AWLC 2020

FRIB Superconducting Linac SRF Commissioning

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Facility for Rare Isotope Beams/Michigan State University

MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

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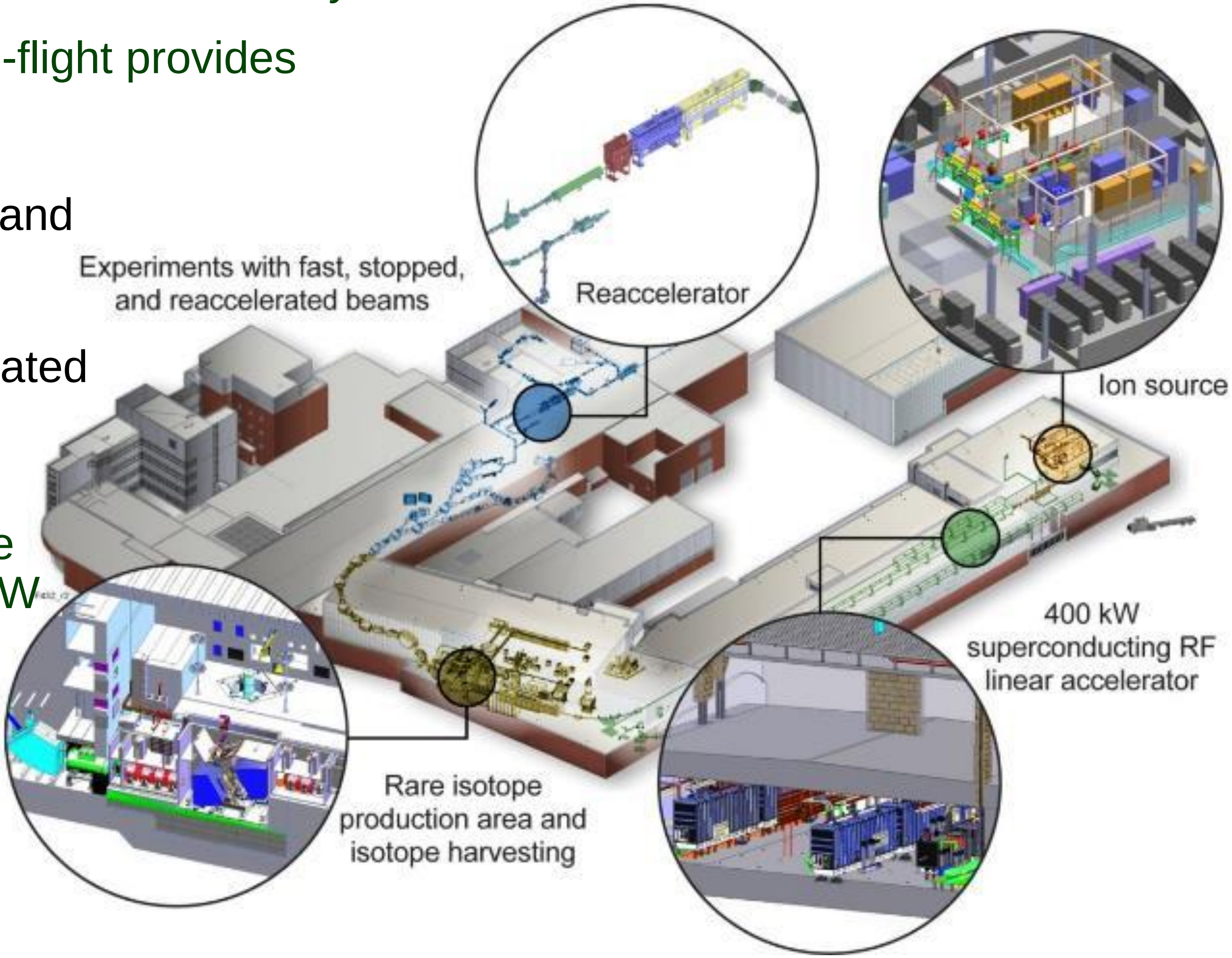
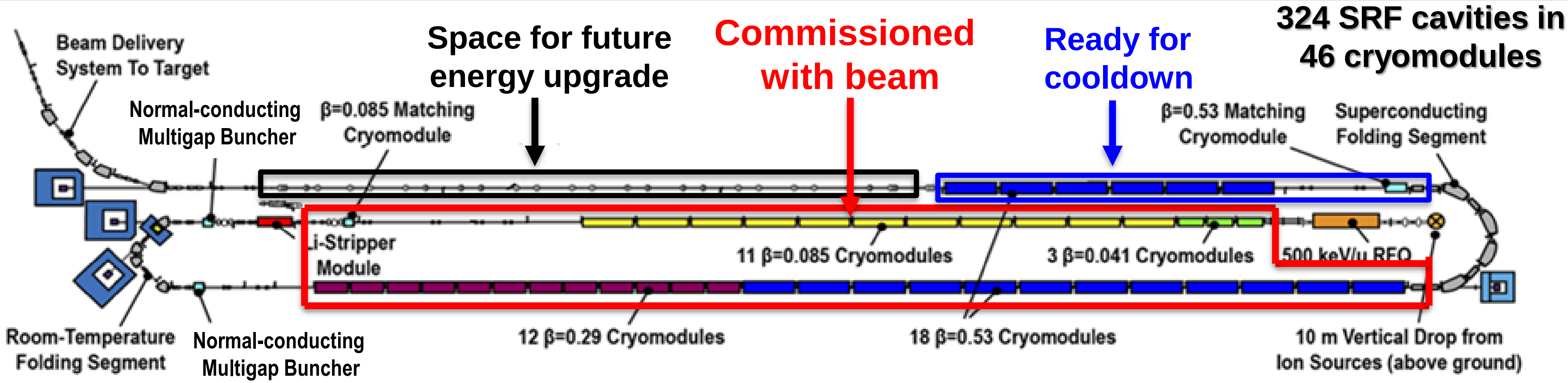
FRIB

- Key feature is >200 MeV/u, 400 kW heavy ion drive beam such as uranium
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - Beams of all elements and short half-lives
  - Experiments with fast, stopped, and reaccelerated beams
- Linac space is allocated for future energy upgrade to 400 MeV/u, 400/800 kW (FRIB400)



FRIB Superconducting Linac



- Progress in the staged commissioning
  - **Achieved >200 MeV/u Ar, >180 MeV/u Xe beam** with the first and second linac segments
  - The remaining cryomodules have been offline-tested and installed in the linac. RF commissioning is planned in this winter
- Will present the SRF cavity performance in SRF and beam commissioning

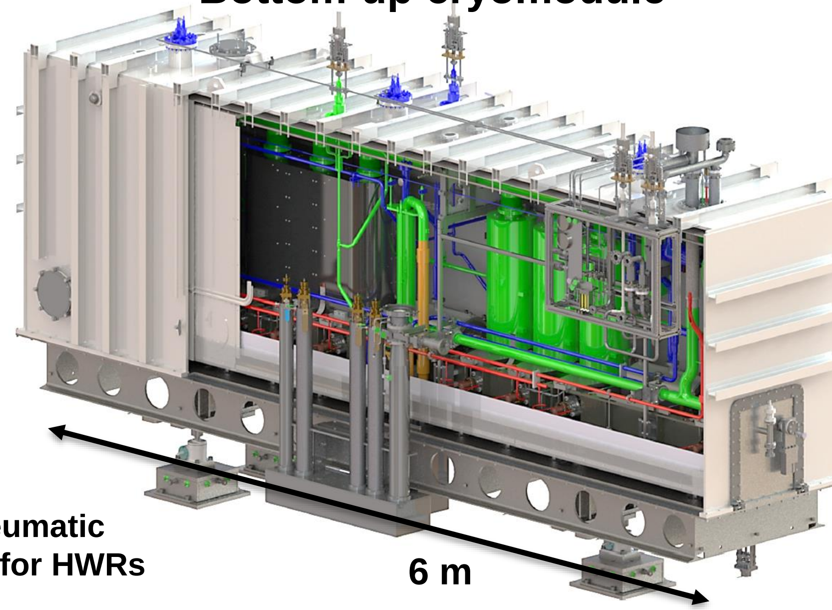
FRIB SRF Cavities and Subsystems

All different types of SRF cavities and subsystems have been commissioned with beam

80.5 MHz QWRs

322 MHz HWRs

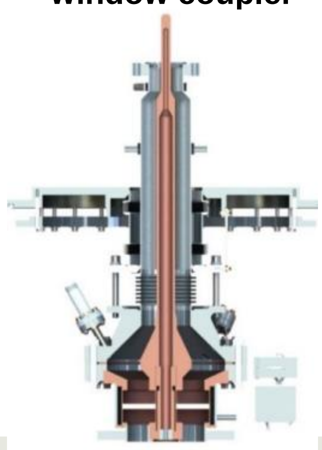
Bottom-up cryomodule



80.5 MHz double window coupler

Stepper motor tuner for QWRs

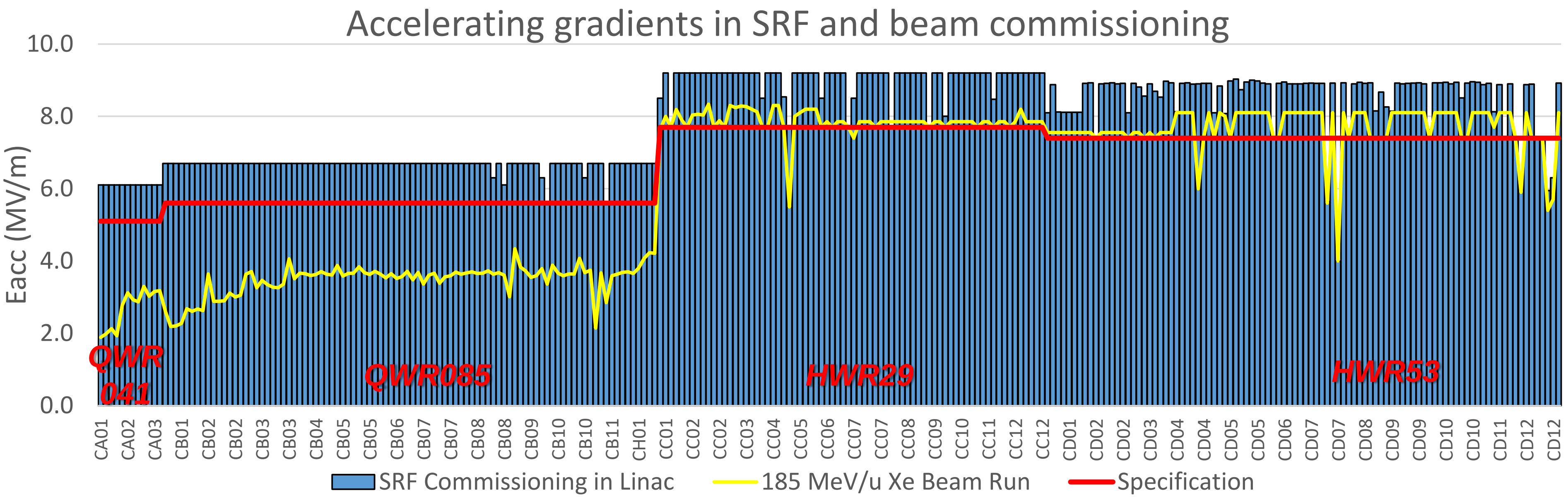
322 MHz single window coupler



Pneumatic tuner for HWRs

8 T SC solenoid integrated with XY dipole steering coils

Accelerating Gradient in Linac



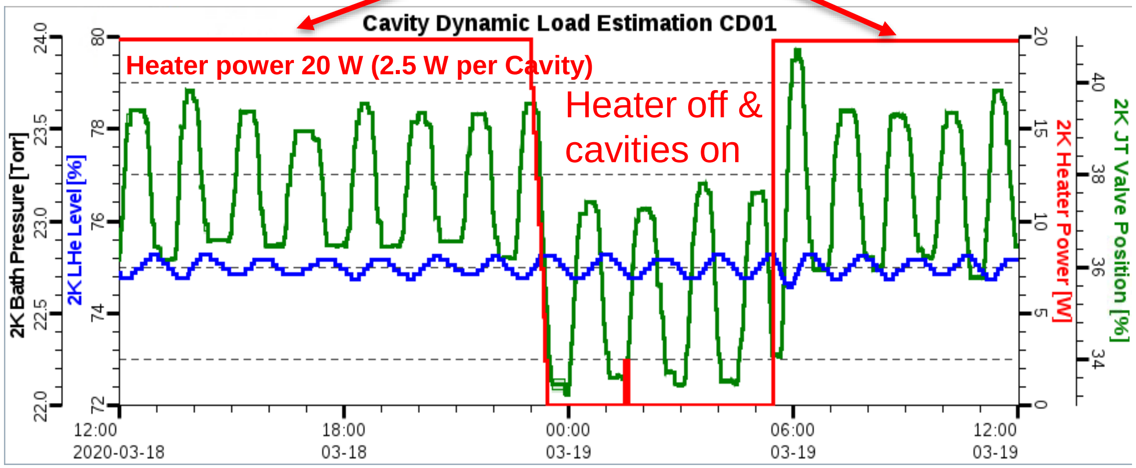
(administrative limit: 20% higher than spec)

Most cavities are operated at the design gradient or higher

- Few exceptions are due to field emission, however, their lower gradients were compensated by the other cavities
- The net accelerating voltage exceeds the FRIB specification

Cavity Q0 in Linac
322 MHz half-wave resonators at 2 K

- Average Q0 is approximately three times the specification
  - In linac, measured dynamic loads with a calibrated 2K heater. These results are roughly consistent with the offline-cryomodule (dP/dt) and vertical (RF) test results



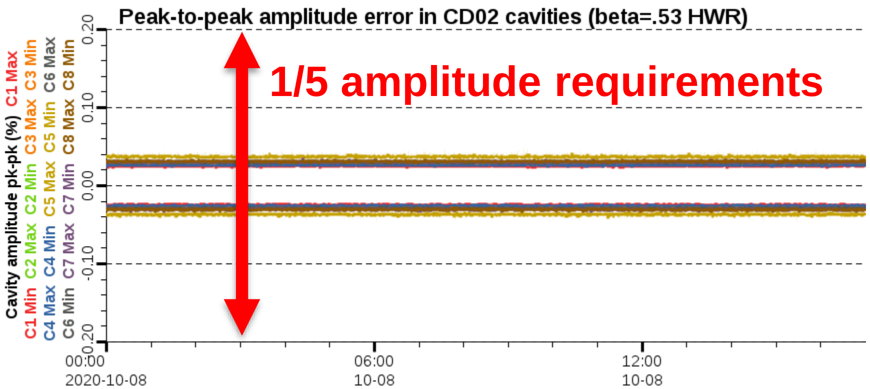
Average dynamic load < 2.5 W
Average Q0 > 2.4e10.
Specification Q0 is 7.9e9

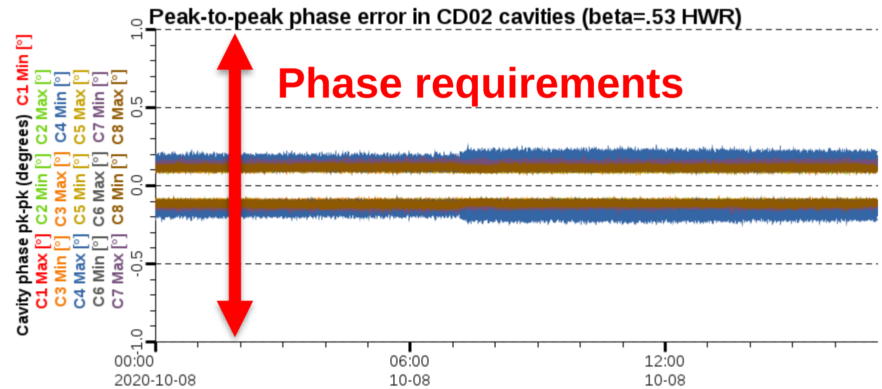
- No hydrogen Q disease after partial warm-up
  - Partially warmed up and stayed in the temperature range from 50 K to 150 K for 12 days. Cooled back down when the temperature reached to 200 K
  - Observed no measurable changes in Q0, i.e. no hydrogen Q disease
  - All cavities were hydrogen-degassed at 600ºC for 12 hours after bulk BCP

Amplitude and Phase Stability

- Amplitude and phase errors meet the requirements with ample margins

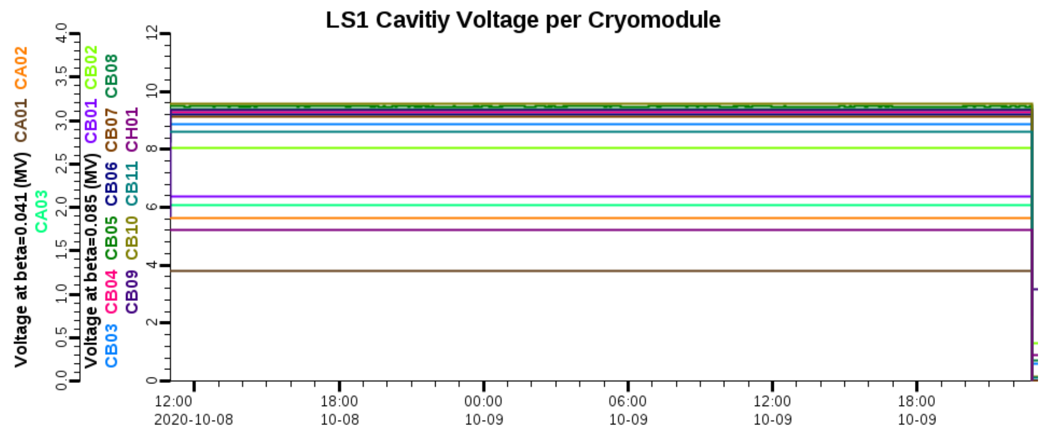
Typical amplitude and phase errors in β=0.53 cavity cryomodules (17 hour run)





- Also, the resonance control is stable in relatively long-term operation

104 QWRs ran for
36 hours with no RF trips



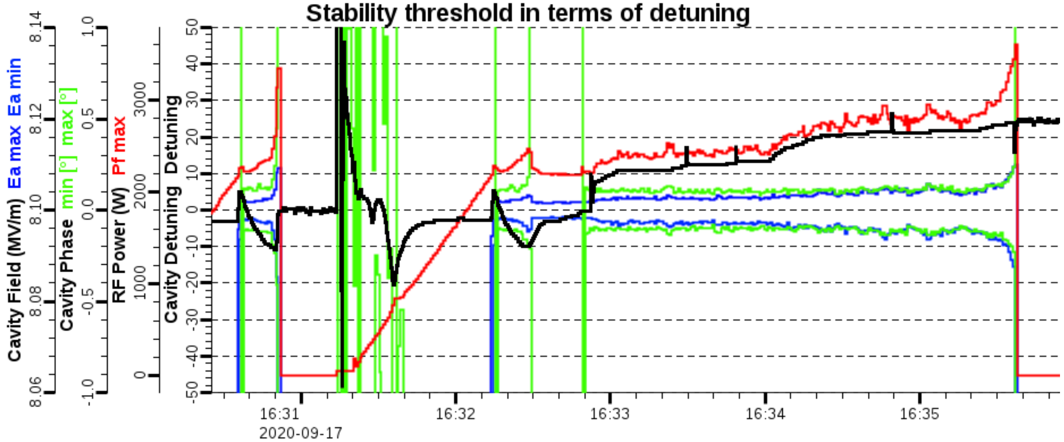
Suppression of RF-induced Instability
Essential to achieve stable resonance control

- Pondermotive-instability-like behavior appeared, which is not microphonics. However, this completely disappeared with an improved amplitude and phase control

A β=0.53 HWR @ 8.1 MV/m (+10% higher than the design gradient)

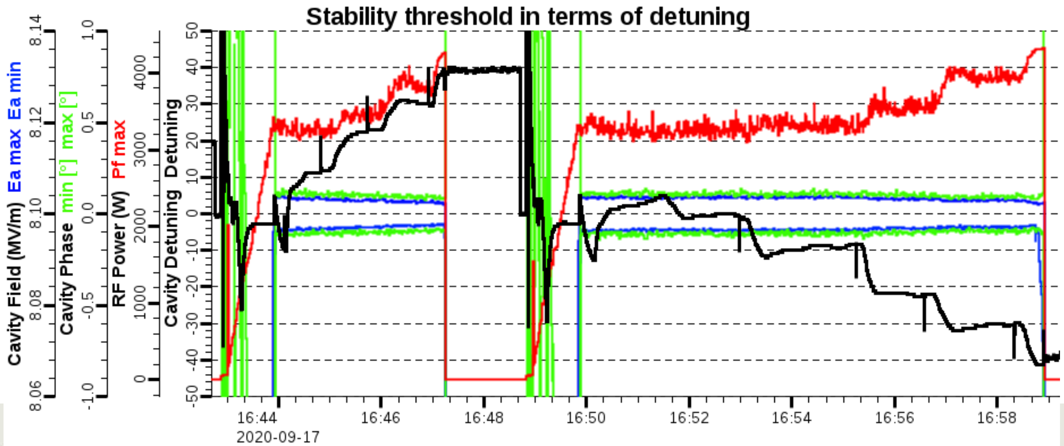
Original control

Controller BW (BWc) = 96 Hz
(cavity bandwidth = 34 Hz)
Stability window: -10º < ψ < +22º,
ψ: detuning angle



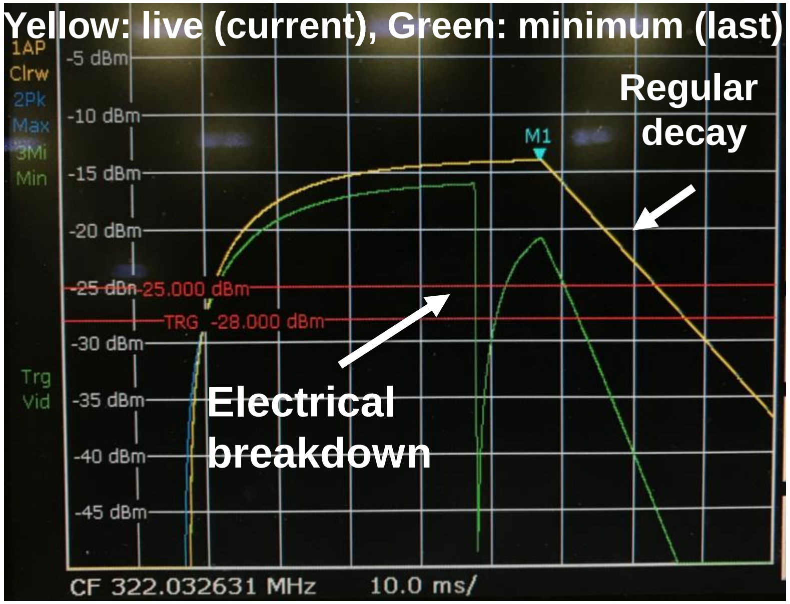
Improved control

Amplitude-loop BWc = 760 Hz
Phase-loop BWc = 96 Hz
No instability within ~±45º detuning,
i.e. the cavity bandwidth

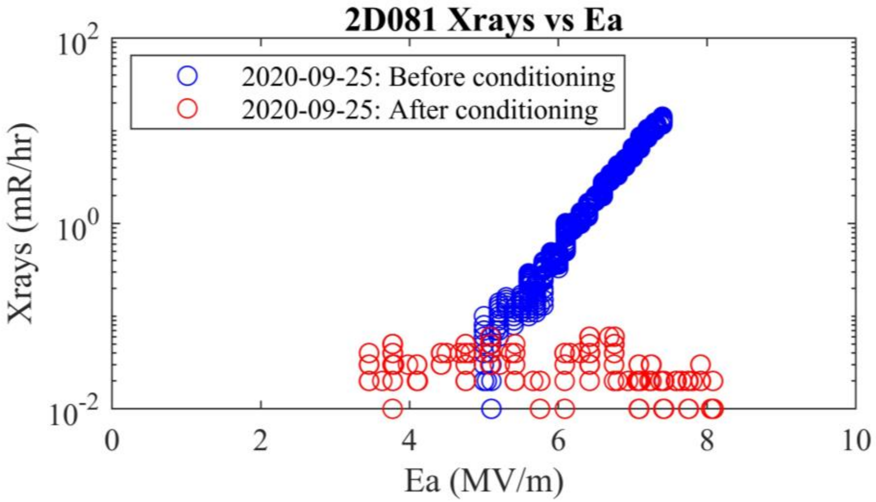


RF Conditioning
Useful to mitigate field emission in our case

Cavity field



FE improvement after electrical breakdown: this cavity was initially degraded in the linac after the first online test



- In pulsed RF conditioning, field emission is improved when the electrical breakdown is induced
- One cavity with 7 times electrical breakdowns: no measurable Q0 degradation
- **However, this could not cure all cases:** sometimes limited by FE-induced thermal breakdown.

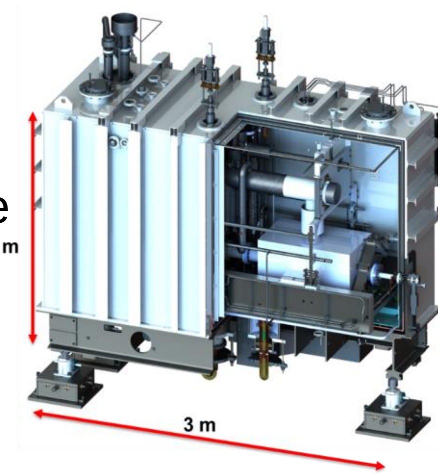
SRF R&D for FRIB400

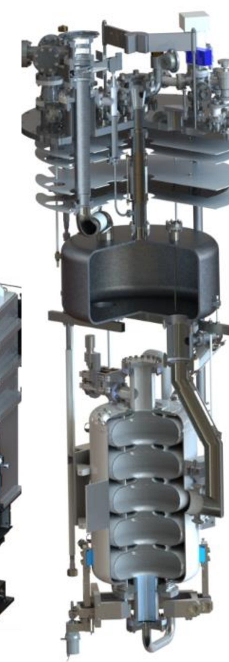
Energy upgrade to 400 MeV/u for uranium beam

- Design
  - 644 MHz, β_{opt} = 0.65, 5-cell elliptical cavity
  - Goal: $Q_0 = 2 \times 10^{10}$ at 2 K, E_{acc} = 17.5 MV/m
  - Total 55 cavities in 11 cryomodules
- SRF R&D Progress and Plan
  - Built/building 3 multi-cell cavities, 3 single-cell cavities
  - Achieved the design goal in the undressed cavities with the standard ILC recipe
  - Pursuing high Q0 R&D in collaboration with FNAL, ANL
  - Plan to test jacketed cavity with frequency tuners
  - FPC and prototype-cryomodule have been designed
- FRIB SRF Facility Upgrade
  - New EP facility, N-doping in the existing baking furnace
- Strong collaboration with other labs
  - FNAL: N-doping, tuners and resonance control
  - ANL: electropolishing

Jacketed cavity with tuner

Prototype cryomodule





Summary

- With successful commissioning of the SRF cryomodules in the first and second linac segments, FRIB achieved >200 MeV/u Ar, >180 MeV/u Xe beam.
- Cavity operation is stable and reliable. SRF provided 100% availability in the last two-week beam commissioning (Oct 2020).
- SRF commissioning of the remaining 7 cryomodules will be complete in this winter.
- At the same time, we are pursuing SRF R&D for Energy Upgrade.