NAPAC2019

FRIB

Large-Scale Dewar Testing of FRIB Production Cavities: Statistical Analysis

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FRIB SRF Cavities: Overview

Cavity Parameters				
Type	QWR	QWR	HWR	HWR
β	0.041	0.085	0.29	0.53
f_0 (MHz)	80.5	80.5	322	322
$<E_a>$ (MV/m)	5.1	5.6	7.7	7.4
$<E_{pk}>$ (MV/m)	30.8	33.4	33.3	26.5
$<B_{pk}>$ (mT)	54.6	68.9	59.6	63.2
E_{pk}/E_a	6.1	6	4.3	3.6
B_{pk}/E_a (mT/(MV/m))	10.8	12.4	7.7	8.6
Number of Cavities				
Needed	**12+4=16**	**92+8=100**	**72**	**148**
Certified	**16**	**100**	**75**	**141**
Completion	**100%**	**100%**	**100%**	**95%**

Total Cavity Requirement: 336
Data analyzed based on：332

- **Resonators made from sheet Nb (RRR>250): deep drawing and electron beam welding**
- **Jacketed resonators delivered to FRIB by vendors**
- **Final preparation steps at MSU:**
  - **borescope inspections**
  - **bulk etching (BCP 120 μm)**
  - **hydrogen degassing (600°C x 10 hr)**
  - **light etch (BCP 20 μm)**
  - **high-pressure rinsing: robotic system**
  - **Indium seal for QWR bottom flange, copper gasket for all ports**
  - **no low-temp bake**

Design criteria example:
B_{pk} (@ op. Ea) < 70 mT, ASAC recommendation

W. Hartung, MOPLO17

Outline

1. Dewar test
2. Thermal Quench, MP, FE and Q-slope in FRIB SRF cavities
3. SRF material parameter statistics for FRIB cavities
4. Summary

Dewar test for FRIB Cavities

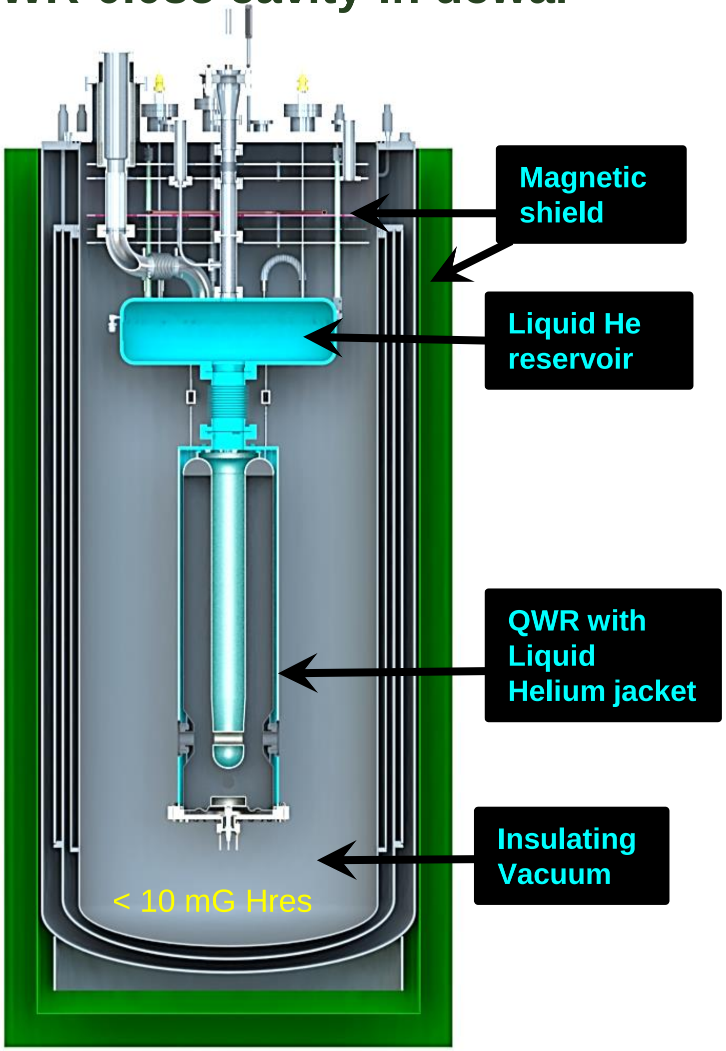
- **~1 hour cooling down from RT to 4.3 K**
- **4.3 K:**
  - Q_0 vs. E_{acc}
  - MP conditioning
- **Cooling from 4.3 to 2K:**
  - Q_0 vs. T
- **2K:**
  - Q_0 vs. E_{acc}
  - FE conditioning

Specification and Achievements at 2 K

	E_{acc} (spec-VTA) / Achieved (MV/m)	Q_0 (spec-VTA) / Achieved
QWR-0.041	5.6 / 10.5 ± 0.7	1.4E9 / 5.7 ±0.7E9
QWR-0.085	6.1 / 9.1±0.3	2E9 / 4.0 ± 1.0E9
HWR-0.29	8.5 / 12.6 ± 0.6	6.7E9 / 1.4 ± 0.2E10
HWR-0.53	8.1 / 12.0 ± 0.6	9.2E9 / 1.9 ± 0.3E10

- **SRF cavities exceed the FRIB requirements**
- **Performance margin = factor of 2 on average**

QWR-0.085 cavity in dewar



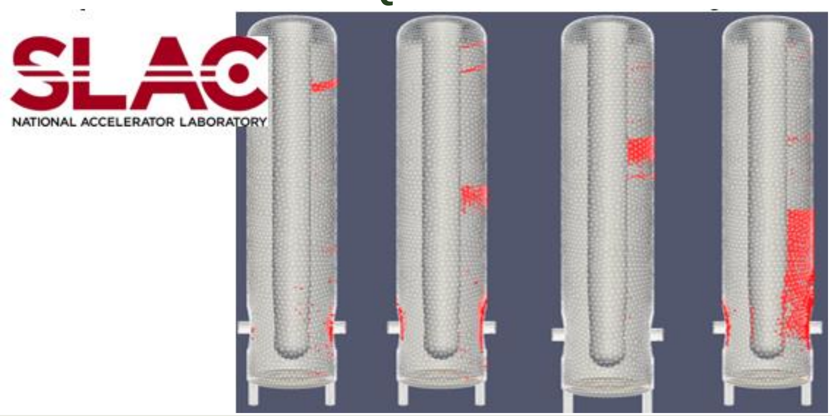
Performance Limits for FRIB Cavities: Overview

Limitation	FRIB Status
Thermal Breakdown	▪ **mostly good** • 5 out of 332: thermal breakdown below E_a goal (<2%) • 74 out of 332 (~20%): thermal breakdown, E_a > 10 MV/m
Multipacting	▪ most cavities have MP, but can condition ▪ conditioning times tolerable (< 2 hr/test) ▪ conditioning times vary from cavity to cavity
Field Emission	▪ **mostly good** ▪ some reworks to reduce X-rays (~10%) ▪ most cavities have x-rays <100 mR/hr at design field
High Field Q-slope	▪ **good for present FRIB goals** ▪ may need to do better for FRIB energy upgrade

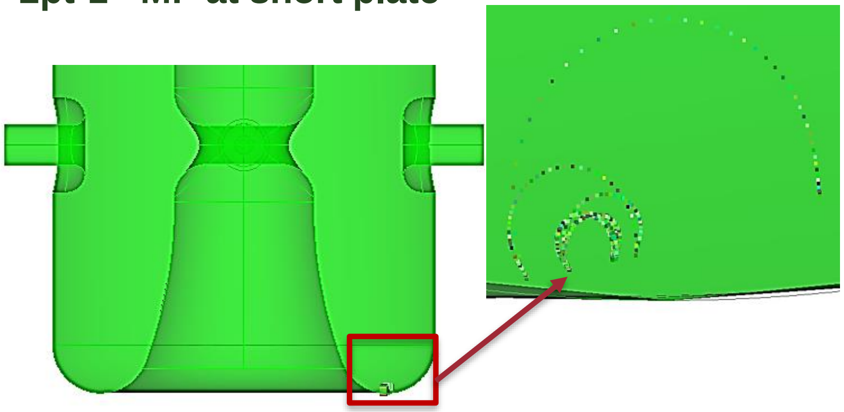
Multipacting

Barrier Type	QWR-0.041	QWR-0.085	HWR-0.29	HWR-0.53
Low	0.002-0.005 MV/m jump over and avoid	0.004 - 0.007 MV/m jump over and avoid	NA	NA
Middle	NA	0.06 - 0.09 MV/m	0.05 - 0.3 MV/m	0.03 - 0.2 MV/m
High (2 pt-1st at short plate)	0.6 -1 MV/m	0.5 - 0.8 MV/m	2.6 - 4.2 MV/m	2.2 - 4 MV/m
Post high	NA	NA	5 - 7 MV/m	4 - 5 MV/m
conditioning time	<2 hours/test (Dewar test; faster if variable coupler) (<30 mins in cryomodule, over-coupled FPC)			

MP middle barrier in QWR



2pt-1st MP at short plate



Thermal Breakdown

Thermal Breakdown: mostly good for FRIB spec.

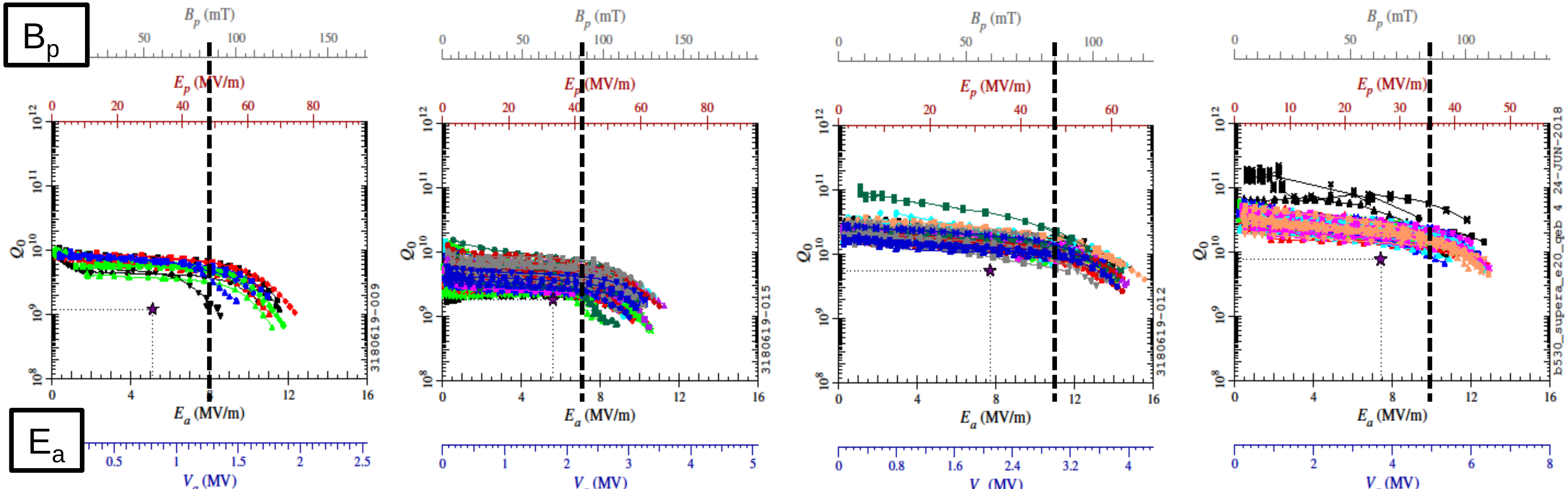
Type	Number Tested	Thermal breakdown (< gradient goal)	Notes
QWR-0.041	16	0	• 6/16 (40%) thermal breakdown at ~10.5 MV/m (spec: 5.1 MV/m) • Surface/EBW defect
QWR-0.085	100	0	• 9/100 (10%) thermal breakdown at ~10 MV/m (spec: 5.6 MV/m) • Surface/EBW defect
HWR-0.29	75	2 (2%)	• 24/75 (30%) thermal breakdown at ~13 MV/m (spec: 7.7 MV/m) • Surface/EBW defect
HWR-0.53	141	3 (2%)	• 35/141 (25%) thermal breakdown at ~12 MV/m (spec: 7.4 MV/m) • Surface/EBW defect

Field Emission: needed re-preparation 10%

Type	Number Tested	Number of FE reworks	Reasons
QWR-0.041	16	2 (~13%)	Contamination particles and scratches on surface
QWR-0.085	100	9 (~8%)	Contamination particles and scratches on surface
HWR-0.29	75	7 (~10%)	Contamination particles, not optimized HPWR, residual acid
HWR-0.53	141	22 (~16%)	Contamination particles, not optimized HPWR, residual acid

High Field Q-slope

- **Pure high field Q-slope (HFQS) without X-rays: often observed in each FRIB cavity family**
  - **typical phenomena for BCP cavities, post-etch baking cannot help**
  - **physical mechanism still not so clear**



QWR-0.041: 10 (63%)   QWR-0.085: 47 (47%)   HWR-0.29: 47 (65%)   HWR-0.53: 38(27%)

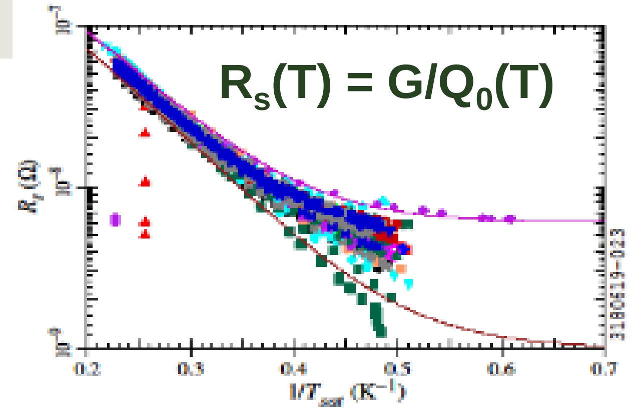
Onset of HFQS: B_p~85 mT

- **For the future FRIB energy upgrade to mitigate HFQS:**
  - **EP + low temp. bake**
  - **new BCP recipe**

FRIB Production SRF Parameters Statistics

- R_s vs 1/T fit (at low field) provides material information
- 3-parameter BCS fit:

$$R_S = \boxed{C_{RRR}} R_1^{\frac{\boxed{\left(\frac{\Delta}{\kappa_B}\right)}}{T}} \left(\frac{f}{f_1}\right)^2 \exp\left(-\frac{\boxed{\frac{\Delta}{\kappa_B}}}{T}\right) + \boxed{R_{res}}$$



Type	f_0 (MHz)	Number counted	C_{RRR}	Δ/κ_B (K)	R_{res} (nΩ)
QWR-0.041	80.5	10	1.36±0.21	14.91±0.87	2.21±0.69
QWR-0.085	80.5	38	1.49 ±0.36	14.25±1.79	4.12±1.40
HWR-0.29	322	57	1.88±0.22	18.40±0.66	3.75±0.97
HWR-0.53	322	82	1.84±0.17	18.26±0.40	3.32±0.92

- QWR data complication: tuning plate RF contact not always perfect
- HWR data: no RF contact issues, so results more indicative of intrinsic properties
  - Energy gap consistent with BCS theory
  - Residual resistance 3~4 nΩ, of which ~1 nΩ can be explained by residual magnetic field in the Dewar

Summary

- FRIB linac requires large-scale production of superconducting for QWRs and HWRs, ~350 cavities total.
- Dewar testing provides statistics data on production resonator performance
- FRIB cavities meet the performance goals (accelerating gradient, quality factor) with a factor two margin on average
- Performance is limited by thermal breakdown (2%), field emission (10%), high-field Q slope (50%)
- For future large scale projects with more ambitious field goals, HFQS is a concern if BCP used

Thank You For Your Attention!