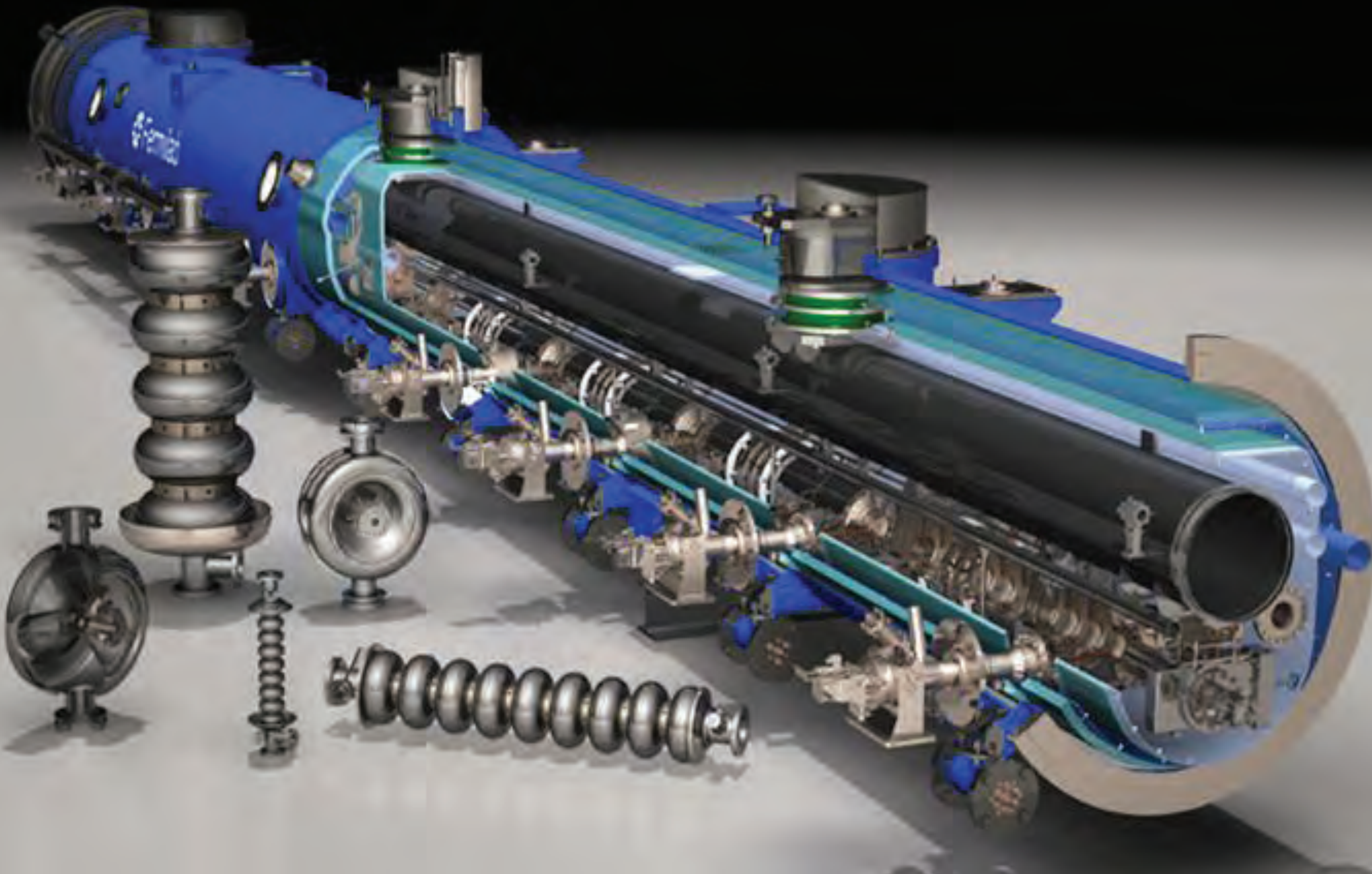
SRF Cavity Development for Project X



Bob Kephart

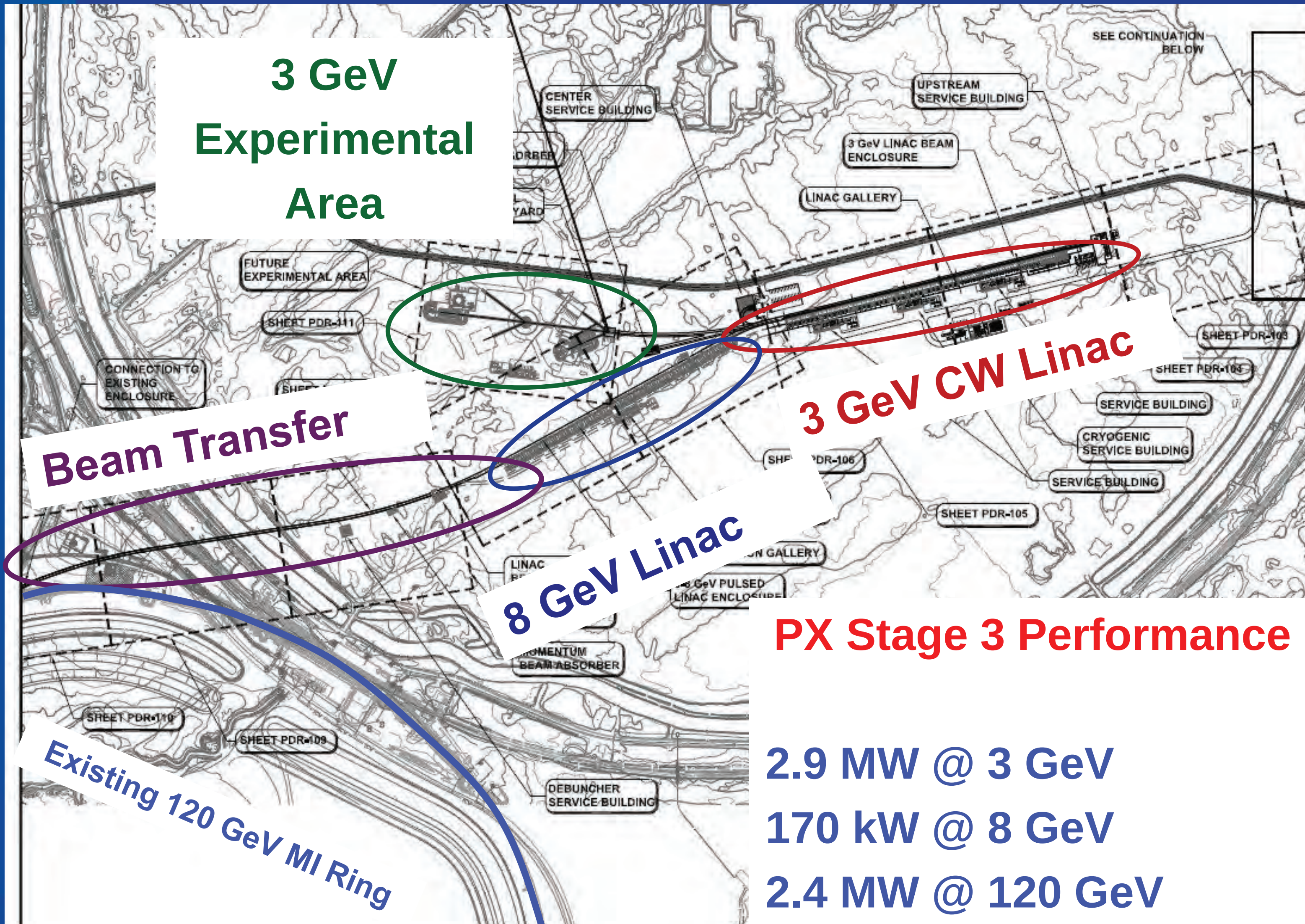
U.S. DEPARTMENT OF ENERGY

Fermilab

Project X

- Unique proton facility based on a 3 MW, 3 GeV SRF continuous-wave (CW) linac & 3-8 GeV pulsed SRF linac
  - Multiplies low-energy flux of protons at Fermilab by 100
  - Enables a broad program of Intensity Frontier Physics experiments
- Support experiments simultaneously at 1 GeV, 3 GeV, 8 Gev and 60-120 GeV at high beam power
  - Delivers >2 MW to Long Baseline Neutrino Experiments simultaneously with >3 MW for rare decays
- Can serve as a future front end of neutrino factory or muon collider

Project X Layout



PX Stage 3 Performance

2.9 MW @ 3 GeV
170 kW @ 8 GeV
2.4 MW @ 120 GeV

PX Reference Design Performance Goals

Linac		
Particle Type	H^-	
Beam Kinetic Energy	3.0	GeV
Average Beam Current (1/3 GeV)	2/1	mA
Linac pulse rate	CW	
Beam Power to 1 GeV program	1000	kW
Beam Power to 3 GeV program	2870	kW
Pulsed Linac		
Particle Type	H^-	
Beam Kinetic Energy	8.0	GeV
Pulse rate	10	Hz
Pulse Width	4.3	msec
Cycles to Recycler/MI	6	
Particles per cycle to Recycler/MI	2.7×10^{13}	
Beam Power	340	kW
Beam Power to 8 GeV program	170	kW
Main Injector/Recycler		
Beam Kinetic Energy (maximum)	120	GeV
Cycle time	1.2	sec
Particles per cycle	1.5×10^{14}	
Beam Power at 120 GeV	2400	kW

simultaneous

SRF Cavity and CM R&D at Fermilab

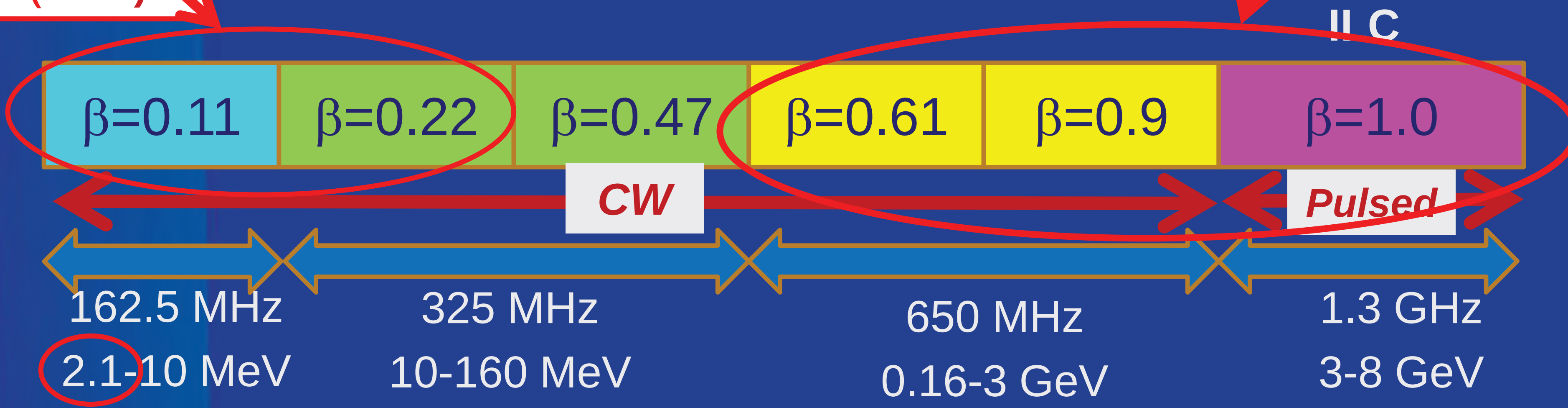
- Adoption of a 3 GeV CW linac followed by a 3-8 GeV pulsed linac for Project X in 2010 results in a powerful new intensity frontier machine, but presents new challenges
  - Need six different cavities optimized for changing velocity (β) of Protons
  - Four different frequencies (162.5, 325, 650, 1300 MHz)
  - Five of these cavities are completely <u>new</u> 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 development for ILC

Technical Risk ➔ Prototype (PXIE)

Project Cost Risk

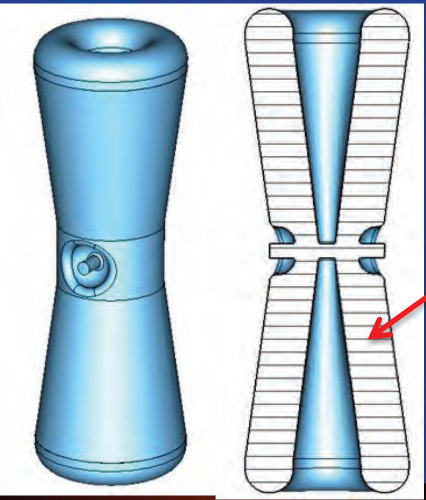
PX SRF Linac Technology Map



Section	Freq	Energy (MeV)	Cav/mag/CM	Type
HWR (β_G=0.11)	162.5	2.1-10	9 /6/1	Half Wave, solenoid
SSR1 (β_G=0.22)	325	10-42	16/8/ 2	Single Spoke, solenoid
SSR2 (β_G=0.47)	325	42-160	36/20/4	Single Spoke, solenoid
LB 650 (β_G=0.61)	650	160-460	42 /14/7	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	460-3000	152/19/19	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 /28 /28	9-cell elliptical, quad

Accomplishments

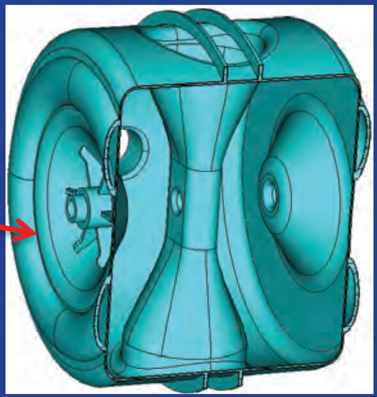
162.5 and 325 MHz Cavities



- **HWR (β = 0.11) Half Wave Resonator (collab ANL)**
  - Cavity design complete, ordering parts, CM design in progress
  - Very similar to cavities & CM already manufactured by ANL
  - Optimize to achieve tight packing in PX front end
- **SSR1 (β = 0.22) Single Spoke Resonator**
  - Started under HINS program and is therefore more advanced
  - Two prototypes fabricated by industry, processed in collaboration with ANL, and tested at Fermilab as part of HINS
  - One cavity dressed with He vessel, coupler tuner
  - Two cavities in fabrication at IUAC-Delhi (Q3 FY13)
  - Ten cavities fabricated by US industry (6 have arrived, 2 tested)
  - Tests in progress (next slides)

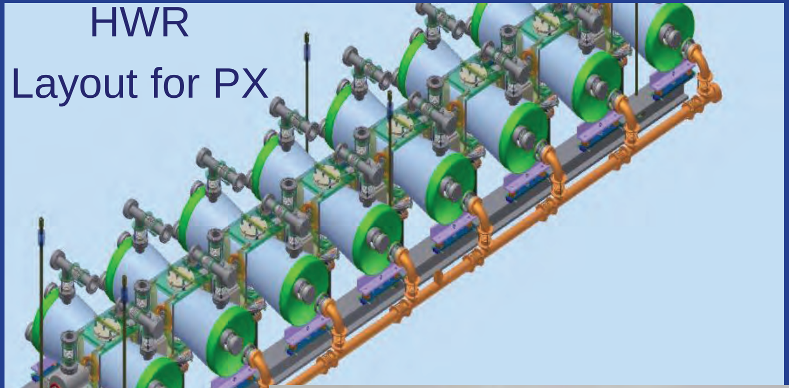
SSR2 (β = 0.47)

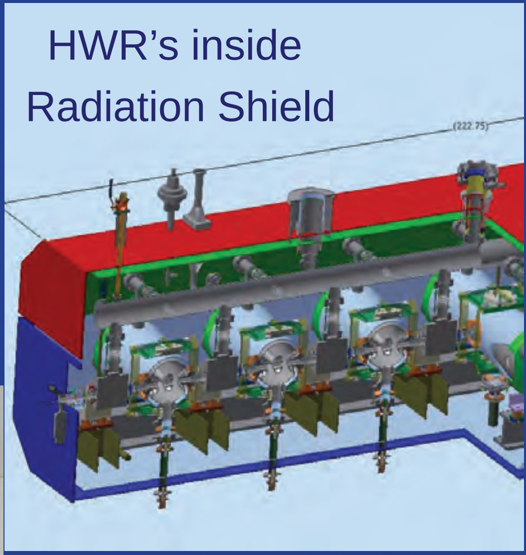
- EM design complete
- Mechanical design is advanced
- Prototype in FY13-14



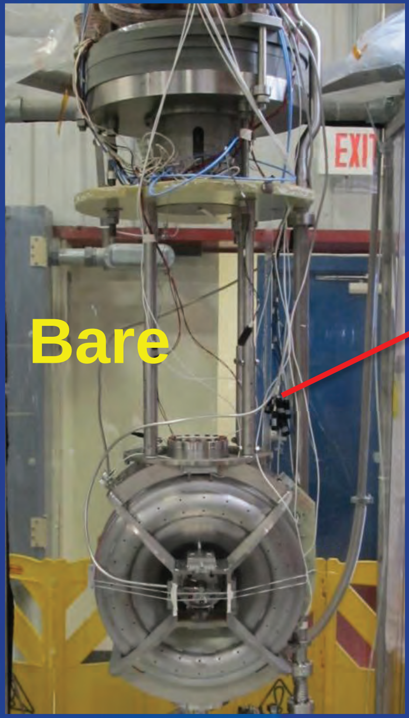
Half Wave Resonators for Project X (ANL)

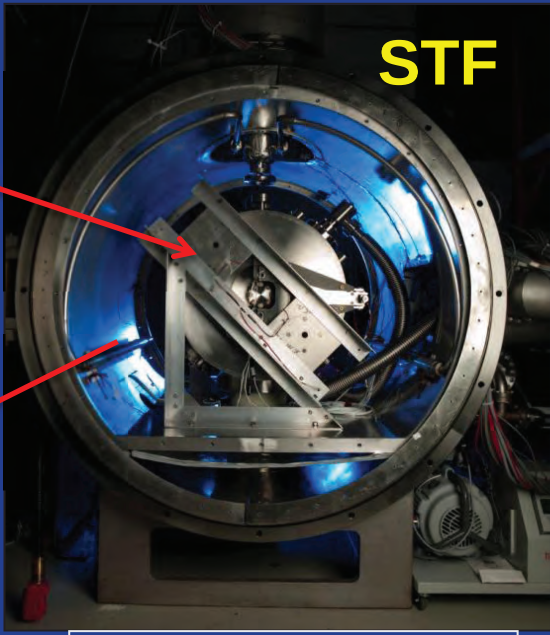
- 162.5 MHz β_{OPT}=0.11 Half Wave Resonators (HWR) are very efficient for low velocity Protons (or H-)
- Only one cryomodule of HWRs is required for acceleration from 2.1 MeV to 10 MeV in Project X
  - Total accelerating voltage in the HWR CM is 13.6 MV
  - Single Cryomodule < 6 meters long provides comfortable margins
  - Comparable with the ATLAS cryomodules built at ANL (hence collaboration)





325 MHz Test Capabilities Developed





SSR-1 prototypes are tested in the VTS-1 vertical dewar (normally used for 1.3 GHz cavity testing) with the addition of new electronics and tooling.

Spoke Test Facility enables testing of "dressed" 325 MHz single-spoke resonators.

Operated previously at 4.8 K (pulsed RF)

Upgrades for 2 K CW operation in process

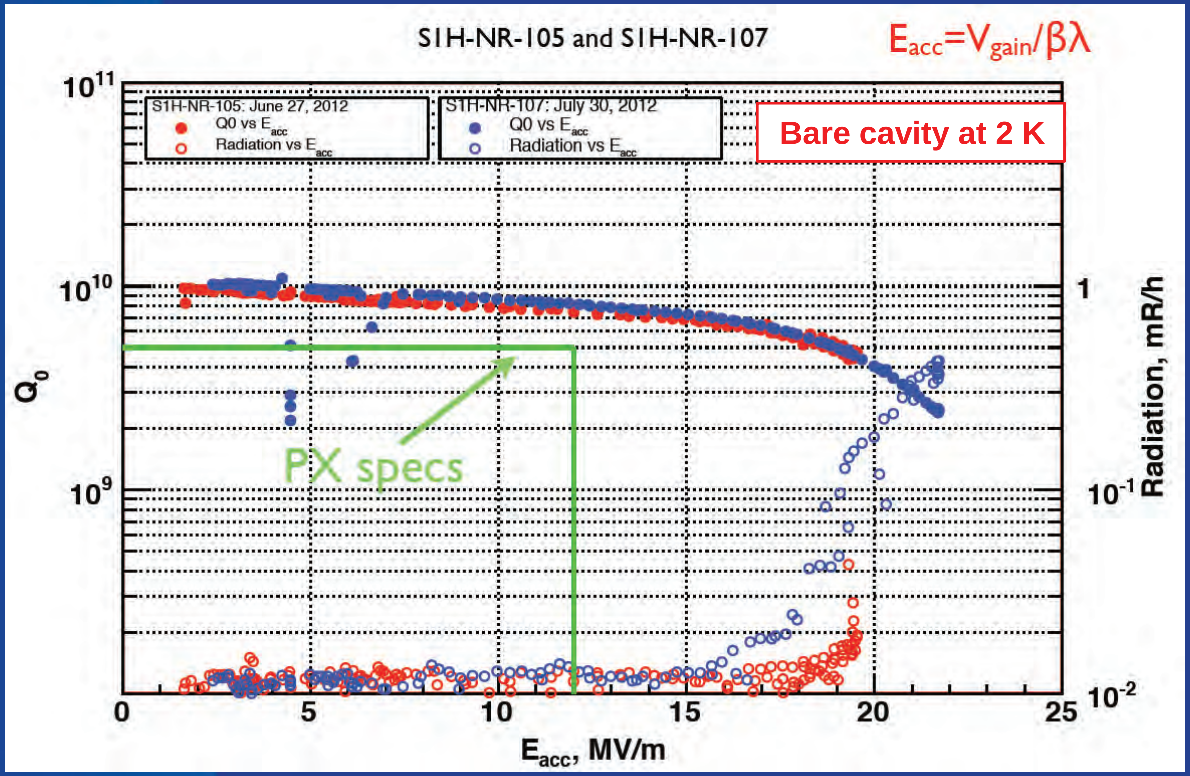
Dressed SSR-1

Includes RF couplers, tuners, and magnetic shielding

Prototype tested in STF, excellent results at 4.8K

SSR1 Fabrication at Roark

New 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
- This is first test of 2 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 nearly complete
- Ordering parts
- Expect to dress cavities in FY13 for first SSR cryomodule

650 MHz Cavity Development & Prototypes

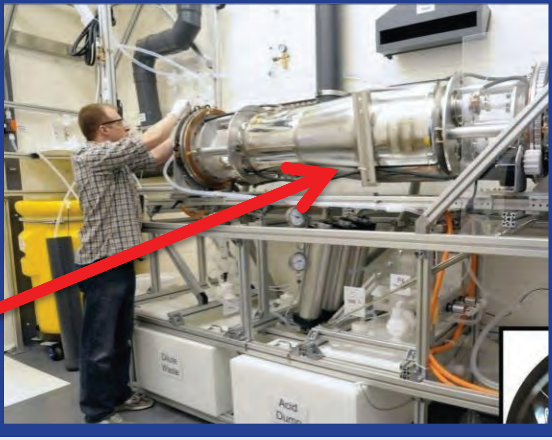
- 650 MHz cavities/cryomodules are cost drivers for Project X
  - Studying cost reduction methods & Q_0 improvement
- Status & Prototypes:
  - Two single-cell $\beta = 0.6$ cavities prototyped at JLab
  - Six single-cell $\beta = 0.9$ cavities prototyped recently received from U.S. industry, Four five-cell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

5-cell EM and mechanical design complete

CAD Rendering!

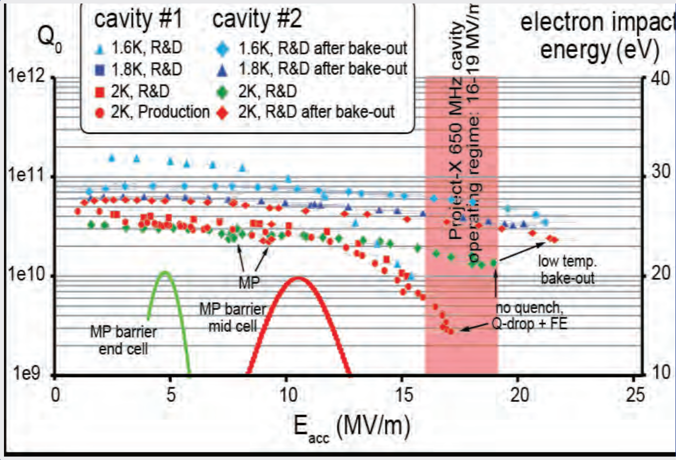
650 MHz Cavity Processing & Testing

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



- Prototype tests: Single cells processed and tested at both JLAB and ANL/FNAL

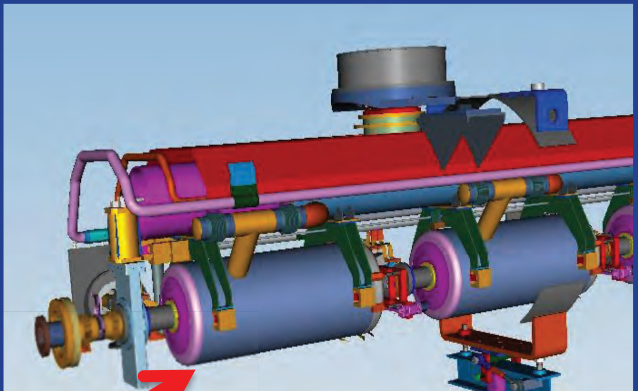
- Both single-cell $\beta = 0.6$ cavities show excellent Q_0 at Project X gradients (JLAB and FNAL tests)
- Single cell $\beta = 0.9$ cavities will be processed and tested at ANL/FNAL in the Fall
- Expect 1st five cell cavities from AES in Q1 FY13

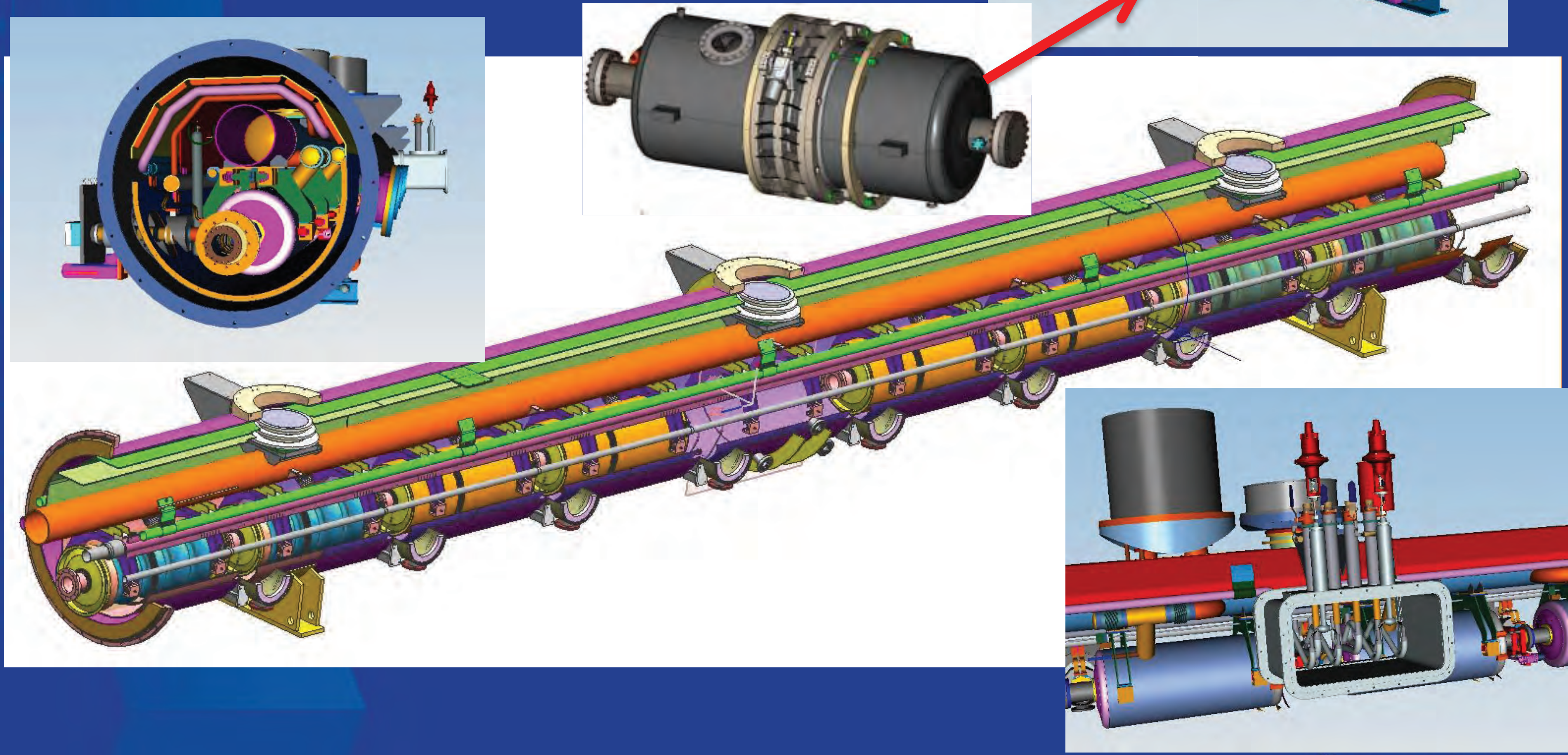


650 MHz 1-cell β= 0.6 test at JLAB

650 MHz CM Design Status

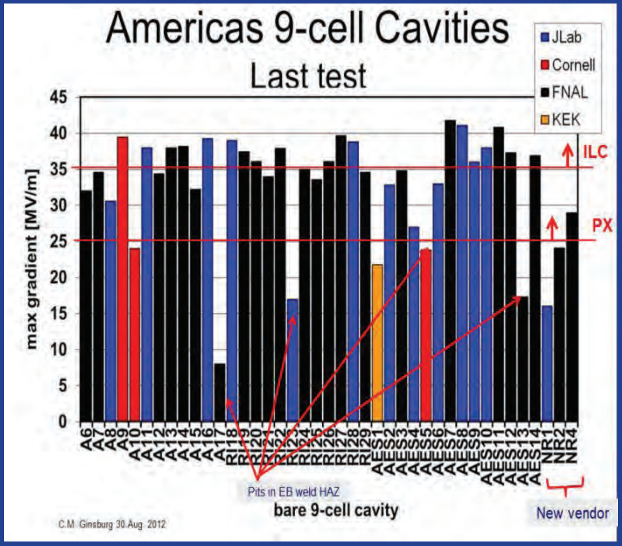
- Cryomodule conceptual design advanced
  - Very high heat flux (over 200 W per CM)
  - Stand-alone 8-cavity cryomodule, variant of ILC CM
  - Looking at tuner options (blade vs lever vs wedge)
  - 3-D CAD models, collaboration with India





1300 MHz Development for PX

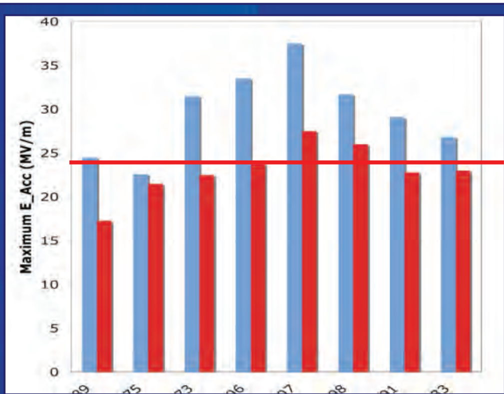
- Has been driven by: ILC SRF goals
  - S0 >35 MV/m bare cavities
  - S1 31.5 MV/m dressed cavities in a ILC Cryomodule
  - S2 Beam test of full ILC RF unit (CM, klystron, modulator)
  - All of this benefits the 3-8 GeV pulsed linac for Project X
- Accomplishments:
  - Excellent progress on gradient improvement
  - ANL/FNAL EP facility: world class performance
  - 18 Dressed cavities
  - CM2 populated with 35 MV/m cavities,
  - Parts for 4 more 1.3 GHz cryomodules
  - Cost reduction (e.g. tumbling vs. EP, & cavity repair)



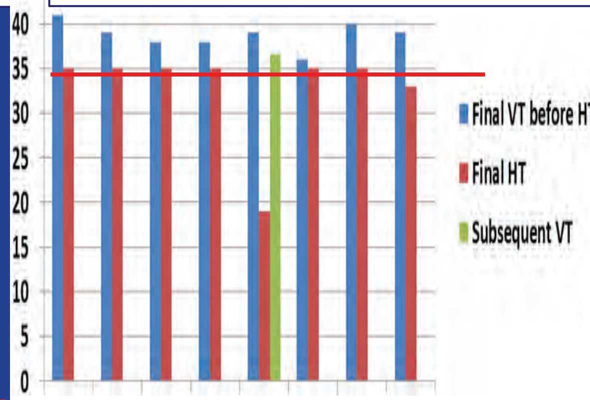
- Excellent progress on all of these
- CM1 tests complete, CM2 installation in progress

NML Status and Plans

CM1 ave gradient = 23.7 MV/M



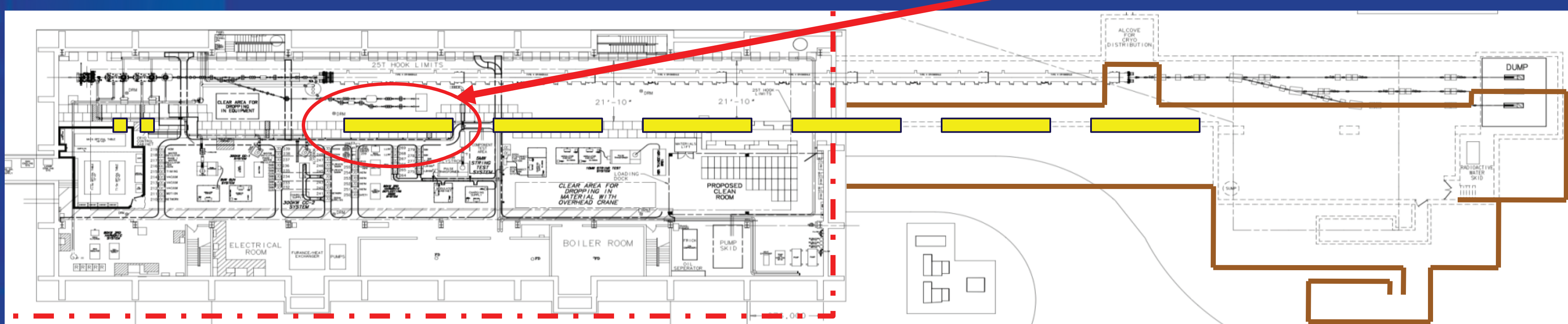
CM2 ave gradient = ~35 MV/M



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)
- Operating NML as CM test stand
- With the end of ILC funding in FY13, submitting proposal to DOE finish this facility and operte as an AARD facility

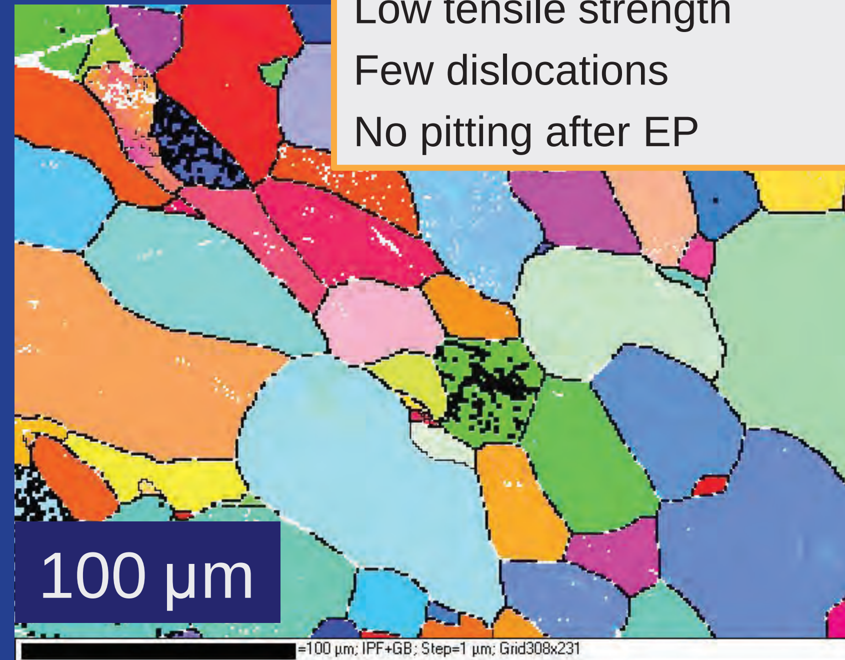
SRF Materials Research

- SRF Materials R&D program focuses on
  - Scientific understanding of SRF surfaces leading to:
    - High gradients, 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 effects which promote 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, coatings, plasma cleaning…)
- SRF Materials R&D level of effort:
  - ~7 FTE staff, ~$600K M&S, including operations of ICPA

Improving the Niobium Supply

Recent batch:
High tensile strength
Too many dislocations
Pitted cavities

Batch delivered in 2009
Low tensile strength
Few dislocations
No pitting after EP

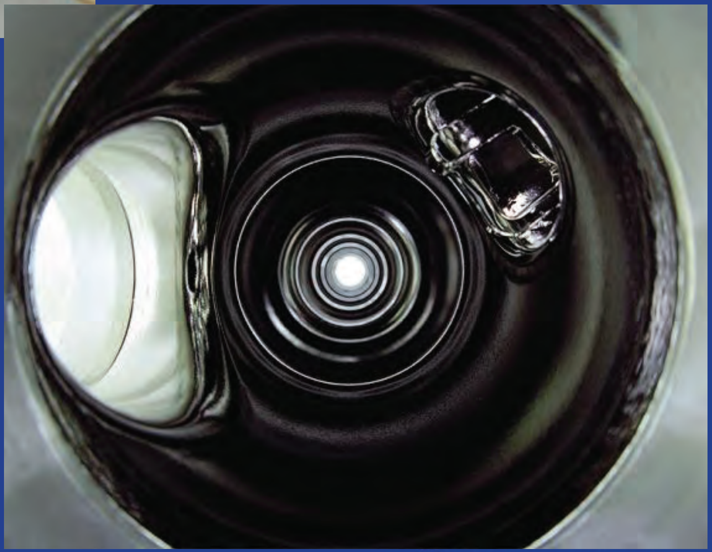


Niobium vendor found a new process that is less variable and exceeds our spec. Unfortunately, the new sheets were not compatible with later processing. Our SEM upgrade showed why, and led to a tighter specification.

Reference: A. Romanenko results

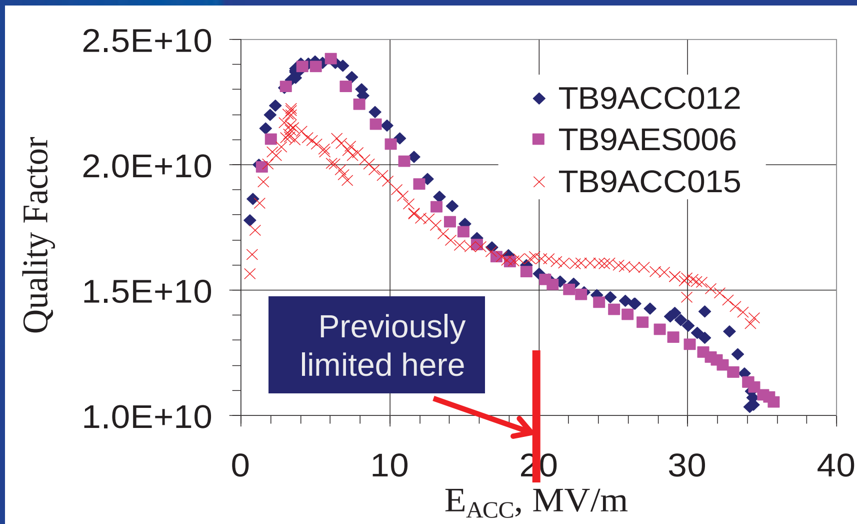
Centrifugal Barrel Polish

C. Cooper Recipe Media

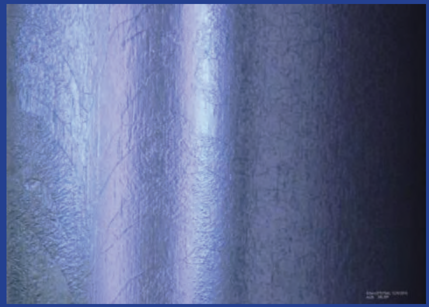


- Breakthrough in the process @ FNAL
- Drastic reductions in acid use.
- Mirror-like inner surface
- Demonstrated cavity gradients > 35 MV/M
- FNAL CBP design has been adopted by several other SRF institutions

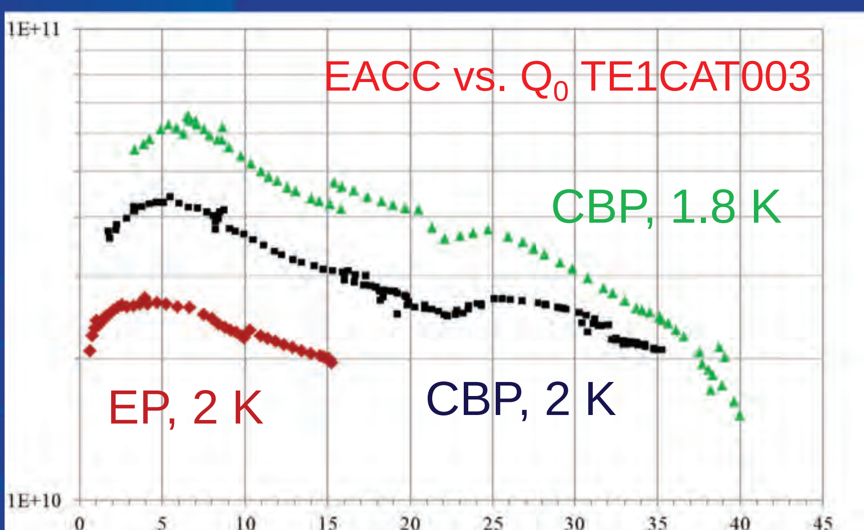
Cavity Results – CBP Repairs

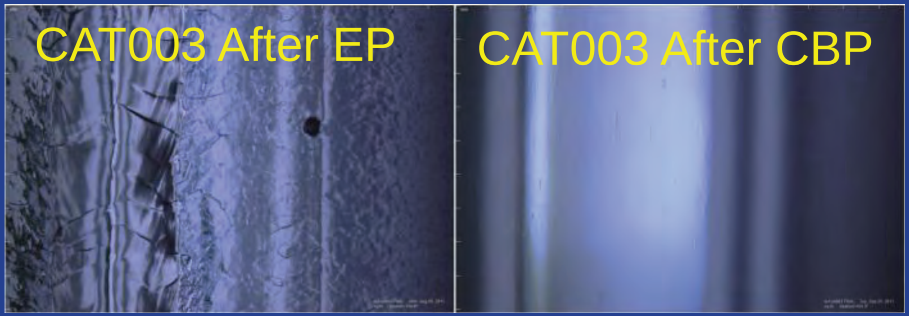


ACC015 Before CBP



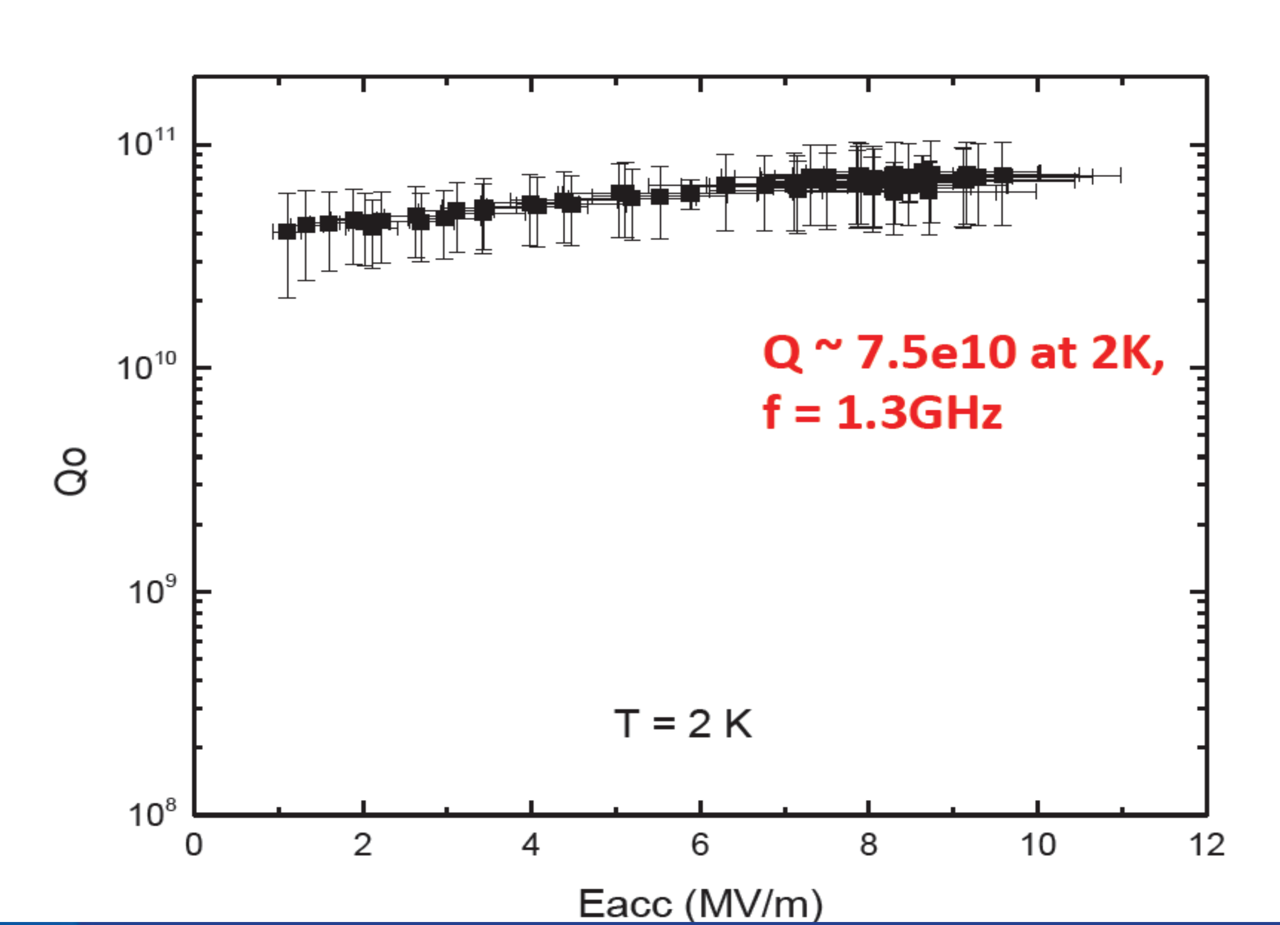
After CBP and 40 microns EP – Pit completely removed





- 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. Nb-Cu)

SRF R&D @FNAL
World record cavity Q0's with NbN



- Early result, but a potential game changer for SRF CW applications! (cavity quench limited by defect)

Summary

- Project X is a powerful and flexible new proton source proposed for construction at Fermilab

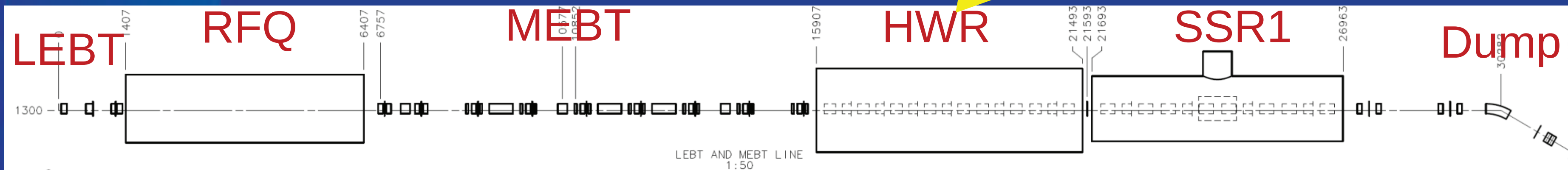
- Fermilab is has mounted a large R&D effort to develop the cavities, cryomodules, SRF infrastructure and trained technical staff required to build this machine
- The FNAL SRF program
  - Supports both Project X, ILC, and other Office of Science goals
  - Leverages existing FNAL infrastructure (bldgs., cryo, etc)
  - Lots of infrastructure has been built and is now in operation
  - Focused effort to transfer SRF technology to U.S. Industry
  - Focused effort to understand the science of SRF surfaces with the goal of improving SRF cavity performance (gradient, Q0, reduced costs)

- Making steady progress towards our goals

extras

PXIE Program

SRF



LBNL, FNAL   FNAL, SLAC   ANL   FNAL

32 m, 30 MeV

PXIE goal = demonstrate:

- Ion source lifetime
- LEBT pre-chopping
- Vacuum management in the LEBT/RFQ region
- Validation of chopper performance
- Kicker extinction
- Effectiveness of MEBT beam absorber
- MEBT vacuum management
- Operation of HWR in close proximity to 10 kW absorber
- Operation of SSR with beam
- Emittance preservation and beam halo formation through the front end

New NML Buildings Complete (ARRA funded)

New Electronics building above tunnel extension

New Cryomodule Test Facility

New 500 W @ 2 K refrigerator

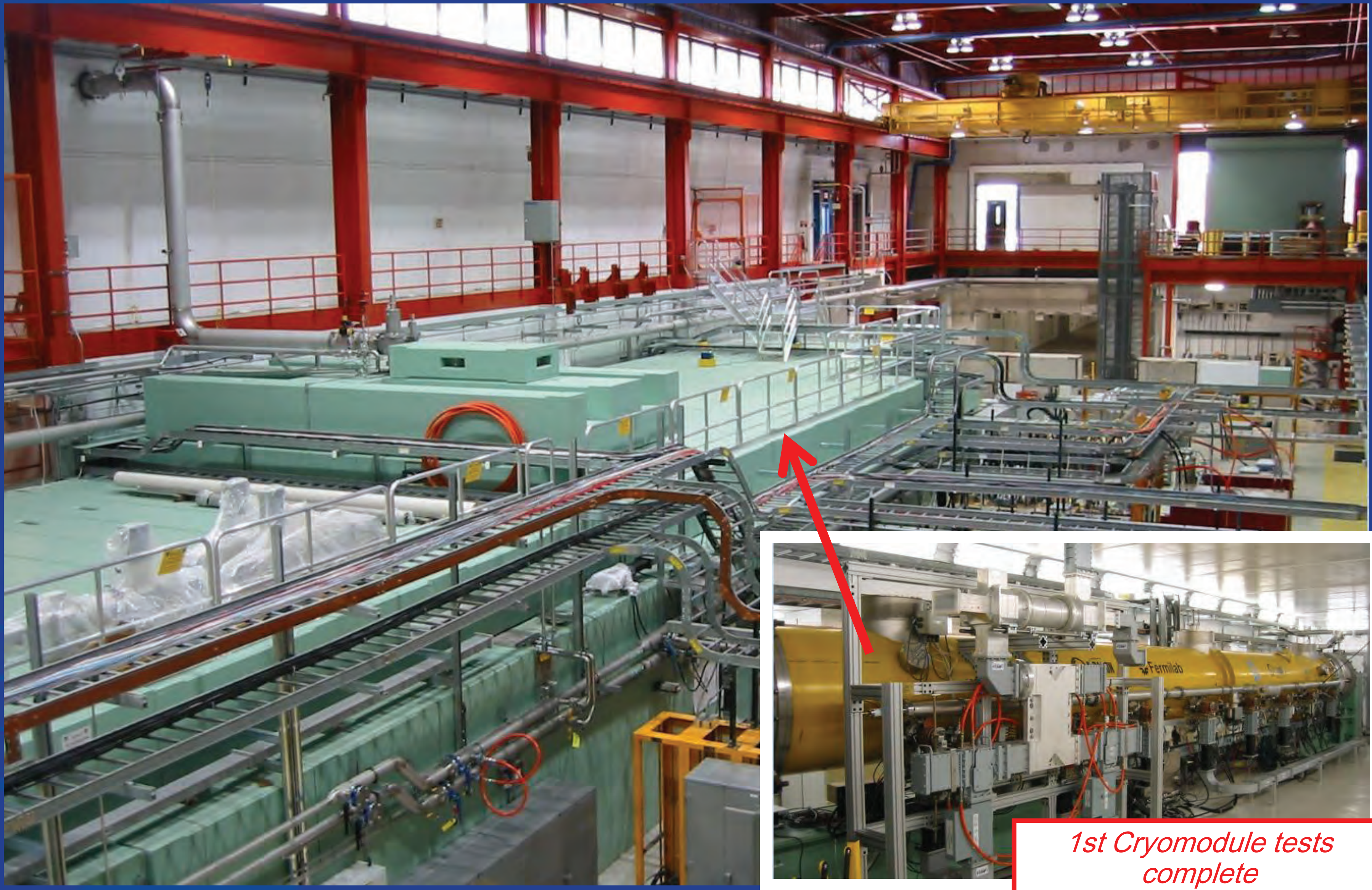
(under fabrication in industry)

will be located in CMTF bldg

Compressor building

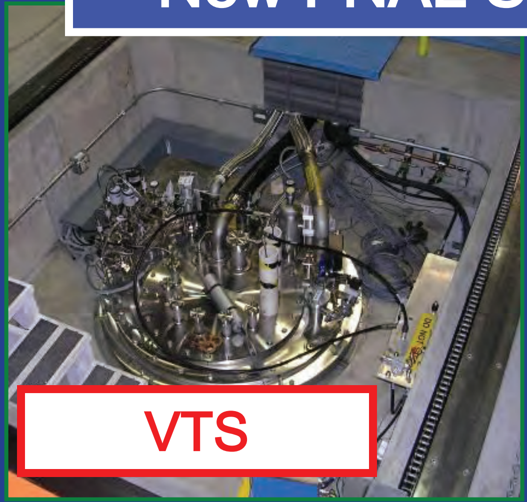
PXIE

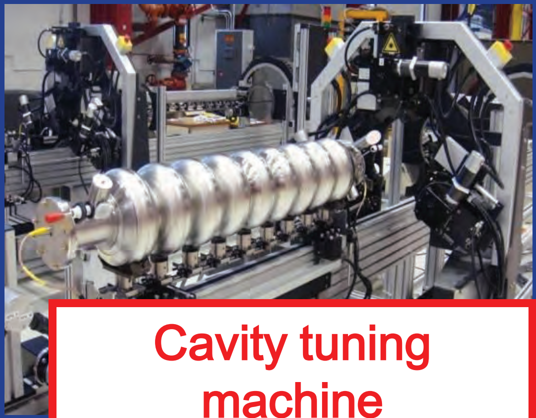
NML: RF Unit Test Facility

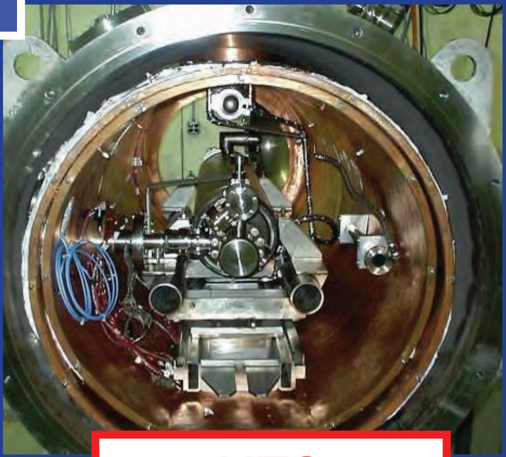


New FNAL SRF infrastructure


VTS


VTS


Cavity tuning machine


HTS


String Assembly


MP9 Clean Room


Final Assembly


VTS2 Dewar


New Vacuum Oven