FRIB Linac SRF Commissioning:
Lessons Learned in Field Calibration, Mitigation of Field Emission, and Resonance Control

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Outline

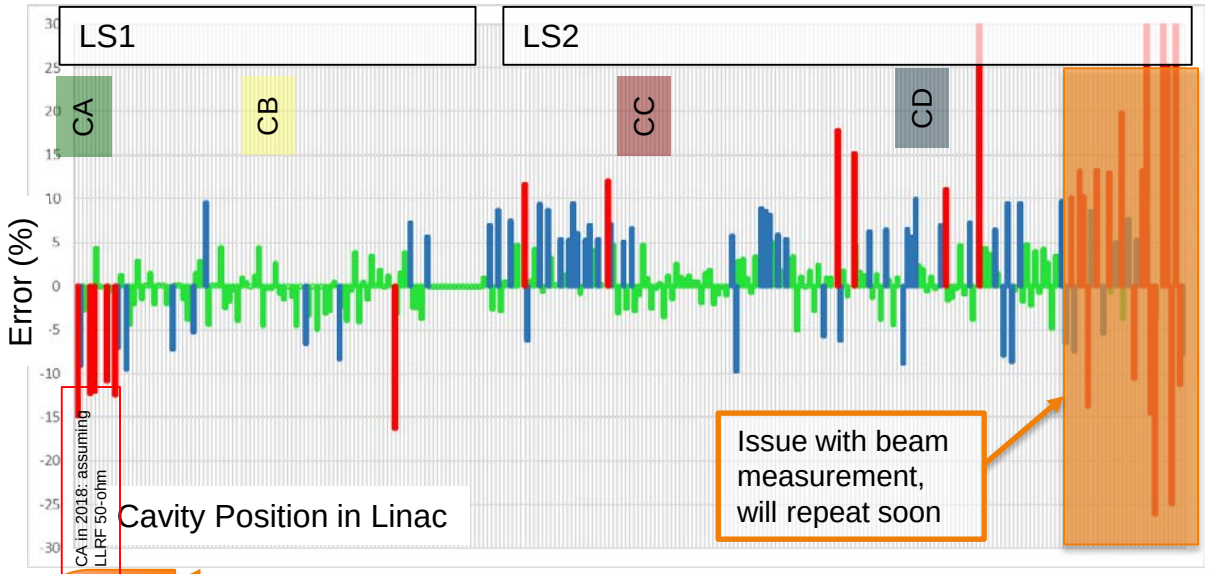
- RF to beam based calibration comparison
  - Results from FRIB testing
  - FRIB approach to calibration
  - Troubles that happened at FRIB with the RF calibration
- Gradient achievement at FRIB
  - RF locking stability at high gradient
  - Treatments to FE
- Linac Thermal Cycle
- Conclusion / closing remarks & time for questions

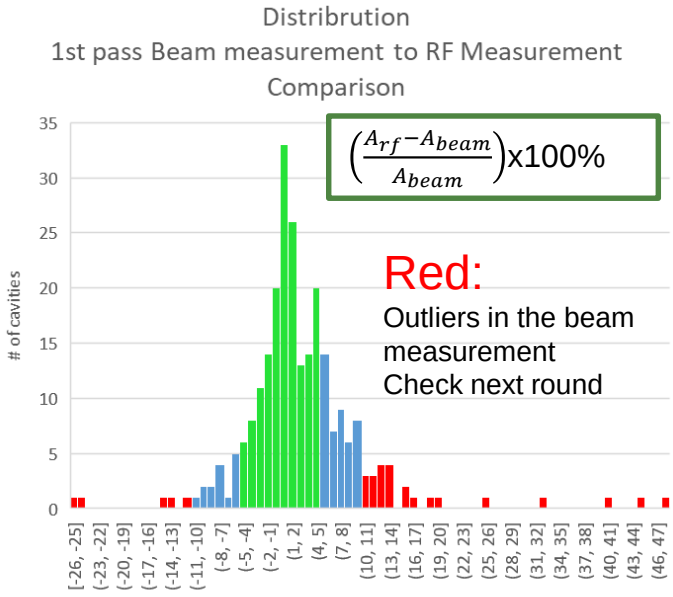
SRF Calibration Results from FRIB

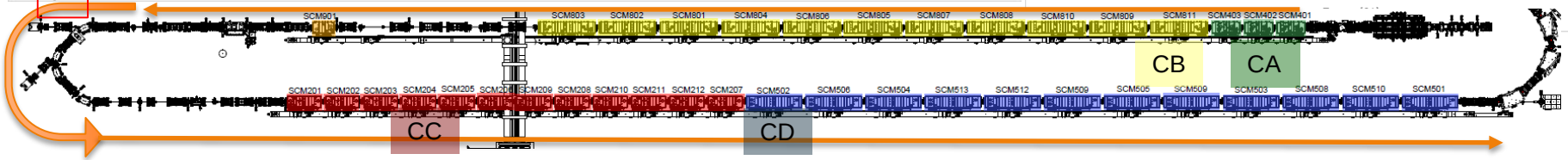
Goal for SRF Commissioning (testing cavities before beam ops)

- The goal in SRF commissioning is to ensure stable operation of beam at the level SRF group promised, going back to bunker test, VTA, design goals. Consider AP group as the customer.
- In SRF commissioning, SRF experts are responsible to set the maximum amplitude (a max set point managed by channel access) considering the following
  - » RF locking long term stability
  - » Field Emission – avoid deconditioning effects
  - » RF coupler temperature stability
  - » RF power use (max peak power and max average power managed by amplifier system owners)
- Adding more margin to offset RF calibration errors is not necessarily desirable since we can approach fundamental limits that could actual reduce the gradient in the cavity.
  - **It is better to have confidence in the RF measurement.**

SRF Calibration Results from FRIB so Far





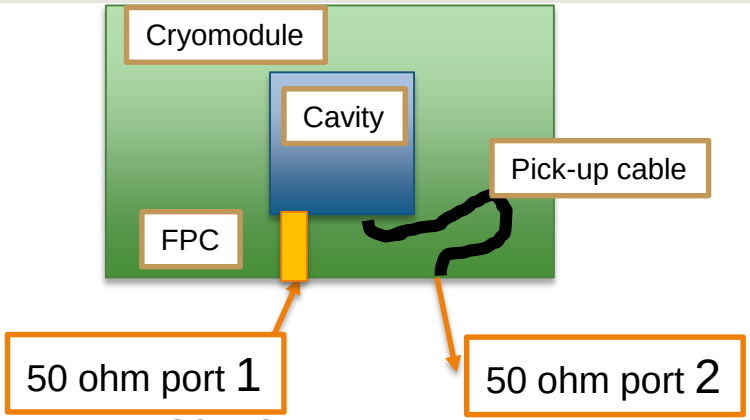


- In CA commissioning (12 cavities, Spring 2018), we noticed rather large discrepancy with beam based measurements. Started corrective measurement for next sets (next slides)
- Did corrective measures for CB (104 cavities, Spring 2019) and overall gradient match the RF calibration within 2%, although there were some outliers
- In HWR commissioning (168 cavities, Spring 2020,…, Fall 2020). Overall, gradient consistent with RF calibration, need to repeat some beam measurements
- LS3 (HWR) scheduled for this Spring

Corrective measures for Mismatch
Goal to have RF error from mismatch < 10%

Mismatch in Cryomodule

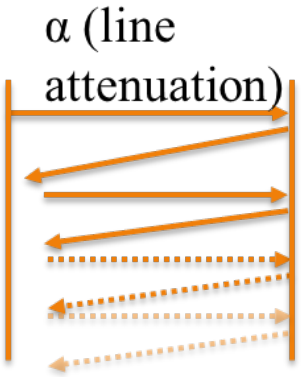
- We use Low level measurement with 50 ohm to get |S21| and QL (QL=QEXT1) (VNA, spectrum analyzer) to get Qe2
- If pickup cable inside cryomodule has mismatch (feedthrough), the result Qe2 will cover that
- If input coupler has mismatch, the Qe2 doesn't represent cavity field (but input is usually matched very well)



S21, QL measurement
For cavity field calibration

Mismatch in LLRF

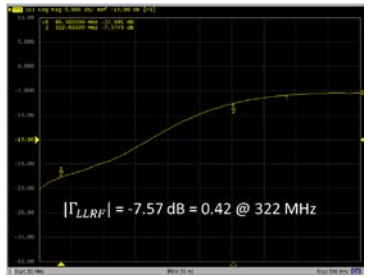
- We attribute the inconsistency with CA beam calibration to LLRF mismatch.
- If the LLRF is mismatched, the standing wave pattern on the pick-up line can bring in a big error (including mismatches in module)
- In FRIB we chose to add more padding to reduce the SW power and reduce error in LLRF measurement. (increase α until error from reflection is less than 5%)
- RF error if function of Γ,α, and line length



Γ (reflection)

Γ (SRF cavity)
Assume -1

Γ (llrf)

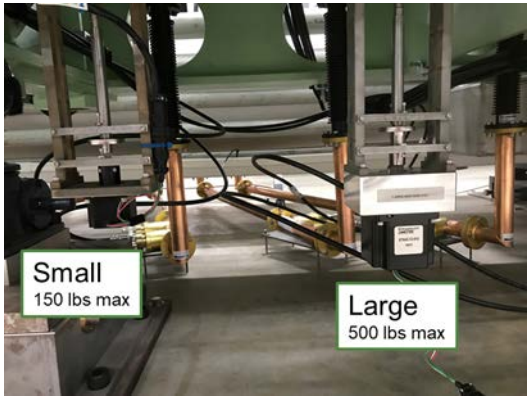


Common Issues faced with RF calibrations

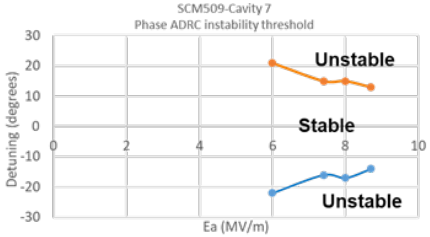
- Mismatched RF line or adaptor used in the calibration can give a large error!!
  - Do periodic review of data as the measurements are being done. We found that 1-2 days of work needed to be repeated after using a mismatched adaptor for the FPC.
  - Develop built in consistence check in the measurement (repeat measurement after changing line length or adding attenuator)
- Noise, microphonics adds jitter to QL measurement (VNA BW measurement)
  - Use spectrum analyzer and do decay measurement.
- LLRF internal calibration issues
  - In some cases, the settings in the LLRF box were wrong. During SRF commissioning, keep consistency check before high power
- Transmission line, amplifier mismatch
  - Check QL again after attachment to the high power amplifier

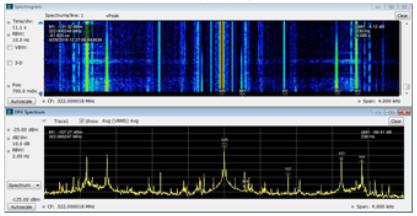
Gradient Achievement in FRIB Resonance Control Perspective

- LS1 Story & Early Commissioning (2018, 2019)
  - In LS1, 1/104 SRF cavities had microphonics problems and it could not be used reliably. It was labeled “do not use” for the first rounds of commissioning. We have since improved control parameters and it operates stable.
  - External stepper motors are used for tuning (no fast tuner). We have a few trips from tuner slips, so we are upgrading the motor which has more torque and does not experience tuner slips



- LS2 (HWRs at 2K) Story & Pursuit of High Gradient (2020)
  - We did not build long term high gradient operation of HWRs in the bunker test campaign before the 1st round of LS2 beam commissioning in March 2020
  - In the 1st round, we limited operational gradient to 10 % lower than the operational specification to reduce time to set LLRF parameters (SRF commissioning time reduced for early beam commissioning)
  - In summer 2020, we had dedicated time (additional week) in bunker testing of the last FRIB HWR module to develop better understanding of high gradient operation.
  - As a redul

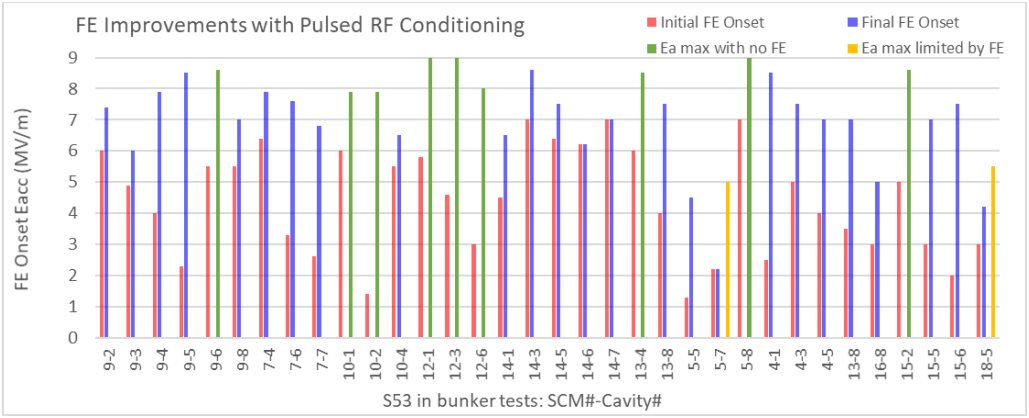




Control BW stable region decreases at higher gradient; RF system excites mechanical modes. **Solved after fine tune control parameters (separate amplitude and phase)**

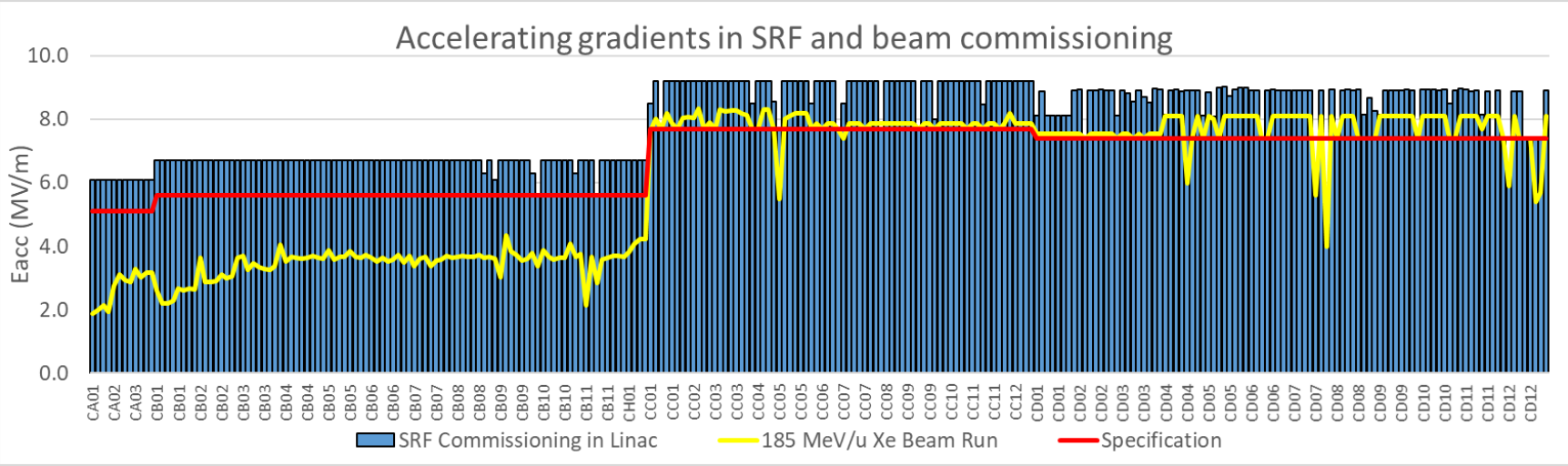
Gradient Achievement in FRIB Field Emission Perspective

- Field emission doesn't go away after thermal cycle
  - Bunker test to tunnel, thermal cycle in tunnel did not improve FE cavities.
- The first cryomodule, which was also a "production prototype" had 5/8 cavities with field emission limiting performance, but the cryomodule meets average gradient specification
  - Suspect attempts on in-situ conditioning of FPCs without bias
- In the rest of the linac, 27/272 SRF (10%) cavities have X-rays > 0mR/Hr.
  - In LS1 (QWRs) none of the FE limits gradient
  - In LS2 (HWRs) 18 cavities with FE:
    - » 3 had heavy FE in bunker test and the gradient is reduce in linac operation. We did not improve on those
    - » 5 corrected with pulse RF conditioning, 13 have CW Xrays < 10 mR/HR. We will track for degradation.
    - » Result: 8/272 cavities are on lower than design gradient (< 3%)
- Pulse conditioning in bunker tests
  - Has promising results
  - Held conditioning into linac
- When pulse not successful
  - not enough power available, or
  - Cavity quenches before e break-down



FRIB Gradient Achievement So Far

LS3 SRF Commissioning is happening now, beam tests being planned in Spring



- FRIB Linac:
  - 8 SRF cavities limited by field emission below specification value (8/272)
    - » Considering options to recover performance, but all these cavities had the FE in the bunker test & the module can achieve the overall gradients in average
  - 225 SRF cavities have no problem (FE, locking) staying stable at the administrative limit (10% over specification)
  - 52 more cavities are being tested right now in LS3, the last SRF linac segment for FRIB baseline.

Thermal Cycle Effect
In Summer 2020, all FRIB modules warmed up!!

- No reduction in field emission
  - As known from bunker test to linac commissioning
- All cavities needed to repeat multipacting conditioning!
  - Expected yes but still inconvenient
- No degradation of Q0 noticed for 2K operation, all cryomodules did a deguassing step before warm up
  - See Sang-hoon's slides from yesterday about the dynamic load measurements

Conclusion

- RF Field Level Calibration
  - FRIB field calibration results look good so far. We took advantage to learn a lesson during staged beam commissioning and addressed a previously unknown issue about the LLRF mismatch.
- Gradient Achievement: Resonance Control
  - High gradient operation of FRIB cavities needed a longer study to understand the bandwidth of stable operation. After that, there seems to be no amplitude based on amplitude control.
- Gradient Achievement: Field Emission
  - Pulse conditioning in bunker tests was successful and retained conditioning after installing to linac
  - A few deconditioned during operation (Xrays go up fast) and trip. We turned off or reduced field until they can be recovered by pulse conditioning.