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Experience and Lessons in FRIB Superconducting Quarter-Wave Resonator RF Commissioning

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On behalf of FRIB team

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U.S. DEPARTMENT OF ENERGY | Office of Science

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Outline

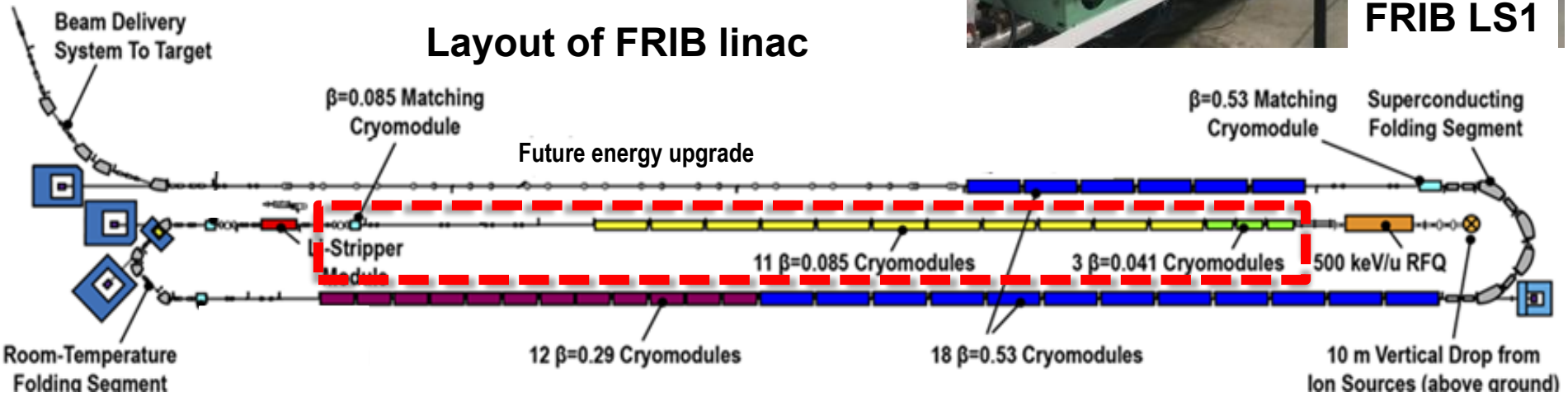
- Introduction
  - FRIB linac segment 1 (LS1) with quarter-wave resonators (QWR)
- Performance of QWR cryomodules
  - Accelerating gradients, multipacting, field emission
  - Solenoid, alignment, RF power coupler
  - Phase and amplitude stabilities, beam loading compensation
- Lesson learned from commissioning
  - Stepper motor in slow frequency tuner
  - LS1 operated at 4.5 K
- Summary

Introduction

- FRIB **Linac Segment 1 (LS1)** has been commissioned with ion beam
  - Accelerated Ar, Kr, Ne, Xe beam up to 20.3 MeV/u
- **15 cryomodules** with **104 SRF cavities**, 12 β=.041 QWRs and 92 β=.085 QWRs (80.5 MHz), **39 SC solenoids** (8 T)
- RF and beam commissioning was done at 4.5 K
  - The cryomodules integrated with cryogenics were tested also at 2 K, the design temperature

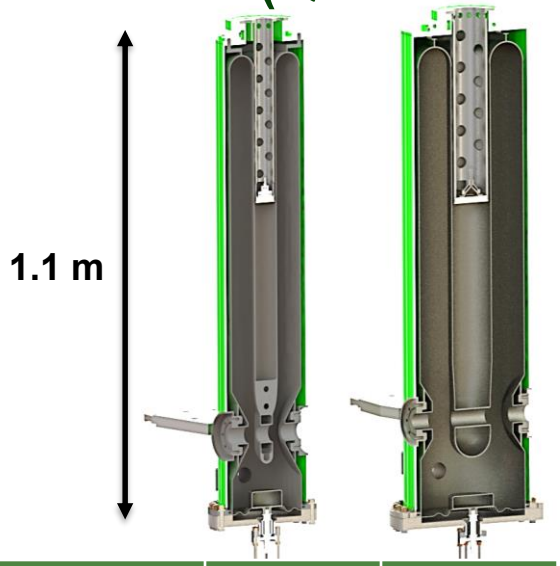
FRIB LS1

Layout of FRIB linac



LS1 Cryomodules

3x (QWR041 Cryomodule: 4x β=.041 QWRs + 2x 25 cm Solenoids)
11x (QWR085 Cryomodule: 8x β=.085 QWRs + 3x 50 cm Solenoids)
1x (QWR085 Matching Cryomodule: 4x β=.085 QWRs)



	β=0.041 QWR	β=0.085 QWR
f_0 (MHz)	80.5	80.5
V_{acc} (MV)	0.81	1.8
E_{acc} (MV/m)	5.1	5.6
E_{pk} (MV/m)	31	33
B_{pk} (mT)	55	69
Dynamic load (W)	1.3	3.8
BW (Hz)	40	40
RF Power (kW)	0.3/0.7	1.1/2.5

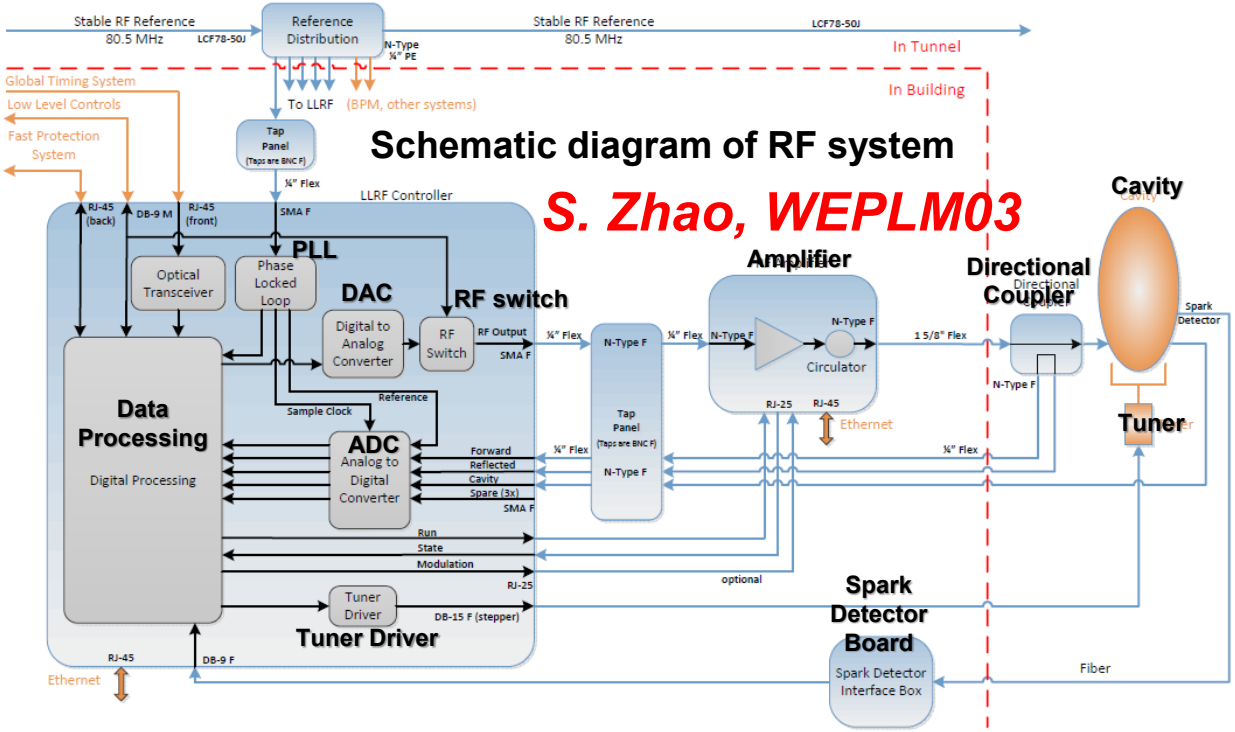
(No/With beam)

QWR085 cryomodule

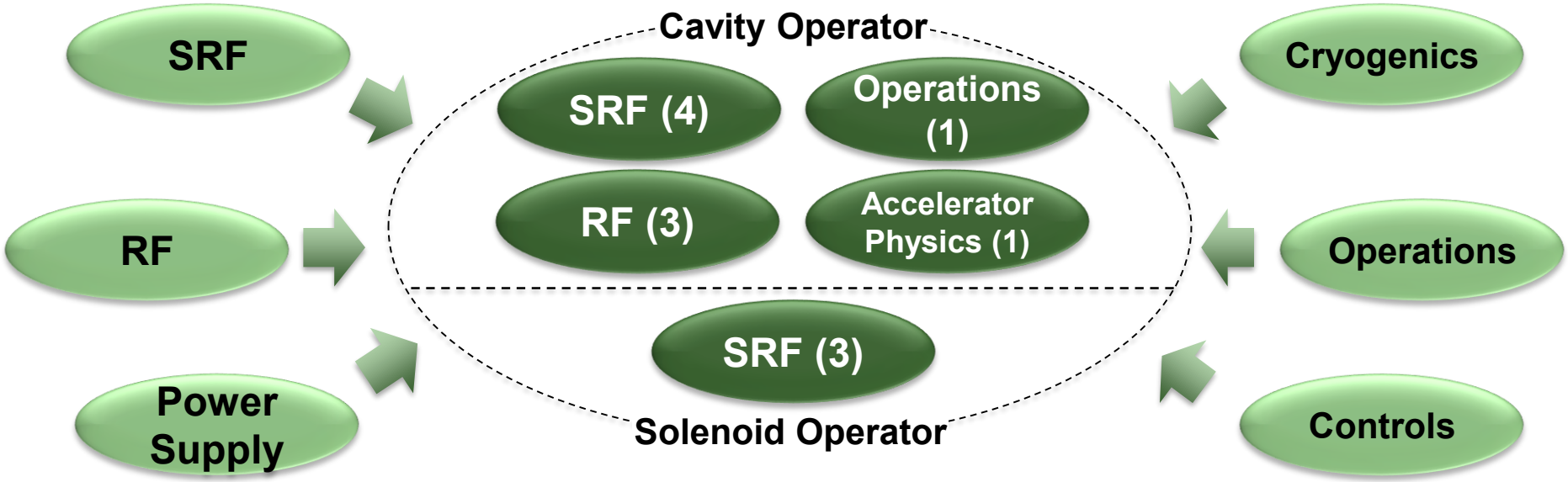
8 T SC solenoid integrated with XY dipole steering coils

RF System for QWR Cryomodule

- 2 kW amplifier unit contains 3 RF ‘pallets’ with their own circulators and dummy loads. 2-way and 4-way combiners are used for up to 4kW or 8kW output power
- LLRF controller supports amplitude and phase lock with active disturbance rejection control and also digital self-excited loop. Tuner control board is integrated in the LLRF controller



RF Commissioning Team
Lab-wide supports for efficient RF commissioning



- (SRF task leader + 2-3 cavity operators) per shift ***H. Ao, WEPLH09***
- RF commissioning: 3 – 11 pm, Linac installation: 8 am – 3 pm
- Completed ~1 cryomodule, 8 separate RF systems, per day

Cryomodule RF Commissioning
Optimized for this large-scale SRF linac

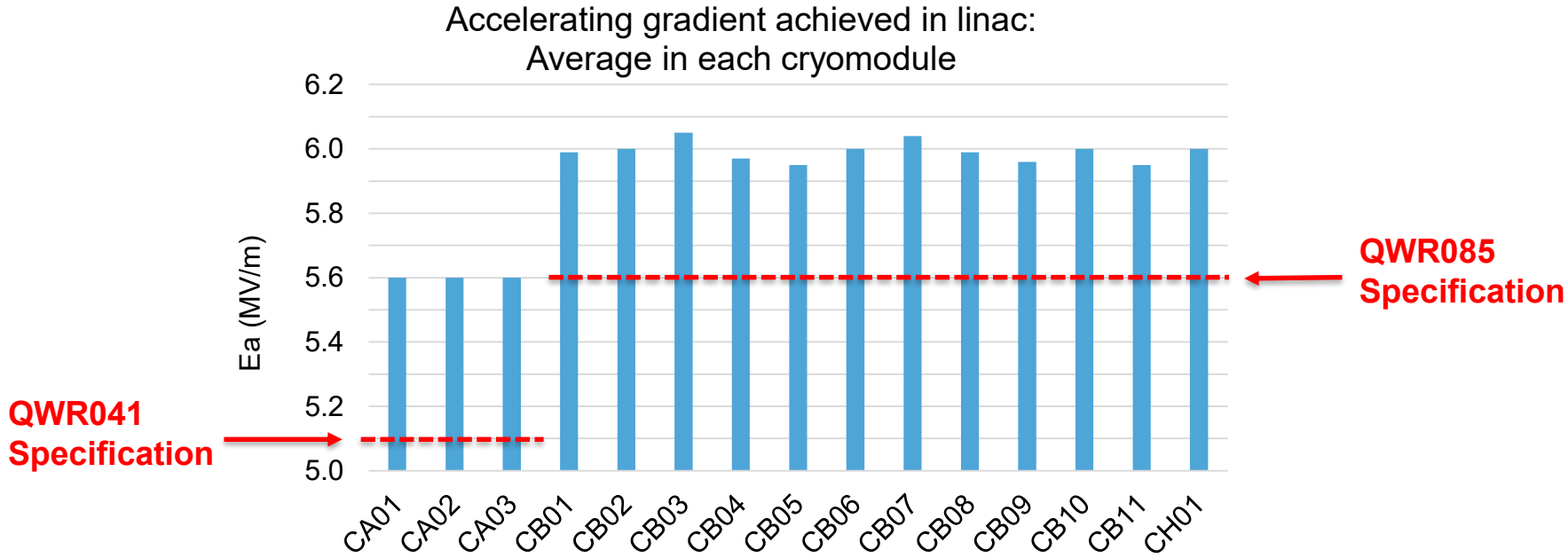
- LLRF integration tests: debug as much as possible before tunnel is secured

	Mode	Details
Low-level RF integration test (tunnel open)	Amplitude: open Phase: open Slow tuner: on	• Verify LLRF controller, tuner operation, microphonics, as well as cables and connections
High-power RF commissioning (tunnel secured)	Amplitude: open Phase: Self-excited loop Slow tuner: disabled	• Check interlocks • Verify cavity voltage calibration • Condition MP • Check FE (and condition if necessary)
	Amplitude: locked Phase: locked to clock Slow tuner: on (Real operation mode)	• Check RF feedback and tuner controls • Long-term demonstration • Verify amplitude and phase stabilities, coupler heating

- Most work was on the Control System Studio (CSS) screens, which allows multiple cavity operation by one operator
- Any issues/faults are documented and tracked
- RF parameters and settings are systematically managed ***H. Maniar, TUPLE01***

Accelerating Gradient
Achieved the design gradients in all 104 cavities

- RF commissioning
  - All 104 cavities in LS1 met the specification with 10-20% margins

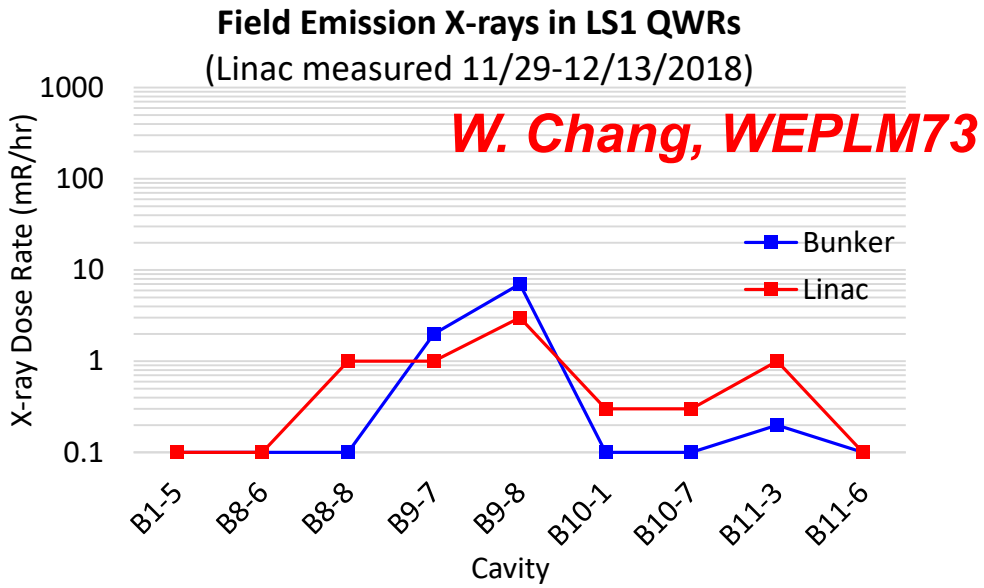


- Beam Commissioning
  - Accelerating voltages were chosen as required by the beam
    - » For example, Kr beam: QWR041: 2.0 to 3.6 MV/m, QWR085: 3.6 to 5.9 MV/m

T. Maruta, THZBA3

Field Emission and Multipacting
No conditioning effects during beam commissioning

- Field emission (FE)
  - No remarkable changes from the offline test bunker to the linac
  - No measurable changes after cycling of the cryomodule beamline gate valves



- Multipacting (MP)

Turn on RF with initial $P_{forward}$ ~20 W (Eacc ~1 MV/m)

Processed out by CW conditioning

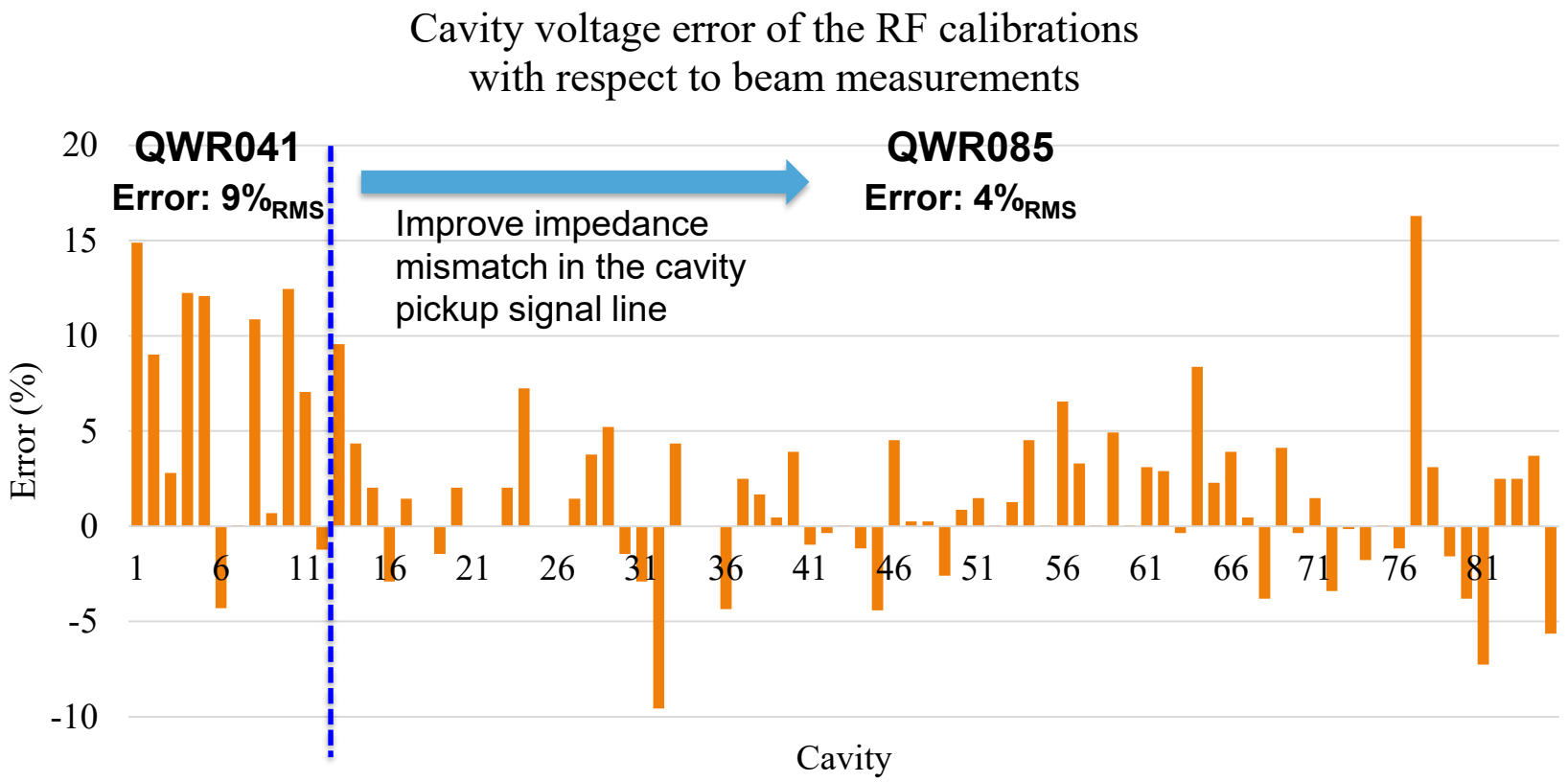
Multipacting bands (in terms of Eacc)

MP band	QWR041	QWR085
Low	2-5 kV/m	4-7 kV/m
Middle	Not observed	0.05-0.08 MV/m
High	0.6-1 MV/m	0.5-0.9 MV/m

W. Hartung, MOPLO17

Cavity Voltage Calibration

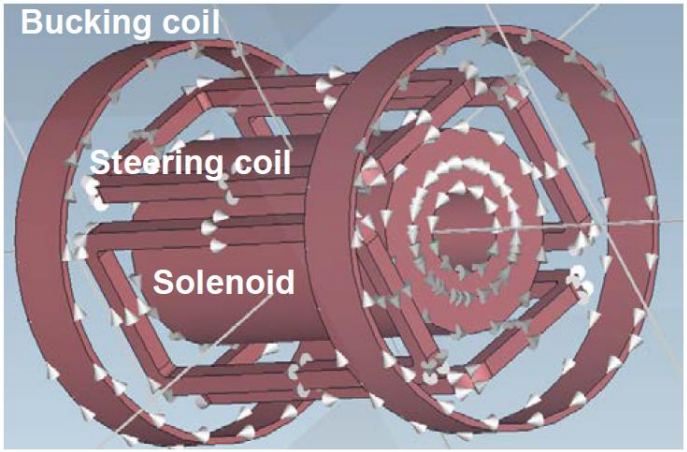
RF calibration is roughly consistent with the beam measurements



Superconducting Solenoid
No operational issue

- Solenoid current
  - Linac cryomodule commissioning: tested at 75 A (6.7 T focusing magnetic field, tested to 8 T in the offline cryomodule tests), dipole steering coils were tested at 15 A
  - Beam commissioning: operated at 20-60 A, dipoles were operated at <5 A
- Gas-cooled lid: gas flow controlled by solenoid valves
- All solenoids were reliably operated
  - No solenoid or dipole coil was quenched
  - Controls on the lead voltage and lid-cooling gas flow worked well as optimized

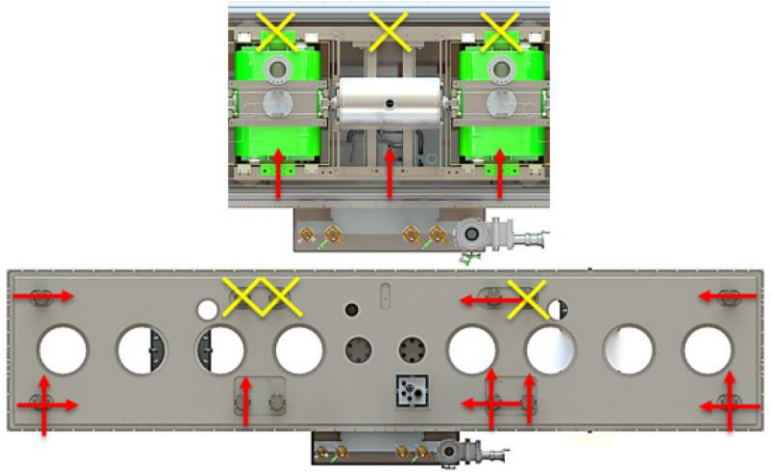
Superconducting solenoid integrated with XY dipole steering coils



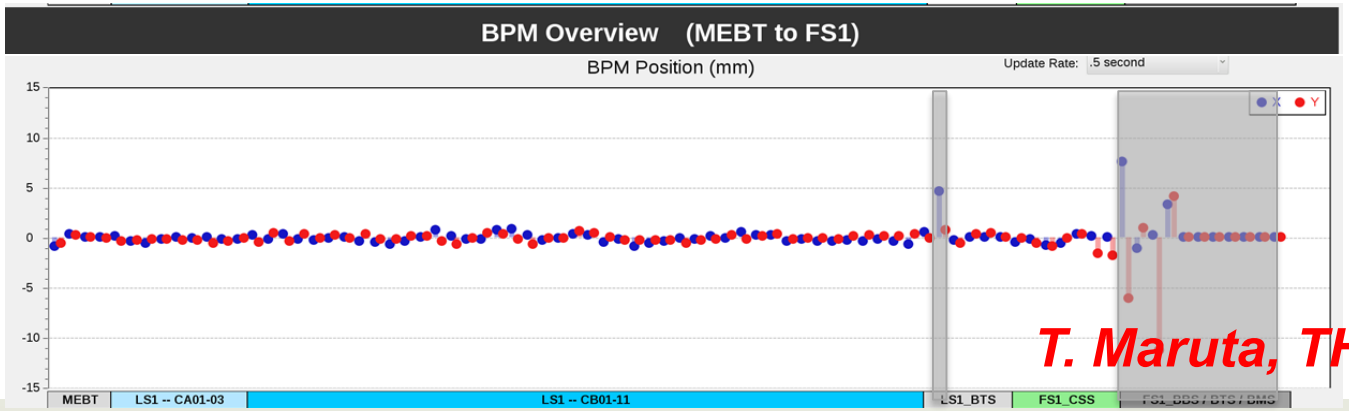
Coldmass Alignment
Benefit from bottom up cryomodule design

- Coldmass misalignments at 'cold' are within the alignment budget, ±1 mm

Cryomodule	Resonator		Solenoid	
	Horizontal RMS/Max Error (mm)	Vertical RMS/Max Error (mm)	Horizontal RMS/Max Error (mm)	Vertical RMS/Max Error (mm)
β=0.041 (4)	0.12/0.26	0.19/0.52	0.12/0.26	0.05/0.13
β=0.085 (11)	0.26/0.79	0.24/0.72	0.13/0.37	0.11/0.43
β=0.085M (1)	0.07/0.15	0.07/0.13	-	-
β=0.29 (12)	0.32/0.89	0.26/0.	0/0	0/0
β=0.53 (12*)	0.28/0.71	0.56/0.89	0/0	0/0
β=0.053M (1)	0.11/0.157	0.11/0.26	-	-



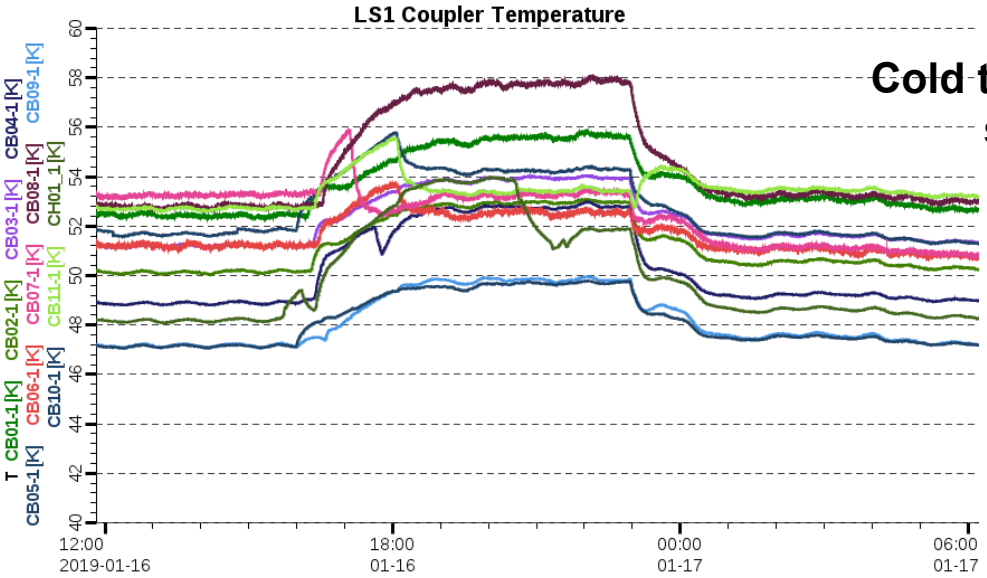
- In beam commissioning, only 10% of the design dipole fields were required for correction of argon beam in LS1



T. Maruta, THZBA3

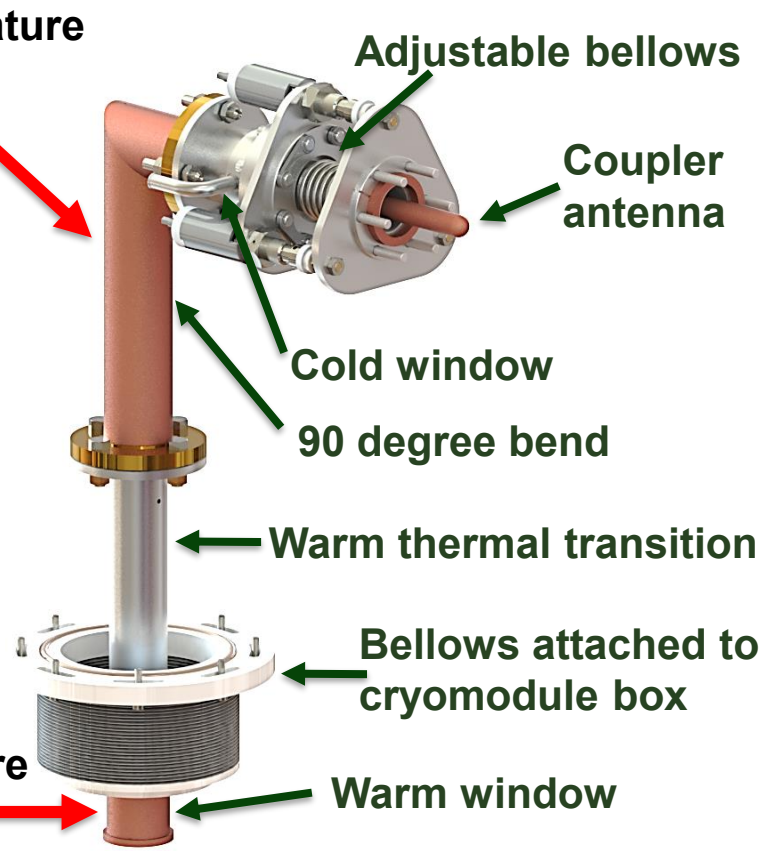
80.5 MHz RF Power Coupler
No overheating or multipacting

- ΔT at the cold temperature sensors < 6 K @ 1 kW



- ΔT at the warm temperature sensors < 2 K
- No nonlinear ΔT with respect to $P_{forward}$

80.5 MHz RF Power coupler
Based on 1-5/8" coax



Amplitude and Phase Stability without Beam

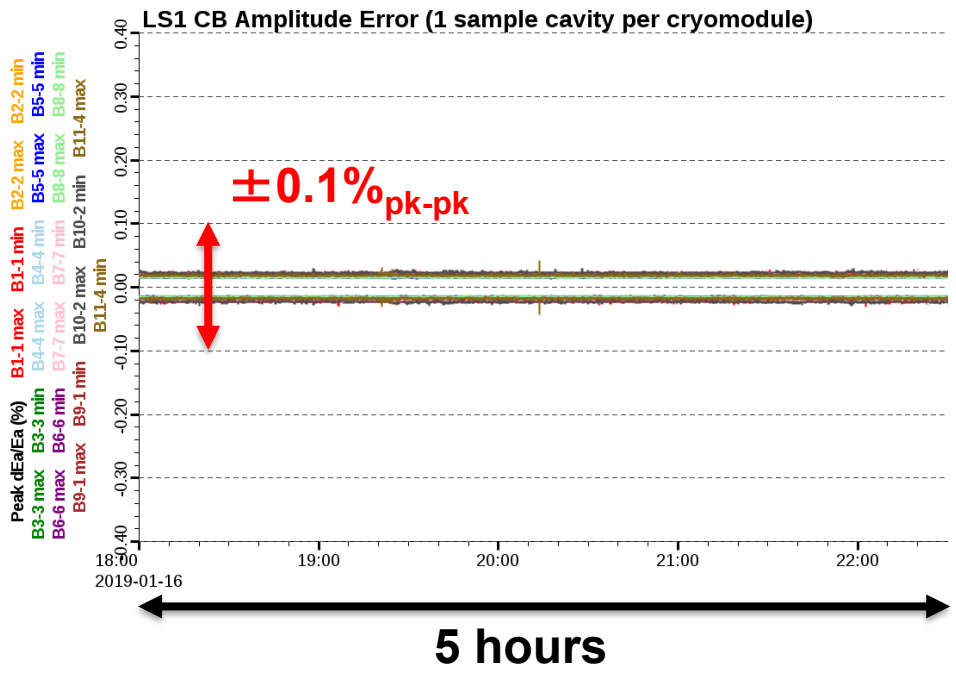
Achieved the stability goals with ample margins

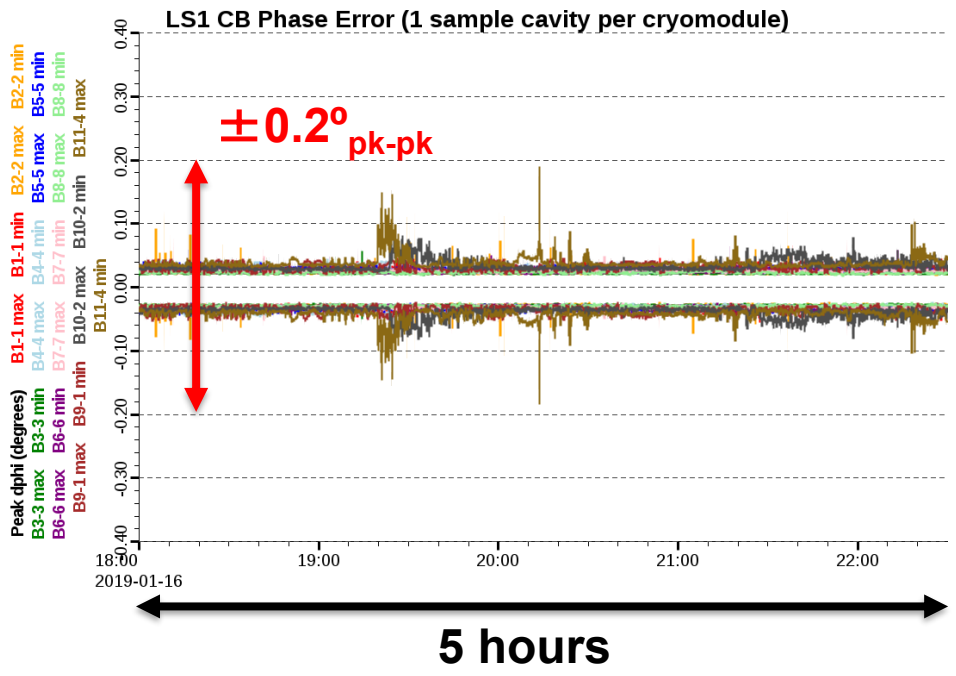
Amplitude and phase stability at the full design gradients

- Amplitude tolerance: $\pm 1\%_{pk\text{-}pk}$, measured errors: < $\pm 0.1\%_{pk\text{-}pk}$
- Phase tolerance: $\pm 1^{o}_{pk\text{-}pk}$, measured errors: < $\pm 0.2^{o}_{pk\text{-}pk}$

Amplitude and phase errors in selected LS1 cavities

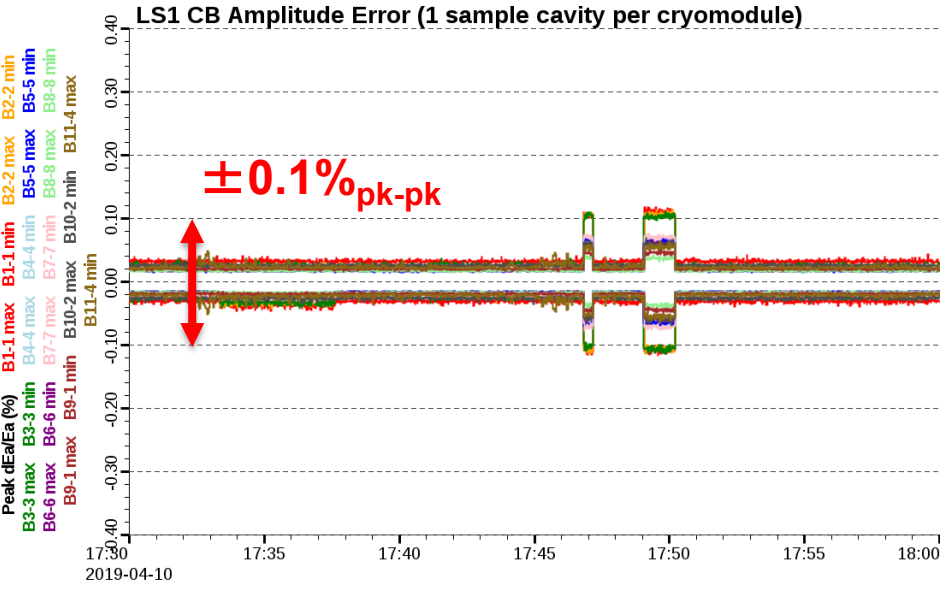
(measured using FPGA with ~100 kHz bandwidth)

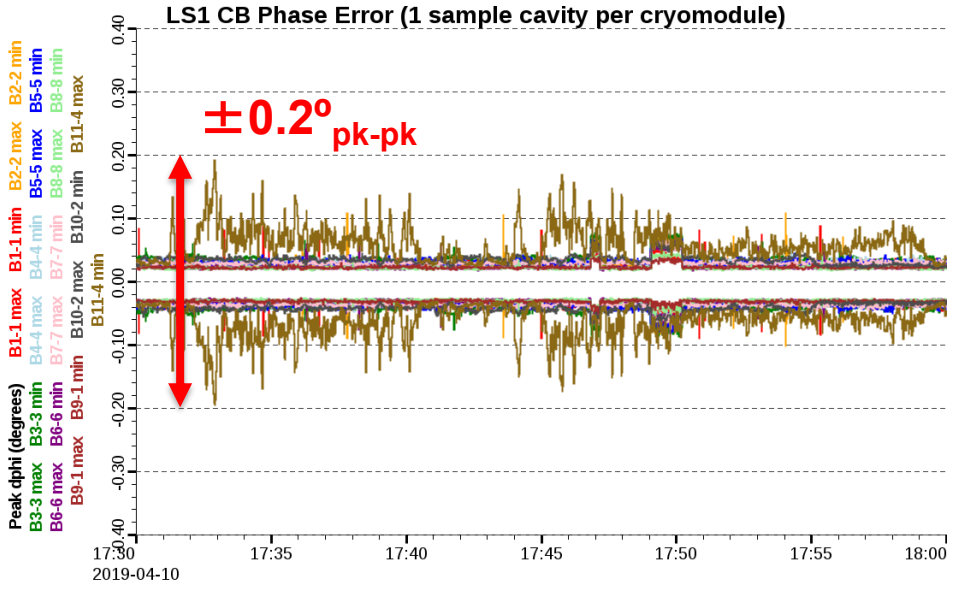




Amplitude and Phase Stability with Beam
The stability is preserved even with the pulsed beam

- High-peak-current pulsed beam in the commissioning
  - Peak current 130 μA: 1/3 max design current
  - Pulse length 6 ms: comparable to the cavity RF filling time 8 ms
  - Repetition rate: 5 Hz
- Stabilities are almost preserved with the pulsed beam
  - Pulsed beam mode would be useful for future beam power ramp up: pulsed mode
  - Only feedback control was used

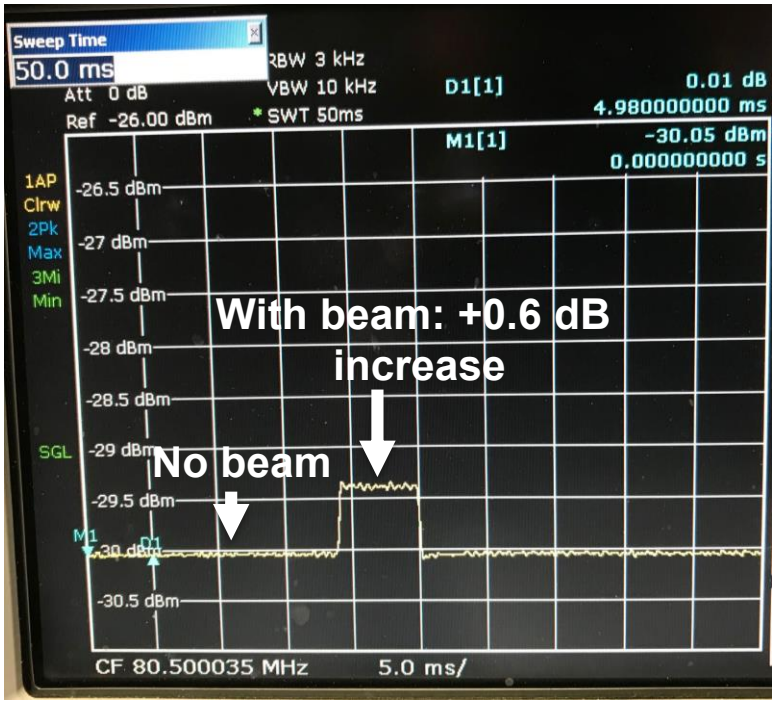




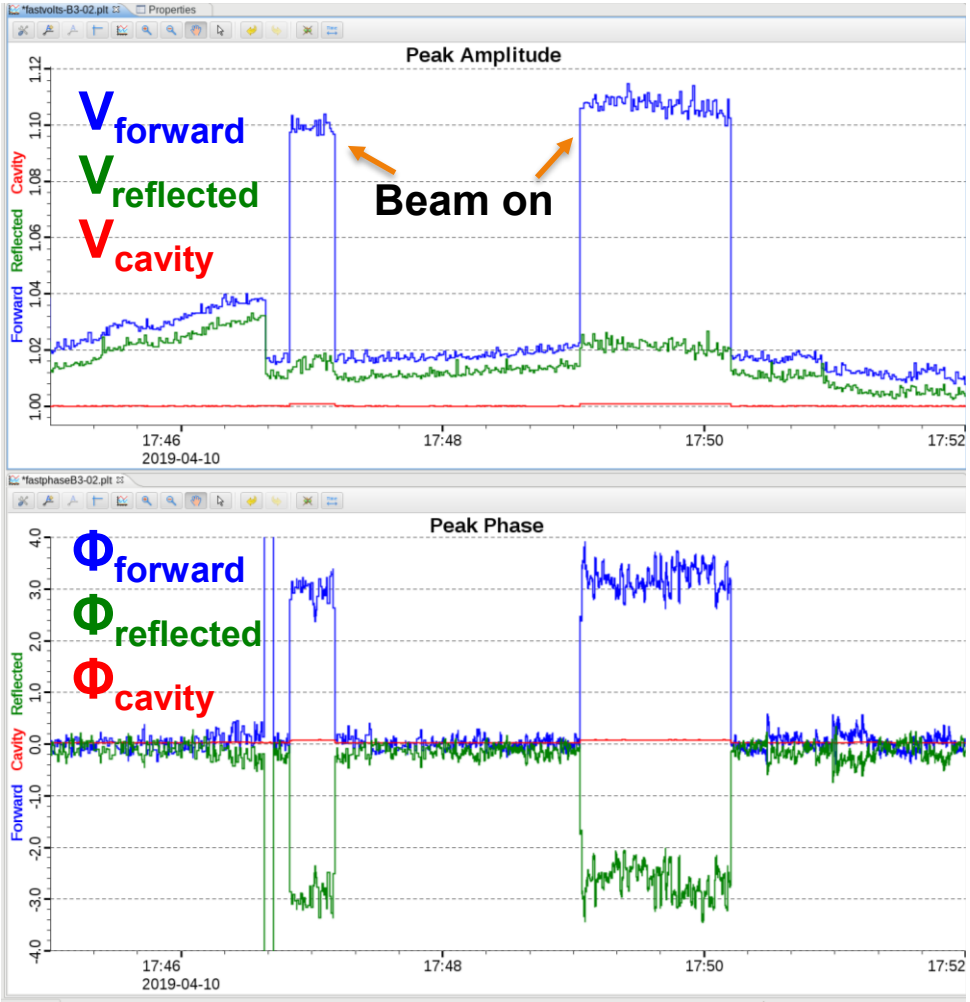
Transient Beam Loading Voltage Compensated By RF Feedback Control

Pulsed Waveform in 50 ms

Forward RF power, $P_{forward}$

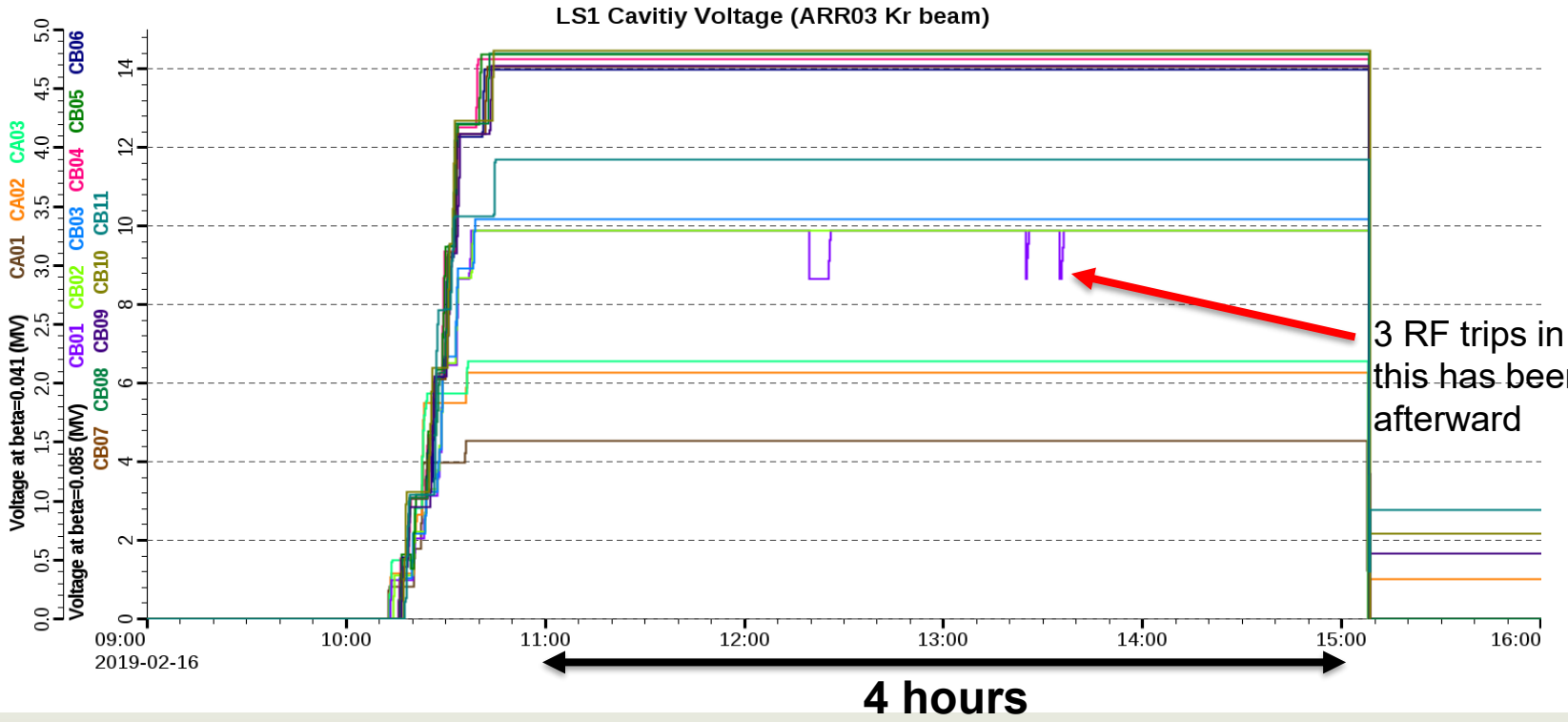


Peak detection over 7 minutes



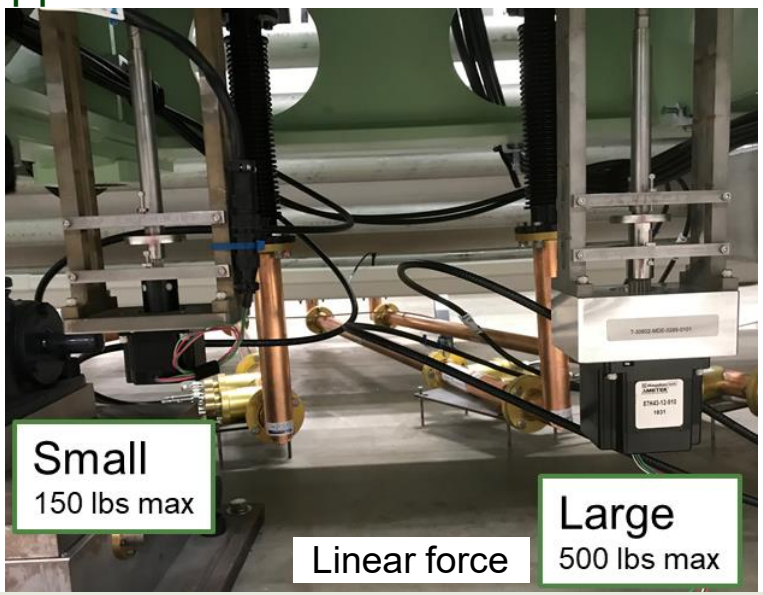
Reliability of Cavity Operation

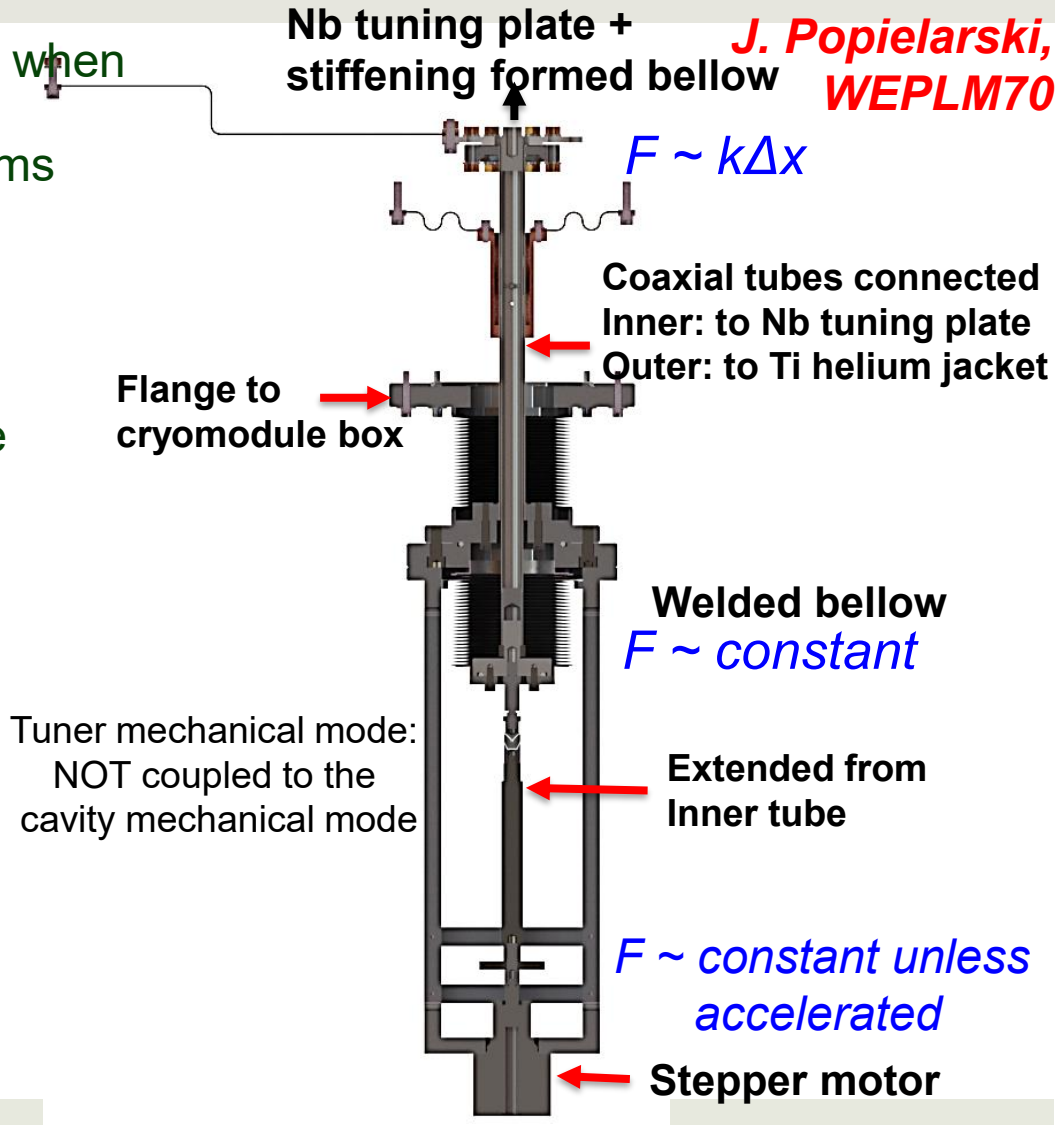
- A few to several trips per 15 hour shift in the whole LS1
  - Main source: tuner stepper motor, which was fixed after the beam commissioning
  - One cavity not used: potential microphonics/resonance control issue, under investigation
- No conditioning effects happened in the cavities/couplers during beam commissioning



Mitigation of the Tuner Stepper Motor Issue

- Issue: sudden jump of the tuning plate when it starts to move, especially changes direction; not a typical backlash (in terms of range) or mechanical deadband
- Possible cause: loose force when accelerated (no encoder in stepper)
- Solution: replaced with a higher torque stepper motor



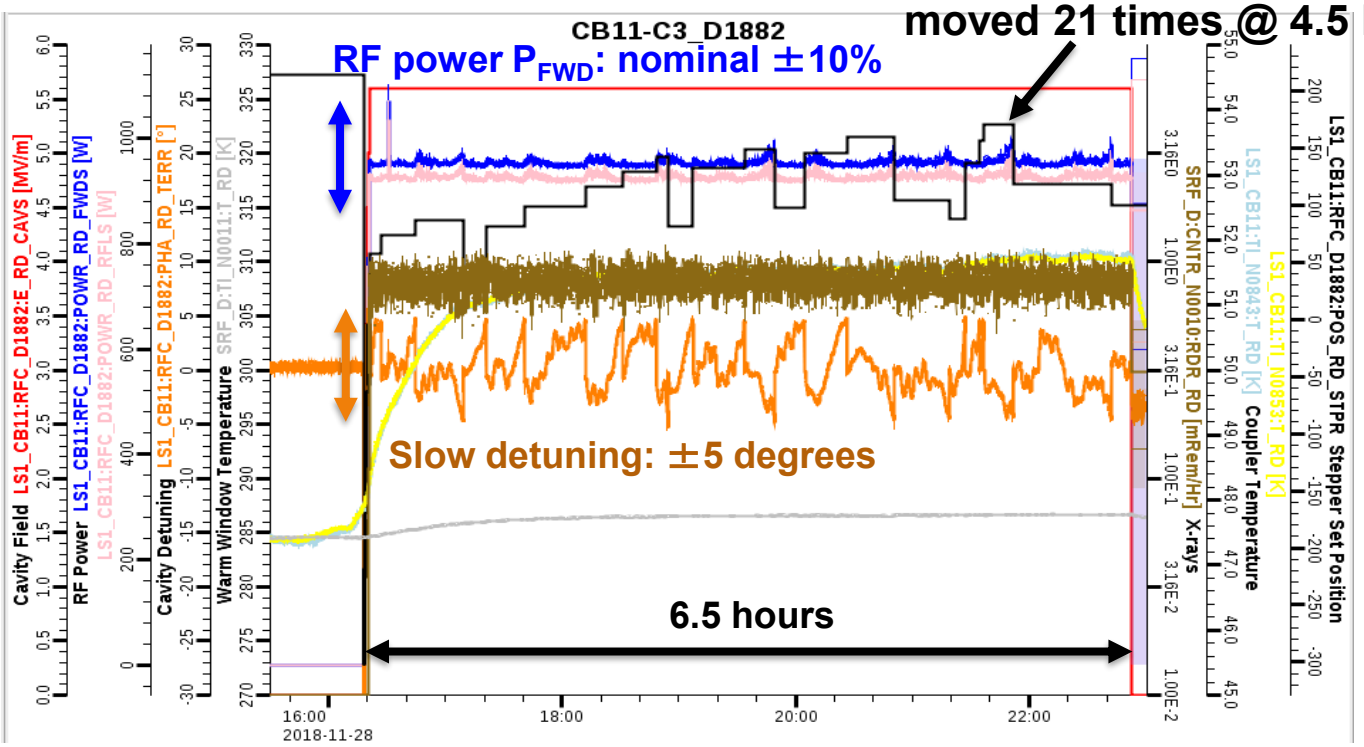


Resonance Control Performance at 4.5 K

80.5 MHz QWRs were stable at 4.5 K

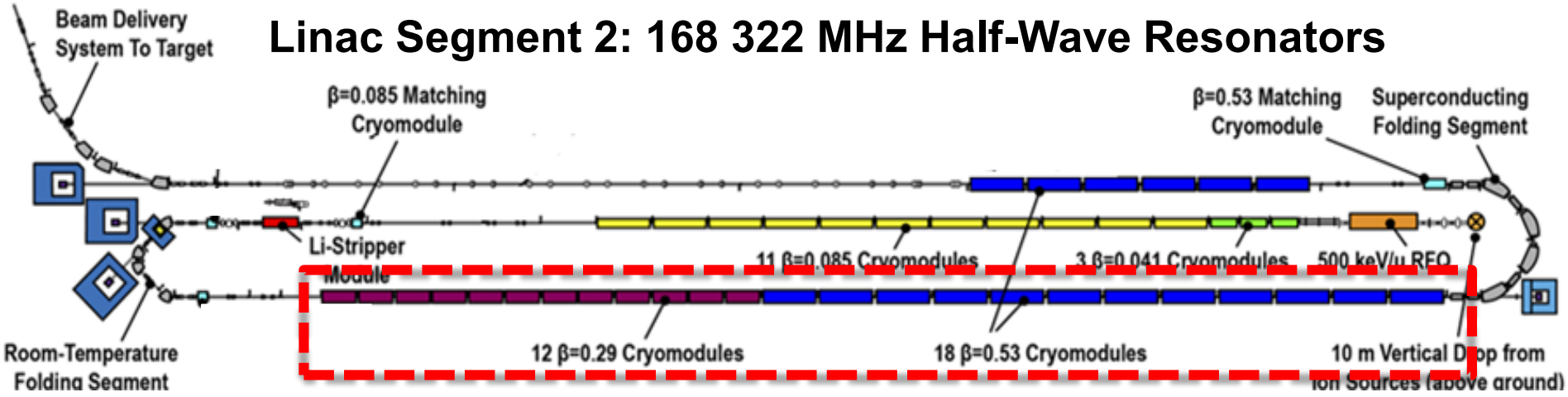
- Pool boiling effect is negligible: with -2 to -5 Hz/Torr df/dp, <8 W wall dissipation power, 40 Hz bandwidth in QWR085
- Microphonics resonant with the cavity mechanical mode: managed not to be excited
- Slow tuner: moves a few times per hour with on-off control with the hysteresis band

CB11-C3 @ 5.6 MV/m, 4.5 K



Summary

- LS1 cryomodules with 104 QWRs have been commissioned
  - Achieved the design gradient, amplitude and phase stability
  - Provided stable SRF operation for the beam commissioning to achieve 20.3 MeV/u ion beams
- Next step: commission 24 cryomodules containing 168 322 MHz Half-Wave Resonators
  - 13 cryomodule have been cooled down (as of 9/4/19), LLRF integration tests have been started



Acknowledgements

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  - SRF: T. Xu, J. Popielarski, W. Hartung, W. Chang, K. Saito, M. Xu, C. Zhang, H. Ao, J. Schwartz, S. Miller, C. Compton, L. Popielarski, K. Witgen
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  - Operations: G. Machicoane, H. Ren, C. Morton, J. Stetson
  - Controls: L. Hodges, M. Konrad, E. Daykin, S. Beher
  - Beam Instrumentation and Measurement: S. Lidia, J. Crisp
  - Power Supply: R. Bliton
  - And the whole FRIB project team
- Collaborations
  - Argonne National Laboratory
  - Jefferson Lab

Talks/Posters Related to FRIB LS1 QWR Commissioning

- **MOPLO17:** Walter Hartung, “Large-Scale Dewar Testing of FRIB Production Cavities: Results”
- **MOYBB4, MOPLO16:** Cong Zhang, **“**Large-Scale Dewar Testing of FRIB Production Cavities: Statistical Analysis”
- **TUPLE01:** Harsh Maniar, “Python Application for RF Commissioning at FRIB”
- **WEPLM03:** Shen Zhao, “The LLRF Control Design and Validation at FRIB”
- **WEPLM73:** Wei Chang, “Bunker Testing of FRIB Cryomodules”
- **WEPLH09:** Hiroyuki Ao, “FRIB Driver Linac Integration to Be Ready for Phased Beam Commissioning”
- **WEPLM70:** John Popielarski, “FRIB Tuner Performance and Improvement”
- **WEPLM71:** Mengxin Xu, “Thermal Performance of FRIB Cryomodules”
- **THZBA3:** Tomofumi Maruta, “Status of Beam Commissioning in FRIB Driver Linac”
- **WEPLM62:** Kellen McGee, “First Cold Test Results for a Medium-Beta 644 MHz Superconducting 5-cell Elliptical Cavity for the FRIB Energy Upgrade”