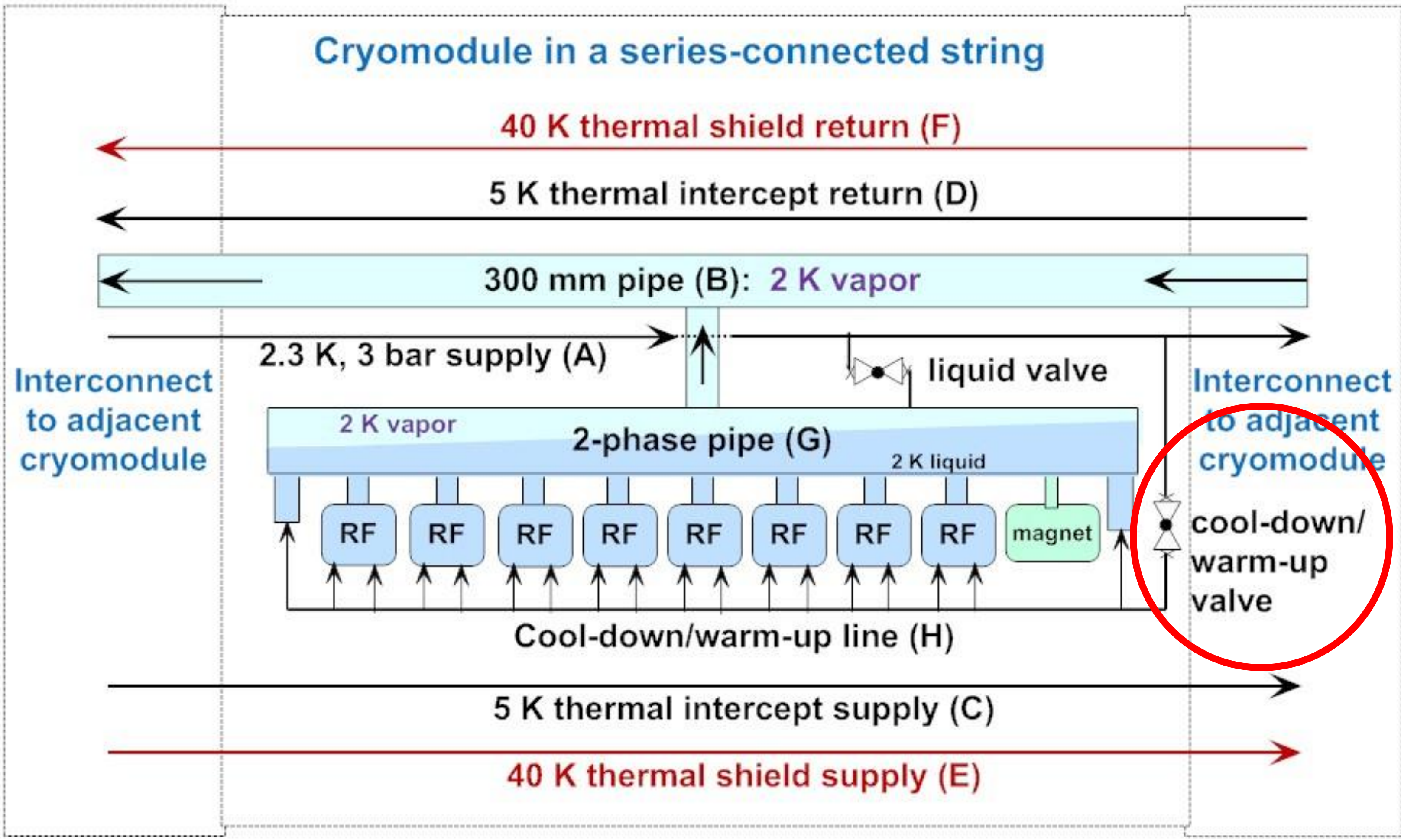
Circuit (Line)

A. 2.2 K subcooled supply
B. Gas return pipe (GRP)
C. Low temperature intercept supply
D. Low temperature intercept return
E. High temperature shield supply
F. High temperature shield return
G. 2-phase pipe
H. Warm-up/cool-down line

Operating Parameters	A	B	C	D	E	F	G	H
Pressure, [bar]	3	0.031	3	2.8	3.7	2.7	0.031	3
Temperature, K	2.4	2.0	4.5	5.5	35	55	2.0	2.0

Slide courtesy T. Peterson, Fermilab

LCLS II CM Flow Scheme

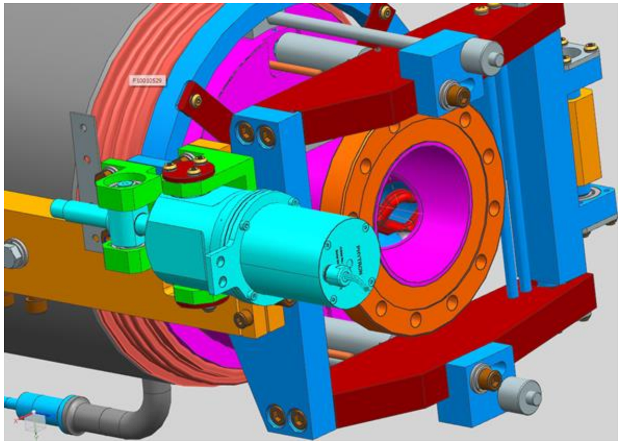


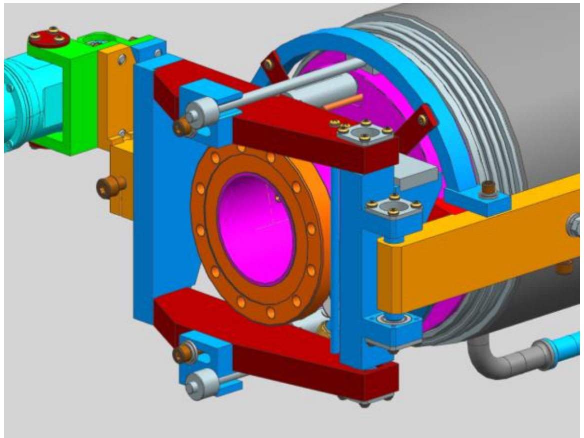
"Fast" cool-down is a new requirement not yet reflected in formal documents

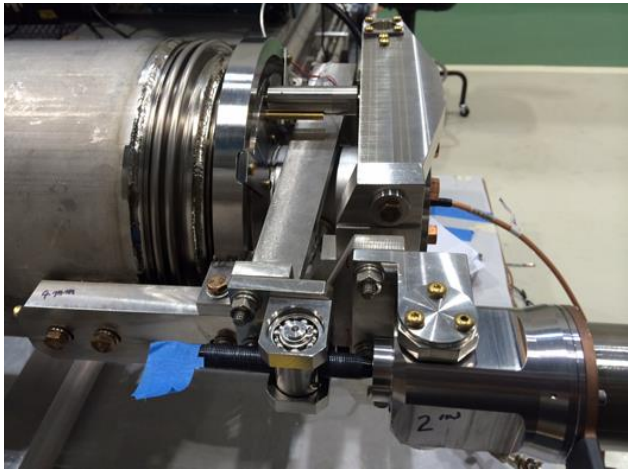
Slide courtesy T. Peterson, Fermilab

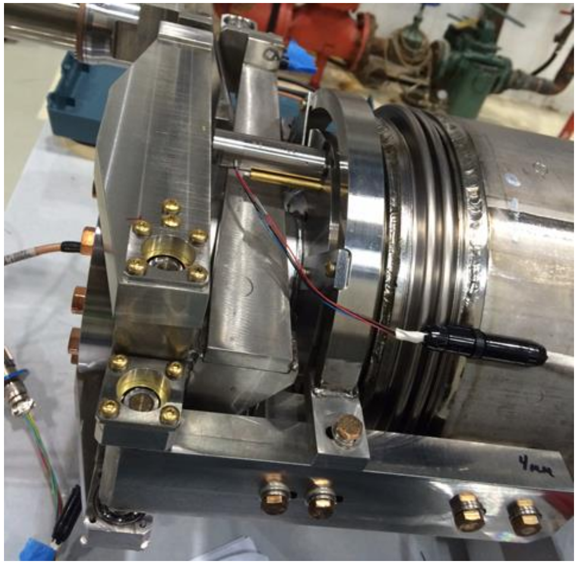
LCLS II Tuner

design included several features specific to requirements that electromechanical actuator and piezo-elements replaceable through special designated port





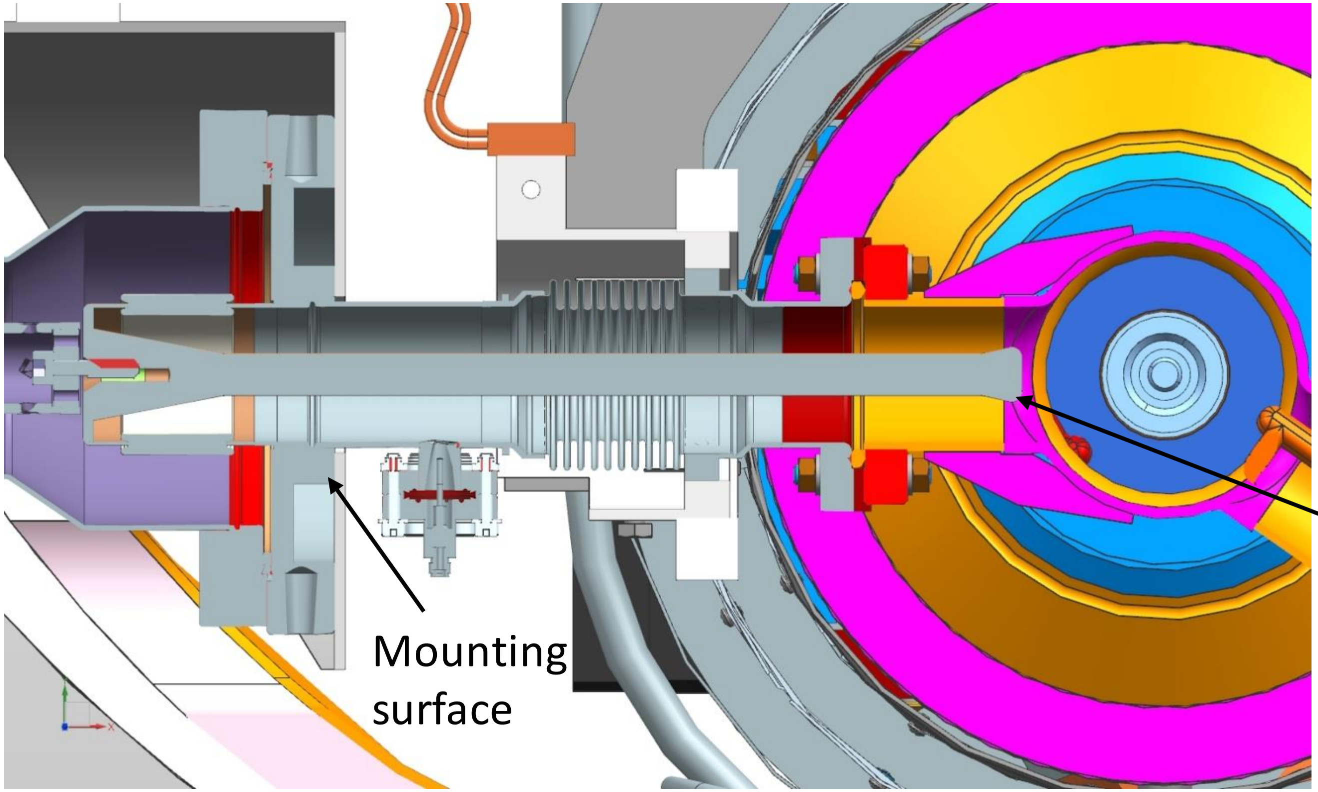




Slide courtesy Y. Pischalnikov, Fermilab

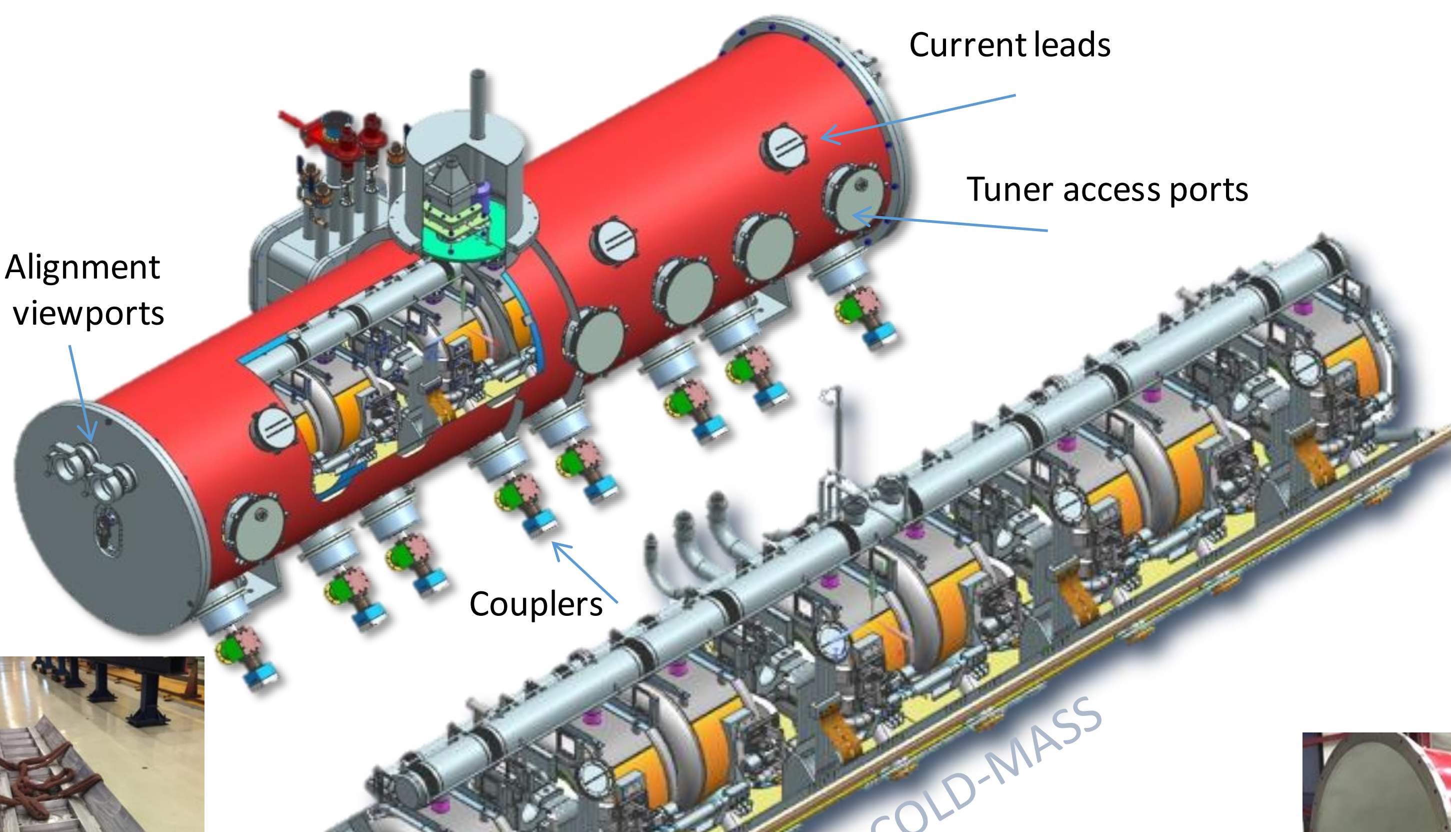
LCLS II Fundamental Power Coupler

- Modifications/Design changes (from TTF3)
  - Cold end



Slide courtesy K. Primo, Fermilab

SSR1 Cryomodule

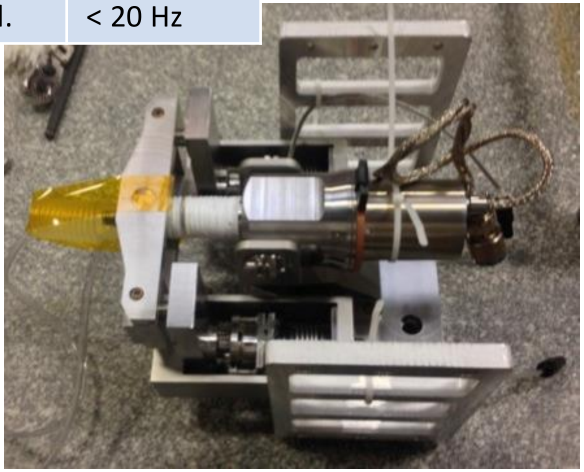


5.2 m long
8 Cav + 4 Magnets
Bottom-supported elements with warm strongback

PIP II SSR1 Ancillaries: Prototyping

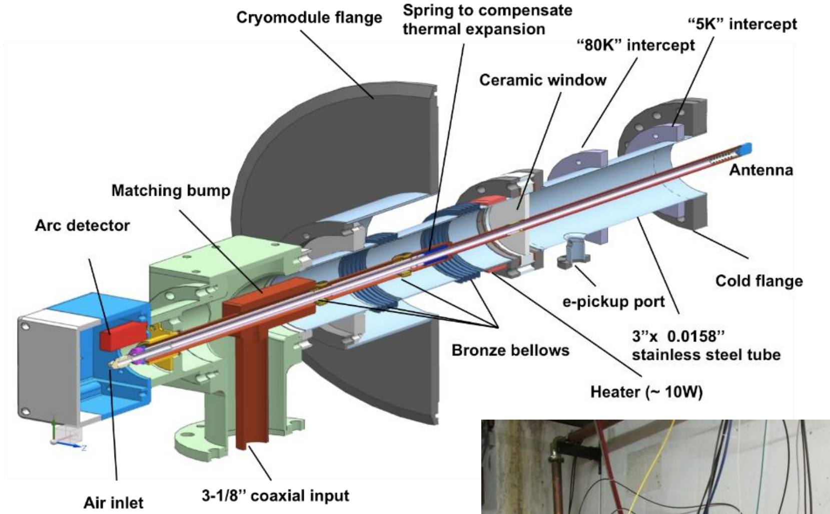
Parameter	Req.
Coarse range	> 135 kHz
Fine range	> 1 kHz
Coarse resol.	< 20 Hz

SSR1 Tuner



Cartridge with motor and piezos

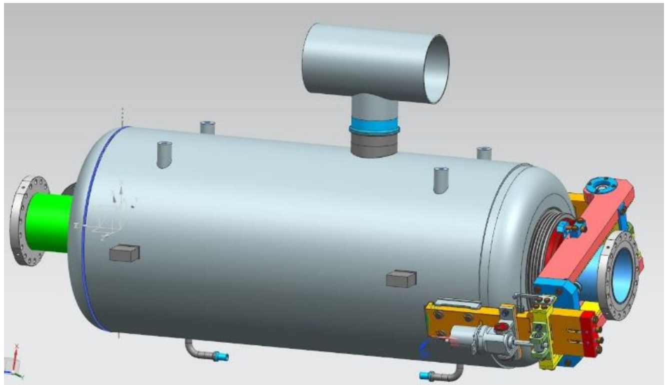
325 MHz coupler anatomy

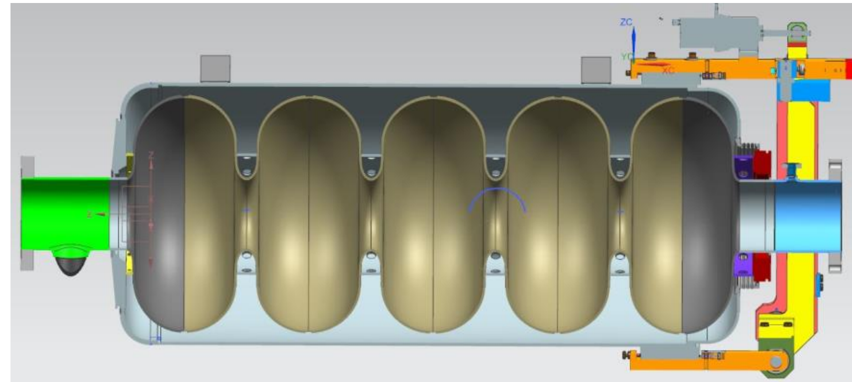


Input coupler:

Coupler test stand

PIP II 650 MHz Dressed Cavity





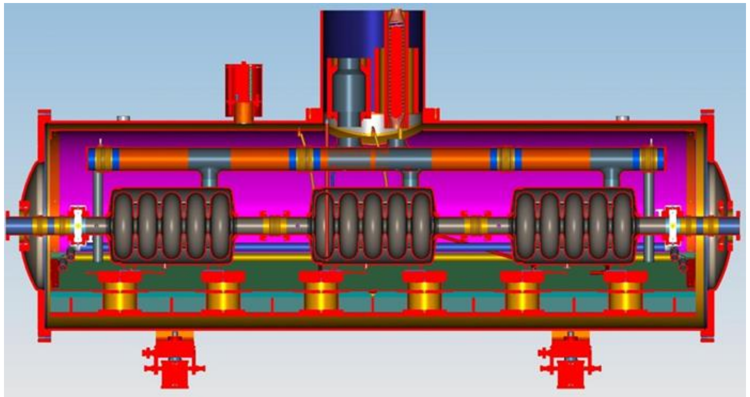
- LB650 dressed cavity optimization is in progress
- HB650 dressed cavity optimization is done
  - Stiffening ring position R=100 mm and bellow radius R=125 mm accepted
  - LFD Coefficients for tuner stiffness 80 kN/mm -0.69 Hz/(MV/m)^2
  - dF/dP for tuner stiffness 20 - 80 kN/mm is less than 12 Hz/mbar.
  - Cavity stiffness is ~ 3.0 kN/mm and tuning sensitivity is ~ 160 kHz/mm.
  - Modal analysis has been done. Lowest longitudinal mode ~ 100 Hz with 20-80 kHz/mm tuner stiffness.
  - Stresses analysis has been done for internal pressure of 2 bar + gravity load at RT
    - Stresses in cavity are acceptable
    - Stresses in bellow are allowable for 5 mm pitch

Slide courtesy T. Khabiboulline, Fermilab

PIP II 650 MHz Cryomodule

Low-Beta Cryomodule

- 11 total cryomodules
- 3 cavities each (650 MHz, 5-cell)
- 33 total cavities
- No magnets internal to the cryomodule
- Approximate length = 3.9 m

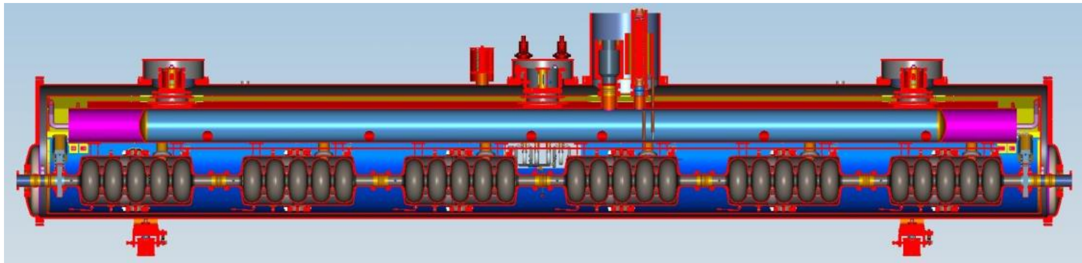


Concept 1 (room temperature strongback)

- Many design features common with the current SSR1 cryomodule design
- Coupler port locations are fixed with respect to the vacuum vessel
- Support system not subject to thermal distortions during cooldown
- To date, unproven

High-Beta Cryomodule

- 4 total cryomodules
- 6 cavities each (650 MHz, 5-cell)
- 24 total cavities
- No magnets internal to the cryomodule
- Approximate length = 9.5 m



Concept 2 (XFEL-like design)

- Design concepts are direct descendants of the XFEL design
- Could possibly use tooling common to XFEL-like cryomodules
- Coupler positions change during cooldown
- Support pipe can distort during cooldown

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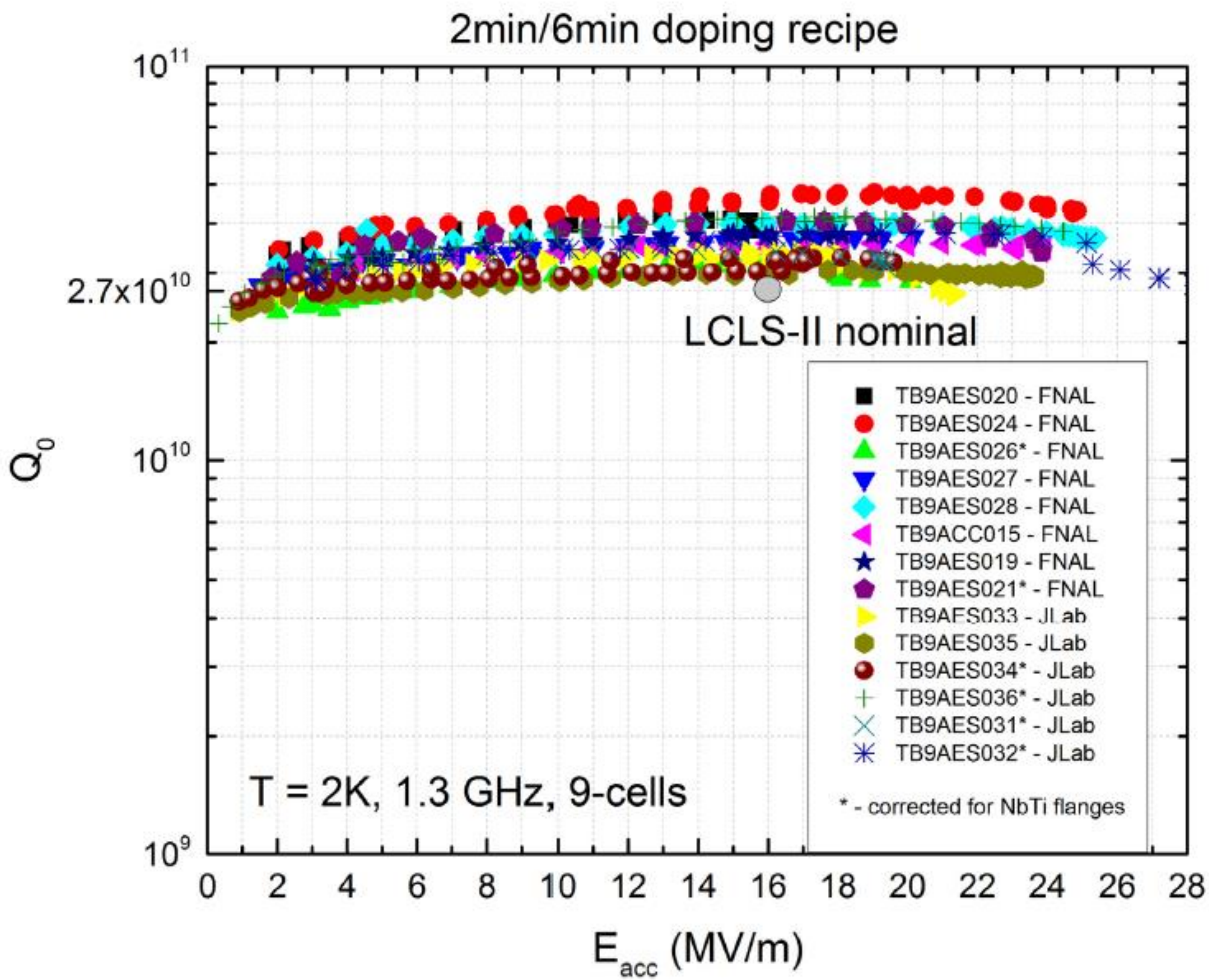
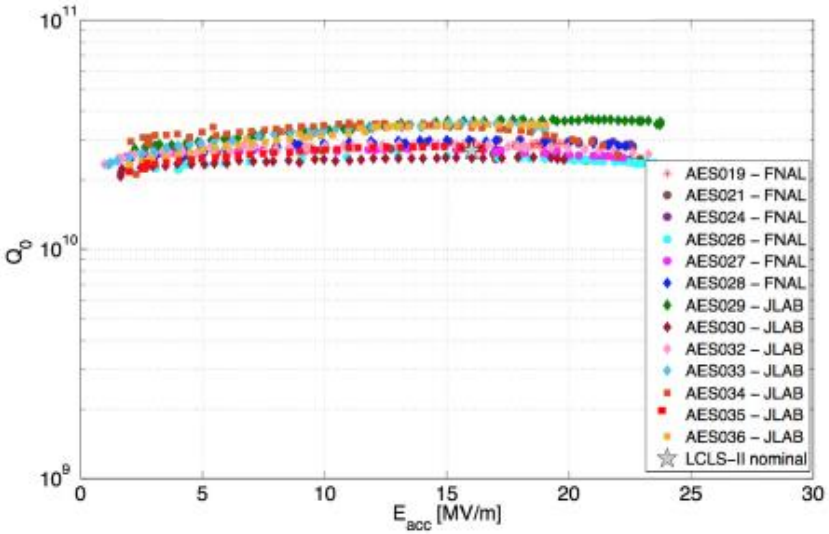
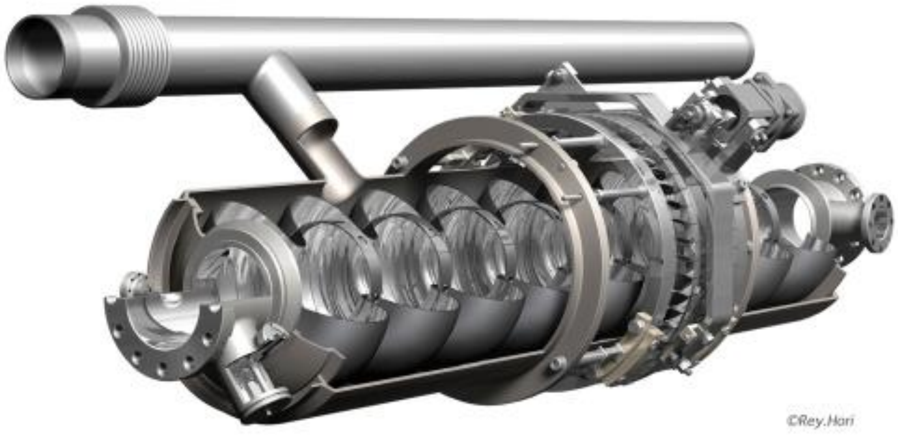
LCLS II pCM Cavities



Slide courtesy A. Grassellino, Fermilab

Fermilab LCLS II Post He-Vessel Welding





16 cavities dressed @ FNAL in LCLS-2 vessels ready for the prototype cryomodules – string assembly has begun, cryomodule results expected for mid 2016

Avg VT performance still exceed >3e10 at 16 MV/m, 2K post dressing

Four N doped nine cells horizontally tested in one cavity cryomodule (HTS) exceeding LCLS-2 specifications (for fast cooldowns from 45K)

Fully integrated test : high power coupler, HOMs, tuner, magnetic shielding, thermal straps exceeding 3e10 @ 16MV/m, 2K – <u>proof of principle that very high Q via N doping can be preserved all the way into cryomdoule</u>

Slide courtesy A. Grassellino, Fermilab

LCLS II Integrated Test

- Q_0 Exceeds Specification in the Presence of Coupler and HOMs
- Q_0 ~ 3.1×10^{10} @16 MV/m at 2K
- No detectable field emission

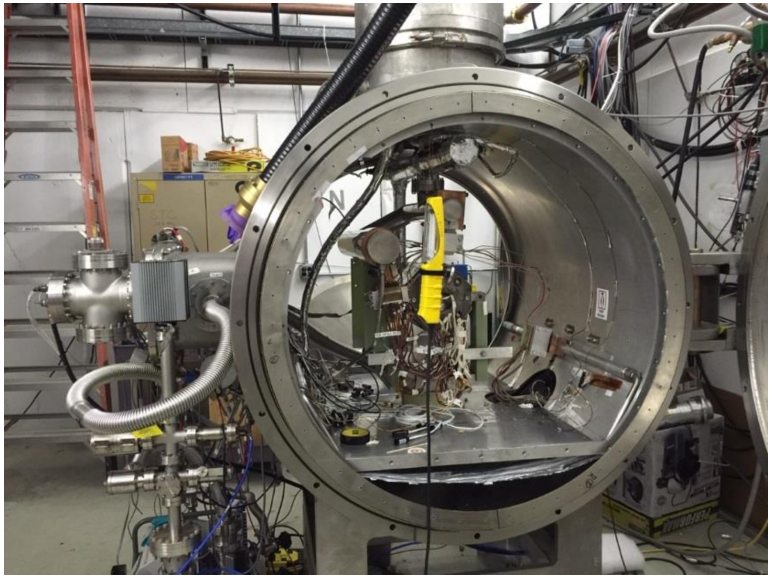
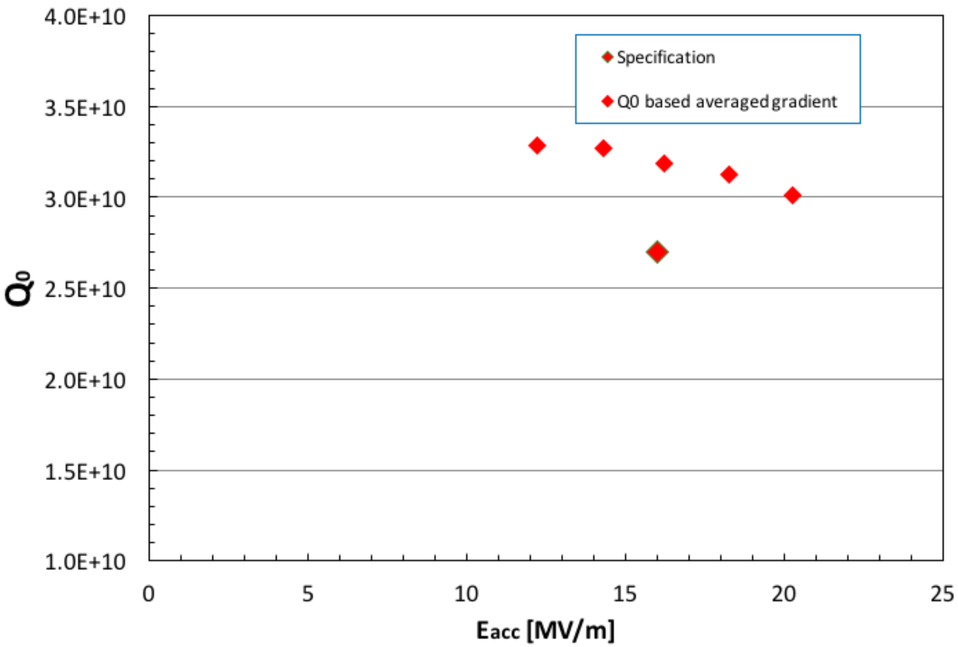


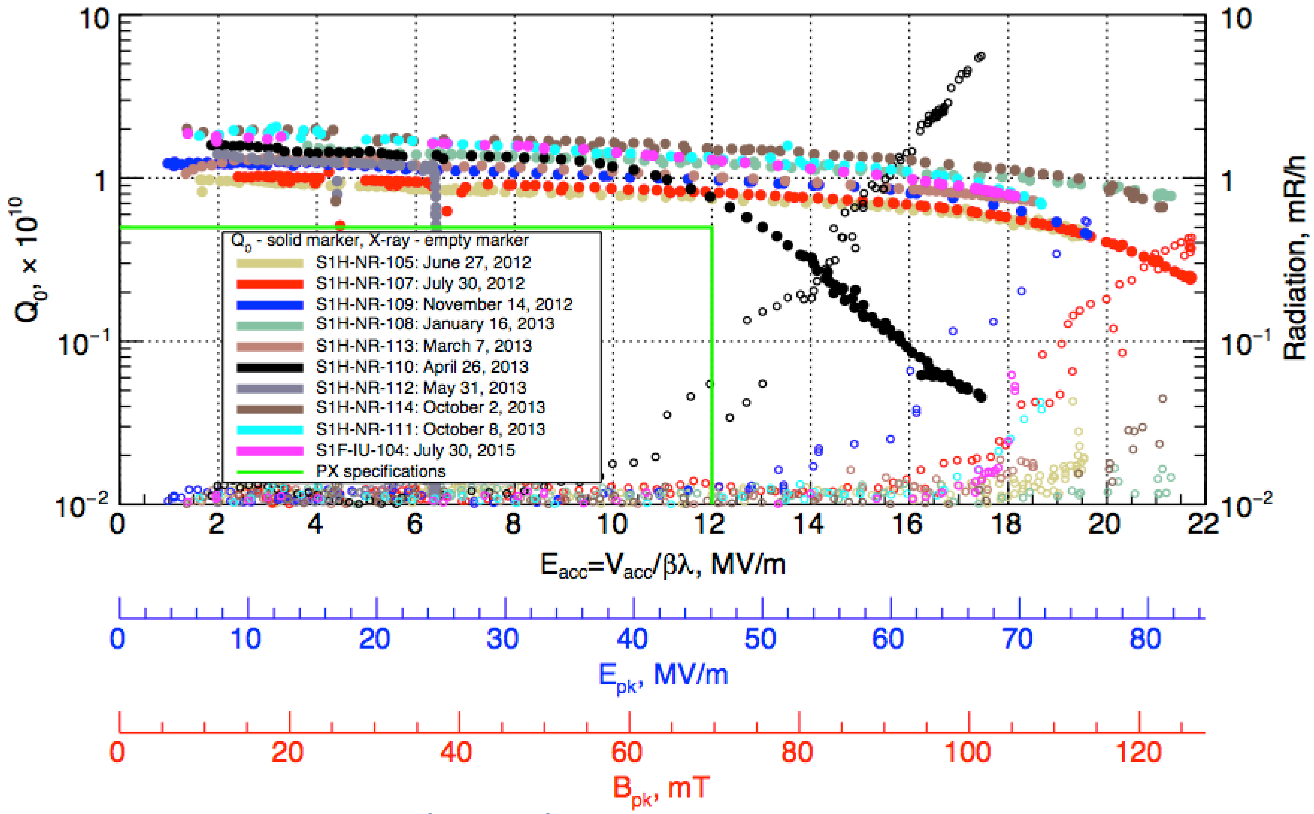
Image from V. Kashikhin



Slide courtesy G. Wu, Fermilab

PIP II SSR1 Vertical Test

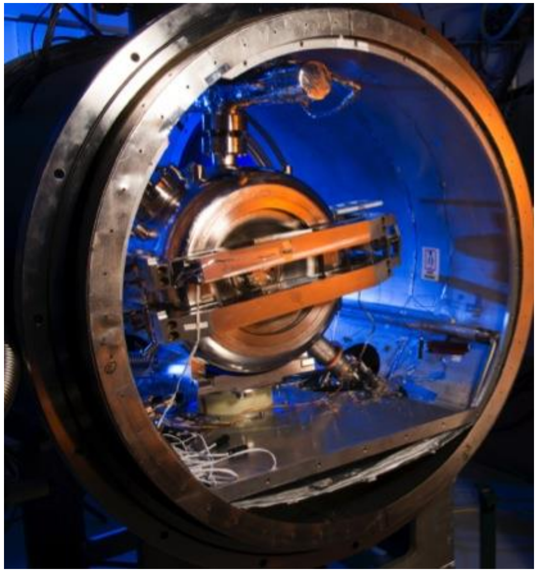
SSR1 cavities (Q_0 vs E_{acc} @ 2K)

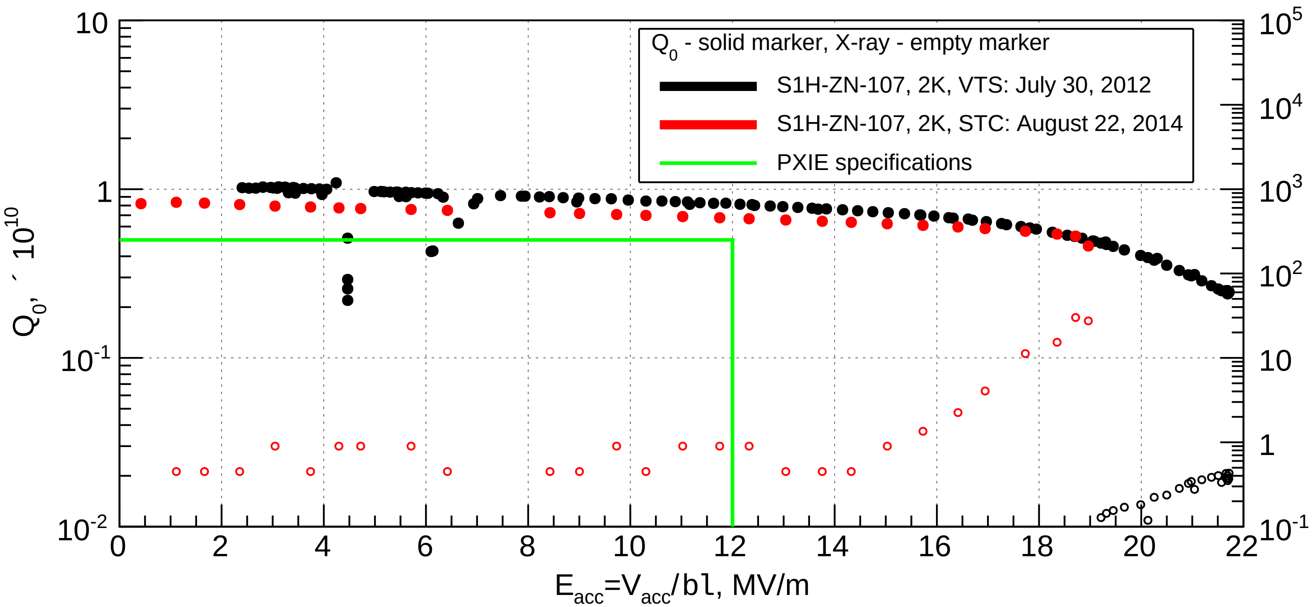


Two SSR1 cavities were received from IUAC (India) part of the Indian Institutions and Fermilab Collaboration (IIFC). The summary plot shows one IUAC cavity (S1F-IU-104, magenta) together with all Fermilab cavities tested so far.

PIP II SSR1 Horizontal Test

- First jacketed SSR1 successfully tested in STC at 2K. Exceeded PIP-II requirements. No degradation seen after welding process.
- Fully integrated tests with pre-production Tuner



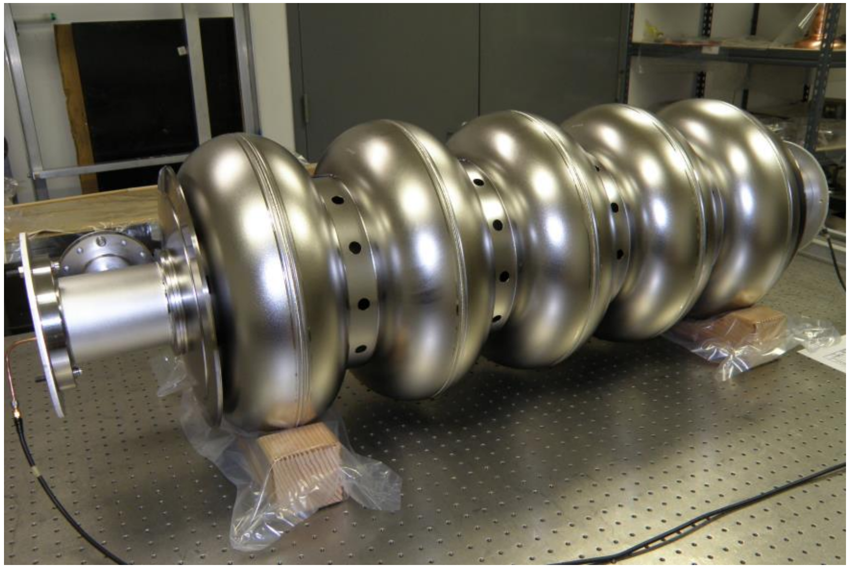


PIP II 650 MHz Procurement

650 MHz section:

Currently Available Cavities:

<u>1-Cell 650 MHz*</u>	<u>5-Cell 650 MHz</u>
1. B9AS-AES-001	1. B9A-AES-007
2. B9AS-AES-002	2. B9A-AES-008
3. B9AS-AES-003	3. B9A-AES-009
4. B9AS-AES-004	4. B9A-AES-010
5. B9AS-AES-005	*VTS Tested
6. B9AS-AES-006	



Expected Cavities:

<u>1-Cell 650 MHz</u>	<u>5-Cell 650 MHz</u>
Pavac, Inc.	Pavac, Inc.
Five are delivered and VTS-tested	Five to be delivered in 2016.

PIP II Development Status (6/1/2015)

- SRF Development Status

Cavity	Frequency	Cavity Type	Beta	Collaboration?	Cavity EM Design Complete	Cavity Mech Design Complete	Single Cell / Prototype Ordered	Full Cavity Prototype Received	Prototype Tested	Cavities for CM Ordered	Cavities for CM Received	Cavities for CM Tested	Cavities for CM Dressed	CM Cold Mass Design	CM Parts Ordered	# of CM Assembled	Est % complete
Half Wave Resonator (HWR)	162.5 MHz	1-HWR CW	0.11	ANL	yes	yes	yes	yes	yes	9	9	2	2	yes	yes	15%	70
Single Spoke Resonator 1 (SSR1)	325 MHz	1-spoke CW	0.22	India	yes	yes	2	2	2	10	10 +2	10	6	80%	70%	not started	75
Single Spoke Resonator 2 (SSR2)	325 MHz	1-spoke CW	0.47	India	yes	yes	not started	not started	not started	not started	not started	not started	not started	not started	not started	not started	10
Low Energy 650 (LE 650)	650 MHz	5-cell CW	0.6	India, JLAB	yes	yes	5	not started	not started	not started	not started	not started	not started	not started	not started	not started	10
High Energy 650 (HE 650)	650 MHz	5-cell CW	0.9	India	yes	yes	5 of 10	4	not started	9	4	not started	not started	5%	not started	not started	20

- Green: complete
- Yellow: in progress
- Red: not started

- Overview of projects – LCLS II and PIP II
- Technical challenges
- Facilities
- Design efforts
- Critical Elements and Subsystems
- **Plans and schedule**
- Future R&D

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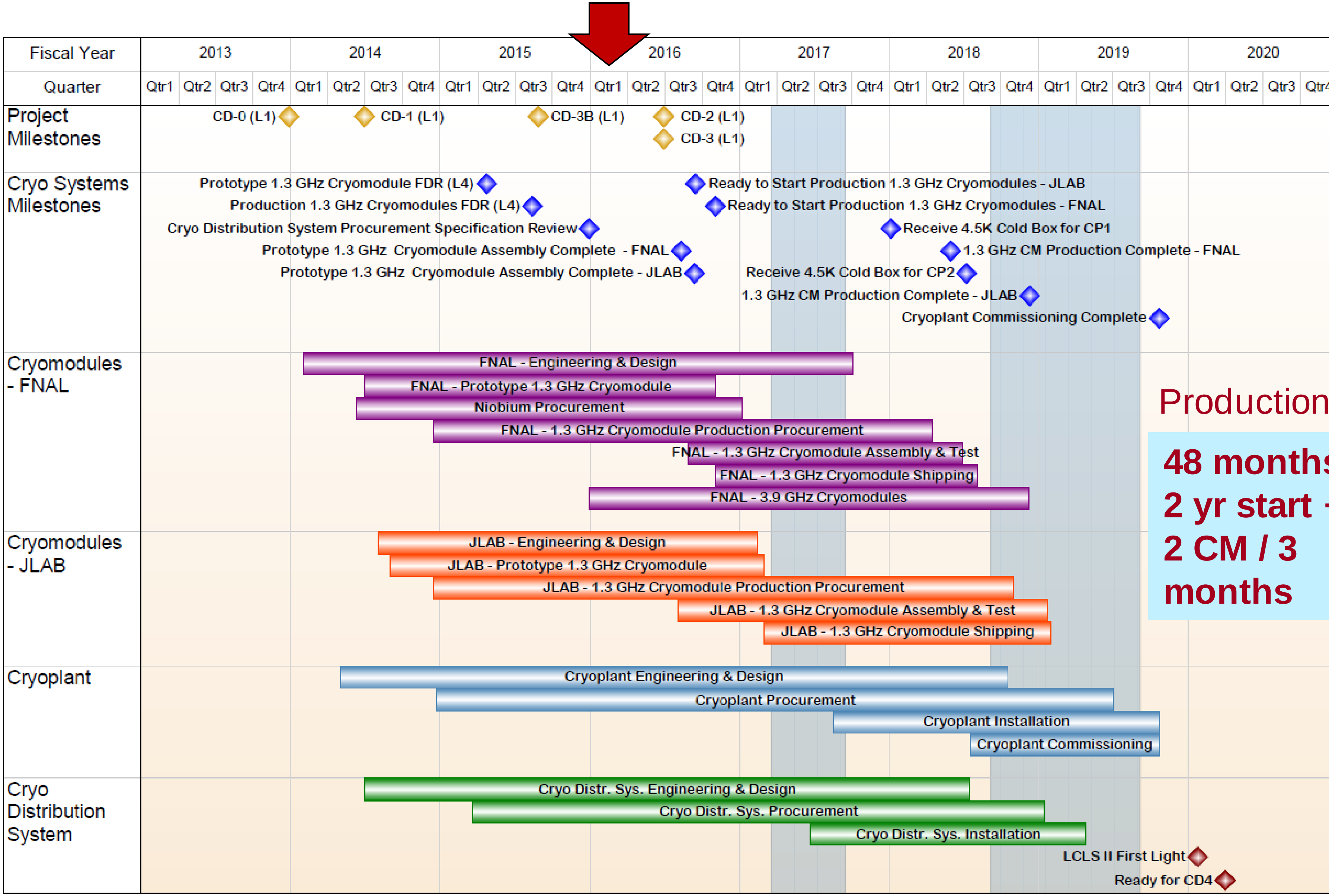
LCLS II Schedule



Production:

48 months
2 yr start +
2 CM / 3 months

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PIP II SRF Schedule

- FY16
  - SSR-1 horizontal testing
  - SSR-1 prototype cryomodule string assembly
  - 650 MHz R&D and design
- FY17
  - SSR-1 prototype cryomodule cold mass, module
  - 650 MHz cavity qualification
  - Receive HWR from Argonne
- FY18
  - RF commissioning of HWR
  - Installation of SSR-1 prototype cryomodule at PXIE

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- Overview of projects – LCLS II and PIP II
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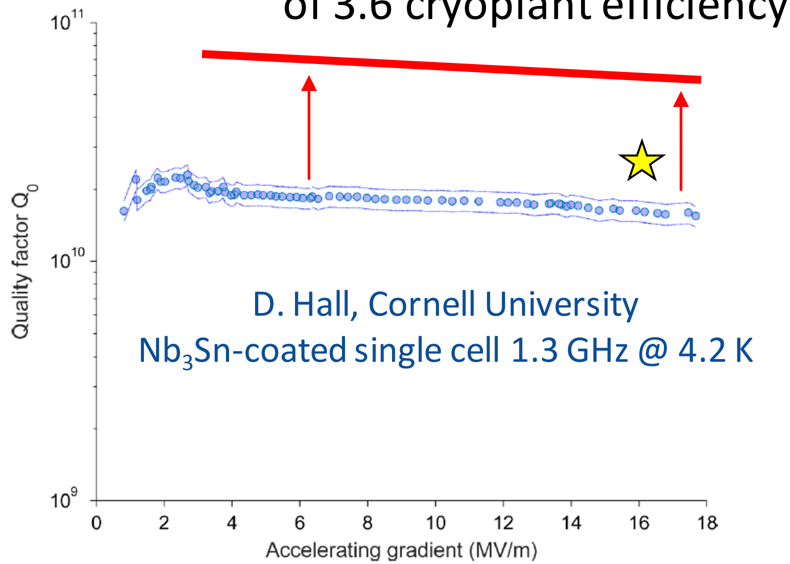
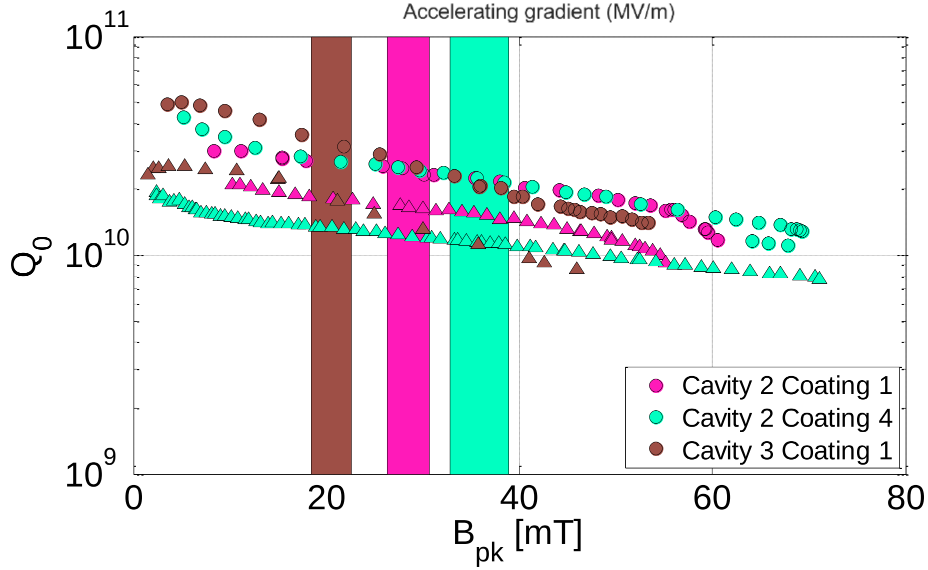
Great Potential of Nb_3Sn

- High Q_0 at medium fields **demonstrated**: many machines – CW proton accelerators, circular high energy e^+e^- colliders, light sources, industrial accelerators, many more possibilities
- High E_{acc} **predicted**: high energy machines

Equivalent at 2 K: factor of 3.6 cryoplant efficiency

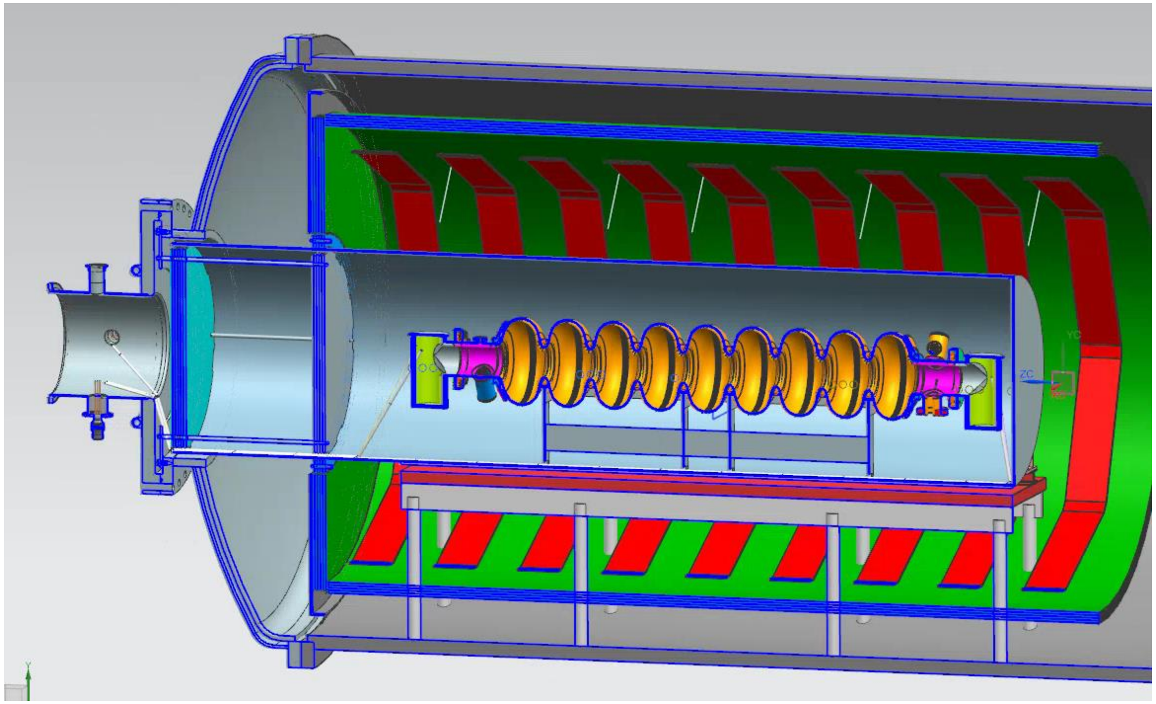


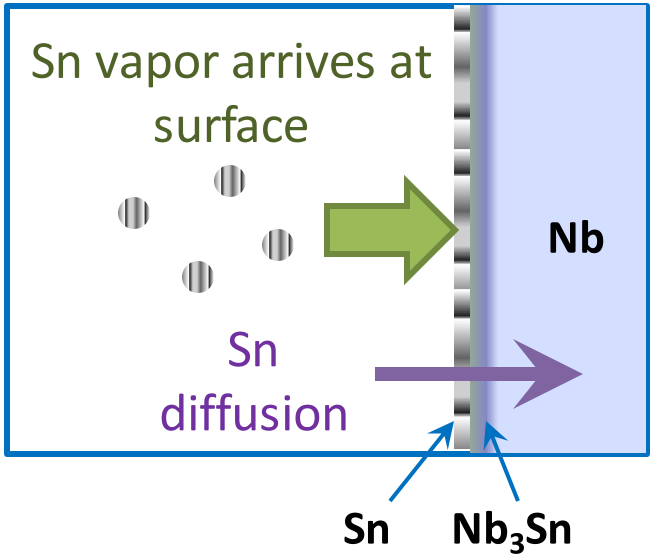


S. Posen, M. Liepe, and D. L. Hall, *App. Phys. Lett.*, 106, 082601 (2015).

Fabrication Technique

- Vapor diffusion – start with niobium cavity and coat with tin vapor in UHV furnace
- Similar to Nb prep with extra treatment step
- Wide parameter space to explore still – T vs time, tin vapor pressure vs time, nucleation technique, pretreatment, post-treatment, cooldown





R&D for the Future

- Nb_3Sn coatings
  - Benefit to cryogenic efficiency demonstrated, predicted potential for high field operation
- Niobium coatings on copper cavities
  - significant cost savings for materials
- Magnetron RF power supplies
  - cost reduction could have substantial impact for high power accelerators

Summary

- Very active SRF program at Fermilab for upcoming projects
  - LCLS II
  - PIP II
  - Full development from design to production
- SRF R&D
  - High Q_0 breakthrough technology nitrogen doping
  - Passive compensation for LFD and df/dp
  - Resonance control

Acknowledgements

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