SRF Technology for PIP-II and PIP-III at Fermilab

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Outline

- PIP-II Project Overview
  - PIP-II Goals and Performance Parameters
  - Accelerator Complex Components
- SRF LINAC Cryomodules
  - 162.5 MHz Half Wave Resonator Cryomodule
  - 325 MHz Single Spoke Resonator Cryomodules (SSR1, SSR2)
  - 650 MHz Elliptical Resonator Cryomodules (Low Beta, High Beta)
- Critical Subsystems
  - RF Couplers
  - Resonance Control & Tuners
- A look ahead: PIP-III
- Acknowledgments

PIP-II Goals

The goal of PIP-II is to support long-term physics research goals as outlined in the P5 plan, by delivering world-leading beam power to the U.S. neutrino program and by 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 ongoing 8 GeV programs including Mu2e, g-2, and short-baseline neutrino exp.
- Provide an upgrade path for Mu2e
- Provide a platform for extension of beam power to LBNF to >2 MW
- Provide a platform for multi-MW, high duty factor beam operations for future experiments

Technical Approach

- Construct a modern 800-MeV superconducting linac of CW-capable components, operated initially in pulsed mode

PIP-II SC Linac Parameters and Performance Goals

Performance Parameter	PIP (Now)	PIP-II	
Particle Species	H-	H-	
Output Beam Energy to Booster	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.54	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	17	kW
Linac Beam Power Capability (@>10% Duty Factor)	4	~200	kW
Booster Protons per Pulse	4.3×10^{12}	6.5×10^{12}	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	166	kW
Beam Power to 8 GeV Program (max)	32	83	kW
Main Injector Protons per Pulse	4.9×10^{13}	7.5×10^{13}	
Main Injector Cycle Time @ 60-120 GeV	1.33*	0.7-1.2	sec
LBNF Beam Power @ 60-120 GeV	0.7*	1.0-1.2	MW
LBNF Upgrade Potential @ 60-120 GeV	NA	2.4	MW

*NOvA operations at 120 GeV

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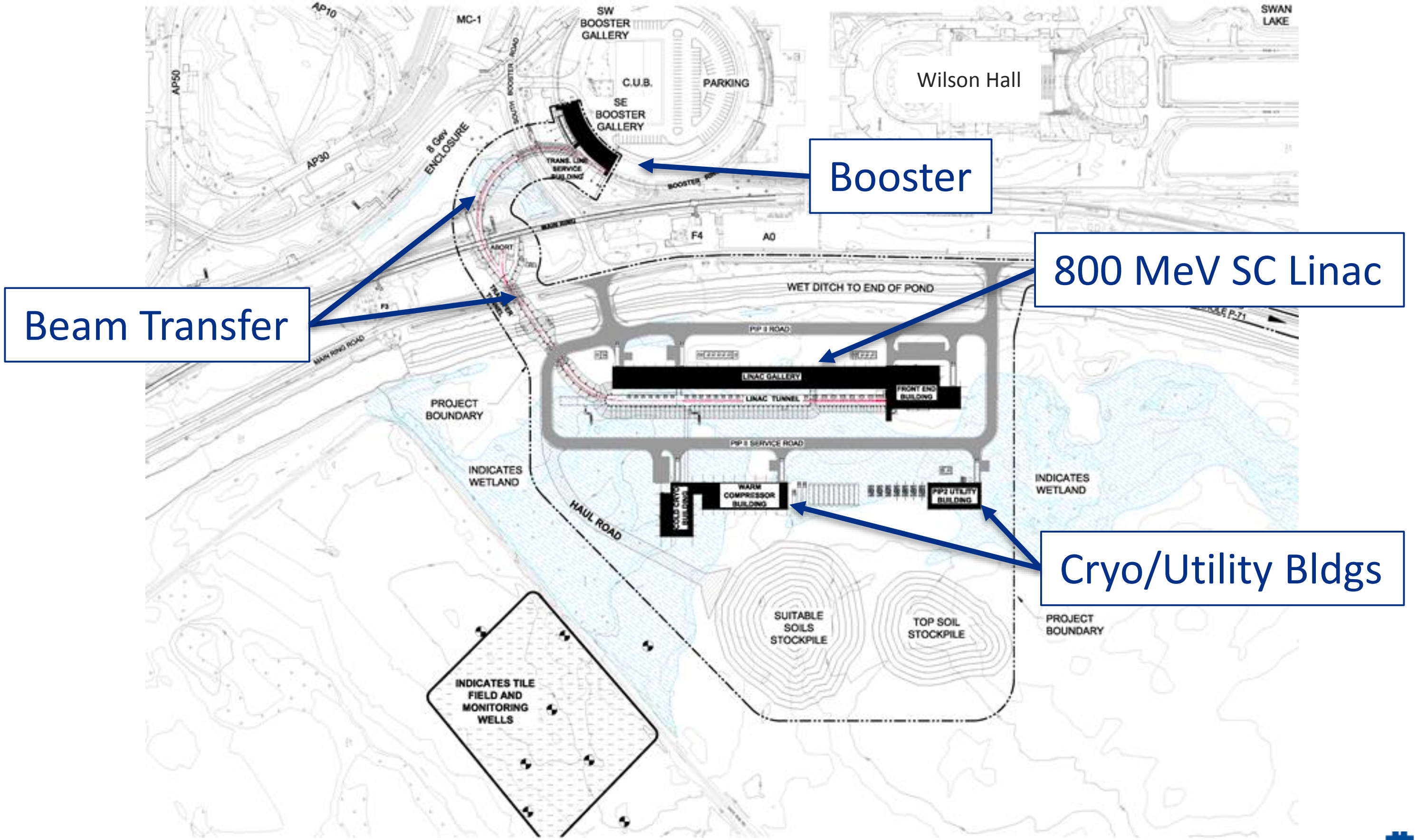
PIP-II Accelerator Complex Components



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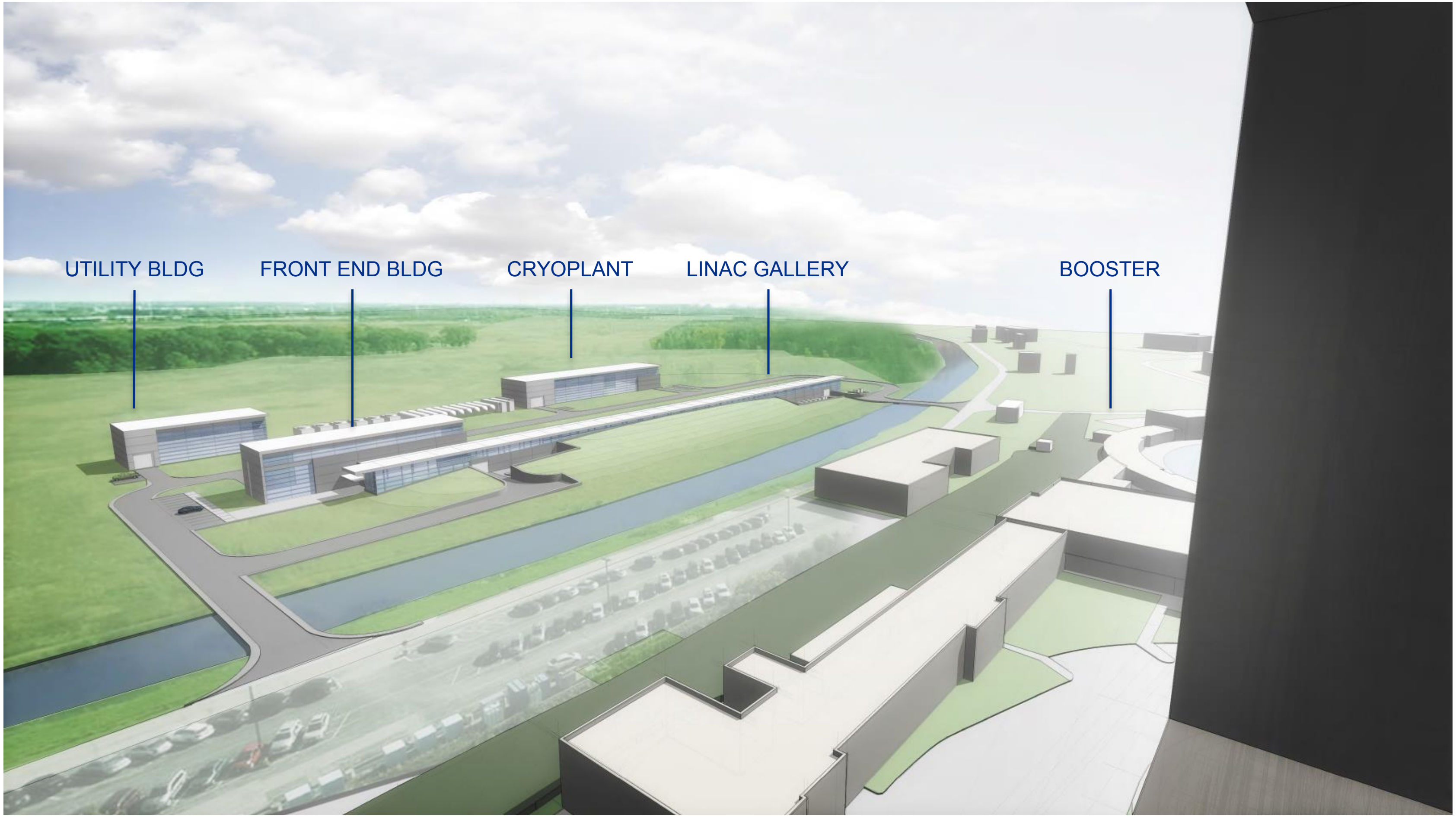

UTILITY BLDG
FRONT END BLDG
CRYOPLANT
LINAC GALLERY
BOOSTER

SRF Linac Cryomodules

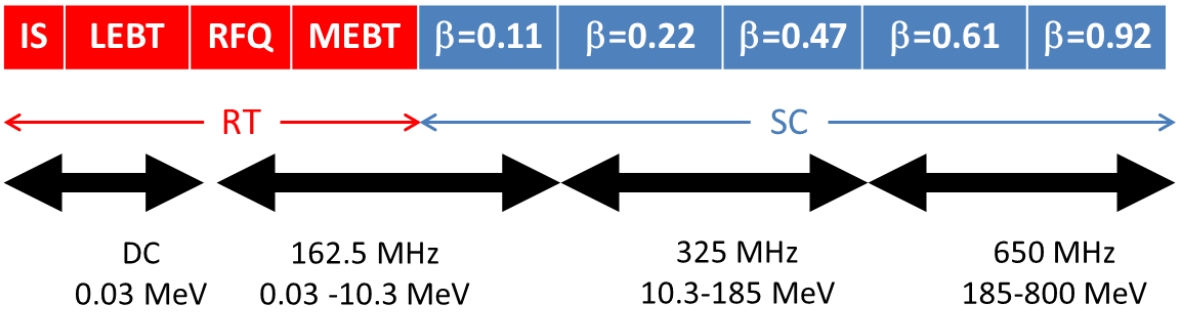
Technical and Production Challenges

- Design and build five CM types to operate in both a low-duty factor pulsed mode and continuous wave mode to achieve near and long-term machine operating goals. (Half-Wave Cryomodule is CW only)
- Compromise between operating cavity bandwidth and RF power requirements
- Maintain low cryogenic loads to maximize efficiency for eventual CW operation
- Low quantity production of each CM type limits efficiency

Design Approach

- Use a common CM design platform for CM types SSR1, SSR2, LB650 and HB650
- Leverage high Q0 techniques on all elliptical cavities
- Implement robust resonance control system to minimize RF power requirements

PIP-II Technology Map



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

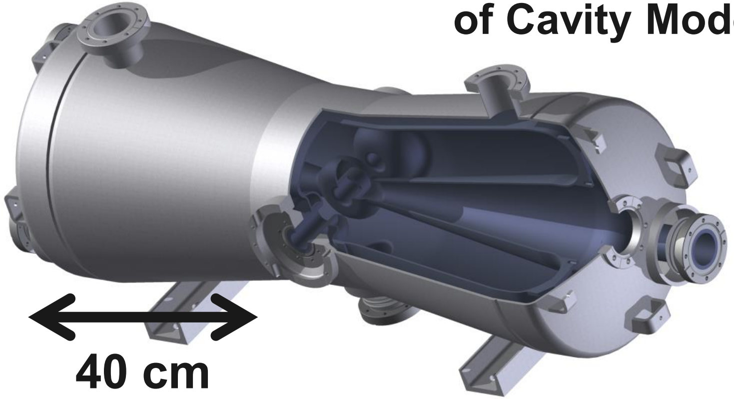
162.5 MHz Half-Wave Cryomodule Development at ANL

Cavity Type	HWR
Frequency	162.5 MHz
Optimal β	0.112
Effective Length	20.7 cm
Aperture	33 mm
E_{peak}/E_{acc}	4.7
B_{peak}/E_{acc}	5.0 mT/(MV/m)
G	48 Ω
R_{sh}/Q	272 Ω

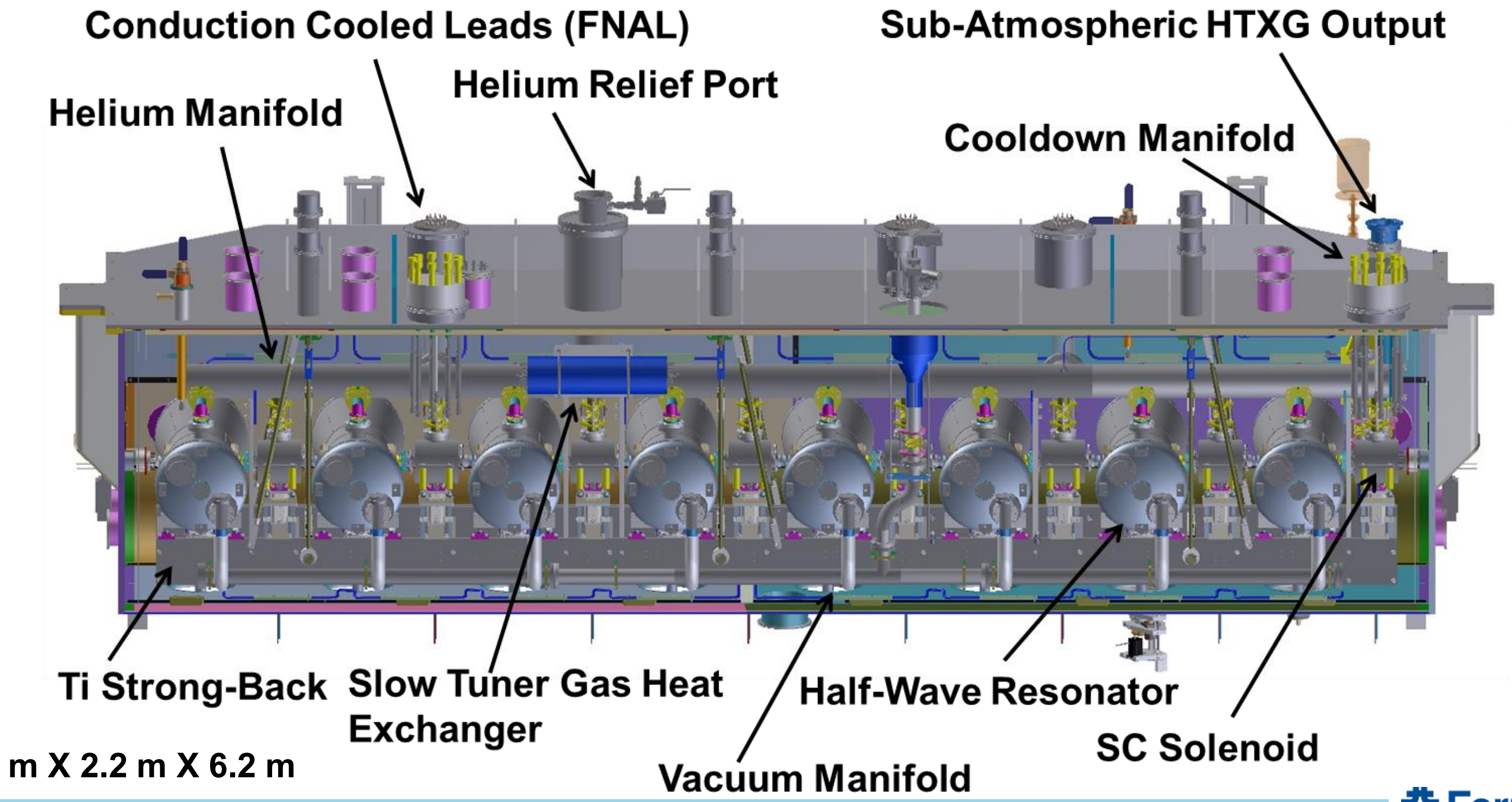
- Highly optimized conical-halfwave resonators:
  - B. Mustapha et al, IPAC12, Pg. 2289.
  - Z. Conway et al, LINAC12, Pg. 624.
- Compact lattice layout and 2 K cryomodule:
  - P. Ostroumov et al, LINAC12, Pg. 461.
- 6 of required 8 resonators tested and ready for operation. Remaining two ready for acceptance testing.

Z. Conway, WEYA05

Cut-Away View of Cavity Model

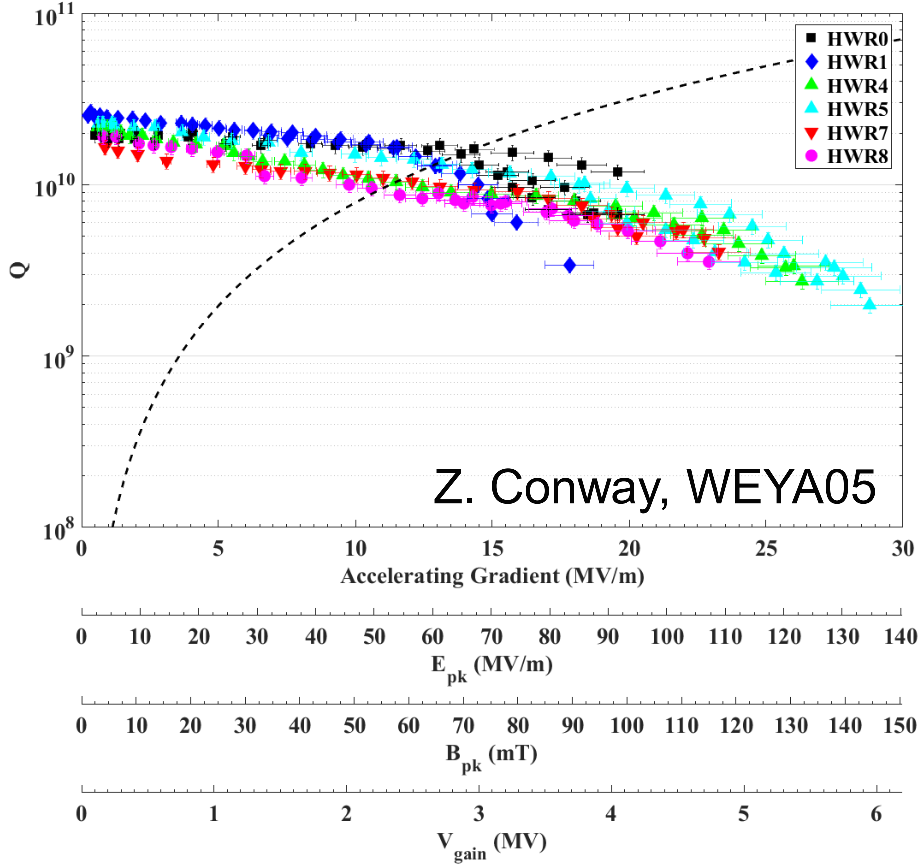


Half-Wave Cryomodule Sub-components



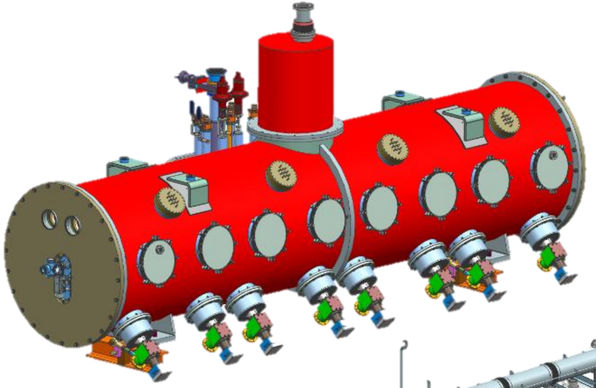
2.2 m X 2.2 m X 6.2 m

HWR Cavity Performance & Trial Assembly



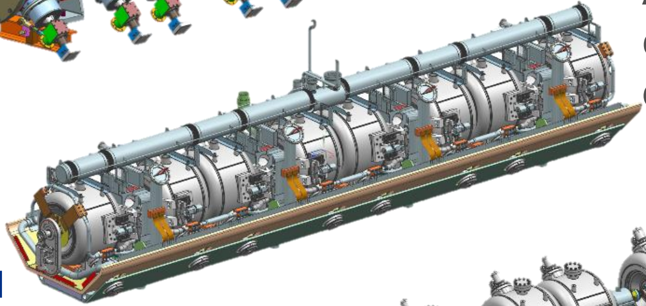
Cold Mass & Lid Going into the Box

325 MHz Single Spoke Cryomodules (SSR1)



- Two SSR1 CMs required for PIP-II
- Acceleration range: 10 – 35 MeV
- Active resonance control of cavities is operated by piezo driven tuners

SSR1 EM Parameters	Value
Frequency	325 MHz
Shape	SSR
β_g, β_{opt}	0.215, 0.22
$L_{eff} = \beta_{opt}\lambda$	203 mm
Iris aperture	30 mm
Inside diameter	492 mm
Bandwidth f_0/Q	90 Hz
E_{pk}/E_{acc}	3.84
B_{pk}/E_{acc}	5.81 mT/(MV/m)
G	84 Ω
R/Q	242 Ω



SSR1 coldmass

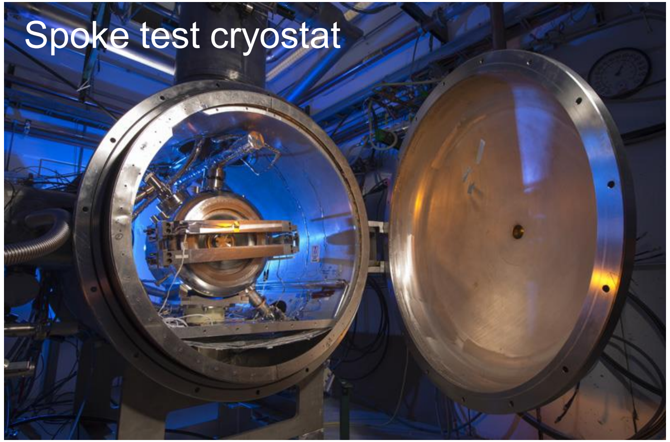
Each CM contains

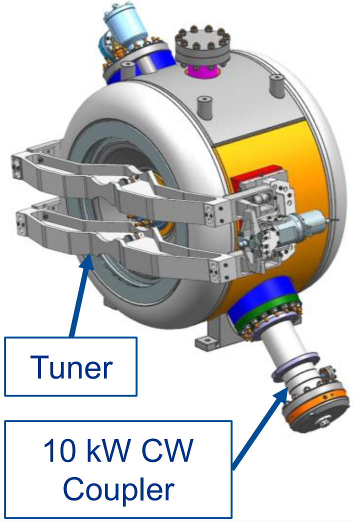
- 8 SSR1 cavities with β_{opt} = 0.222 operating at 325 MHz, 2K
- 8 input power couplers operating up to 10 kW CW
- 4 magnet packages operating at 2K. Each one contains a focusing solenoid and four corrector coils

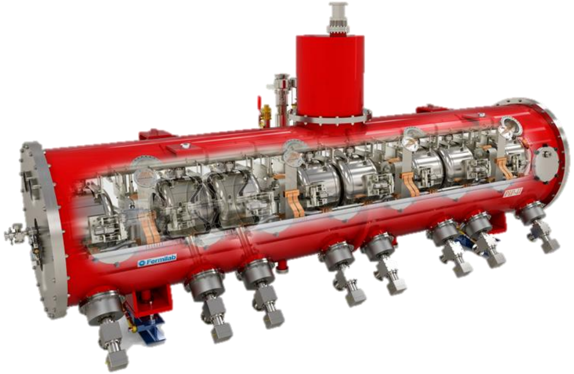
SSR1 string assembly

325 MHz SSR1 Cryomodule Status

- 10 cavities dressed, proceeding through qualification sequence
  - Light chemistry, cleanroom, VTS, and horizontal test
- 2 DAE (IUAC, BARC, RRCAT) cavities to be installed in the string
- String assembly start scheduled Feb. 2018
- New CM assembly Facility (Lab2) prepared for SSR1 CM
- SSR1 is technical platform for all downstream PIP-II CM designs







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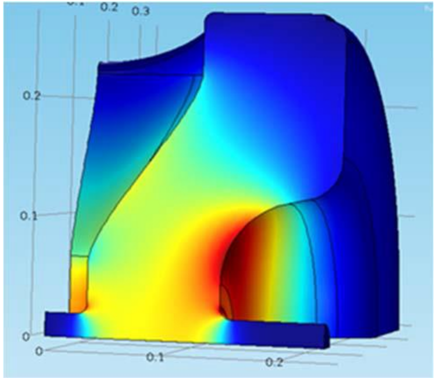
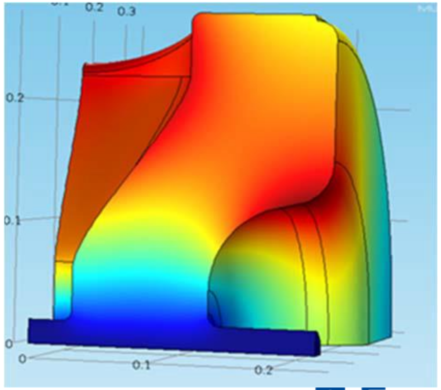
325 MHz Single Spoke Cryomodules (SSR2)

- Seven SSR2 CMs required for PIP-II
- Acceleration range: 35 – 185 MeV
- Each cryomodule contains:
  - 5 SSR2 Cavities
    β_{opt} = 0.47 operating at 325 MHz, 2K
  - 5 input power couplers operating up to 17 kW CW
  - 3 magnet packages operating at 2K. Each one contains a focusing solenoid and four corrector coils
  - Lattice: cavities (C) and focusing solenoids (S) is SCCSCCSC
- Active resonance control is operated piezo driven tuners

SSR2 EM Parameters	Value
Frequency [MHz]	325
Optimal beta	0.475
Effective length [m]	0.438
E_{peak}/E_{acc}	3.38
B_{peak}/E_{acc} [mT/(MV/m)]	5.93
G [Ω]	115
R/Q [Ω]	297



SSR2 Electric (top) and Magnetic (bottom) 3D fields computed by COMSOL.



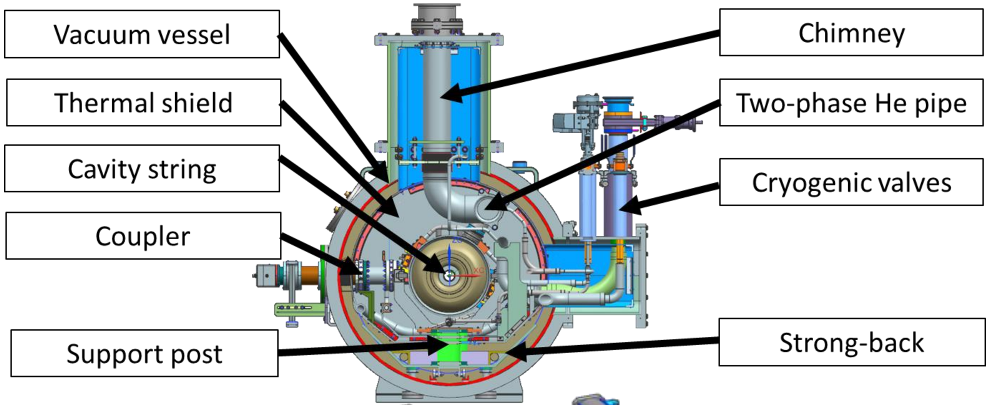
Status

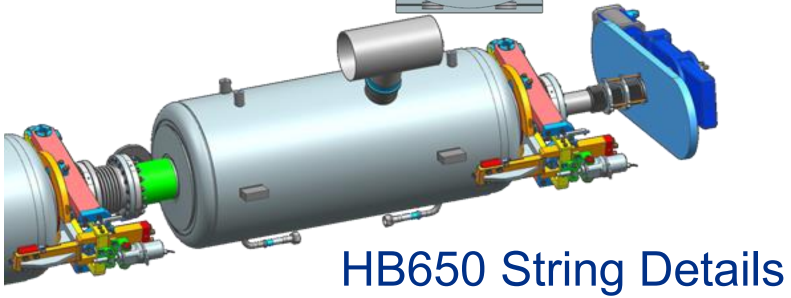
- Least developed of the 5 PIP-II CM types, but CM design is very similar to SSR1
- Cavity RF design mature, including multipacting minimization, but not finalized
- Collaborative design (FNAL and BARC Mumbai) through the IIFC.
- The first bare cavity is planned to be manufactured by Nov. 2019 at BARC.

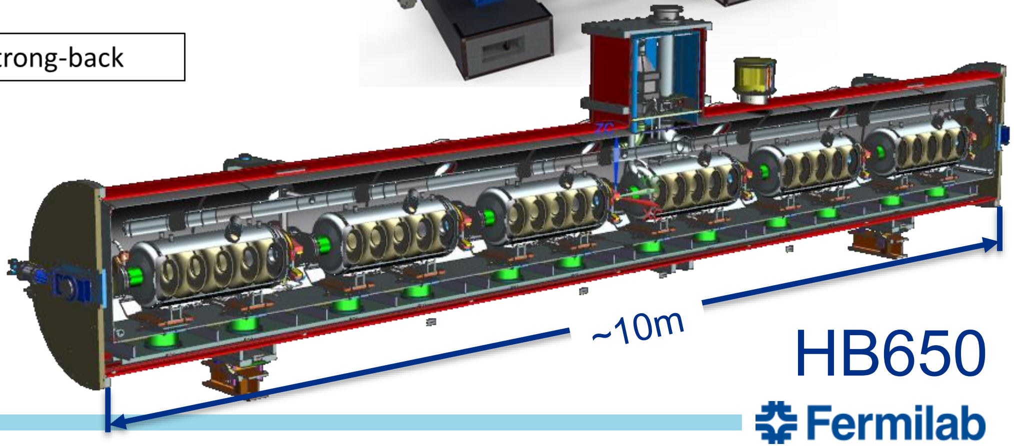
650 MHz Elliptical Cryomodules (B0.61, B.92)

Design Strategy

LB650 & HB650 cryomodules are composed of three LB650 or six HB650 cavities without any solenoids. Like the SSR1 cryomodule, the design of LB/HB650 cryomodules are based on a strong-back at room temperature that support the cavities from the bottom.




HB650 String Details

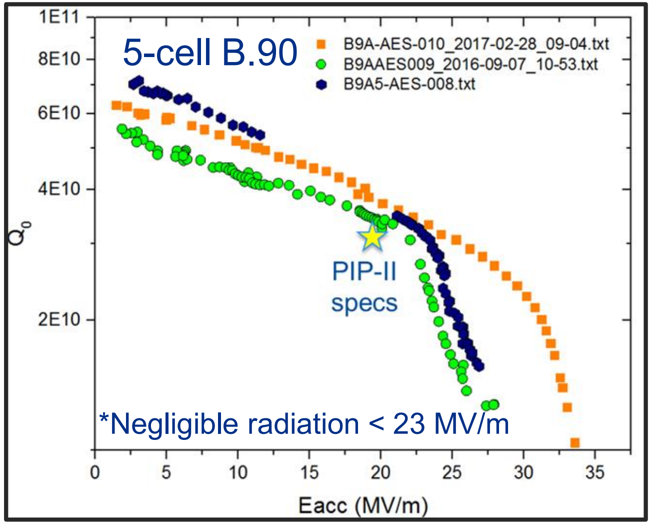


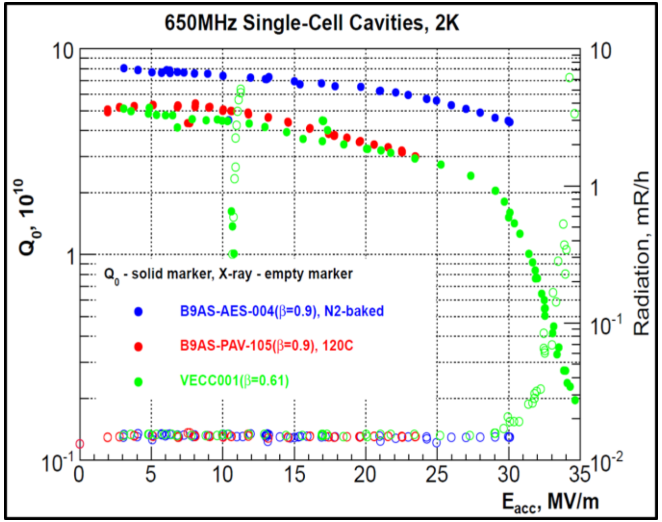
650 MHz Elliptical Cryomodules (B.61, B.92) – Cavity Results

650 MHz Cavity E&M Parameters

Cavity Parameters	LB650	HB650
β_G	0.61	0.92
β_{opt}	0.65	0.97
$R/Q(\beta_G)$, Ohms	327.4	576
$E_{surf}/E(\beta_G)$	2.43	2.1
$B_{surf}/E(\beta_G)$, mT/MV/m	4.6	3.94
G, Ohms	187	260
Energy gain per cavity MeV	11.7	19.9

- Three of four multi-cell B.90 cavities qualified through VTS.
- Q0 > 3.5 E10 @ 20 MV/m
- Minimal radiation due to FE induced X-Rays during several tests up to Eacc < 25 MV/m.





650 MHz 5-cell cavity on HPR Tool

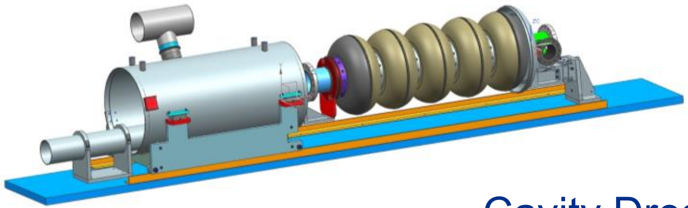
650 MHz Elliptical Cryomodules Status

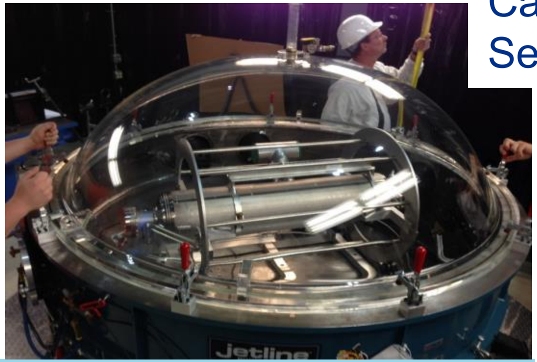
Cryomodule Design Activities

- 11 LB650 CMs, 4 HB650 CMs
- FNAL HB650 CM design continues through 2018, implementing lessons learned on SSR1 and LCLS-II designs.
- RRCAT-Indore, in collaboration with FNAL, is designing the 3-cavity LB650 CM based on the same principals as the HB650 CM.
- HB650 pre-series CM will be constructed at FNAL in 2019-2020 and serve as a test-bed for all 650 MHz CMs.
- VECC and INFN-Lasa, in collaboration with FNAL, are finalizing the prototype LB650 5-cell cavity designs. Production to begin in 2018.

Near Term Cavity Goals

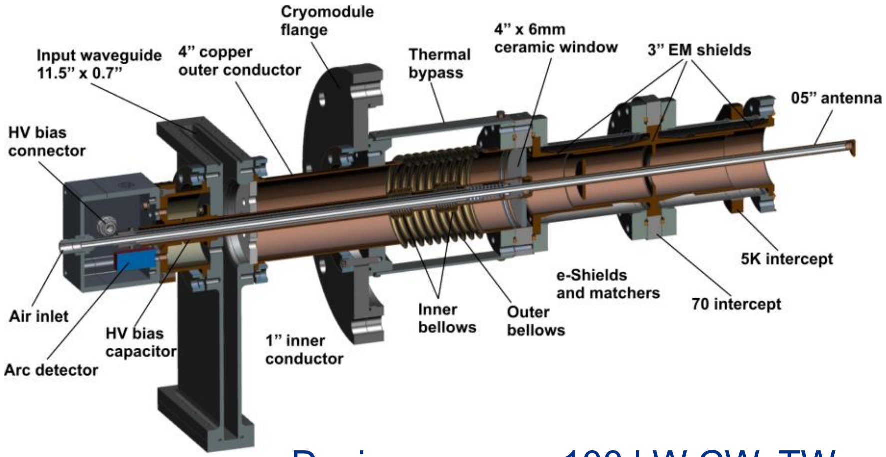
- Dress, vert. test and qual. 4 dressed cavs by 02/18
- Horizontally test 2 cavs by 12/18
    - Full high-power test with couplers/tuners



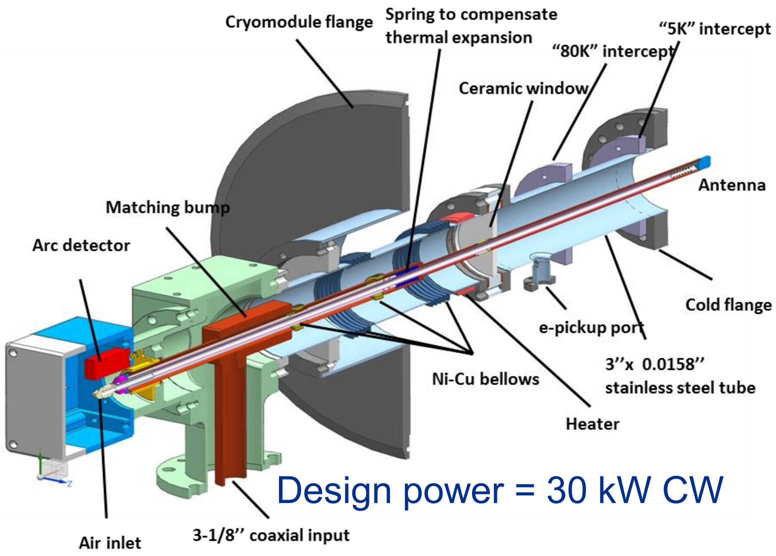


Cavity Dressing Setup at FNAL

RF Couplers



Design power = 100 kW CW, TW



Design power = 30 kW CW

650 MHz	Power Dissipation		
P, kW	2K, W	5K,W	70K,W
0 kW	0.15	0.6	3.3
100 kW	0.55	0.93	6.2
300 kW	1.52	1.6	11.5

- Windows – Al_2O_3
- Antennas – Air cooled
- Multipactor – HV Bias

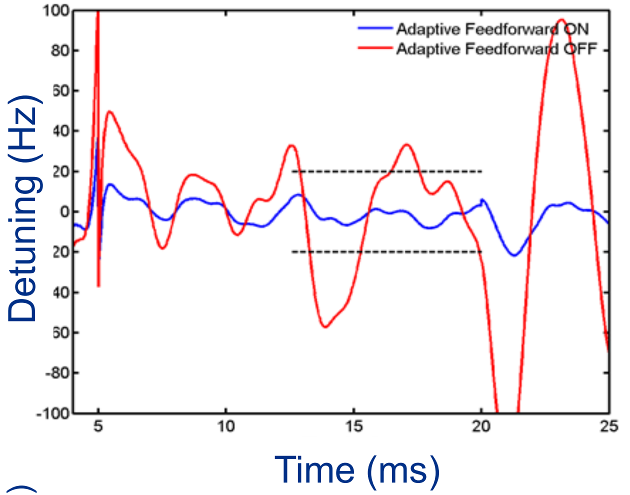
Status

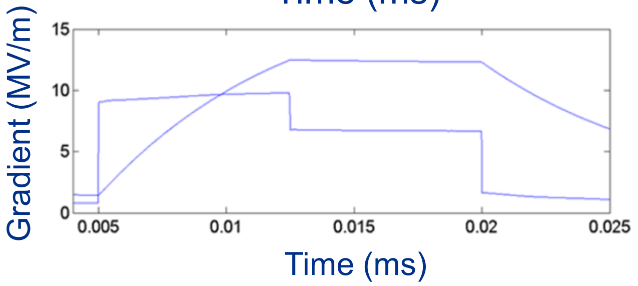
- 30 kW Production Couplers due 09/17
- 100 kW R&D out for contract

325 MHz	Power Dissipation		
P, kW	2K, W	5K, W	70K, W
0	0.06	0.58	2.02
3	0.10	0.81	2.35
6	0.15	1.03	2.68
20	0.35	2.07	4.25
30	0.50	2.82	5.36

Resonance Control Program

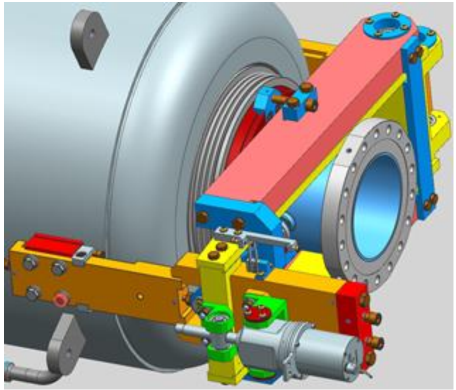
- Continue improvement of feedback algorithm applied to SSR1 cavity
  - Synergy of LCLS II and PIP II active resonance control efforts
  - Upgrade plans include automating setting of filter bank parameters based on the cavity transfer functions.
- During production testing at STC of multiple SSR1 cavities continue improvement of overall compensation algorithm, work at PIP II operational conditions for all cavity types.
- Study/improve stability of compensation algorithm – **currently capable to control SSR1 to ~ 40 Hz pk-to-pk, within a factor of 2 PIP-II specs.**
- Transfer algorithm/software from R&D electronics to PIP LLRF system.





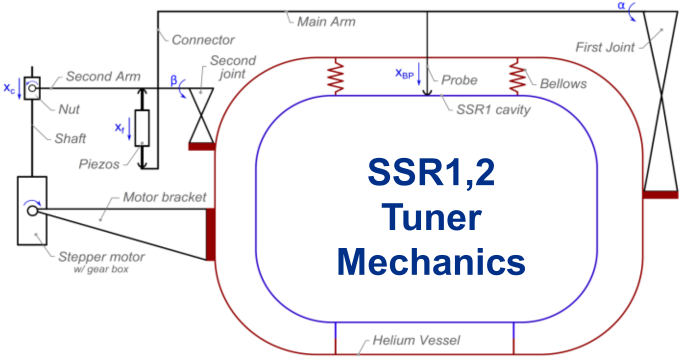
- **SR1 STC operating condition**
- **Eacc >12.5 MV/m**
- **25 Hz repetition rate**
- **7.5 ms fill & 7.5 ms flat-top**

Cavity Tuners – 325 & 650 MHz CMs



LB/HB650 Double Lever Tuner

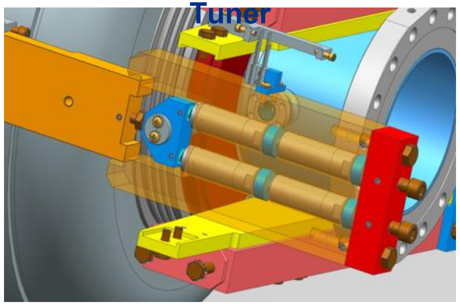
- 650 MHz tuner design adapted from LCLS-II
- Tuners must be stiff (> 60kN/mm) to combat LFD
- Piezo loads must be balanced with cavity/HV system stiffness
- Mechanical hysteresis must be minimized



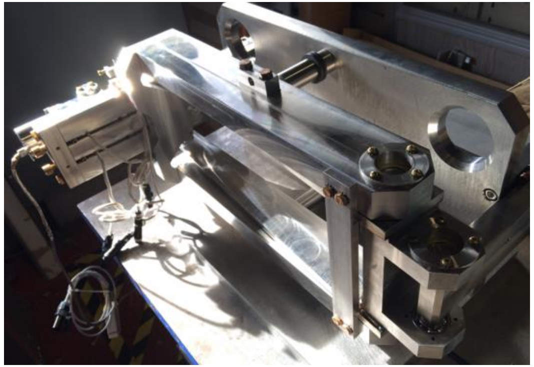
Coarse tuning
$\Delta f_c \geq 135\, kHz \rightarrow x_{BPc} \geq 250 \mu m$
Active compensation of **uncertainty** due to **cooldown**, **preload** the system

Fine tuning
$\Delta f_f \geq 1\, kHz \rightarrow x_{BPf} \geq 1.85 \mu m$
Actively compensate the frequency shifts due to **microphonic**

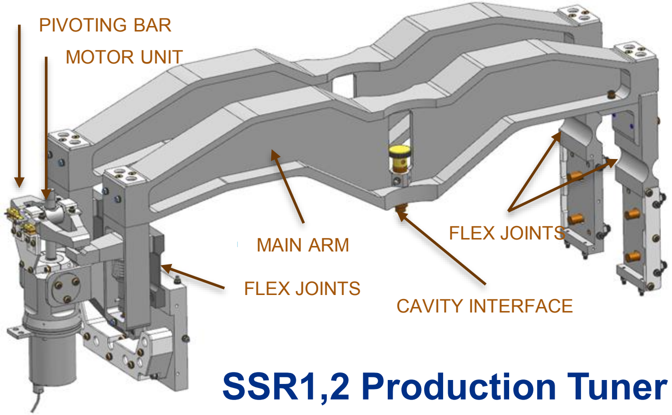
Passive tuning
$k_{pass} \geq 30\, N/\mu m$
Passively **minimize the pressure sensitivity** of the cavity



4 piezo-capsules for fast/fine tuning Maximal forces on the piezos ~ 3kN



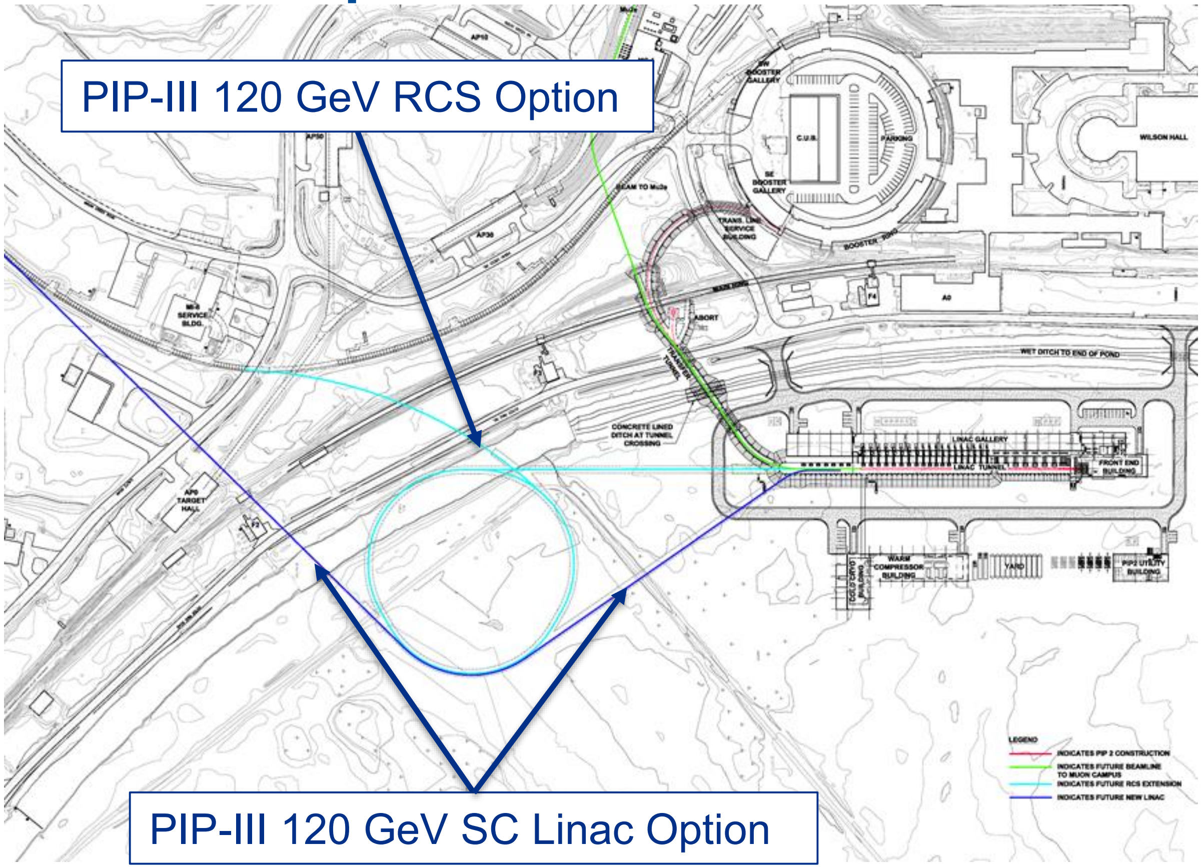
Prototype 650 MHz tuner



SSR1,2 Production Tuner

A look ahead: PIP-III – SRF Linac Option

- 3rd Phase in Multi-stage Plan
  - PIP->PIP-II->PIP-III
- Provides multi-MW beam to future experiments
- 2.5 MW Beam Power to first customer, LBNF
- 0.8-3 GeV 650 MHz Linac
- 3-8 GeV 1.3 GHz Linac
- Or --- 0.8-8 GeV RCS
- Date: After 2030



Acknowledgements

- Local Partners
  - Argonne National Laboratory
    - HWR (Z. Conway)
    - **Speaker – Mike Kelly**
- International Collaborators (many names!)
  - DAE Institutes
    - BARC – SSR1, SSR2, RF
    - VECC – LB650
    - RRCAT – LB650, HB650, RF
    - IUAC – LB650, SSR1
  - INFN LASA
    - LB650 (Pagani, et al.)
- FNAL
  - (P. Derwent, S. Holmes, V. Jain, S. Kazakov, D. Passarelli, Y. Pischalnikov, V. Roger)