FRIB

SRF Cavity Testing: Tutorial

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MICHIGAN STATE UNIVERSITY

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Topics

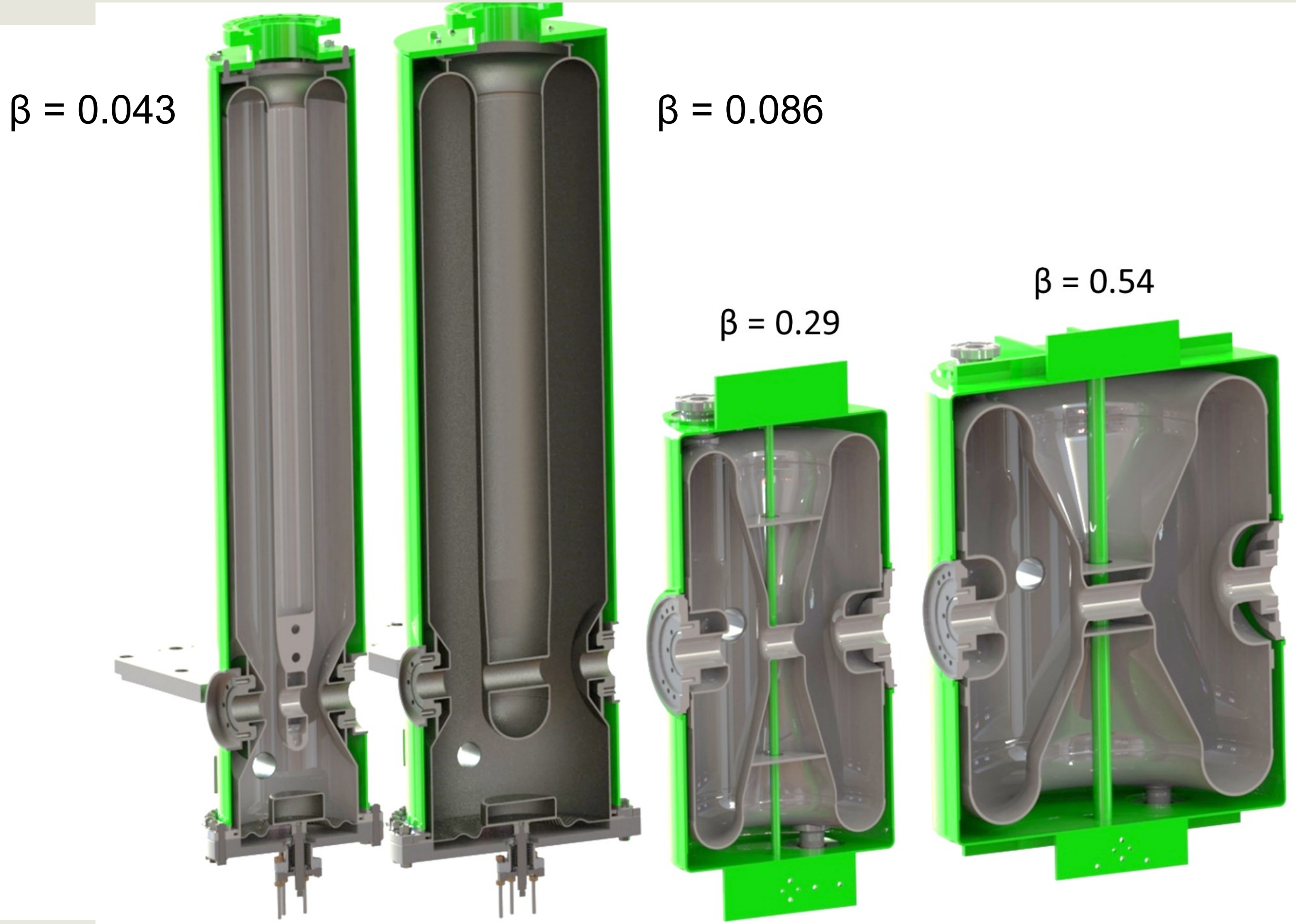
- Why?
- When?
- How?
- Calibrations, analysis
- Steps
- Phenomena
- Diagnostics

Cavity Testing: Why?

Cavity Testing: Why?

- Development
- Prototyping
- Production
- Repair, refurbishment
- Example: FRIB production

FRIB Resonators



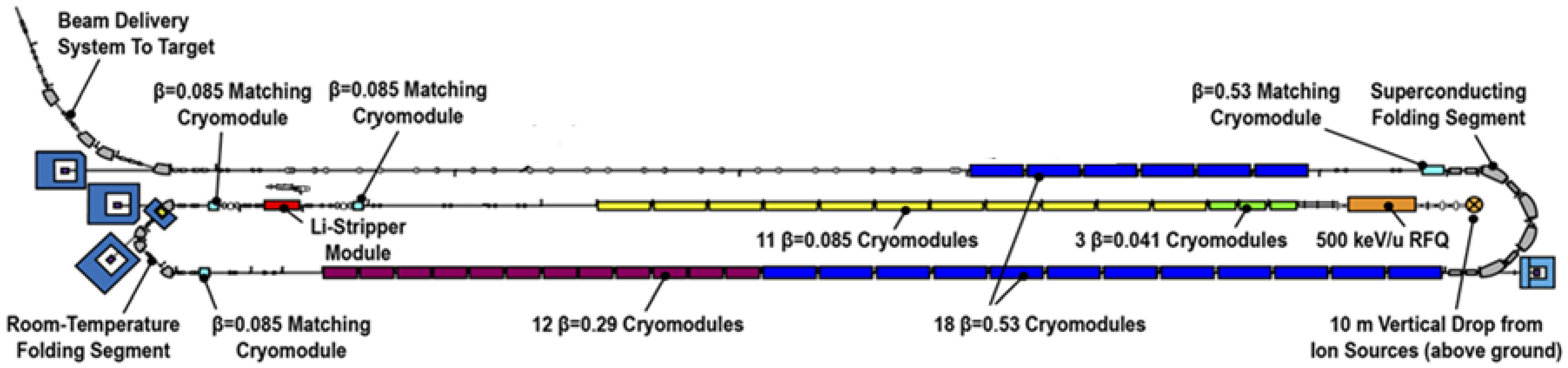
FRIB Resonator Parameters

Cavity Parameters				
β_m	0.043	0.086	0.29	0.54
Type	QWR	QWR	HWR	HWR
f_0 (MHz)	80.5	80.5	322	322
R_a/Q_0 (Ω)	401.6	455.4	224.4	229.5
G (Ω)	15.3	22.3	77.9	107.4
Goals for 2 K Operation				
V_a (MV)	0.81	1.78	2.09	3.70
E_a (MV/m)	5.1	5.6	7.7	7.4
E_p (MV/m)	30.8	33.4	33.3	26.5
B_p (mT)	54.6	68.9	59.6	63.2
Q_0	$1.2 \cdot 10^9$	$1.8 \cdot 10^9$	$5.5 \cdot 10^9$	$7.6 \cdot 10^9$
Number of Cavities				
In Linac	12	92	72	148

FRIB Linac

Resonators

β / Type	Number in Linac
0.043 / QWR	12
0.086 / QWR	92
0.29 / HWR	72
0.54 / HWR	148



Cavity & cryomodule production: 2015-2020

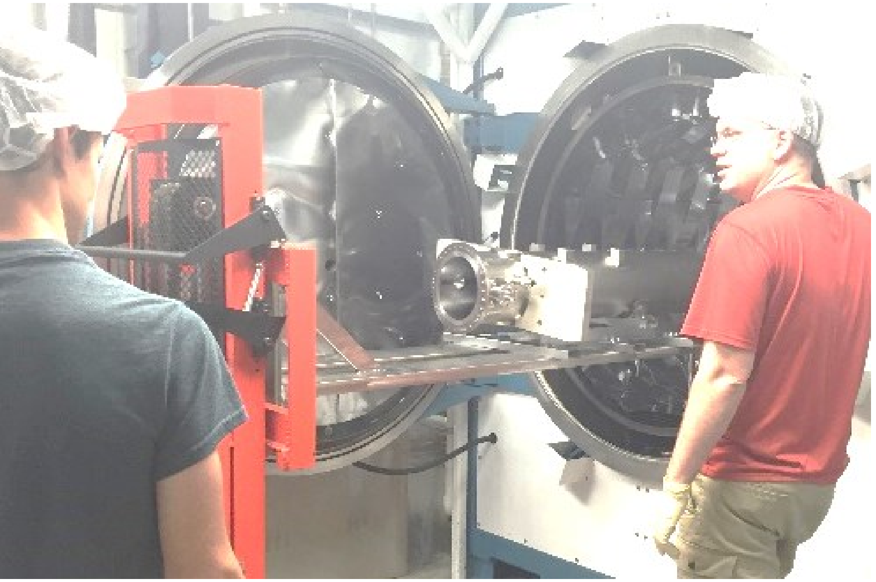
User operations began May 2022

Cavity Testing: When?

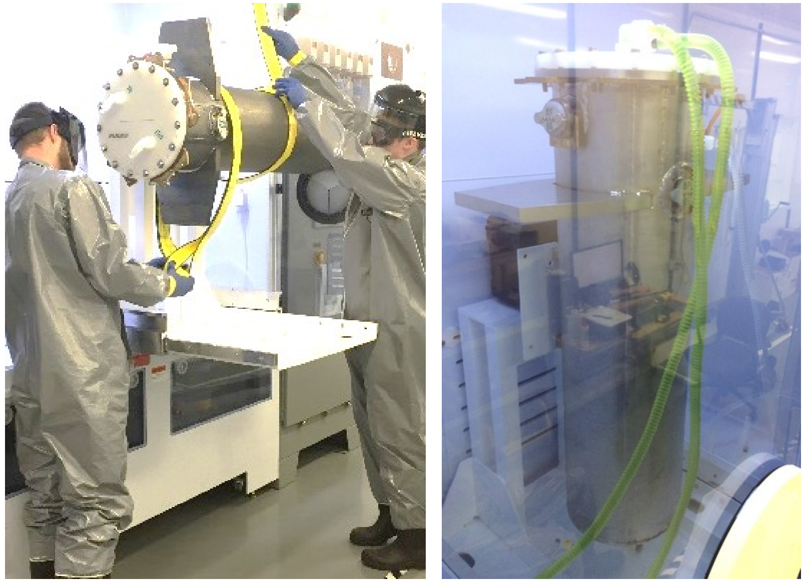
Example: FRIB Cavity Production Steps

- Fabrication
- Jacketing
- Borescope inspection
- Heavy etch
- Borescope inspection
- Heat treatment
- Light etch
- HPWR
- Clean Room assembly
- Cold test
- Cold mass assembly
- Cryomodule assembly

Cavity Preparation Steps: FRIB



Heat treatment (β = 0.043 QWR)



Chemical etching
(BCP of β = 0.086 QWR)

Rinsing: high-pressure ultra-pure water in clean room (HPWR of β = 0.29 HWR)

Cavity Testing: How?

Things We Need

- RF Couplers
- Cleanliness
- Vacuum
- Magnetic shielding
- Cold
- Personnel protection
- RF power
- RF control
- Diagnostics

Things We Need

- RF Couplers
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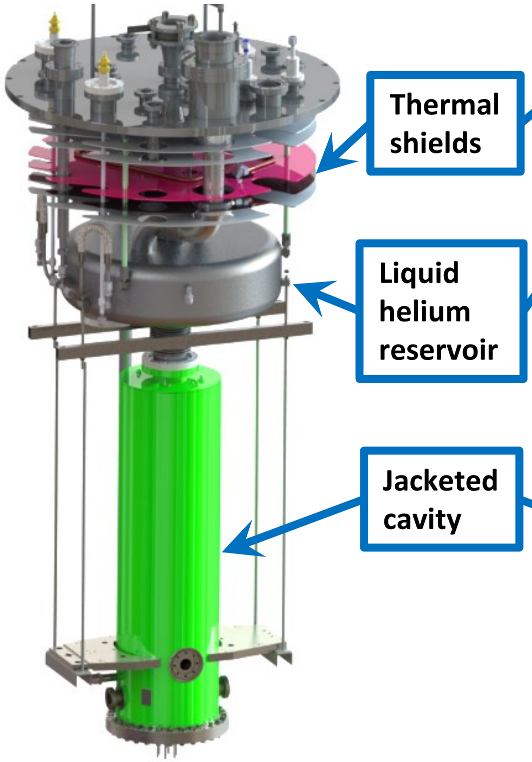
Things We Measure

- RF power (warm)
- Bath pressure (warm)
- Cavity temperature (cold)
- Liquid level (cold)
- X-ray flux (warm)
- Static magnetic field? (cold)

Test Prep: FRIB jacketed cavities



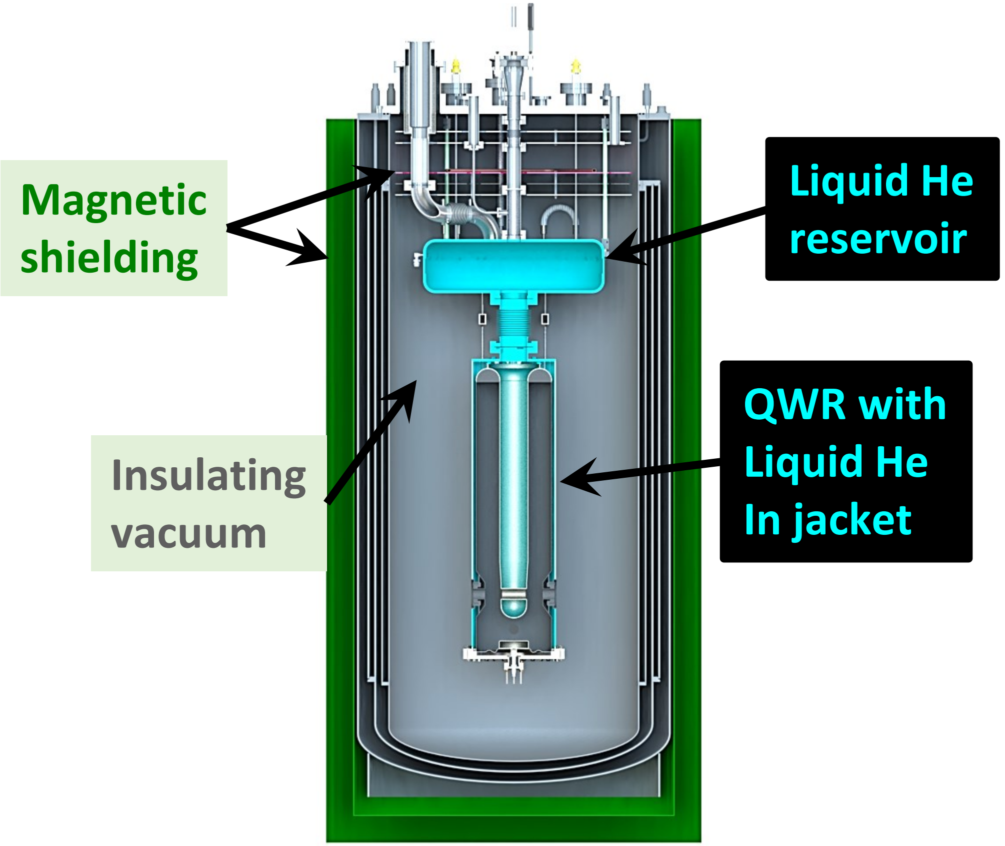
β = 0.086 on insert

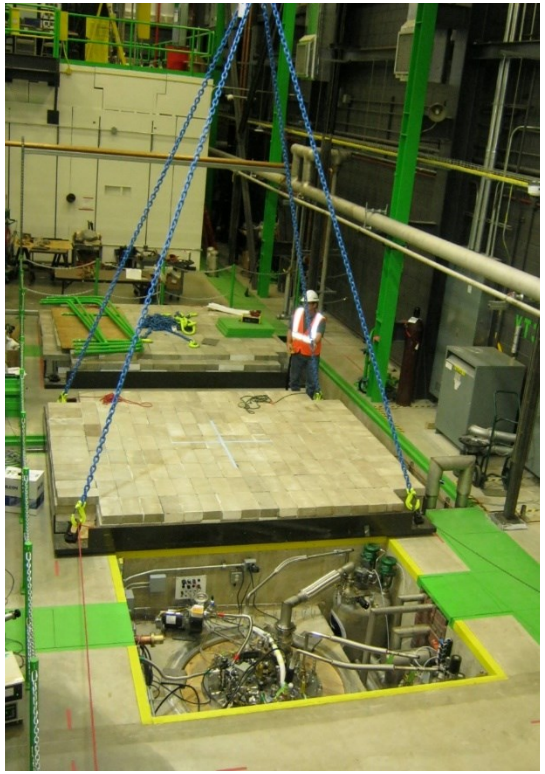
β = 0.54 on insert

β = 0.29 with variable coupler

Test Prep: FRIB jacketed cavities

β = 0.041 into Dewar





Radiation shield installation

Free Oscillation:
Undriven cavity

Driven cavity

RF Measurements and Analysis

Measure: CW

ω = angular frequency

P_f = forward power

P_r = reverse power

P_t = transmitted power

Measure: Modulated

τ_L = decay time

Over-/under-coupled

(P_e = emitted power)

Calculate

P_d = dissipated power

U = stored energy

Q_L = loaded quality factor

β_1= input coupling factor

β_2 = pickup coupling factor

Q_0 = intrinsic quality factor

$Q_{ext,1}$ = input coupling strength

$Q_{ext,2}$ = pickup coupling strength

Infer

from cavity model

R_s = surface resistance

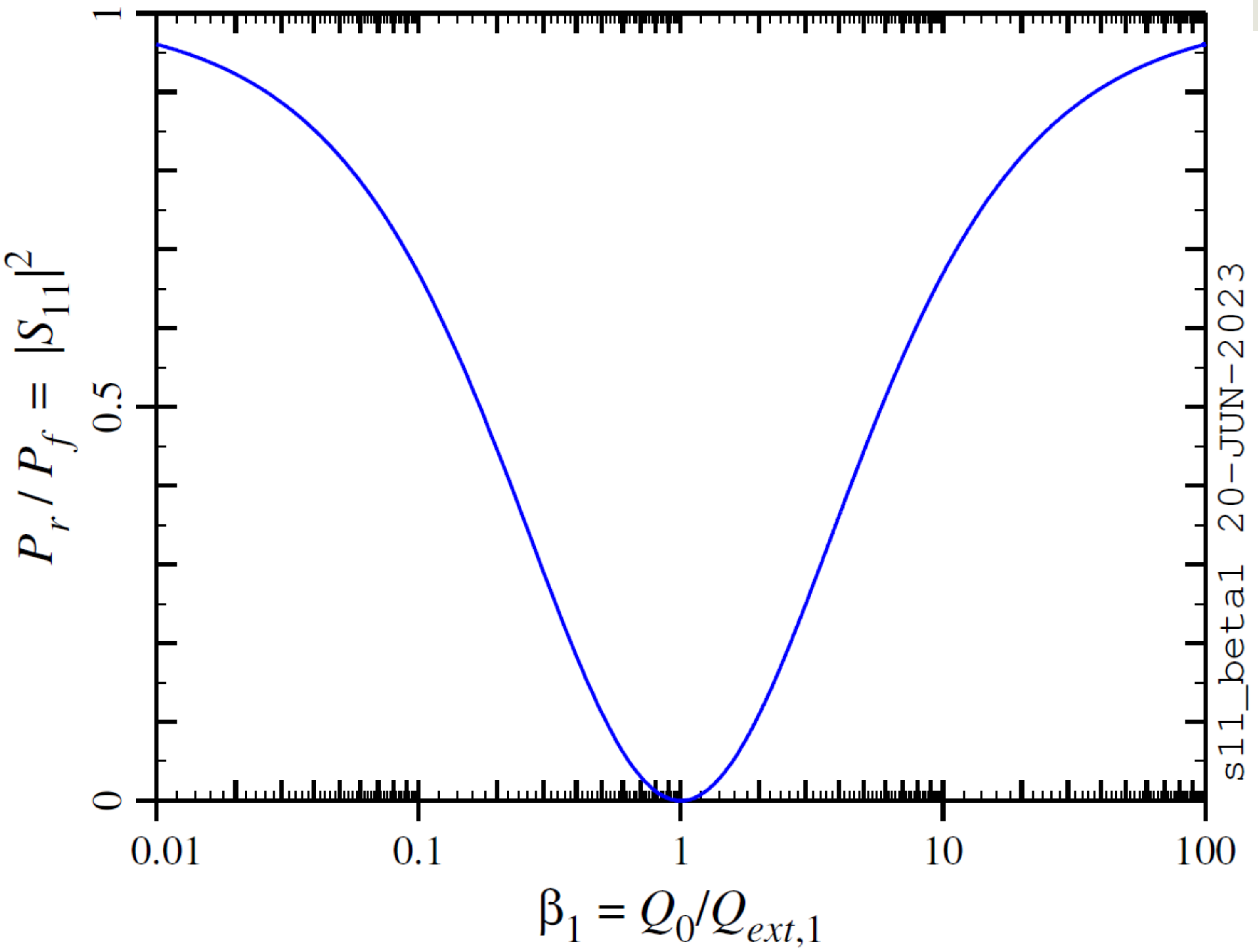
E_a = accelerating gradient

E_p = peak surface electric field

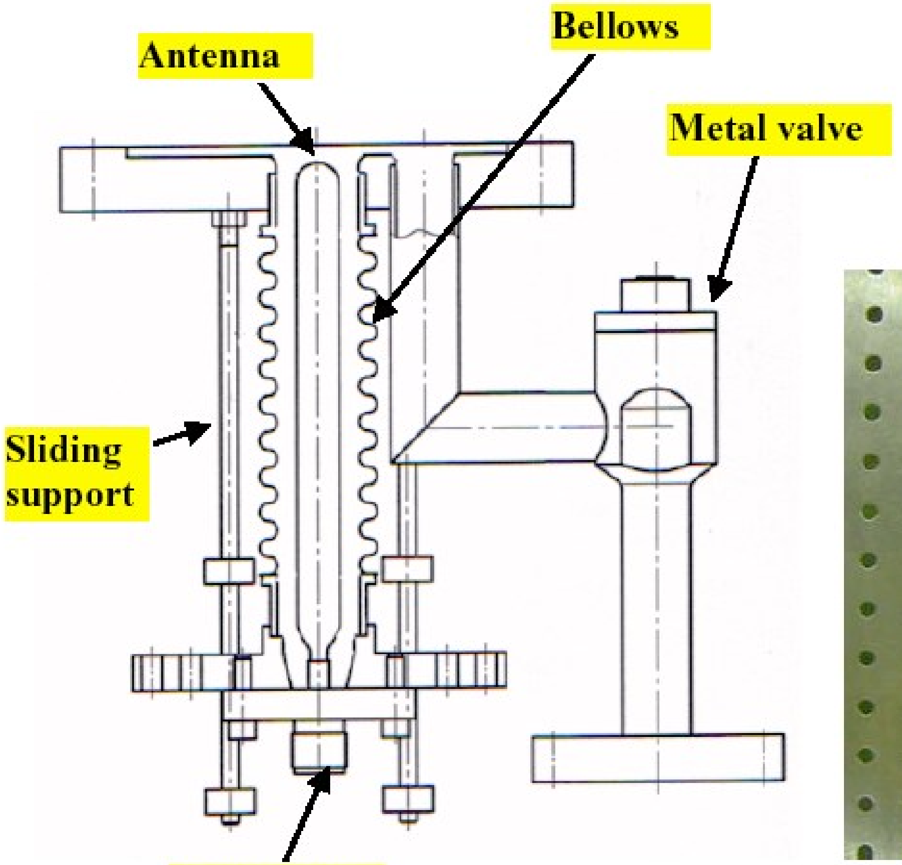
B_p = peak surface magnetic field

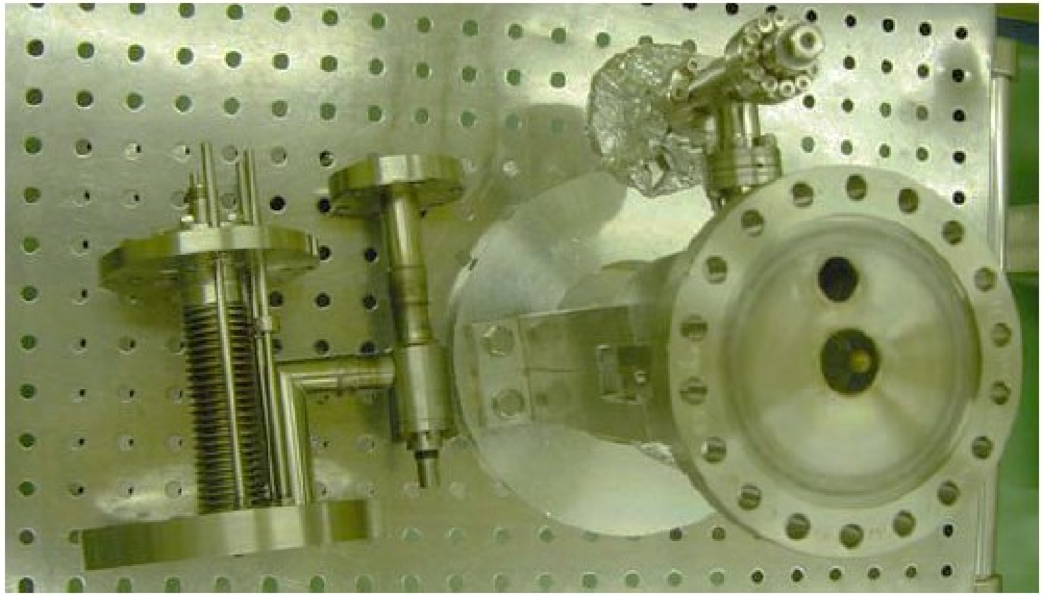
V_a = accelerating voltage

Input Coupler: matched vs mismatched



Variable coupler: KEK design





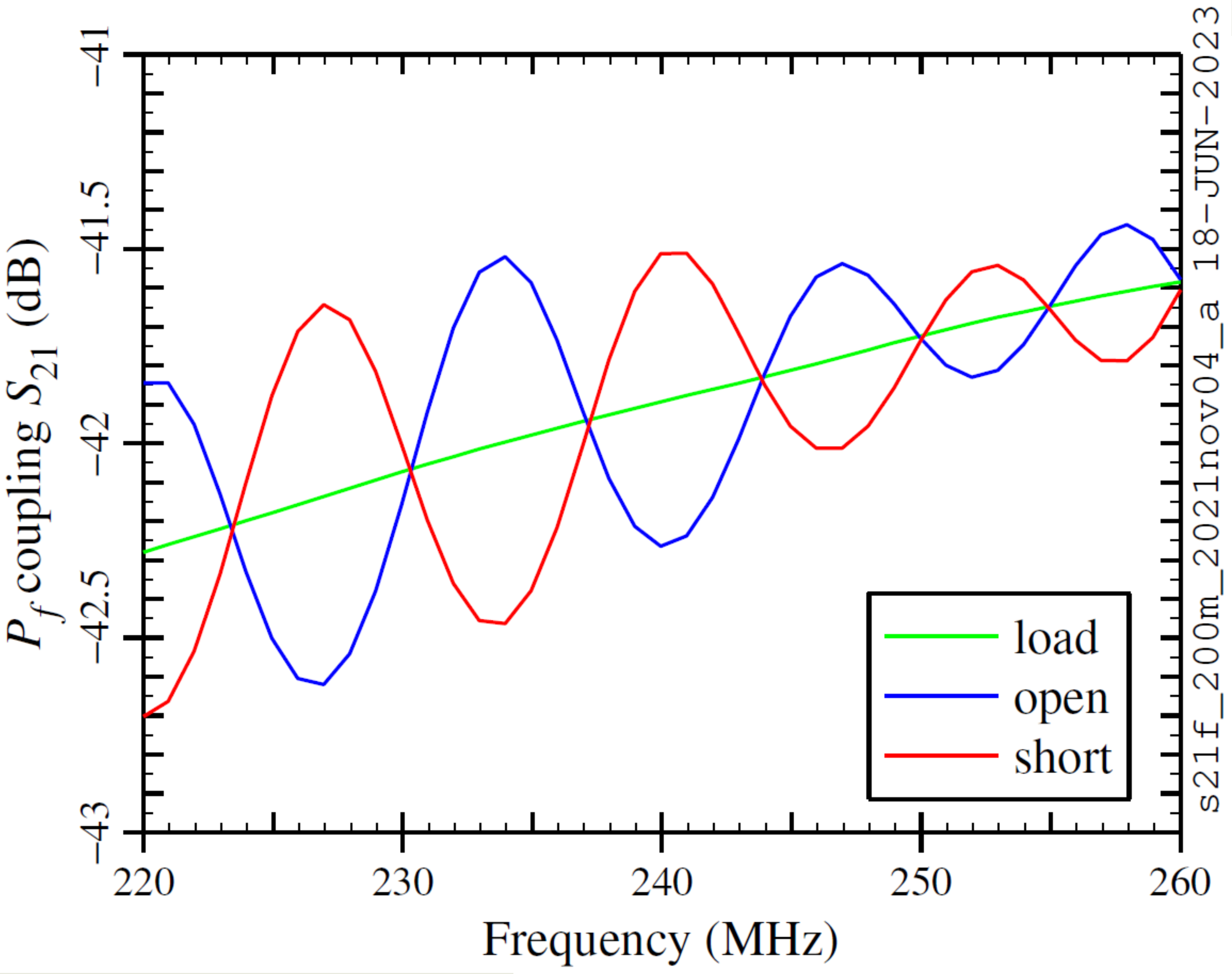
Variable input coupler for the vertical test in KEK

Kenji Saito

Cavity Testing: Calibrations, analysis

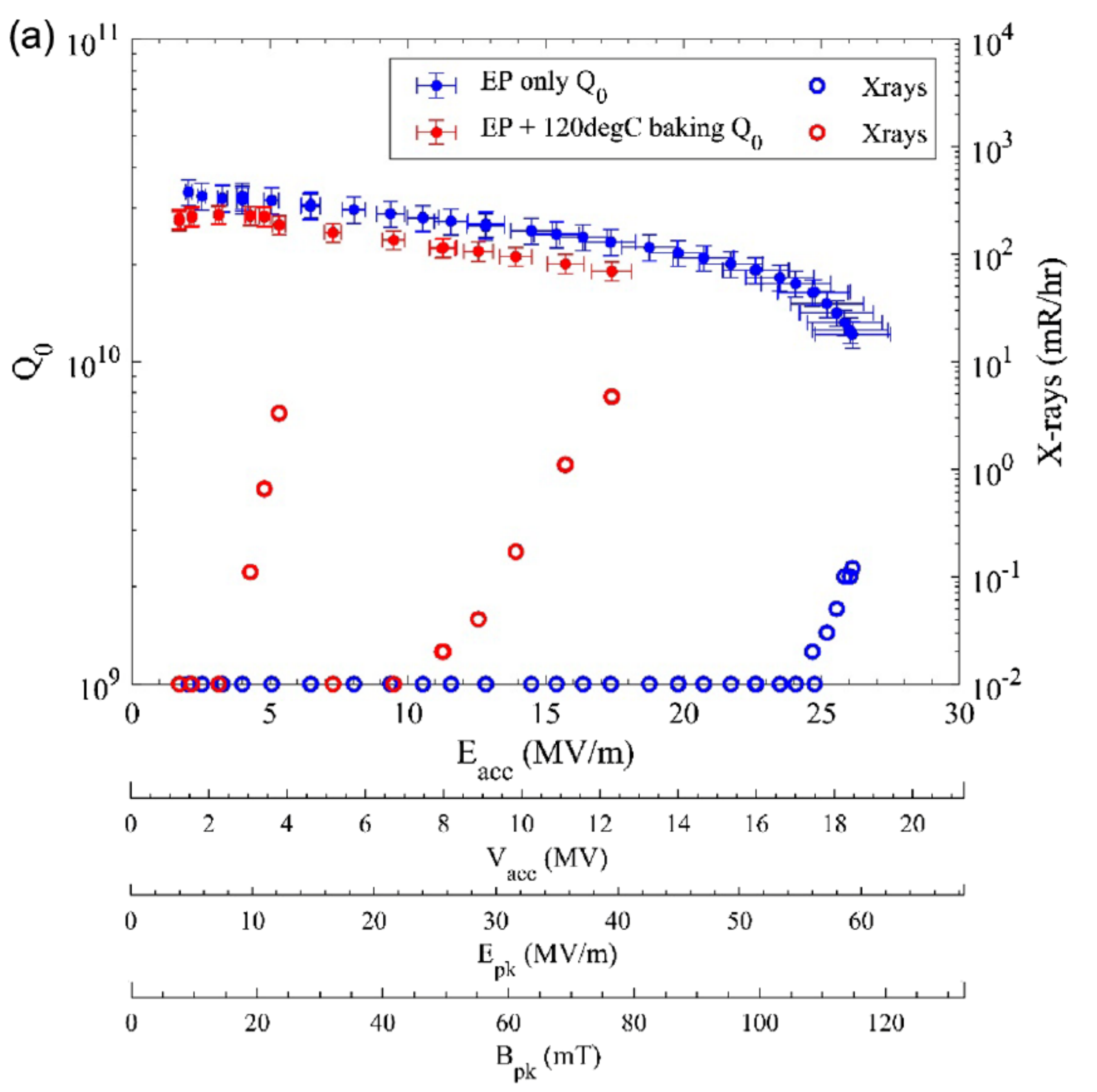
Imperfect RF system: mismatch

Cables + circulator + directional coupler: forward power coupling for different cable terminations



Systematic Errors: analysis

- Error estimates and error bars for field and quality factor: excellent practice
- Example: β = 0.65 energy upgrade cavity [K. McGee et al, *Phys Rev Accel Beams* **24**, 112003 (2021)]



Systematic Errors: analysis and correction
Examples of Recent Work

Measurements, calibrations, error analysis

T. Powers, "Theory and Practice of Cavity RF Test Systems," in *Proc. SRF 2005*, Ithaca, NY, USA, Paper SUP02, p. 40-70.

Assessment of imperfect directivity, stray reflections, off-resonance errors; mitigations

J, Holzbauer et al, "Systematic uncertainties in RF-based measurement of superconducting cavity quality factors," *Nucl Instrum Methods Phys Res A*, **830**, p. 22-29 (2016).

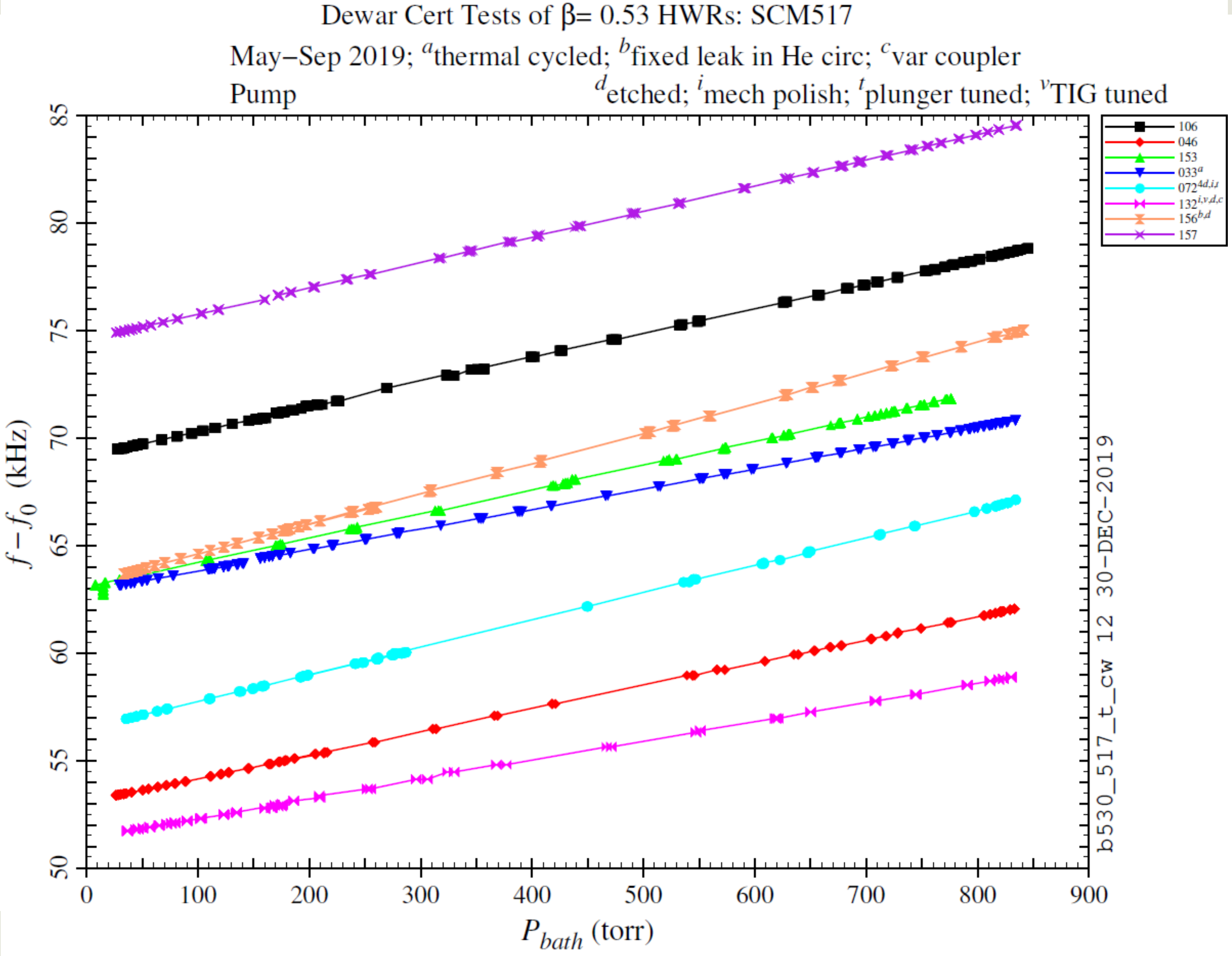
Assessing and correction errors with vector approach

J. Holzbauer et al, "Improved RF measurements of SRF cavity quality factors," *Nucl Instrum Methods Phys Res A*, **913**, p. 7-14 (2019).

Analysis of RF measurements: supplemental parameters

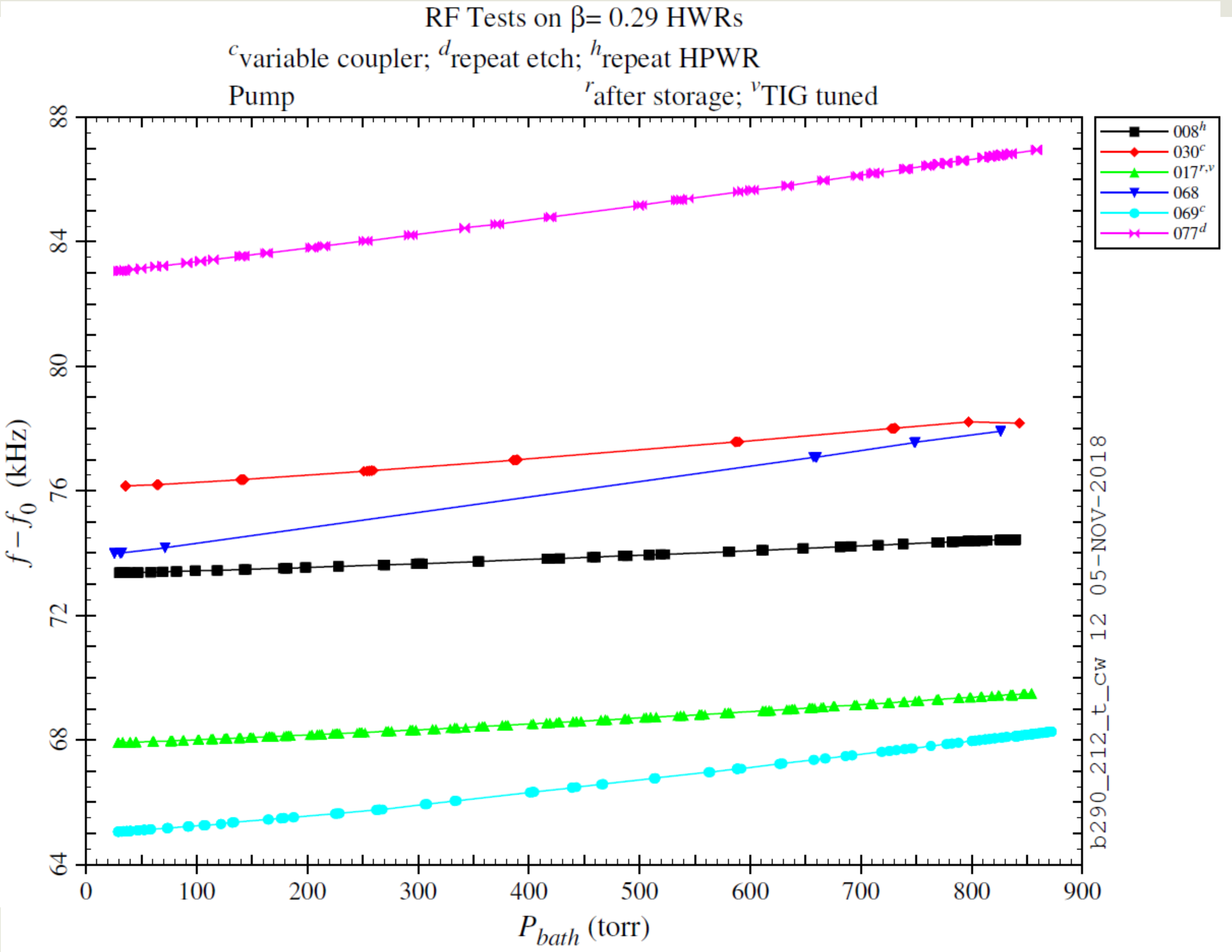
Resonant frequency dependence on bath pressure

- Measurements: 8 FRIB β = 0.53 HWRs



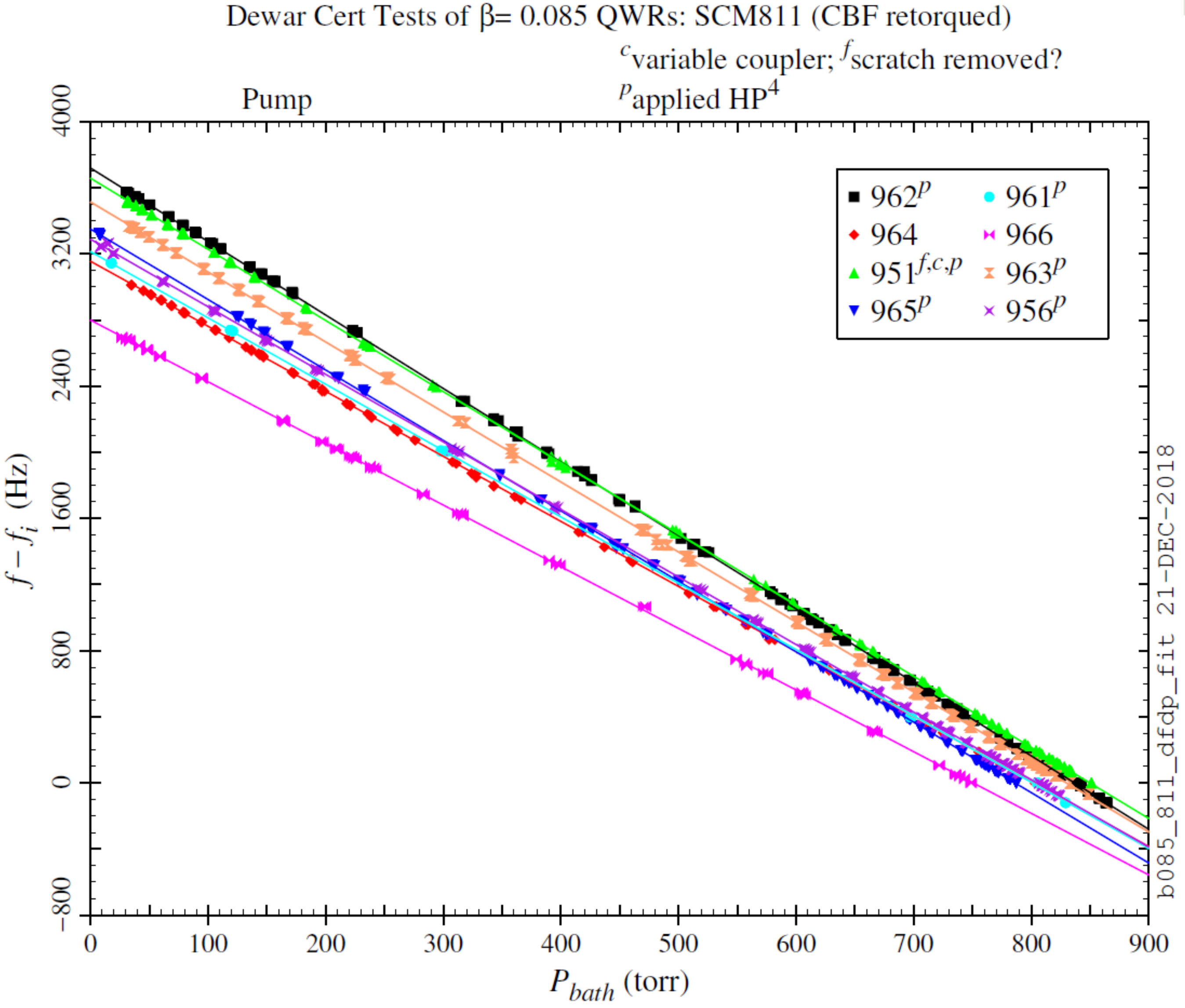
Resonant frequency dependence on bath pressure

- Measurements: 6 FRIB β = 0.29 HWRs



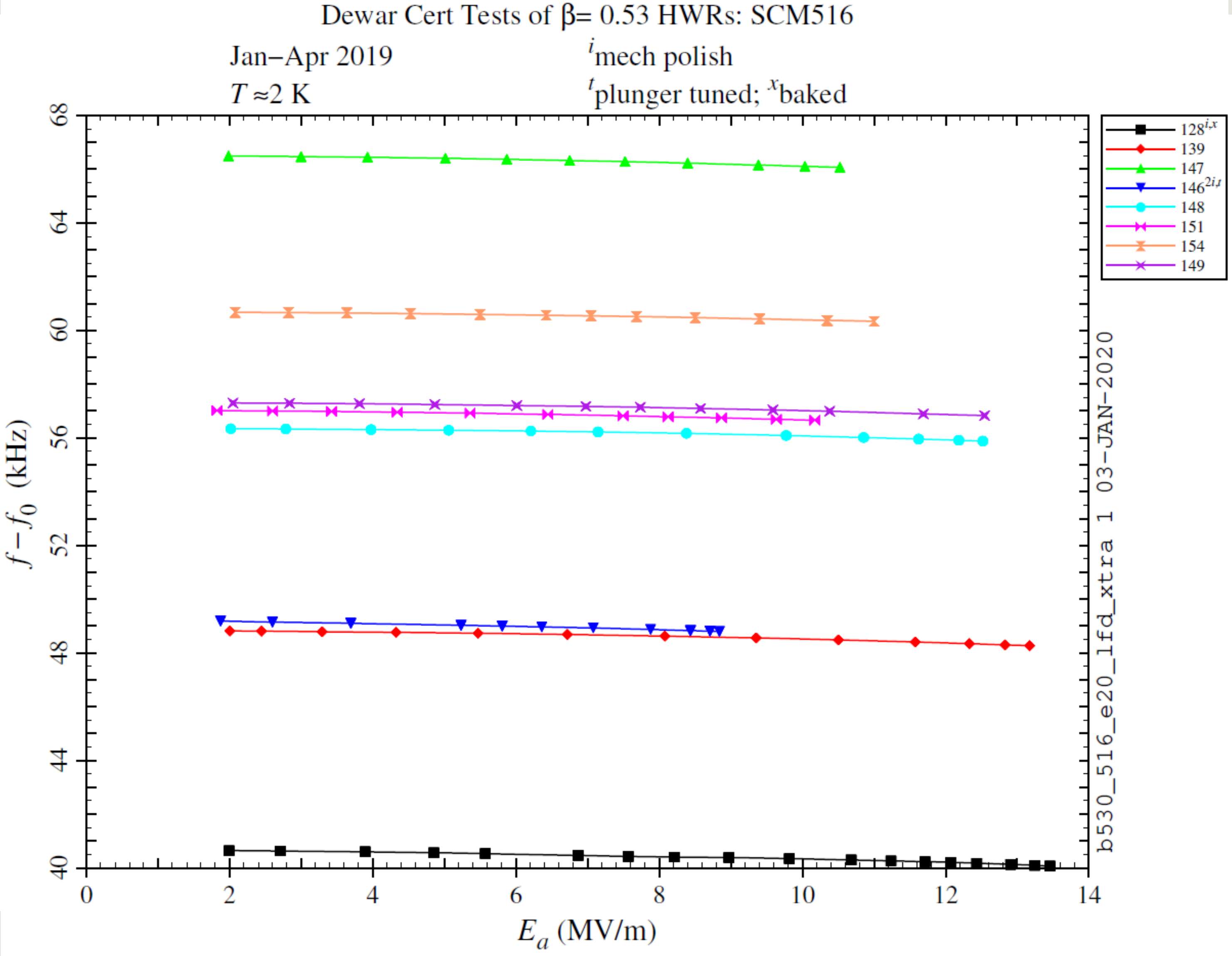
Resonant frequency dependence on bath pressure

- Fitting: 8 FRIB β = 0.085 QWRs



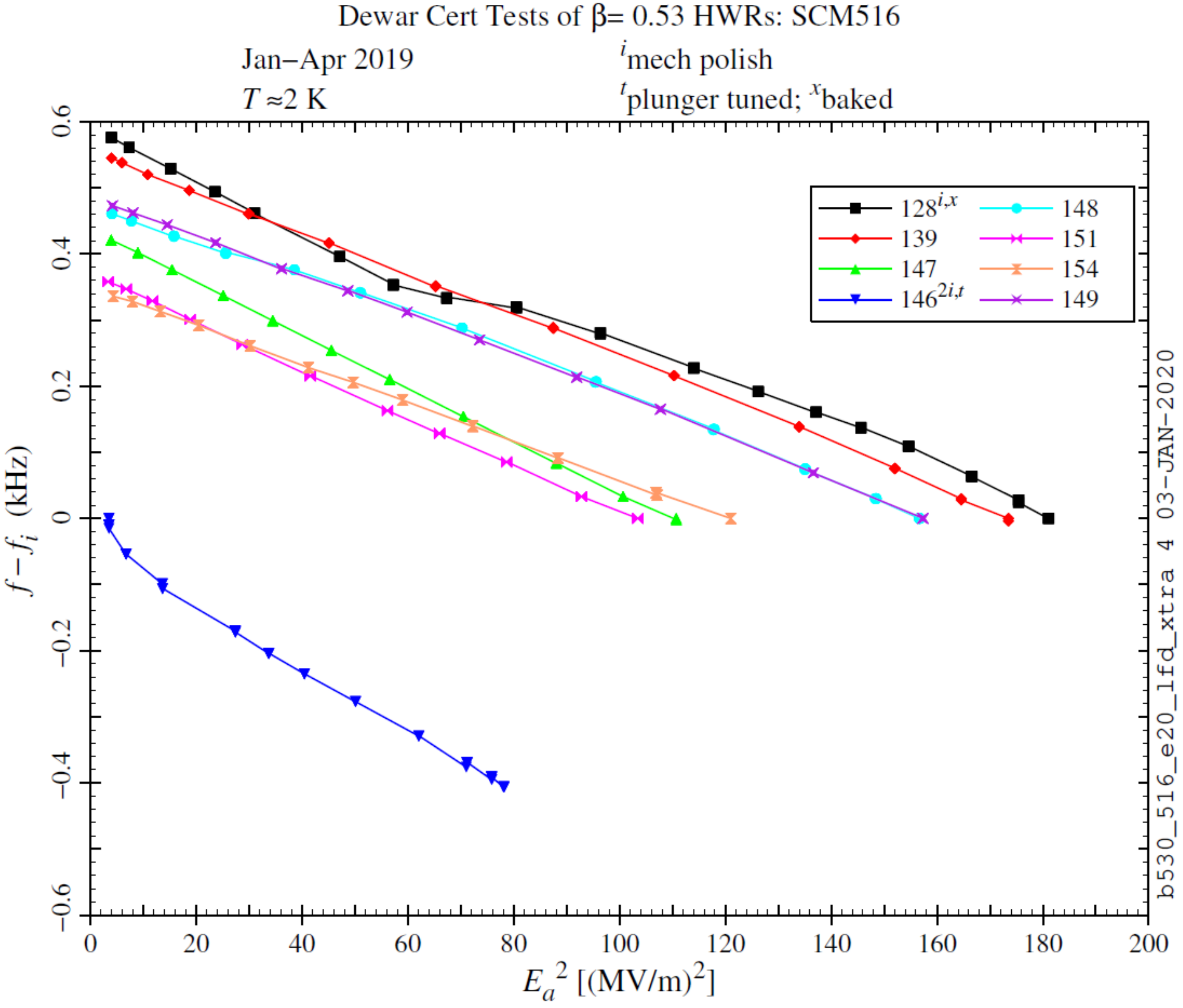
Lorentz force detuning

- Measurements: 8 FRIB β = 0.53 HWRs, T ≈ 2 K
- Frequency vs field



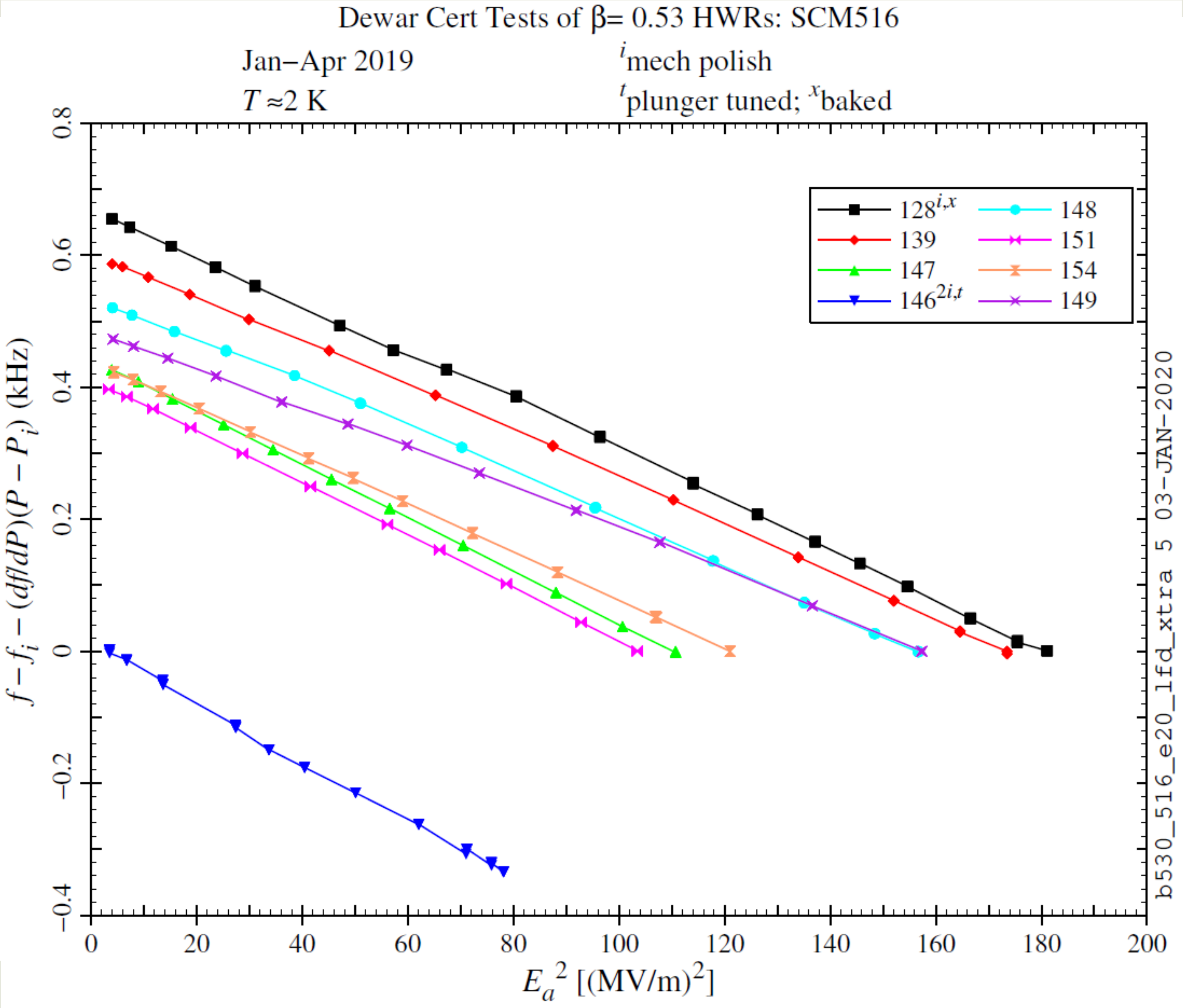
Lorentz force detuning

- Measurements: 8 FRIB β = 0.53 HWRs, T ≈ 2 K
- Frequency vs field squared



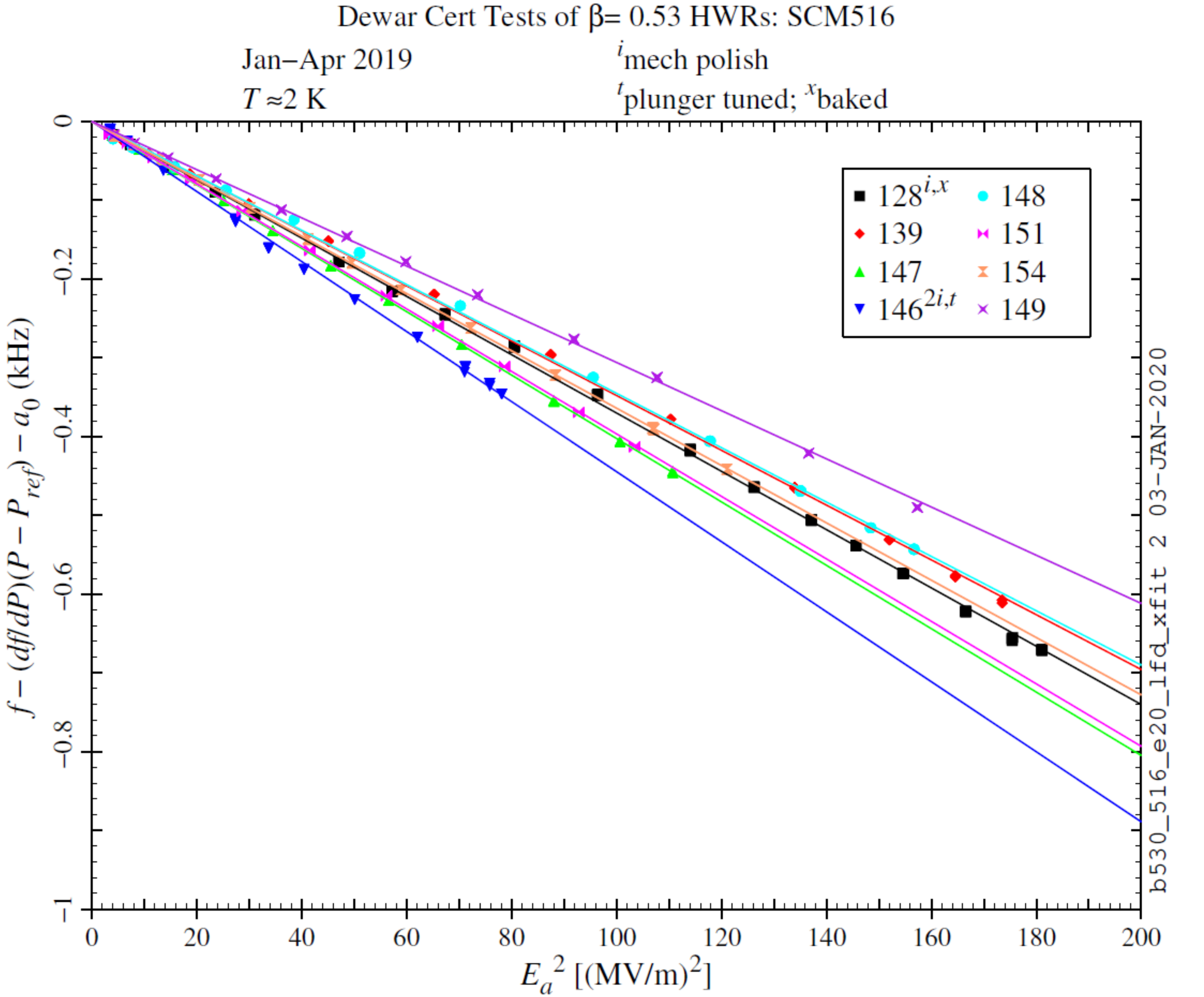
Lorentz force detuning

- Measurements: 8 FRIB β = 0.53 HWRs, T ≈ 2 K
- Compensate for bath pressure changes



Lorentz force detuning

- Measurements: 8 FRIB β = 0.53 HWRs, T ≈ 2 K
- Compensate for bath pressure changes and fit



Low-field losses: BCS and residual

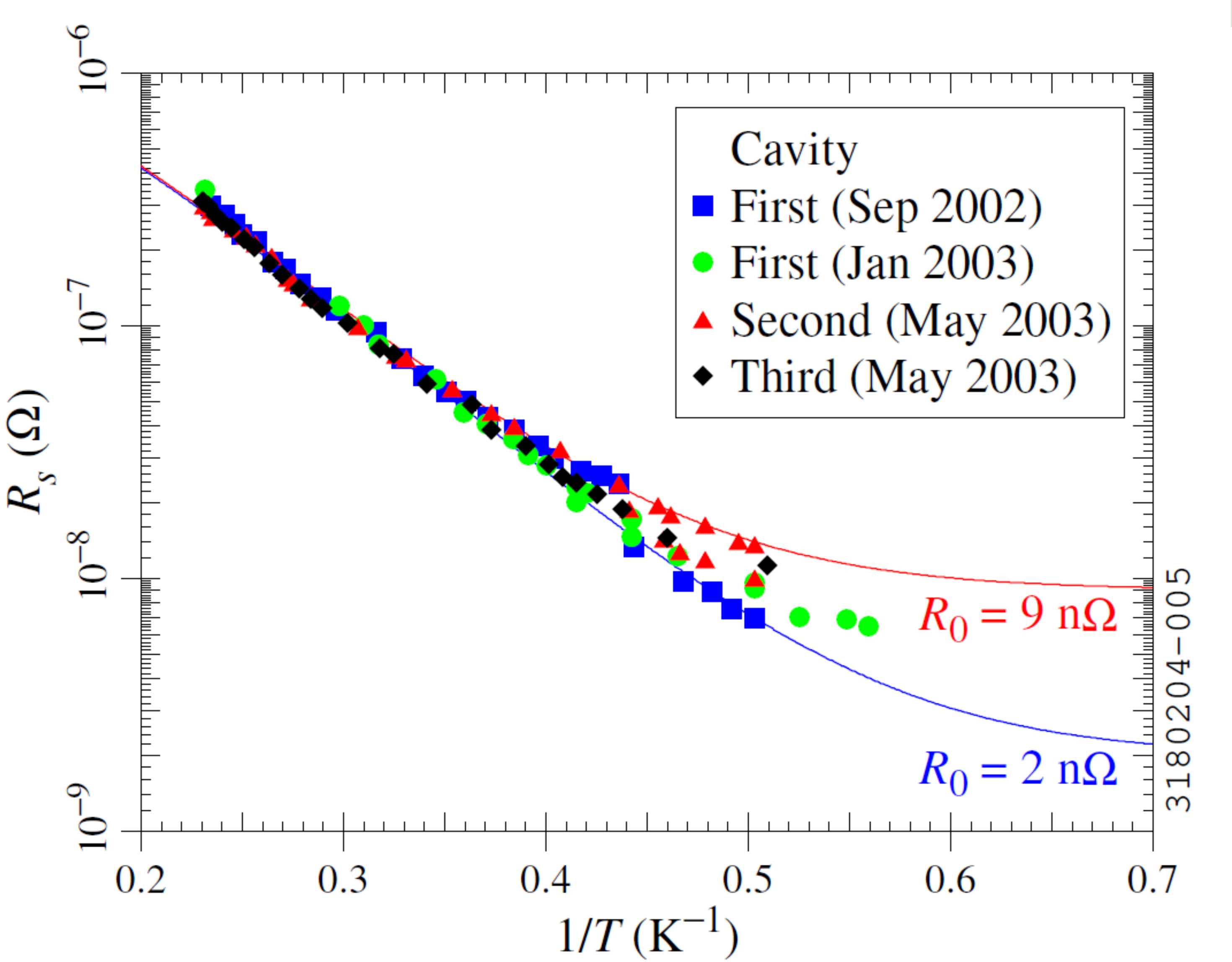
$$R_s(T) = R_0 + C_{\mathrm{RRR}} R_1 \frac{T_\Delta}{T}\left(\frac{f}{f_1}\right)^2 \exp\left(-\frac{T_\Delta}{T}\right), \qquad (1)$$

where T is the temperature, f is the rf frequency, $T_\Delta = 17.67$ K, $R_1 T_\Delta = 2 \times 10^{-4}\ \Omega$K, and $f_1 = 1.5$ GHz; R_0 is the temperature-independent residual surface resistance. The coefficient C_{RRR} is 1 for reactor grade Nb (RRR = 25) and about 1.5 for high purity Nb with RRR = 250. As the surface purity can be different from the bulk purity, C_{RRR} can be considered to be a fitting parameter. Equation (1) is valid for $f \ll 1$ THz and $T \leq 4.6$ K.

From C. Compton et al, *Phys Rev ST Accel Beams* **8**, 042003 (2005); adapted from textbook by Padamsee, Knobloch, & Hays

Low-field losses: BCS and residual

- B = 0.47 “RIA” prototype cavities



From C. Compton et al, *Phys Rev ST Accel Beams* **8**, 042003 (2005)

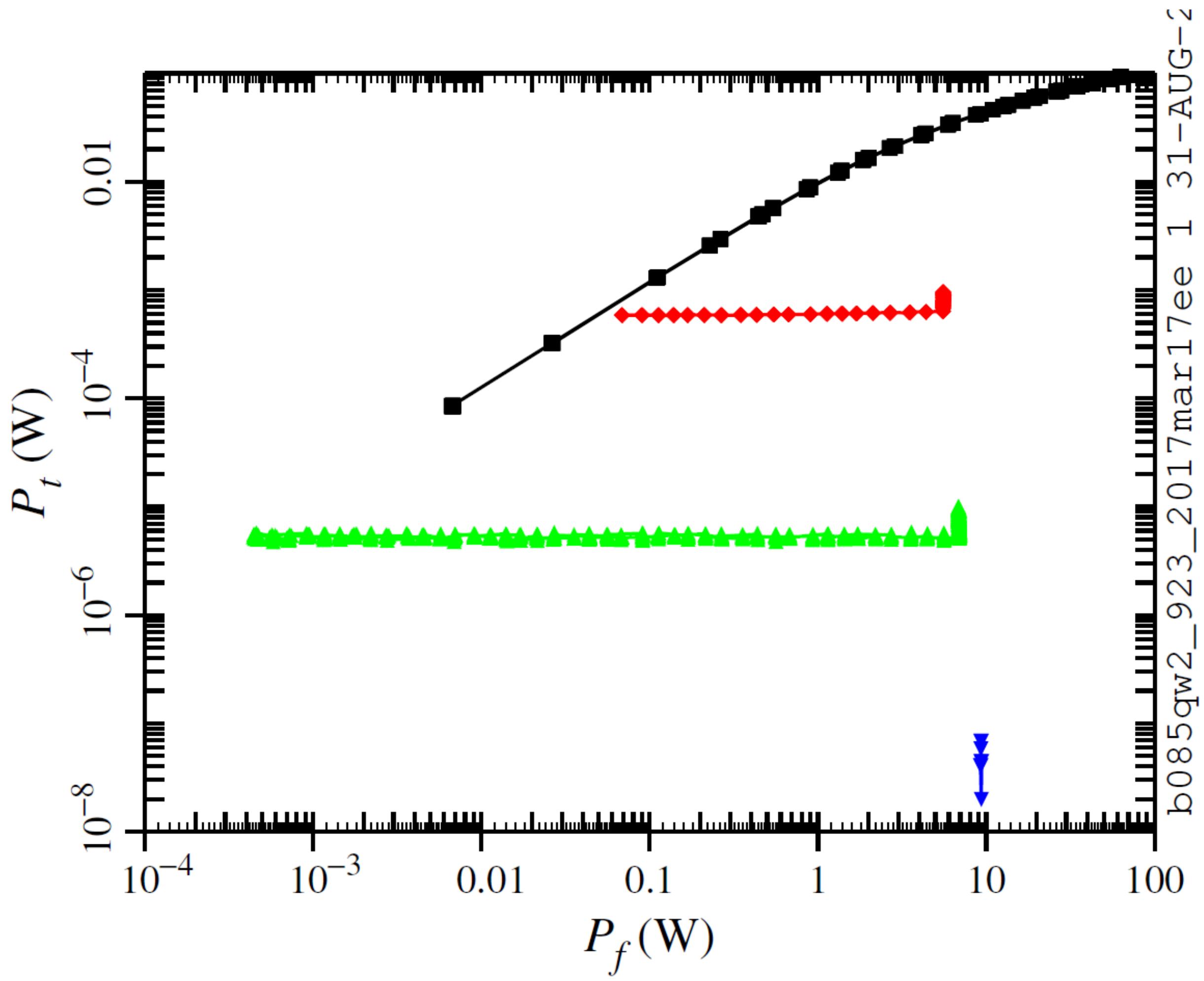
Cavity Testing Steps: FRIB Production Example

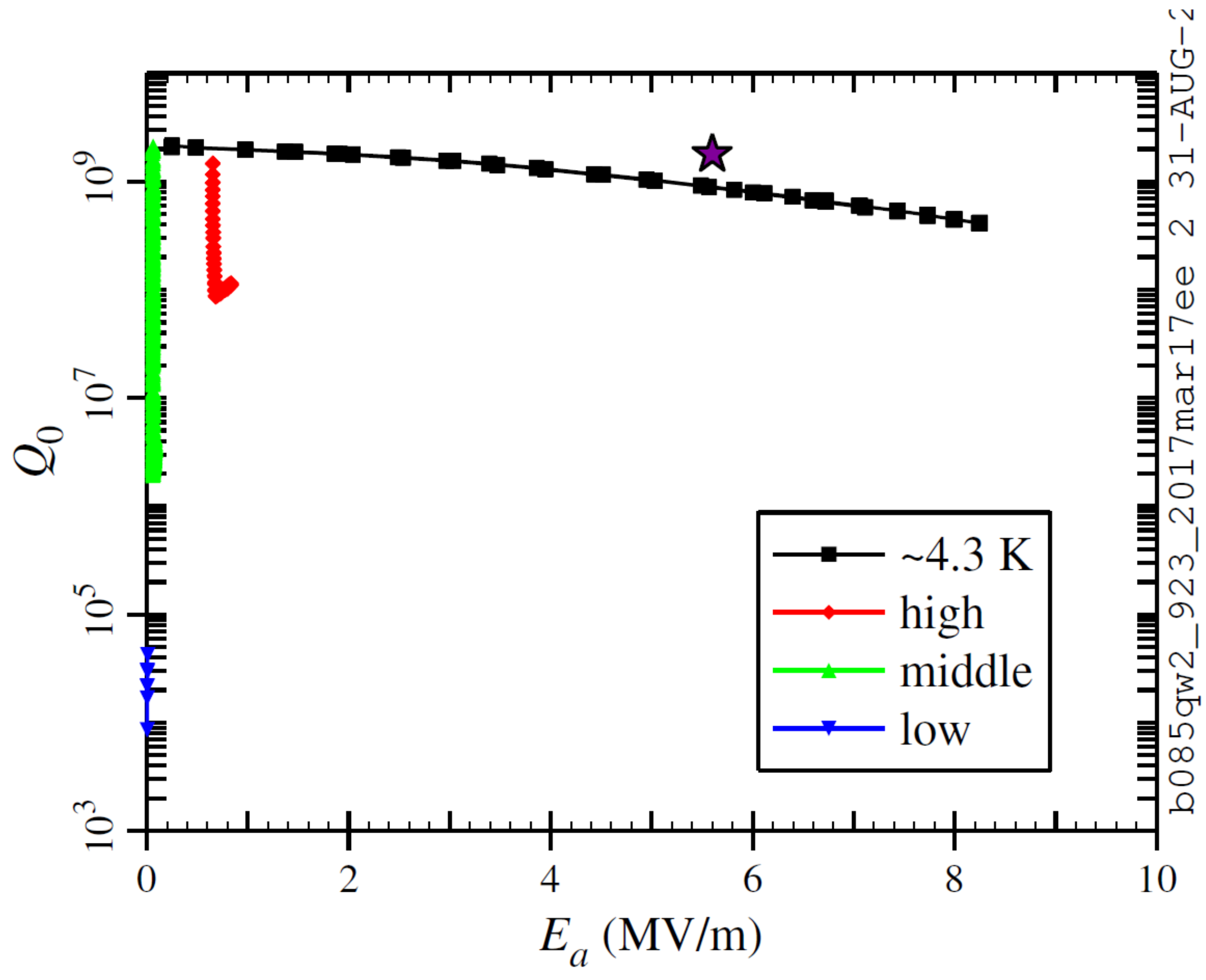
- Warm RF calibrations
- Cool down/cold RF calibrations
- Fill
- ~4.2 K measurements
  - CW; modulated; (de)condition
- Pump to ~2 K + low-field measurements
- ~2 K measurements
  - CW; modulated; (de)condition
- Cold RF calibrations
- Warm up/warm RF calibrations

Cavity Testing: What do we see? What do we learn?

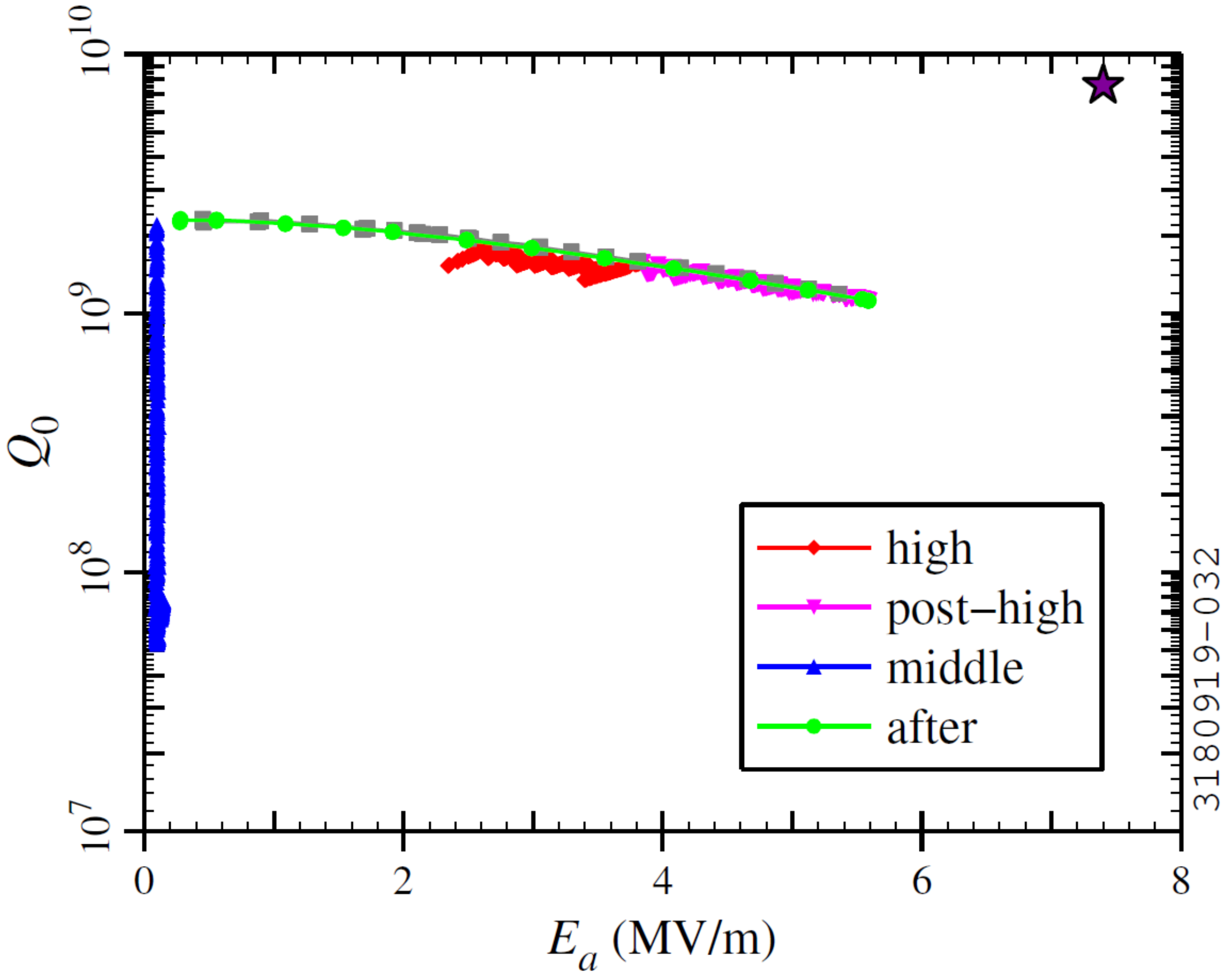
Multipacting

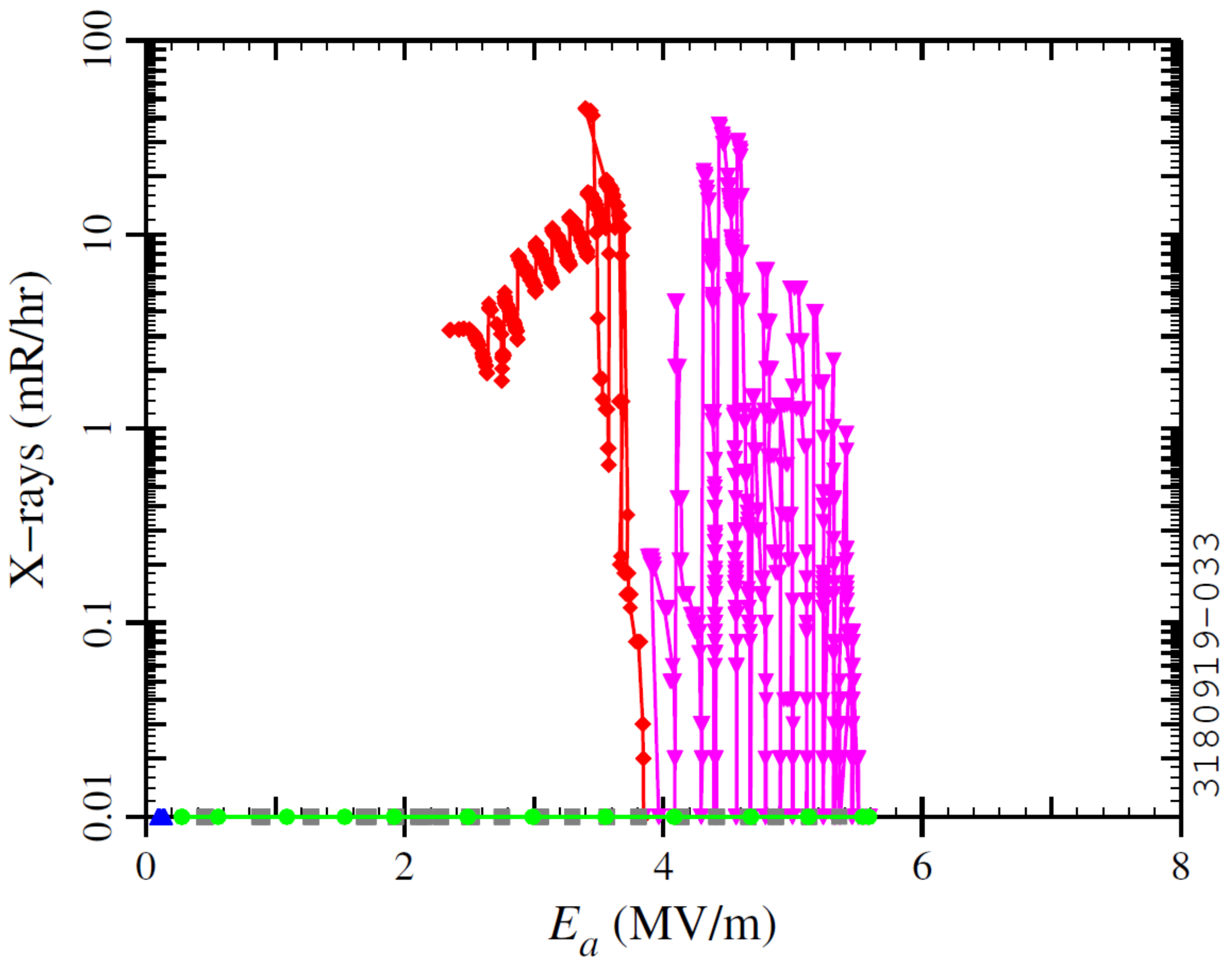
Example: barriers for FRIB β = 0.086 QWR





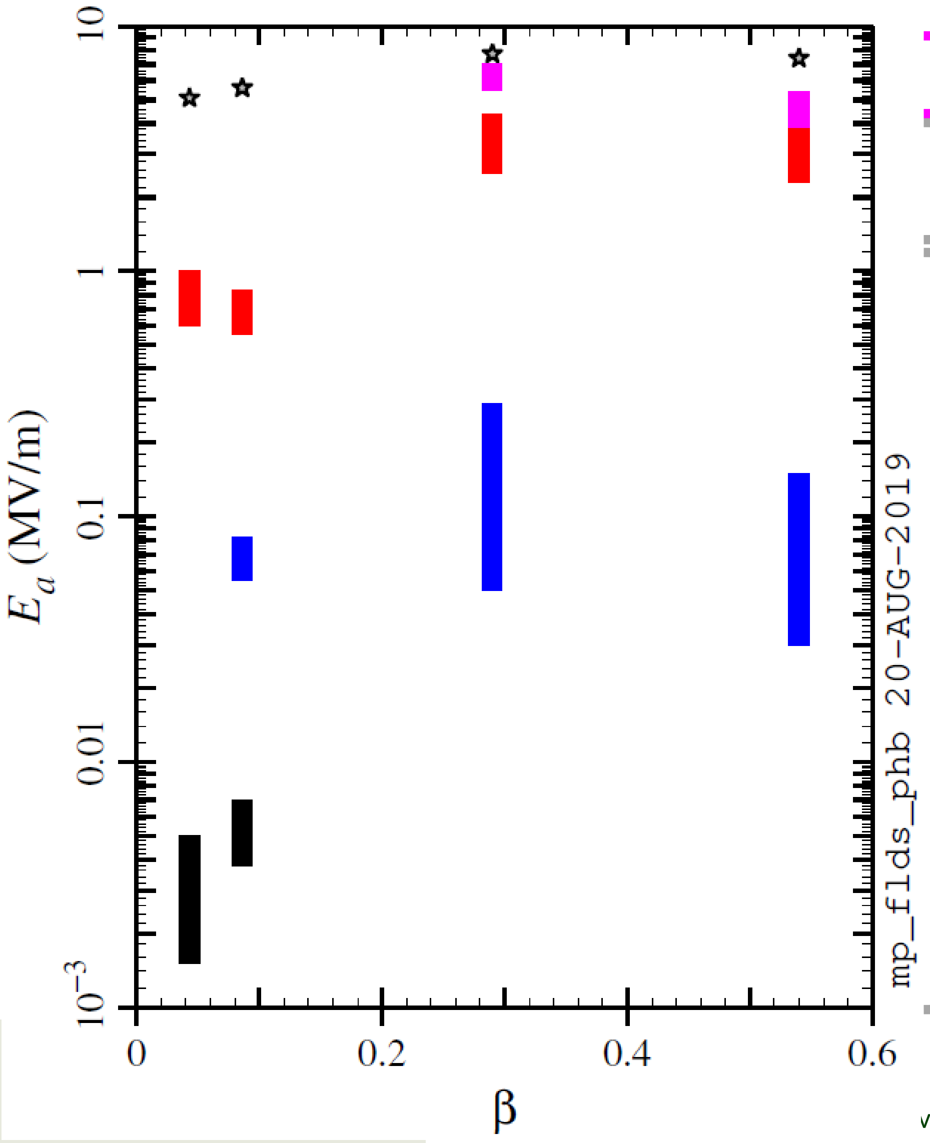
Example: barriers for FRIB β = 0.54 HWR





Multipacting Barriers in FRIB Resonators

Notes	Conditioning Strategy	Observations
Cavity and coupler fields interact?	CW (raise P_f slowly, wait for X-rays to go away)	X-ray spikes
$(q_e B_p)/(\omega_{RF} m_e) \approx 2.5$; 2-pt in short plate?	CW with P_f up to ~25 W, (raise P_f slowly)	steady X-rays
	CW with P_f = 1 to 6 W, (constant P_f)	no X-rays
	Jump over and avoid	



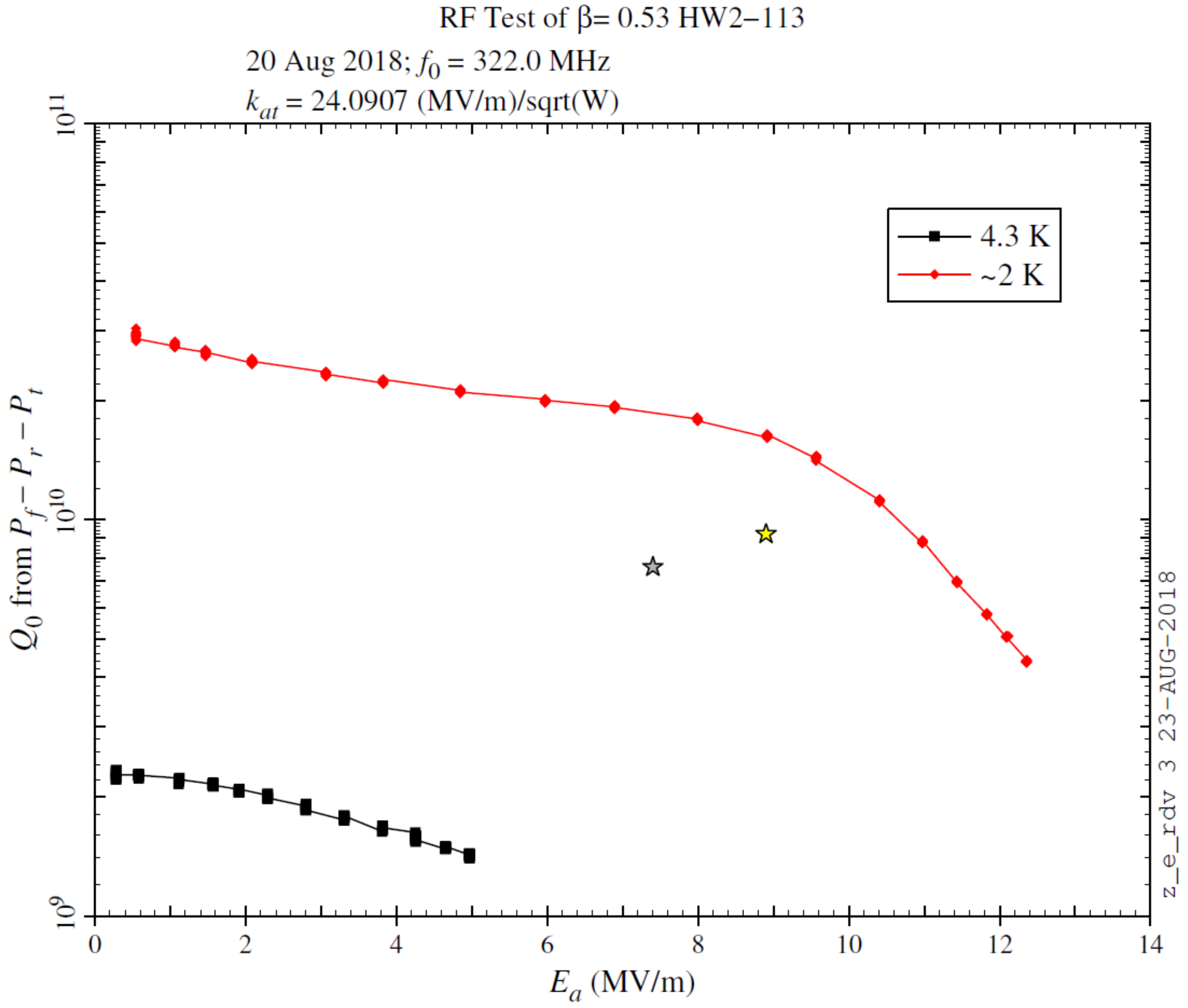
MP Conditioning Times: FRIB resonators

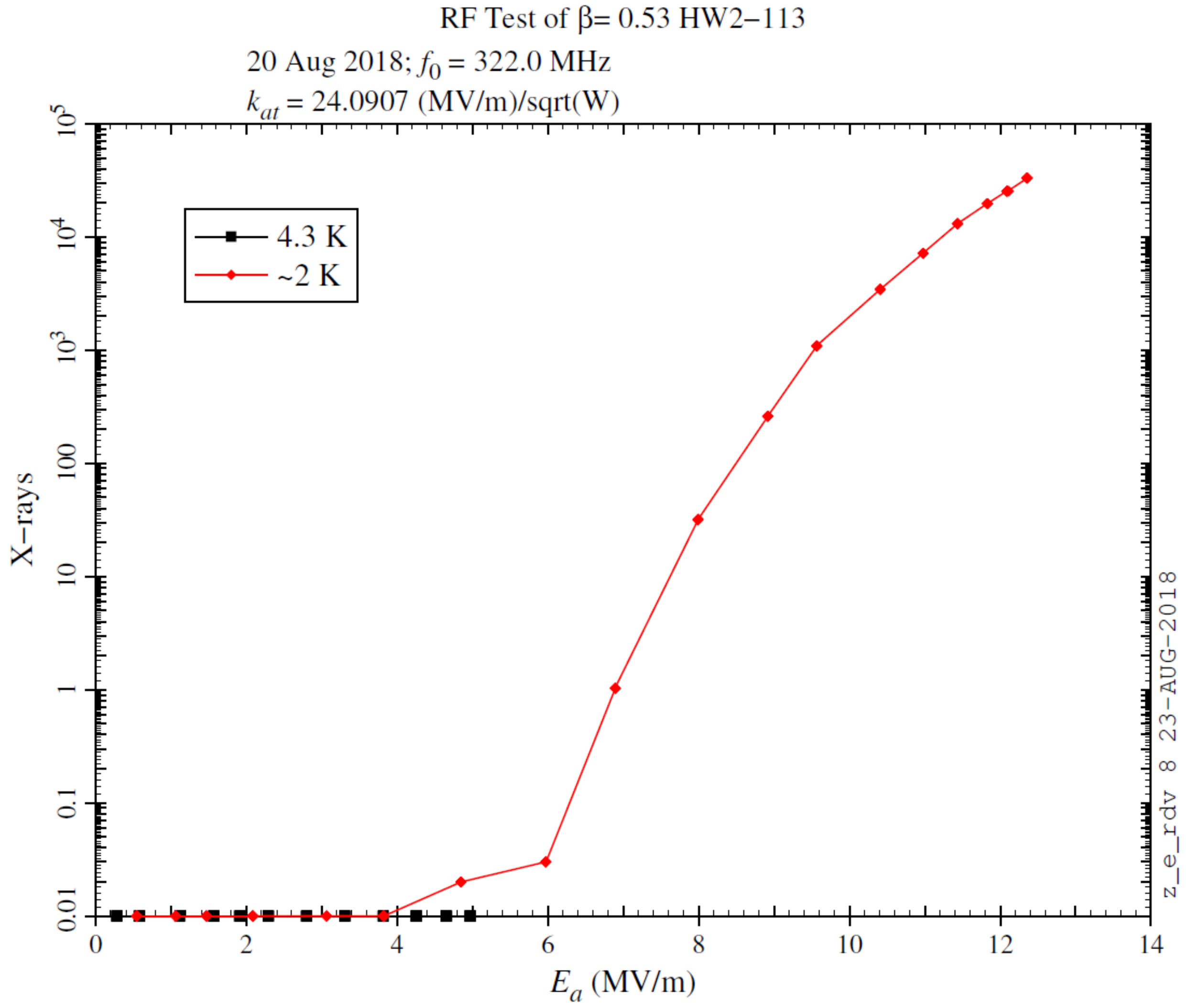
Coupler	Fixed		Variable	
MP band	High	Middle	High	Middle
β	**Average conditioning time (min)**			
0.085	30 ± 13	137 ± 66	30 ± 12	28 ± 14
0.29	57 ± 40	118 ± 65	22 ± 11	40 ± 19
0.53	66 ± 46	47 ± 42	41 ± 32	24 ± 21

C. Zhang et al, *Nucl Instrum Methods Phys Res A*, **1014**, 165675 (2021)

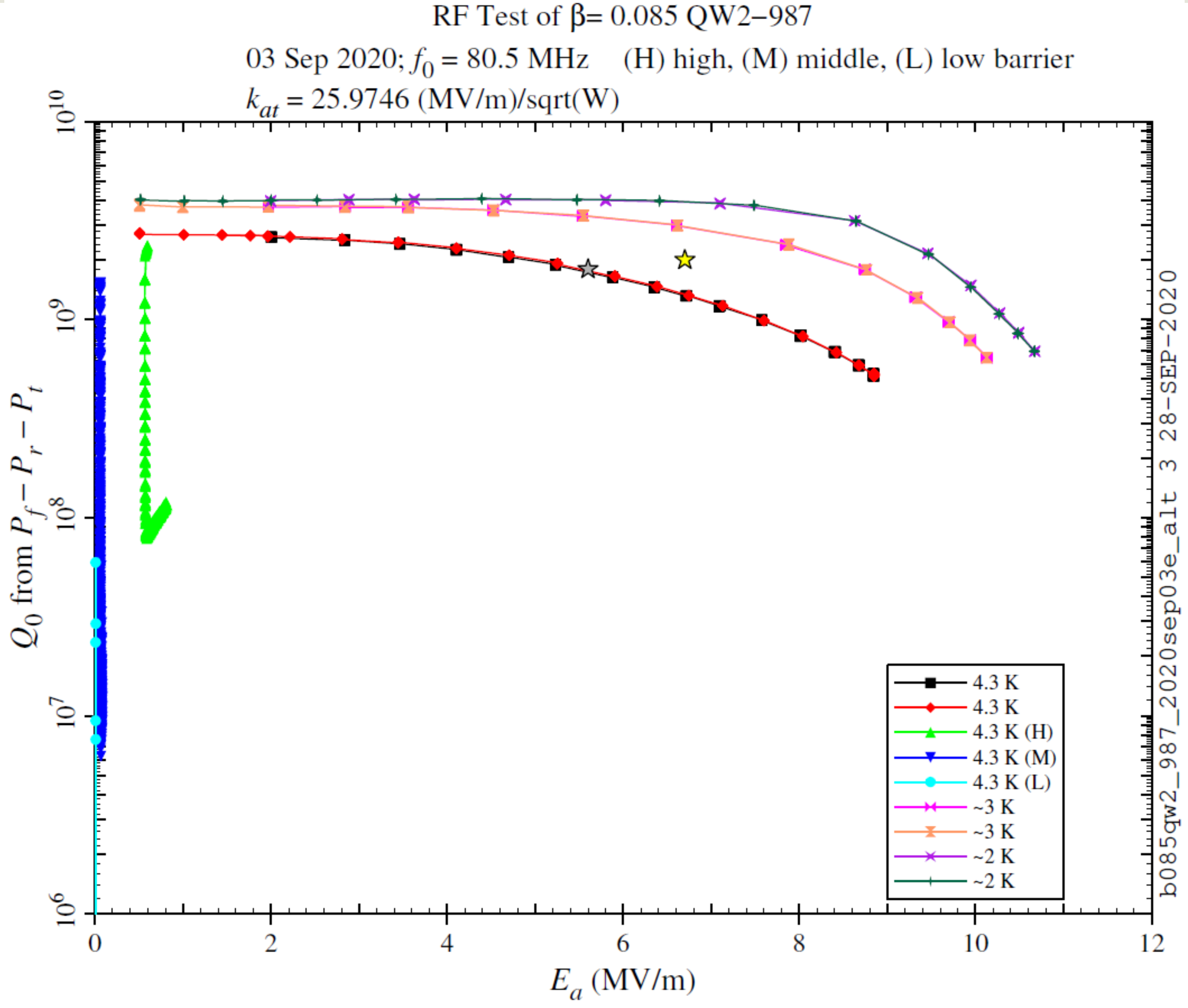
Field Emission

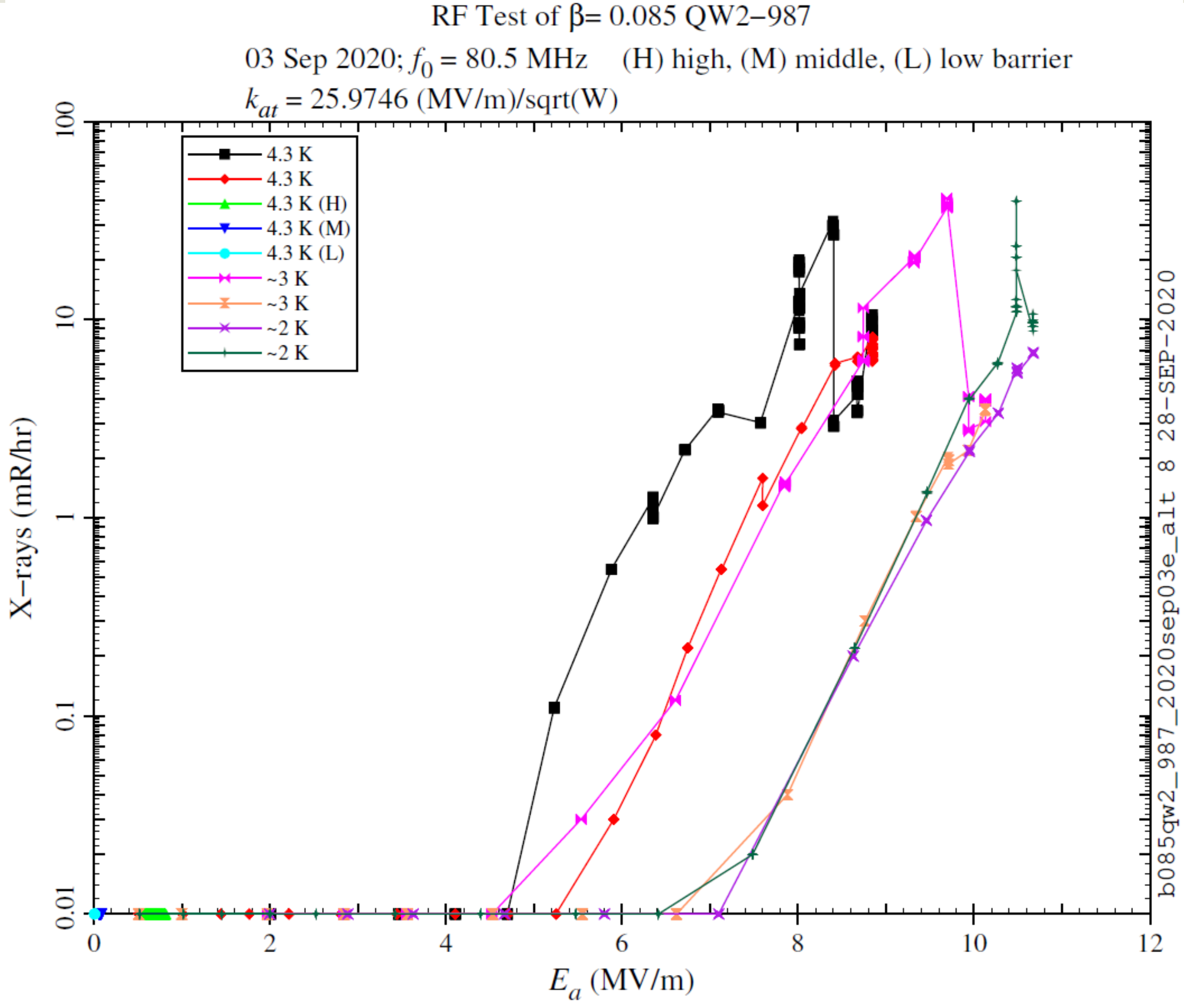
Field emission example: FRIB β = 0.53 HWR



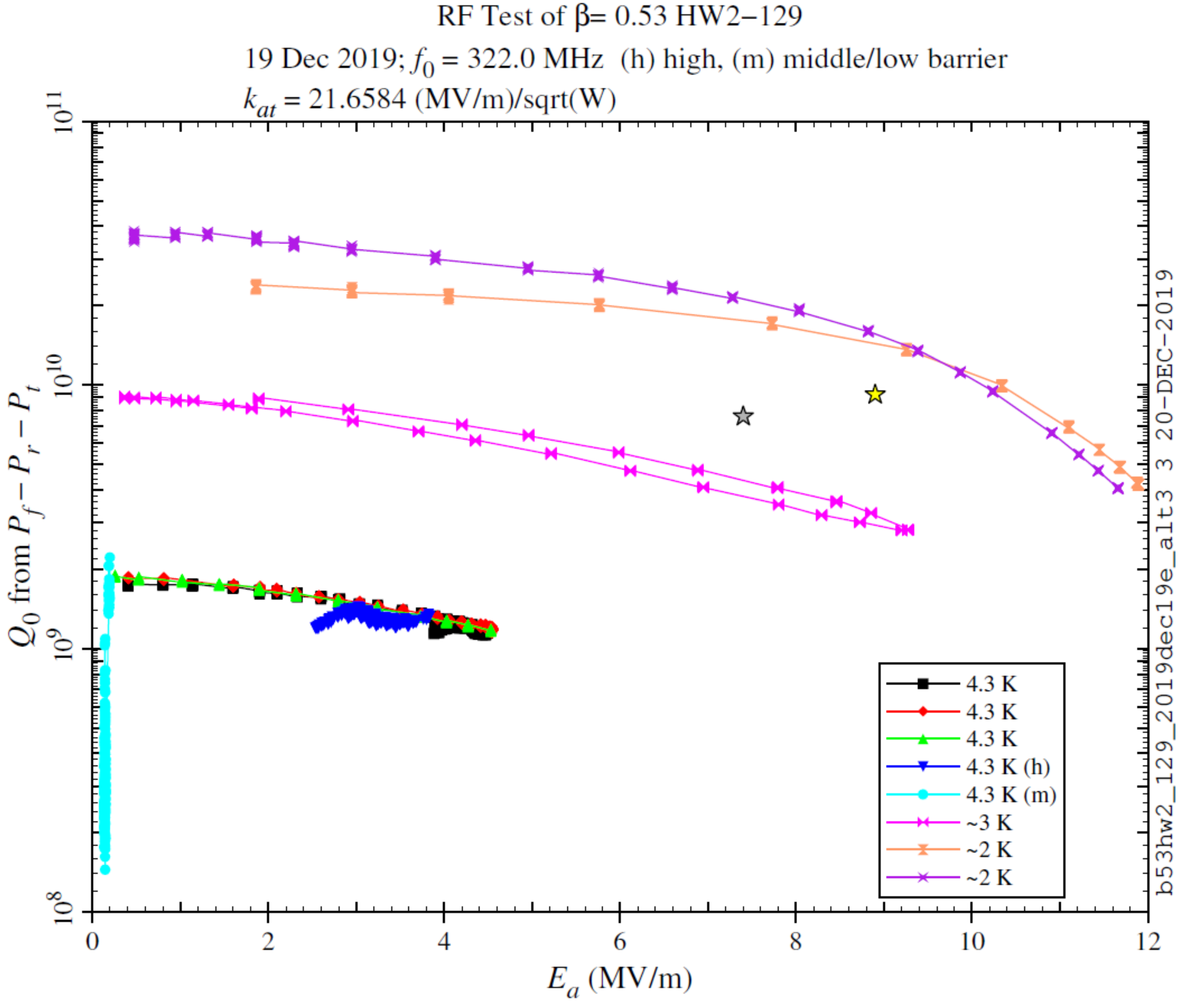


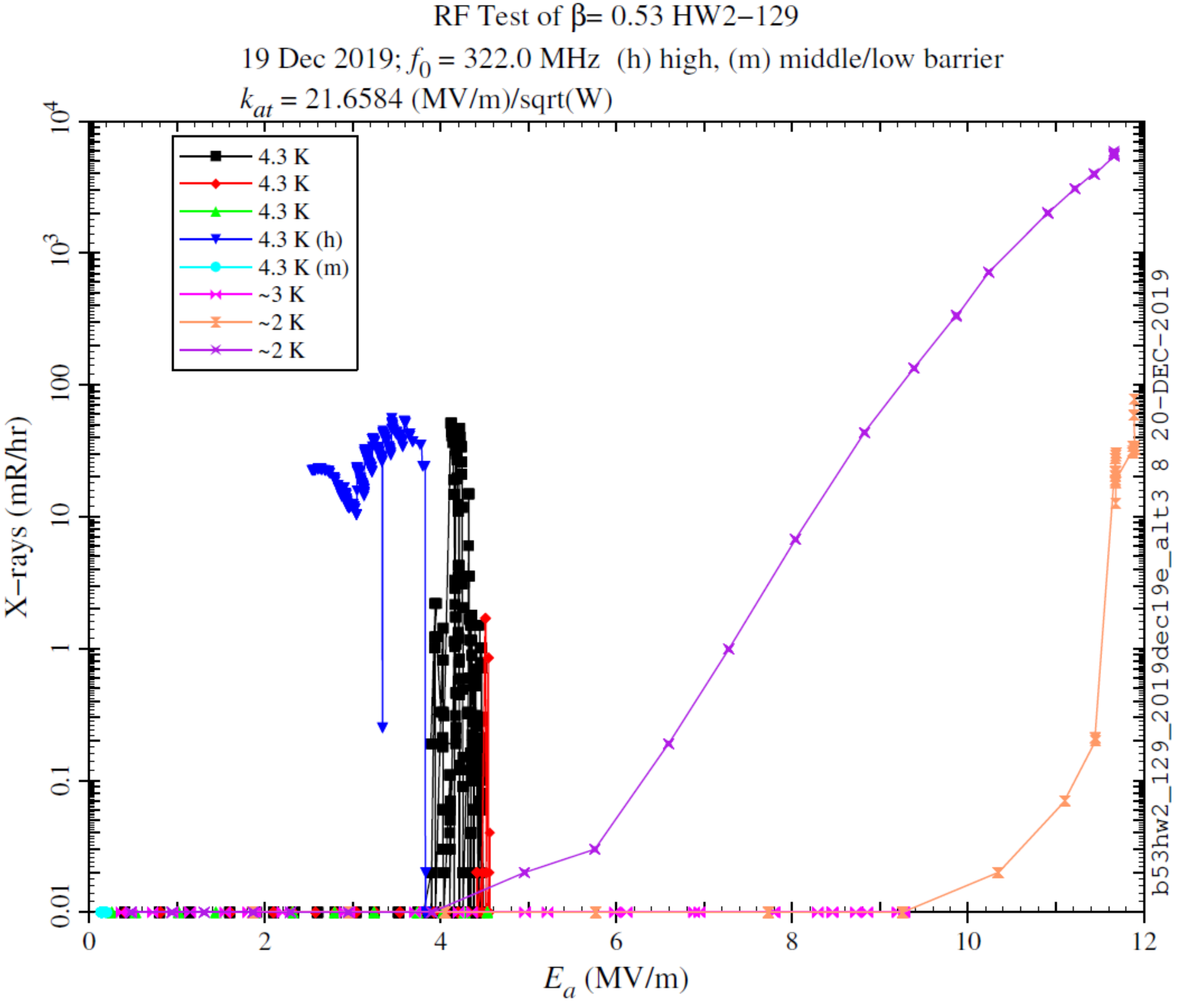
Field emission: RF conditioning
FRIB β = 0.085 QWR



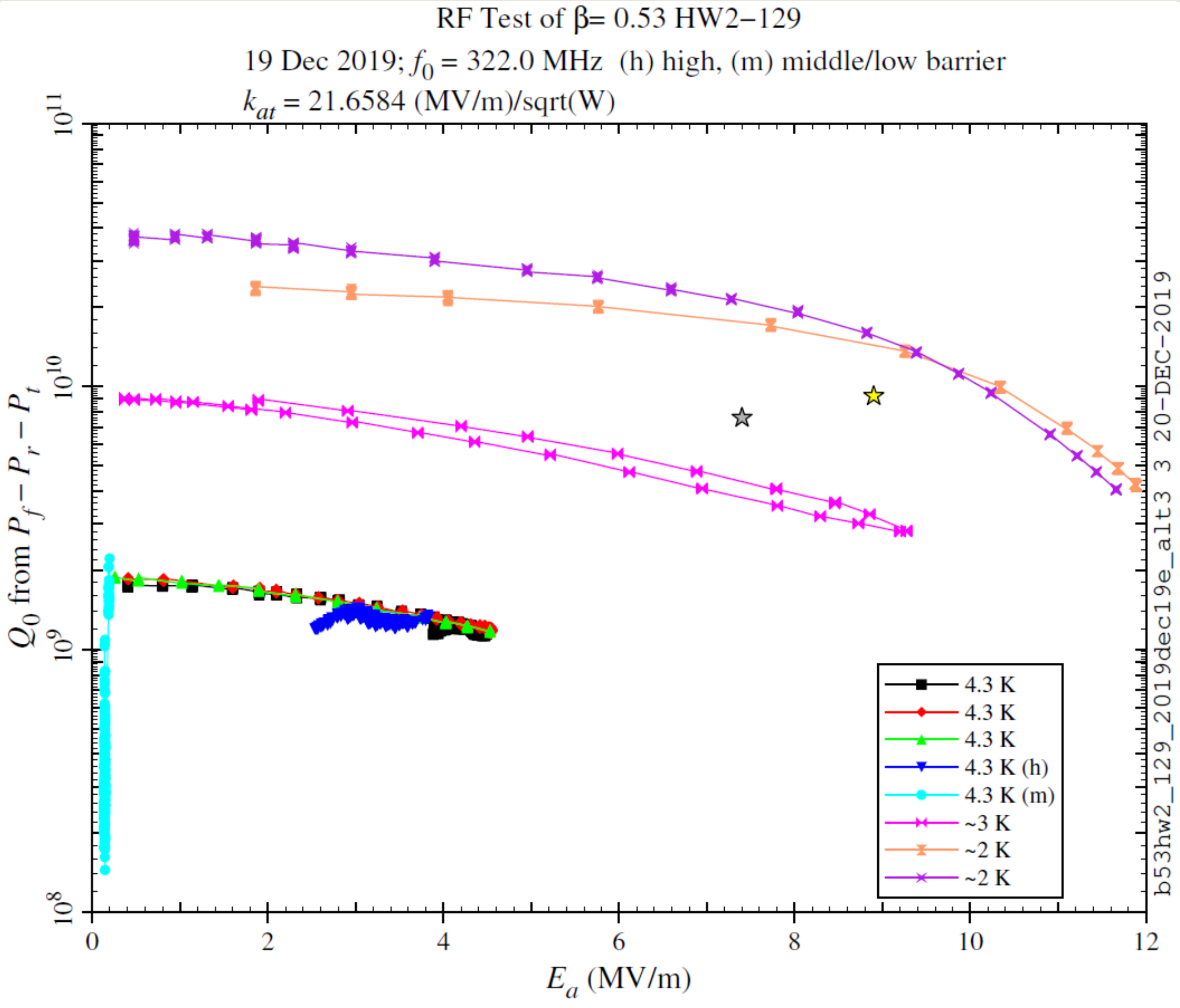


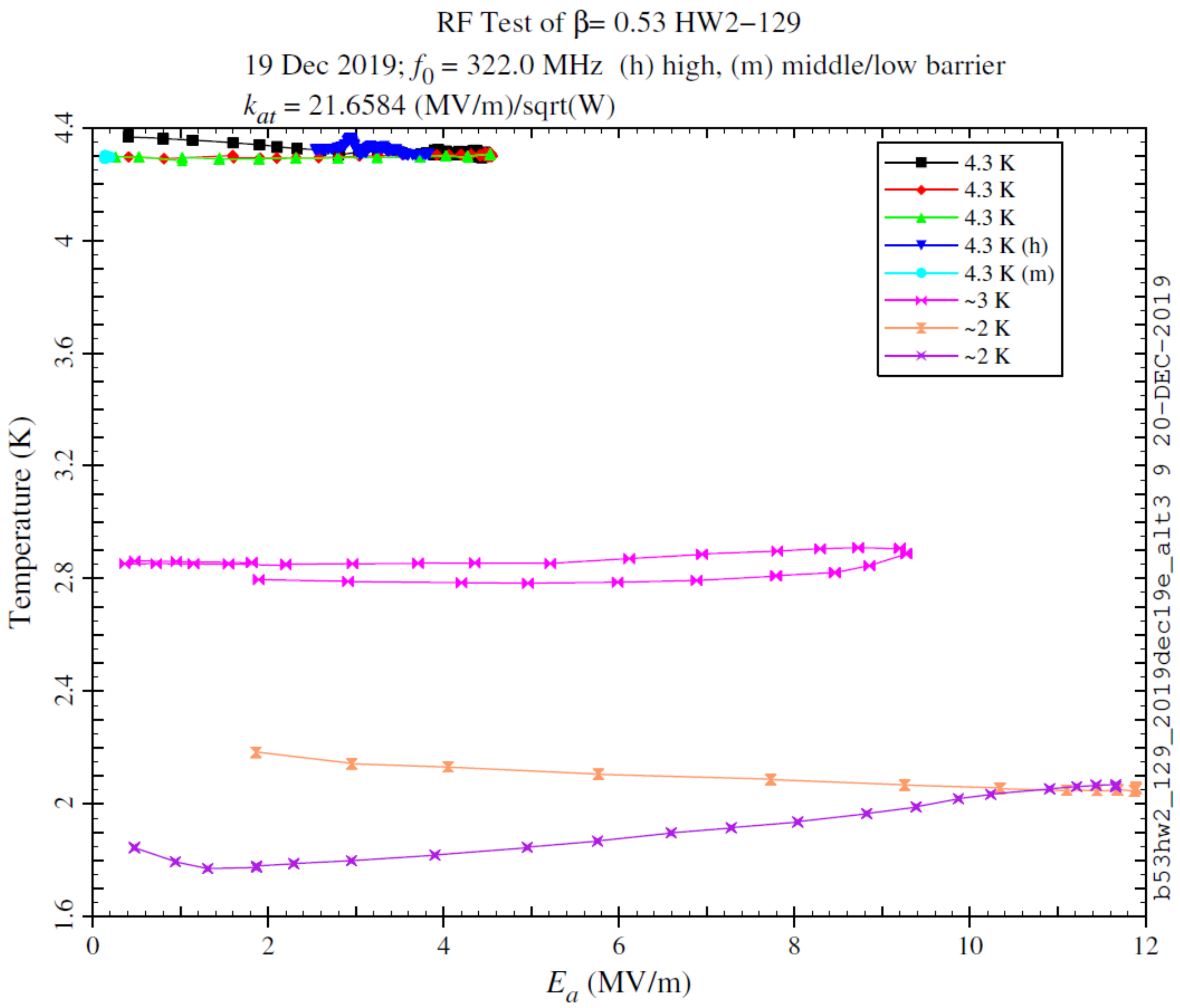
Field emission: RF conditioning, or not
FRIB β = 0.53 HWR





Field emission: RF conditioning, or not
FRIB β = 0.53 HWR





Field emission "rework" Steps

- Repeat water rinsing
- Repeat etching and rinsing
- Repeat borescope inspection, guided repair
- Ideal world: locate with diagnostics + guided repair

Figure 2: HWR polishing using the borescope (right) and a manual polishing tool (left).

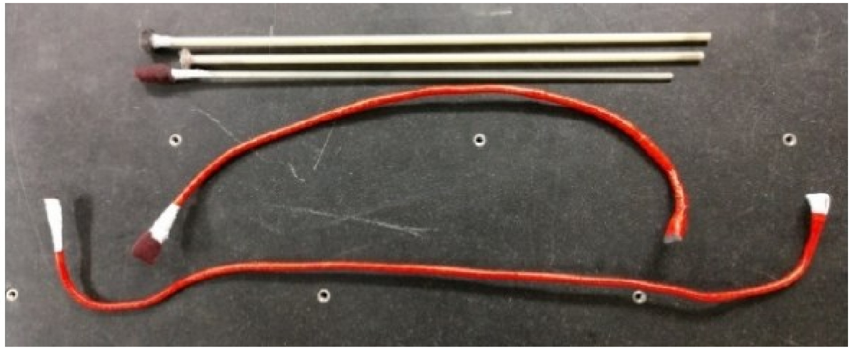
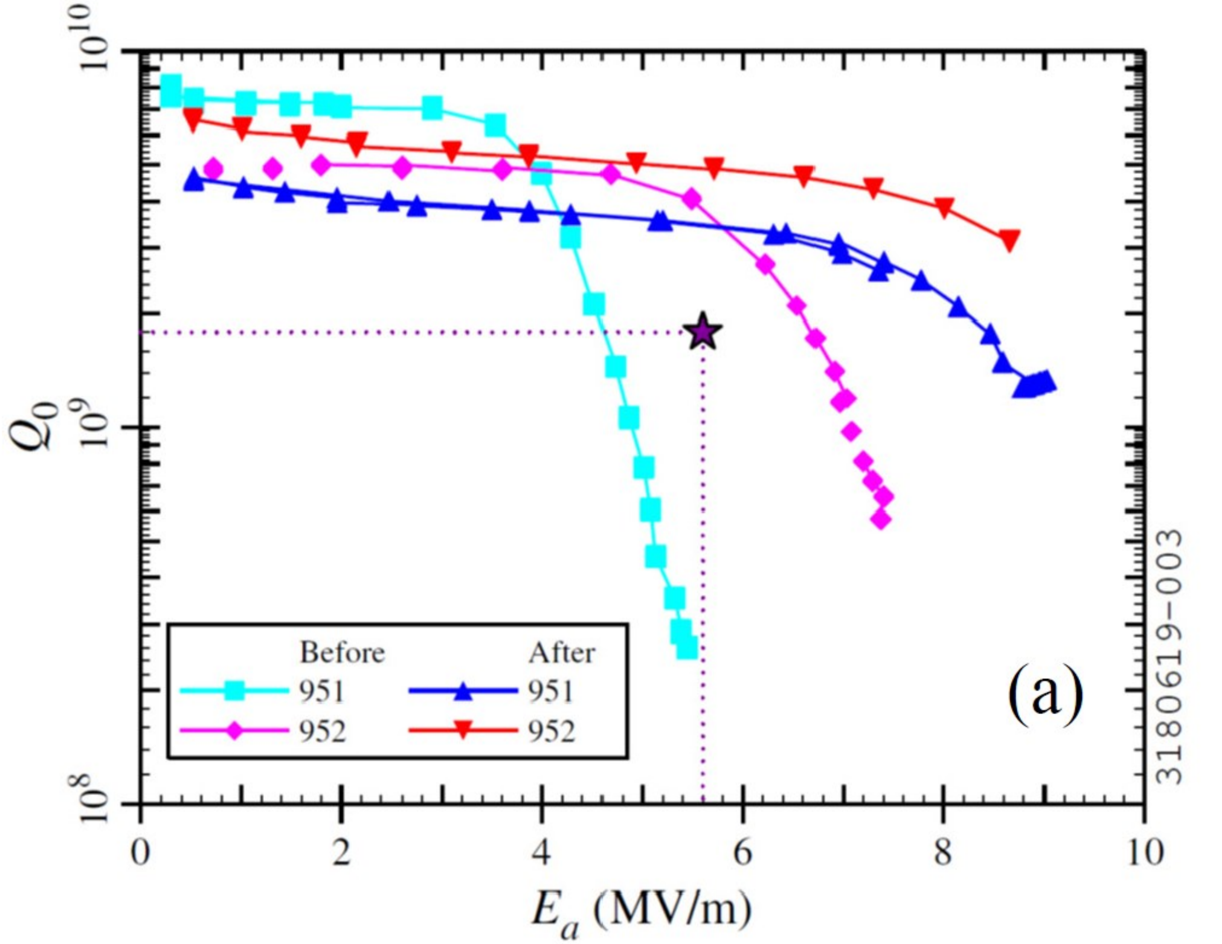
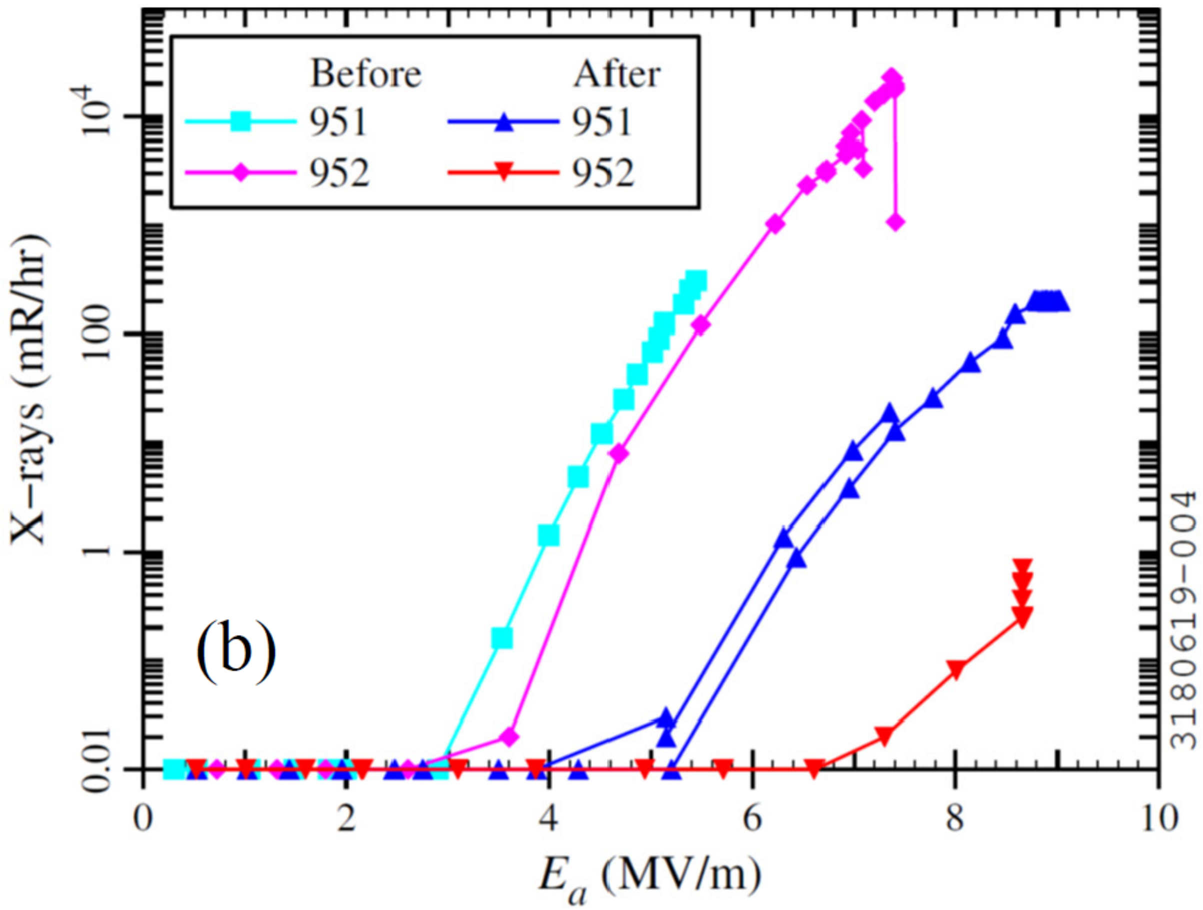


Figure 3: Examples of cavity polishing tools. The tools are bent as needed to reach features via the available access ports.

C. Compton et al, SRF 2019, MOP005

Field emission reduction via guided repair: mechanical polishing





C. Compton et al, SRF 2019, MOP005

Example: Q_0 and X-rays for FRIB β = 0.53 HWRs

Gray: certified

Colors: FE rework

Red: before rework

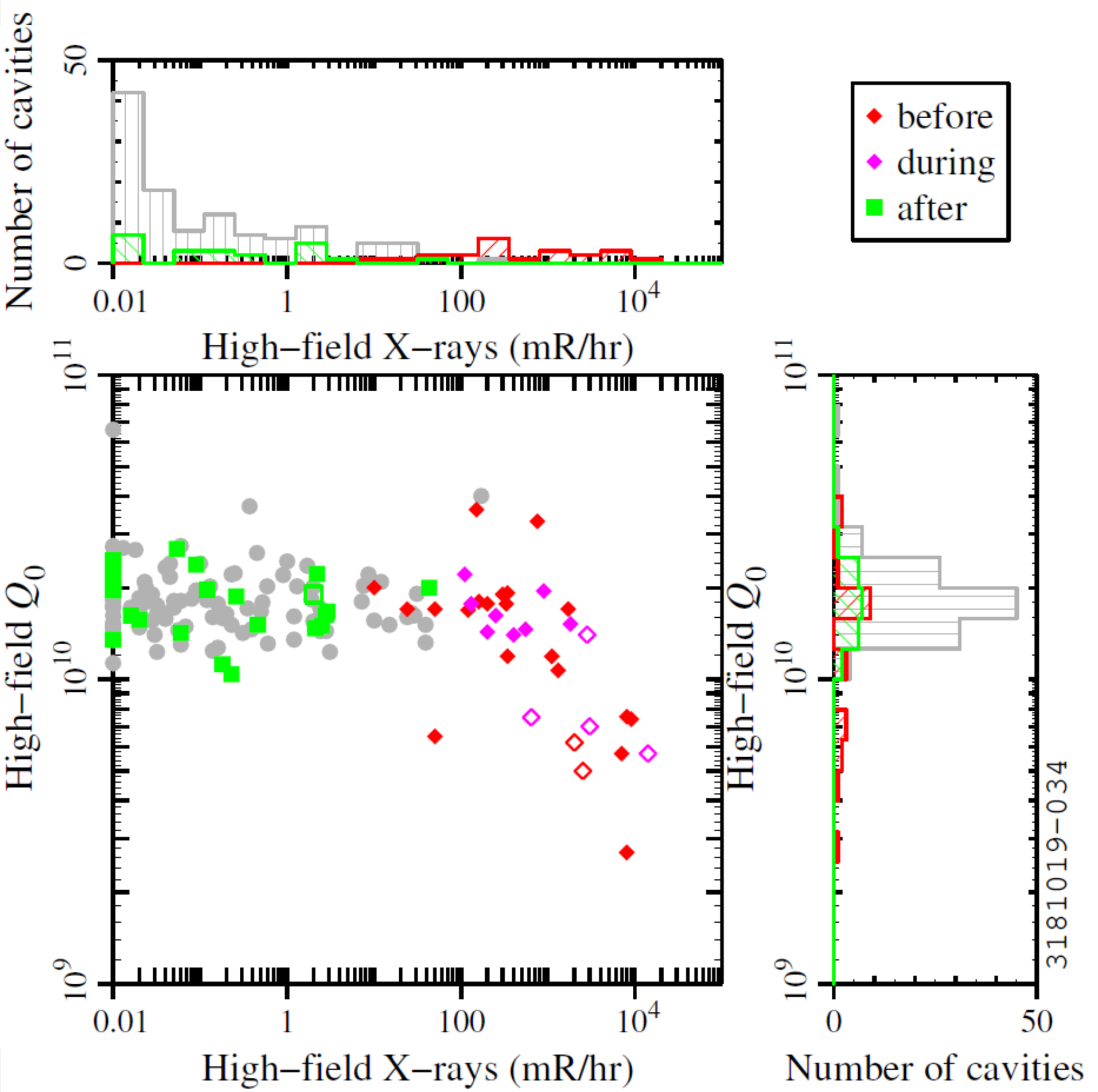
Magenta: during rework

Green: after rework

Solid: at 8.9 MV/m

Hollow: at max field, below 8.9 MV/m

W. Hartung et al, NAPAC 2019, MOPLO17



FRIB resonators: field emission reworks

FRIB Production Statistics

β	0.041	0.085	0.29	0.53
Number of cavities tested	16	106	72	152
Number of FE reworks	2	8	5	21

C. Zhang et al, *Nucl Instrum Methods Phys Res A*, **1014**, 165675 (2021)

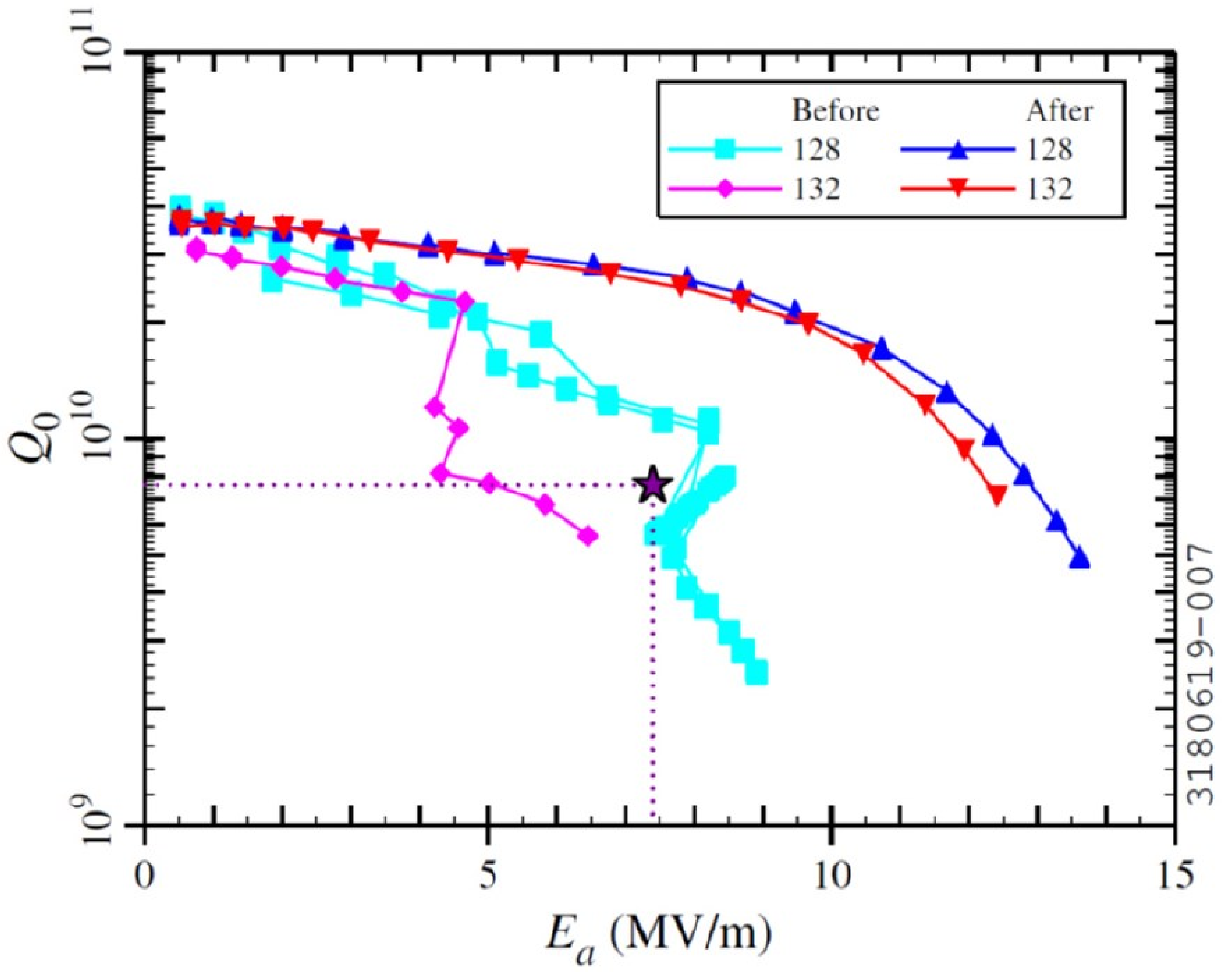
Rare phenomena
(we would like to think)

Thermal Breakdown

β	0.041	0.085	0.29	0.53
TB incidence	31%	7%	32%	28%
Number of early TB cases	0	0	2	6

C. Zhang et al, *Nucl Instrum Methods Phys Res A*, **1014**, 165675 (2021)

FRIB Cavity Examples: “*Q*-switch”



C. Compton et al, SRF 2019, MOP005

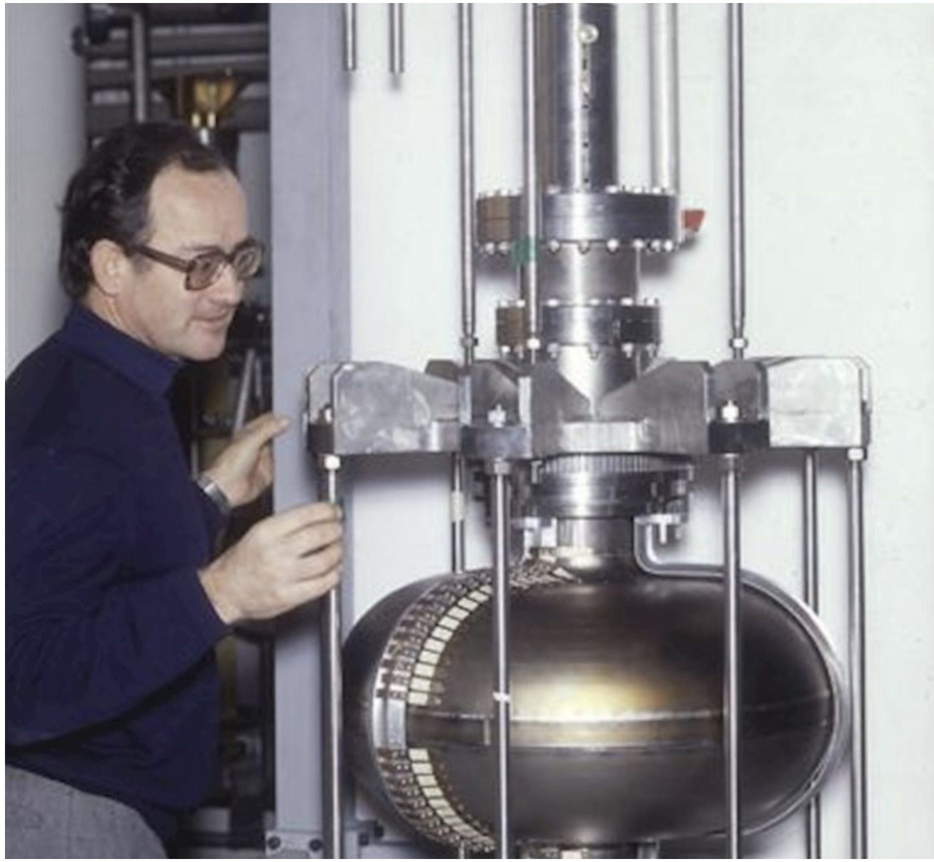
FRIB Cavity Example: *Q*-switch mitigation with polishing

Figure 10: Polishing of S53-128 feature: (a) as received, before etching; (b) after etching and test; (c) after initial polishing, "opening up"; (d) shelving with void underneath; (e) top material removed, blending void area to adjacent surface; (f) fragment broken off during polishing.

C. Compton et al, SRF 2019, MOP005

Cavity Testing: Supplemental diagnostics

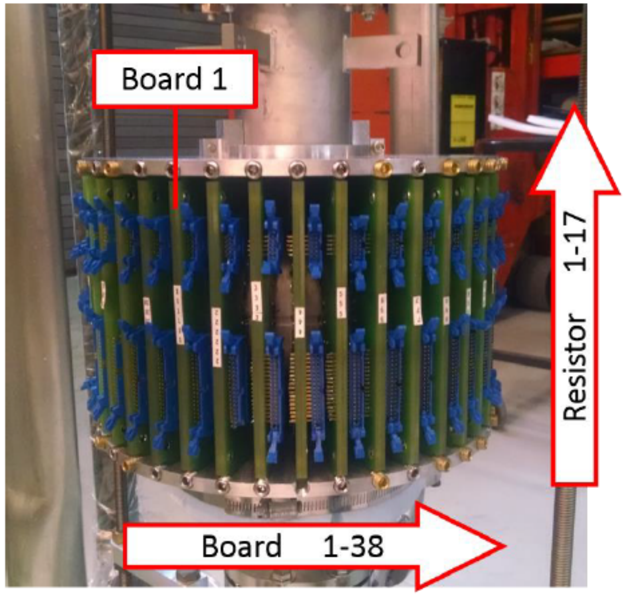
Thermometry: Rotating Example



CERN

Thermometry: Fixed Example

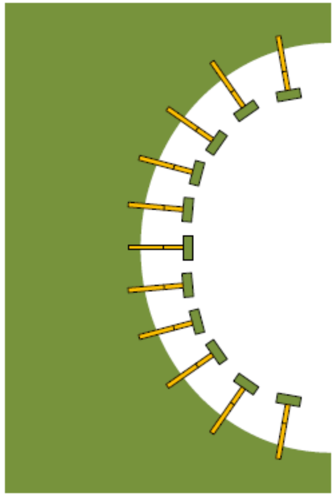
Cover cavity is 100's of thermometers
-Allen Bradley carbon resistors

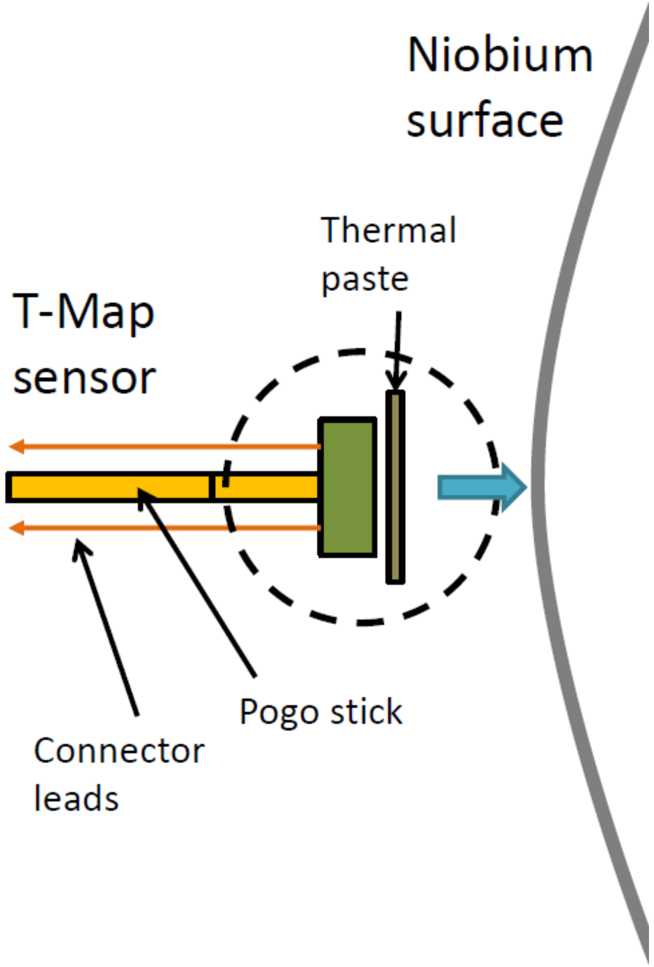


Original T-map:

Jens Knobloch, 'Advanced Thermometry Studies of Superconducting Radio-Frequency Cavities', Ph.D. Thesis, Cornell University (August 1997).

T-Map board





Cornell system: Ryan Porter, SRF 2021, TUOFDV05

X-ray energy spectrum measurements: Example

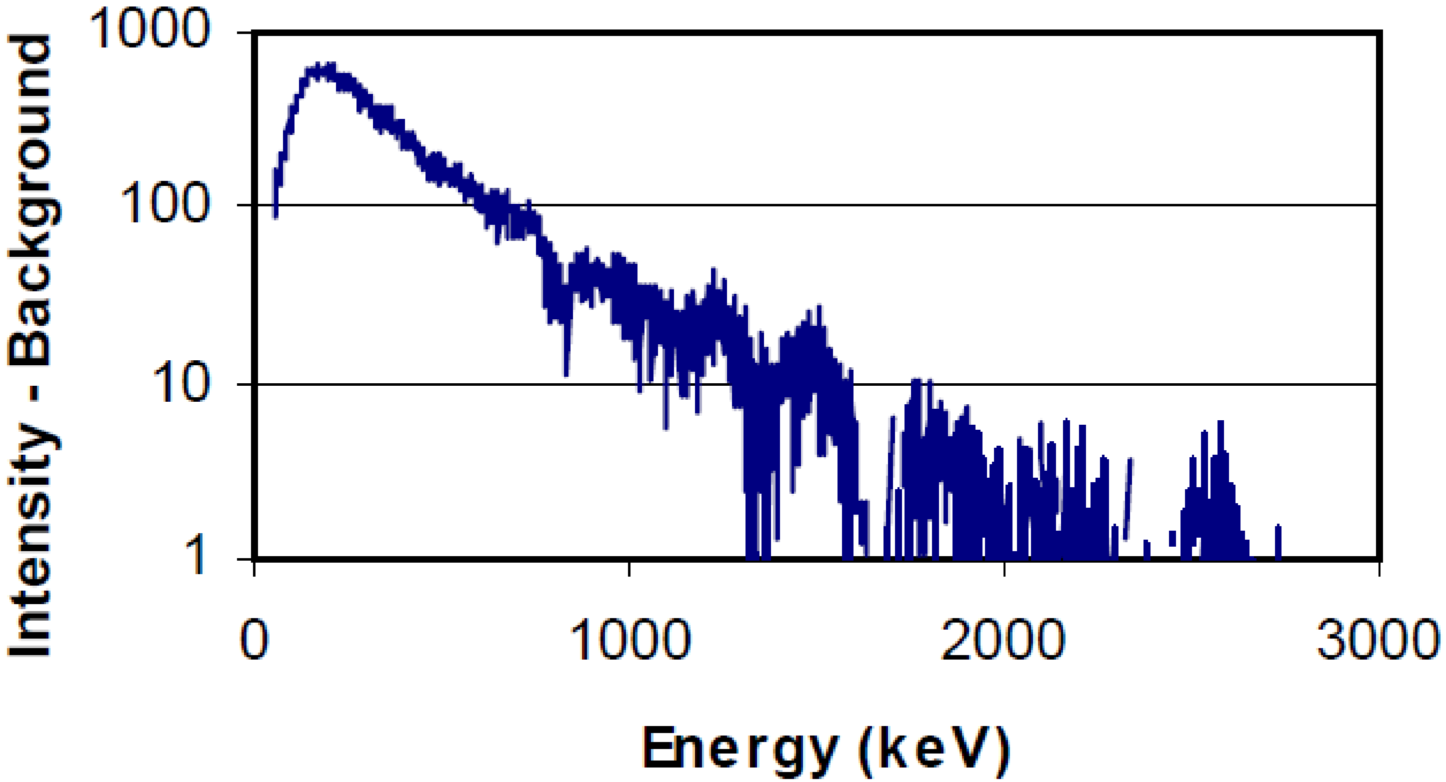
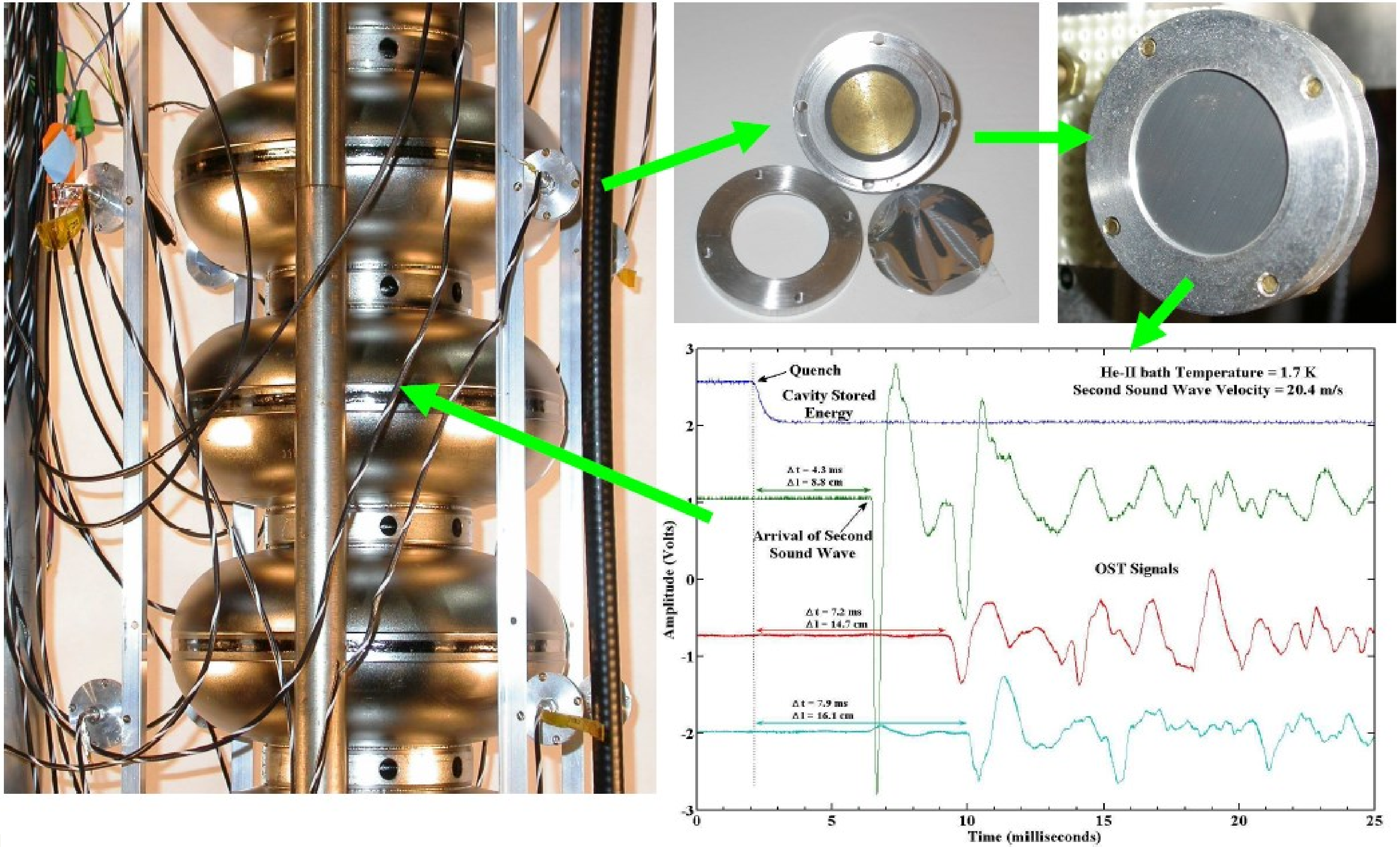


Figure 2: A typical x-ray energy spectrum from a β=0.47 single cell cavity measured on top of the Dewar lid [2]. The peak electric field level in the cavity was 21.88MV/m and the maximum electron kinetic energy 1200keV.

S. Musser et al, PAC 2003, TPAB068

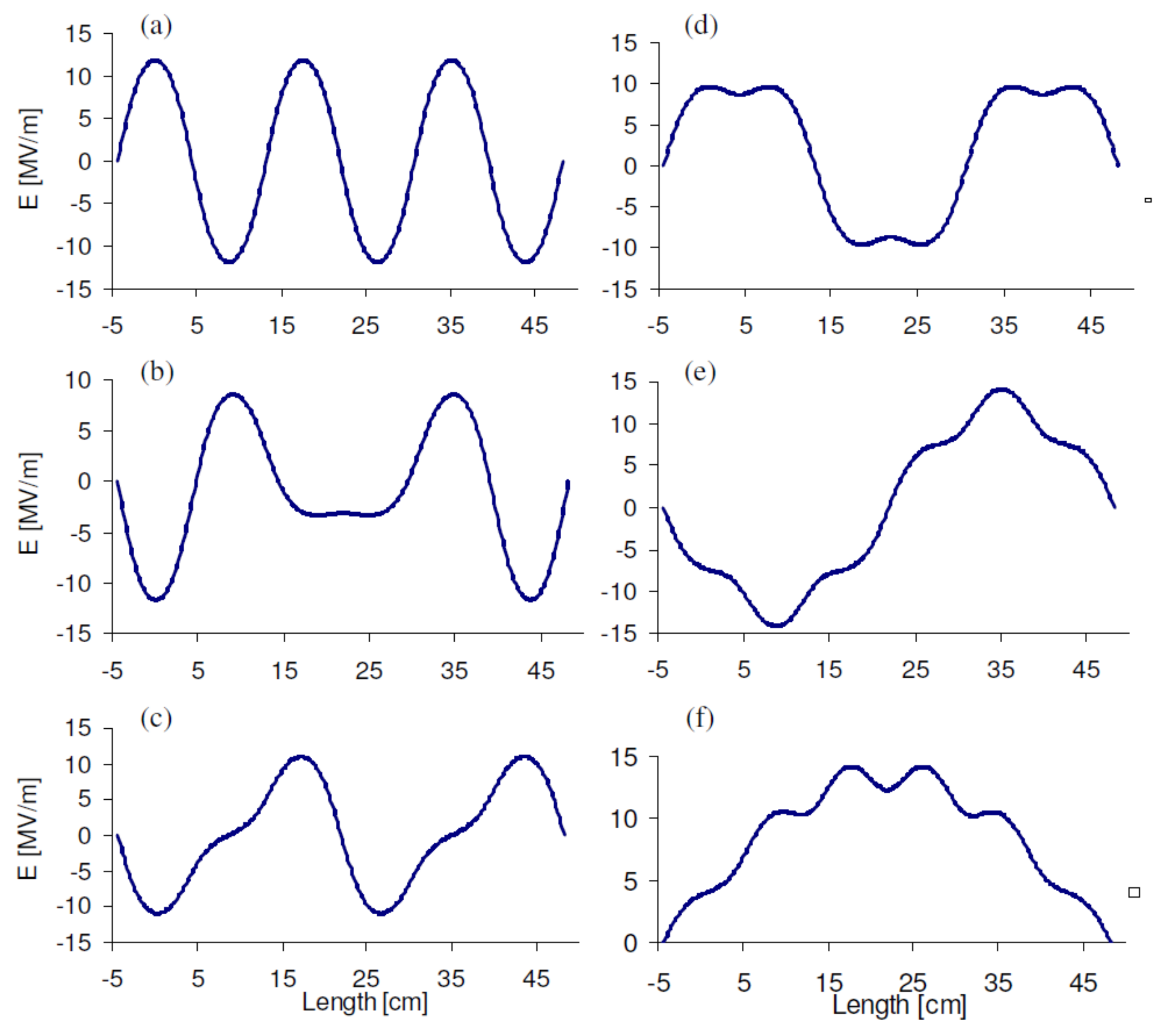
Second Sound: Localize thermal breakdown sites



Z. Conway, SRF 2009, TUOAAU05

Multi-mode measurements example: fundamental passband

Electric field along the axis of a 6-cell cavity for modes in the fundamental passband (Susan Musser, *X-Ray Imaging of Superconducting Radio Frequency Cavities*, PhD Dissertation, MSU, 2006, Fig. 5.3)



Cavity Testing: Special systems and methods

- "Integrated" test setups
- "Horizontal" test cryostats
- Cryomodule tests
- "Online" testing

Summary

- Cavity testing is an important part of SRF endeavors, including development, production, and operation
- Testing methods for different cavities and different facilities are similar, with some variations
- Important aspects: calibrations, analysis, attention to systematic errors
- "The Proof Of The Pudding Is In The Eating"

More Information

- Past SRF conference tutorial sessions
  - 2021: J. Popielarski; emphasis on certification criteria, safety; cryomodule testing
  - 2019: T. Powers: emphasis on RF system, analysis, errors, math
  - And so on…
- Books
  - H Padamsee, Jens Knobloch, Tom Hays, RF Superconductivity for Accelerators, Wiley, New York, 1998, Chapt. 8
- SRF courses at accelerator schools
  - USPAS
  - CERN Accelerator School
  - And so on…