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Status and Results of Mid-T Baking for PIP-II LB 650 MHz Cavities

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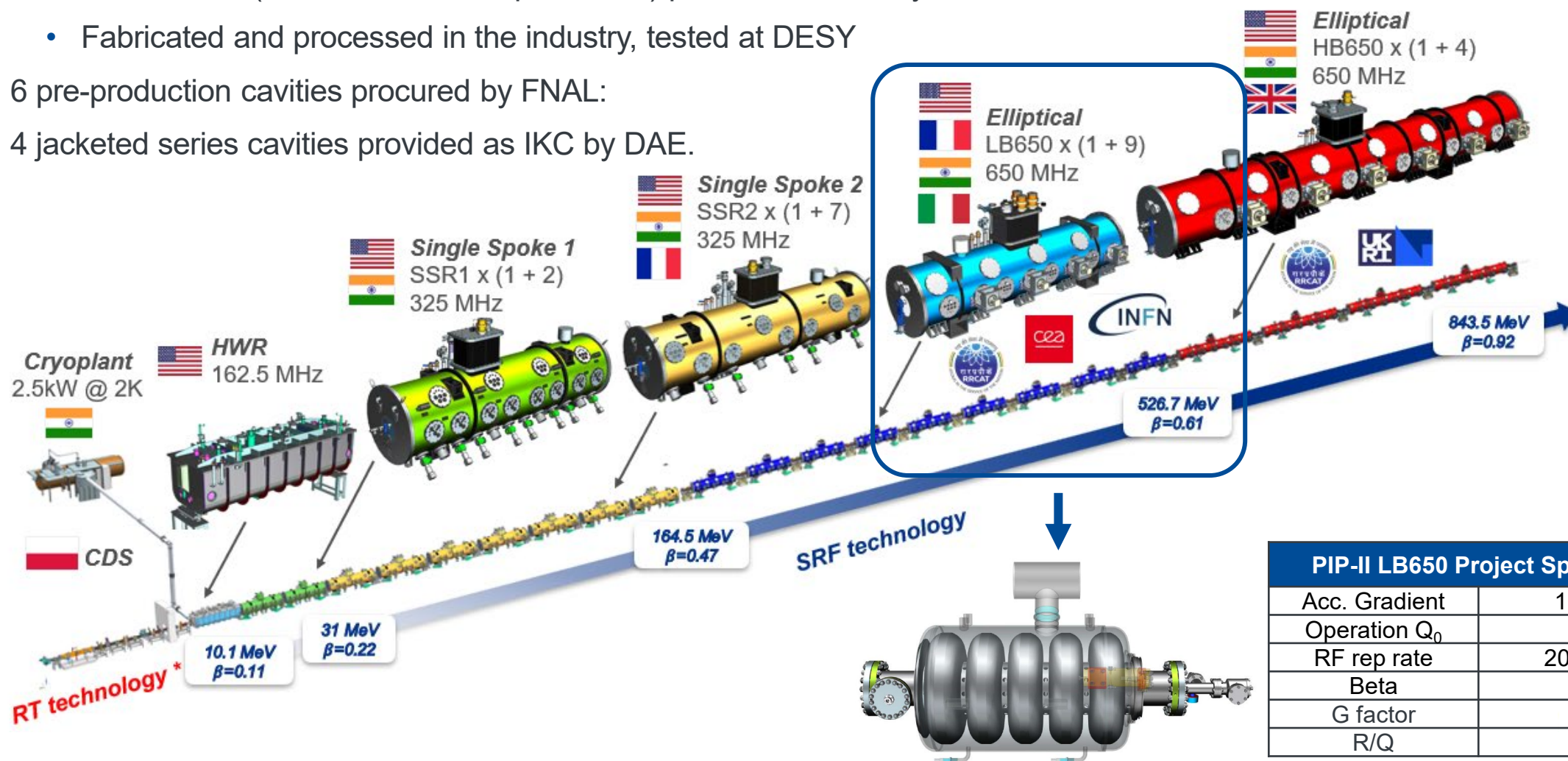
Outline

- ✓ PIP-II LB650 Scope
- ✓ Surface Preparation Recipe & Furnace data
- ✓ Mid-T Results for Pre-production Cavities
 - Tests results after EP
 - Test results after Mid-T
 - Test results after jacketing
- ✓ Field Emission Mitigation
- ✓ STC Test Results after HPC Assembly
- ✓ Technology Transfer to Industry
- ✓ Conclusion

PIP-II LB650 Scope



- 9 CMs (+1 pre-production CM) assembled and tested at CEA with HPCs and tuners provided by FNAL
- 38 series cavities (4 cavities / CM +2 pre-series) provided as IKC by INFN:
 - Fabricated and processed in the industry, tested at DESY
- 6 pre-production cavities procured by FNAL:
- 4 jacketed series cavities provided as IKC by DAE.



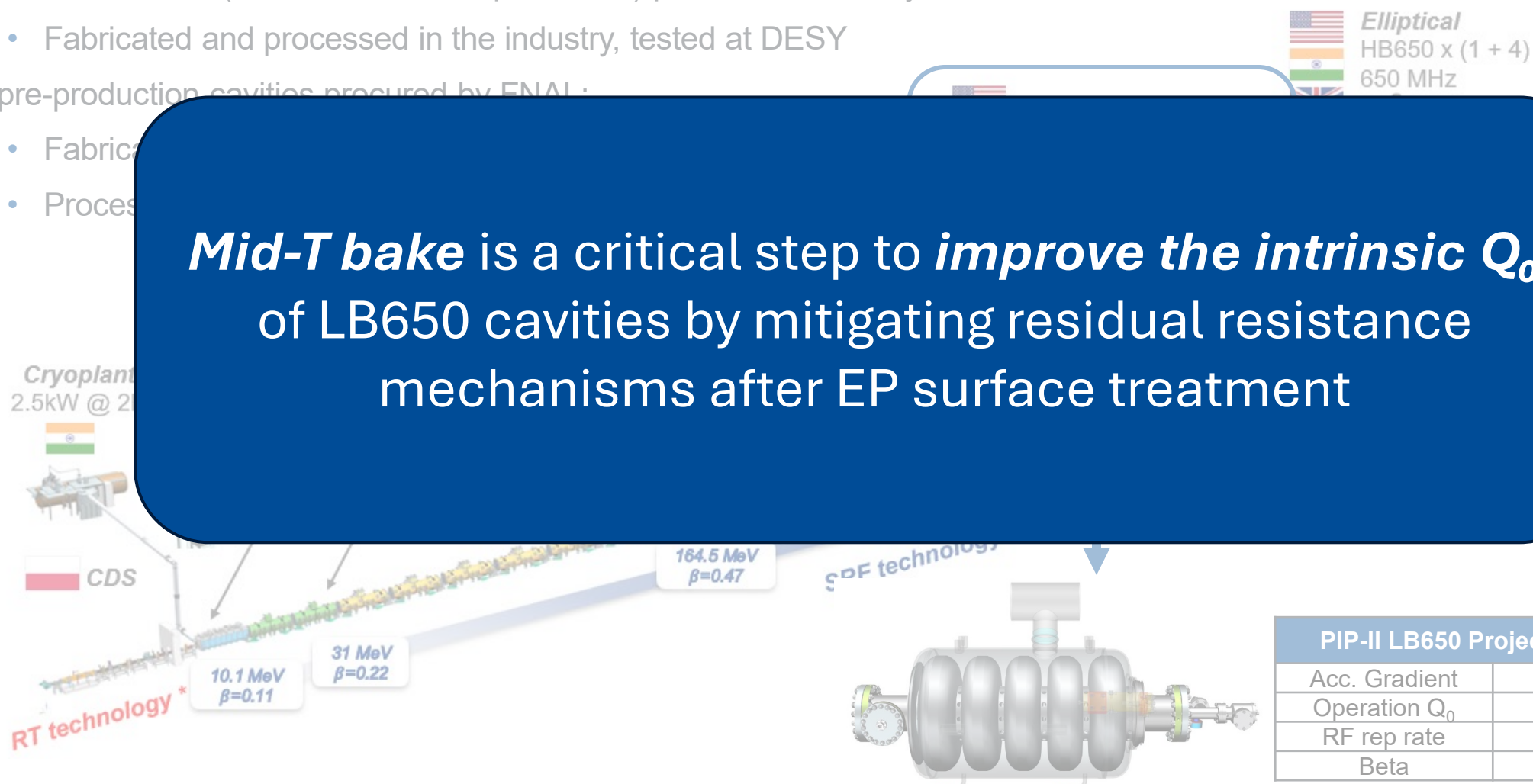
PIP-II LB650 Project Specifications	
Acc. Gradient	16.9 MV/m
Operation Q_0	$2.4 \cdot 10^{10}$
RF rep rate	20 Hz to CW
Beta	0.61
G factor	193 Ω
R/Q	341 Ω

PIP-II LB650 Scope



- 9 CMs (+1 pre-production CM) assembled and tested at CEA with HPCs and tuners provided by FNAL, transported to FNAL.
- 38 series cavities (4 cavities / CM +2 pre-series) provided as IKC by INFN:
 - Fabricated and processed in the industry, tested at DESY
- 6 pre-production cavities procured by FNAL:
 - Fabricated
 - Processed

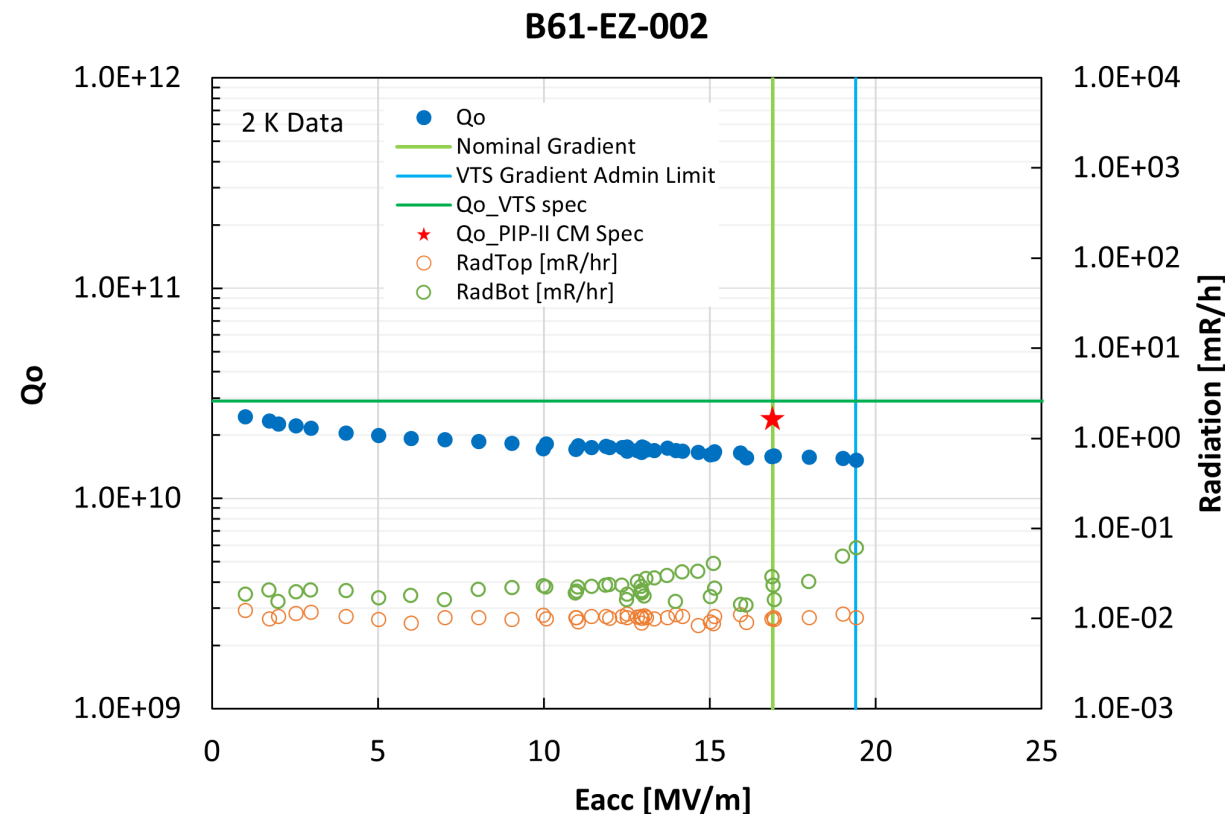
Mid-T bake is a critical step to ***improve the intrinsic Q_0*** of LB650 cavities by mitigating residual resistance mechanisms after EP surface treatment



List of cavities for the LB650 ppCM

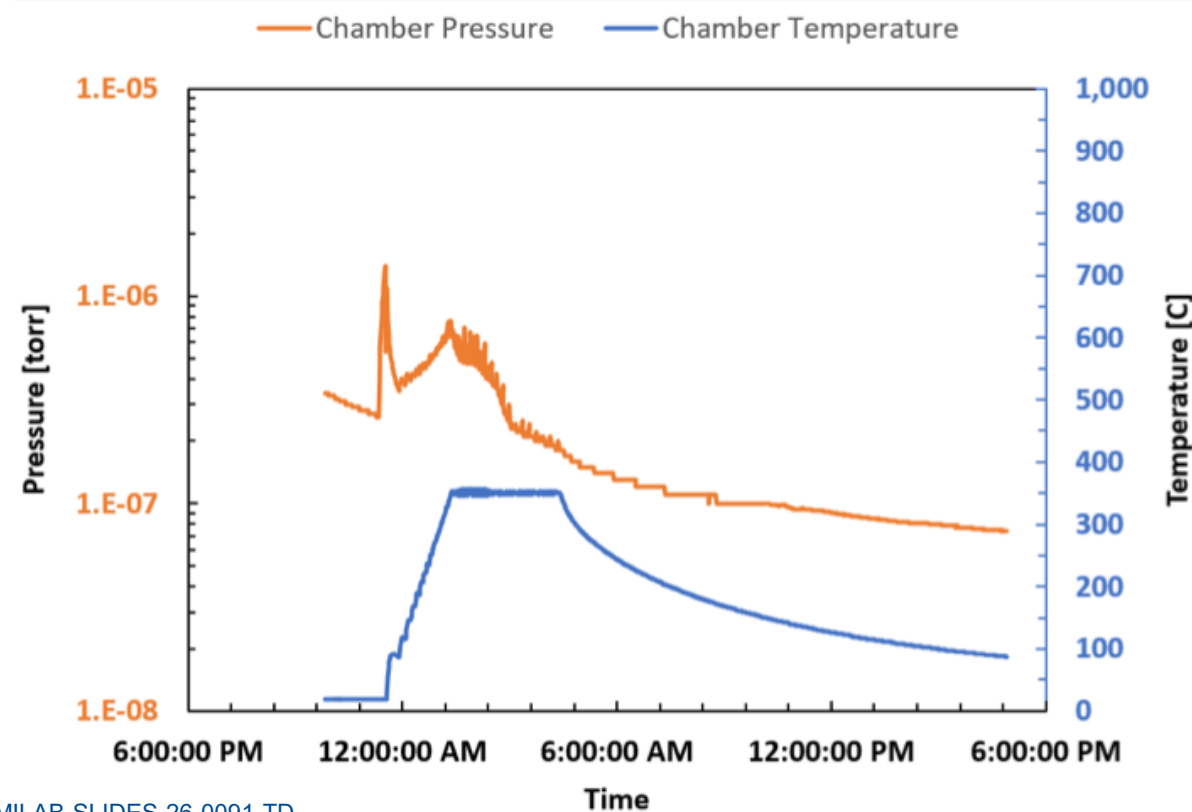
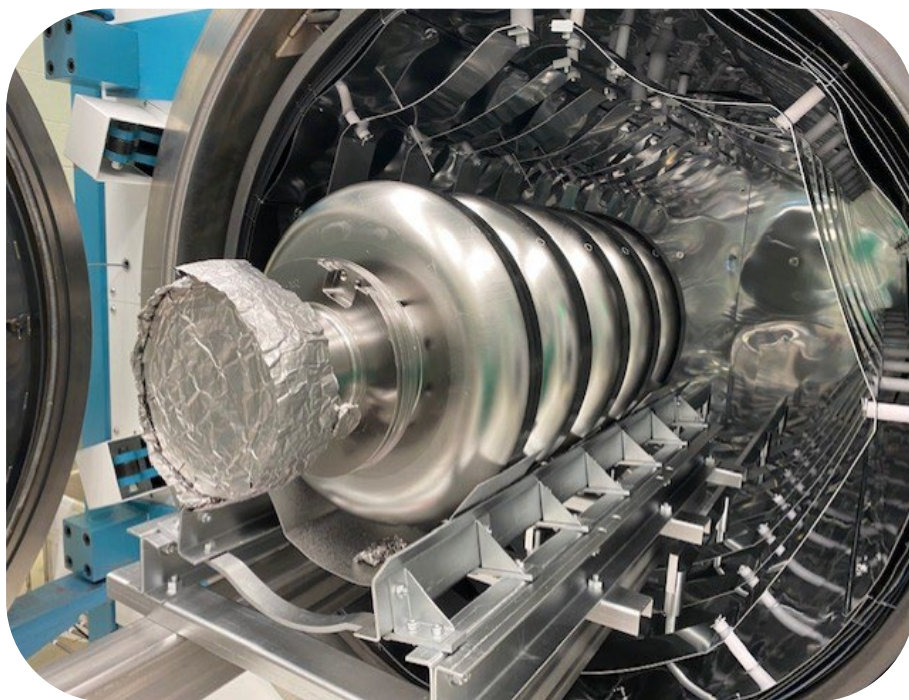


Serial Number	Status
B61-EZ-001*	Available for plasma processing studies
B61-EZ-002*	Available as a spare for LB650 CMs
B61C-EZ-101	ppLB650 CM string
B61C-EZ-102	
B61C-EZ-103	
B61C-EZ-104	



- B61-EZ-00# are prototype cavities procured by INFN and processed and tested in collaboration between INFN and FNAL
- B61-EZ-10# are pre-production cavities processed, jacketed, and tested at FNAL

Surface Preparation Recipe & Furnace data

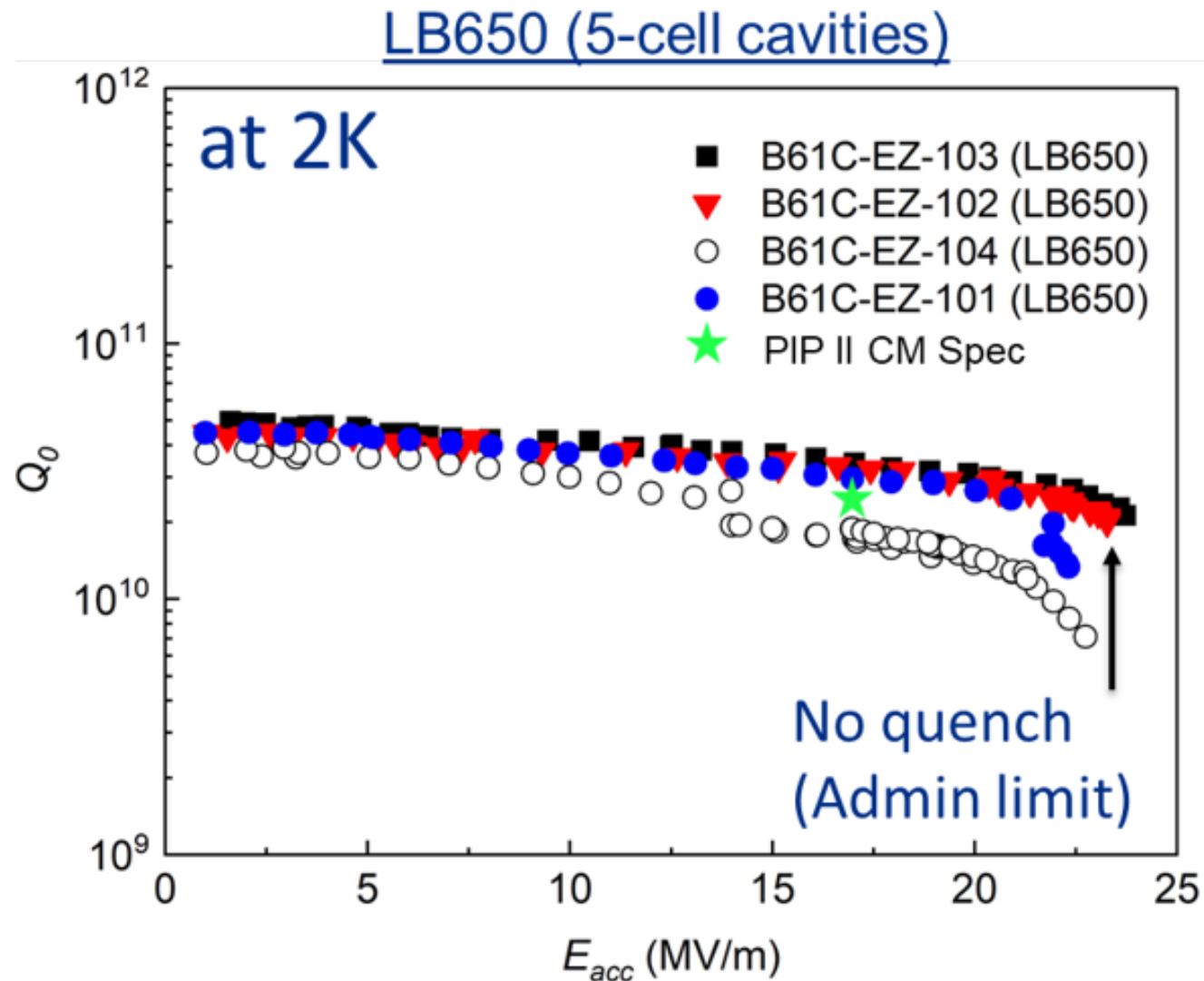


EP Baseline Results for pp - Cavities



Q_0 @ 16.9 MV/m	Administrative Gradient Limit (Before mid-T)
2.90E+10	22.4 MV/m

- EP cathode and parameters were optimized for the LB650 geometry to achieve a smooth cavity surface, improve removal uniformity, and achieve good performance that meets the gradient specification.



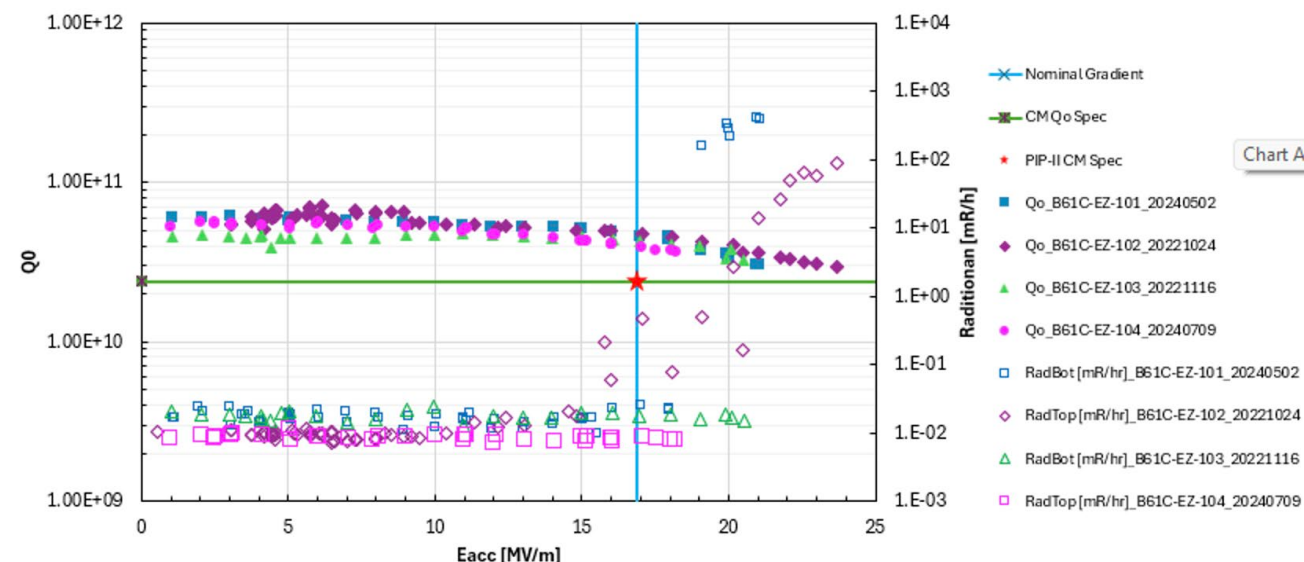
V. Chouhan et al., NIMA, **1051** (2023) 168234

Mid-T Results for pp - Bare Cavities



Cavity	Mid-T recipe	Qo @ 16.9 MV/m	Rs @ 16.9 MV/m (nΩ)
B61C-EZ-101	350C, 3h	3.9E+10	4.9
B61C-EZ-102	300C, 3h	3.7E+10	5.2
B61C-EZ-103	300C, 3h	4.4E+10	4.4
B61C-EZ-104	350C, 3h	4.0E+10	4.8

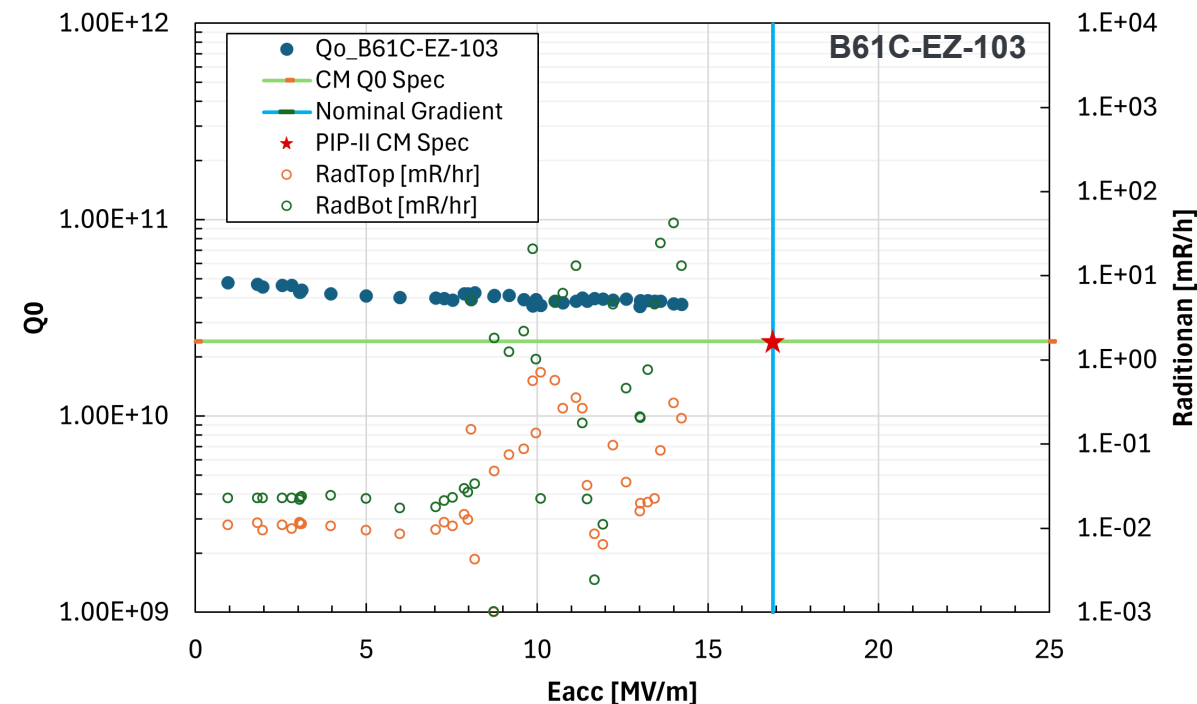
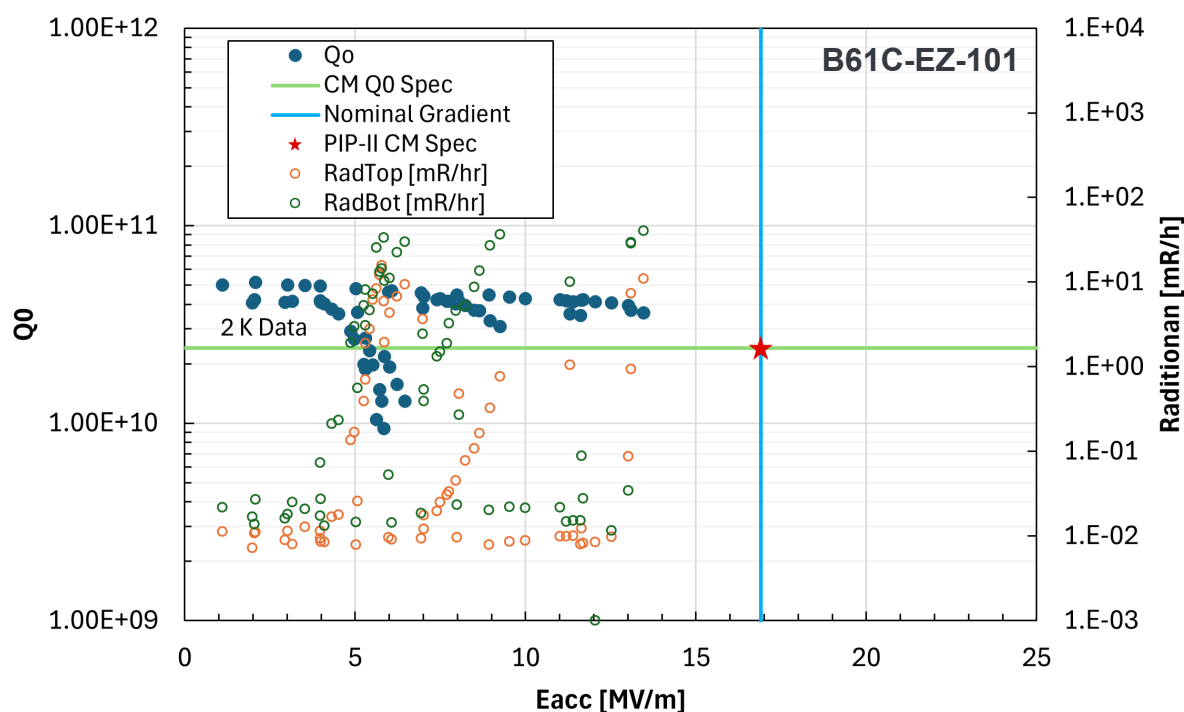
G. Wu et al., SRF2023, MOPMB030



- Q value improved by ~35% after mid-T bake was applied.
- The cavities with no or low radiation were accepted for the jacketing process.



Field Emission Mitigation

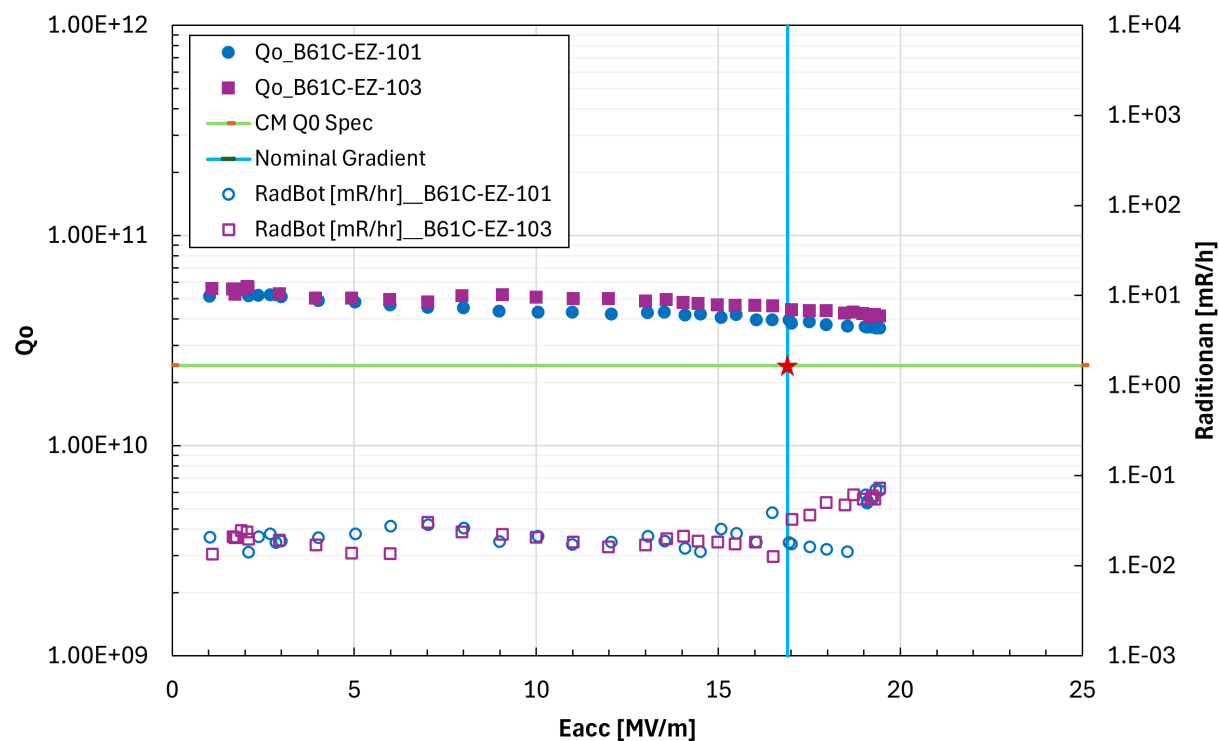


- Two cavities showed consistent field emission despite being processed with HF rinse and re-HPR cycles.
- The tests were aborted before the admin-limit due to field emission turn-on events.
- The cavity Q also degraded following the field-emission turn-on events.

Field Emission Mitigation

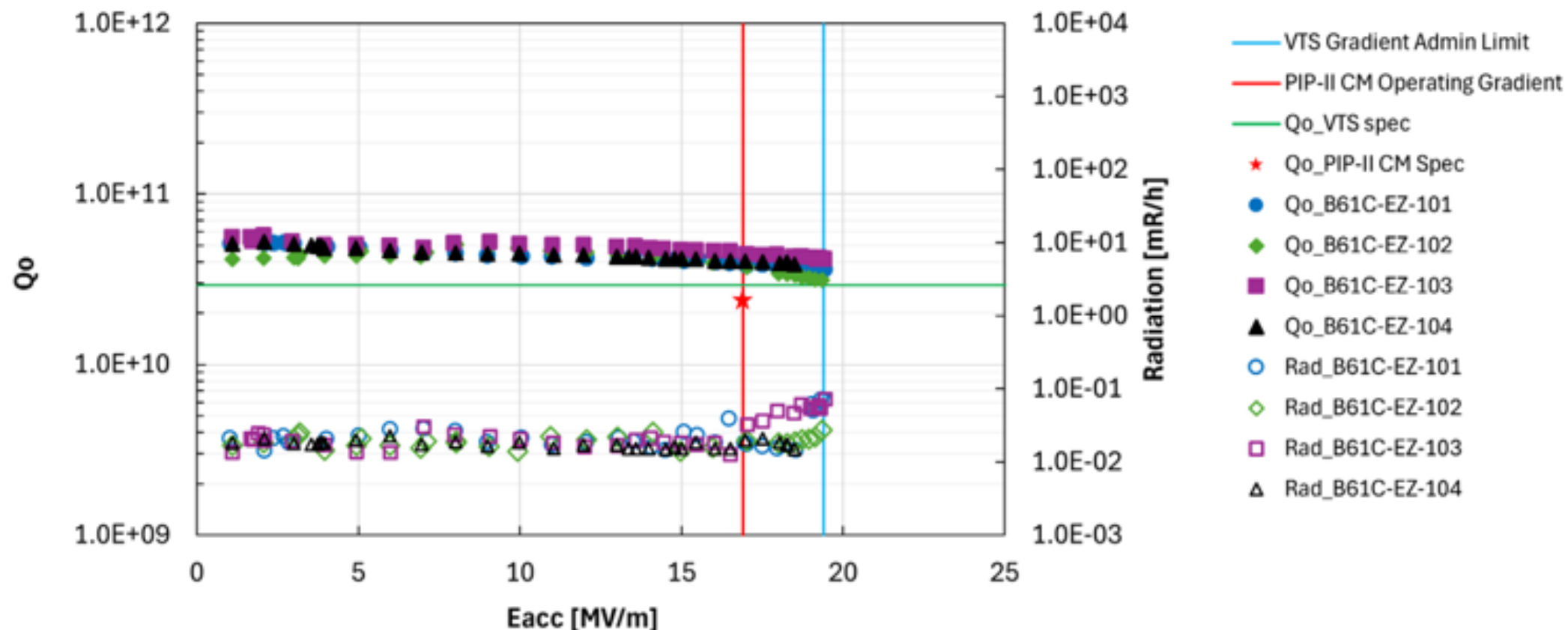
To recover Q value and mitigate the field emission in the mid-T baked jacketed cavities, the following steps were applied:

- 1 μm flash cold EP
- Robotic-assisted assembly



SRF Robotic Assembly Development at Fermilab, C. Narug, WG-4

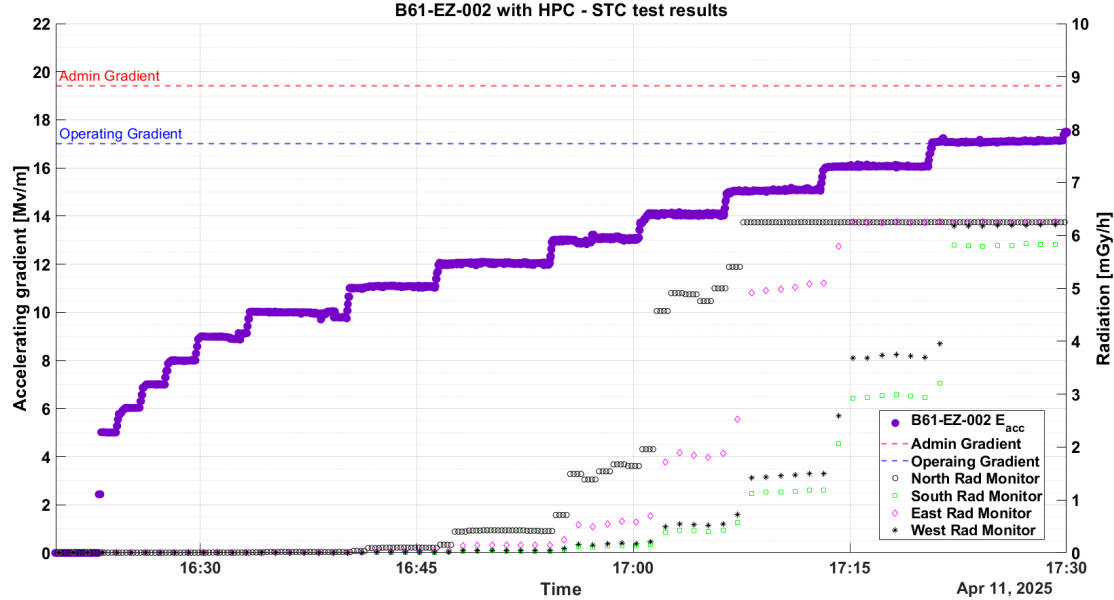
Mid-T Results for pp - Jacketed Cavities



- The cavities were qualified and sent to CEA, where high power couplers were installed to prepare them for horizontal testing and for cryomodule string assembly.



STC Test Results after HPC Assembly



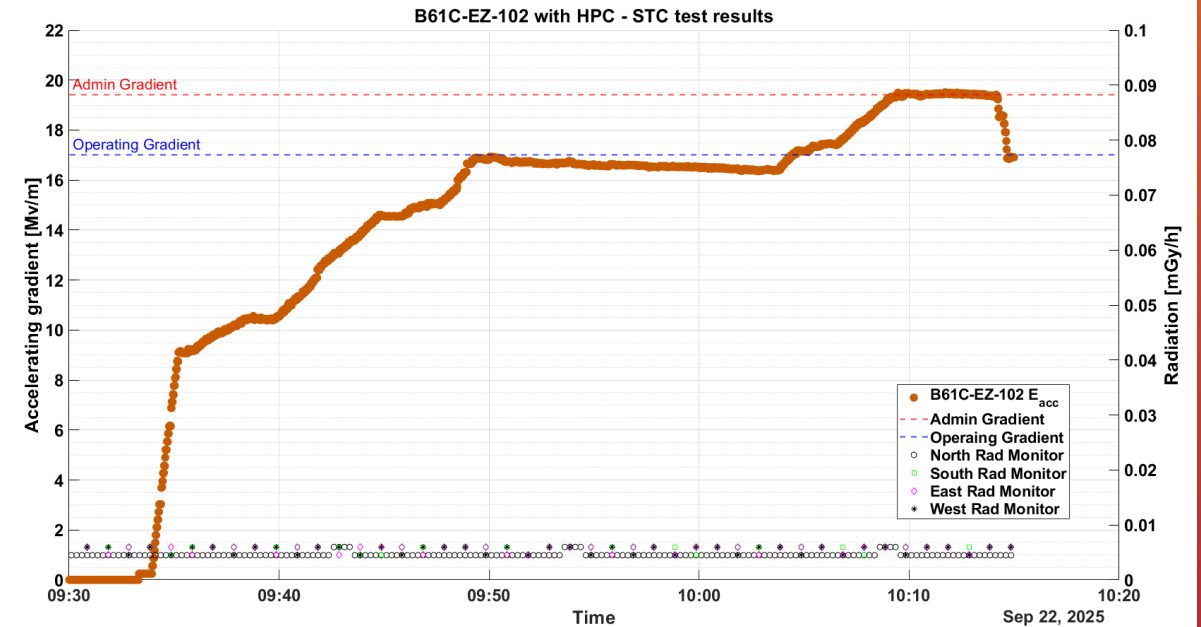
- Tested in the horizontal cryostat at FNAL after high power coupler assembly at CEA - Saclay:
 - B61-EZ-002 received coupler with manual tooling.
 - B61-EZ-102 received coupler with cobot.



HPC installed with mechanical tool



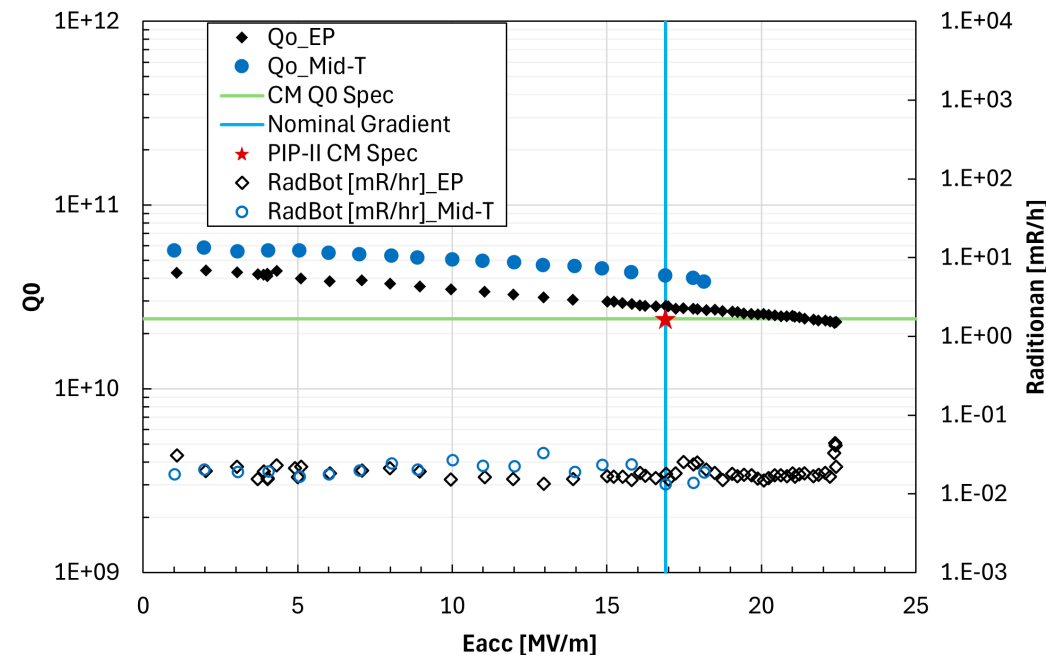
HPC installed with robotic tool





- Series LB650 cavities are going to be mid-T baked in the industry.
- The effectiveness is assessed through a comparison of RF performance before and after mid-T baking, using both historical data from Fermilab prototype cavities and project-specific minimum requirements.
- This evaluation framework is used to determine whether the mid-T bake process as carried out in the industry is considered qualified and ready for application to the PIP-II production LB650 cavities.

Configuration	Required baseline Q_0 @ 16.9 MV/m	Required mid-T Q_0 @ 16.9 MV/m	Measured baseline Q_0 @ 16.9 MV/m	Measured mid-T Q_0 @ 16.9 MV/m
Single-Cell Cavity	2.32E+10	3.19E+10	3.29E+10	3.97E+10
5-cell Cavity	2.11E+10	2.90E+10	2.81E+10	4.15E+10



Conclusion



- Mid-T baking validated as a Q_0 booster: ~35% improvement, all cavities exceed spec
- Field emission successfully mitigated: flash cold EP + robotic assembly solved the problem
- All 4 pre-production cavities qualified for LB650 pp-CM string assembly at CEA
- Mid-T process qualified for industry: both single-cell and 5-cell cavities passed
- Path forward: series cavities 401 & 402 next, industry production to follow

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