Fermilab

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PIP-II SRF Program

Vyacheslav Yakovlev

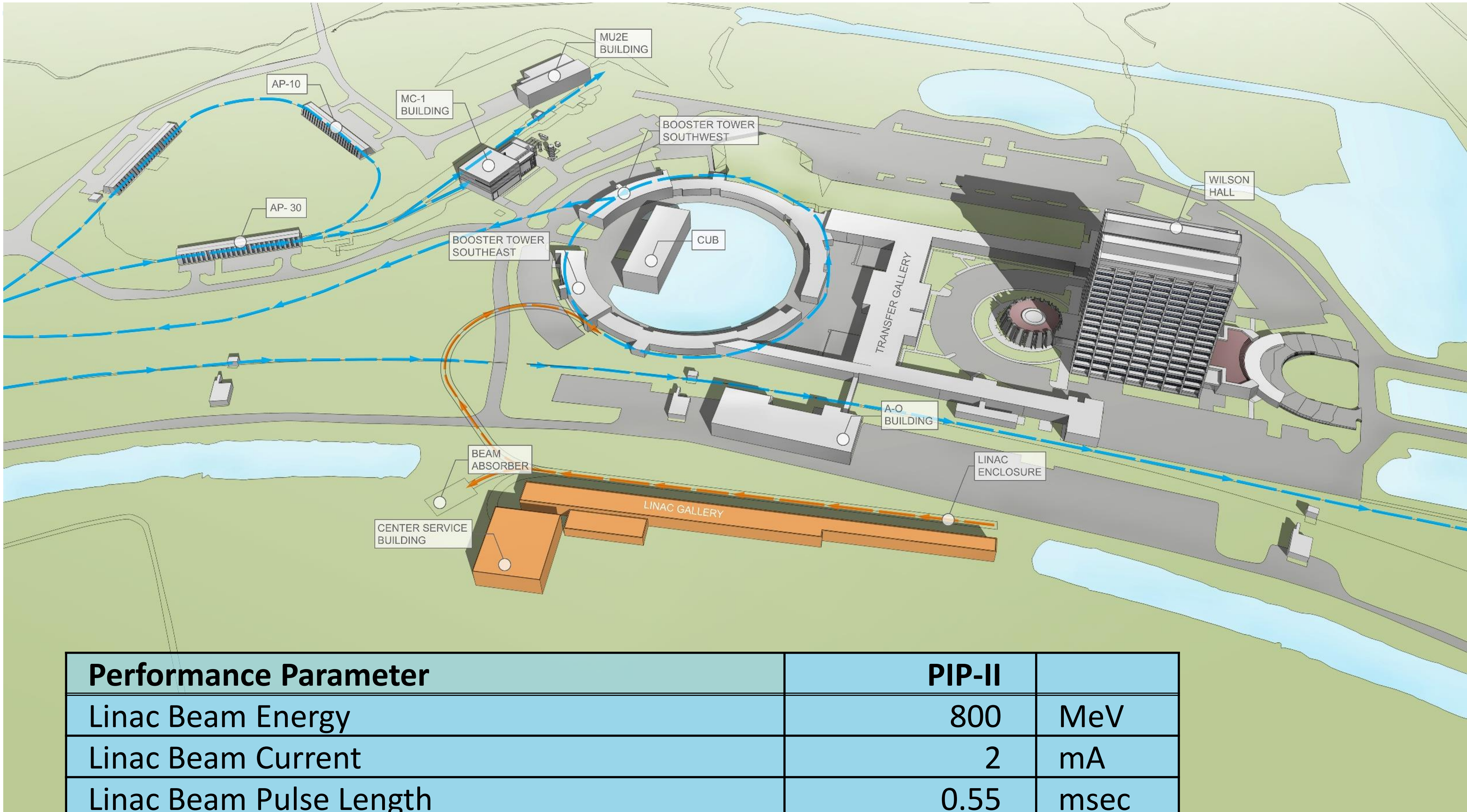
PIP-II Collaboration Meeting

9 November 2015

Outline

- The linac reference design;
- The main challenges and technical risks;
- Relevant R&D;
- Status of RF and mechanical design of CMs;
- Summary

PIP II SC Linac Requirements

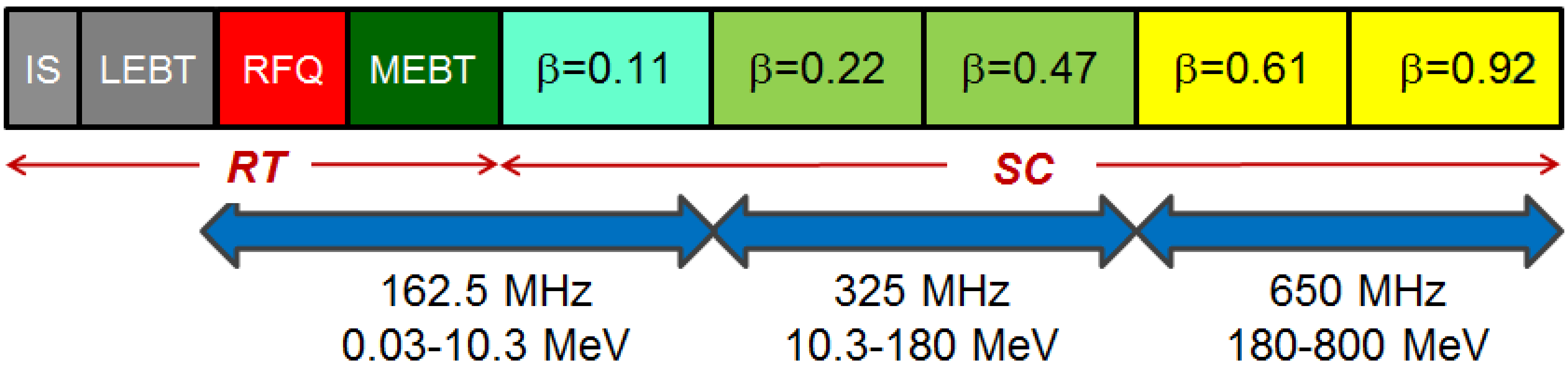


Performance Parameter	PIP-II	
Linac Beam Energy	800	MeV
Linac Beam Current	2	mA
Linac Beam Pulse Length	0.55	msec
Linac Pulse Repetition Rate	20	Hz
Linac Beam Power to Booster	18	kW

The Linac Reference Design

- The reference design is ready:
- Frequency choice: sub-harmonics of 1.3 GHz
  - 162.5 MHz, 325 MHz and 650 MHz;
- RF cavity types and betas:
  - one section of 162.5 MHz HWR type, $\beta = 0.11$ cavity,
  - two sections of 325 MHz spoke-cavity type, SSR1 and SSR2 with $\beta = 0.22$ and $\beta = 0.47$; and
  - two sections of elliptical 650 MHz cavities with $\beta = 0.61$ and $\beta = 0.92$;
- Break points are optimized in order to minimize the number of the cavities;
- CM concept:
  - separate CMs,
  - solenoids for HWR and SSR,
  - no focusing elements for elliptical.
- Operating regimes – both pulsed and CW;
- No HOM dampers.

The Linac Reference Design



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

*Warm doublets external to cryomodules

All components CW-capable

The Linac Reference Design

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

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

The main challenges and technical risks

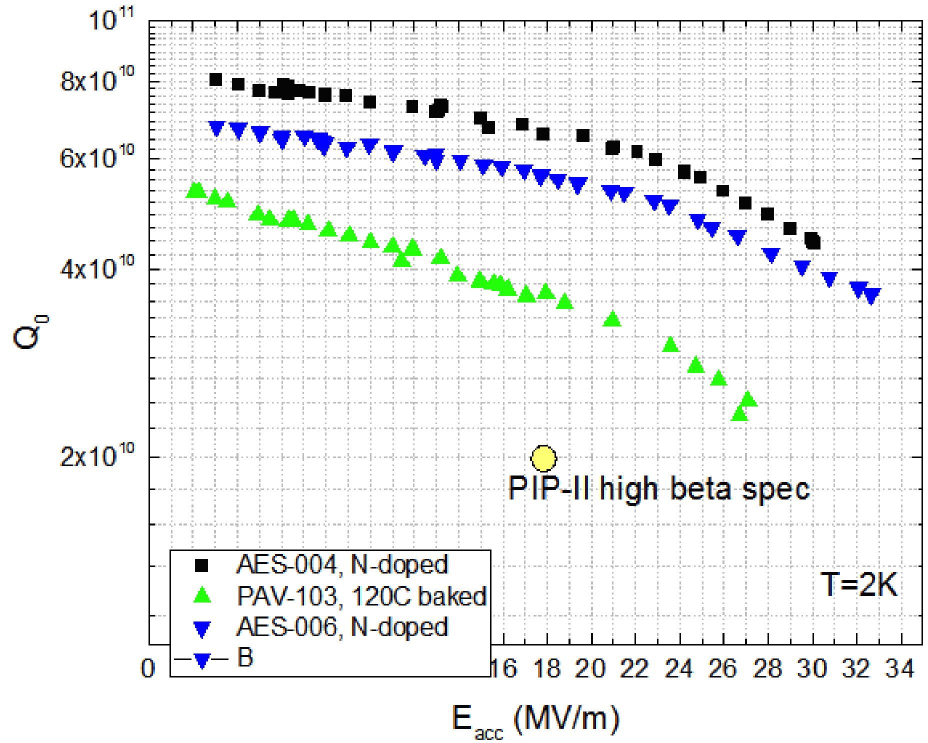
- Future CW operation → cryo-losses → high Q_0 is desired;
- Low beam loading → narrow bandwidth;
  - Pulsed regime → Lorentz Force Detune (LFD);
  - CW regime → microphonics;
- High-Order Modes → "to damp, or not to damp?"

R&D approach:

- High-Q0 program was initiated and is running successfully;
- Resonance Control program is underway in order to mitigate both microphonics and LFD;
- “Passive” mitigation of the cavity detune – improvement of cavity mechanical properties is underway;
- Detailed HOM analysis is performed.

High Q0 R&D program

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



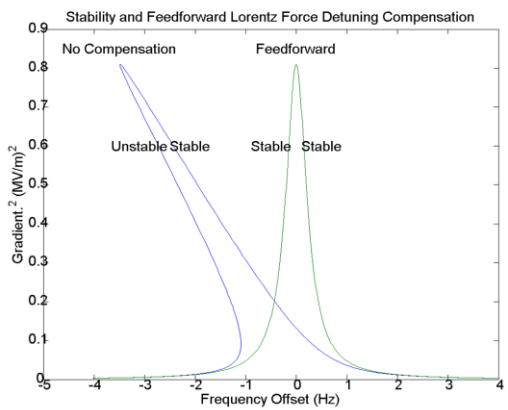
A. Grassellino, WG2

Fermilab
PIP-II

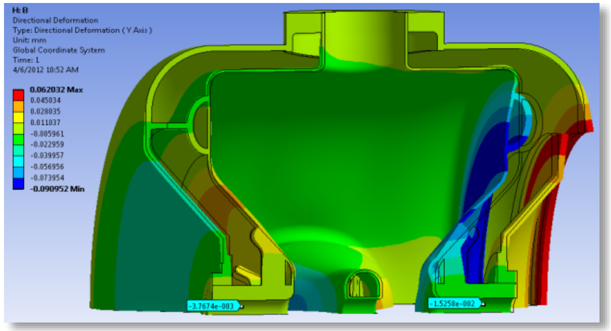
Resonance Control R&D program

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

- Capital and operating cost of machines employing narrow bandwidth cavities can increase rapidly if detuning is not controlled
  - RF plant must have sufficient overhead to maintain constant gradient during PEAK cavity detuning
- If the Lorentz force detunes the cavity by more than several bandwidths the cavity resonance can become unstable (ponderomotive instability)
- Lorentz force can excite mechanical vibrations during pulsed operation
- Active resonance stabilization will be required for successful PIP-II operation



Reduction of df/dp

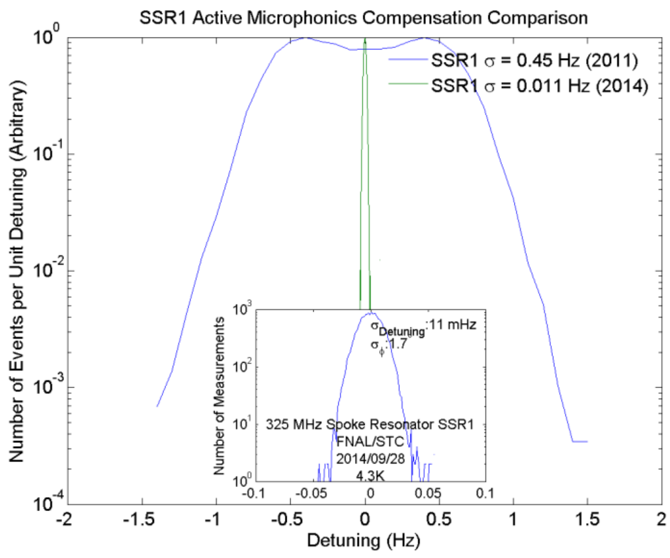


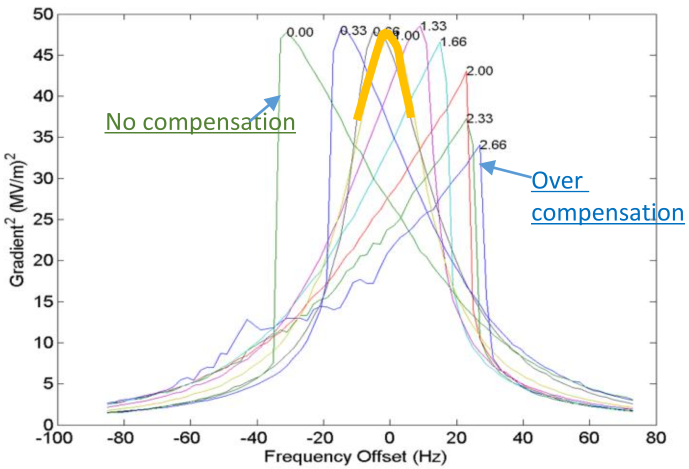
- A self-compensating design was developed allowing low sensitivity to Helium pressure fluctuations, without increasing the stiffness to frequency-tuning.
- Prototype cavity ~ **150 Hz/torr** -> New design ~**4 Hz/torr** (~40 times less)
- Ease of tuning virtually unchanged: 39 N/kHz (bare), 40 N/kHz (with He vessel)

D. Passarelli and L. Ristori, WG2

Resonance Control R&D program

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





Yu. Pischalnikov, WG2

Studies of HOMs in the PIP II

- Small beam current
- Small bunch population

Detailed simulations show:

- Beam Break Up (BBU) should not be a problem;
- "Klystron-type" longitudinal instability does not look to be a problem as well.
- Resonance excitation of the dipole modes does not look to be an issue;
- Accidental resonance excitation of the 5th monopole band in beta=0.9 section may lead to longitudinal emittance dilution, but probability is very small. However, v.2 of the cavity was designed which is free of this issue.

No HOM dampers for PIP II

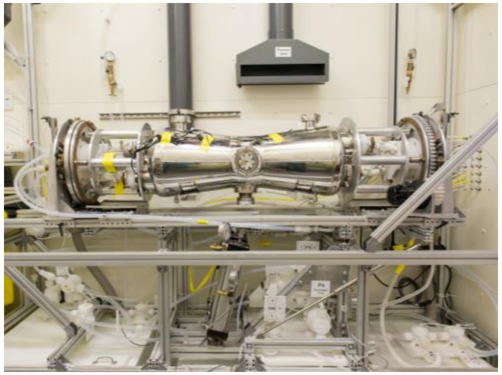
General design approach

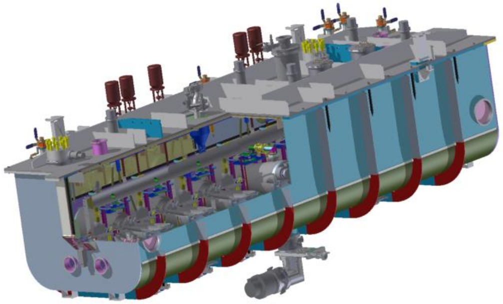
- Most components (couplers, tuners, etc.) should be of the same or similar type;
- Cryomodules should be preferably of the same type and contain mostly the same parts;
- Two types of CMs are to be prototyped,
  - spoke-cavity CM for SSR1 and
  - elliptical cavity CM for HB 650.
- Other CMs will be developed basing on the lessons learned for these CMs.
- HWR, SSR1 – installing in FY18
  - FY19 – final beam parameters (2 mA CW, 25 MeV)

Status of development of critical components. HWR

- 2 HWRs were tested with very high performance:
  - residual resistance is <2.7 nOhm at 15 MV/ m accelerating field (E_{peak}=70 MV/m, B_{peak}=75 mT and voltage = 3.2 MV with the cavity length=0.206m)
  - No X-rays observed up to 70 MV/m E_{peak}
- Fabrication of 9 cavities including helium vessel is complete.
- All remaining 7 cavities will be cold/RF tested in FY16
- The cryomodule vacuum vessel including thermal and magnetic shield delivered from the factory and is being prepared for engineering cool down to nitrogen temperature for the measurements of heat load and alignment of the strongback
- Funding is secured to complete procurement of all remaining cold mass components of the HWR cryomodule
- HWR– installing in FY18 at PXIE

P. Ostroumov, WG1





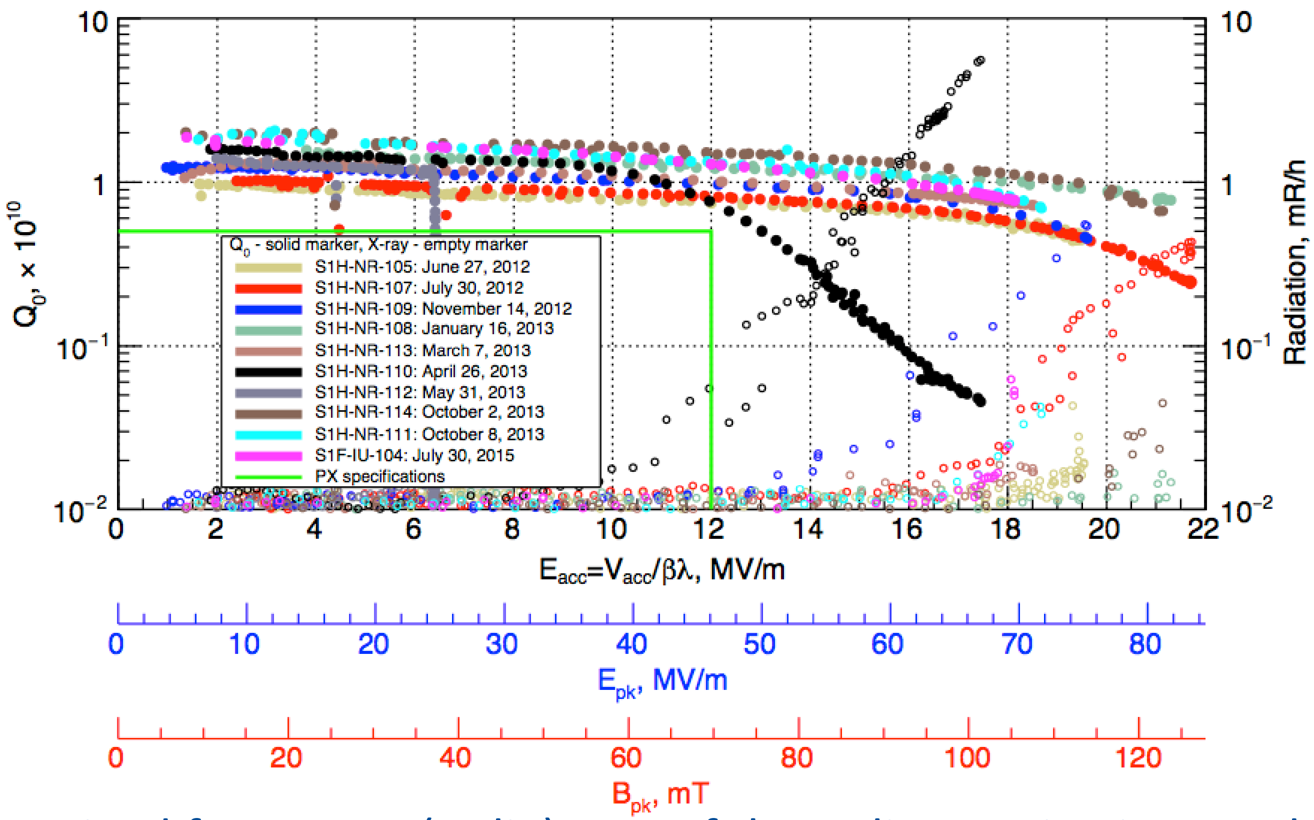
Status of development of critical components. SSR1

- All the ten bare cavities were qualified in VTS
- 9 out of 10 SSR1 cavities were jacketed with the helium vessel;
- All the components of the string assembly were ordered and many of them were received already at Fermilab
- The design of main components was validated by testing the prototypes (Jacketed cavity, Coupler, Tuner, Solenoid…)
- FY 2016 Goals:
  - Qualify all the components of the String assembly.
  - Install the entire String assembly.
  - Finalize the design of the Coldmass and tooling.
  - Advance the microphonics and LFD control.
  - Consolidate the Indian Collaboration (IIFC): SSR1 cavities.

D. Passarelli, L. Ristori, WG2

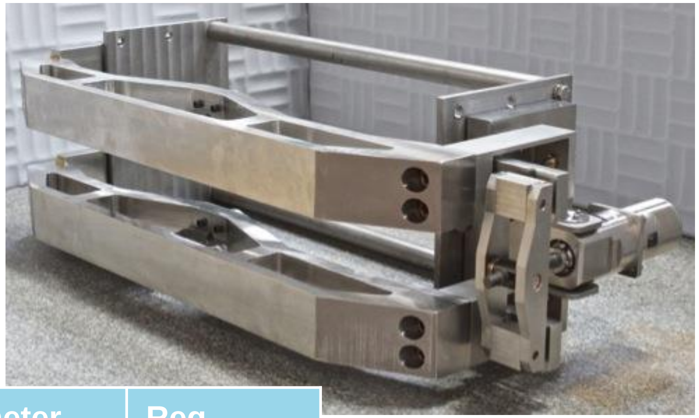
Status of development of critical components. SSR1

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



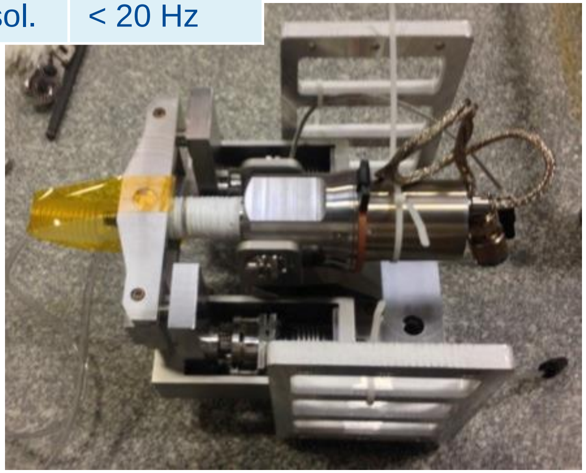
Two SSR1 cavities were received from IUAC (India) part of the Indian Institutions and Fermilab Collaboration (IIFC). The summary plot shows one IUAC cavity (S1F-IU-104, magenta) together with all Fermilab cavities tested so far.

Status of development of critical components. SSR1

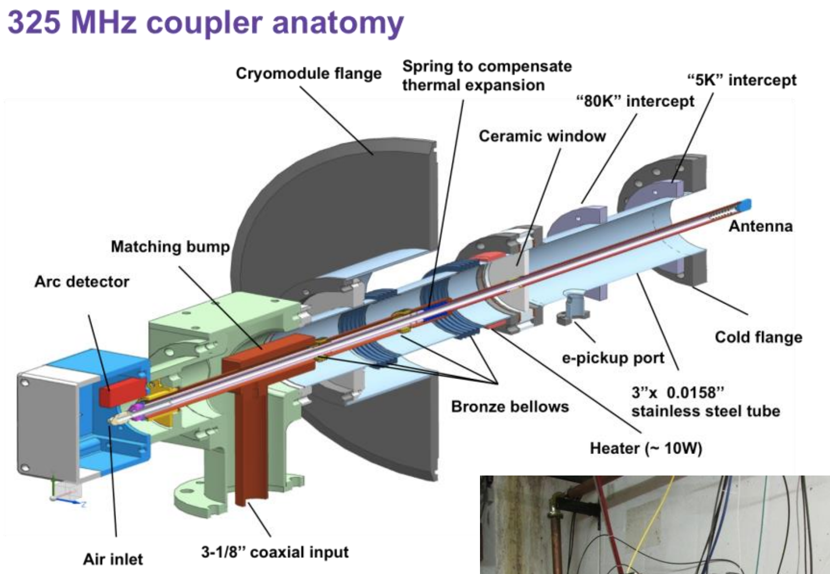


Parameter	Req.
Coarse range	> 135 kHz
Fine range	> 1 kHz
Coarse resol.	< 20 Hz

SSR1 Tuner



Cartridge with motor and piezos

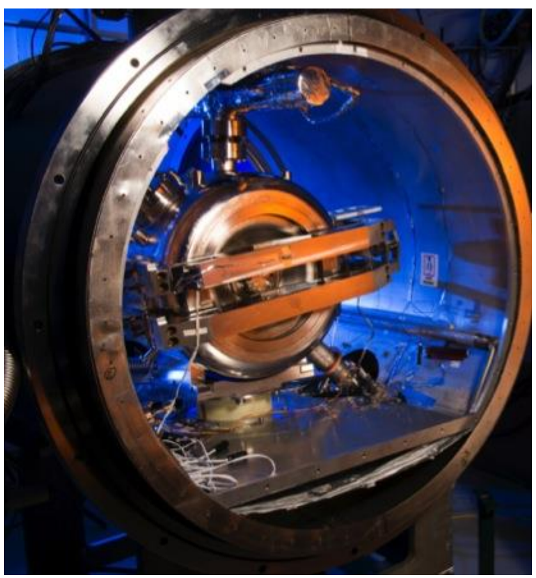


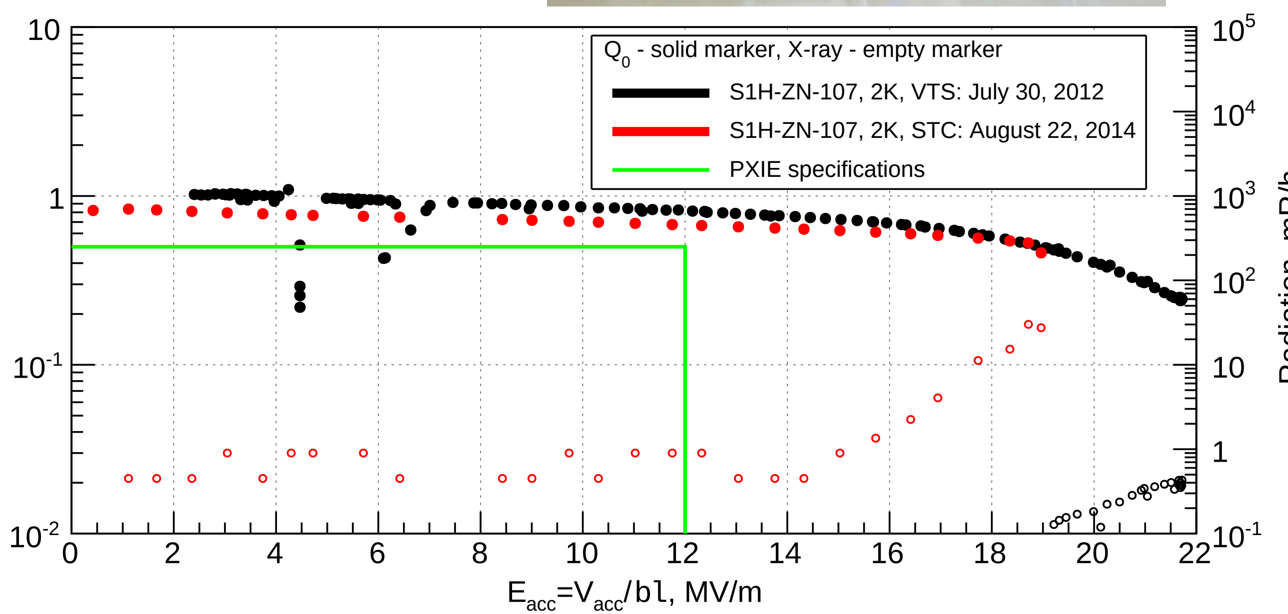
Input coupler:

Coupler test stand

Status of development of critical components. SSR1

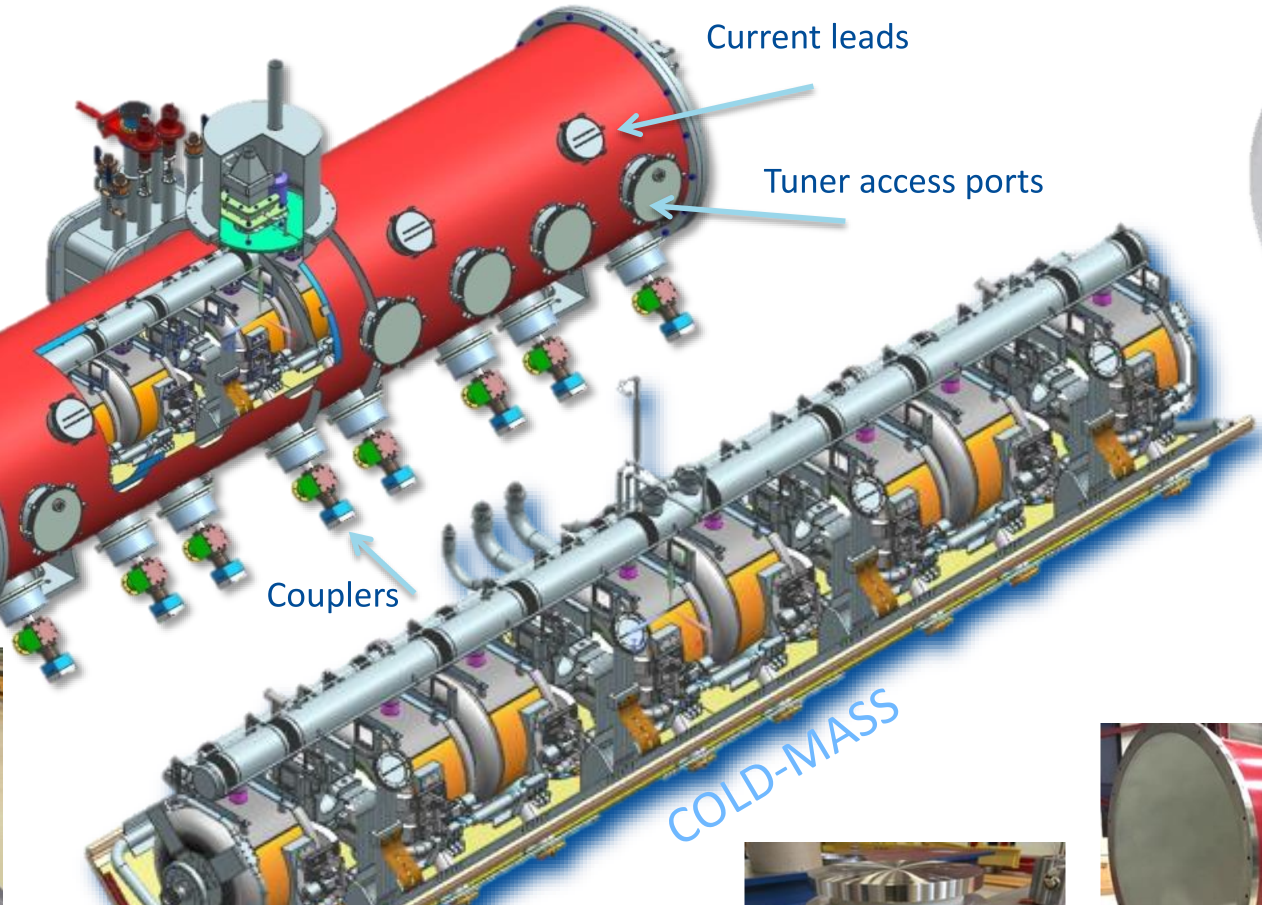
- First jacketed SSR1 successfully tested in STC at 2K. Exceeded PIP-II requirements. No degradation seen after welding process.
- Fully integrated tests with pre-production Tuner



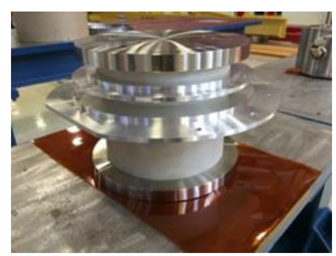


SSR1 Cryomodule

T. Nicol, WG2, D. Passarelli, WG2



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



Status of development of critical components

650 MHz section:

EM design of LB 650 and HB 650.v2* are ready.

- Six single-cell cavities HB 650.v1* are manufactured by AES, one is manufactured by RRCAT.
- Two HB 650.v1* cavities are processed and tested.
- Four 5-cell HB 650 cavities are manufactured by AES and ready for processing and tests.
- Five additional single cell and five five-cells HB 650.v1 cavities ordered from industry (PAVAC).
- Concept design of He vessel for HB 650.v2 with low df/dP and reduced LFD is completed
- Concept design of the tuners (slow and fast) is completed.

*v1 is an initial version having an aperture of 100 mm versus 118 mm for v2.

Status of development of critical components, 650 MHz

650 MHz section:

Currently Available Cavities:

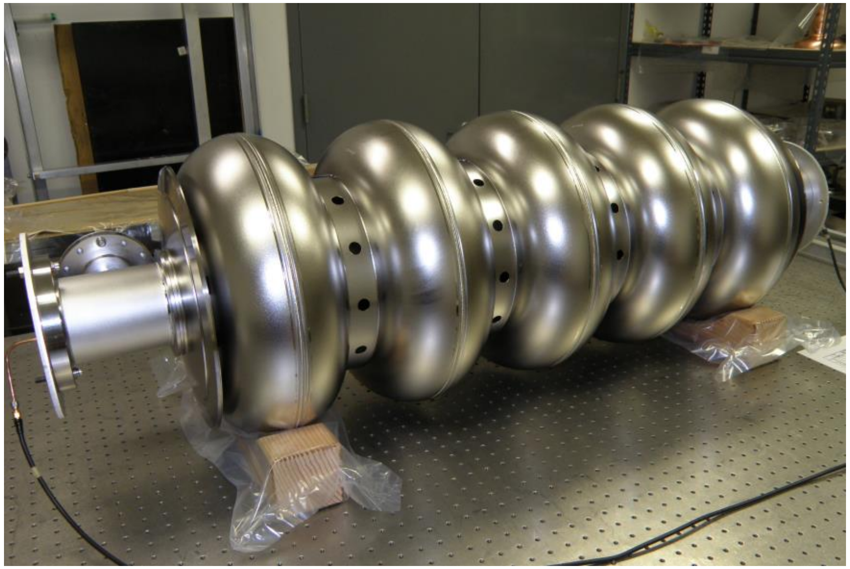
<u>1-Cell 650 MHz*</u>

1. B9AS-AES-001
2. B9AS-AES-002
3. B9AS-AES-003
4. B9AS-AES-004
5. B9AS-AES-005
6. B9AS-AES-006

<u>5-Cell 650 MHz</u>

1. B9A-AES-007
2. B9A-AES-008
3. B9A-AES-009
4. B9A-AES-010

*VTS Tested



Expected Cavities:

<u>1-Cell 650 MHz</u>

Pavac, Inc.

Three are delivered and VTS-tested

Two to be delivered in the end of 2015.

<u>5-Cell 650 MHz</u>

Pavac, Inc.

Five to be delivered in 2015.

Status of development of critical components, 650 MHz

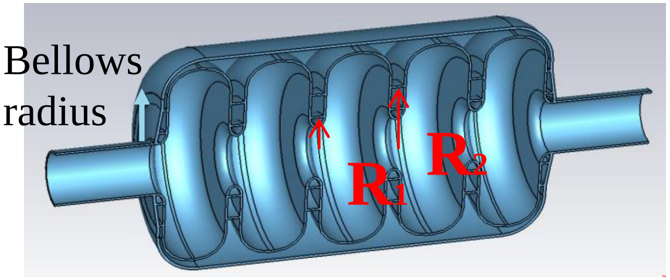
Passive Mitigation of Microphonics and LFD in LB and HB 650 Cavities

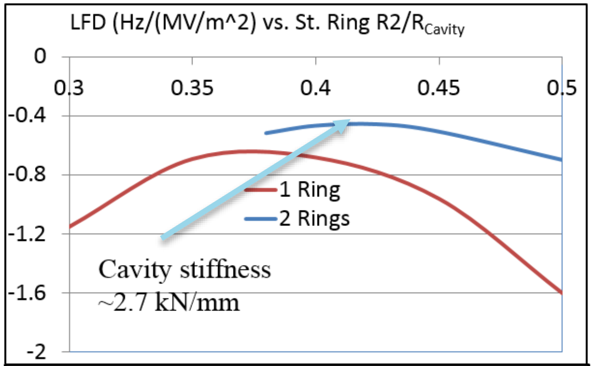
T. Khabiboulline, WG2

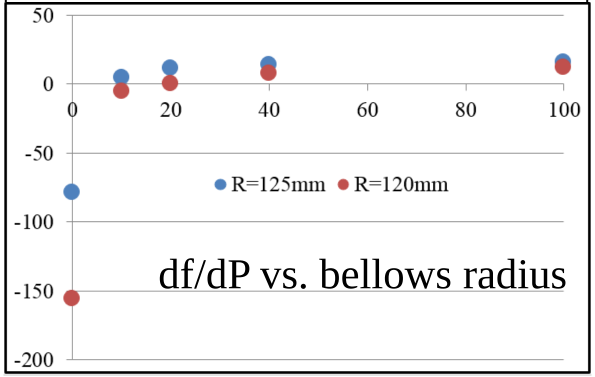
- LB650 dressed cavity optimization is in progress
- HB650 dressed cavity optimization is done
  - Stiffening ring position R=100 mm and bellow radius R=125 mm accepted
  - LFD Coefficients for tuner stiffness 80 kN/mm -0.69 Hz/(MV/m)^2
  - dF/dP for tuner stiffness 20 - 80 kN/mm is less than 12 Hz/mbar.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

Status of development of critical components, 650 MHz

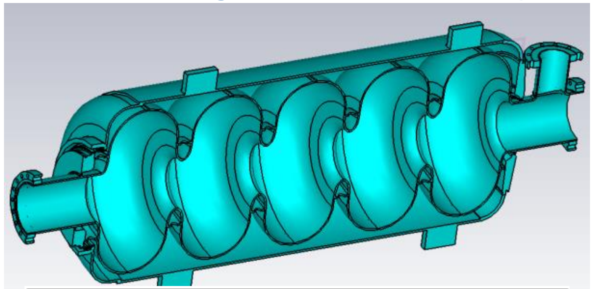
Low-Beta Cavity

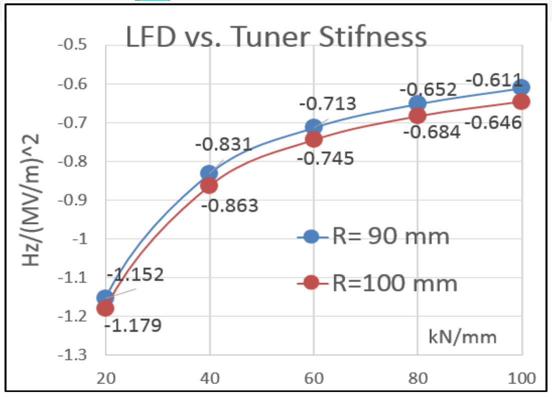


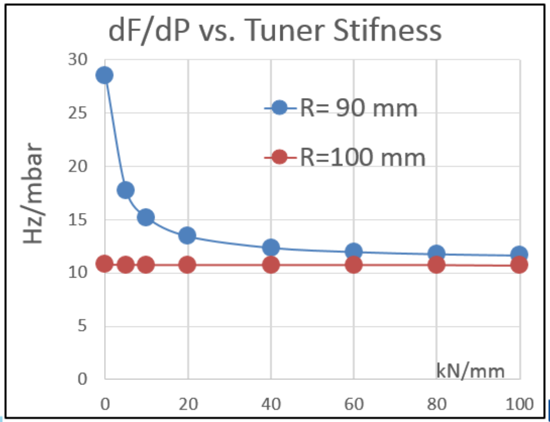




High-Beta Cavity







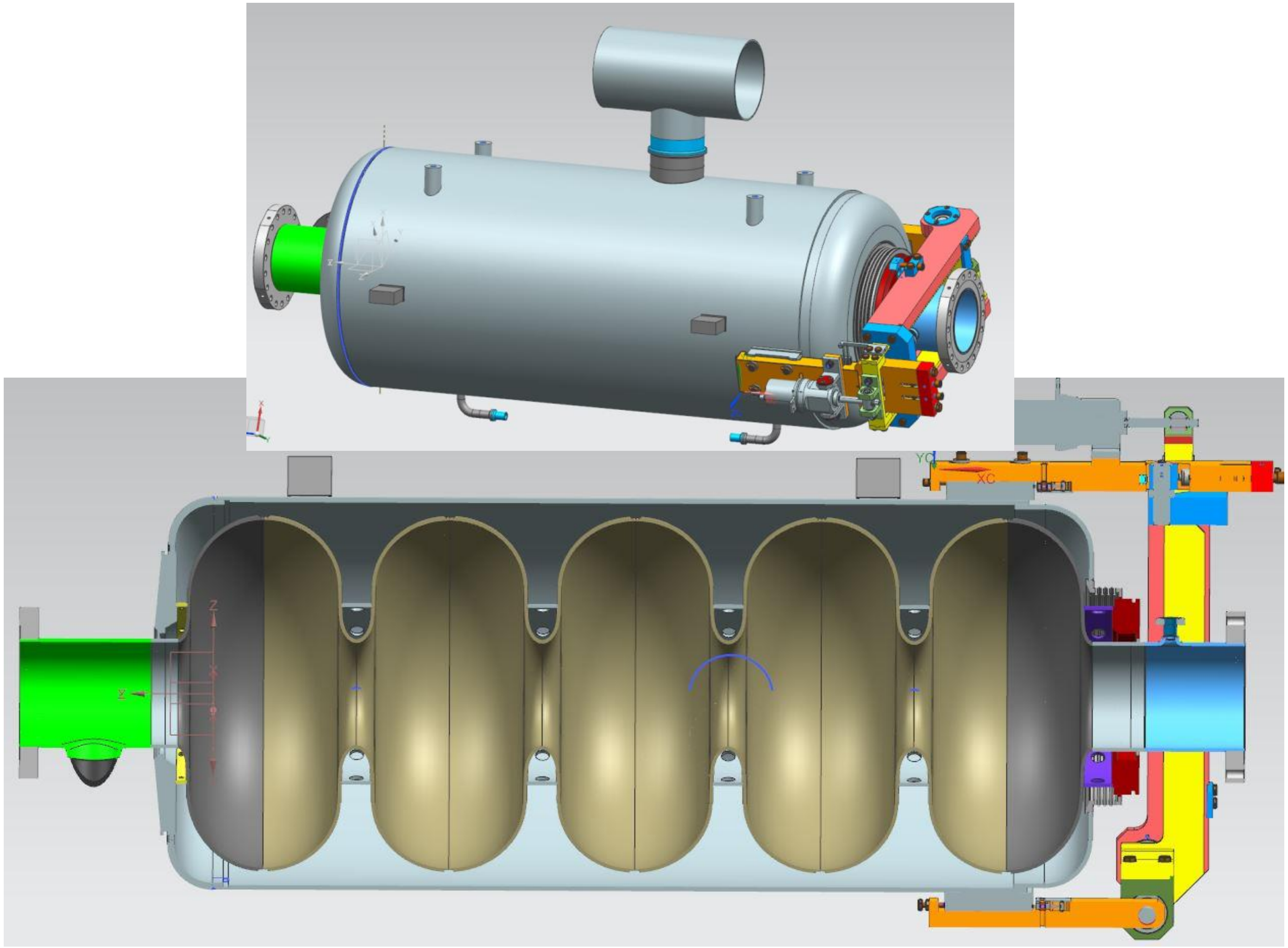
Fermilab PIP-II

Status of development of critical components, 650 MHz

Mechanical Design of HB 650 Cavities — Ch. Grimm, WG2

- Design Requirements
  - Reviewed the stiffening ring locations and thickness of Nb-Ti Spool parts which help satisfy the FRS for dF/dP and LFD
  - Overview of the reduced diameter of the helium vessel bellow, which also has an impact on reducing dF/dP
- Design Issues
  - Study the welding sequence of endgroups and bare cavity for manufacturability
  - Looked at what is required for N-Doping of the Bare Cavity and what is needed post-doping with helium vessel interface parts
  - Reviewed the assembly and welding sequence for dressing the cavities with a helium vessel
- India Deliverables
  - Displayed the first 650 MHz β=0.9 single-cell cavity built and delivered by RRCAT
  - Stated the current deliverables for multi-cell cavities to be tested at FNAL and eventually installed in the first cryomodule

Status of development of critical components, 650 MHz

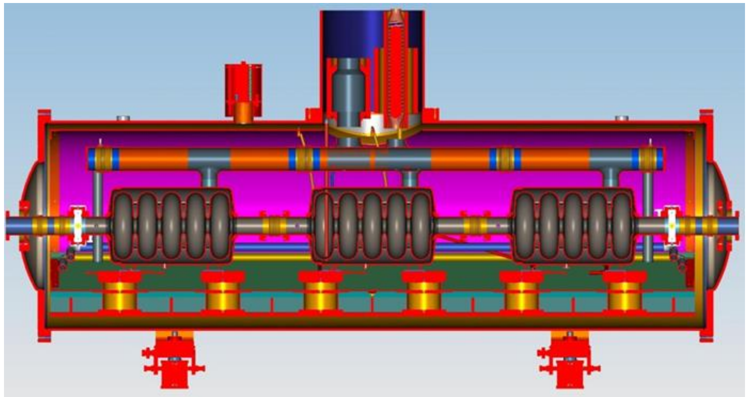


All Analysis Performed as a Dressed Unit

Status of development of critical components, 650 MHz CMs

Low-Beta Cryomodule

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

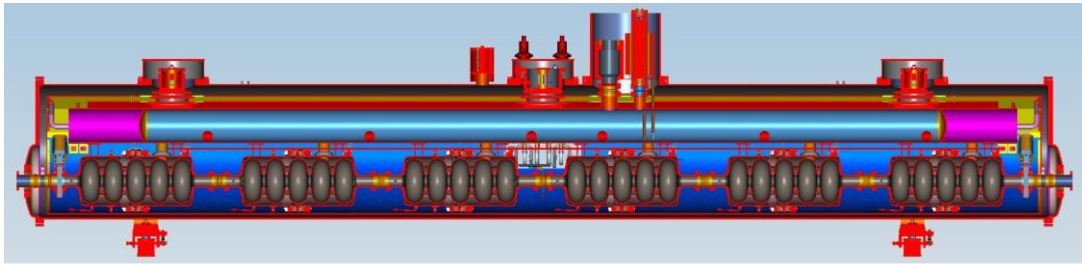


Concept 1 (room temperature strongback)

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

High-Beta Cryomodule

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



Concept 2 (XFEL-like design)

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

T. Nicol, WG2

Status of development of critical components (6/1/2015)

- SRF Development Status

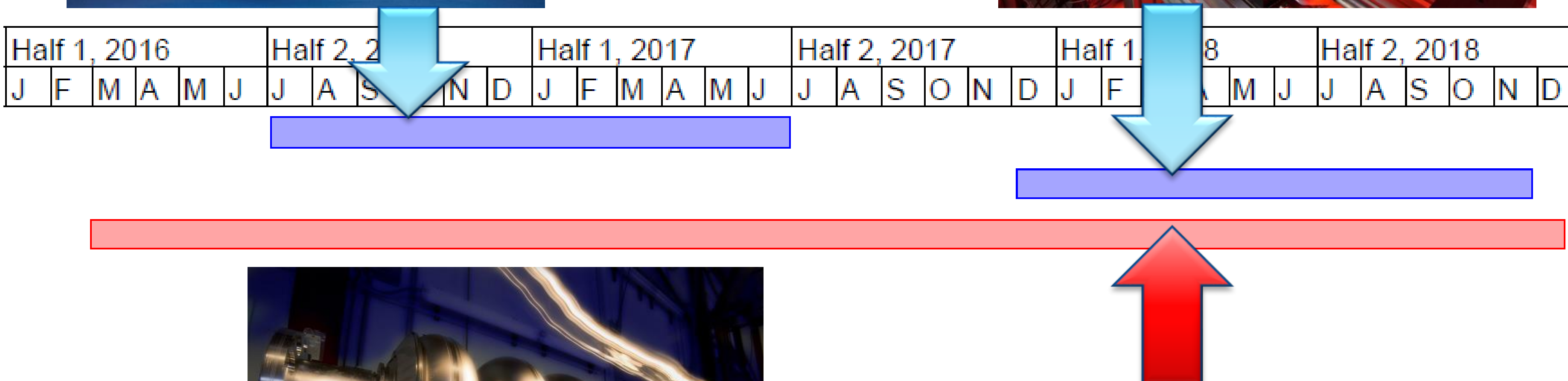
Cavity	Frequency	Cavity Type	Beta	Collaboration?	Cavity EM Design Complete	Cavity Mech Design Complete	Single Cell / Prototype Ordered	Full Cavity Prototype Received	Prototype Tested	Cavities for CM Ordered	Cavities for CM Received	Cavities for CM Tested	Cavities for CM Dressed	CM Cold Mass Design	CM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

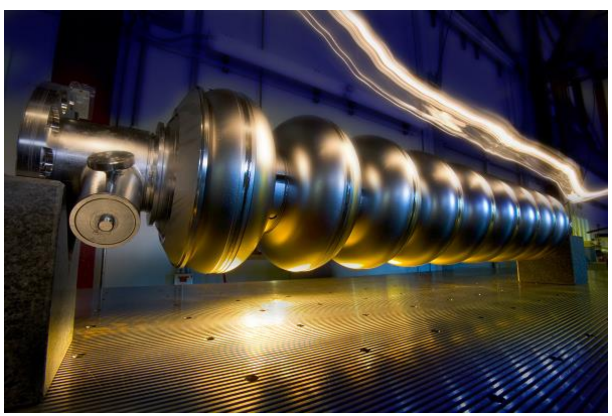
- Green: complete
- Yellow: in progress
- Red: not started

Cryomodule Assembly Conflict

S. Posen

PIP II





LCLS II

Fermilab

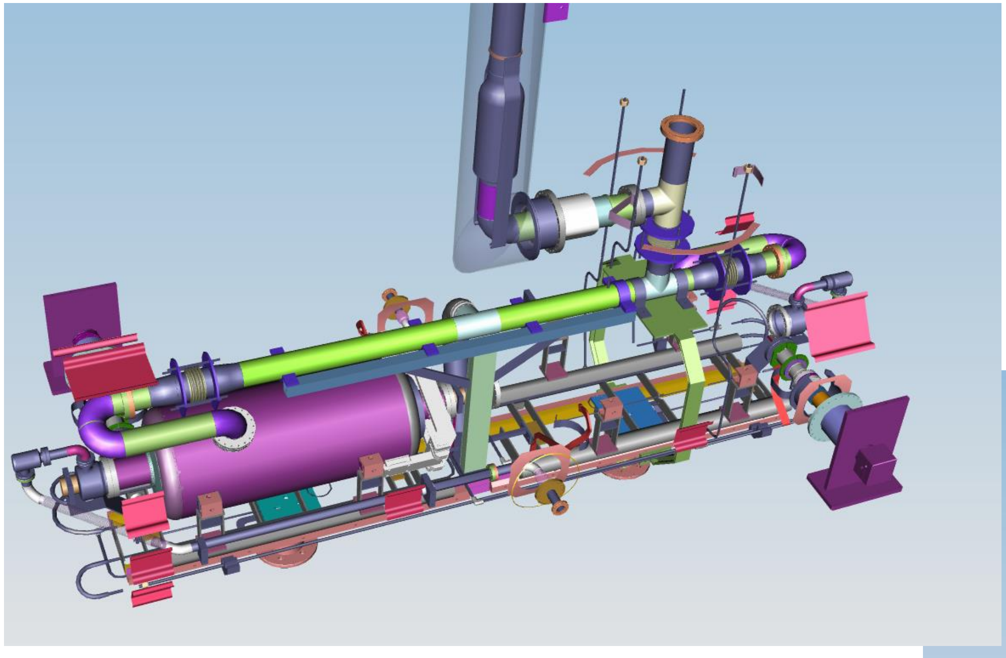
Completed Cleanroom at LAB2

HTS-2 Facility – Overview

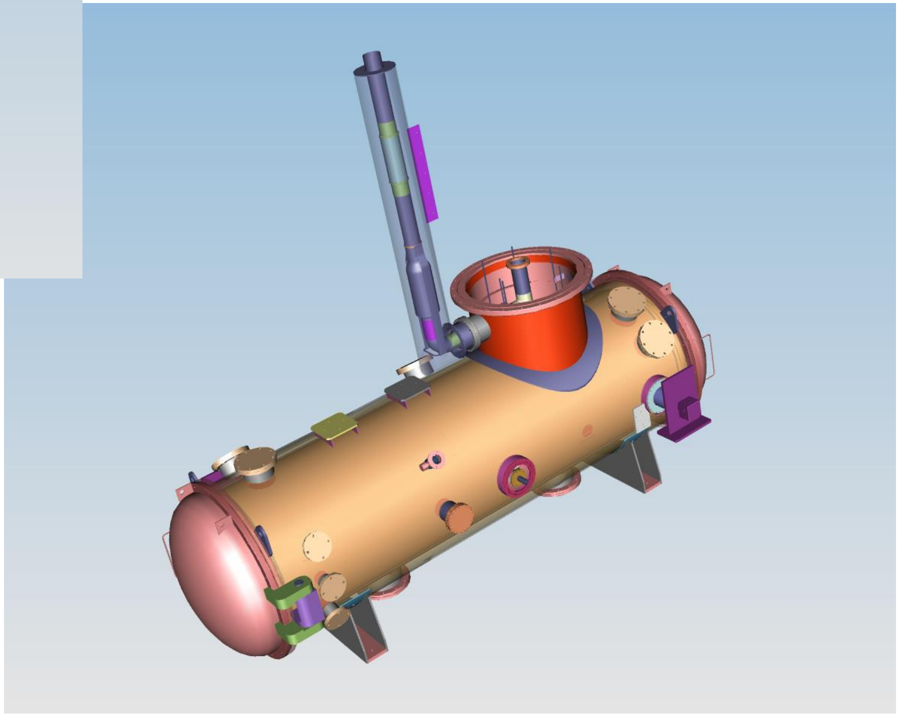
J. Ozelis, WG2

- A new horizontal test facility at FNAL, called HTS-2, is being established to meet the needs of the PIP-II SRF program, as a collaborative effort between Fermilab and the Indian Institutes Collaboration for PIP-II.
- We will leverage the developments/contributions being pursed in RF, LLRF, Controls etc., as part of the existing IIFC R&D program for HTS-2. Detailed deliverable specifications for some systems (LLRF, controls) remain to be developed.
- Fabrication Specification (SOW) for HTS-2 cryostat completed end of July 2015 and after internal review is now out for vendor bid.
  - Expect fabrication completed, shipped to RRCAT Feb 2017
- FNAL is preparing the facility to accept an integrated HTS-2 and commission it in FY18.
- First dressed 650MHz cavity test planned for 1^{st} quarter CY2018.

HTS-2 Facility – Details : Cryostat Design



- Preliminary Design Review 8/2013
- Intermediate Design Review 11/2014
- Procurement Readiness Review 3/2015
- Fabrication Specification (SOW) for vendors completed end of July 2015
- After internal review FS is now out for vendor bid



- Based on procurement timeline from RRCAT, expect:
  - Purchase sub-committee and committee approvals by end of Jan 2016
  - RRCAT Council and DAE approvals by mid-April 2016
  - PO placed May 2016
  - Fabrication completed, shipped to RRCAT Feb 2017

Summary

- The linac reference design is ready;
- The main challenges and technical risks are identified;
- Relevant R&D are organized and are in progress;
- The concept design of most critical parts is done;
- The low energy part of the linac is in process of fabrication;
- We work intensively in the frame of IIFC collaboration on the 650 MHz CM design;
- LCLS II activity is well-aligned to PIP II and is very beneficial to it.