SRF Cavity Test Results for PIP-II

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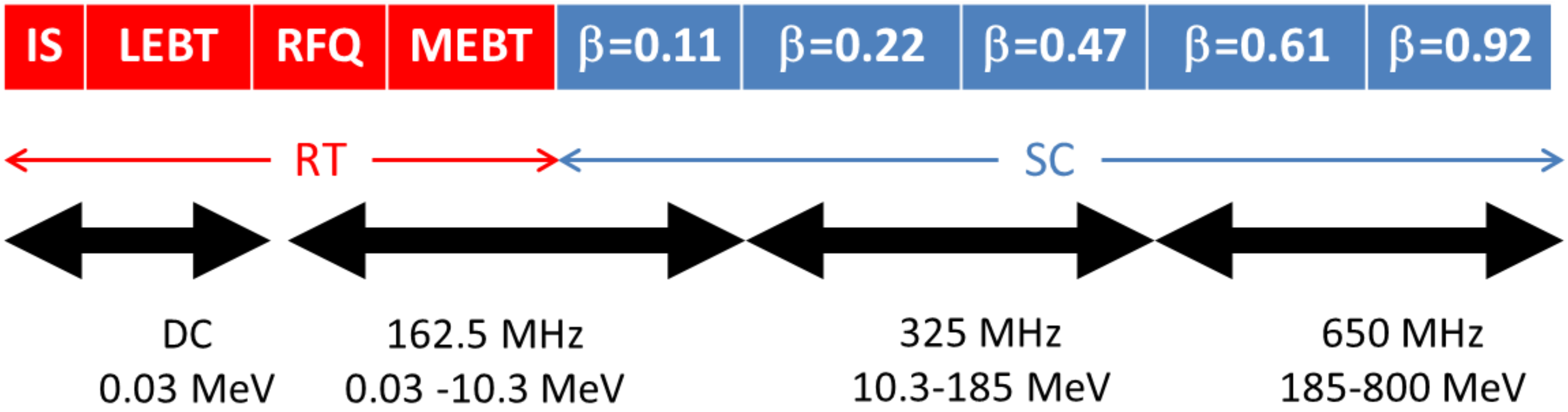
6th Open Collaboration Meeting on Superconducting Linacs for High Power Proton Beams

May 23rd-24th, 2016

Outline

- PIP-II Technology Map
- Latest SRF Cavity Test Results
  - 162.5 MHz Half-wave Resonators (HWR)
  - 325 MHz Single Spoke Resonators (SSR1)
  - 650 MHz High Beta R&D
- Indian Institutes Fermilab Collaboration (IIFC)
  - SSR1
  - 650 MHz High Beta and Low Beta
- Resonance Control

PIP-II Technology Map



IS | LEBT | RFQ | MEBT | β=0.11 | β=0.22 | β=0.47 | β=0.61 | β=0.92

RT | SC

DC
0.03 MeV

162.5 MHz
0.03 -10.3 MeV

325 MHz
10.3-185 MeV

650 MHz
185-800 MeV

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 Resonators*

- 8 HWR cavities
- 8 SC solenoids
- 1 CM

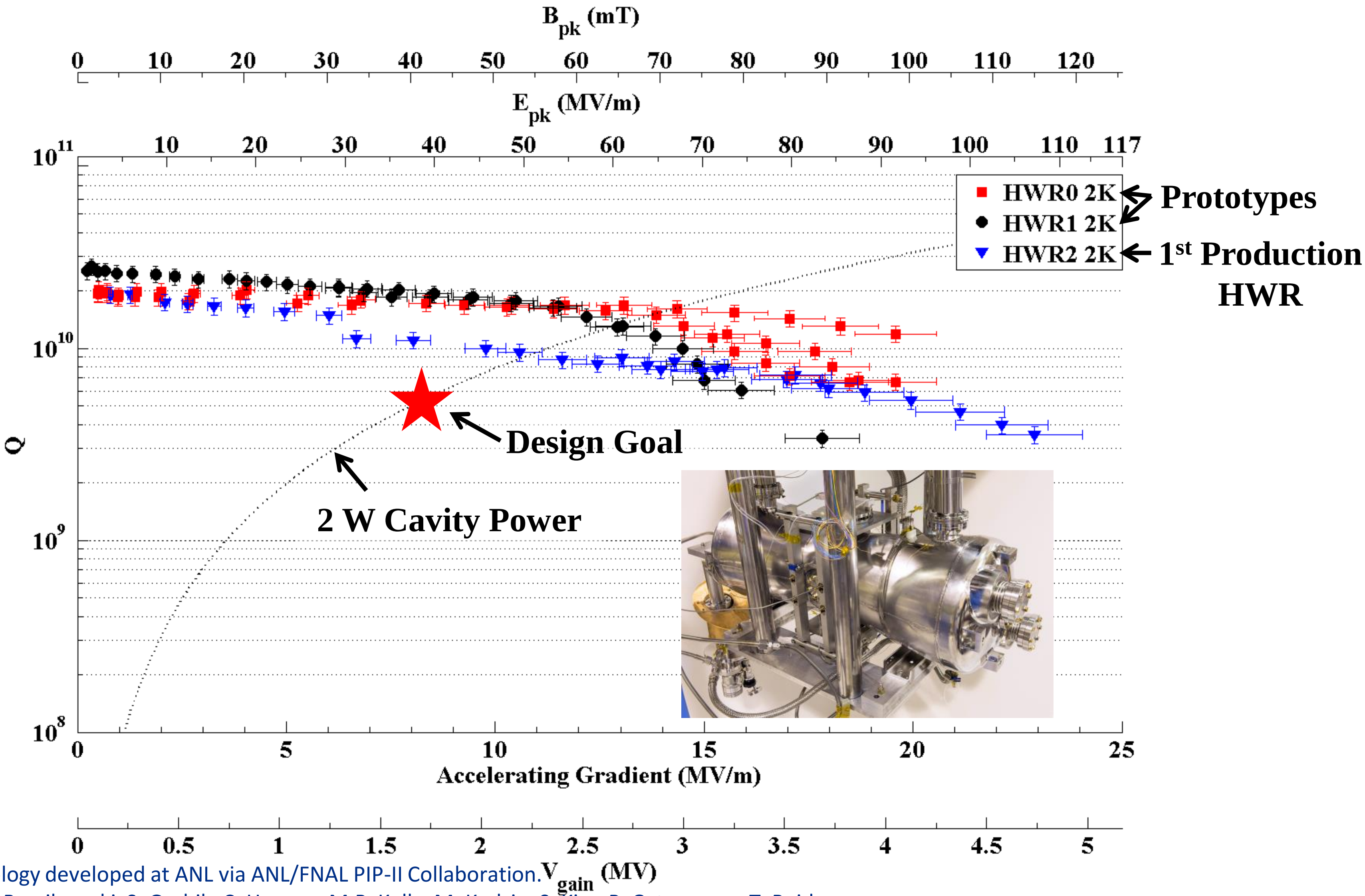
Cavity Type	HWR
Freq. (MHz)	162.5
β	0.112
l_{eff} (cm, $\beta\lambda$)	20.68
E_{pk}/E_{acc}	4.7
B_{pk}/E_{acc} (mT/(MV/m))	5.0
QR_s (Ω)	48.1
R_{sh}/Q (Ω)	272

Bulk and light EP of jacketed HWR @ ANL

Bare HWR before jacketing

*HWR technology developed at ANL via ANL/FNAL PIP-II Collaboration.
Z. Conway, A. Barcikowski, S. Gerbik, C. Hopper, M.P. Kelly, M. Kedzie, S. Kim, P. Ostroumov, T. Reid.

Half-Wave Resonator Results*



Prototypes

1st Production HWR

Design Goal

2 W Cavity Power

*HWR technology developed at ANL via ANL/FNAL PIP-II Collaboration.

Z. Conway, A. Barcikowski, S. Gerbik, C. Hopper, M.P. Kelly, M. Kedzie, S. Kim, P. Ostroumov, T. Reid.

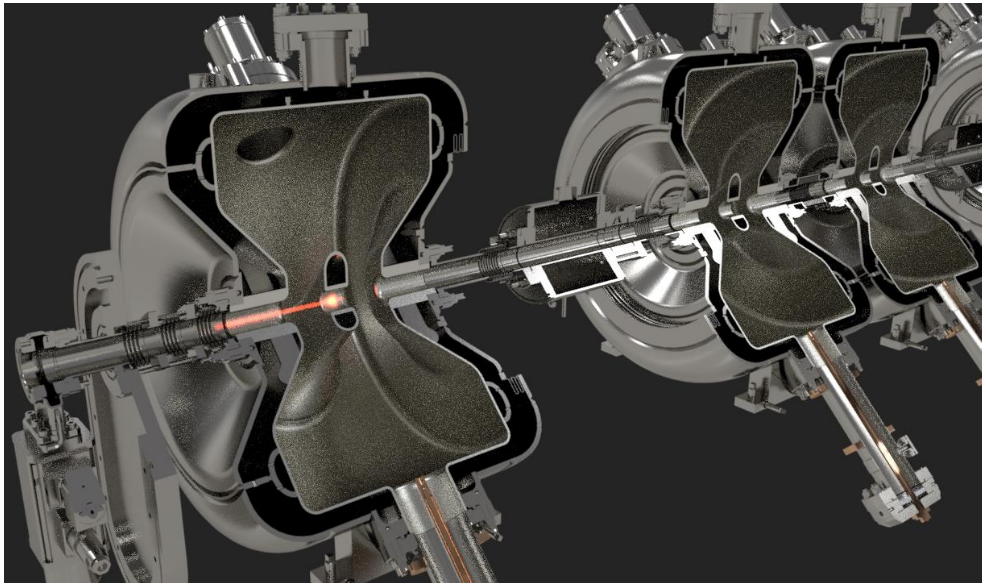
325 MHz SSR1 Resonators

- 16 SSR1 Cavities
- 8 SC Solenoids
- 2 production CMs
- 1 CM tested in PXIE

FNAL—Ristori, Orlov, Passarelli, et al.

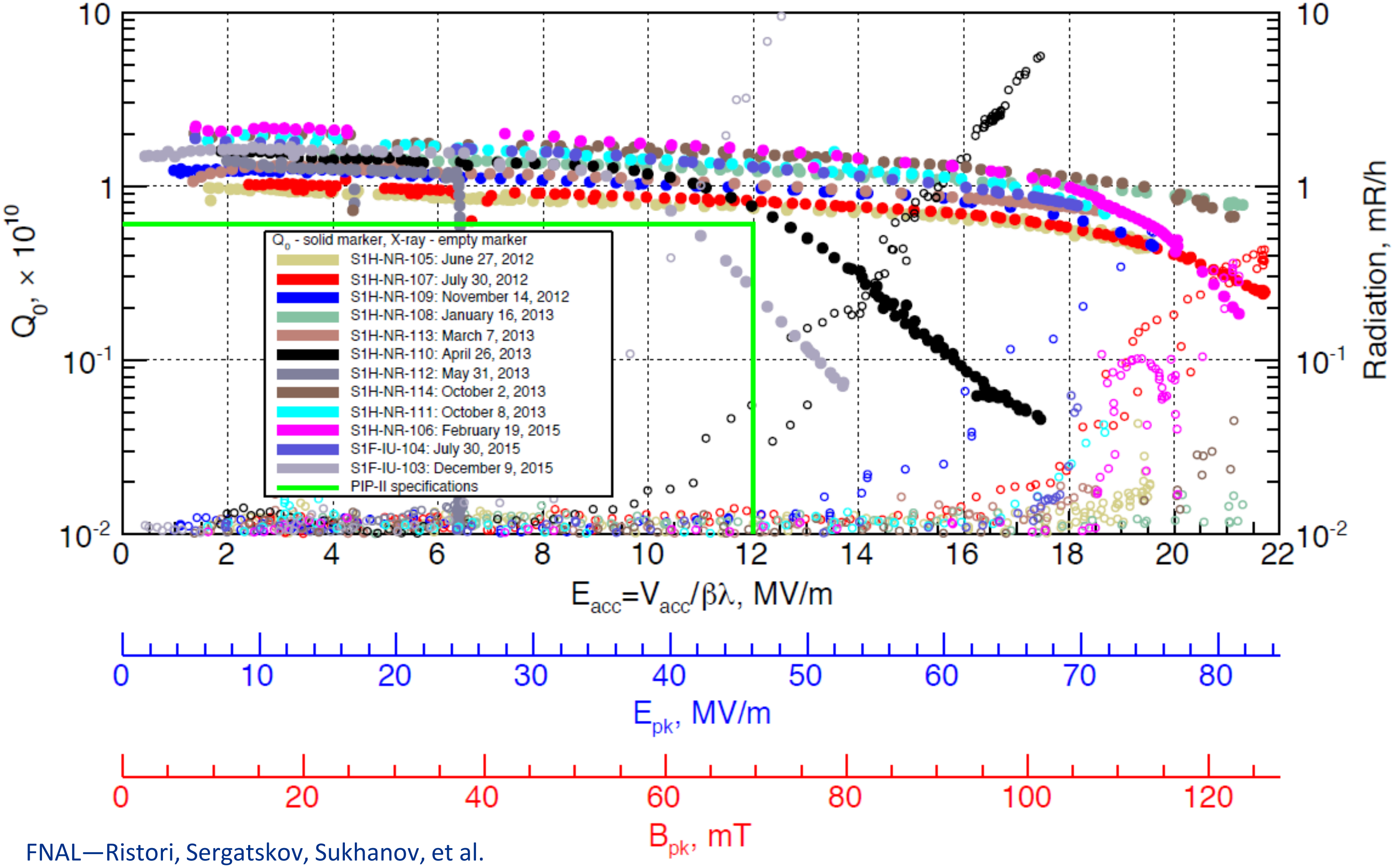
Table 1: Cavity operational and test requirements

Parameter	**Value**
RF resonant frequency	325 MHz
Bandwidth	±20 Hz
Operating accelerating gradient (E_{acc})	12 MV/m
Quality factor (Q_0) at E_{acc}	$> 5 \cdot 10^9$
Operating gain per cavity	2 MeV
Maximum power dissipation at 2 K	5 W
Sensitivity to He pressure fluctuations	< 25 Hz/Torr
Field flatness	±10%
Operating temperature	$1.8 \div 2.1$ K
Operating pressure	$16 \div 41$ mbar (differential)
Maximum allowable working pressure	2 bar at 293 K, 4 bar at 2 K
RF power input per cavity	6 kW (CW, operating)
Max Leak Rate (room temp)	$< 10^{-10}$ atm · cc/s



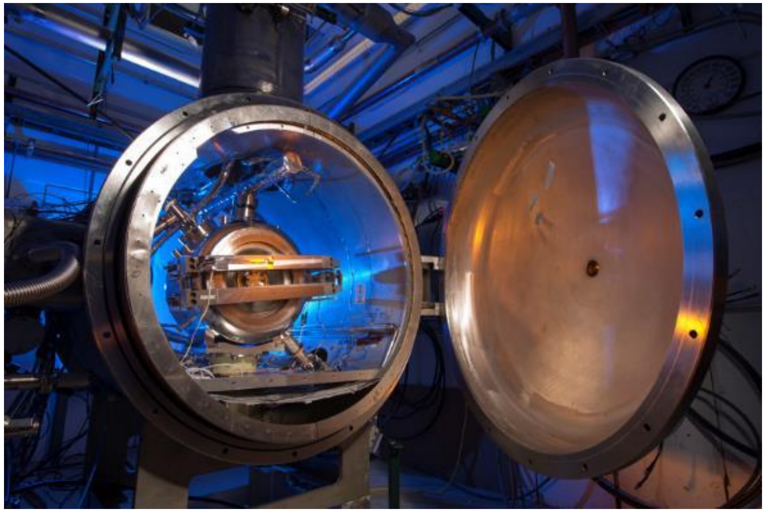
325 MHz SSR1 Results

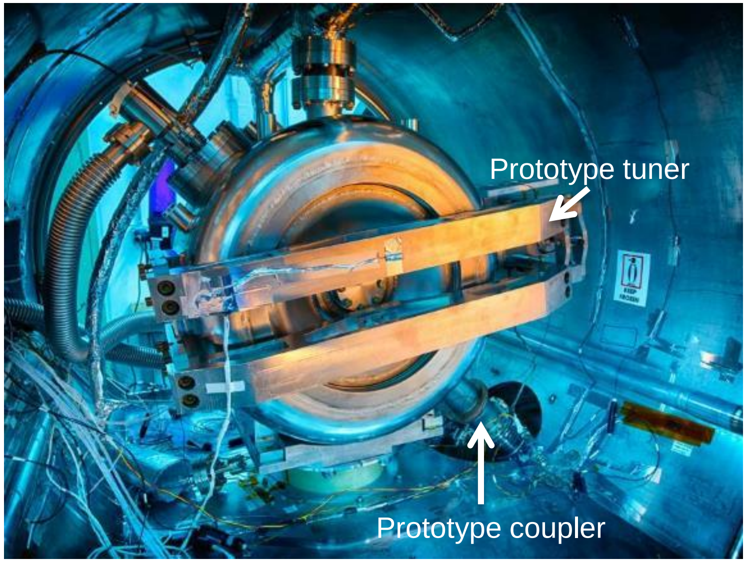
- 9 fully qualified bare cavities through VTS, 1 through STC
- 1 IIFC (IUAC) collaboration cavity fully qualified through VTS



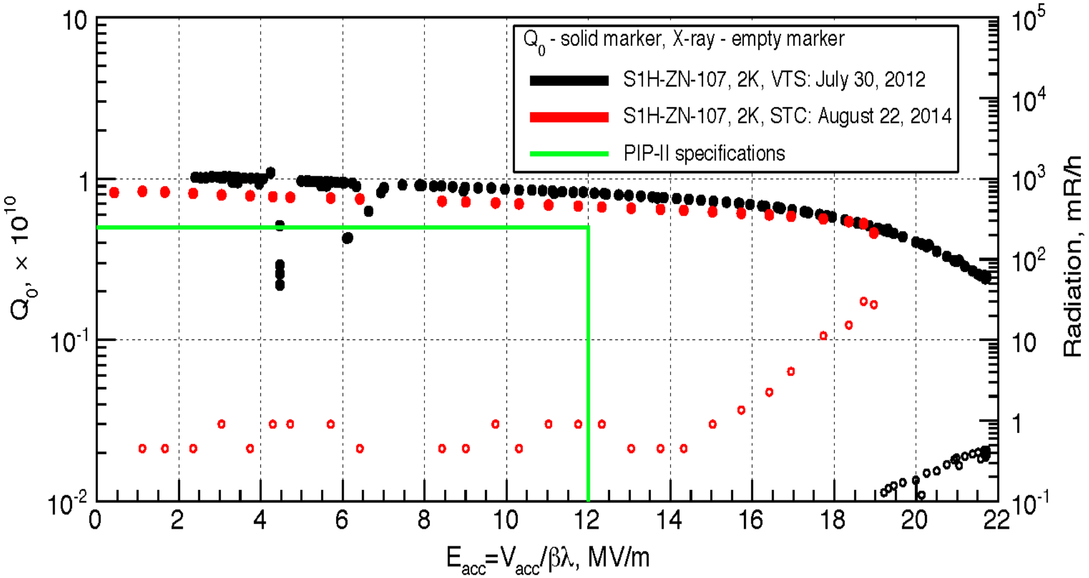
FNAL—Ristori, Sergatskov, Sukhanov, et al.

S107 "Ice Breaker" Fully-Integrated Tests in STC





- First jacketed cavity was tested in the STC cryostat
- Prototype coupler and prototype tuner installed
- Performance of cavity, coupler and tuner were confirmed with a total of 3 tests, latest Jan 2016
- Prototype coupler on RF Test Stand (Room Temp) tested to failure at 47 kW (3x requirement)

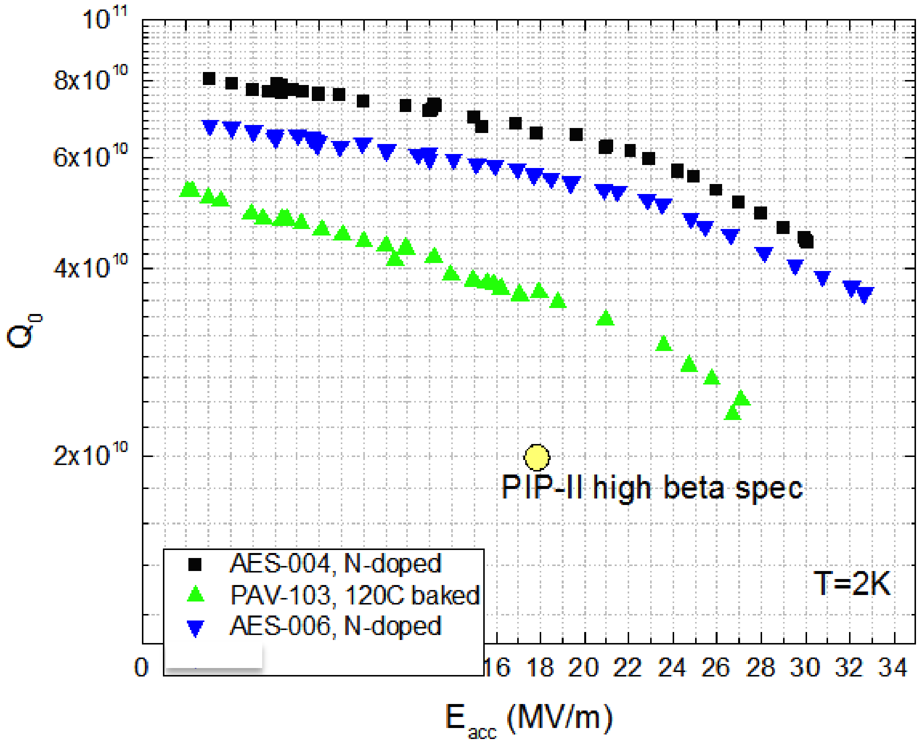


No Q0 degradation found in comparison of performance of cavity S107 in VTS (black) and STC (red). Mild FE present in STC consistently through each test.

Original Result of Cold Tests of the Fermilab SSR1 Cavities, A. Sukhanov et al., Proceedings of LINAC2014, Geneva, Switzerland

650 MHz High Beta Single-Cell Q0 R&D

- 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)



FNAL—Grassellino, Melnychuk, Merio, Rowe, Sergatskov, et al.

650 MHz High Beta Multi-cell Results

Processing Regime

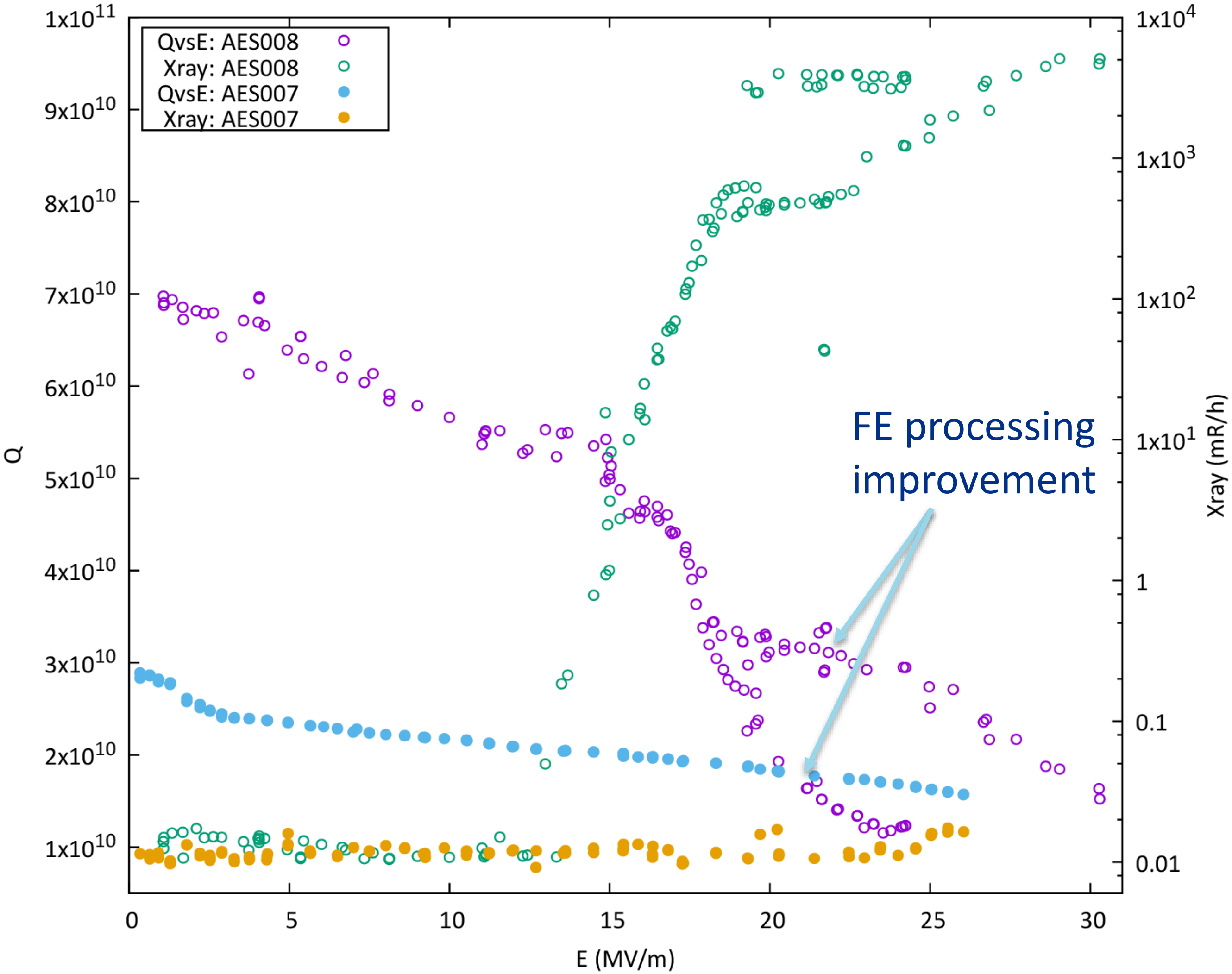
- 120 um EP
- 800C Degas + 2/6 N2
- RF tuning
- 20 um EP (AES008)
- 5 um EP (AES007)
- VTS Prep

AES008

- Excellent Q0 +gradient
- Multi-pacting
- High FE
- No Quench
- Aggressive re-cleaning
- Re-rinsed
- 2nd Test FE persisted

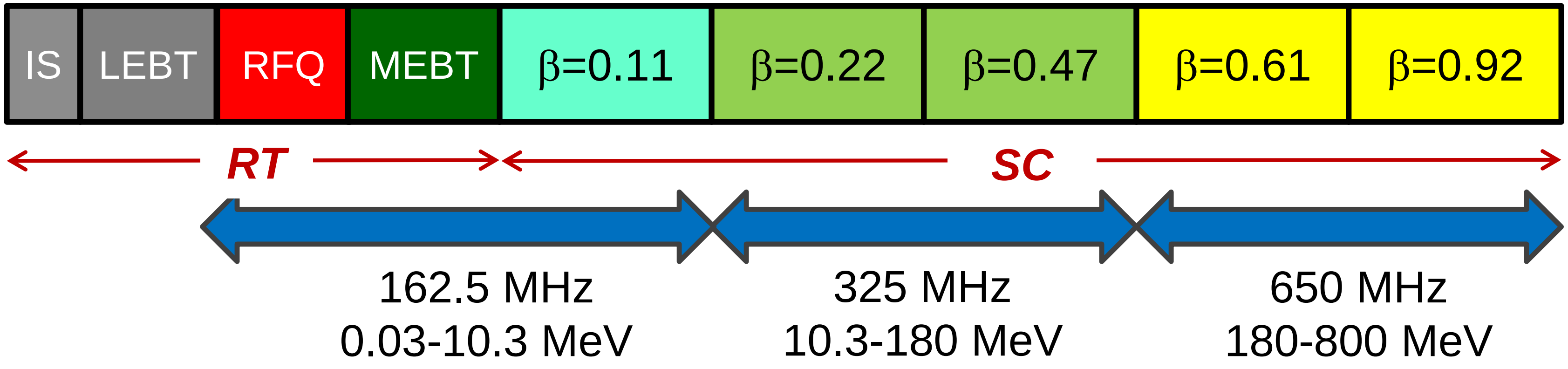
AES007

- Moderate Q0
- Over-doped
- Quench @ 27 MV/m
- No FE
- Minimal multipacting
- More EP needed



FNAL—Sergatskov, Grassellino, Melnychuk, Merio, Rowe, et al.

Indian Institutes Fermilab Collaboration Org.



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RT

SC

162.5 MHz
0.03-10.3 MeV

325 MHz
10.3-180 MeV

650 MHz
180-800 MeV

Dressed SRF Cavities

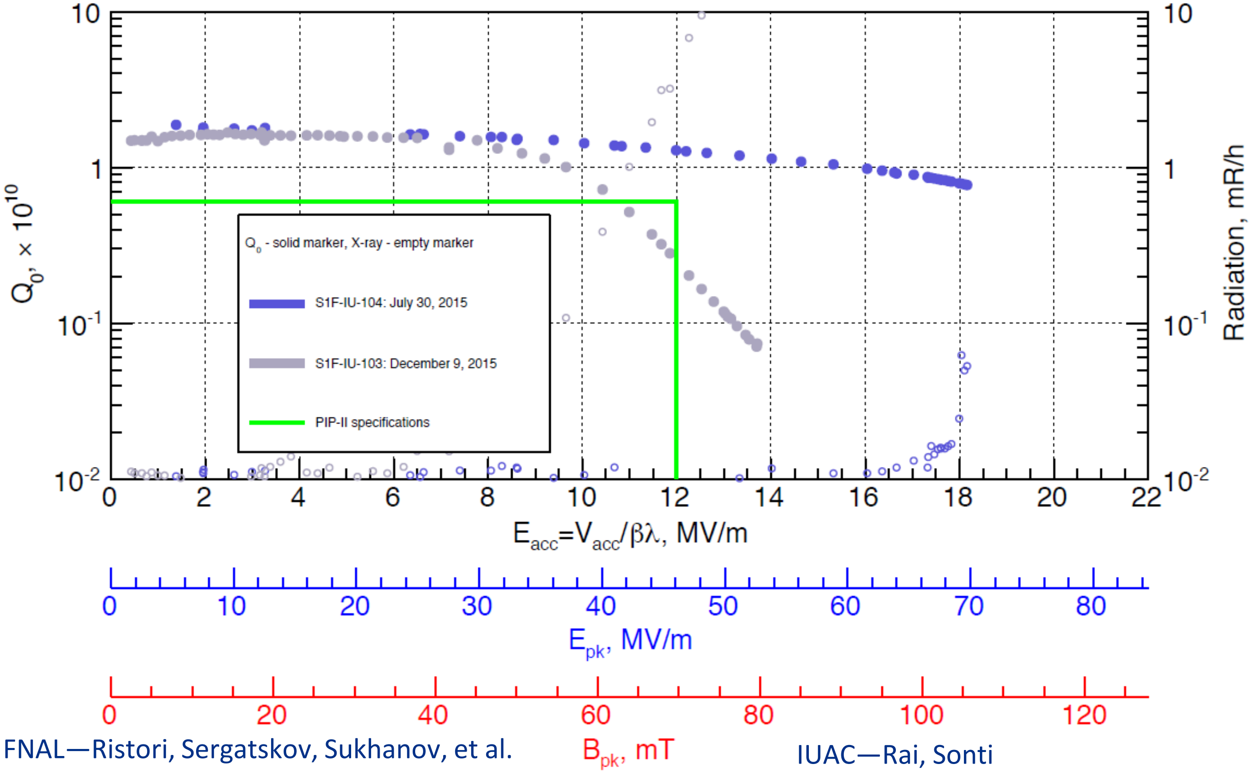
- β = 0.22: IUAC & VECC
- β = 0.47: BARC & IUAC
- β = 0.61: VECC/(Europe?)
- β = 0.92: RRCAT
- 325 MHz RF Power: BARC
- 650 MHz RF Power: RRCAT

Non SRF components (BARC)

- Cryogenic Plant and Distribution
- RF
  - LLRF
  - Protection System
- Instrumentation: BPM, BLM
- Controls
- MEBT Magnets

Indian Institutes Fermilab Collaboration (IIFC)

- IUAC delivered two SSR1 cavities
- Chemically processed at ANL and cold-tested at Fermilab
  - IUAC fabricated cavity meets the PIP-II specifications
- Cavities will be dressed at IUAC/BARC, then prepared and tested at FNAL/STC



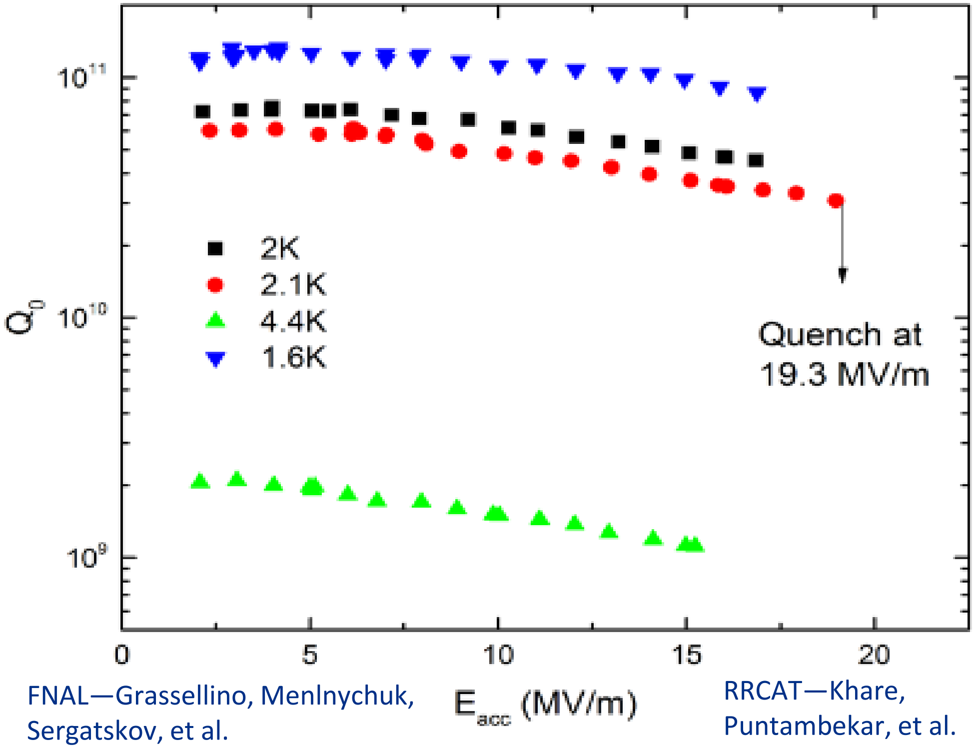
FNAL—Ristori, Sergatskov, Sukhanov, et al.

IUAC—Rai, Sonti

Indian Institutes Fermilab Collaboration (IIFC)

- RRCAT/IUAC Fabricated one Nb HB650 650 MHz single-cell cavity (July 2013).
  - Processed & tested at FNAL/ANL
  - The cavity achieved E_{acc} 19.3 MV/m with Q > 4E10 at 2K.
  - VECC B6AS-VECC-001 processing now at FNAL/ANL, expected test June 2016

B9AS-RRCAT-301 @ VTS



FNAL—Grassellino, Menlnychuk, Sergatskov, et al.

RRCAT—Khare, Puntambekar, et al.

B9AS-RRCAT-301 VTS results

Strategy and Status – Resonance Control R&D

- PIP II specific requirements for SRF Cavities Resonance Control:
  - Low beam loading → narrow bandwidth of the cavities
  - High accelerating gradient (~20MeV/m)
    - → large Lorentz Force Detuning
    - → significant residual vibration/ excessive microphonics

Pulsed SRF accelerators, existing and projects	**Cavities Half-bandwidth, Hz**	**LFD, Hz**	**LFD/HBW**
SNS(LB/HB)	550/500	300/100	***0.55/0.2***
ESS(HB)	500	400	***0.80***
FLASH/XFEL	185/141	550	***3/4***
PIP II (LB/HB)	29/29	253/317	***9/11***

Lorentz Force Detuning is an issue!

FNAL – Pischalnikov, Holzbauer, Schappert

History of Development LFD Compensation Algorithms at FNAL
Adaptive Least Square Algorithm for LDF compensation

Algorithm initially developed during ILC program to compensate LDF detuning for 9-cell 1,3GHz elliptical cavities. Pulse operation - (1ms-fill+1ms-flat).

Algorithm deployed at FNAL (NML/CM1-2) and at KEK during S1G program (for different type of cavity/tuner systems)

LFD suppression from ~1000Hz → to ~20Hz
(compensation factor ~50)

Adaptive Least Square Algorithm is universal … also successfully applied for LFD compensation for:

- ILC cavities operating at long pulse (4ms-fill +5ms-flat) (Project X)

LFD suppression from 400Hz → to 30Hz *(factor ~15)*

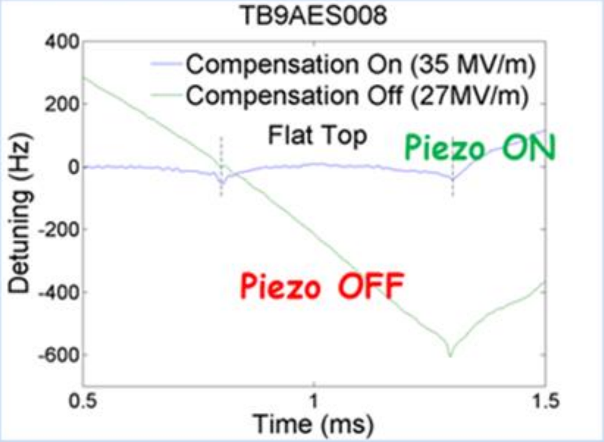
SSR1 cavities operating at (1ms-flat+1ms-flat) (HINS)

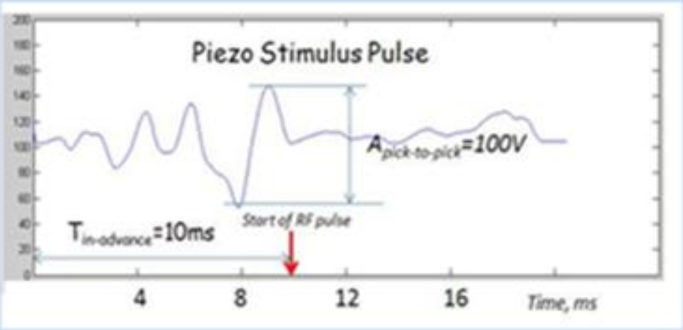
LFD suppression from 3,5KHz → to 75Hz
(factor~20)

Will test this algorithm for LFD compensation for PIP II operation regime

1.3GHz for ILC/XFEL pulse operation

LFD during 1,3ms RF-pulse (Fill+FlatTop) ~2300Hz
After LS LFD compensation -- to less than 20Hz during 1,3ms pulse

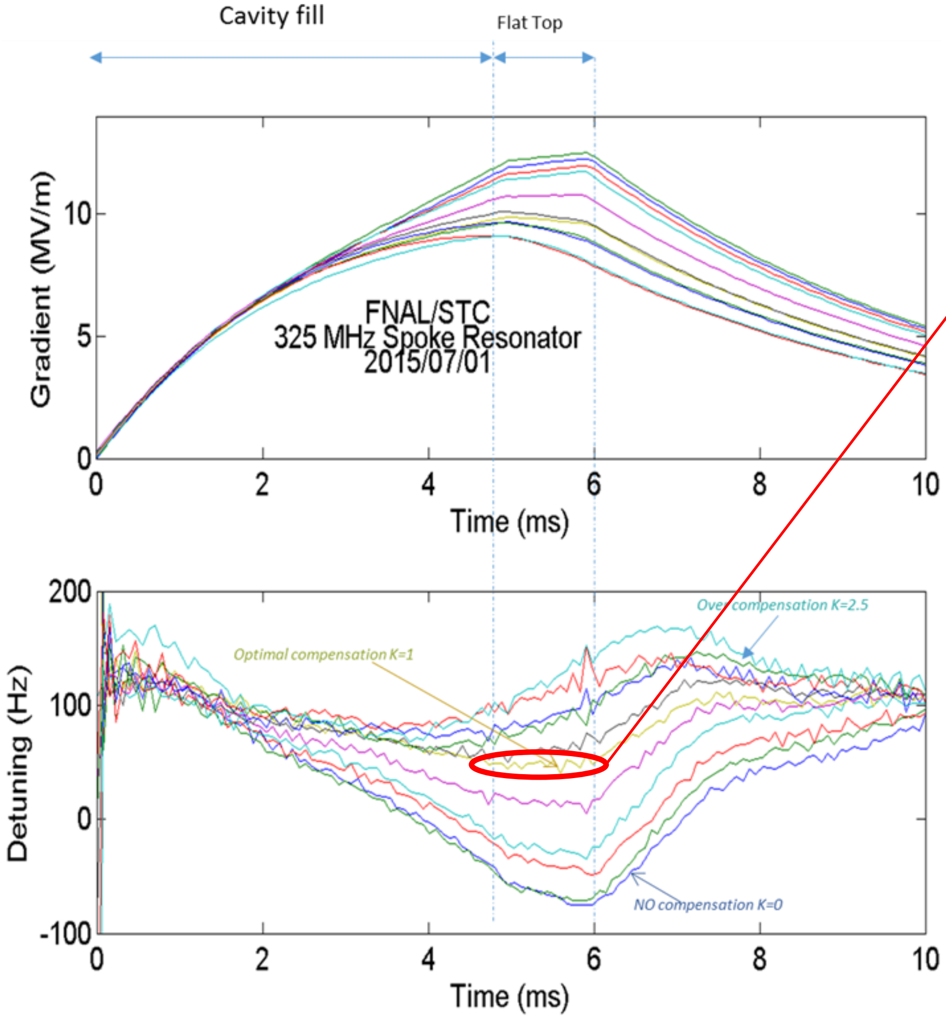




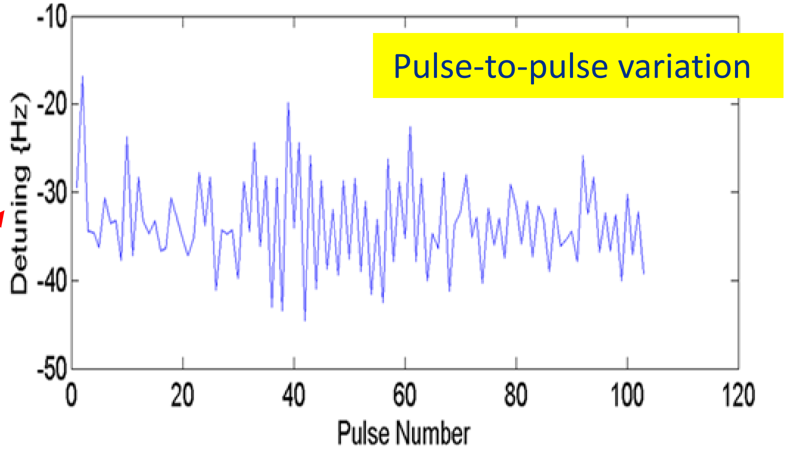
Y. Pischalnikov and W.Schappert, "Adaptive Lorentz Force Detuning Compensation" Fermilab Preprint-TM2476-TD
W.Schappert et. al.," Resonance Control in SRF Cavities at FNAL", PAC2011, New York, USA

Compensation LFD in Pulsed SSR1 (325MHz) cavity (STC/FNAL)

LFD compensation → feed-forward algorithm
(piezo-stimulus pulse proportional to $E_{acc}{}^{2}$)



Average detuning during flat top (1ms) for 100 pulses



Pulse-to-pulse variation

Simple feed-forward algorithm significantly suppressed LFD. However, cavity detuning from pulse-to-pulse is still ~30Hz (peak-to-peak)– this is close, but above PIP II specs.

PIP-II requirements for detuning less than 20Hz (peak)…

Next step is to apply feed-back algorithm to compensate for microphonics and residual vibration, then test with beam in PXIE…

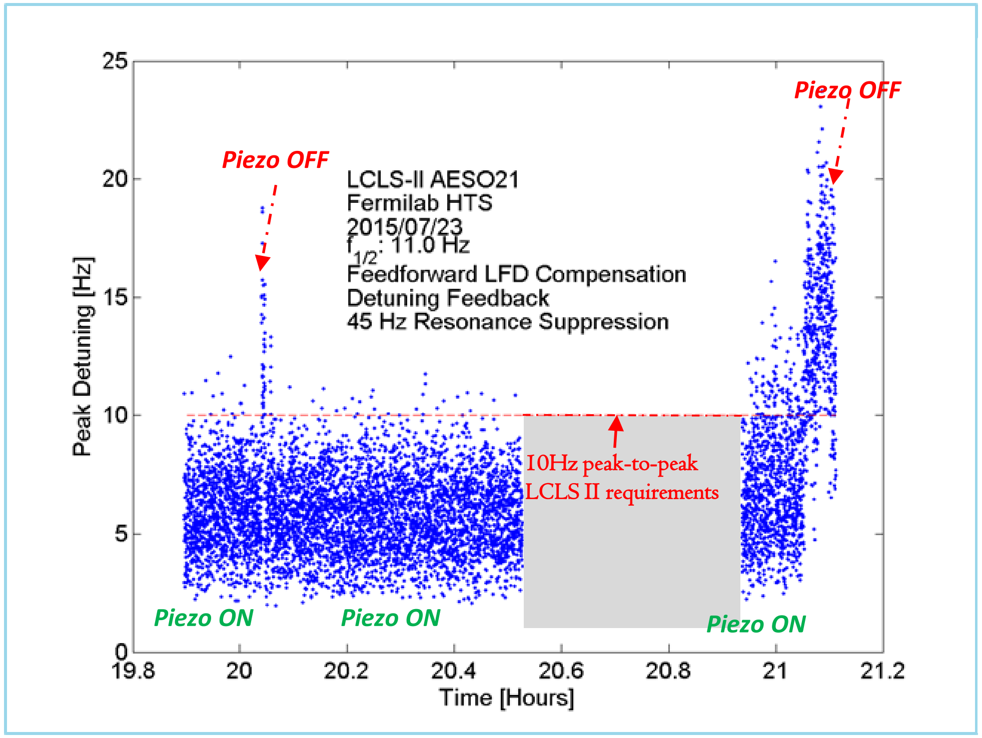
FNAL – Pischalnikov, Holzbauer, Schappert

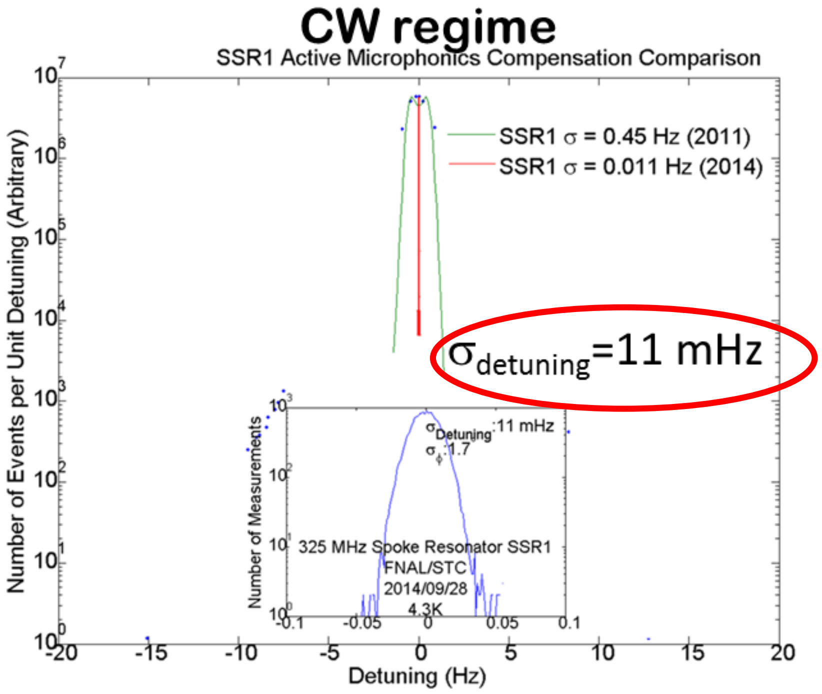
Microphonics Compensation in a CW LINAC

Synergy of LCLS-II & PIP-II Resonance Control Programs

- There are several projects (in operation or under construction) with low beam loading (narrow bandwidth SRF cavities) that operated in CW regime.
- Active Resonance Control of the narrow bandwidth cavities for CW machine is complicated but not as complex and challenging as Pulsed Operation.

Active Resonance Control of the LCLS II Cavity (HTS/FNAL)

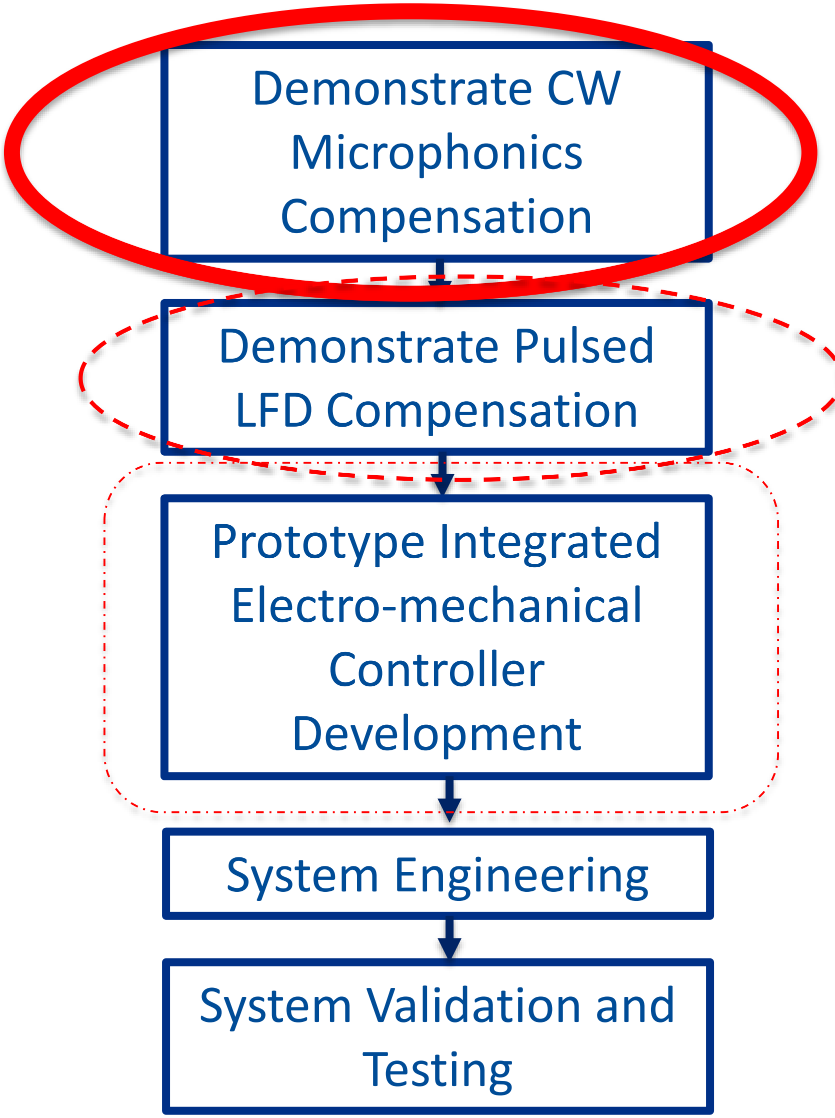




FNAL – Pischalnikov, Holzbauer, Schappert

Current Resonance Control Program for PIP-II

- Focus is on unambiguous demonstration of CW microphonics compensation
  - Adaptive LFD control of pulsed cavities well understood
    - Preliminary demonstration of feedforward LFD control in pulsed cavities
  - Largest source of residual detuning is pulse-to-pulse variation
  - Compensation requires feedback
    - Feedback at the levels required for PIP-II has been demonstrated at low gradients using ad-hoc techniques
- Optimal control provides a coherent mathematical framework for this type of problem



Demonstrate CW Microphonics Compensation

Demonstrate Pulsed LFD Compensation

Prototype Integrated Electro-mechanical Controller Development

System Engineering

System Validation and Testing

Acknowledgements

- ANL HWR CM Development - Zack Conway, Lead
- FNAL SSR1 CM Development – Leonardo Ristori, Lead
- FNAL/IIFC HB 650 MHz CM Development
  - Tom Nicol, FNAL Lead
  - Prashant Khare, IIFC (RRCAT) Lead
- FNAL/IIFC LB 650 MHz CM Development
  - Tom Nicol, FNAL Lead
  - Sumit Som, IIFC (VECC) Lead
- FNAL Cavity Performance – Grassellino, Lead
- FNAL Resonance Control – Pischalnikov, Lead
- ANL Cavity Chemistry – Reid, Lead