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SRF Development for PIP-II: Status and Challenges

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17th International Conference on RF Superconductivity (SRF 2015)

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Outline

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

Proton Improvement Plan II (PIP-II) mission

❑ Particle Physics Project Prioritization Panel (P5) Science Drivers:

- Use the Higgs Boson as a New Tool for Discovery
- Pursue the Physics Associated with Neutrino Mass
- Identify the New Physics of Dark Matter
- Understand Cosmic Acceleration : Dark Energy and Inflation
- Explore the Unknown : New Particles, Interactions, and Physical Principles

❑ Proton Improvement Plan II (PIP-II):

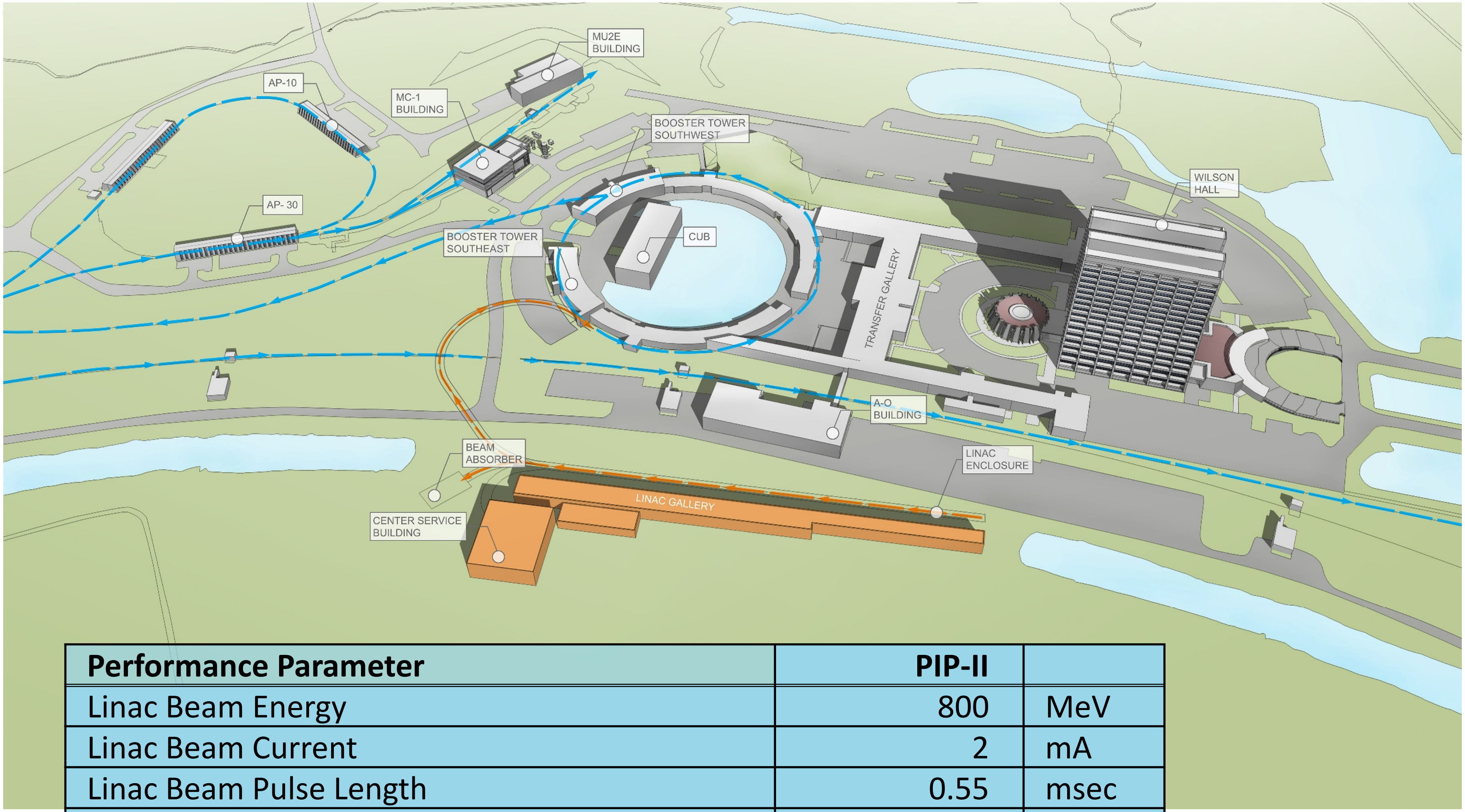
The PIP-II goal is to support long-term physics research goals by providing increased beam power to neutrino experiments, while providing a platform for the future.

Proton Improvement Plan II (PIP-II) mission and strategy

- Increase Main Injector power
  from 700 kW (NOvA) to >1 MW (LBNF)
  in the energy range 60 – 120 GeV
- Increase Booster power from 80 to 160 kW
  - 8 GeV program: SBNE, …
- Future upgrades
  1. Mu2e at 0.8 GeV and ~100 kW
  2. Beam power to LBNF to >2 MW
  3. Provide a platform supporting a high duty factor/CW operation for future intensity frontier experiments
- Goal is 1 MW in 2024
- Construction phase is 5 years: 2019-23

⇒ CD-3 in FY19/20
  - CD-2/3a in FY18
  - CD-1 in FY16/17
  - CD-0 in FY15
- The DOE has signed a major SRF agreement with India to co-develop an ~1 GeV CW SRF proton accelerator.

PIP II SC Linac Requirements

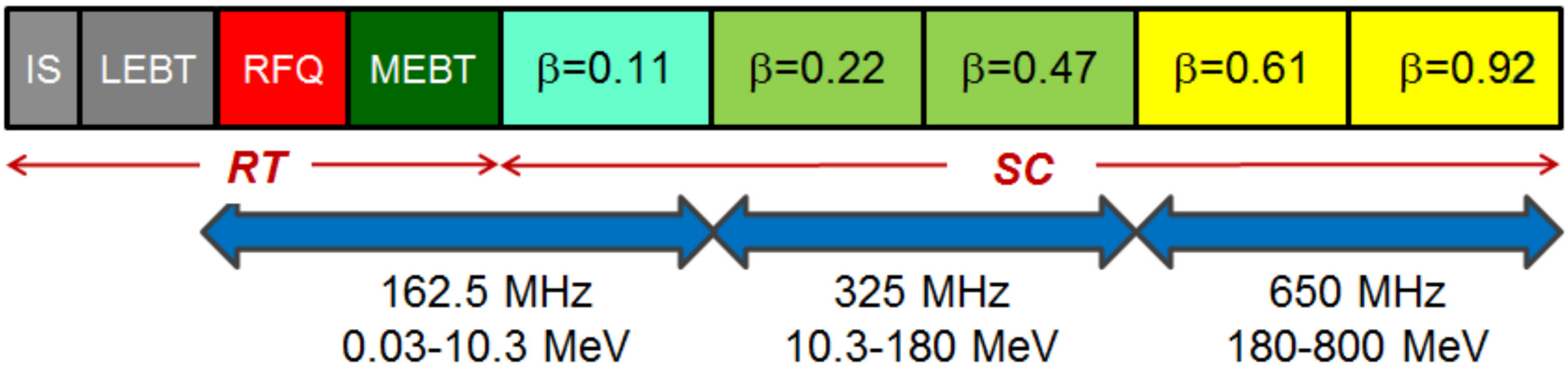


Performance Parameter	PIP-II	
Linac Beam Energy	800	MeV
Linac Beam Current	2	mA
Linac Beam Pulse Length	0.55	msec
Linac Pulse Repetition Rate	20	Hz
Linac Beam Power to Booster	18	kW

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 ($E_{peak} \gtrsim 40$ MV/m – field emission; $B_{peak} \gtrsim 70$ mT);

The main challenges and technical risks

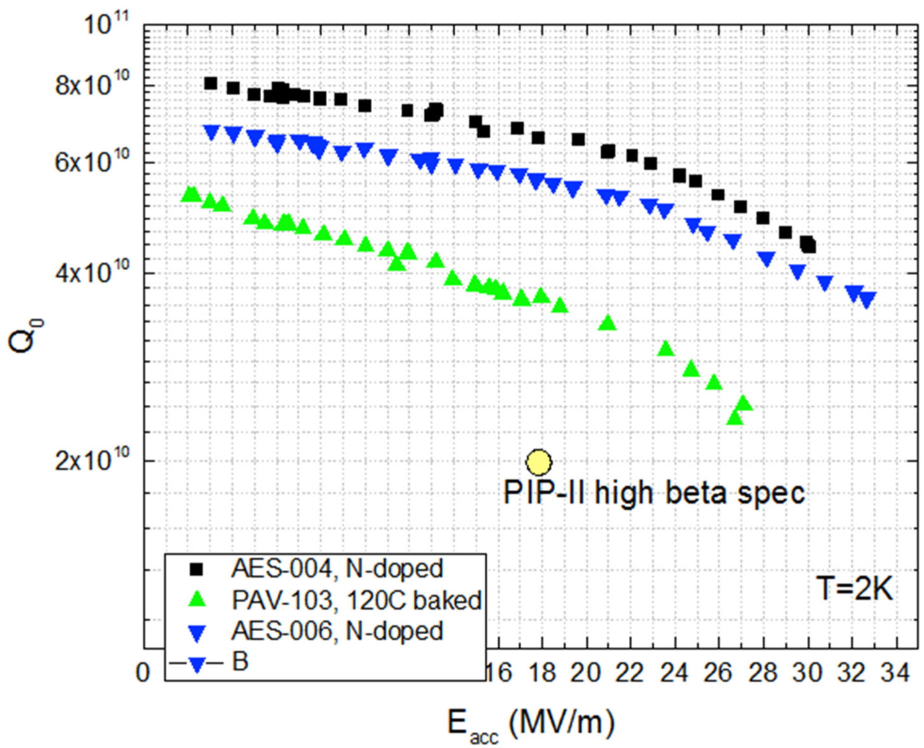
- Future CW operation → cryo-losses → high Q_0 is desired;
- Low beam loading → narrow bandwidth;
  - Pulsed regime → Lorentz Force Detune (LFD);
  - CW regime → microphonics;
- High-Order Modes → “to damp, or not to damp?”

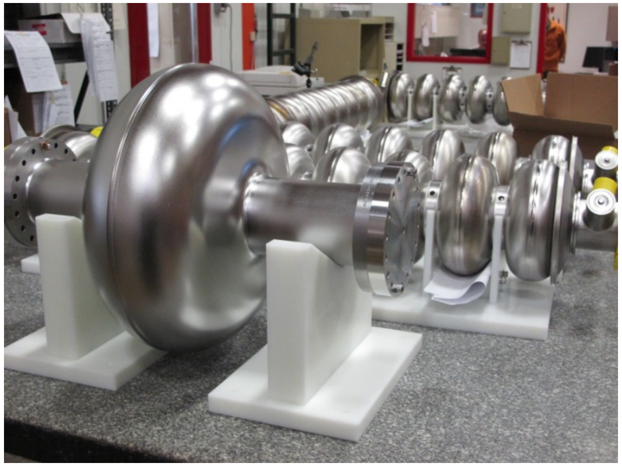
R&D approach:

- 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)



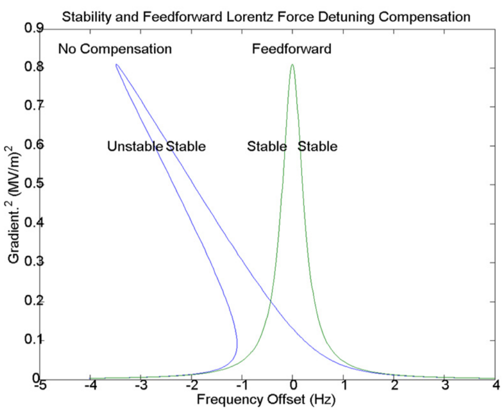


A. Grassellino, MOYGB2, IPAC15, Richmond; **MOBA06, MOPB029, MOPB091**

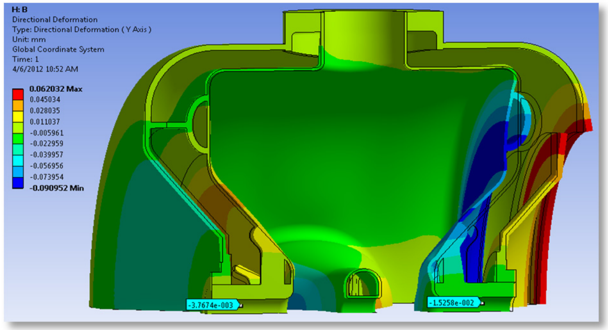
Resonance Control R&D program

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

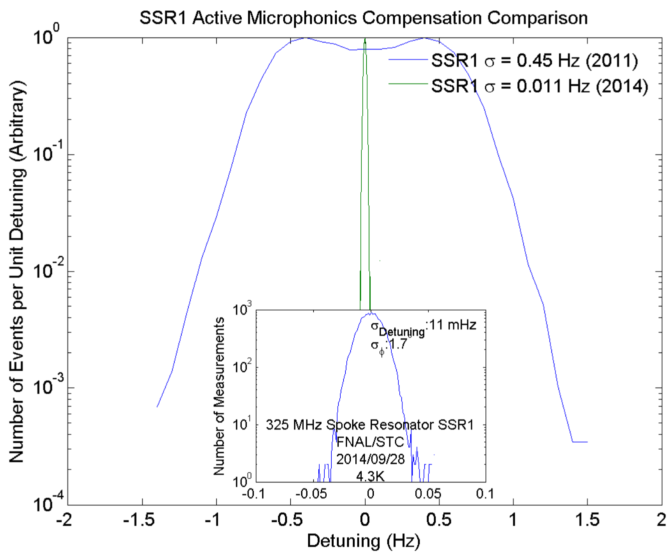


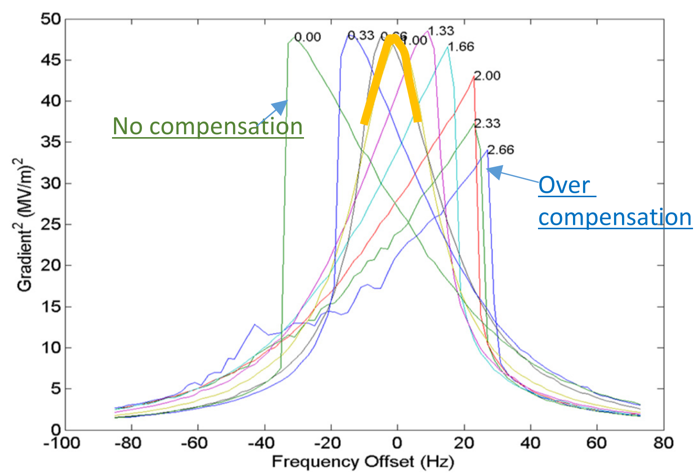
- A self-compensating design was developed allowing low sensitivity to Helium pressure fluctuations, without increasing the stiffness to frequency-tuning.
- Prototype cavity ~ **150 Hz/torr** -> New design ~**4 Hz/torr** (~40 times less)
- Ease of tuning virtually unchanged: 39 N/kHz (bare), 40 N/kHz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

D. Passarelli, L. Ristori, IPAC12

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





Poster TUPB095
"Resonance Control for Narrow Bandwidth SRF Cavities"

(W. Schappert, Yu. Pischalnikov, J. Holzbauer)

Studies of HOMs in the PIP II

- Small beam current
- Small bunch population

Detailed simulations show:

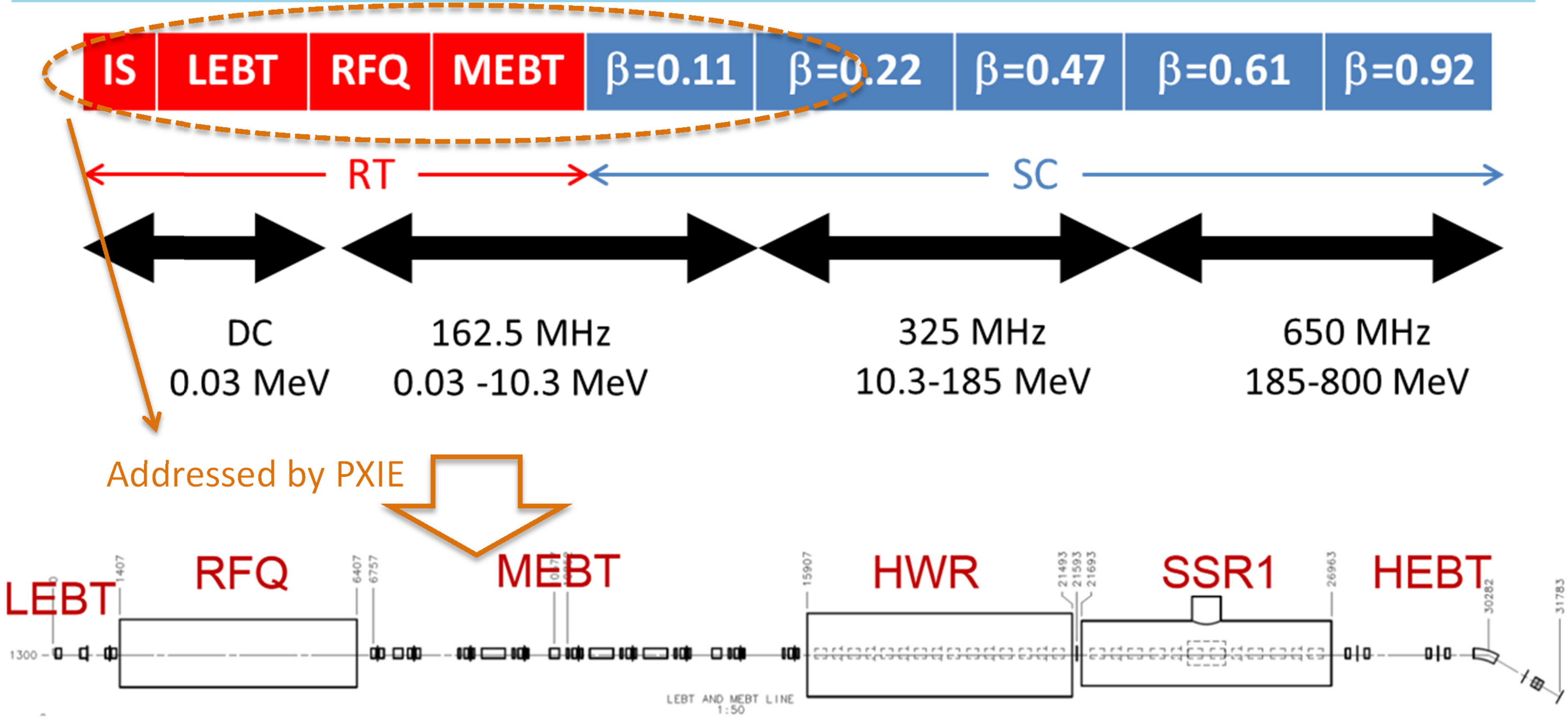
- Beam Break Up (BBU) should not be a problem;
- "Klystron-type" longitudinal instability does not look to be a problem as well.
- Resonance excitation of the dipole modes does not look to be an issue;
- Accidental resonance excitation of the 2d monopole band in beta=0.9 section may lead to longitudinal 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.

PXIE: R&D program for PIP-II front end



30 keV H-, 5 mA from 1 µs to DC

2.1 MeV, CW 4-vane, 4- module. Designed and manufactured at LBNL.

~10 m, with bunch-by-bunch selection. Magnets are being made by BARC, India.

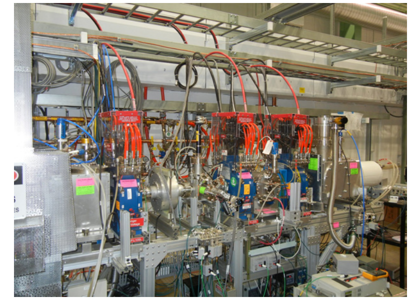
162.5 MHz, 10 MeV. Designed and being manufactured at ANL.

325 MHz, 25 MeV.

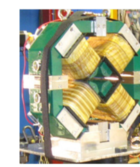
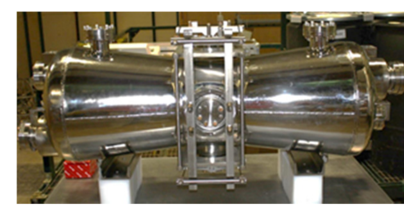
Diagnostics and 2 mA CW, 25 MeV dump.

PXIE: R&D program for PIP-II front end

- LEBT- fully commissioned.
- RFQ - Being prepared for shipment to Fermilab.
- MEBT - Components are under development
  - First section will be used for RFQ beam characterization
  - FY17- full-length with prototype components of the chopping system
  - FY18- bunch-by-bunch selection
- HWR, SSR1 – installing in FY18
  - FY19 – final beam parameters (2 mA CW, 25 MeV)



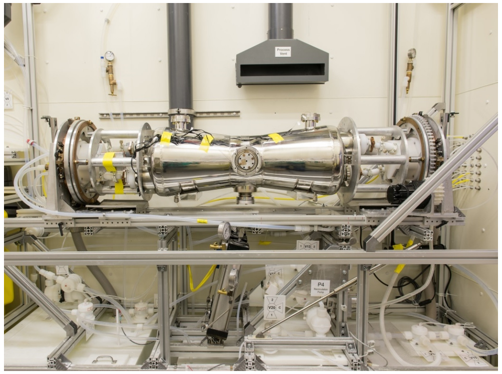


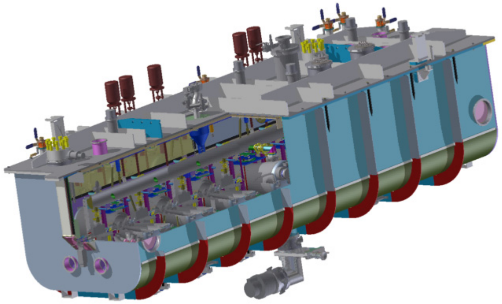



Status of development of critical components. HWR

- 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 8 cavities including helium vessel is complete, the 9th cavity (spare) is being jacketed this month.
- 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

Z. Conway, WEBA05
"Achieving high peak fields and low residual resistance in half-wave cavities"





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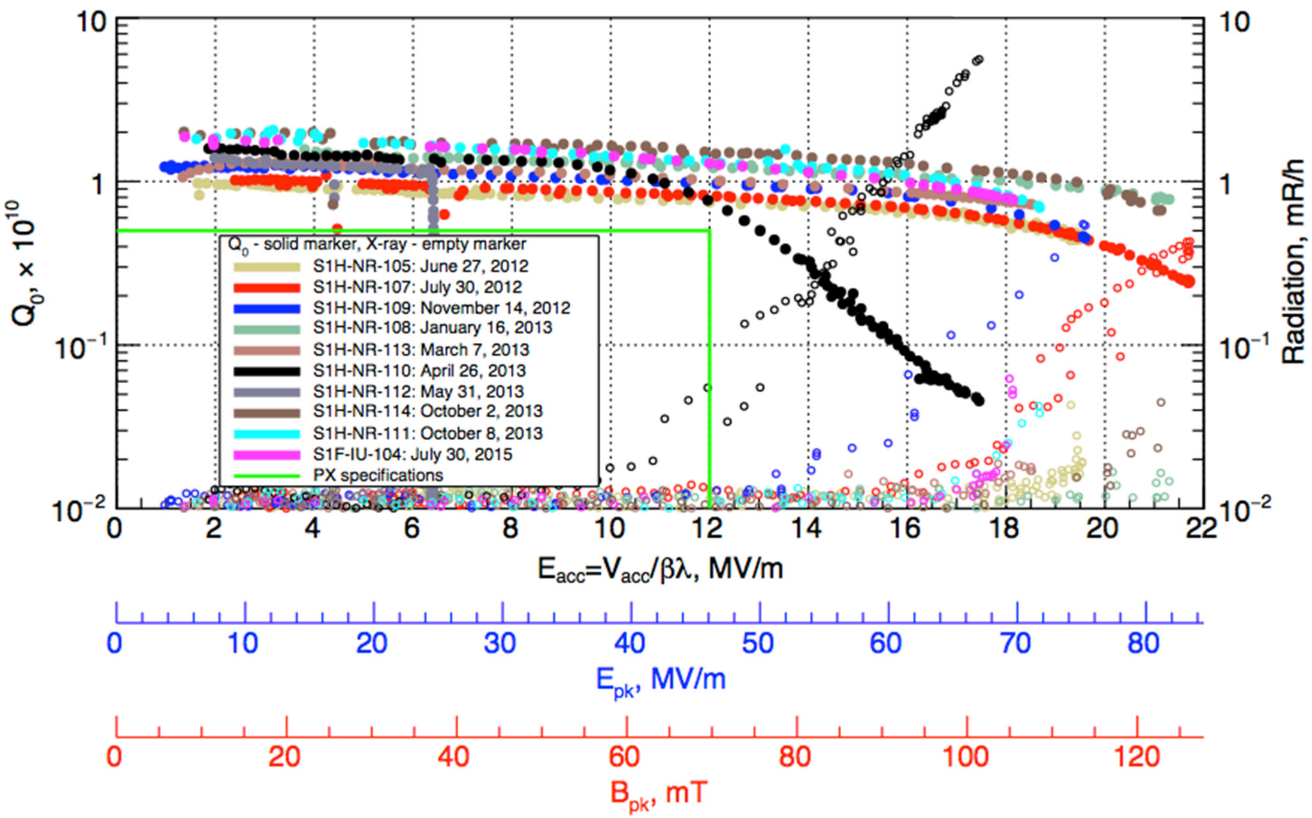
Status of development of critical components. SSR1

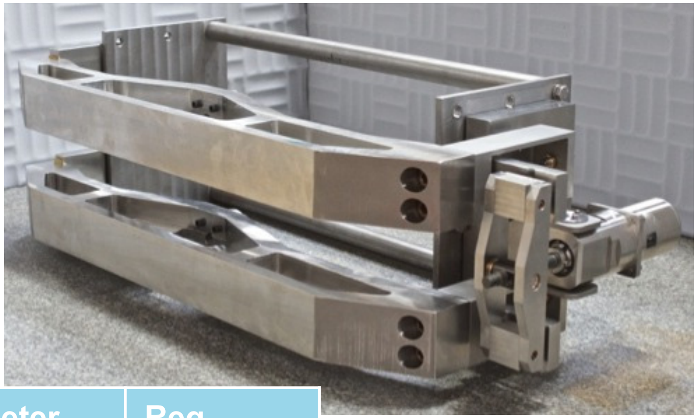
SSR1 cavities (Q_0 vs E_{acc} @ 2K)

TUPB073



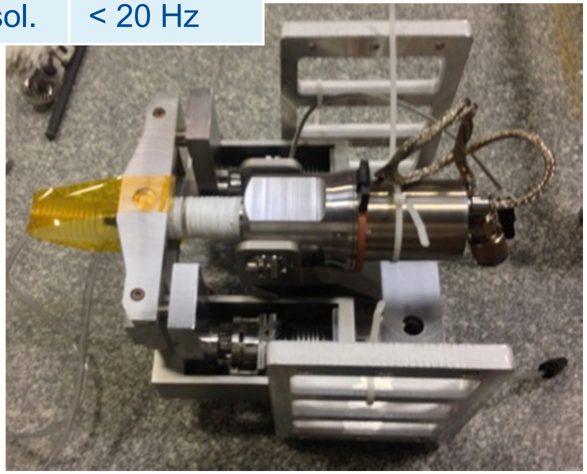
*Two SSR1 cavities were received from IUAC (India) part of the Indian Institutions and Fermilab Collaboration (IIFC). The summary plot shows one IUAC cavity (S1F-IU-104, magenta) together with all Fermilab cavities tested so far.

Status of development of critical components. SSR1



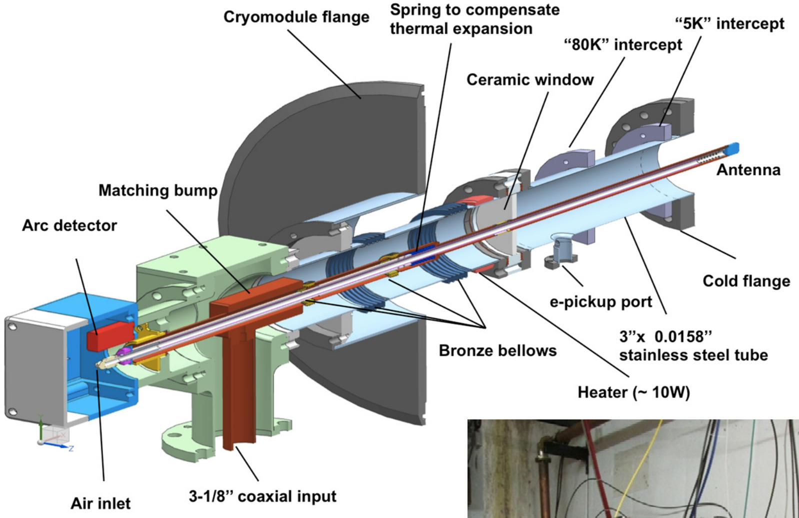
Parameter	Req.
Coarse range	> 135 kHz
Fine range	> 1 kHz
Coarse resol.	< 20 Hz

SSR1 Tuner



Cartridge with motor and piezos

325 MHz coupler anatomy



Input coupler:

Coupler test stand

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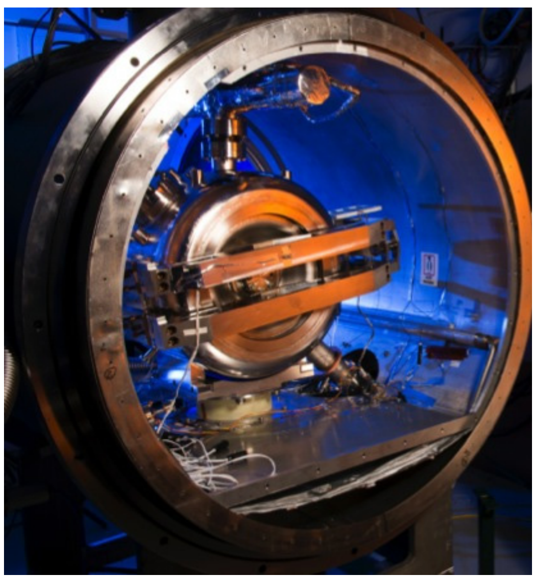
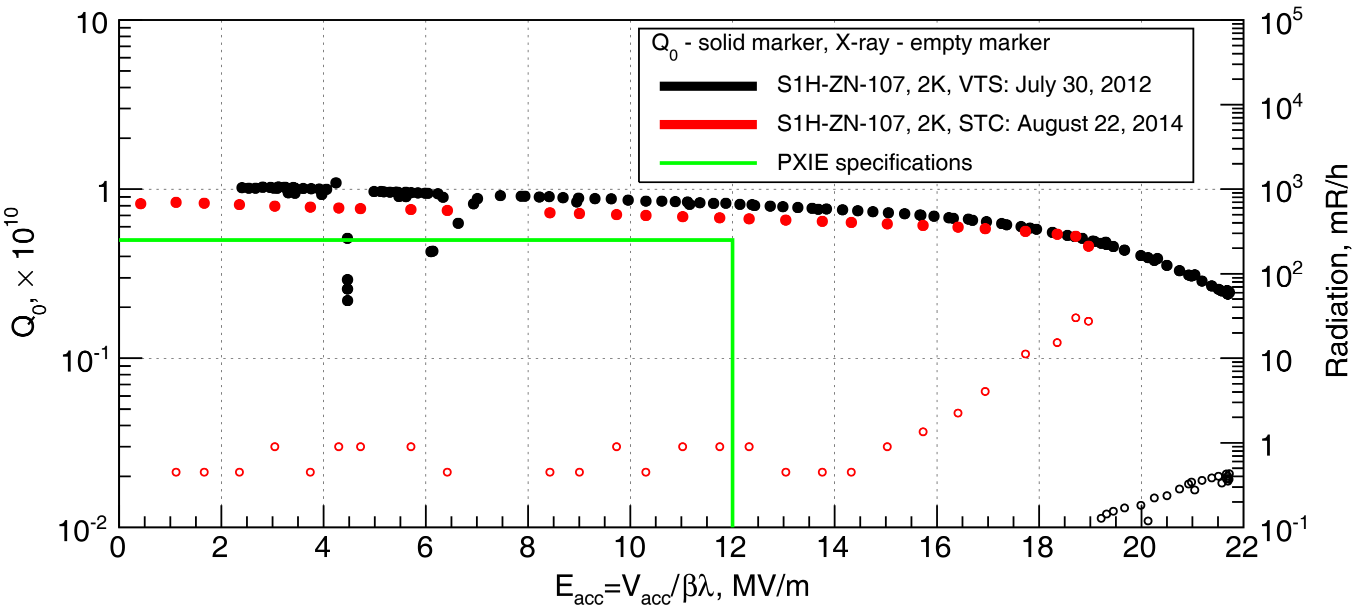
Status of development of critical components. SSR1

- First jacketed SSR1 successfully tested in STC at 2K. Exceeded PIP-II requirements. No degradation seen after welding process.
  - http://accelconf.web.cern.ch/AccelConf/LINAC2014/papers/mopp055.pdf
- Fully integrated tests with pre-production Tuner (TUPB061)

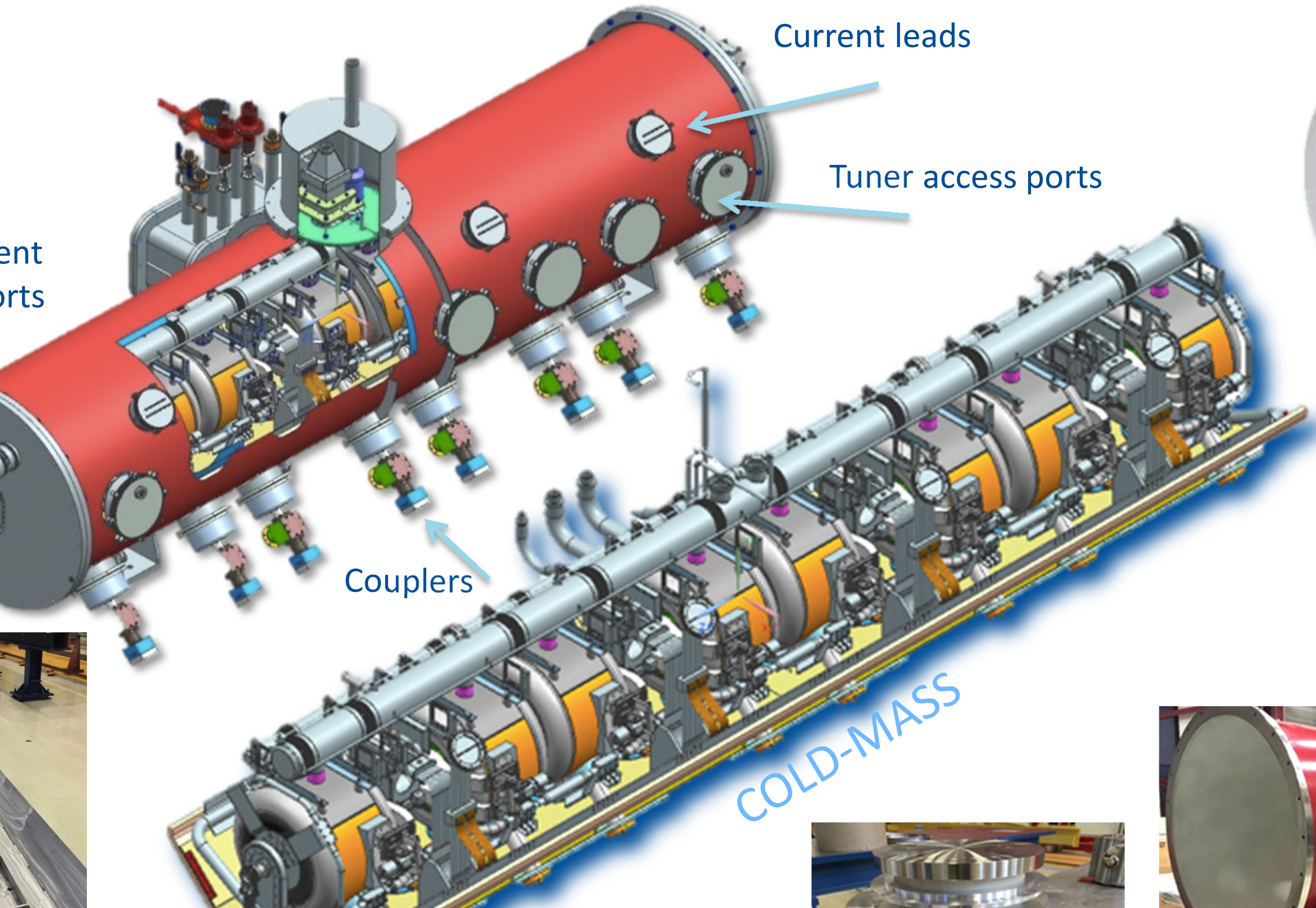




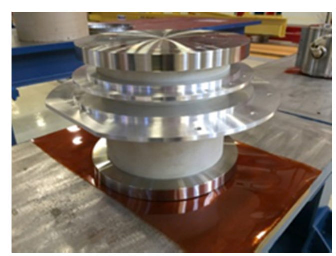
SSR1 Cryomodule

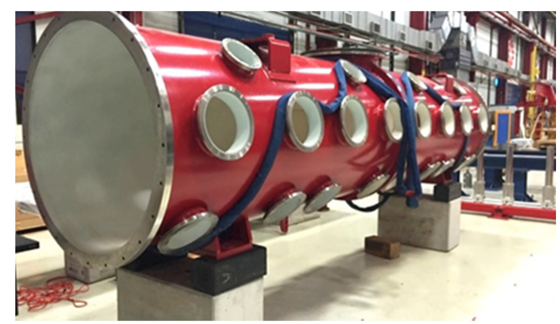
L. Ristori, T. Nicol, Y. Orlov, D. Passarelli, M. Parise

http://accelconf.web.cern.ch/AccelConf/PAC2013/papers/thpma09.pdf



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





Status of development of critical components

650 MHz section:

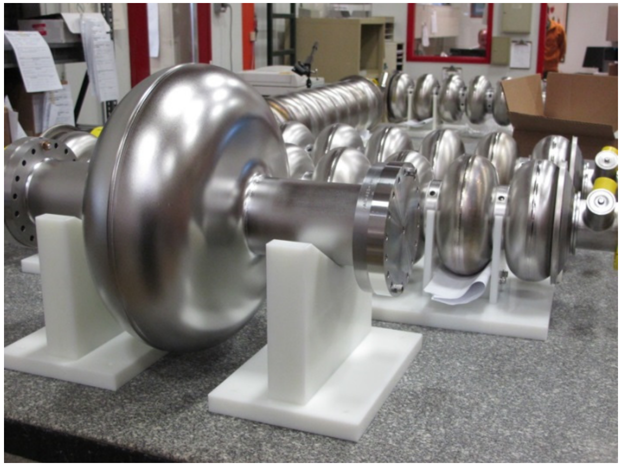
EM design of LB 650 and HB 650.v2* are ready.

- 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 120 mm versus 118 mm for v2.

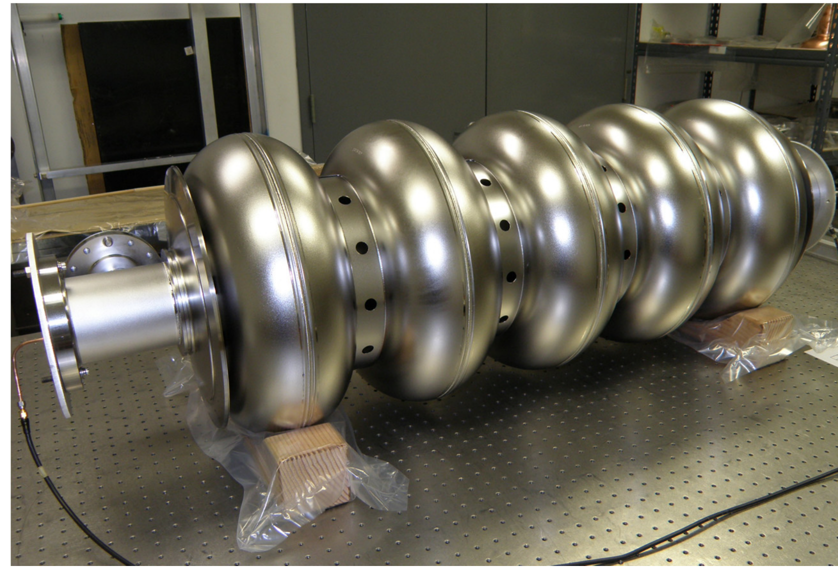
Status of development of critical components, 650 MHz

650 MHz section:



Currently Available Cavities:

1-Cell 650 MHz*	5-Cell 650 MHz
1. B9AS-AES-001	1. B9A-AES-007
2. B9AS-AES-002	2. B9A-AES-008
3. B9AS-AES-003	3. B9A-AES-009
4. B9AS-AES-004	4. B9A-AES-010
5. B9AS-AES-005	*VTS Tested
6. B9AS-AES-006	

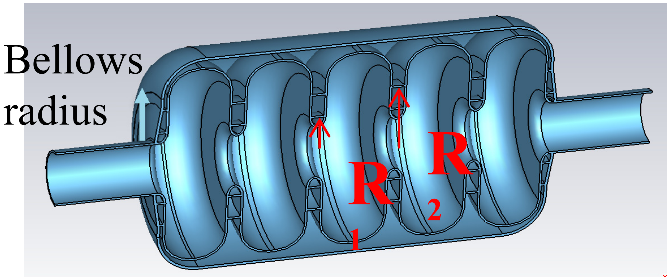


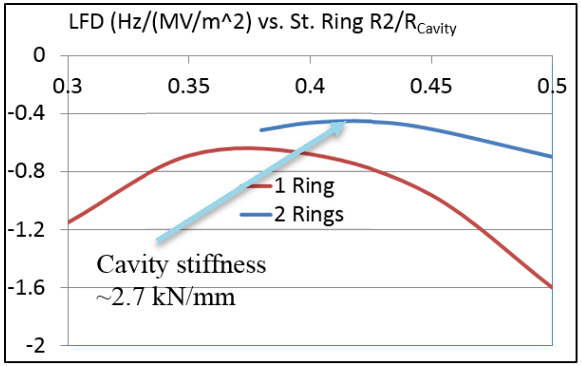
Expected Cavities:

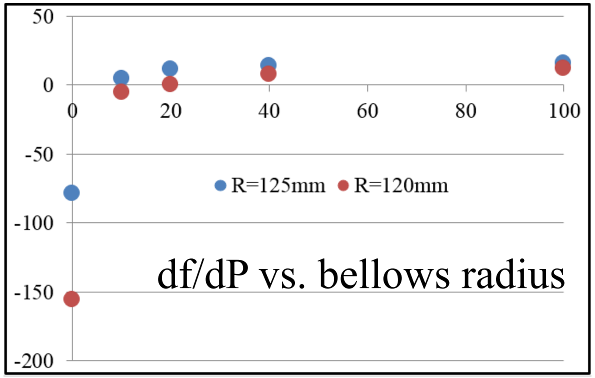
1-Cell 650 MHz	5-Cell 650 MHz
Pavac, Inc.	Pavac, Inc.
Three are delivered and VTS-tested	Five to be delivered in 2015.
Two to be delivered in the end of 2015.	

Status of development of critical components, 650 MHz

Low-Beta Cavity

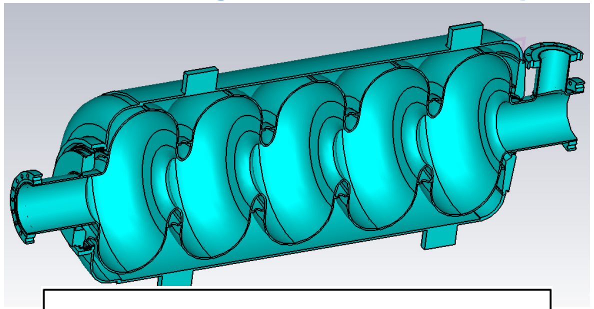


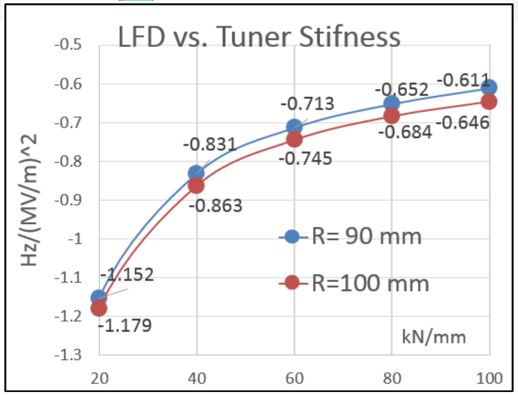


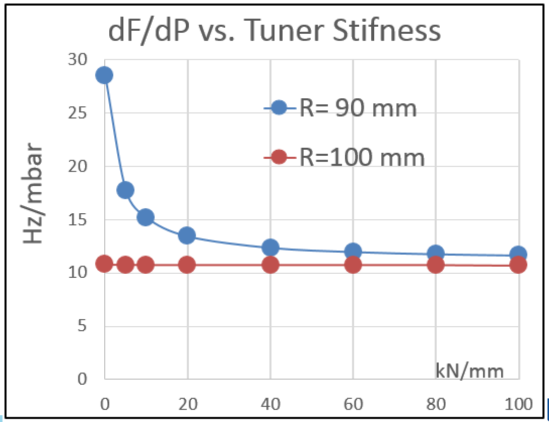


Poster THPB014

High-Beta Cavity







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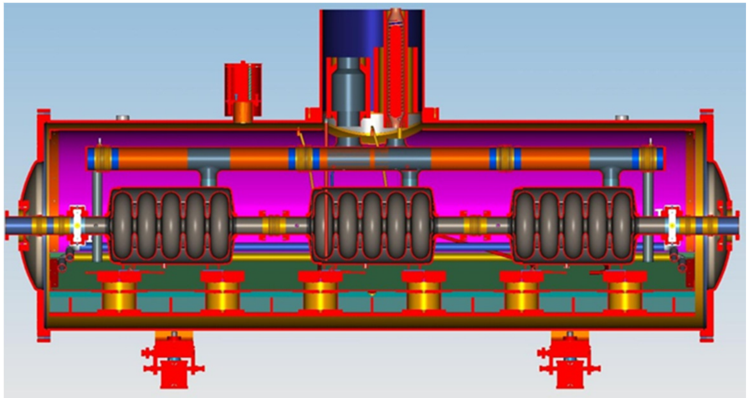
Status of development of critical components, 650 MHz CMs

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

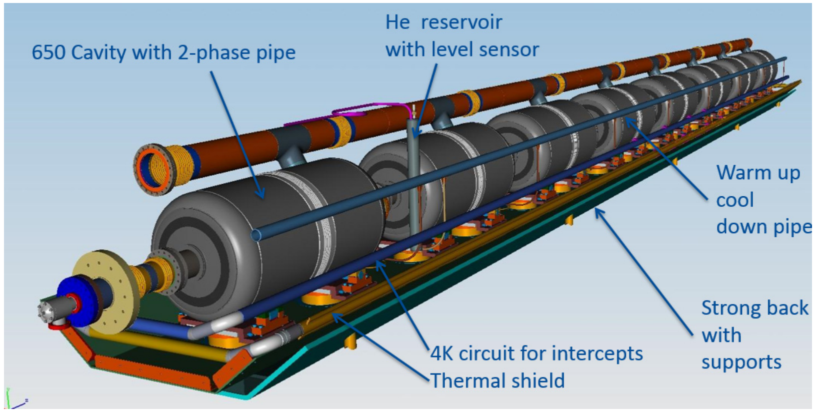


Concept 1 (room temperature strongback)

- 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

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.

Acknowledgements

Many thanks to colleagues, from whom I have obtained the information for this presentation – Anna Grassellino, Steve Holmes, Timergali Khabiboulline, Valeri Lebedev, Oleksandr Melnychuk, Tom Nicol, Peter Ostroumov, Yuriy Pischalnikov, Sam Posen, Leonardo Ristori, Allan Rowe, Warren Schappert and Alexander Shemyakin.