FNAL Superconducting RF Program

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Fermilab Science and Technology Review
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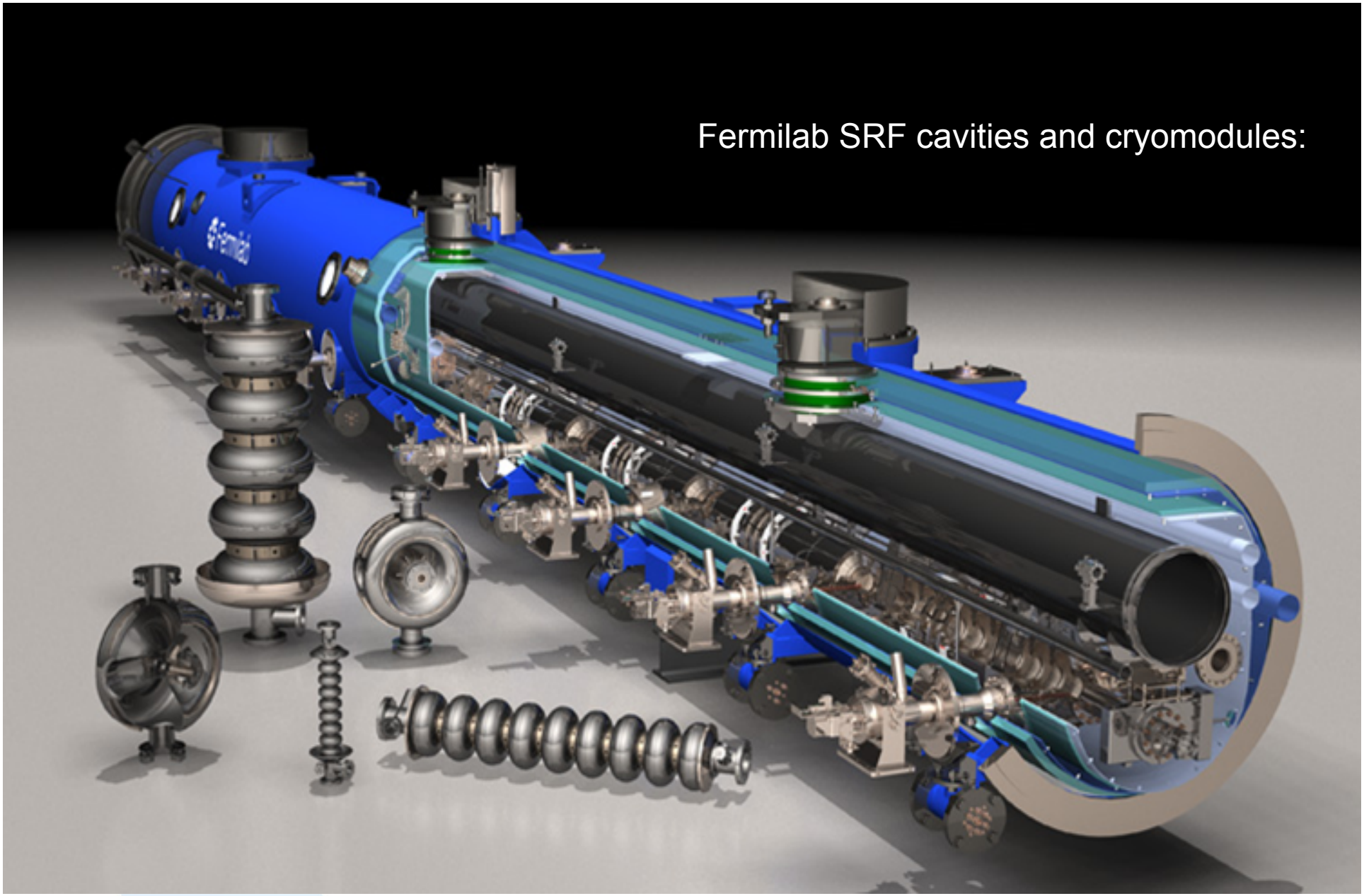
U.S. DEPARTMENT OF ENERGY | Office of Science

Fermilab

Outline

- Goals, Approach, and Context of FNAL SRF Program
- Accomplishments & Status
- Plans for FY14 and beyond
- ES&H & QC
- Summary


Fermilab SRF cavities and cryomodules:

Goals of the Fermilab SRF Program

- Support the strategic goals of the U.S. HEP program
  - Intensity frontier: Project X or other options
  - Energy frontier: future colliders (International Linear Collider & Muon Collider)
- Develop low-beta SRF cavities and cryomodules for the acceleration of high intensity Proton beams
- Develop β=1 SRF cavities and cryomodules for the Project X pulsed linac (3-8 GeV) and/or for future HE colliders
- Develop related SRF infrastructure and technology that can be applied to other Office of Science projects
- U.S. SRF Industrialization to permit fabrication of future projects

General Approach of the R&D Effort

- Build on experience
  - Take full advantage of existing U.S. SRF capabilities and infrastructure (close collaboration with ANL, JLAB, and Cornell)
  - International Collaborations (India, DESY, KEK, INFN, etc)

- Contribute to existing programs
  - Participation in global ILC R&D program
- Enable new programs
  - Project X at Fermilab

- Establish new collaborations
  - Collaboration on LCLS-II
  - Cryo-module for Crab cavities for LHC upgrade @ CERN (in collaboration with ODU/JLAB, BNL and SLAC)
  - Possible collaboration with China

Context of SRF Activity at Fermilab

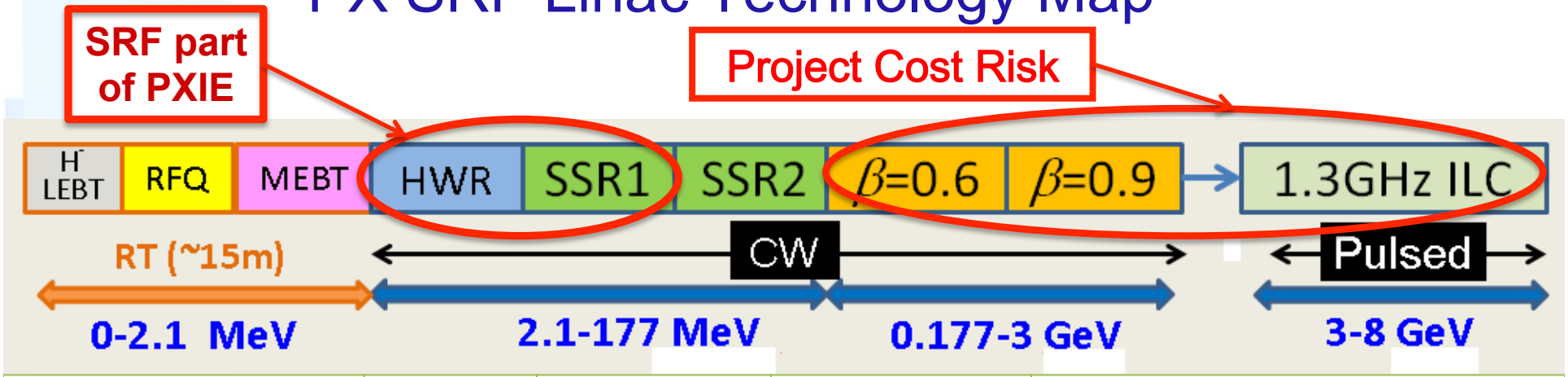
- SRF activities are supported by:
  - General Accelerator Development
  - SRF Infrastructure
  - LCLS-II funds (BES)
  - Accelerator Operations Test stand and cryo operations, etc.
- Plus one-time ARRA SRF funds of ~$53 M in FY09
- Fermilab SRF activities are managed as an integrated program to avoid duplications and promote efficiency
- Because of past emphasis on ILC R&D ➔There is substantial ongoing activity on 1.3 GHz technology
  - R&D on gradient, quality factor, and manufacturing yield
  - Development of US cavity vendors (ARRA procurements)
  - Cavity process/test and construction of 1.3 GHz cryomodules
  - LCLS-II activities are closely related

Context of SRF Activity at Fermilab

- Adoption of a 3 GeV CW linac followed by a 3-8 GeV pulsed linac for Project X in 2010 results in a powerful new intensity frontier machine, but presents new challenges
  - Need six different cavities optimized for changing velocity (β) of Protons
  - Four different frequencies (162.5, 325, 650, 1300 MHz)
  - Five of these cavities are completely new for Project X (vs. 2 for SNS)
  - CW cavities ➔ large heat loads, 2 K operation ➔changes to CM designs
  - Operation at significantly higher gradients than SNS to reduce costs

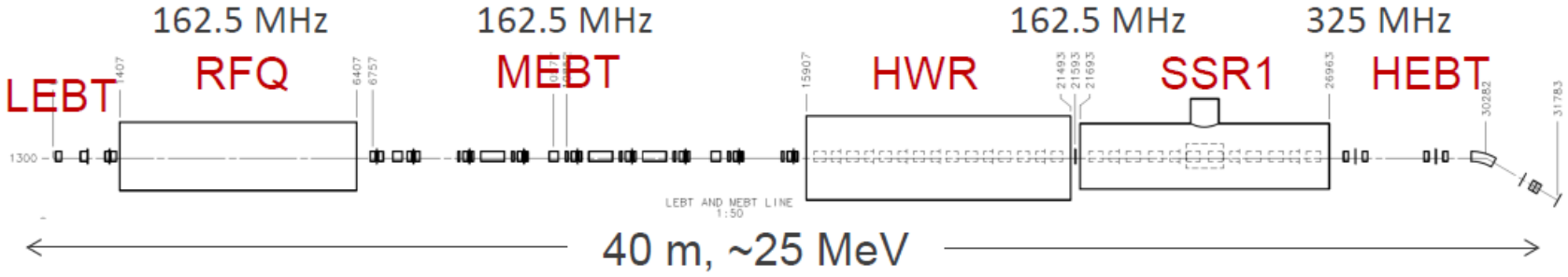
- The development of these cavities & CM is a major new effort
  - A strong R&D program is needed to reduce risks and costs
  - Need to design, order, process new cavity types and cryomodules
  - Benefits enormously from the SRF infrastructure and the experience gained with 1300 MHz cavities and CM…
  - Actively modifying our SRF infrastructure to address the new challenges associated with PX cavities and CM (Modest changes since much was generic)

PX SRF Linac Technology Map

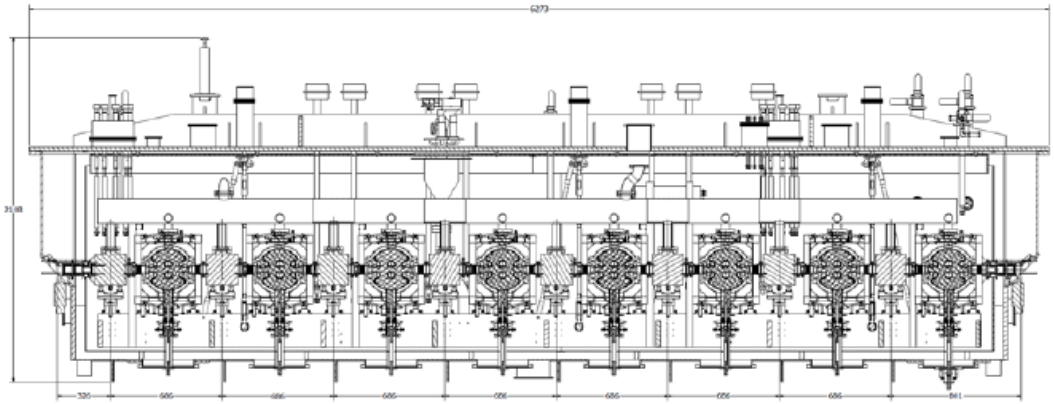


SRF Cavity Type	Freq, MHz	Energy (MeV)	Cav/mag/CM	CM type, length
HWR (β_G=0.11)	162.5	2.1-11	8 /8/1	scscscscscscscsc, 5.3m
SSR1 (β_G=0.22)	325	11-38	16 /8/ 2	csccsccsccsc, 4.8m
SSR2 (β_G=0.51)	325	38-177	35 /21/ 7	sccsccsc, 6.5m
LB 650 (β_G=0.61)	650	177-480	30 /20/5	cccfdccc, 7.1m
HB 650 (β_G=0.9)	650	480-1000	42 /16/ 7	cccccc, 9.5m (Stage1)
HB 650 (β_G=0.9)	650	1000-3000	120/30/ 15	cccccccc, 11.2m (Stage 2)
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 / 28/ 28	ccccfcccc, 12.6m (Stage 3)

PXIE Layout and HWR Cryomodule



- 8 HWRs operating at 162.5 MHz
- Acceleration of H^- beam from 2.1 MeV to 10 MeV in CW regime
- Total accelerating voltage: 1.7 MV×8=13.6 MV



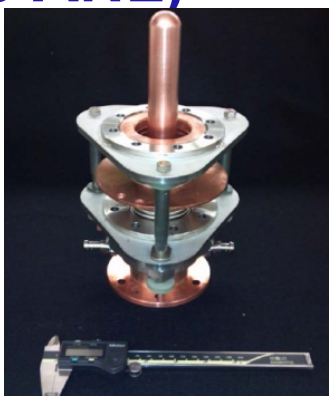
- Favorable beam dynamics as compared to the 325 MHz cavities: higher accelerating gradients, less defocusing, linear motion in longitudinal phase space

- PXIE = Technical demonstration the PX front end
- SRF goals: development of HWR CM and SSR1 CM

Accomplishments

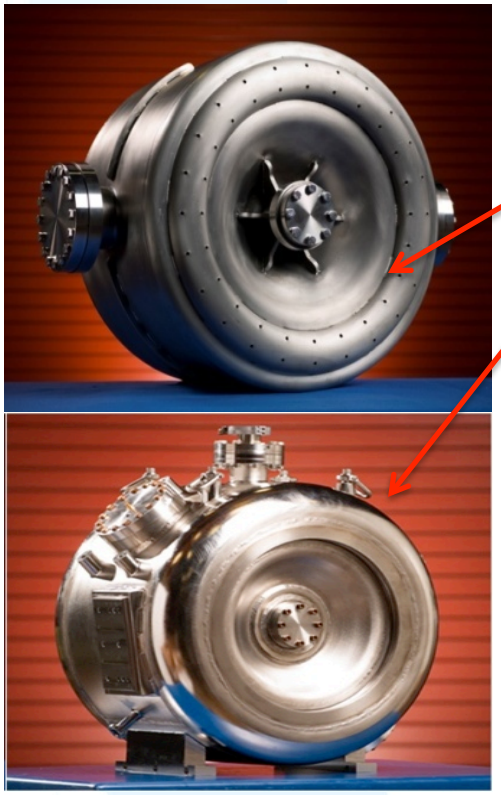
162.5 HWR Cavities and CM

- **HWR (β = 0.11) Half Wave Resonator (collab ANL)**
  - Very similar to cavities & CM already manufactured by ANL
  - Optimized to achieve tight packing in PX front end
  - Cavity design complete, many parts in hand from Industry,
  - Two prototypes fabricated, will be tested soon
  - Variable coupler successfully tested 0→ 9 KW
  - CM design complete, reviewed, and parts being orders



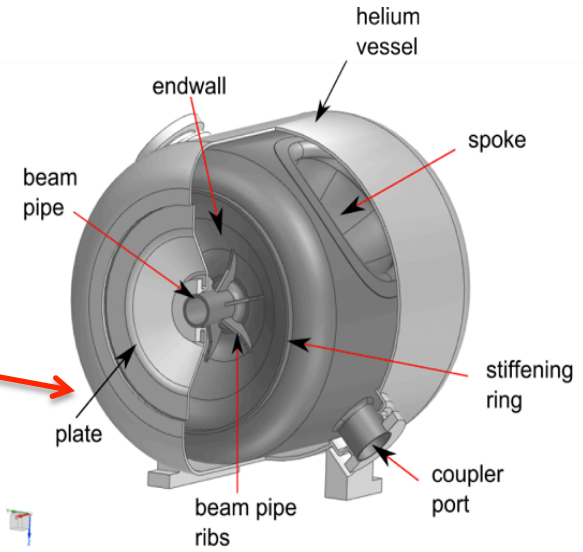
Accomplishments

325 MHz Cavities and CM



- **SSR1 (β = 0.22) Single Spoke Resonator**
  - Two prototypes fabricated by industry, processed in at ANL, and tested at Fermilab as part of HINS
  - Ten cavities fabricated by industry (8 tested, meet specs)
  - One new cavity dressed with He vessel, coupler tuner
  - Two cavities in fabrication at IUAC-Delhi (Q3 FY13)
  - Tests in results (next slides)

- **SSR2 (β = 0.51)**
  - EM design complete
  - Mechanical design is advanced
  - Prototype in FY14



Accomplishments
Status of New 325 MHz SSR1 Cavities

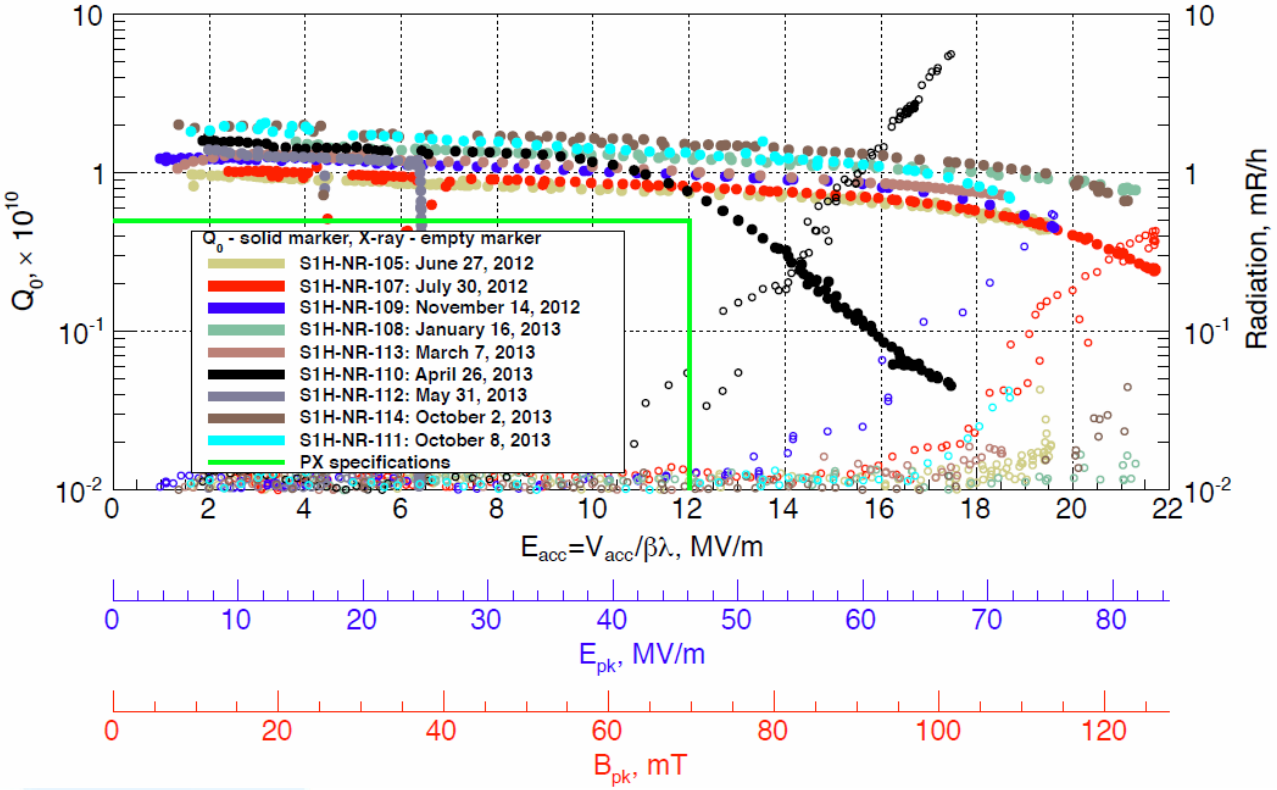
- Received all 10 cavities: Performed incoming inspections (Visual, CMM, leak check, RF)
- Nine cavities processed and cold tested, Excellent results $E_{acc} \geq 17$ MeV/m compared to operation value of 12 MeV/m.
- Ordering parts to dress cavities
- One cavity is dressed.

	Deep drawing	Sub-assy EBW	Freq. trimming	Final EBW	Delivery to FNAL	QC	Bulk BCP	Bake + RF tune	Light BCP	VTS	Jacketing	Light BCP	STC	Status
S1 ZN 101					11-May-07									
S1 RK 102					31-Jul-08						Oxidized			Will be replaced with S115
S1 IU 103														
S1 IU 104														
S1 NR 105					9-Mar-11					20 MV/m				
S1 NR 106				equator repair	24-Oct-11				leaks					Back @ Roark. Whole end-wall will be re-manufactured
S1 NR 107					4-Nov-11					22 MV/m				
S1 NR 108					4-Nov-11					21 MV/m				
S1 NR 109					19-Dec-11					20 MV/m				
S1 NR 110					19-Dec-11					17 MV/m				
S1 NR 111				equator repair	31-Dec-12					19 MV/m				
S1 NR 112					10-Dec-12					17 MV/m				
S1 NR 113		spoke repair			10-Dec-12					19 MV/m				
S1 NR 114		spoke repair			31-Dec-12					21 MV/m				
S1 RK 115														

ready for activity		in progress	
completed		issue	
		issue resolved	

Accomplishments

SSR1 Prototypes Exceed PX Performance Specs.



- 120-150 micron BCP and HPR at ANL/FNAL processing facility then 120 C bake
- Low FE depends on optimized nozzle design for effective HPR of surface

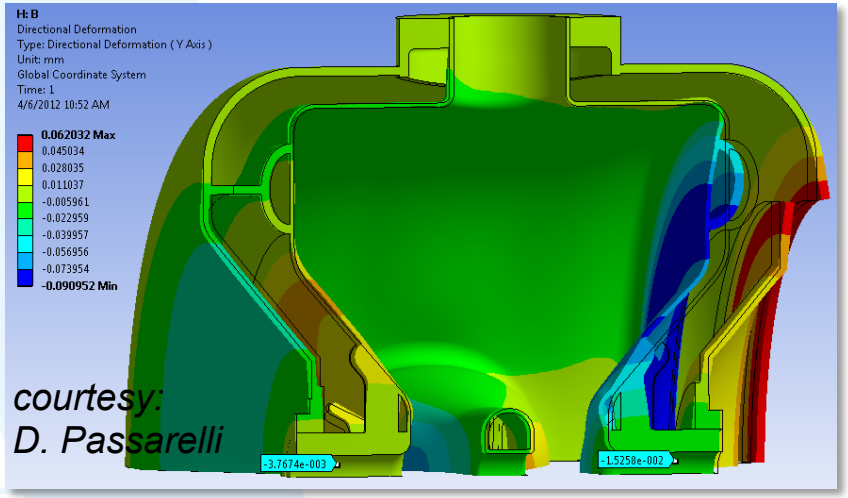
- Two previous SSR1 spoke resonators performed very well in bare cavity tests
- Above are the tests of 9 cavities from U.S. Vendor (Roark) production of 10 cavities
- Performance at 2 K is above requirements for Project X in both Q_0 and gradient

- Revised design of helium vessel and tuner are complete
- The first new SSR1 cavity is dressed.
- Measured df/dP = ~10 Hz/Torr

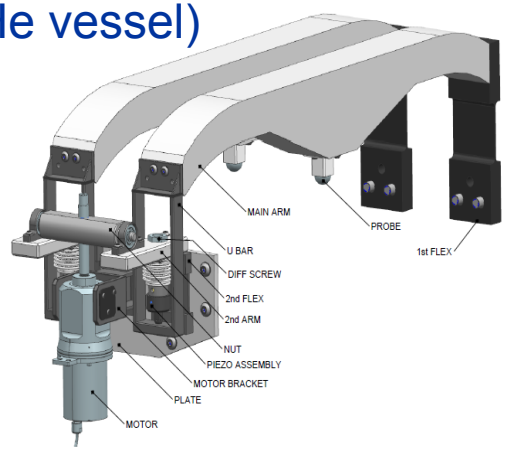
Accomplishments

SSR1 He Vessel and tuner

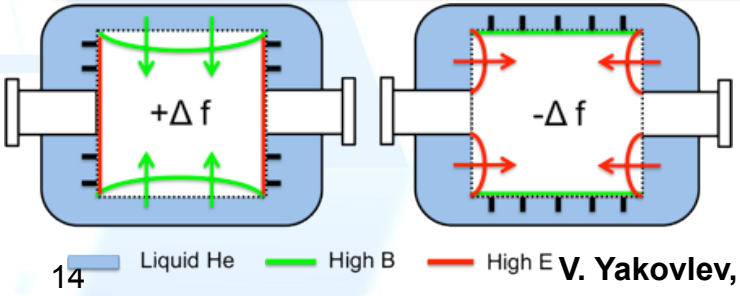
- Pressure of L_{He} can vary by ± 0.5 Torr in the cryomodule
- SSR1 must operate within a small bandwidth ± 20 Hz
- A self-compensating design was developed allowing low sensitivity
- Despite non-negligible deformations (see picture), net shift is very low
- Bare cavity ~ 600 Hz/Torr, with He vessel ~ 10 Hz/torr (measured)
- Ease of tuning 39 N/kHz (bare), 40 N/kHz (with He vessel)



courtesy:
D. Passarelli

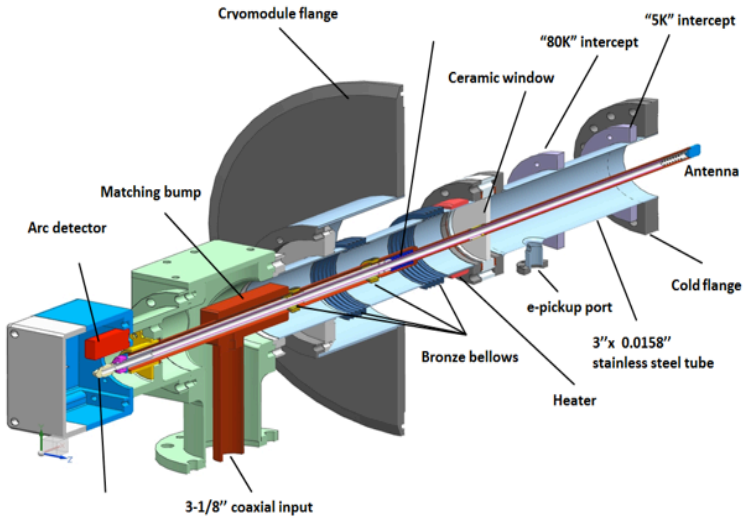


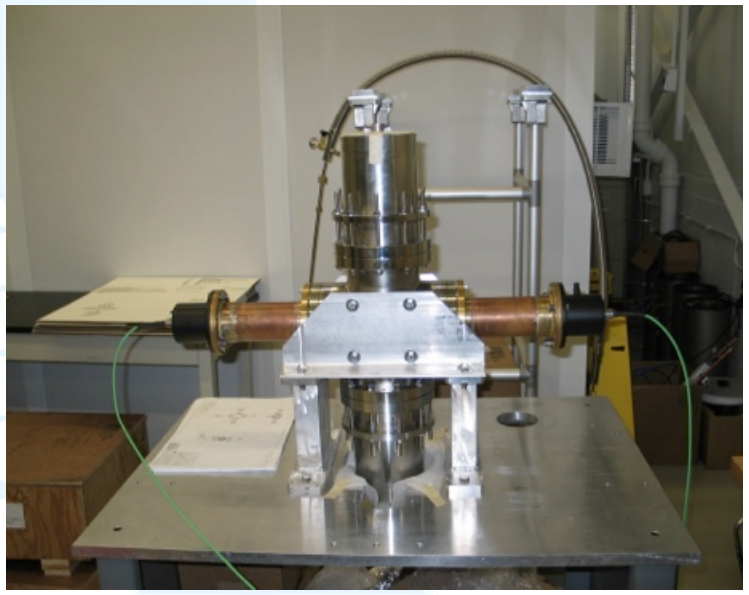
Actuating elements of the tuning system



- **Deformations in high E and B regions balance out resulting in a small frequency shift (Slater's Theorem)**

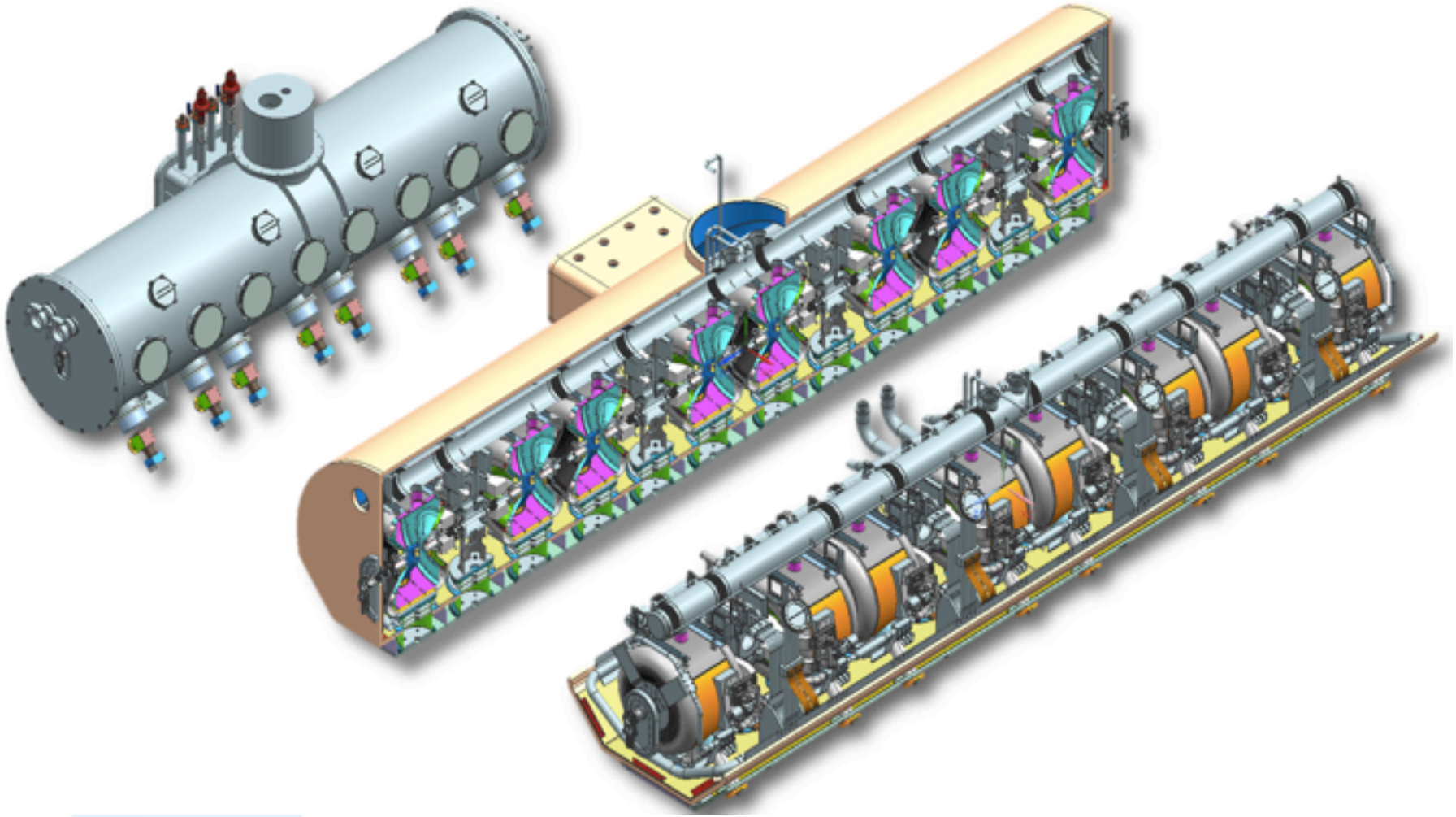
SSR1 Couplers:





- The coupler is designed for 30 kW traveling wave (TW) at full reflection
- Three couplers are ordered and expected to be manufactured in this fall.
- The test stand is ready

The SSR1 cryomodule



CM contains 8 cavities and 4 focusing solenoids

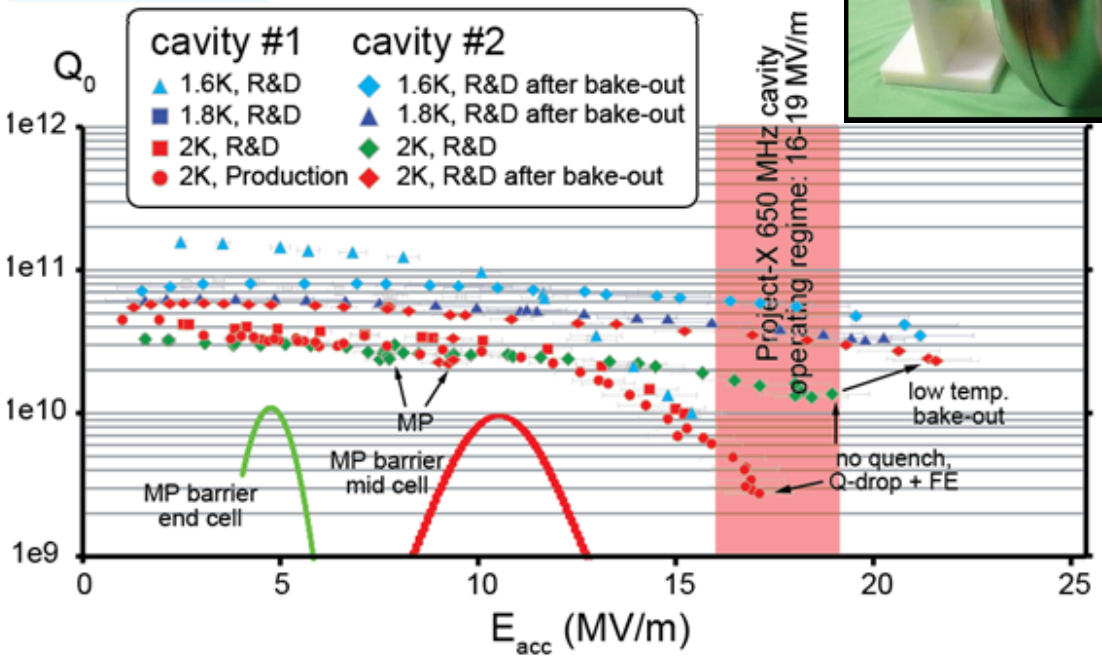
650 MHz Cavity Development & Prototypes

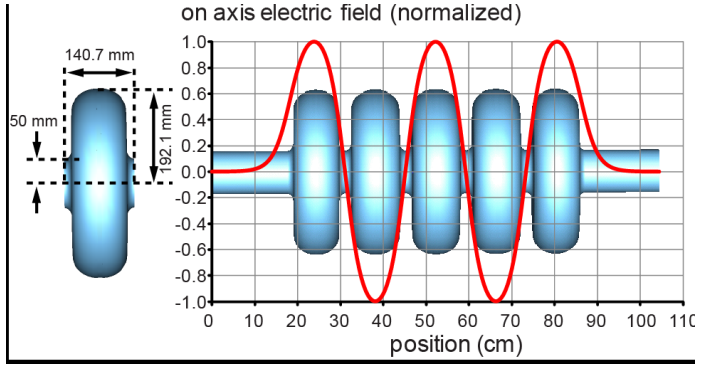
- 650 MHz cavities/cryomodules are cost drivers for Project X
  - Studying cost reduction methods & Q_0 improvement
- Status & Prototypes:
  - Two single-cell β = 0.6 cavities prototyped at JLab
  - Six single-cell β = 0.9 cavities prototyped recently received from U.S. industry, Four five-cell β = 0.9 cavities ordered (AES)
  - 5 additional single cell and 5 five-cells β = 0.9 cavities ordered from industry (PAVAC) on ARRA funds
  - Prototypes at both β are also being fabricated in India

Four 5-cell cavities are fabricated by AES

Accomplishments

JLAB version of the 650 MHz, beta=0.61 cavity for the Project X



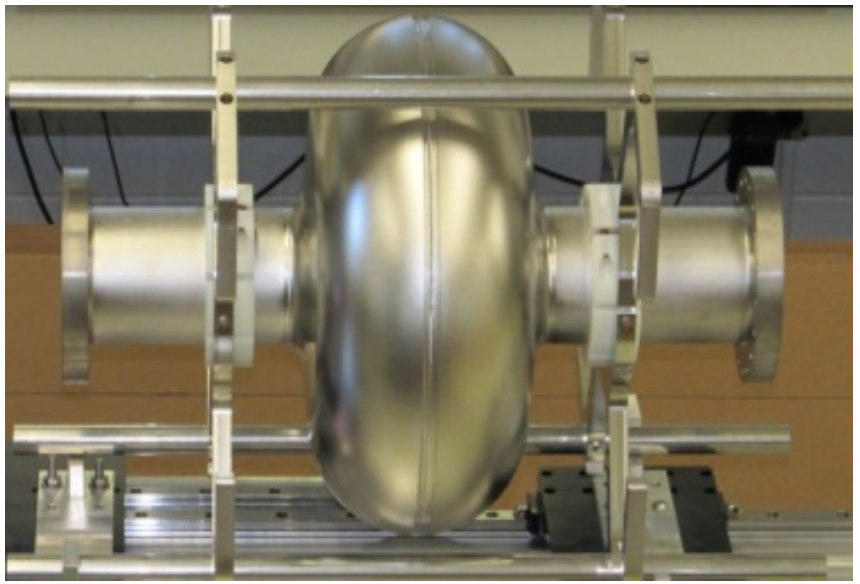


For the cavity #2
Q_0 >4e10 @17MeV/m

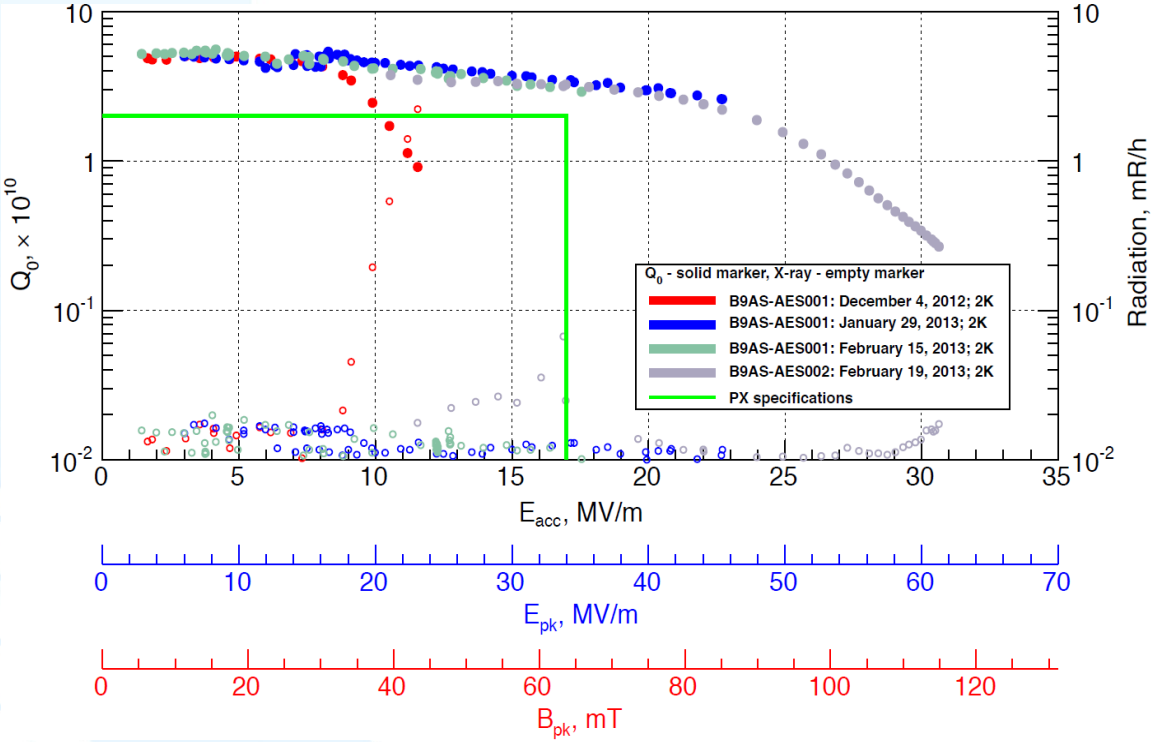
Accomplishments
650 MHz, β = 0.9 Cavity Development & Prototypes

Infrastructure modifications: for 650 MHz complete

- Vertical Test Stand: Electronics, top plate
- Cavity handling & HPR tooling, etc.
- Optical inspection system modifications
- New electro-polishing tool operational for QWR/HWR and ~ for 650 MHz cavities (ANL).



Accomplishments
650 MHz β = 0.9 Cavity Processing & Testing



- AES001 (Jan 29): EP only;
- AES001 (Feb 15): EP + 120°C bake;
- AES002 (Feb 19): BCP only.

Performance at 2 K is above requirements for Project X in both Q_0 and gradient.

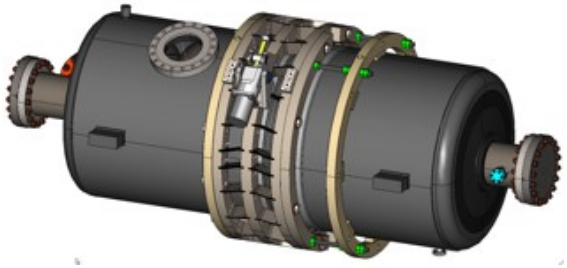
- Step-by-step optimization of the cavity processing procedure.
- Goals: required acc. gradient, high Q_0, no FE, inexpensive.

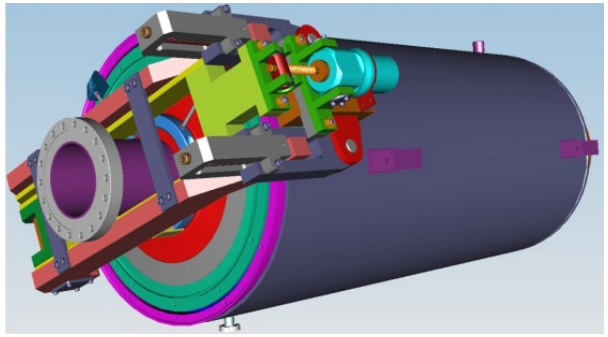
Accomplishments

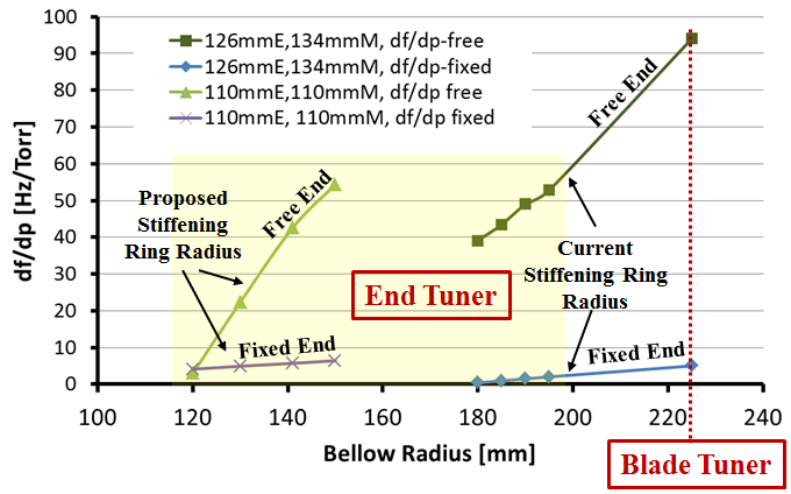
He vessel and tuner design for 650 MHz cavity

Blade Tuner – scaled ILC:

- High df/dP,
- Insufficient tuning efficiency;

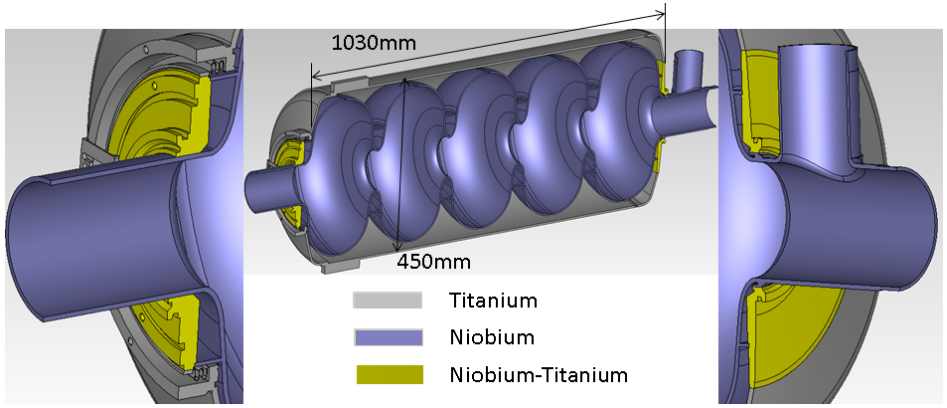






New End Tuner design:

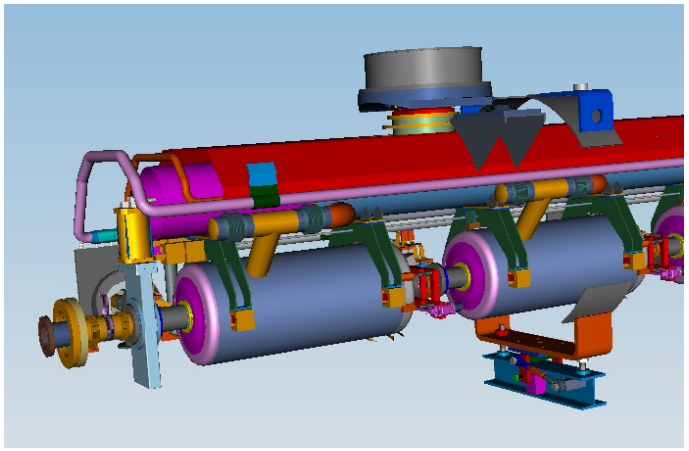
- Low df/dP,
- Mechanical resonances > 60 Hz;
- Good tunability;
- Less expensive.

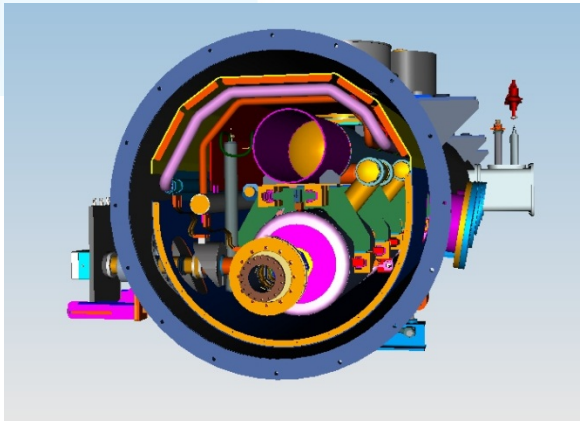


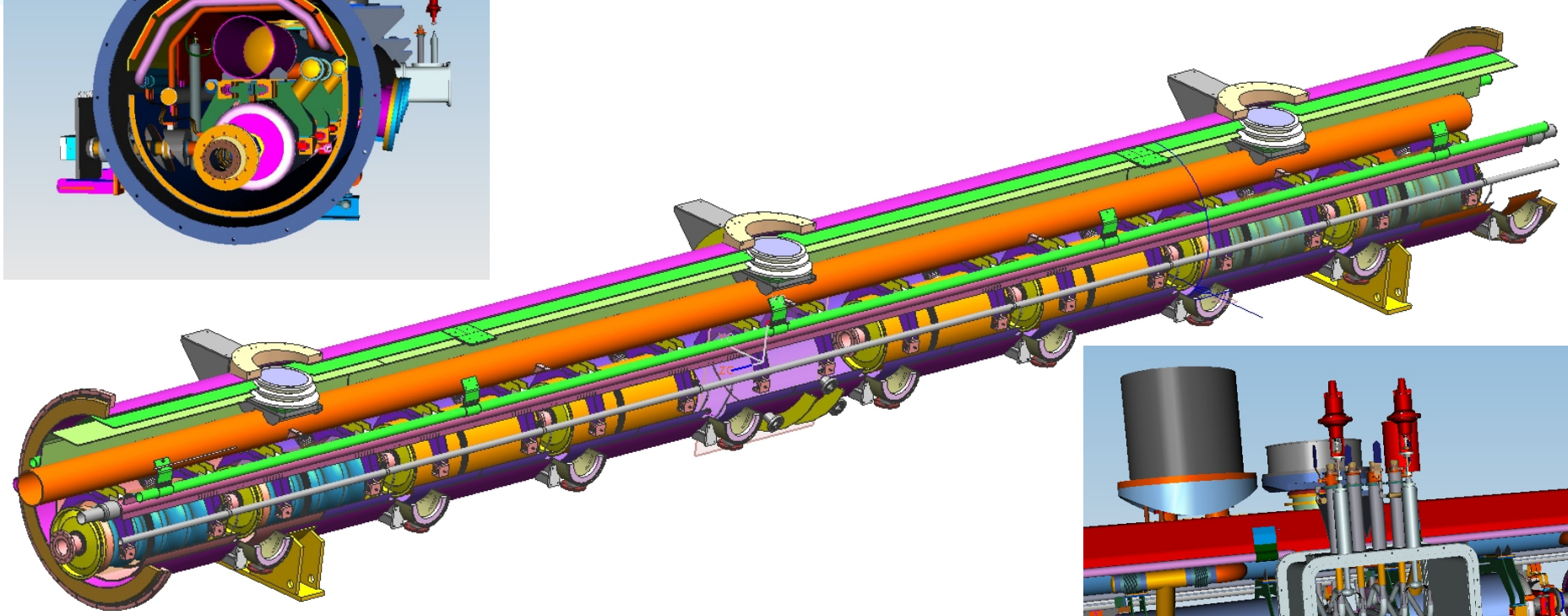
Stiffening rings located to minimize df/dP while maintaining tunability

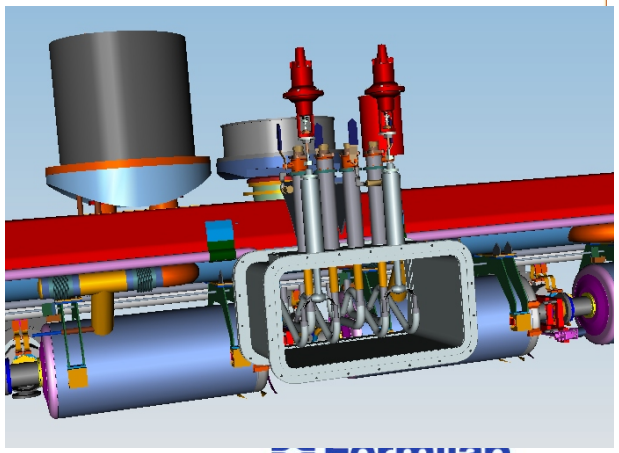
Accomplishments: 650 MHz CM Design

- Cryomodule conceptual design advanced
  - Very high heat flux (over 200 W per CM)
  - Stand-alone 8-cavity cryomodule
  - Variant of ILC cryomodule
  - 3-D CAD models, collaboration with India









1300 MHz Development for ILC and PX

- Goals: ILC SRF goals
  - S0 >35 MV/m bare cavities
  - S1 31.5 MV/m dressed cavities in a ILC Cryomodule
  - S2 Beam test of full ILC RF unit (CM, klystron, modulator)
  - Build and test ~ 1 CM/yr
  - All of this will benefit the 3-8 GeV pulsed linac for Project X
- Accomplishments:
  - Excellent progress on gradient improvement
  - ANL/FNAL EP facility: world class throughput & yield
  - 18 Dressed cavities, CM2 populated with 35 MV/m cavities, have >8 good cavities tested in VTS for CM3
  - Parts for 4 more 1.3 GHz cryomodules (ARRA funds)
  - Cost reduction (e.g. tumbling vs. EP, & cavity repair)
- Excellent progress on all of these
- CM1 tests complete, CM2 is cold and testing has started

Project X Cavity and CM development

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	not started	8	all parts	not started	not started	yes	WIP	not started	35
Single Spoke Resonator 1 (SSR1)	325 MHz	1-spoke CW	0.22	India	yes	yes	2	2	2	10	10	8	1	80%	WIP	not started	50
Single Spoke Resonator 2 (SSR2)	325 MHz	1-spoke CW	0.42	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	2	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	WIP	not started	not started	20
Pulsed Energy 1300 (ILC)	1300 MHz	9-cell pulsed	1.0	DESY, KEK	yes	yes	30	53	43	80	70	43	21	yes	5	2	90

- Project X is powerful, but ambitious (high power, CW, advanced chopper, etc.)
- Progress, but lots of cavity and CM development remains to lower Project risk

LCLS II: Fermilab participation

2014 - 2015 :

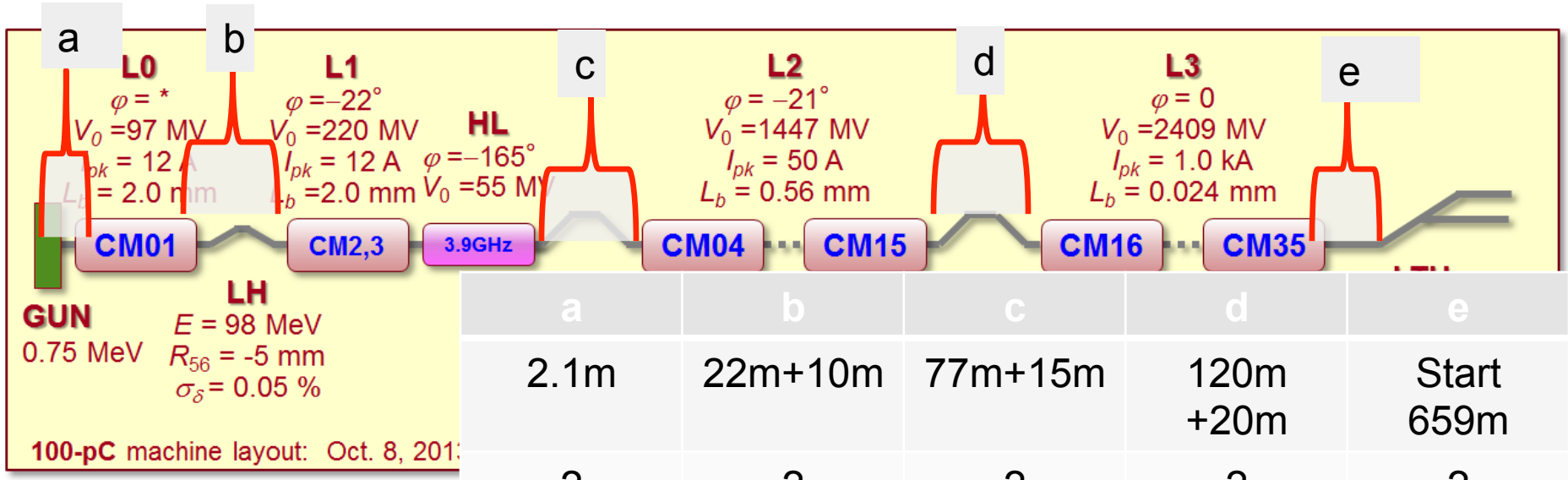
- **One 1.3 GHz pre-production cryo-module: Type IV 8-cavity CM with minimal modifications for CW operation at 16 MeV/m**
  - Extensive use of existing parts (vacuum vessel, cavities, couplers)
  - Design modifications (CM, He vessel, tuner, HOM coupler, main coupler)
  - Part procurement
  - CM assembly
  - CMTF and ASTA modifications to allow CW tests of full LCLS-II CM
  - R&D for Q0 improvement

2015-2018:

- **Production of LCLS II cryo-modules**
  - Eighteen 1.3 GHz cryomodules (144 TESLA – type 9-cell cavities);
  - Three 3.9 GHz cryo-modules (12 FNAL- type 9-cell cavities).

- Major new initiative for FNAL. Previous ILC work has positioned us very well
- Care will be required to minimize impact on PX R&D effort

LCLS-II - Linac and Compressor Layout for 4 GeV

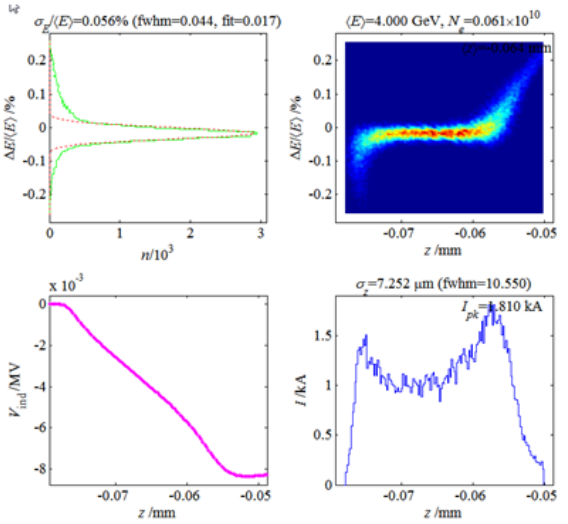


a	b	c	d	e
2.1m	22m+10m	77m+15m	120m +20m	Start 659m
?	?	?	?	?

Linac Sec.	V (MV)	φ (deg)	Acc. Grad. (MV/m)	No. Cryo Mod's	No. Avail. Cav's	Spare Cav's	Cavities per Amplifier
L0	97	*	14.6	1	8	1	1
L1	220	–21	14.1	2	16	1	1
HL	–55	–165	14.5	3	12	1	12
L2	1447	–21	15.5	12	96	6	48
L3	2409	0	15.4	20	160	10	48

P. Emma, L. Wang, C. Papadopoulos

Includes 2-km RW-wake



* L0 cav. phases: ~(-40°, -52°, 0, 0, 0, 13°, 33°), with cav-2 at 20% of other L0 cavity gradients.

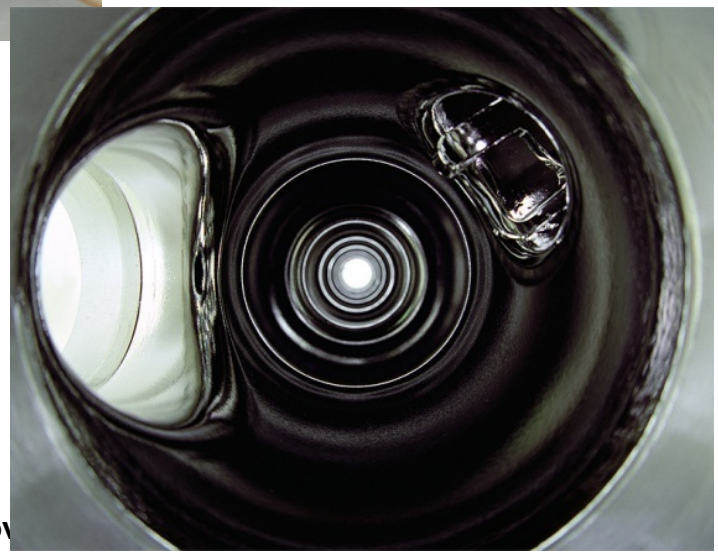
SRF Materials Research

- SRF Materials R&D program focuses on
  - Scientific understanding of SRF surfaces leading to:
    - High gradients, Improved Q_0, and manufacturing yield
    - Nano-scale understanding of performance limitations
  - Targeted cavity process improvements
    - Material Quality Control (Nb spec., eddy current scan, optical inspection)
    - EP Science and CBP @ ICPA
    - Study H uptake and hydride precipitates leading to Q slope
  - Leverages collaborations with Universities and other institutions
    - Multiple ongoing university research initiatives ~10 students/post docs
  - Game-changing improvements (Nb film deposition, Nb3Sn coatings, acid free processing, etc)
  - Have attracted excellent young research team, doing great work!

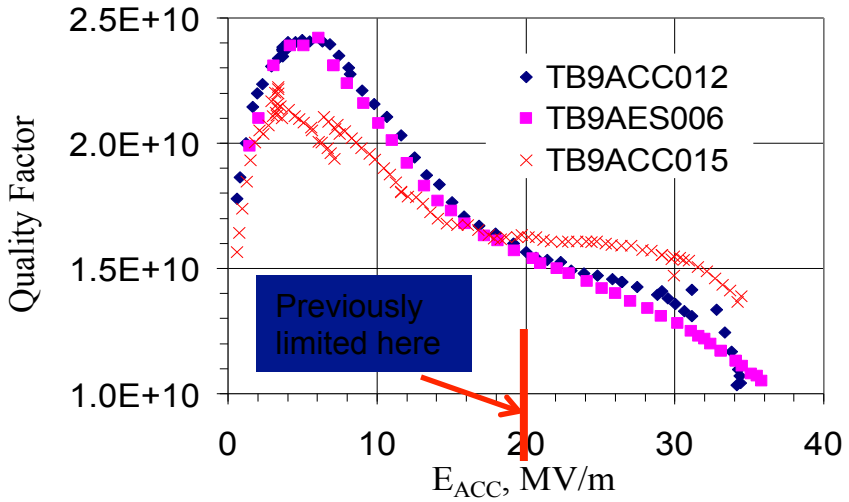
Centrifugal Barrel Polish (CBP)

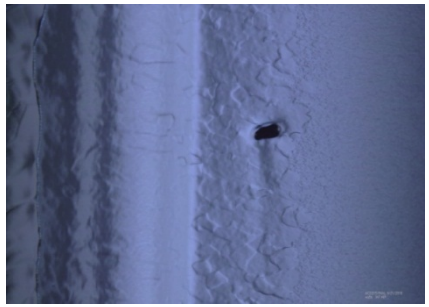
C. Cooper Recipe Media

Breakthrough in the process @ FNAL
Drastic reductions in acid use.
Mirror-like inner surface
25 MV/M with NO chemistry!
Demonstrated cavity gradients > 35 MV/M with light EP

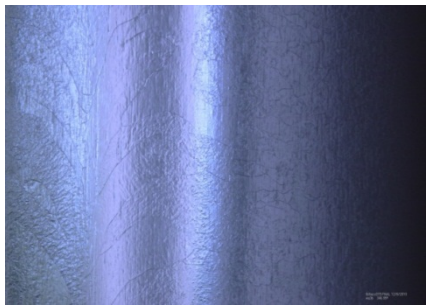


Cavity Results – CBP Repairs

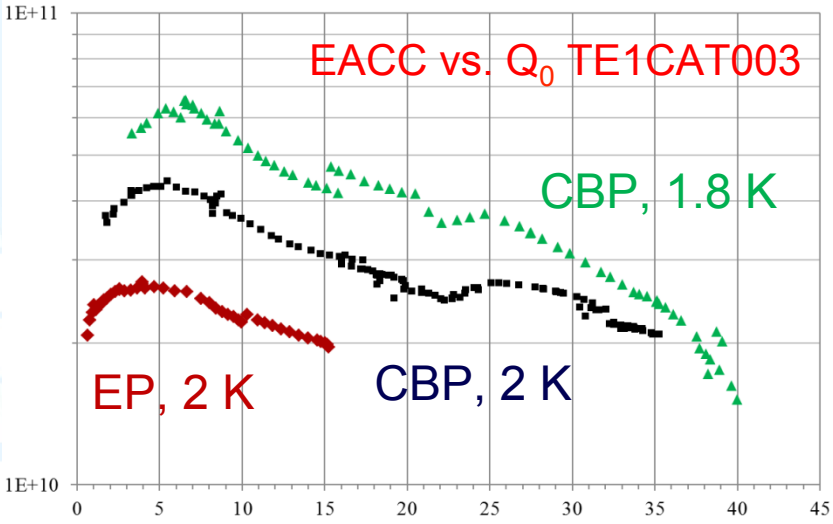


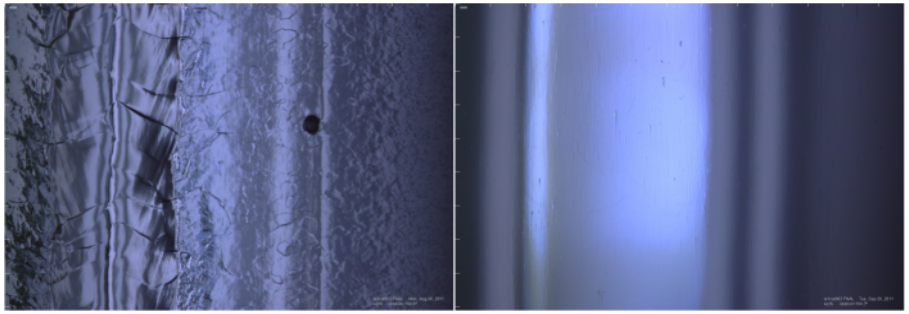


ACC015
Before CBP



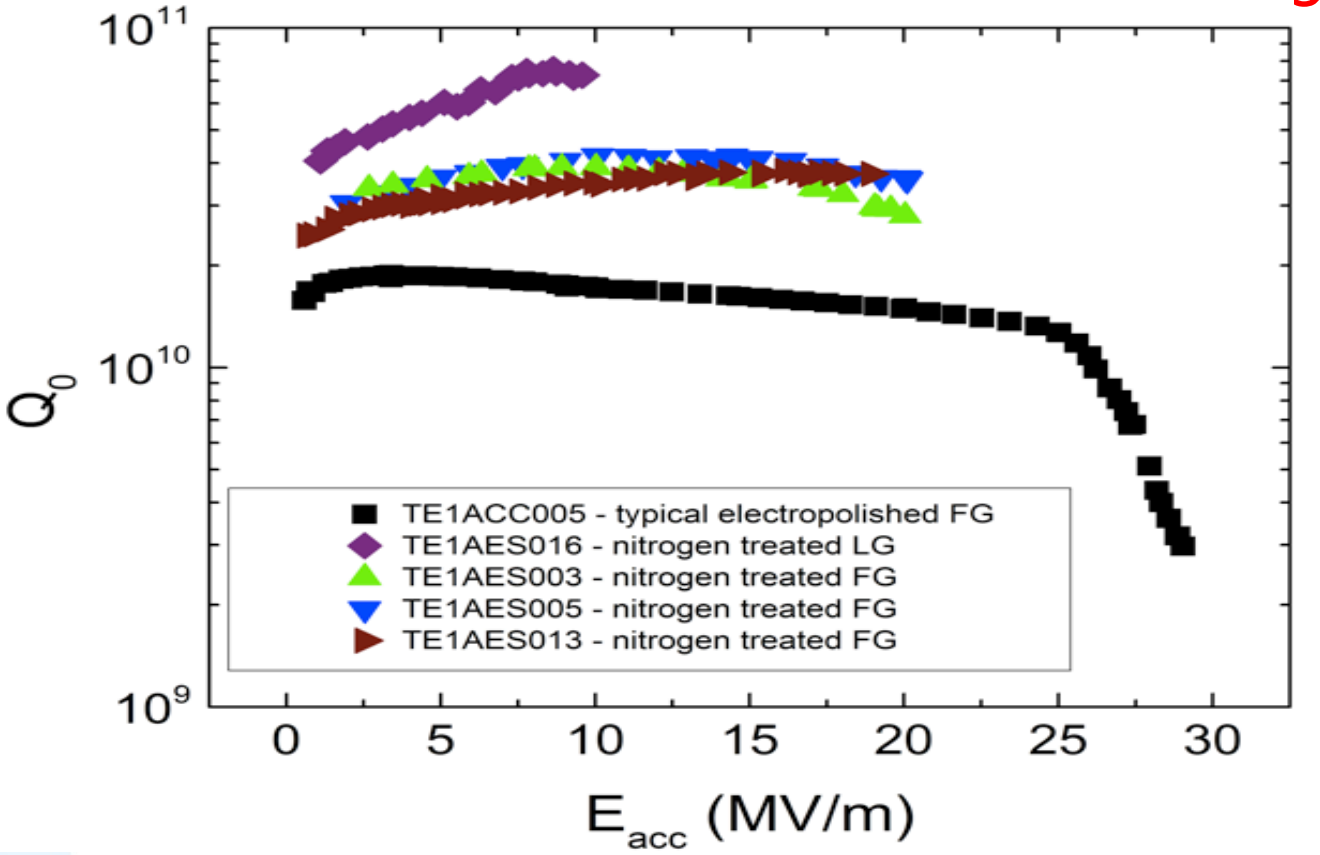
After CBP and 40 microns EP – Pit completely removed





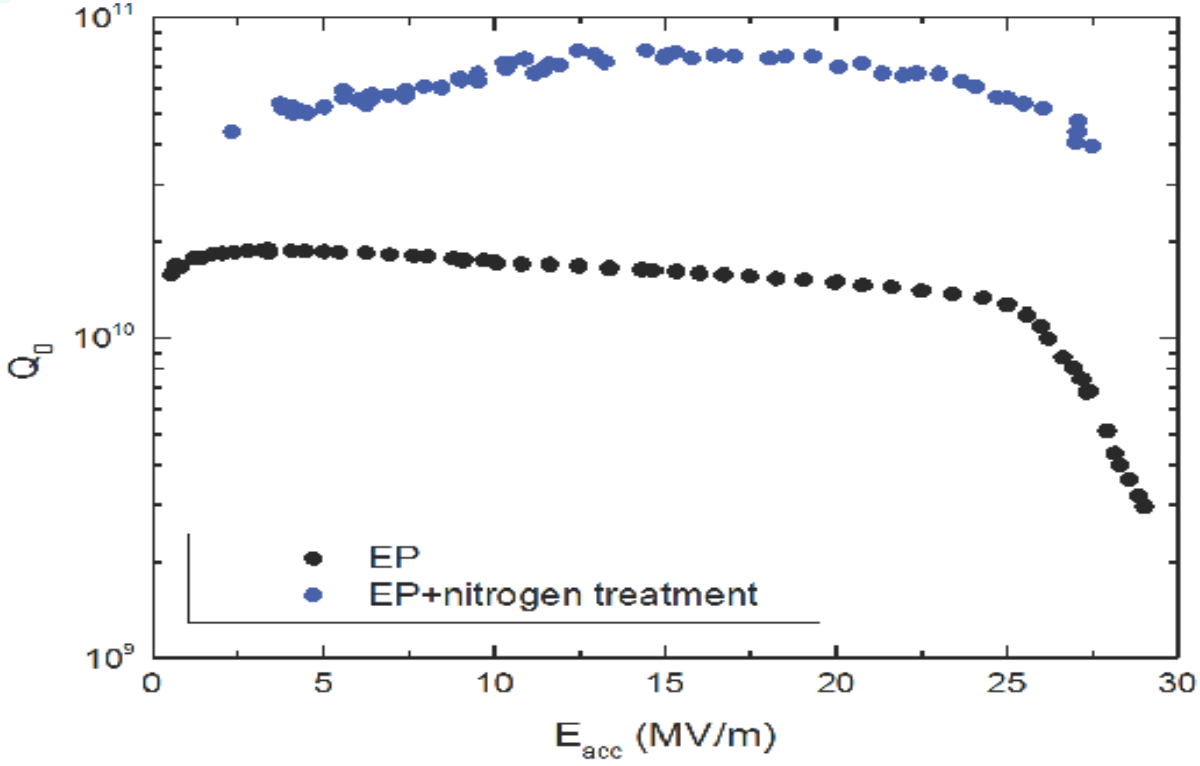
- Demonstrated as a cavity repair method.
- Likely we can ultimately do NO chemistry!
- Exactly the process you want if want to apply coatings to cavities (e.g. NbN or Nb-Cu)

World record cavity Q0's with N2 doping



- 4 cavities above 4 x 10^{10} Q0… but has been limited to ~ 16 MV/M
- Working to fully understand the mechanisms at work at the SRF surface… and to optimize the process
- Extending this effort and CBP to 9-cell cavities

Latest Result with N2 doping



- 4 x 10^{10} Q0 at 27 MV/M
- Potential game changer for SRF CW applications!

FNAL SRF Infrastructure

Goals: Build SRF infrastructure at FNAL including large cryogenic & RF systems and test facilities that are hard for industry to provide

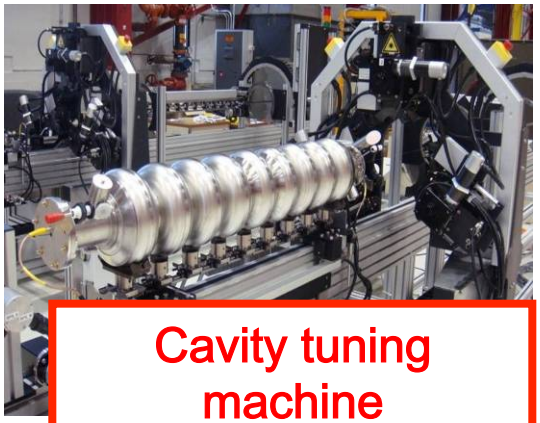
Facility	Designation	Location	Status	India/ARRA Funding	% complete
Cavity Processing Facility	EPF	ANL	Operational		100%
Cavity Prep Facility	CPF	IB4/MP9	Operational	ARRA	100%
CPL R&D Processing Facility	CPL	IB4	Operational		100%
Vertical Test System 1	VTS-1	IB1	Operational		100%
Vertical Test System 2 & 3	VTS-2/3	IB1	Commissioning	ARRA & India	84%
Horizontal Test System 1	HTS-1	MDB	Operational		100%
Spoke Test Facility	STF	MDB	Operational		100%
Horizontal Test System 2	HTS-2	MDB	Construction	ARRA & India	55%
Cavity/CM Assembly Facility	CAF	MP9/ICB	Operational		100%
Advanced Superconducting Test Accelerator	RF unit test ASTA	NML	Construction	ARRA	80%
Cryomodule Test Facility	CMTF	CMTF	Construction	ARRA & India	50%

Planned infrastructure either complete & operational or well into construction

New FNAL SRF infrastructure

VTS

VTS


Cavity tuning machine

HTS

String Assembly

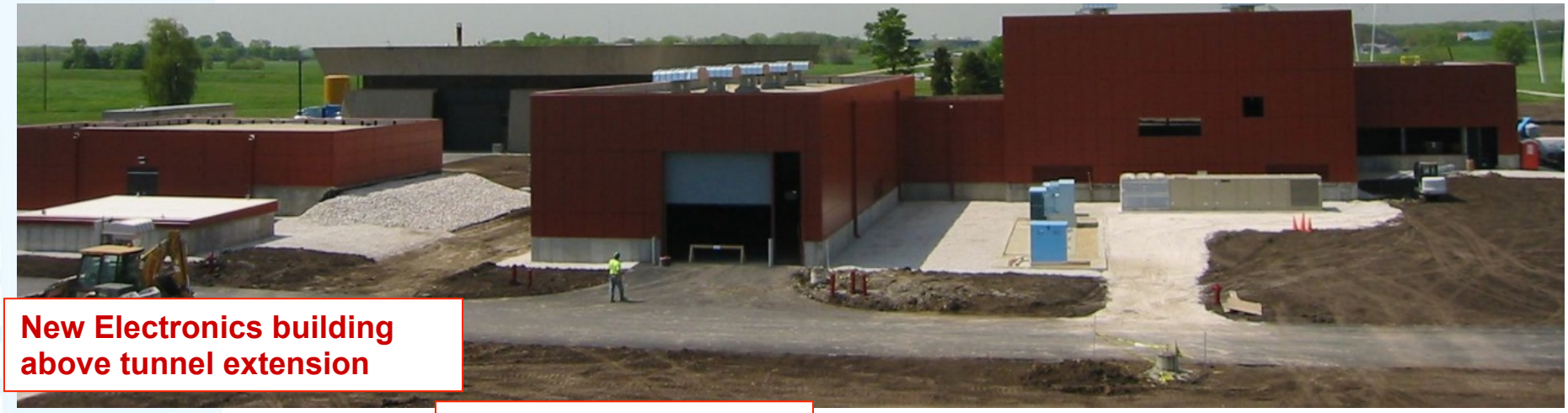
MP9 Clean Room

Final Assembly

VTS2 Dewar

New Vacuum Oven

New NML Buildings Complete



New Electronics building above tunnel extension

New Cryomodule Test Facility

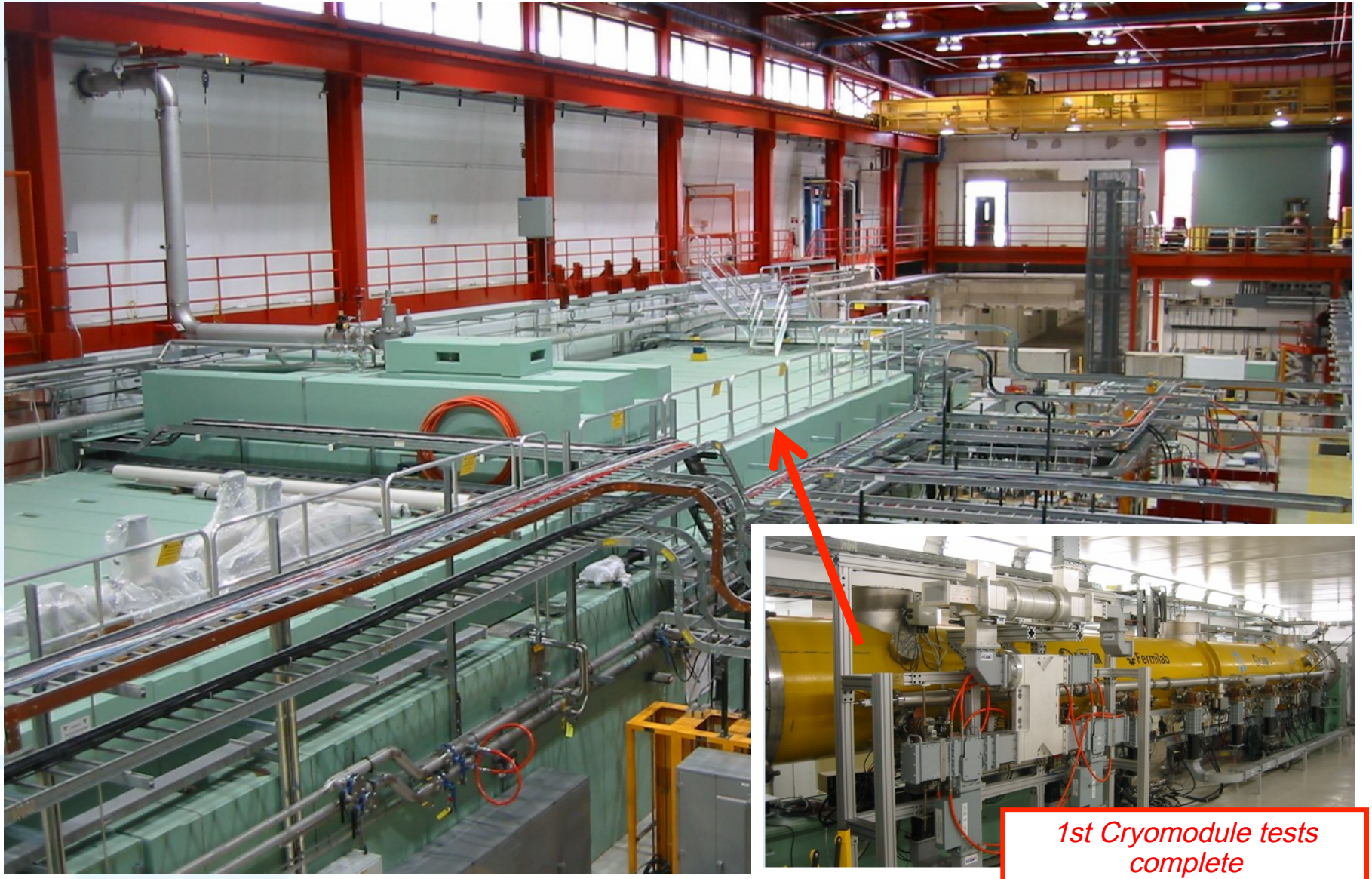
PXIE

New 500 W @ 2 K refrigerator

Installed and first superfluid !

Compressor building

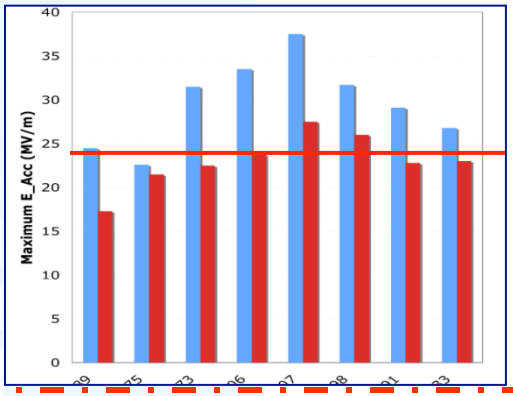
NML: RF Unit Test Facility



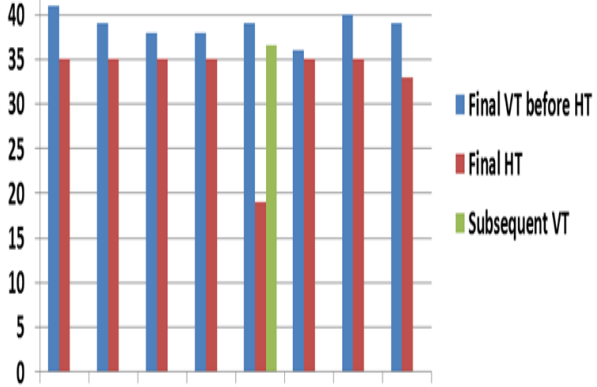
1st Cryomodule tests complete

NML Status and Plans

CM1 ave gradient = 23.7 MV/M



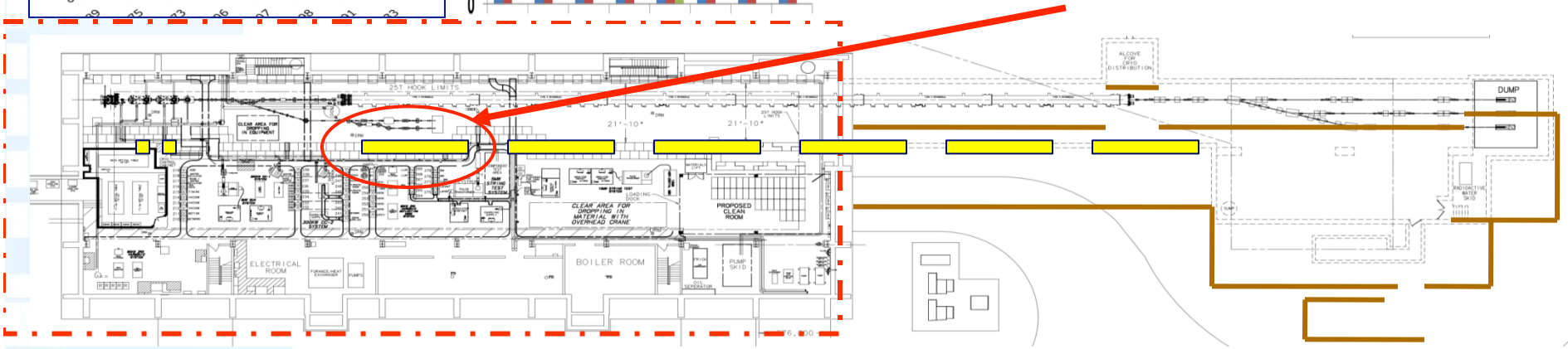
CM2 ave gradient = ~35 MV/M



CM2 installation

CM1 tests complete, swapping for CM2, high gradient CM,

All U.S. Processed Cavities



- Learning a lot! (CM assembly, tuners, LLRF, finding leaks in CM, etc.)
- Installing 40 MeV photo-Injector (end of FY13)…. However….
- OHEP instructions to stop ASTA build out in FY13.. Completing injector and CM2
- Recent ASTA proposal review, awaiting outcome

Plans: FY14 and beyond

- **Cavity development for Project X**
  - Dress all SSR1 cavities and continue SSR1 CM development for PXIE
  - Test 650 MHz cavities from industry and India
  - Complete design and dress 650 MHz cavities
  - Collaborate with ANL on HWR work
  - SRF materials R&D aimed at improved Q0 and cost reduction
- **1300 MHz development**
  - Process and test 1300 MHz cavities to gain experience and provide feedback to U.S. industry.
  - Test CM2 at NML (1st high gradient CM)
- **Infrastructure**
  - Complete ARRA tasks: VTS 2/3, CMTF, etc
  - Complete commissioning of super-fluid refrigerator at CMTF
  - Complete injector at NML by end of FY13
- **Major role in LCLS-II (1.3 GHz cryomodules, 3.9 GHz system)**
  - Requires early completion of CMTF test stands and ASTA refrigeration system

ES&H and Quality

- There are many potential hazards associated with SRF
  - Cryogenics, high pressures, RF, strong acids, etc
  - Must assure safe operation of equipment/facilities
- Functional Requirements Specifications
  - Insure all intended functionality is clear to design team
  - In use for PX components and SRF infrastructure
- Many Technical Reviews (examples)
  - VTS 2/3 cryostat, HWR cavity design, SSR1 cavity and CM, 650 MHz cavity design, New superfluid cryoplant, CM2, etc
- Many Safety Reviews
  - Operational Readiness Reviews for facilities: VTS, HTS, CAF, NML,CM1&2, vacuum ovens, ICPA, ANL EP facility, etc
  - Reviews of components: Dressed cavity, CM2 safety review,
- No injuries in FY13. Doing a lot… but doing it safely
- Extensive cavity and cryomodule QC effort!

Summary

- SRF is a powerful enabling technology envisioned for essentially all new accelerators in support of OHEP and SC projects.
  - Key element in any OHEP plan for Accelerator stewardship
- SRF R&D program at FNAL is productive & successful
  - Supports both Project X, ILC, and other Office of Science strategic goals
  - Leverages existing FNAL infrastructure (bldgs., cryo, etc)
  - Lots of infrastructure is now in operation and is being used effectively
  - Leveraging existing SRF collaborations and building new ones
  - Focused effort to transfer SRF technology to U.S. Industry
- Adjusting to significant changes in program emphasis (LCLS-II)
- Have an excellent team in place with growing SRF expertise and an already impressive list of achievements

Recommendations from FY12 S&T Review

- **FINDINGS**

Fermilab's SRF program is increasingly focused on cavities for proton linacs.

- Project--X consists of six different RF cavities.
- Fermilab continues an active SRF materials research program
- Fermilab continues to view a part of their mission to transfer SRF technology to US industry.
- Overall the SRF budget has decreased from $38.7M in FY11 to $29.3M in FY13.

- **COMMENTS**

- The SRF R&D facility at FNAL is one of the most advanced facilities in the world. It enables FNAL to be in the forefront of SRF technology needed for both Project X and the ILC. The severe cuts in the program due to the elimination of ILC R&D endanger the existing expertise that has been built at the Lab.
- The SRF studies are going well and much progress has been made. These include cavity surface preparation, cryomodule production, high gradient studies and outreach to industry.
- Considerable work has been done on each of the six cavity types needed for Project X.
- The Fermilab SRF materials research program has been very productive.
- The committee as a whole was concerned about the reduction in SRF staff and the potential loss of core people in this area.

- **RECOMMENDATIONS**
- **None**

We agree!