# PIP-II Fermilab R&D Program

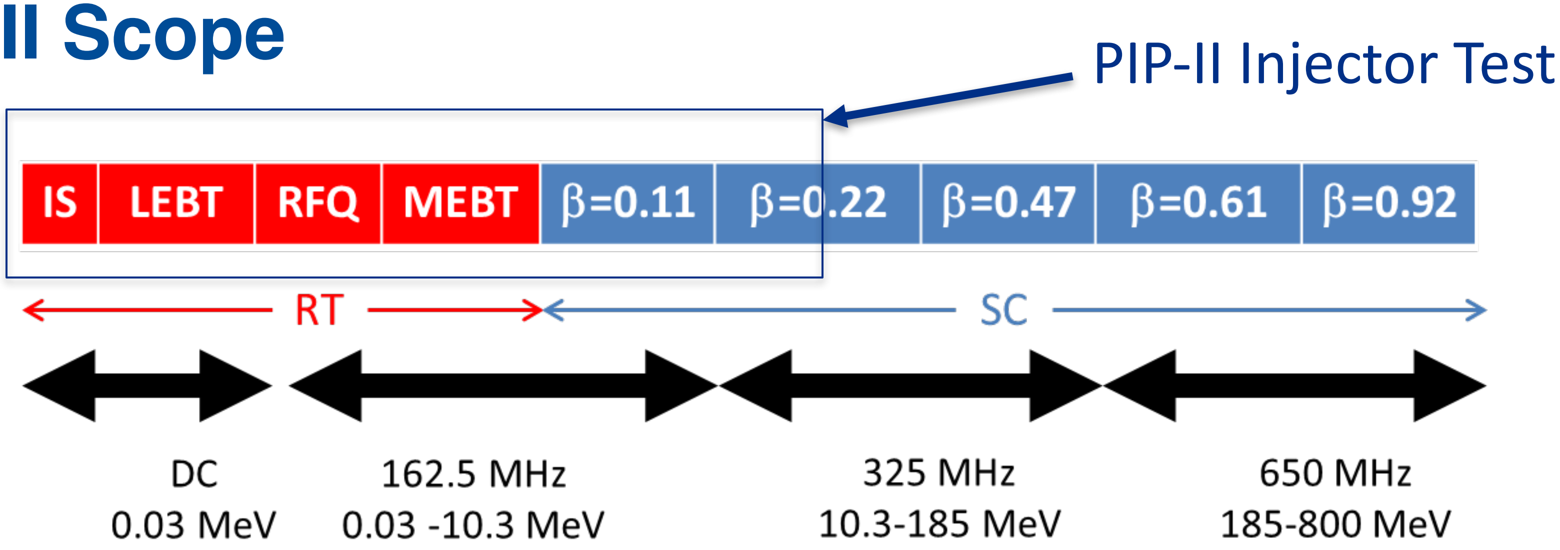
Paul Derwent
IIFC Joint R&D Meeting
4 January 2017

# The PIP-II R&D Program

- The purpose of the R&D program is to mitigate technical and cost risks, by validating the choices made in the PIP-II facility design and by establishing fabrication methods for major sub-systems and components, including the qualification of suppliers
  - Technical risk: impair the ability to meet fundamental performance goals
  - Cost/Schedule risk: compromise the ability to meet currently understood cost or schedule goals

  - To complete in advance of Department of Energy Approval for project construction

# PIP-II Scope



| Section | Freq | Energy (MeV) | Cav/mag/CM | Type |
|---|---|---|---|---|
| RFQ | 162.5 | 0.03-2.1 | | |
| HWR ($\beta_{opt}$=0.11) | 162.5 | 2.1-10.3 | 8/8/1 | HWR, solenoid |
| SSR1 ($\beta_{opt}$=0.22) | 325 | 10.3-35 | 16/8/ 2 | SSR, solenoid |
| SSR2 ($\beta_{opt}$=0.47) | 325 | 35-185 | 35/21/7 | SSR, solenoid |
| LB 650 ($\beta_{opt}$=0.65) | 650 | 185-500 | 33/22/11 | 5-cell elliptical, doublet* |
| HB 650 ($\beta_{opt}$=0.97) | 650 | 500-800 | 24/8/4 | 5-cell elliptical, doublet* |

*Warm doublets external to cryomodules

***All components CW-capable***

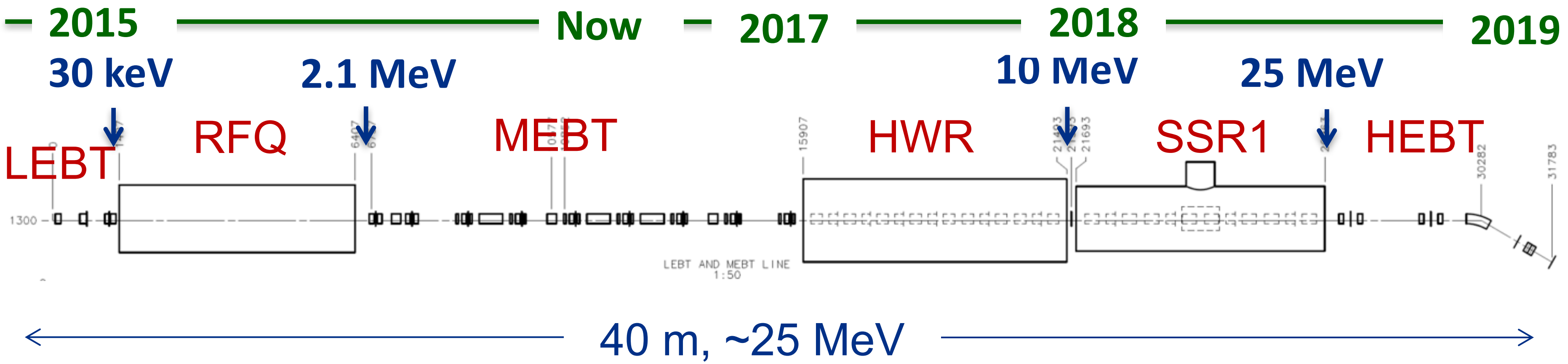
# PIP-II Injector Test: PIP2IT

- Mission Statement:

The PIP-II Injector Test (PIP2IT) facility replicates the front end of the PIP-II linac through the first SSR1 cryomodule. PIP2IT is intended to serve as a complete systems test that will reduce technical risks associated with the PIP-II linac in both pulsed and CW operating modes. It is anticipated that PIP2IT will be operated for several years beyond the initiation of PIP-II construction, with the eventual relocation of major PIP2IT components and systems into the PIP-II linac enclosure, where they will serve as part of the PIP-II front end. The construction and operating period of PIP2IT splits naturally into two phases.

- Phase 1 (R&D plan):
  - retirement of risks associated with operation of the PIP-II linac in pulsed mode as required for neutrino operations and described in the CDR (1% duty factor).
- Phase 2 (post-CD-3):
  - retirement of risks associated with CW operations, in particular as related to utilization of the PIP-II linac for a second generation Mu2e experiment
  - important for future scientific opportunities with PIP-II linac

# PIP2IT: Phase 1 Deliverables


2015 — Now — 2017 — 2018 — 2019

30 keV, 2.1 MeV, 10 MeV, 25 MeV

LEBT, RFQ, MEBT, HWR, SSR1, HEBT

40 m, ~25 MeV

Phase 1 (R&D plan): retirement of risks associated with operation of the PIP-II linac in pulsed mode as required for neutrino operations and described in the CDR (1% duty factor). The primary risks to be retired during this period include:

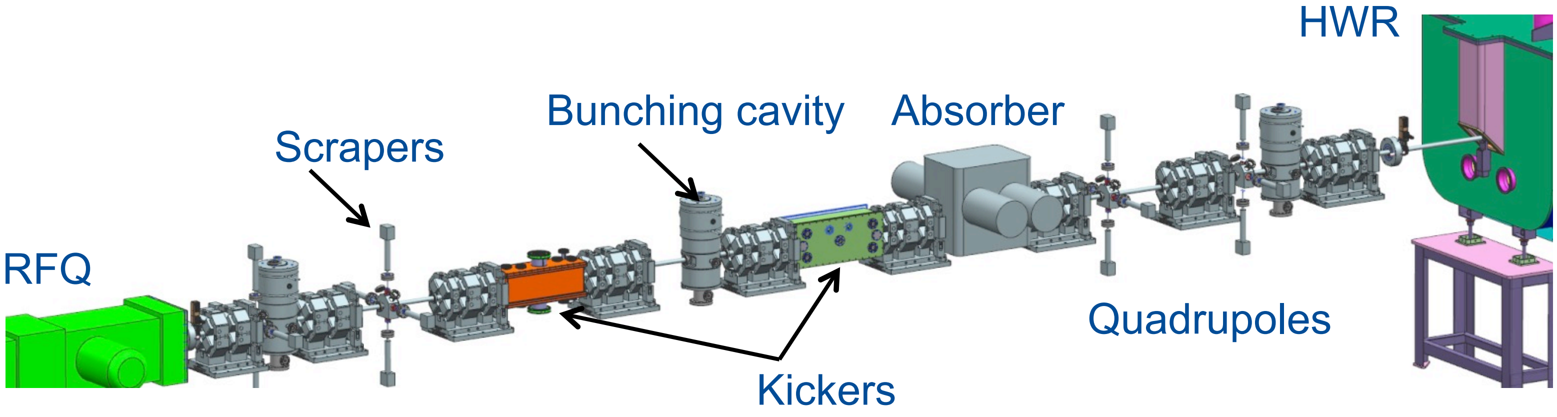
- Achievement of required beam characteristics from the ion source through the SSR1 cryomodule.
- Demonstration of MEBT chopper operations at a level required for Booster injection
- Demonstration of the operation of the HWR cryomodule, with beam, in close proximity to the MEBT beam absorber
- Demonstration of stable beam acceleration in the SSR1 cryomodule, under the full control of prototype RF control systems, including resonance control within the cavities

Collaborators

ANL: HWR
LBNL:LEBT, RFQ
SNS: LEBT
BARC: MEBT, RF
IUAC: SSR1

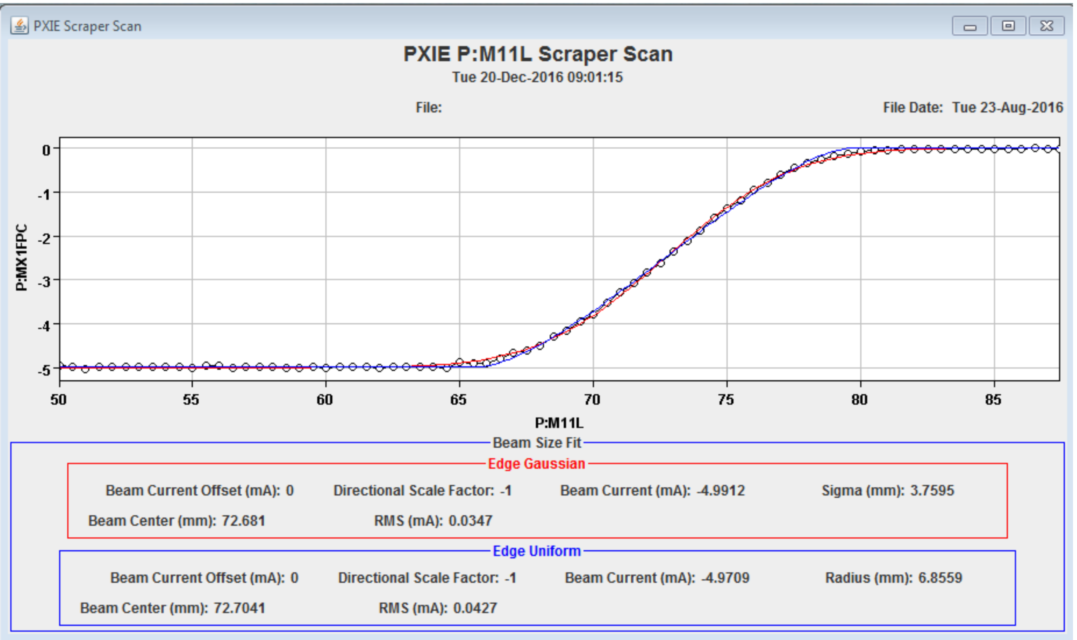
# PIP2IT: MEBT

- The MEBT primary technical deliverables:
  - Beam Chopping
    - Forms the bunch structure required Booster injection
    - Testing Prototype kickers in FY17
    - Testing Prototype absorber in FY17
  - Vacuum Management
    - absorber upstream of SRF Cryomodule
  - Progress Dependent on delivery of BARC quadrupoles
    - Ready for Installation ~4 weeks after delivery



# Beam size measurements

- The beam transverse size is measured by scrapers
  - Full scans with 10-*μ*s bunch trains; ~2σ tails for high-power beam
- Quadrupole scans to reconstruct Twiss functions and emittance



**PXIE P:M11L Scraper Scan**
Tue 20-Dec-2016 09:01:15

File:

File Date: Tue 23-Aug-2016

Beam Size Fit

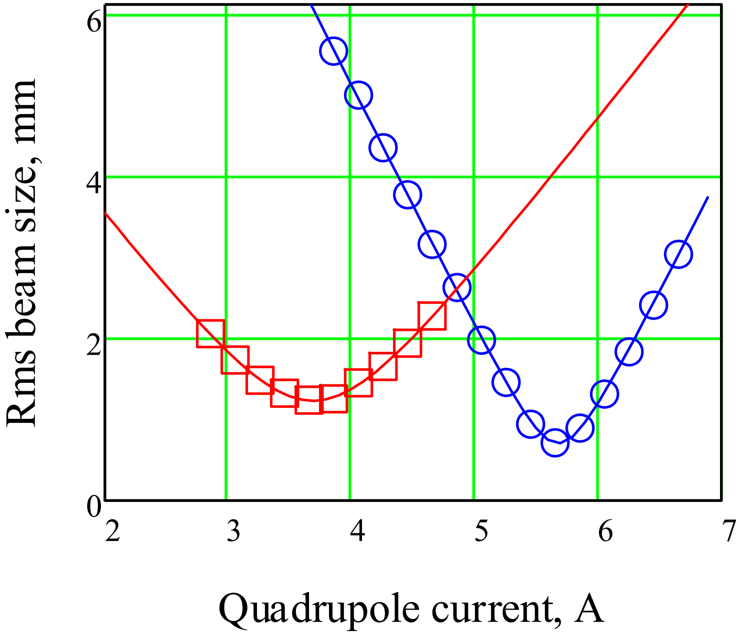
Edge Gaussian

Beam Current Offset (mA): 0
Directional Scale Factor: -1
Beam Current (mA): -4.9912
Sigma (mm): 3.7595
Beam Center (mm): 72.681
RMS (mA): 0.0347

Edge Uniform

Beam Current Offset (mA): 0
Directional Scale Factor: -1
Beam Current (mA): -4.9709
Radius (mm): 6.8559
Beam Center (mm): 72.7041
RMS (mA): 0.0427

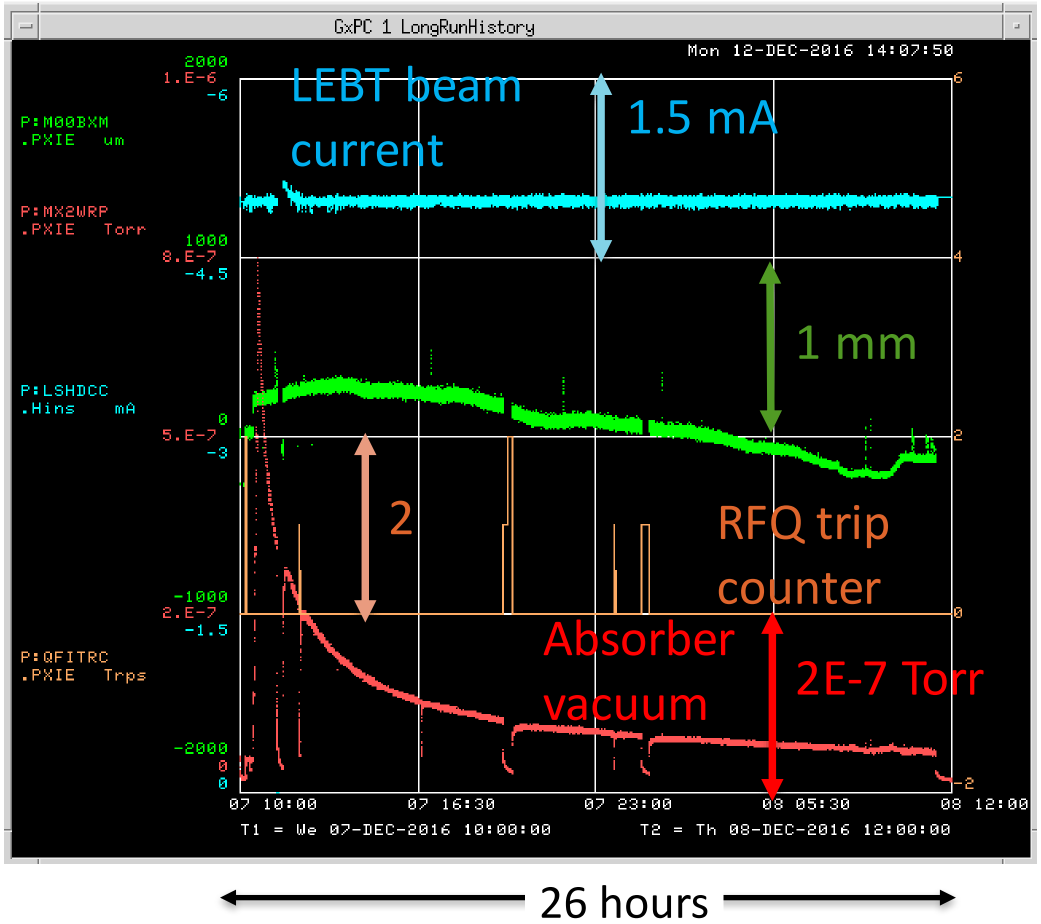
Example of full scraper scan: dump current vs left scraper position. In the quad scans, the rms sizes reconstructed from Gaussian fits were used. Quad M10QF current =4.46A.



Quadrupole scan and fitting (solid curves). Measured rms sizes are shown by circles (X) and squares (Y). Fitted emittances (rms, n) are 0.19 μm X and 0.20 μm Y.

# Long runs

- Several runs at constant beam parameters
  - 9- 24 hours, 2.5 – 0.5 kW of average beam power
    - Ran by operators
  - Beam is reasonably stable
  - Need to improve beam position stability and trip recovery procedures

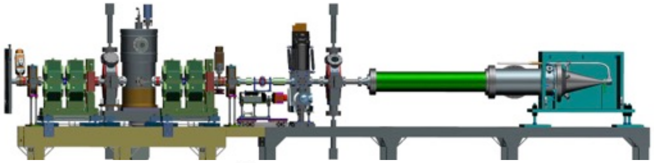


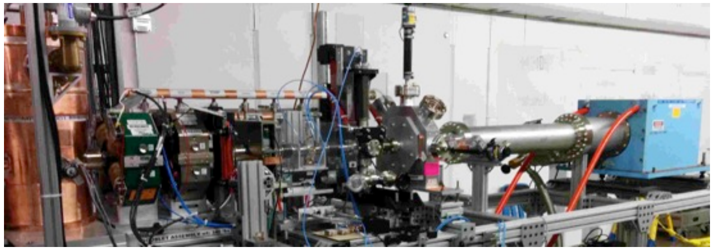
Example of 24-hours of beam running to the absorber prototype. 10 Hz, 4.5 ms 5 mA beam pulse. RFQ in pulsed mode, 10 Hz, 4.8 ms. Dec 7-8, 2016. Beam was up for 97% of time.

# MEBT stages

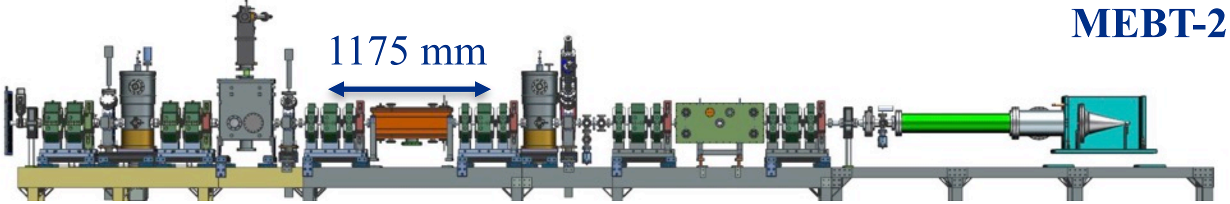
- MEBT is being installed in ~~3~~ 2 main stages, different in the number of focusing elements
  - Full-length MEBT is expected to be installed in 2017

**MEBT-1**



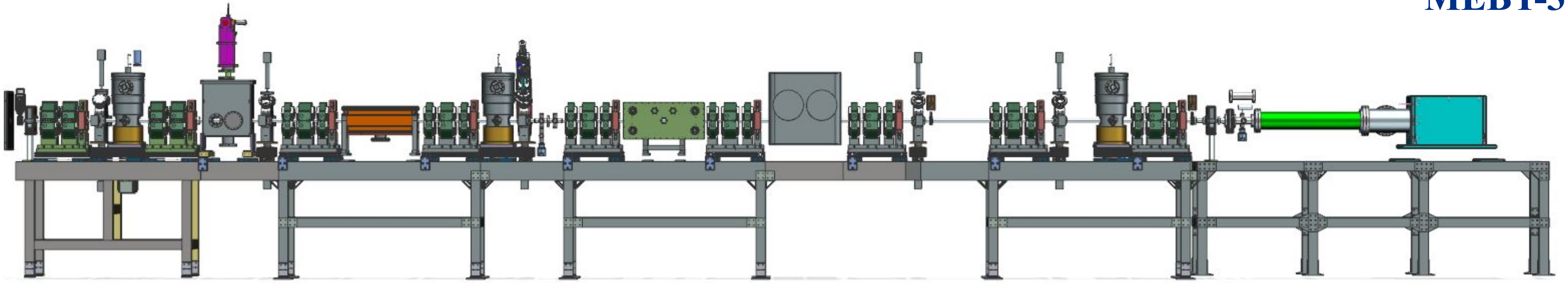


**MEBT-2**



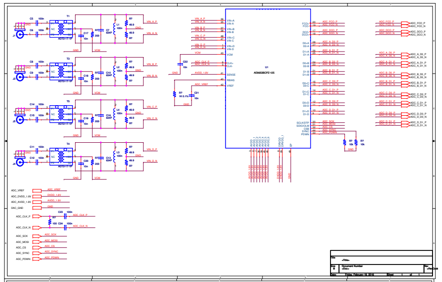
Skip MEBT-2: time constraints due to magnet delivery

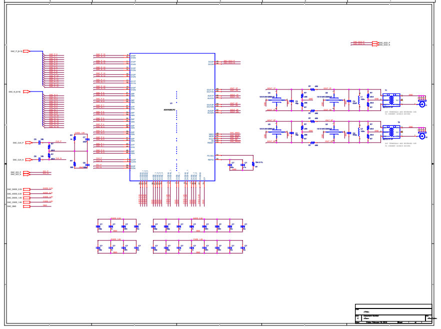
**MEBT-3**

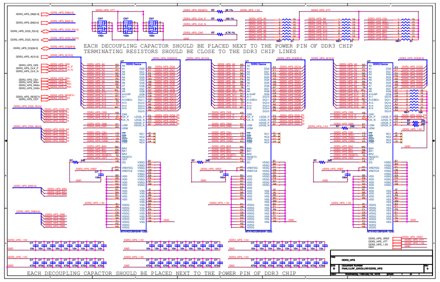


# IIFC LLRF Status

- Seven joints FRSs Approved (two more near approval)
  - TRSs in process
- 8-Channel Down-Converters
  - BARC version is in manufacturing process
- 4-Channel Up-Converters
  - FNAL version tested
  - BARC version is in manufacturing process
- FPGA Board
  - In schematic review process
- ADC-DAC FMC Module
  - Ready for manufacturing
- Resonance Control Chassis
  - Leverage from FNAL LCLS-II design and is in progress
- Prototype RF Protection and Interlock System
  - Delivered & Tests on going
  - Software / Executable process an issue
    - Fermilab Engineering Manual requires source code documentation and maintenance under a suitable version control process







# SRF

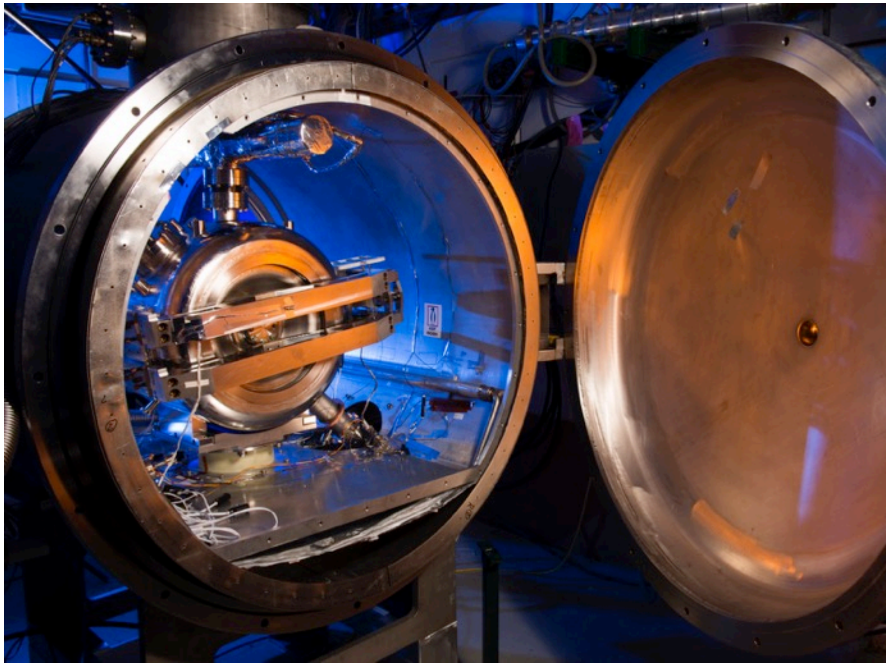
- PIP-II includes
  - 5 different SRF cavity types and cryomodules
    - Half Wave Resonator:
    - 2 Single Spoke Resonators
    - 2 elliptical cavities
  - 3 different frequencies (162.5 MHz, 325 MHz, 650 MHz)

- R&D program:
  - test one complete cryomodule of each frequency to full power
    - HWR & SSR1 @ PIP-II Injector Test with beam : FY19
    - HB650 in a test stand with RF power : FY20
  - test LB650 dressed cavities with RF power : FY19
  - test bare SSR2 cavities in vertical test stand : FY19
  - Resonance control of cavities in pulsed mode operation (Lorentz Force Detuning)
    - Combination of High $Q_{ext}$, pulsed operation
    - Passive means: Mechanical design
    - Developing a piezo-based feed forward and feedback system
  - Application of High $Q_0$ R&D to PIP-II 650 MHz cavities

# SSR1

- Single Spoke Resonator Cryomodule:
  - 8 325 MHz β=0.22 Single Spoke cavities
  - 4 SC focusing solenoids (& BPM)
  - 11 MeV -> 25 MeV

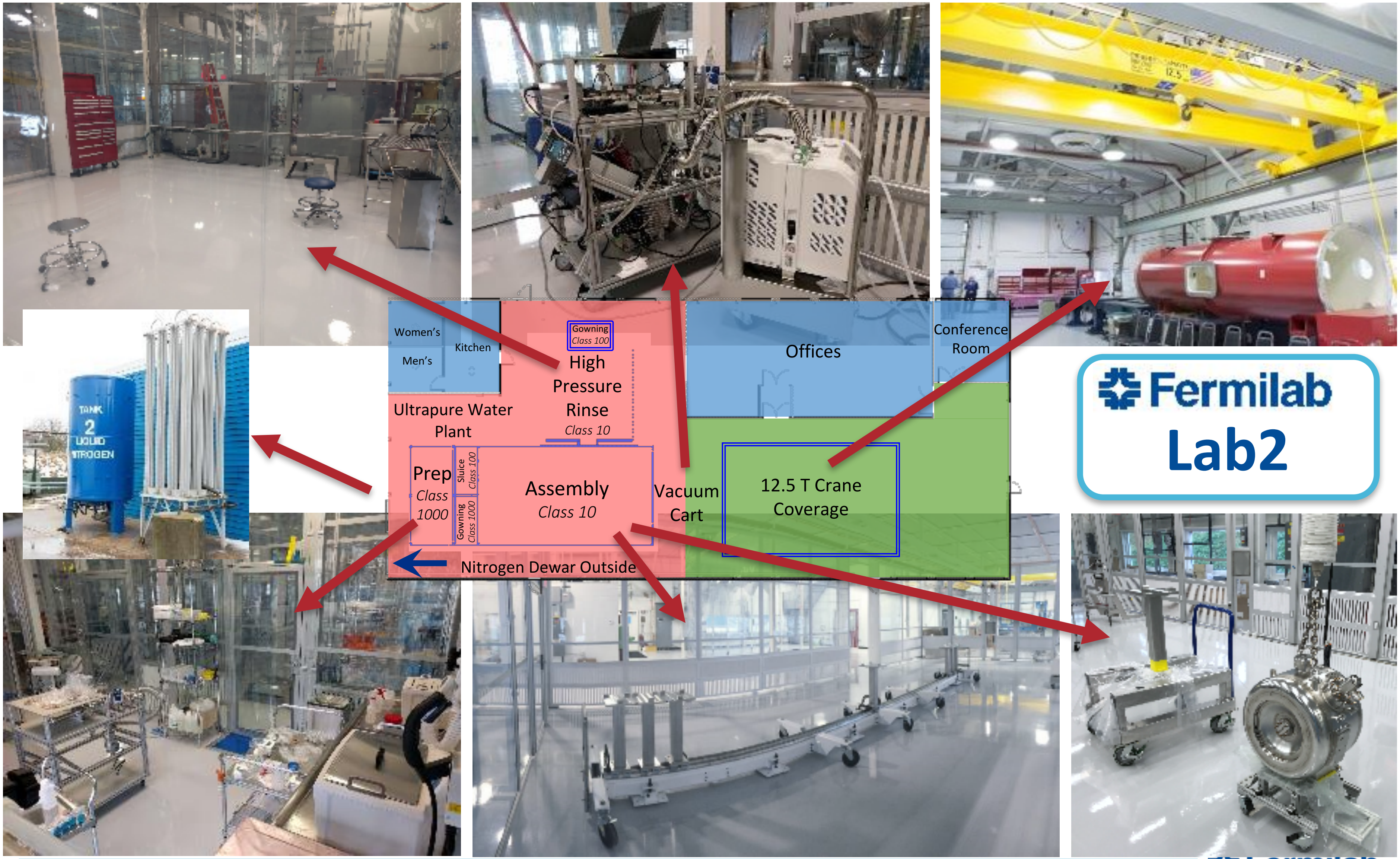
- India Institutes Fermilab Collaboration (IIFC)
    - 12 cavities fabricated (10 FNAL, 2 IUAC New Delhi)
  - Fabrication/Assembly 2017



dressed SSR1 cavity in test cryostat

L. Ristori

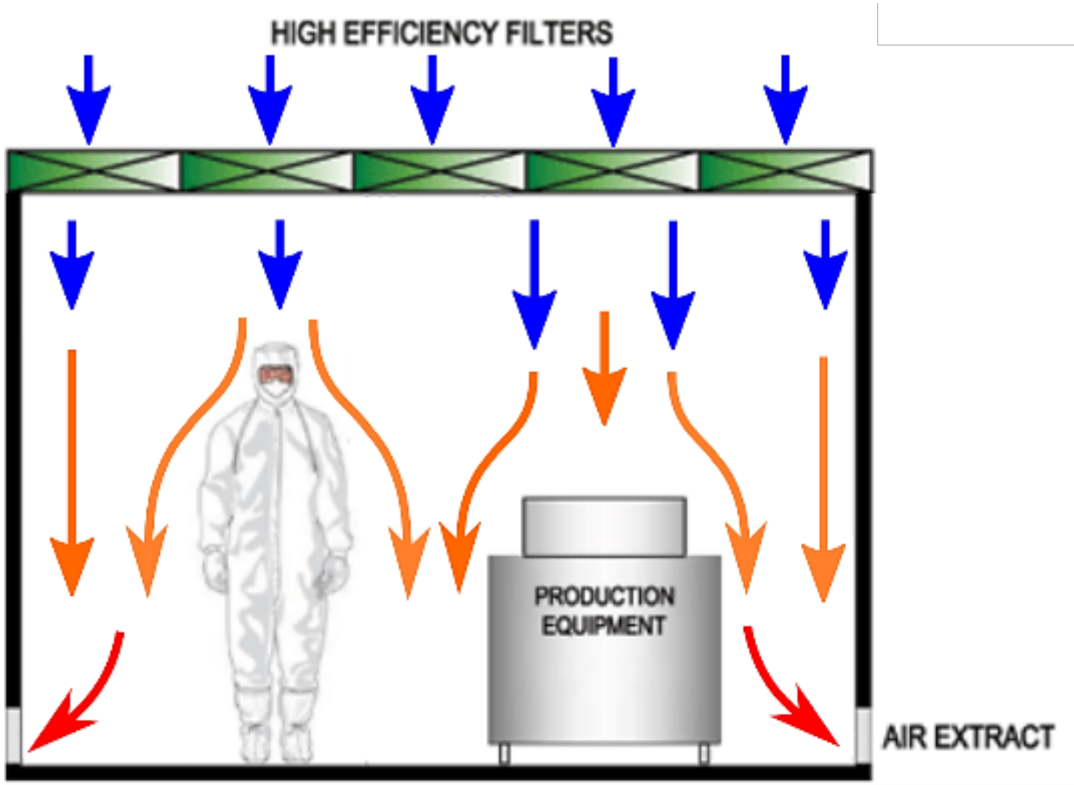
# Lab 2 SRF Cavity & Cryomodule Cleanroom Facility



L. Ristori

# Introduction to Lab2: design and current status

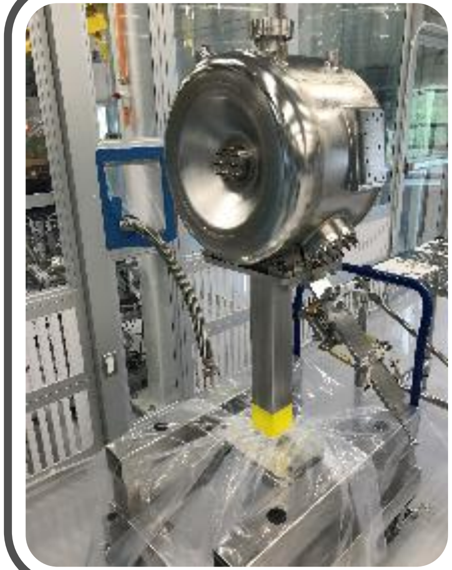
- ☐ **The cleanroom at Lab 2 is ready to receive the SSR1 string assembly**
  - ✓ Single pass design was adopted for Lab2 clean room, air is filtered into the clean room and transferred out into the surrounding building
  - ✓ Cleanroom construction completed and qualified
  - ✓ Ultra Pure Water system and ultrasonic cleaners are fully functional
  - ✓ Crane for US area is finalized
  - ✓ Nitrogen gas lines are installed:
    - 900 gal liquid nitrogen dewar installed
    - Line installation completed



L. Ristori

# Particle free cleanroom assembly for SRF applications

## Example: SSR1 Coupler installation procedure



1.

Cavity is placed on a post inside Lab2 class 10 cleanroom and tooling is installed underneath

Tooling Is previously cleaned using the standard procedure and then assembled in the cleanroom

2.

Connection to vacuum cart is performed and leak checked, RAV is close

Hardware is cleaned using the standard procedure

3.

Cold end tube weldment is cleaned:

- Ultrasonic cleaning for 10 minutes at 25% of the power used for SS in a bath of DI water and simple green.
- Ultrasonic cleaning for 10 minutes at 25% of the power used for SS in a bath of DI water and liquinox

Antenna assy is cleaned :

- Gently wipe with lint free wipes and isopropyl alcohol.

L. Ristori

# Particle free cleanroom assembly for SRF applications

## Example: SSR1 Coupler installation procedure

3.

Vacuum end coupler is assembled and them blow clean with ionized nitrogen and using a particle counter

4.

Cavity is backfilled with ionized nitrogen and the pressure is slightly above atm.

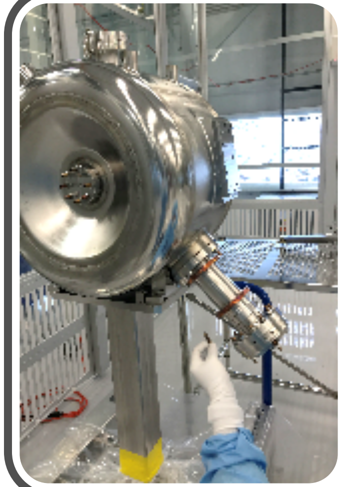
Vacuum end coupler is placed on the tooling

A Teflon cap, held by metal clips, protect the tube from contamination

5.

2 long studs are placed in the cavity flange and used to adjust the tooling and put the vacuum end coupler in the correct position

Once the coupler is aligned all the set screw but the longer ones are removed



6.

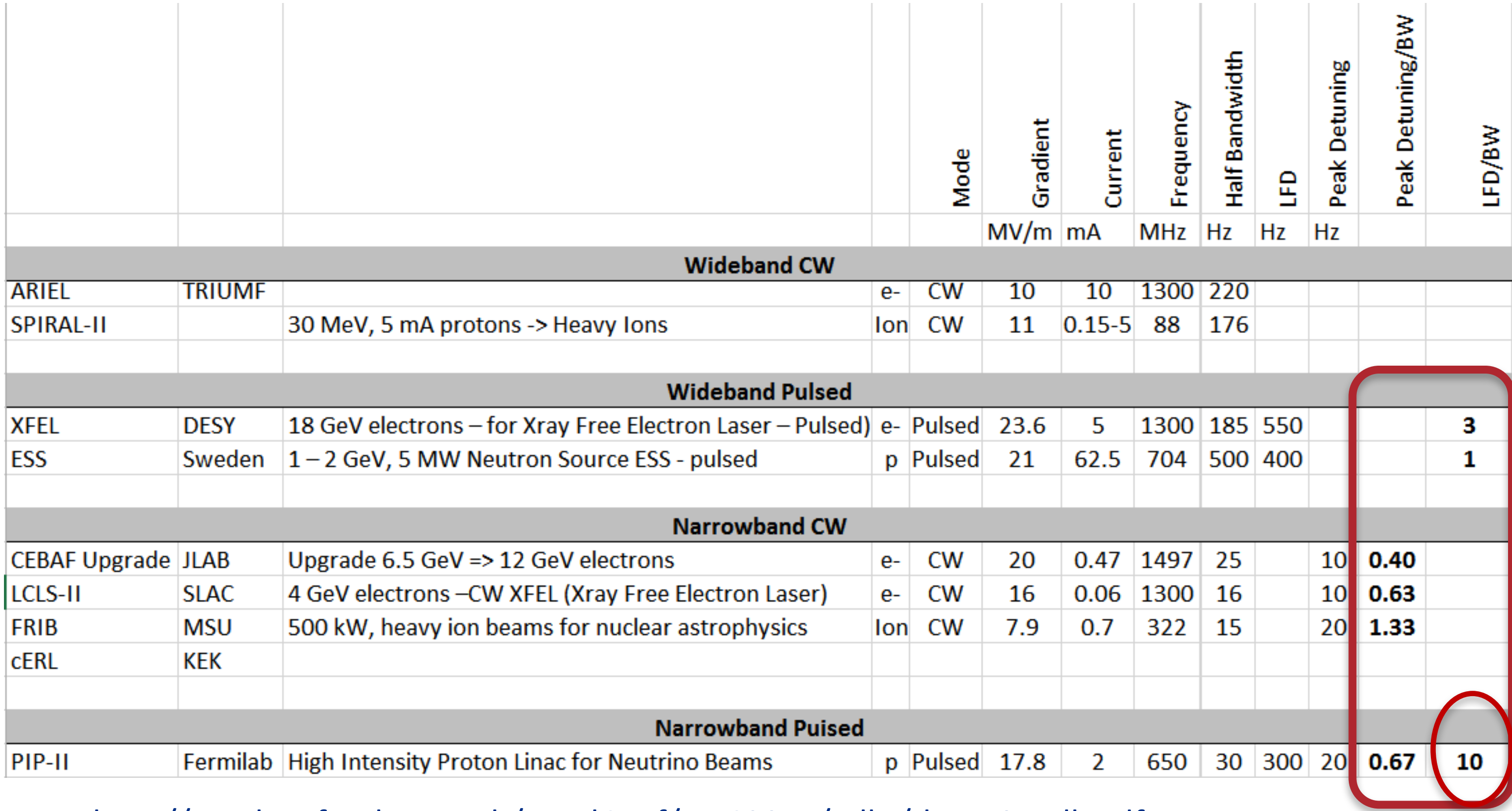
Cavity blank is removed and vacuum end coupler is approached to the cavity flange

Once the coupler is secured the tooling is removed and the torqueing process begin using the standard procedure but with a maximum torque of 250 in lbs

# PIP-II : Resonance Control

W. Schappert

- As cavity gradients rise matched bandwidths narrow
- Minimizing detuning is critical for narrowband machines
- PIP-II presents a unique challenge because of the combination of narrow bandwidths and pulsed operation



| | | | | Mode | Gradient | Current | Frequency | Half Bandwidth | LFD | Peak Detuning | Peak Detuning/BW | LFD/BW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | MV/m | mA | MHz | Hz | Hz | Hz | | |
| **Wideband CW** | | | | | | | | | | | | |
| ARIEL | TRIUMF | | e- | CW | 10 | 10 | 1300 | 220 | | | | |
| SPIRAL-II | | 30 MeV, 5 mA protons -> Heavy Ions | Ion | CW | 11 | 0.15-5 | 88 | 176 | | | | |
| | | | | | | | | | | | | |
| **Wideband Pulsed** | | | | | | | | | | | | |
| XFEL | DESY | 18 GeV electrons – for Xray Free Electron Laser – Pulsed) | e- | Pulsed | 23.6 | 5 | 1300 | 185 | 550 | | | **3** |
| ESS | Sweden | 1 – 2 GeV, 5 MW Neutron Source ESS - pulsed | p | Pulsed | 21 | 62.5 | 704 | 500 | 400 | | | **1** |
| | | | | | | | | | | | | |
| **Narrowband CW** | | | | | | | | | | | | |
| CEBAF Upgrade | JLAB | Upgrade 6.5 GeV => 12 GeV electrons | e- | CW | 20 | 0.47 | 1497 | 25 | | 10 | **0.40** | |
| LCLS-II | SLAC | 4 GeV electrons –CW XFEL (Xray Free Electron Laser) | e- | CW | 16 | 0.06 | 1300 | 16 | | 10 | **0.63** | |
| FRIB | MSU | 500 kW, heavy ion beams for nuclear astrophysics | Ion | CW | 7.9 | 0.7 | 322 | 15 | | 20 | **1.33** | |
| cERL | KEK | | | | | | | | | | | |
| | | | | | | | | | | | | |
| **Narrowband Puised** | | | | | | | | | | | | |
| PIP-II | Fermilab | High Intensity Proton Linac for Neutrino Beams | p | Pulsed | 17.8 | 2 | 650 | 30 | 300 | 20 | **0.67** | **10** |

http://accelconf.web.cern.ch/AccelConf/IPAC2015/talks/thzms3_talk.pdf

# Recent Progress on Active Control

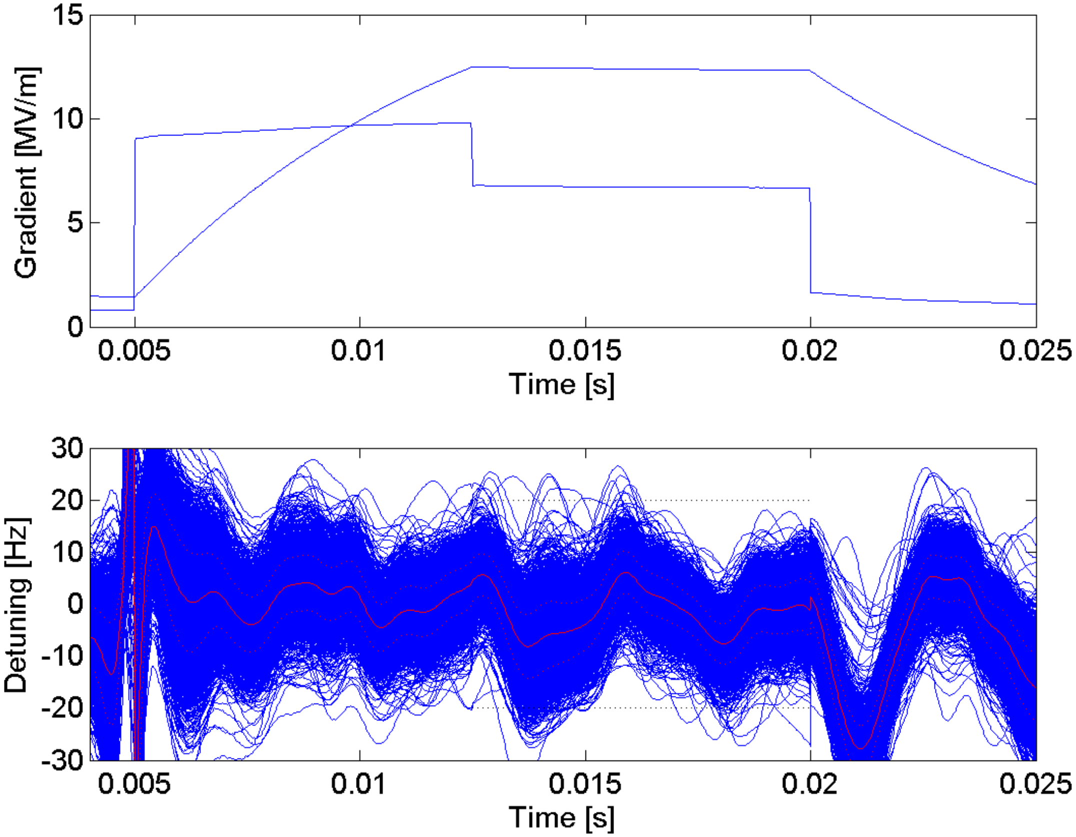
W. Schappert

- Resonance Control has had an extended set of test time at STC while waiting for the next SSR1 cavity to be ready for testing. We estimate 80 working days of testing time, an up time of 60%.
- This extended testing time allowed extensive studies of:
  - Signal qualities/RF circuit
  - Detuning calculation and implementation
  - Feedback/Compensation techniques
- Development of a complementary Self-Excited Loop testing system
- These techniques were developed, coded, and refined first for CW operation, then in pulsed operation.
- This work gives a solid foundation for further testing going forward including different cavity geometries.

# Test Conditions

W. Schappert

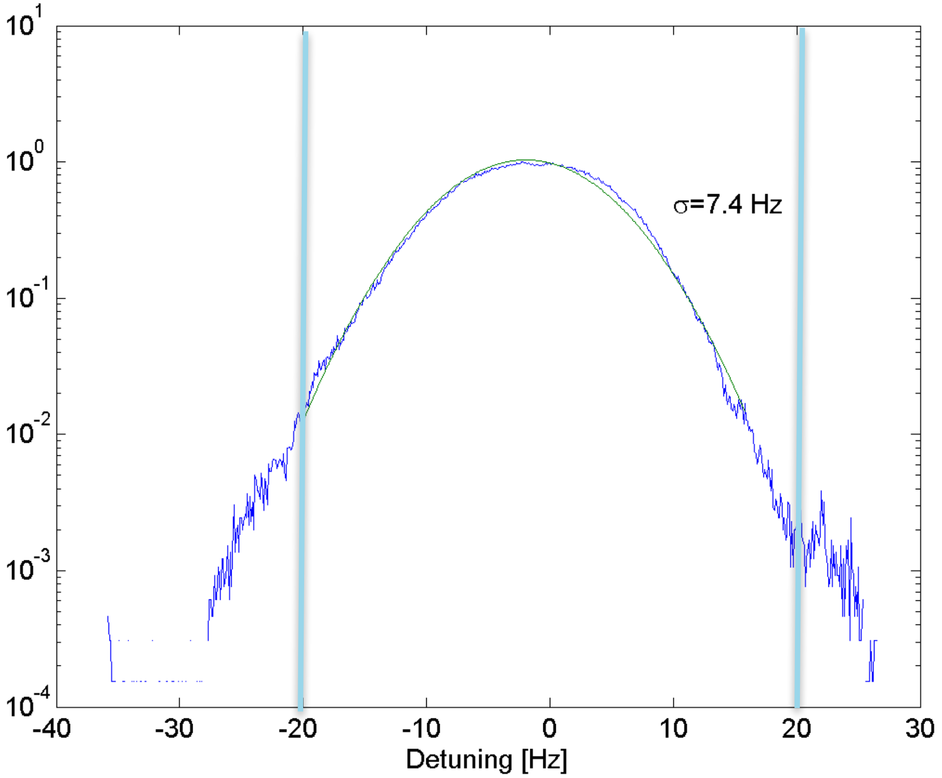
- PIP-II nominal operating conditions
  - 12.5 MV/m
  - 20 Hz repetition rate
  - 15% duty cycle
  - 0.5ms flattop
- STC operating condition
  - >12.5 MV/m
  - 25 Hz repetition rate
  - 7.5 ms fill
  - 7.5 ms flattop



# Preliminary Offline Analysis

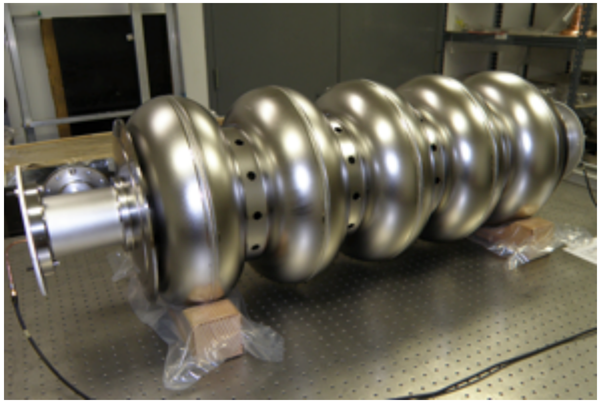
W. Schappert

- Within a factor of 2 of PIP-II specs
  - ~±2.7σ within 20 Hz
- Improvements in feedback may help
  - May be possible to automatically extract optimal coefficients from data



# SRF: HB650

- Elliptical Cavity Cryomodule:
  - 6 650 MHz β=0.97 5 Cell Elliptical cavities
  - Focusing elements are outside the CM

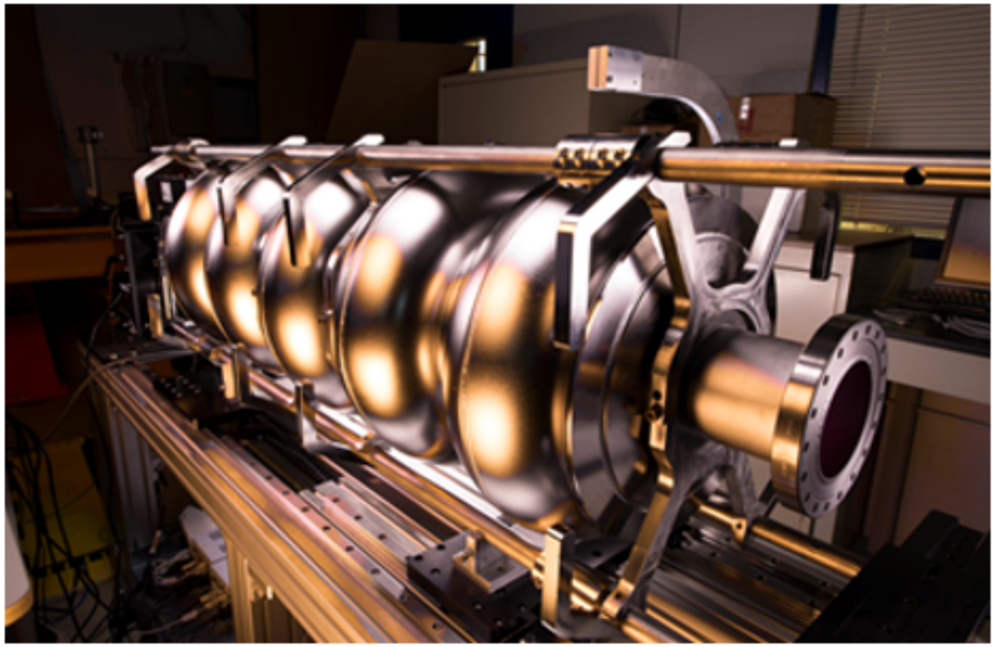


HB650 5 cell cavity

- India Institutes Fermilab Collaboration (IIFC)
  - Cavities of different β at various stages of manufacturing, processing, or testing
  - CM design complete in 2017
  - Test 6 (3 FNAL, 3 RRCAT) dressed cavities in HTS-2

V. Jain

# Current status and plans for 650 MHz $\beta = 0.9$ cavities at FNAL



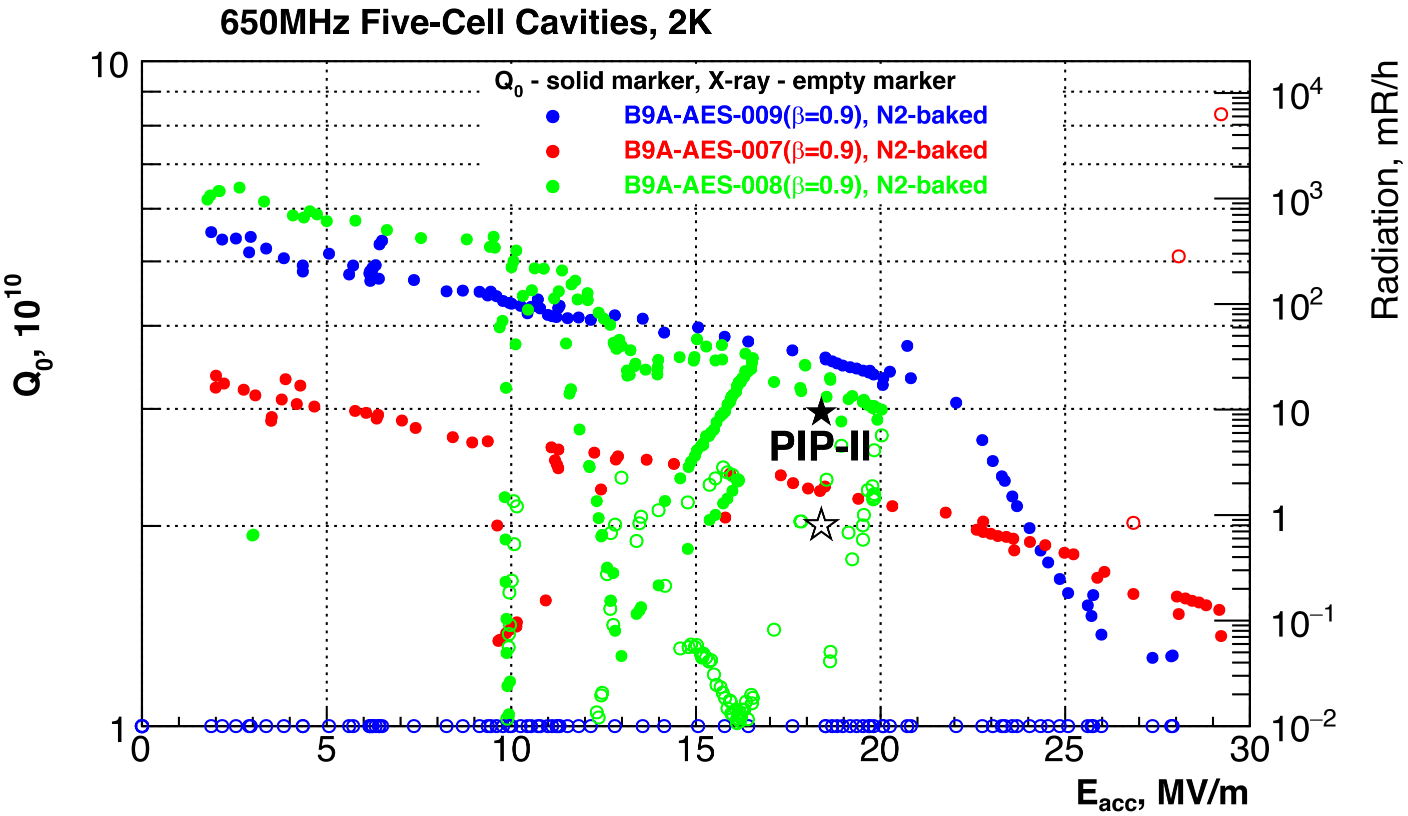
Optical Inspection of 5-cell B=0.9 650 MHz cavity

**Total 5 bare cavities of $\beta$=0.9 cavities are at TD ➔ Four AES + One PAVAC**

5-cell B=0.9 650 MHz cavity prepared for vertical testing.

V. Jain, A. Melnitchouk

# HB650 Cavity performance testing



Five-cell B=0.90 test results.

*A. M. Rowe, et al , CAVITY PROCESSING AND PREPARATION OF 650 MHz ELLIPTICAL CELL CAVITIES FOR PIP-II, LINAC 2016

V. Jain

# Status for Dressing β=0.9 bare cavities

- Cavity components
  - Bare cavity ➔ AES-009 qualified as per revised target, others to be processed/ reprocessed
  - Helium vessel assembly ➔Initiated procurement
  - Bellow ➔ Initiated procurement
  - Ti bellow adapter ring ➔ Procurement to be requested
  - Ti vessel transition ring ➔ Procurement to be requested
- Tooling and fixtures
  - Insertion tooling or medium bertha ➔ Assembled last week at MP9
  - Cavity rotating fixture ➔ Initiated procurement
  - Glovebox ➔ Modification design prepared, Procurement to be requested
- Weld sample preparation and qualification for each type of joint
  - Samples under preparation at Fermilab
- Leak testing setup preparation ➔ Leak testing cans designed, Procurement to be requested

# Schedule of cavity dressing at FNAL

V. Jain

Planning for cavity dressing

1st Cavity dressing

- Rotating fixture ➔ Jan 2017
- Bare cavity ➔ Feb 2017
- Leak testing cans ➔ Feb 2017
- Updating GB for dressing ➔ Feb 2017
- Helium vessel ➔ Mar 2017
- 1st Cavity dressing ➔ April 2017

Testing of dressed cavity in VTS ➔ May 2017

2nd Cavity dressing ➔ June 2017

Testing of dressed cavity in VTS ➔ Aug 2017

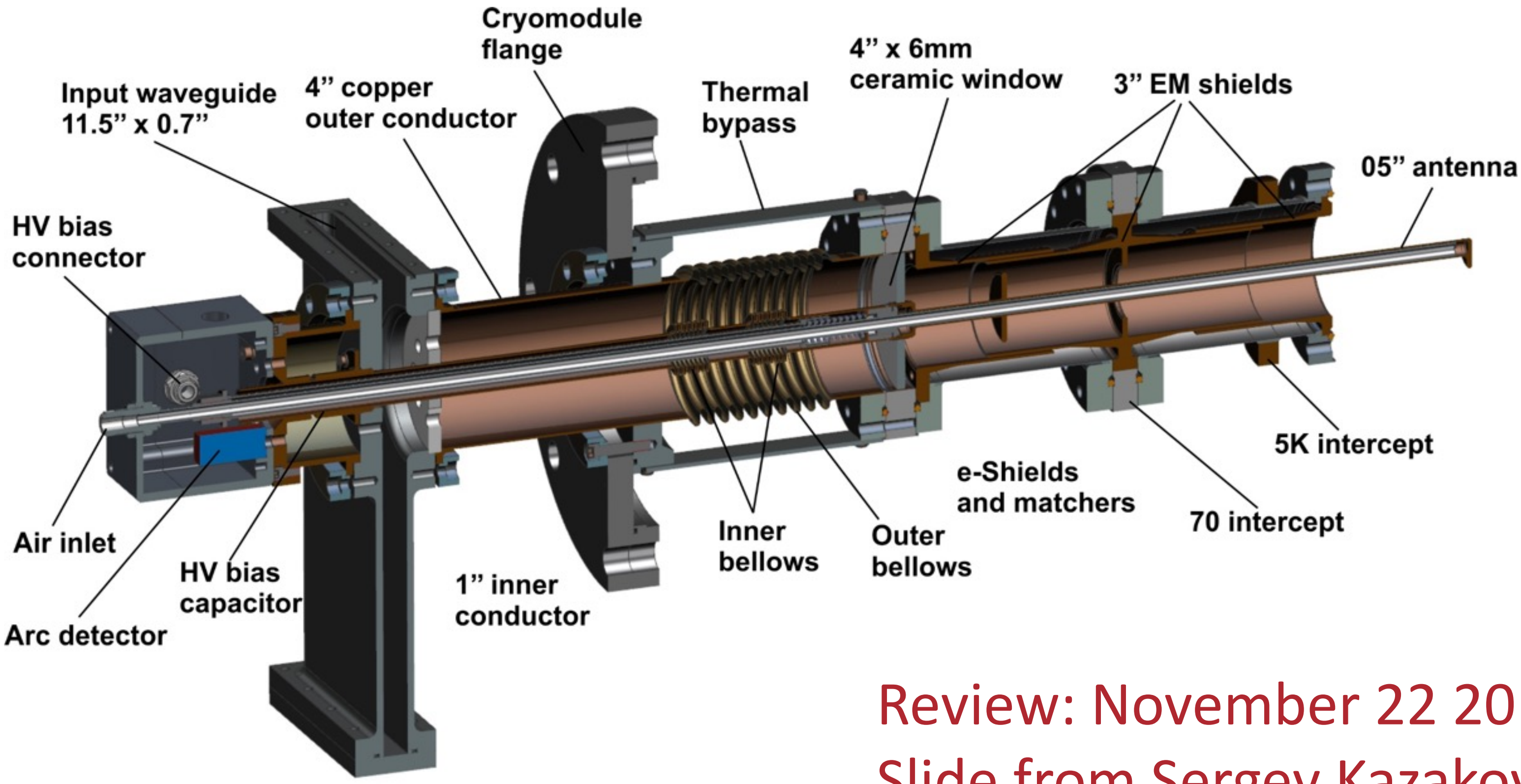
3rd Cavity dressing* ➔ Aug 2017

Testing of dressed cavity in VTS ➔ Sept 2017

* Depends on budget availability

# 650 MHz coupler:  Design Review November 2016

## New design, structure of 650 MHz coupler



Review: November 22 2016
Slide from Sergey Kazakov

# Charge

Charge:

1. Has code adherence and best engineering practices been implemented in this design?
2. Does the prototype coupler design satisfy the Functional Requirement Specification?
3. Have all required specifications and documentation been completed?
4. In carrying out the design for the prototype coupler, were the following important aspects considered: cryomodule integration, RF integration, assembly/alignment challenges, reliability and maintainability?
5. Which of the two design alternatives is most likely to succeed?
6. Is the Testing plan adequate to ensure that the design will be validated? Are there sufficient quantities of prototypes being ordered to validate the design?
7. Is the prototype coupler design ready for procurement? Which design is preferred?

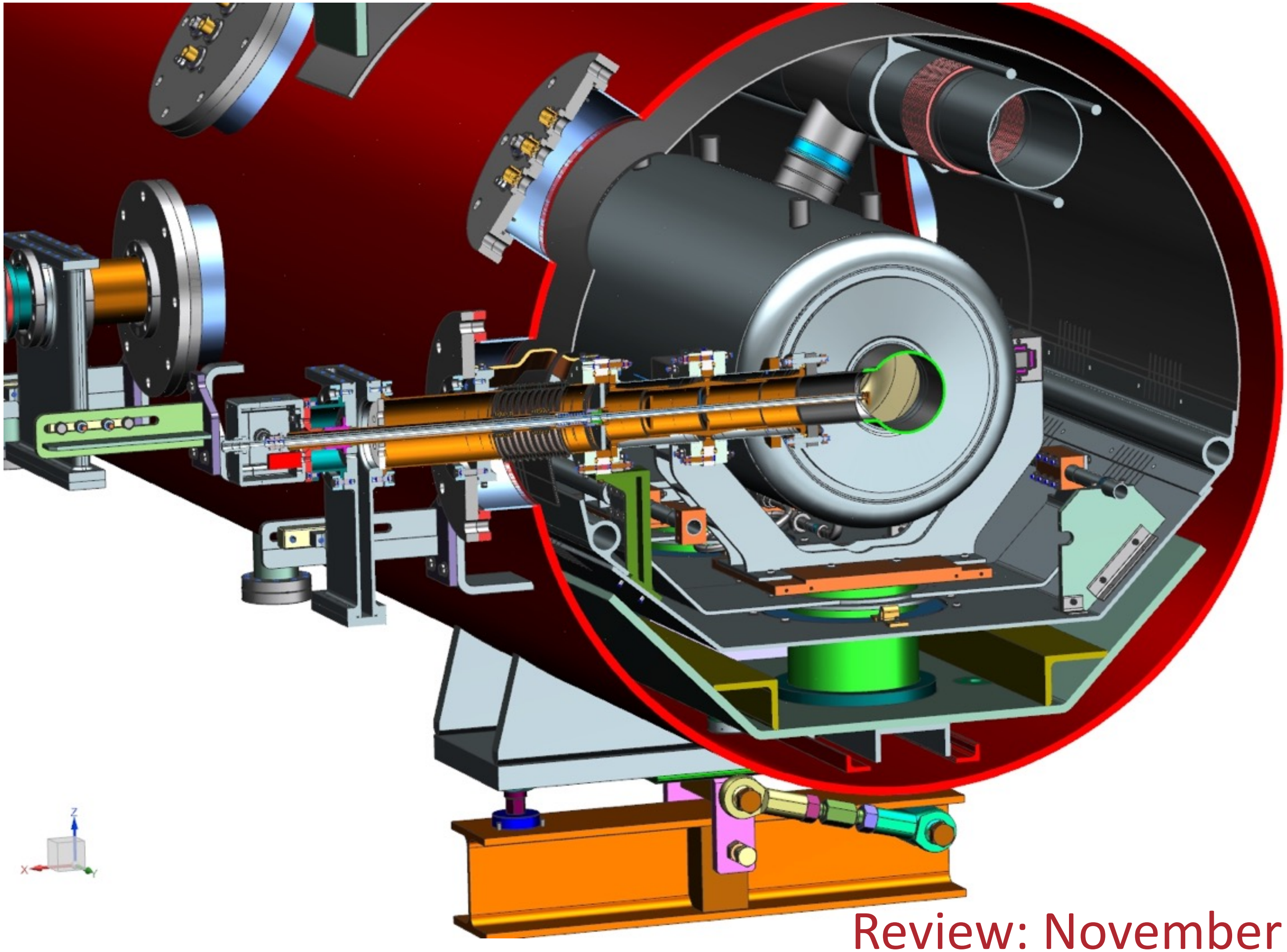
Review: November 22 2016
Slides from Oleg Pronitchev

# Motivation for re-design:

Motivation is based on experience with 325 MHz couplers. 325 coupler (one) was destroyed at power level ~ 50kW (full reflection). 650 MHz has to operate at higher power ~ 100 kW (PIP-II) and higher (for some application). We think the most weak and limiting factor can be high density of electrical current at place of metal and ceramic brazing at inner conductor. We decided to increase the dimeter of inner conductor 2 times (0.5'' ->1'') and increase of ceramic window outer diameter from 3'' to 4''.

Review: November 22 2016
Slide from Sergey Kazakov

# HB 650 MHz Main Coupler on the Cryomodule

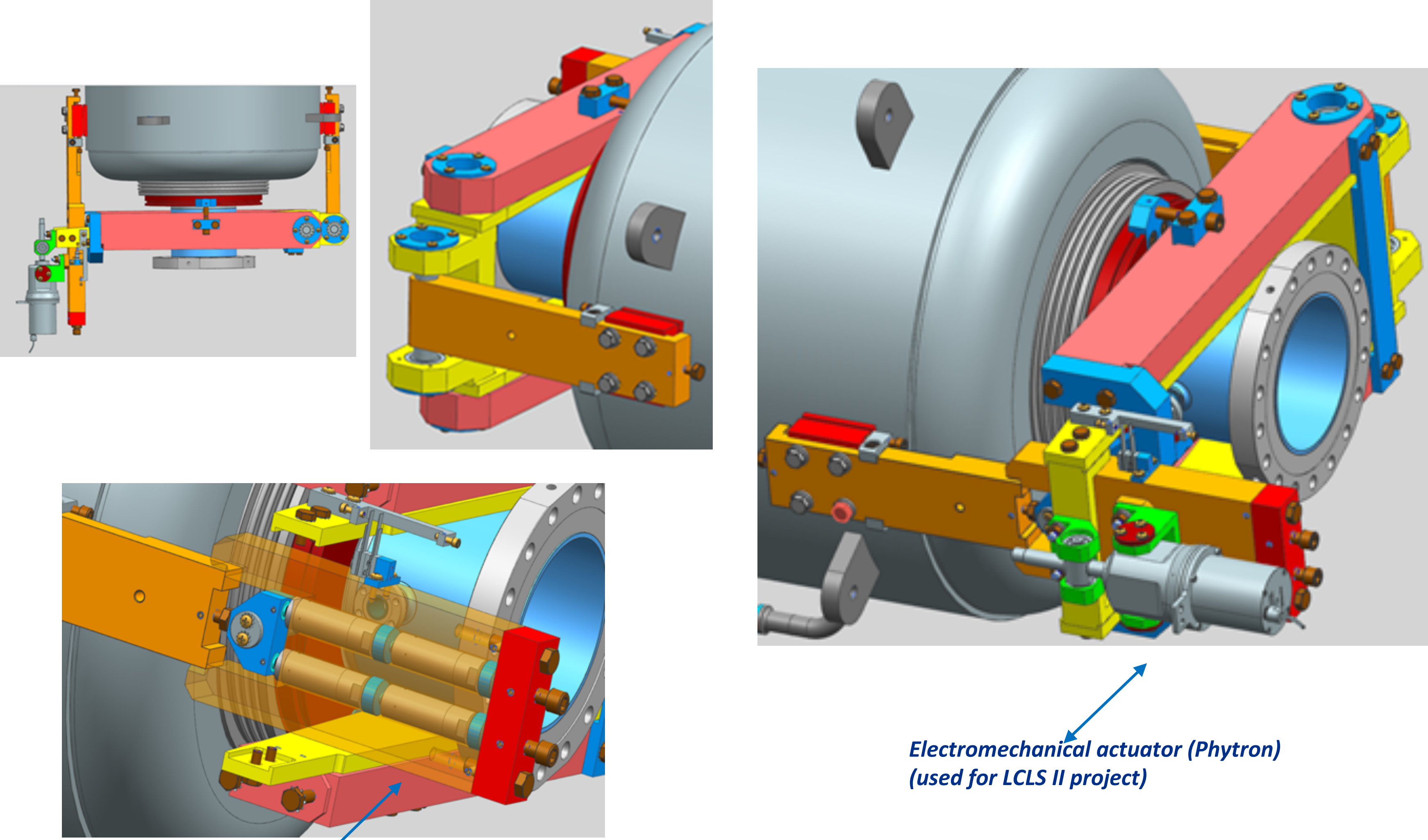


Review: November 22 2016

Slides from Oleg Pronitchev

# 3D-model of the 650MHz tuner

Y. Pischalnikov

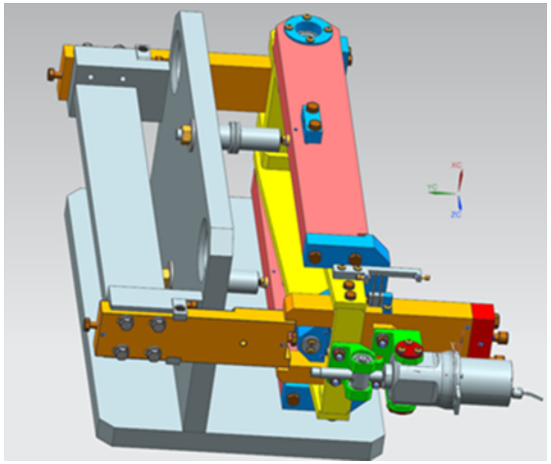


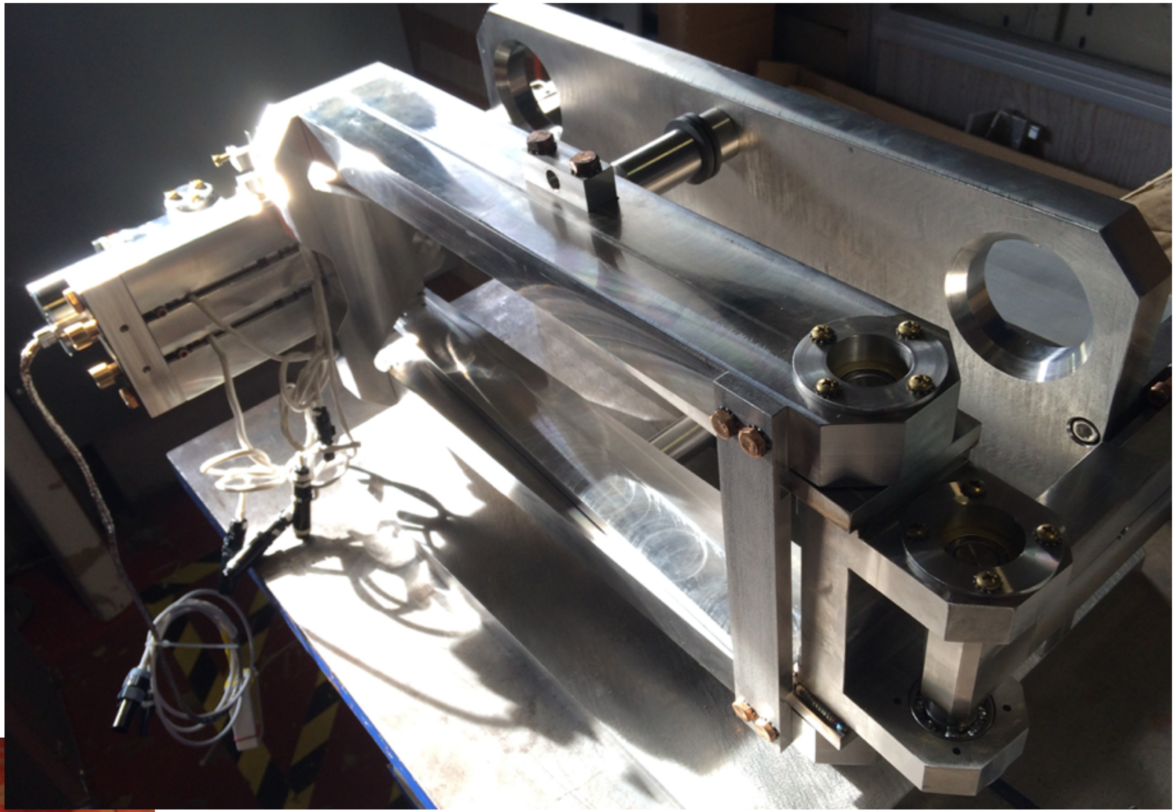
Electromechanical actuator (Phytron)
(used for LCLS II project)

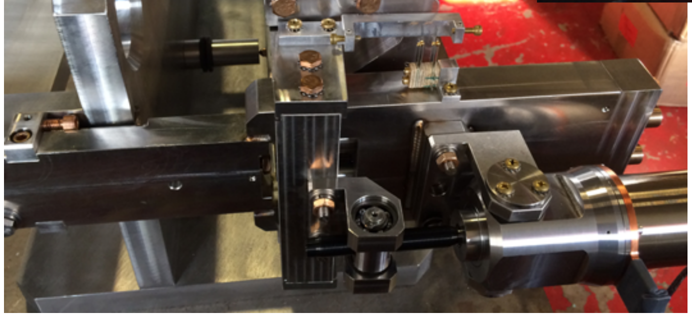
4 piezo-capsules for fast/fine tuning (PI piezo used for LCLS II project)
Maximal forces on the piezos ~ 3kN…

# First prototype tuner assembled on the of the cavity/He vessel mock-up.Ready for tests.

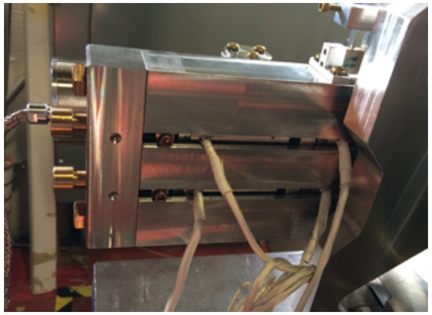
Y. Pischalnikov







*Electromechanical actuator (Phytron)*



*Cartridge with 4 piezo-capsules*

Y. Pischalnikov

# Plan for Tuner Design Verification Tests (warm) for 2017

- Tests with Tuner assembled on the cavity/He Vessel mock-up:
- - stiffness of the tuner (kN/mm);
- - slow tuner range (mm) and sensitivity (um/step);
- - fast/fine tuner range (um) and sensitivity (um/V).

- Tests with Tuner assembled on the first dressed cavity
- - slow tuner range (kHz) and sensitivity (Hz/step);
- - fast/fine tuner range (Hz) and sensitivity (Hz/V)
- - transfer function (piezo-to-cavity response… mechanical
- resonances of the cavity system

# Existing Fermilab Rings:  Scope

- 700 kW -> 1.2 MW:
  - increase pulse intensity
  - Increase pulse frequency

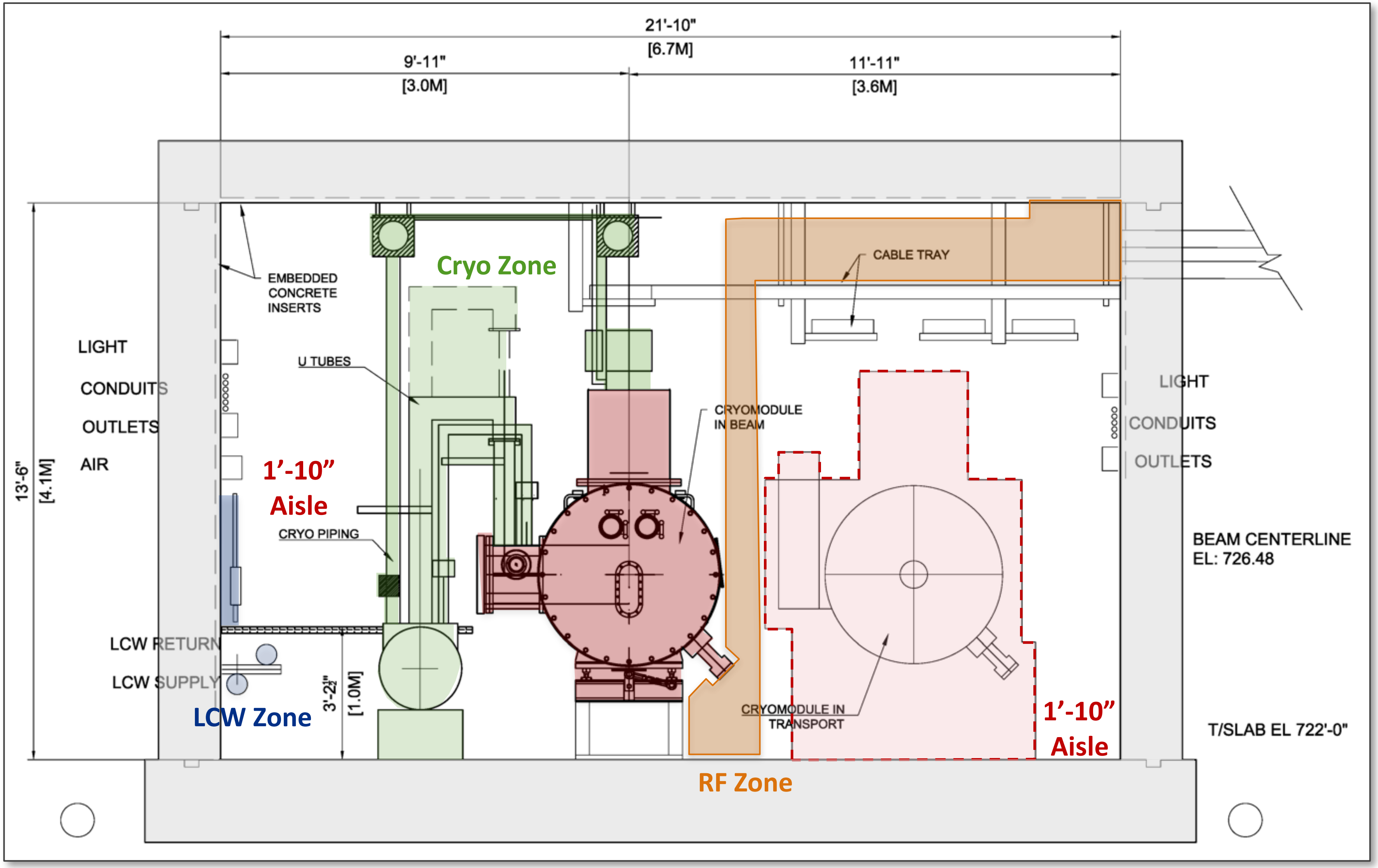
| Parameter | 700 kW | PIP-II |
|---|---|---|
| Booster Injection Energy | 400 MeV | 800 MeV |
| Booster Pulse Intensity | 4.3e12 | 6.4e12 |
| Booster Repetition Rate | 15 Hz | 20 Hz |
| RR Pulse Intensity | 5.2e13 | 7.7e13 |
| RR RF Duty Factor | 60% | 50-100% |
| MI Pulse Intensity | 4.9e13 | 7.5e13 |
| MI Extraction Energy | 120 GeV | 60-120 GeV |
| MI Cycle Time | 1.33 sec | 0.6-1.2 seconds |

# Conventional Facilities– Overview

S. Dixon

S. Dixon

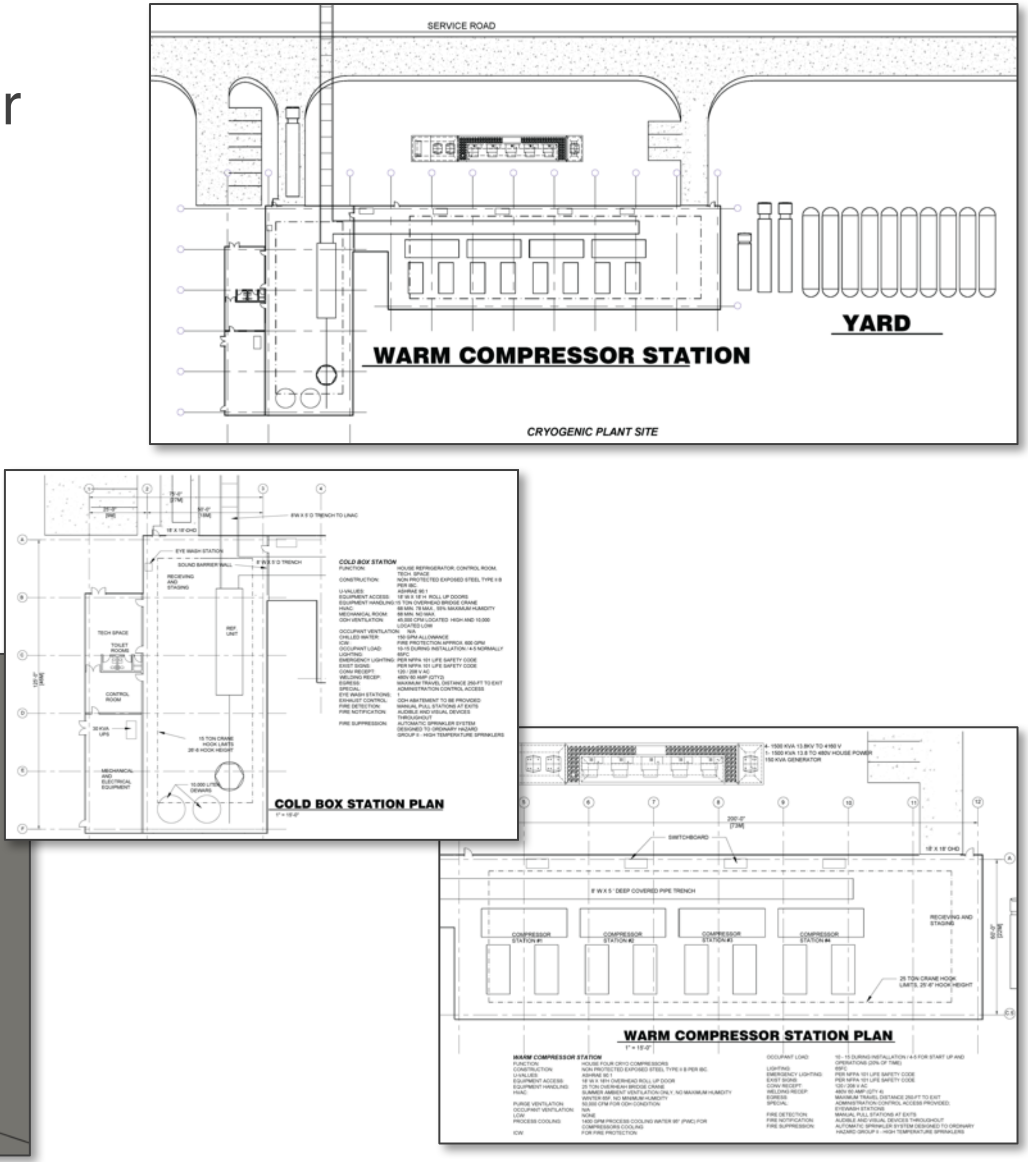
# Typical Linac Cross Section

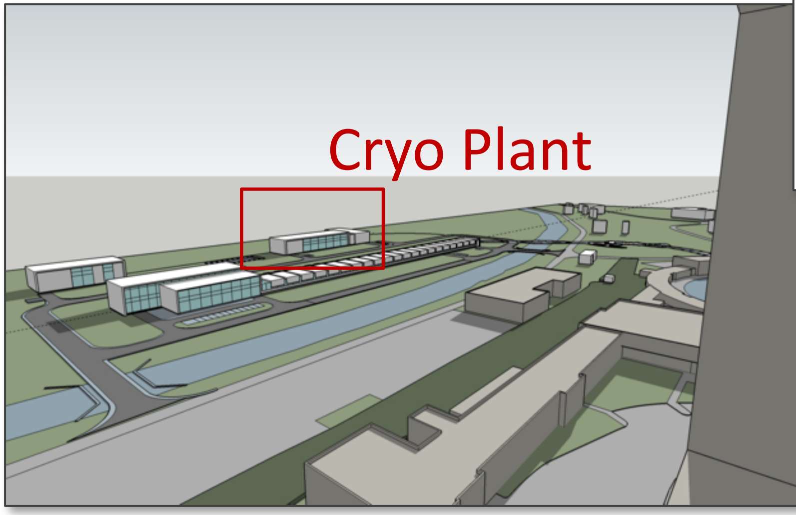


S. Dixon

# Cryo Plant Requirements

- Developed requirements for building to house the cryo plant;
- Based on known, typical cryo plant information and will be updated when more specific information is available





# PIP-II Priorities

- Goal: Complete the R&D Program in advance of Critical Decision 3: Approve Construction
- R&D Goals
  - PIP-II Injector Test
    - Chopper validation
    - HWR and SSR1 Operation with beam
  - SRF/IIFC
    - SSR1 CM (6 US + 2 India)
    - HB650 CM (3 US + 3 India)
    - LB650 + SSR2 Cavities from India (2 + 2)
    - RF systems (8 US + 16 India)
  - Rings
    - 20 Hz: magnet tested, understand control system impact
    - Booster Injection: design and prototype magnet
    - RR/Main Injector RF: PA tested, prototype RR cavity, prototype $\gamma_t$ magnet
- Critical Decision Goals
  - CD-1 : Approve Alternative and Cost Range
    - Q4FY17
  - CD-2/CD3a : Approve Baseline / Long Lead Procurement
    - FY18/19
  - CD3 : Approve Construction
    - FY20

# Progress at Fermilab

- At PIP2IT
  - beam & measurements in the MEBT
    - Awaiting magnets for further expansion

- In SRF
  - Lab 2 progress: assembly of SSR1 cryomodule
  - Resonance control: LFD and active feedback
  - 650 Cavities, Couplers, and Tuners

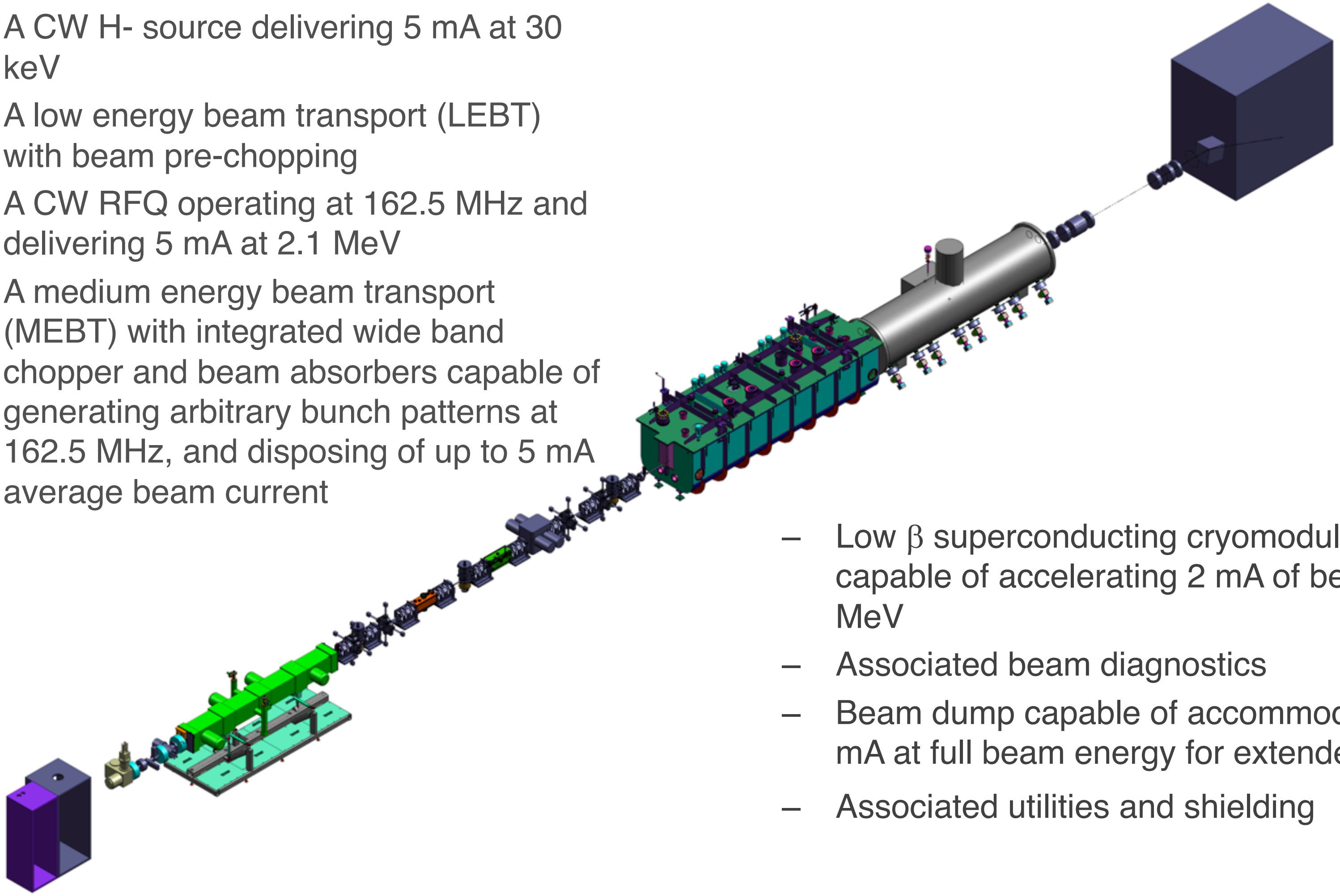
- Civil
  - Tunnel cross sections
  - Cryo Plant Requirements

- Priorities
  - Completion of MEBT: Chopper prototype tests
  - HWR & SSR1 operation with beam
  - 650 Cavity and Cryomodules

# Backups

# PIP-II Injector Test: PIP2IT

- Scope:
  - A CW H- source delivering 5 mA at 30 keV
  - A low energy beam transport (LEBT) with beam pre-chopping
  - A CW RFQ operating at 162.5 MHz and delivering 5 mA at 2.1 MeV
  - A medium energy beam transport (MEBT) with integrated wide band chopper and beam absorbers capable of generating arbitrary bunch patterns at 162.5 MHz, and disposing of up to 5 mA average beam current

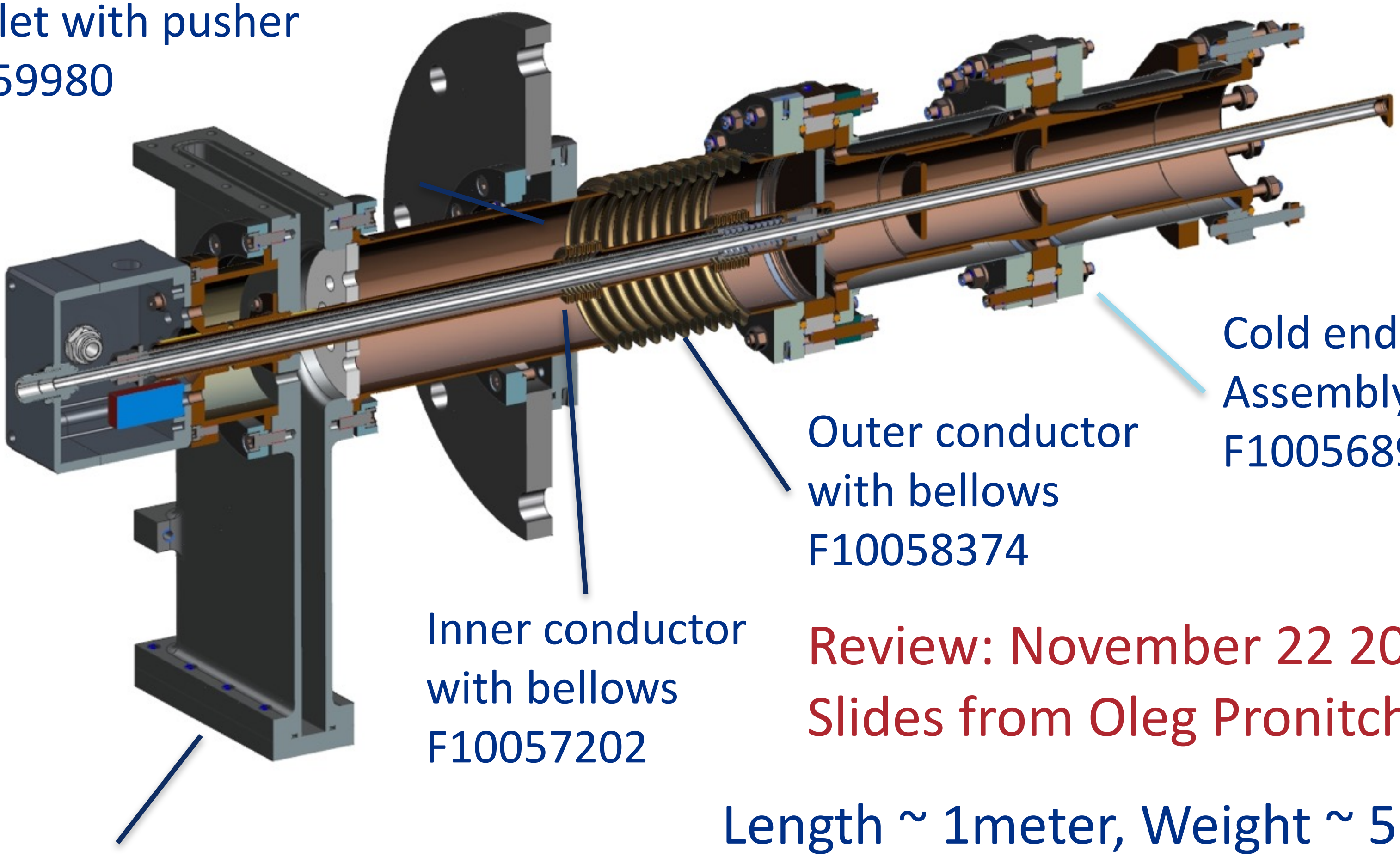


  - Low β superconducting cryomodules capable of accelerating 2 mA of beam to 25 MeV
  - Associated beam diagnostics
  - Beam dump capable of accommodating 2 mA at full beam energy for extended periods.
  - Associated utilities and shielding

# PIP2IT Deliverables

- FY17
  - Test of Chopper Prototypes & Absorber : Q4
  - Full Length MEBT installed : Q4
- FY18
  - Cryogenic Distribution System Installed : Q4
  - HWR Delivery, installation started : Q3
  - SSR1 Delivery : Q4
  - Note:  no beam operation
- FY19
  - SSR1 installation started : Q1
  - Full Length MEBT commissioned : Q3
  - Bunch by bunch chopping demonstrated: Q3
  - HWR / SSR1 RF commissioned : Q4
  - Initial beam to Cryomodules : Q4
- FY20
  - Beam through Cryomodules : Q1
  - Resonance Control Measurements (SSR1) with beam : Q3

# 650 MHz Main Coupler assembly F10056895



Air inlet with pusher
F10059980

Cold end
Assembly
F10056896

Outer conductor
with bellows
F10058374

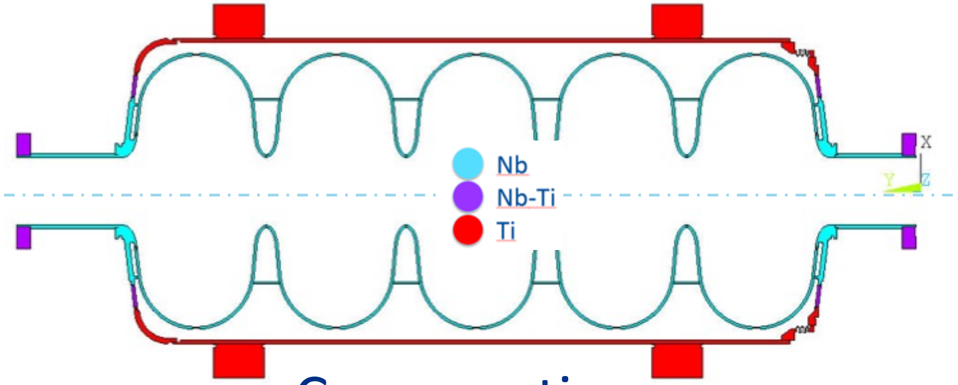
Inner conductor
with bellows
F10057202

Review: November 22 2016
Slides from Oleg Pronitchev

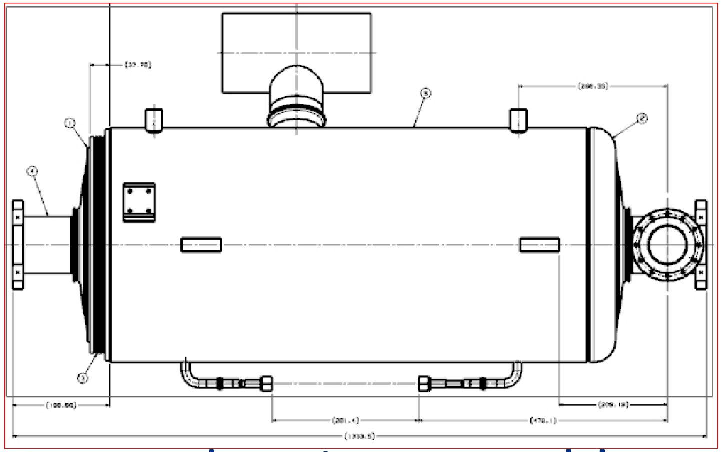
Length ~ 1meter, Weight ~ 50kg

Waveguide assembly
with instrumentation box F10059948

# Dressed cavity β = 0.9



Cross-section



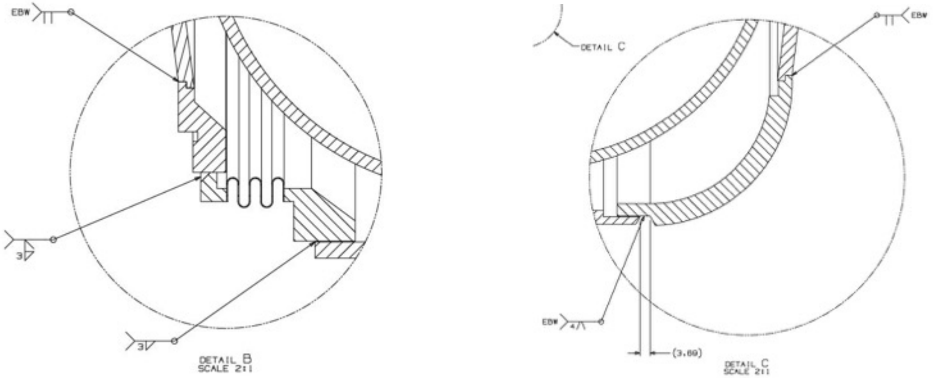
Dressed cavity assembly

Dressed cavity consists of following components:-

1. Helium vessel
2. Transition ring MC end
3. Transition ring FP end
4. Bellow assembly
5. Support lugs
6. Lifting lugs
7. Helium inlet (2 nos.)
8. 2-phase pipe assembly
9. Tuner mounting lugs
10. Magnetic shielding (external)

Weld Joint Configuration for cavity dressing:-

Designed in Accordance with Fermilab ES&H Manual 5031.6 (Dressed Niobium SRF Cavity Pressure Safety)



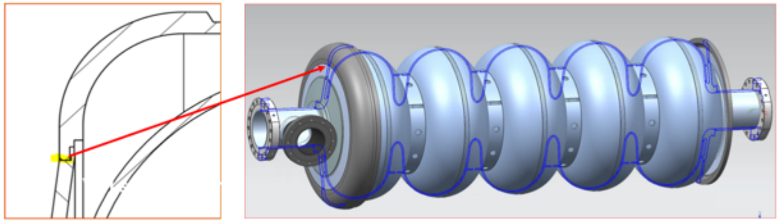
# Cavity Dressing Steps for $\beta$=0.9

Step-1 : Bare cavity preparation
Step-2 : Tack welding #1 preparation in medium bertha
Step-3 : Tack welding #2 & 3 preparation in medium bertha
Step-4 : Cavity installation in rotating fixture and 360° rotating trail inside Glovebox
Step-5: Full penetration welding inside GB

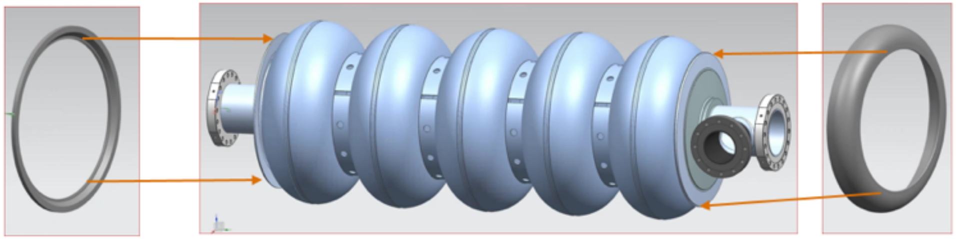
## Step-1

**Bare Cavity Preparation**

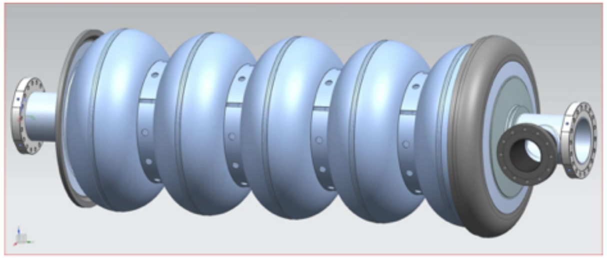
- Modified joint for TIG welding
- Analysis of dressed cavity with modified joint for LC1 to LC5
- NbTi-Ti weld Sample preparation inside GB
- Testing and qualification of samples



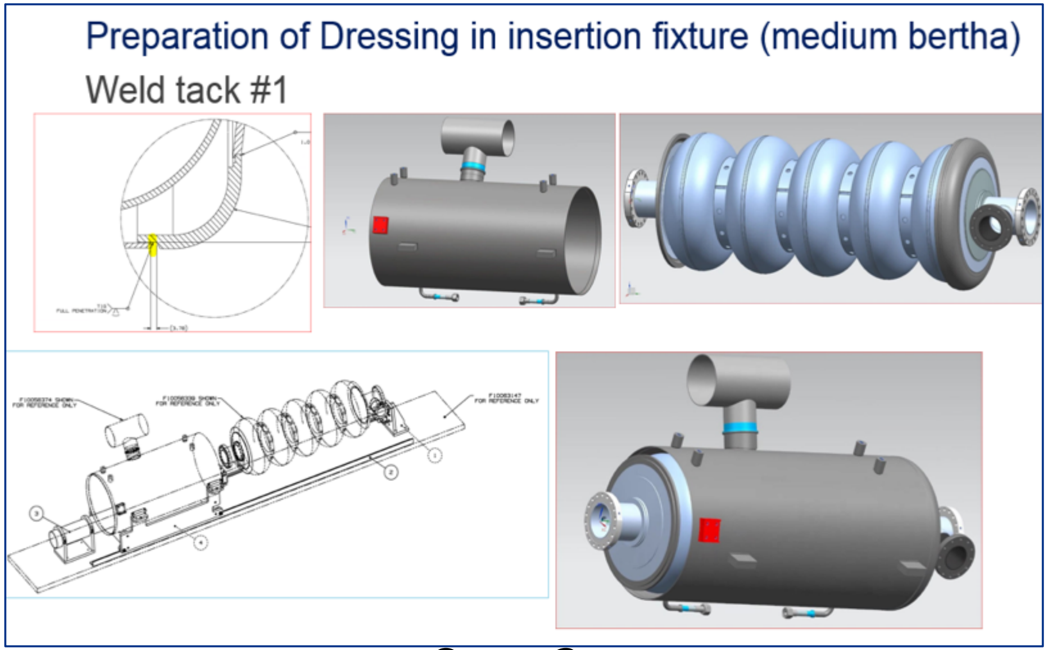
Tack weld



Full weld in GB ➔ Leak testing



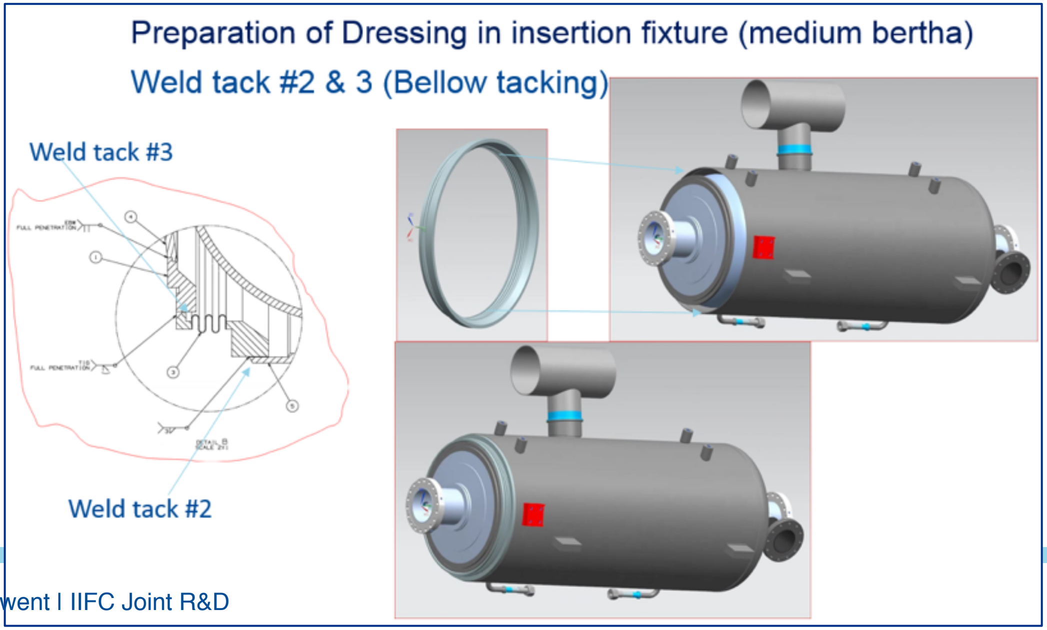
# Step-2



## Preparation of Dressing in insertion fixture (medium bertha)

Weld tack #1

# Step-3



## Preparation of Dressing in insertion fixture (medium bertha)

Weld tack #2 & 3 (Bellow tacking)

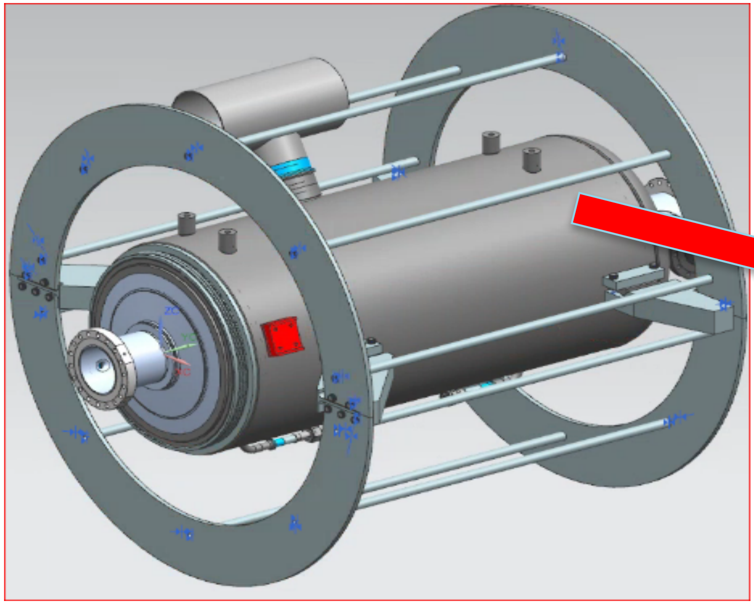
Weld tack #3

Weld tack #2

## Step-4

360° Rotation fixture

➔ Tacked cavity and helium vessel assembly is rotated inside GB

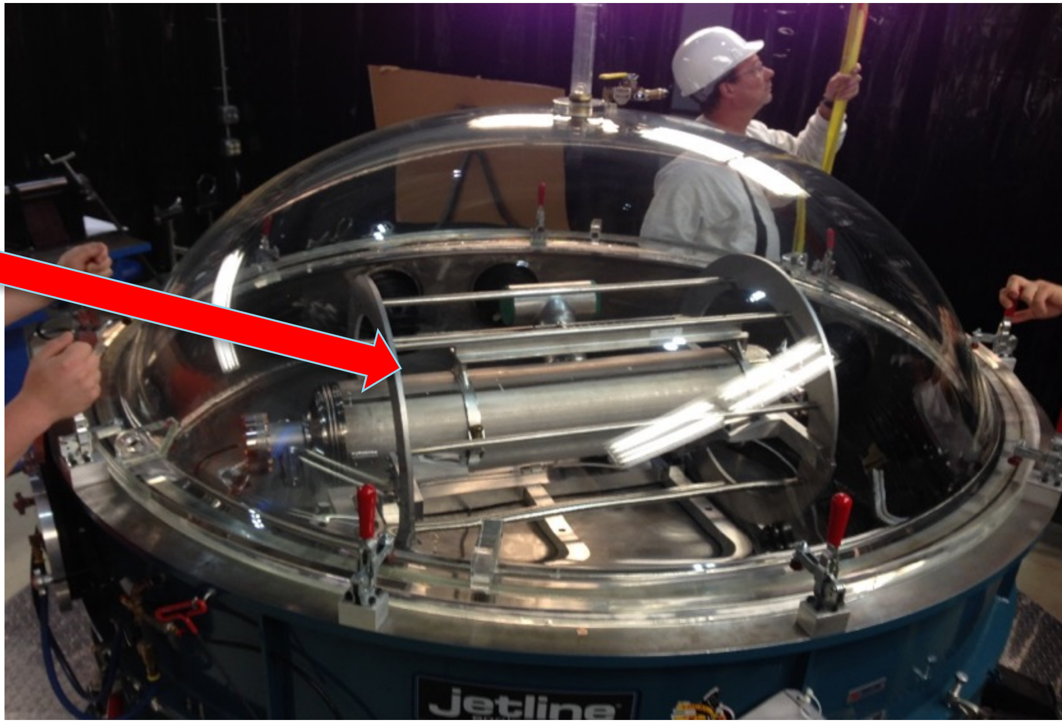


## Step-5

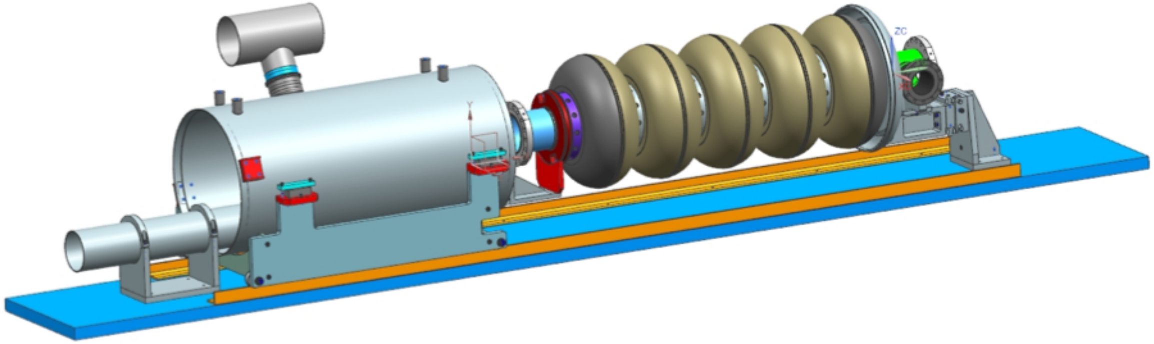
Cavity Welding in GB

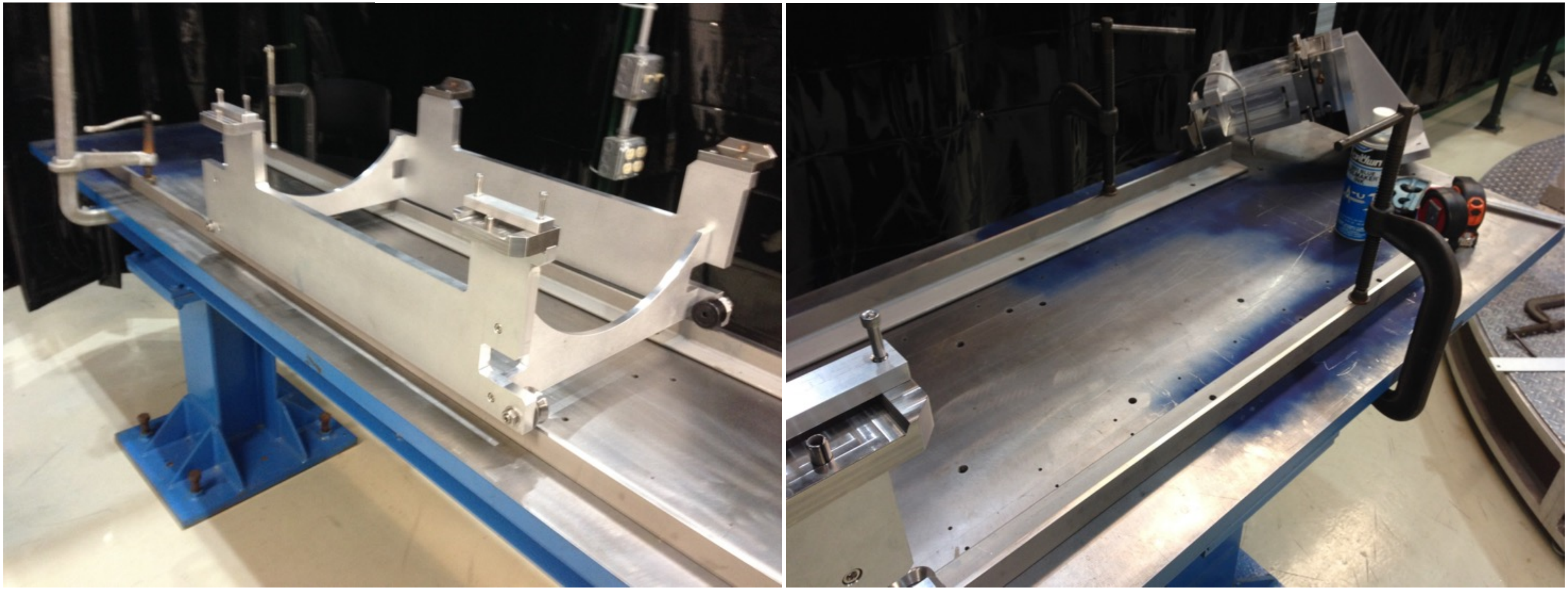
Cavity installation in Rotating Fixture

Full welding similar as sequenced during tack



# Status of medium bertha MP9





Assembled in 1st week of Dec. 2016