Fermilab

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PIP-II Cavities Qualification Challenges

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U.S. DEPARTMENT of ENERGY

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SSRs: The SSR2 Cleaning Challenge

- SSR2 cavities present a unique geometric challenge for SRF surface processing:
  - **Complex Geometry**: Re-entrant surfaces trap contaminants during fabrication.
  - **RF Volume Access**: Conventional HPR struggles to reach all internal zones.
  - **Processing History**: Years of multi-institutional effort to refine the "Recipe" for FE-free surfaces.

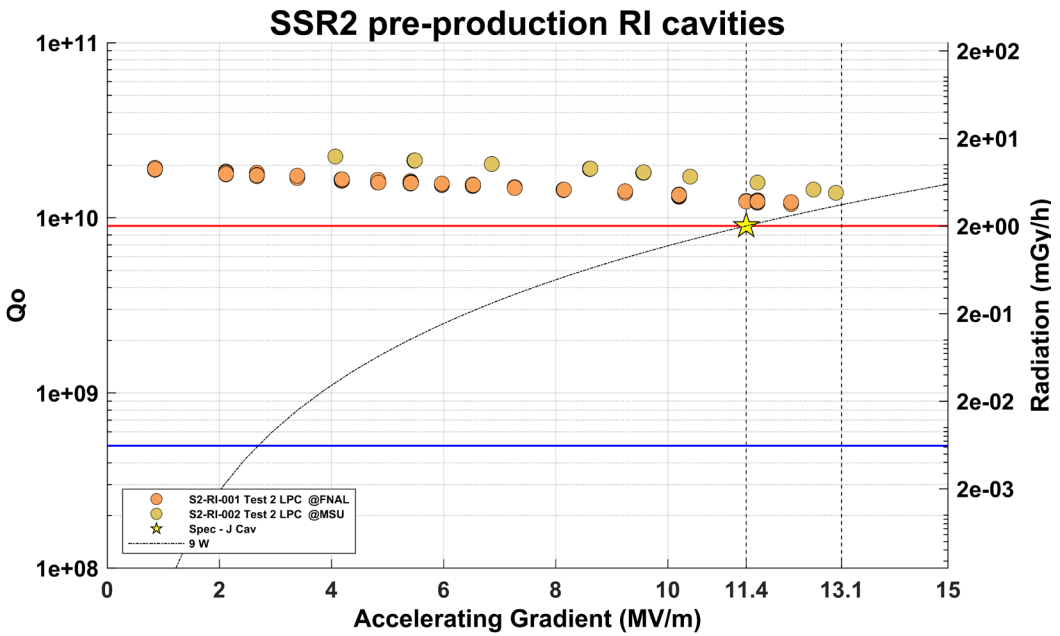
- At last TTC (April 2025) we had 2 FE free cavities out of the 5 required for string assembly achieving the required Q0 and Accelerating Gradient that were the result of years-long effort leading to a final "processing recipe".
- Since then we succesfully qualified the remaining 3 cavities and we went on qualifying 2 additional spare cavities that are going to be integrated in future cryomodules.

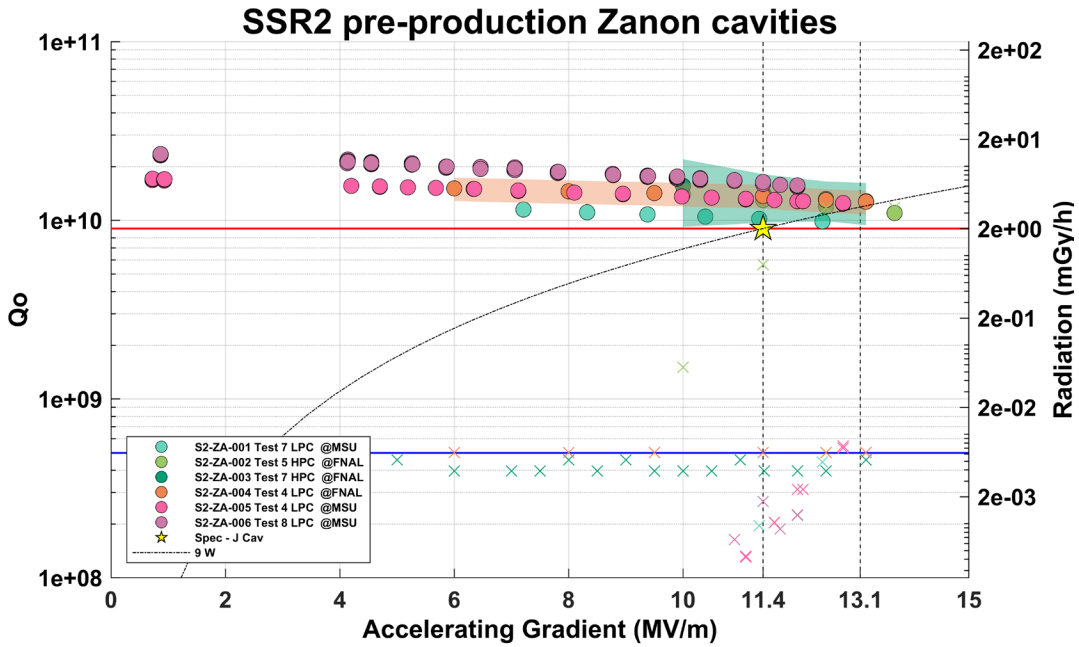
Pre-production SSR2 Cavity and Magnet String Completed using 5 FE Free Cavities

SSRs: The SSR2 Cleaning Challenge

The "new" updated recipe:

- Robotic HPR @MSU
- Manual cleanroom assembly + slow pump down and leak check
- ~~120C Bake to mitigate multipacting~~
- Slow Venting + high flow purging through the DN40 RAV equipped with a filter
- Assembly of HPC performed with the UR16 cobot @FNAL
- No blowing of the holes while removing the bolts on the unity coupler
- Slow Pump down
- No active pumping during cold testing





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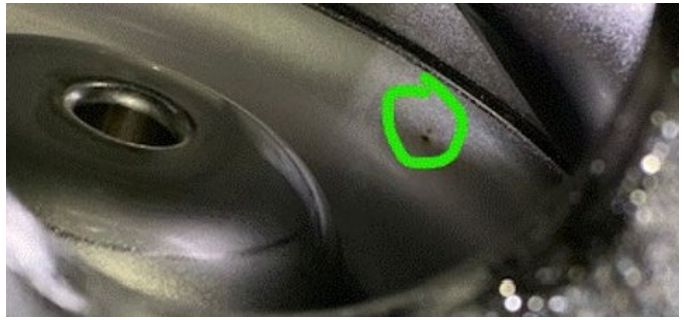
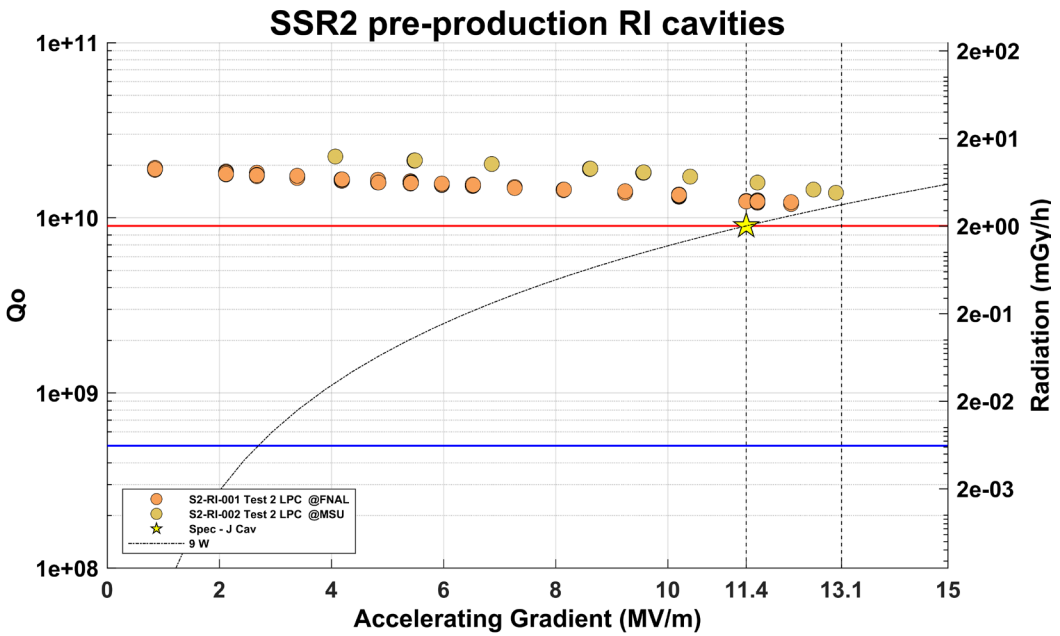
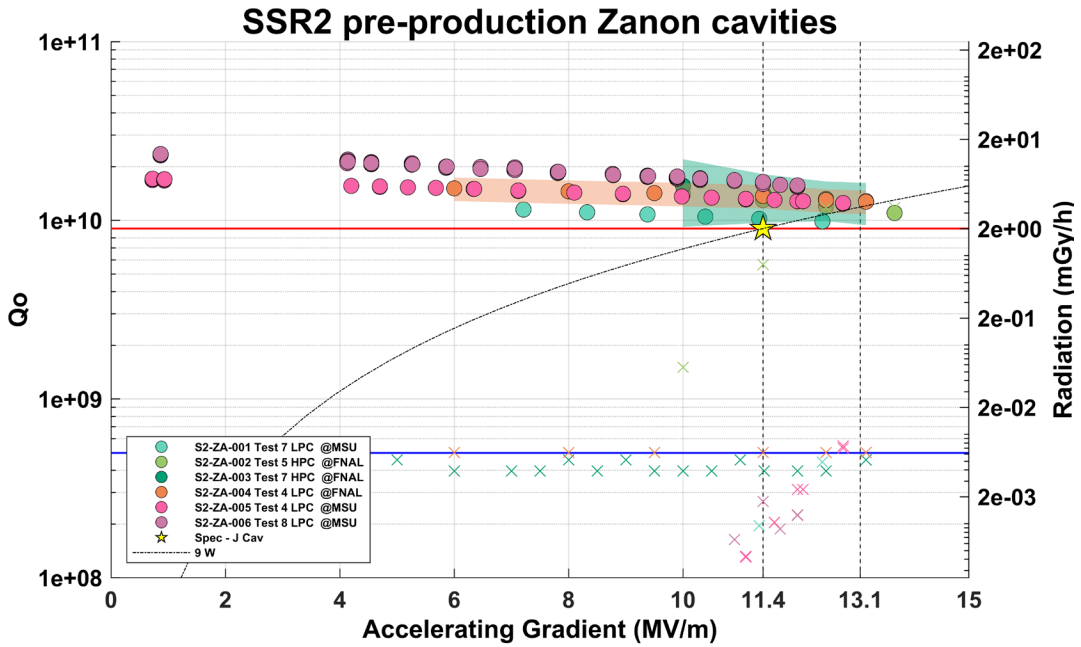
Most of the cavities had oxidation marks due to HPR process. Ultimately. we can say that this is not cause for FE





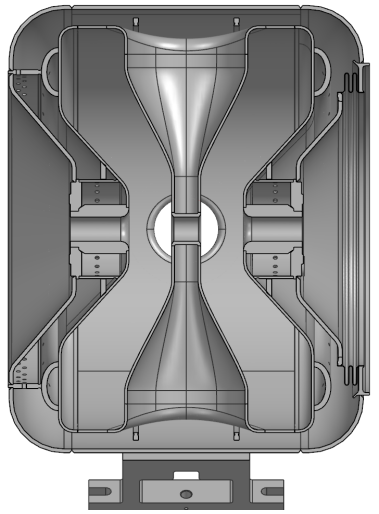


SSRs: SSR1 Cavities

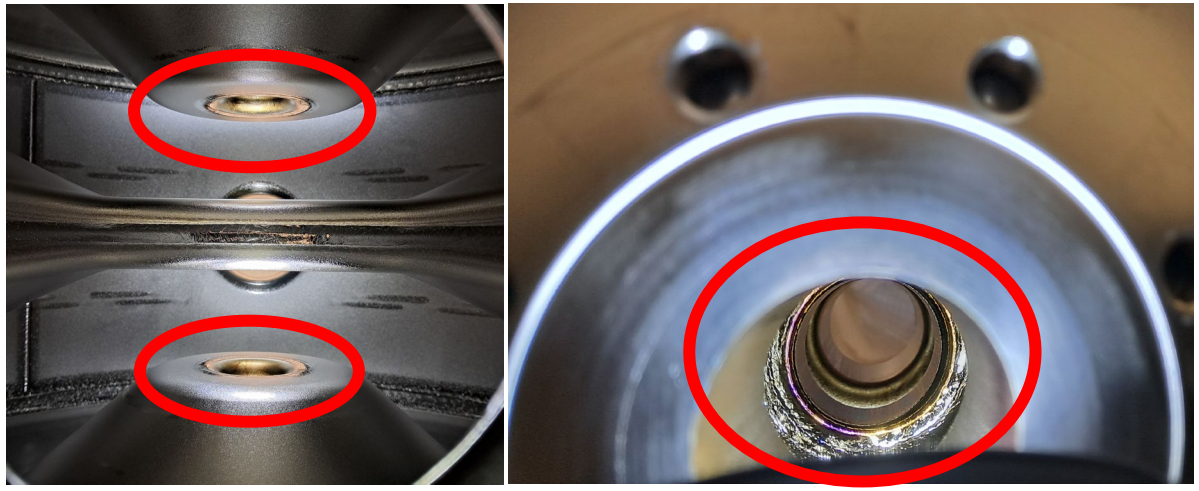
The "starting" recipe – start early to mitigate FE :

Bare cavity received final HPR after bulk BCP, Heat Treatment and light BCP

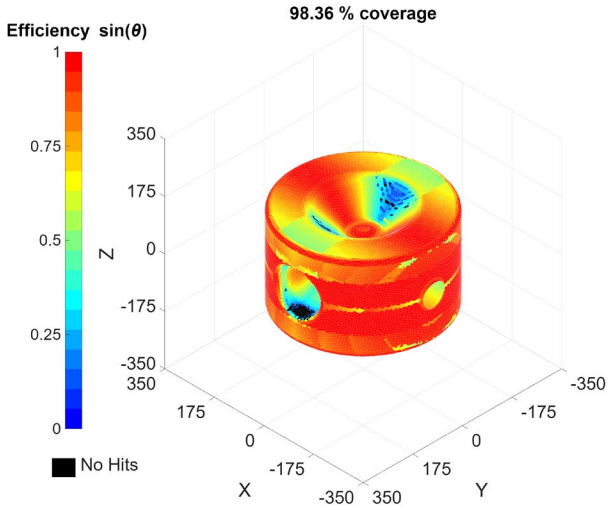
- Long – conventional HPR @Zanon using IJCLab developed nozzle head
- Manual cleanroom assembly + slow pump down and leak check
- 120 Bake – 24 hours
- Sent to FNAL for cold testing



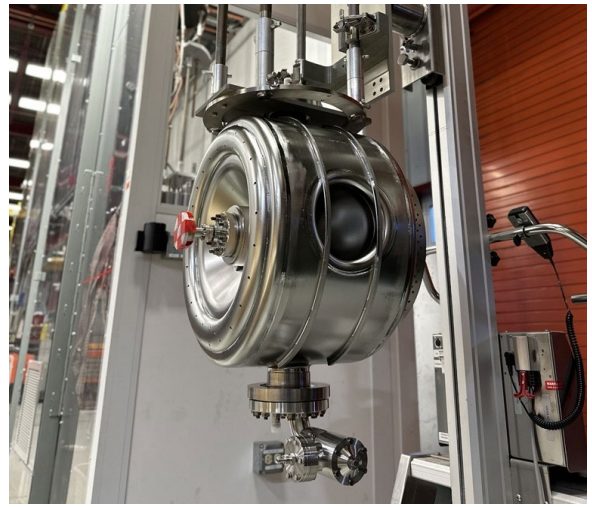
SSR1 Cavity Section: compared to SSR2, conventional HPR should be capable of effectively rinsing the cavity RF surface



Yellow-ish – Purplish color is visible near the beam and spoke pipes is a sign of oxidation due to the HPR process and was visible post HPR --> Nitric acid rinsing was initially employed to get rid of it



HPR Coverage and Efficiency is promising from simulation

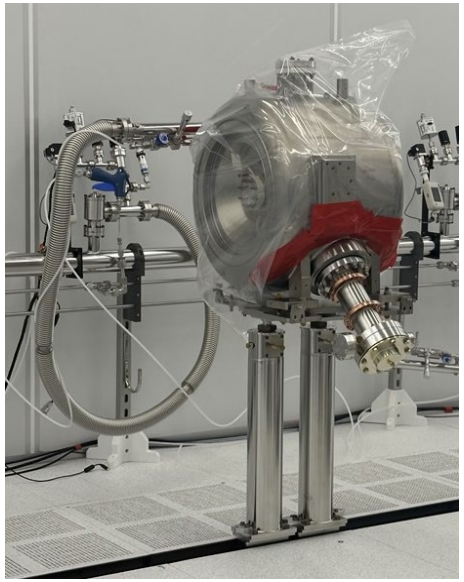


Bare SSR1 S1-ZA-001 at Fermilab to VTS testing. Test failed due to cold leak.

SSRs: SSR1 Cavities

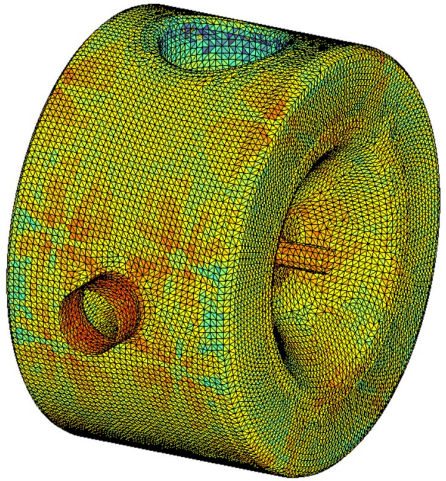
The "final" updated recipe:

- Robotic HPR @MSU
- Manual cleanroom assembly + slow pump down and leak check
- 120 C Bake for 24 hours
- Slow Venting + high flow purging through the RAV equipped with a filter
- Assembly of HPC performed with the UR16 cobot @FNAL
- Blowing of the holes while removing the bolts on the unity coupler
- Slow Pump down
- No active pumping during cold testing



S1-ZA-001 with vacuum side HPC @FNAL after cobotic assembly

Robotic HPR - courtesy of Kyle Elliott, MSU



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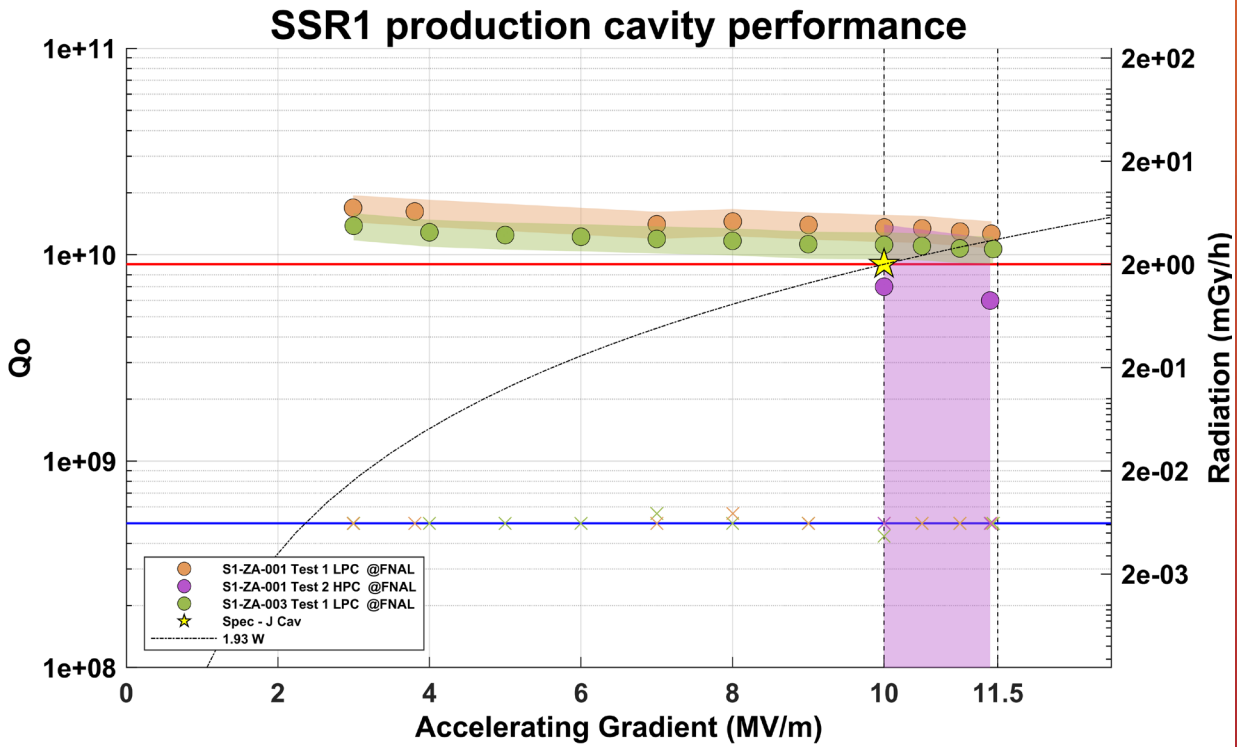
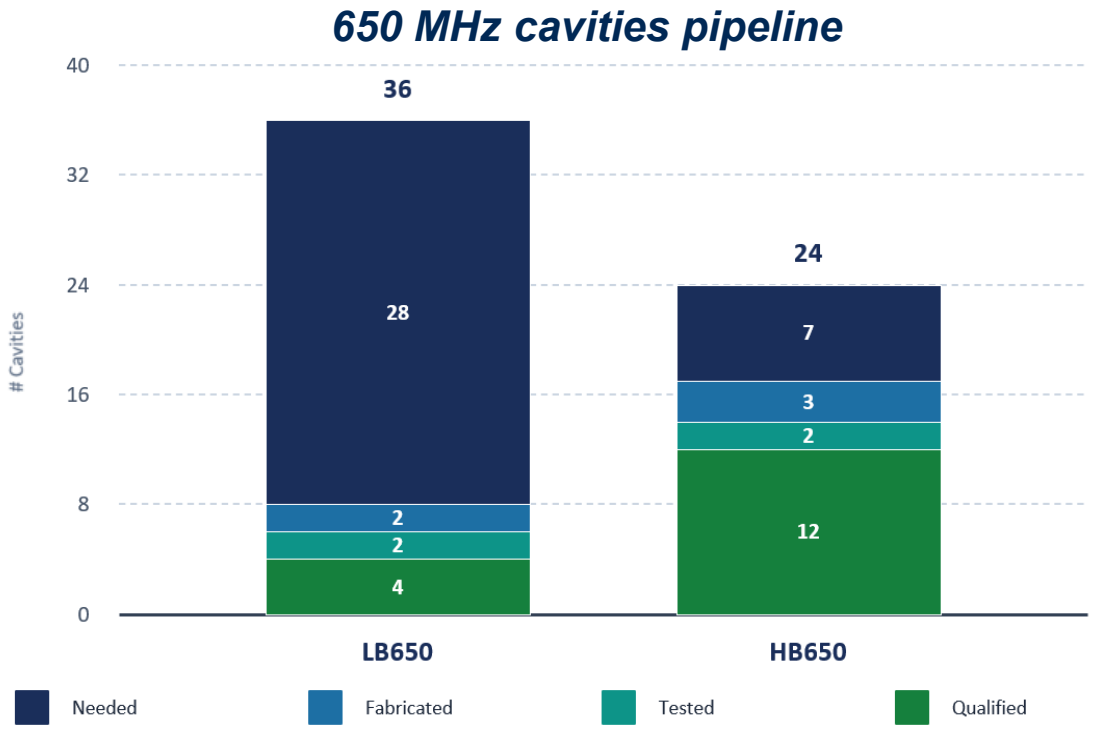
Virtual 100% coverage provides the best possible rinse – courtesy of Blake Gower, MSU



650 MHz Cavities qualification challenges

- Rough equator surface and premature quenching of the cavities.
- Surface defects caused by:
  - Internal bulk defects
  - Defects due to welds
- RF volume contamination leading to field emission.



As a contingency, a total of 48 LB650 and 32 HB650 cavities are being procured for PIP-II

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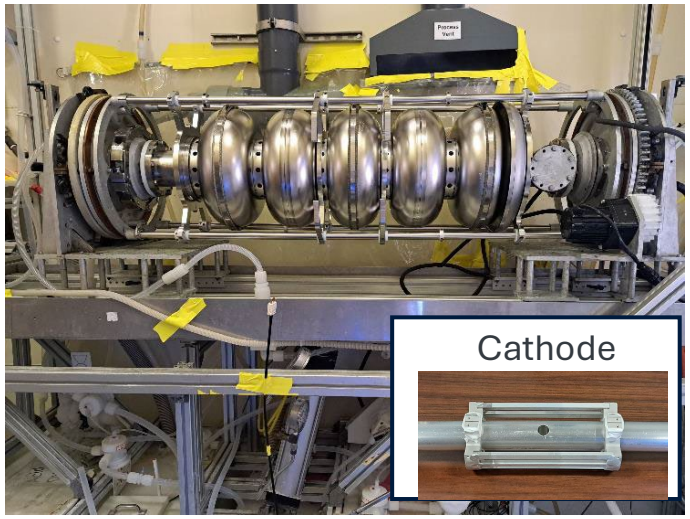
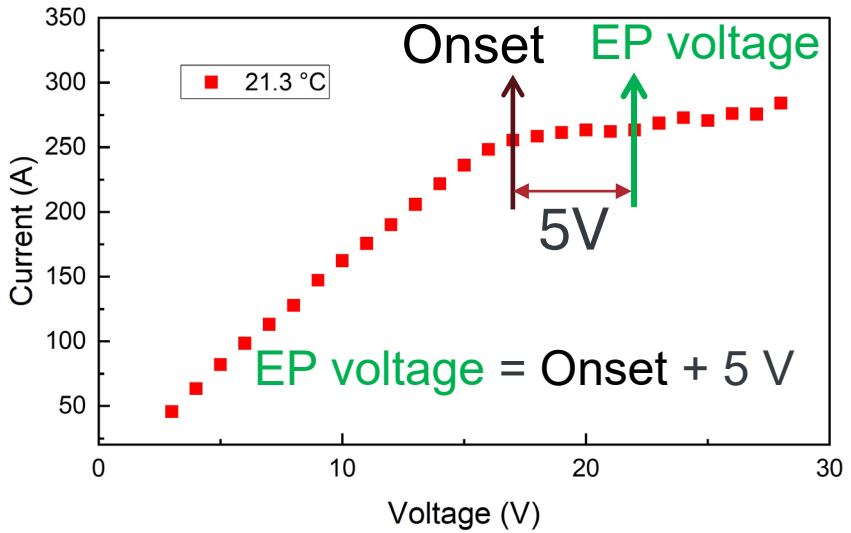
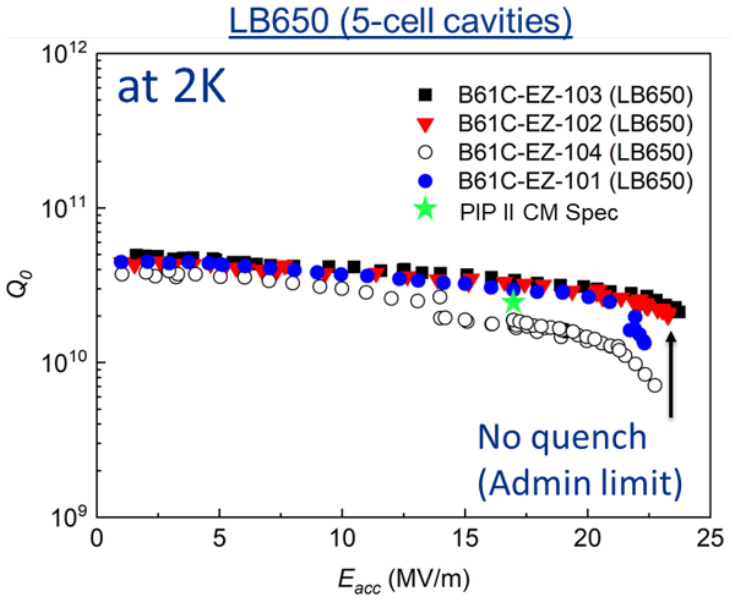
650 MHz: Rough Equator Surface





Parameters	Initial EP	Modified EP	
	Warm/cold EP	*Warm EP*	*Cold EP*
Voltage	18 V	20-25 V	16-22 V
Cavity temperature	22 °C/12 °C	22-25 °C	12 °C
Cathode type	Cathode-I (initial)	Modified cathode with large surface area	

V. Chouhan et al., Nucl. Instrum. Methods Phys. Res. A 1051 (2023) 168234
V. Chouhan et al., **TUPTB041, TUPTB042** SRF2023.

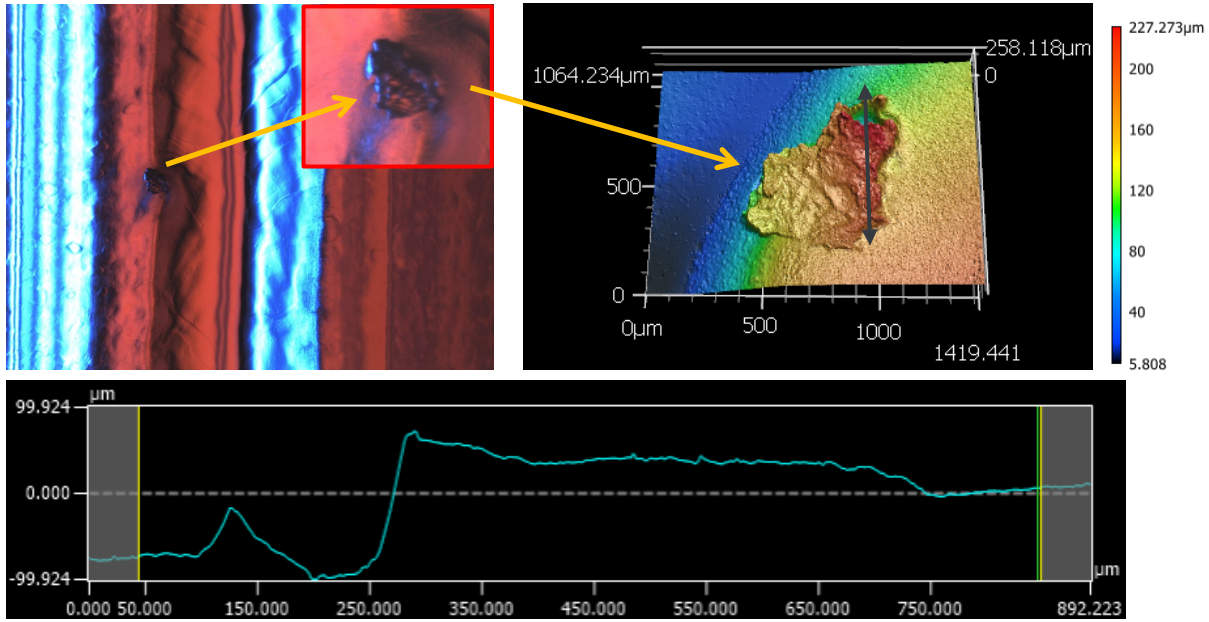


- Optimized EP resolved issues of rough equator surface and premature quenching of the cavities.
- Both LB650 and HB650 cavities met gradient specifications.
- R&D cavity with the optimized cathode and EP conditions showed >50 MV/m (V. Chouhan et al, THPB028, LINAC2024).
- Baseline EP, N-doping, and post N-doping EP protocols were transferred with partner labs and vendor.

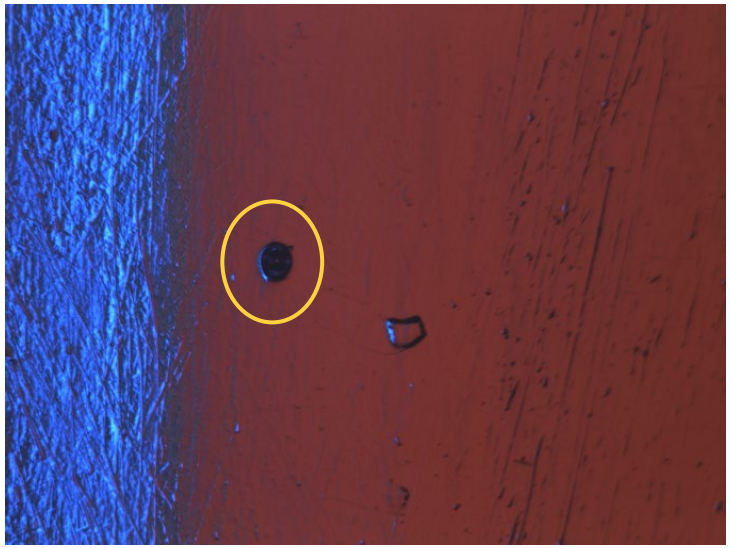
650 MHz: Surface Defects

- One of the four LB650 pre-series cavities was found to have a geometrical defect on its equator surface. The cavity after EP quenched at 20 MV/m. Manual grinding followed by EP was applied.
- Several HB650 cavities were also found with surface defects and were treated with local manual grinding and 60 µm EP reset.

LB650: B61C-EZ-101



HB650: B92D-RRCAT-502



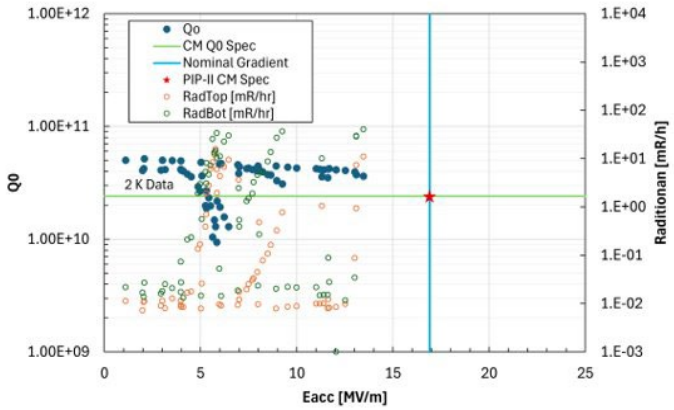
V. Chouhan et al., **TUPTB041,** SRF2023.

650 MHz: Field emission

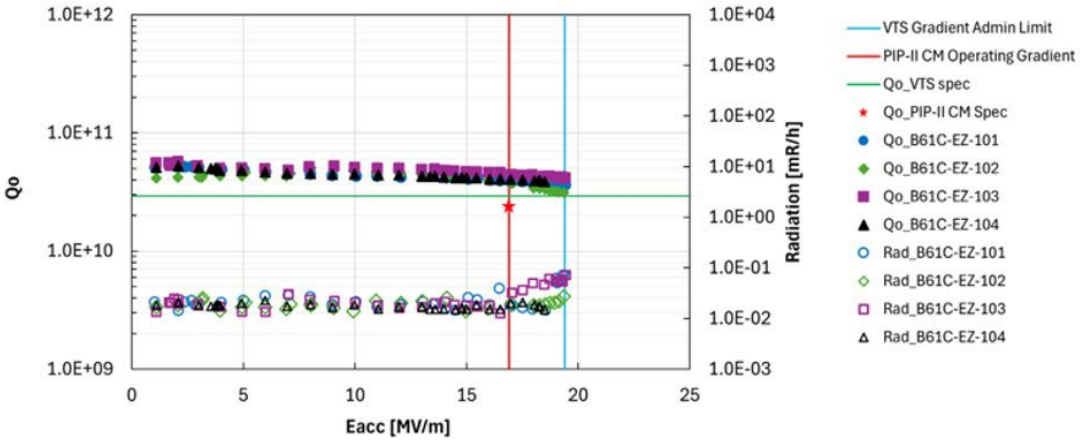
- Two LB650 cavities (B61C-EZ-101 and B61C-EZ-103) after jacketing were showing strong field emission. HPR could not clean the cavities.
- Both jacketed cavities were electropolished for an average removal of 1 µm.
- Additionally, the cobot arm was used to mount the bottom beamline flange.

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

B61C-EZ-101 with FE



Qualified Pre-series LB650 cavities



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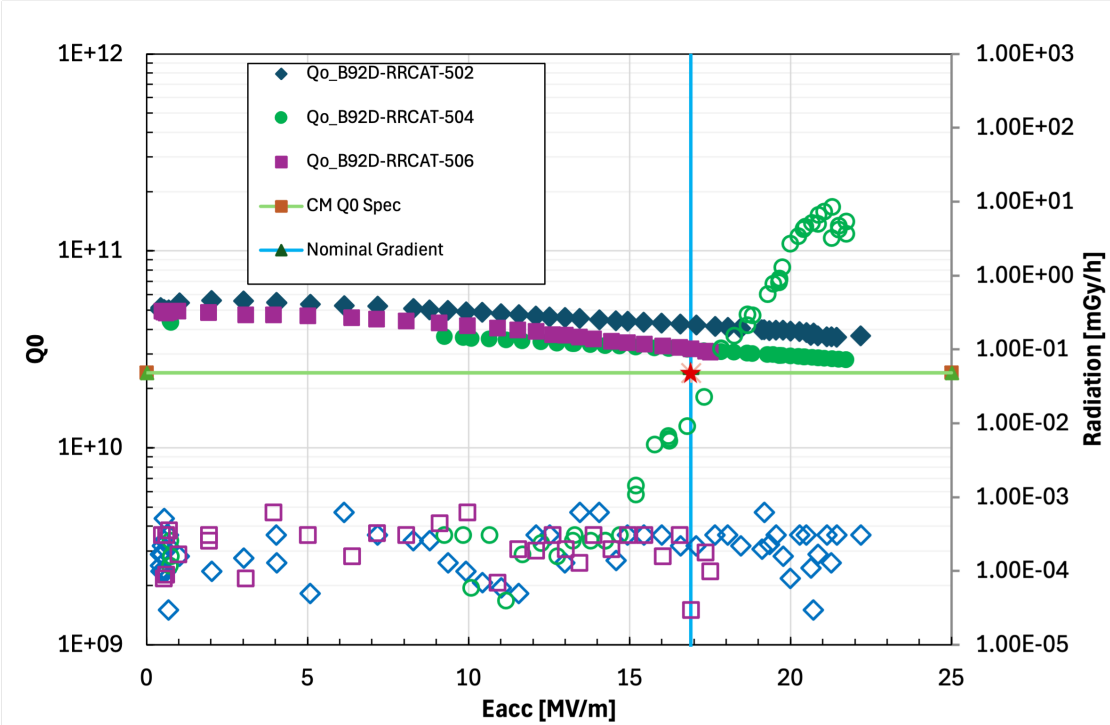
650 MHz: prototype B92 Cavities

- Cavities removed from the prototype cryomodule were processed with HPR and tested at UKRI.
- Three pre-series cavities, B92F-RI-201, B92F-RI-202, and B92F-RI-203, were also re-HPRed at UKRI for FE mitigation and tested.
- 12 HB650 cavities are qualified. B92D-RRCAT-506 quenched at a lower field of 17.5 MV/m.

Serial Number	Status
B92M-ZRI-301, B92M-ZRI-302, B92M-ZRI-303, B92M-ZRI-305, B92M-ZRI-306, B92M-ZRI-307, B92M-ZRI-308, B92M-ZRI-310	Qualified
B92D-RRCAT-502	Qualified
B92D-RRCAT-504	Qualified (0.01 mGy/h at 18.8 MV/m)
B92D-RRCAT-506	FE-free, limited at 17.5 MV/m
B92F-RI-201	Qualified
B92F-RI-202	Vertical test pending
B92F-RI-203	Qualified



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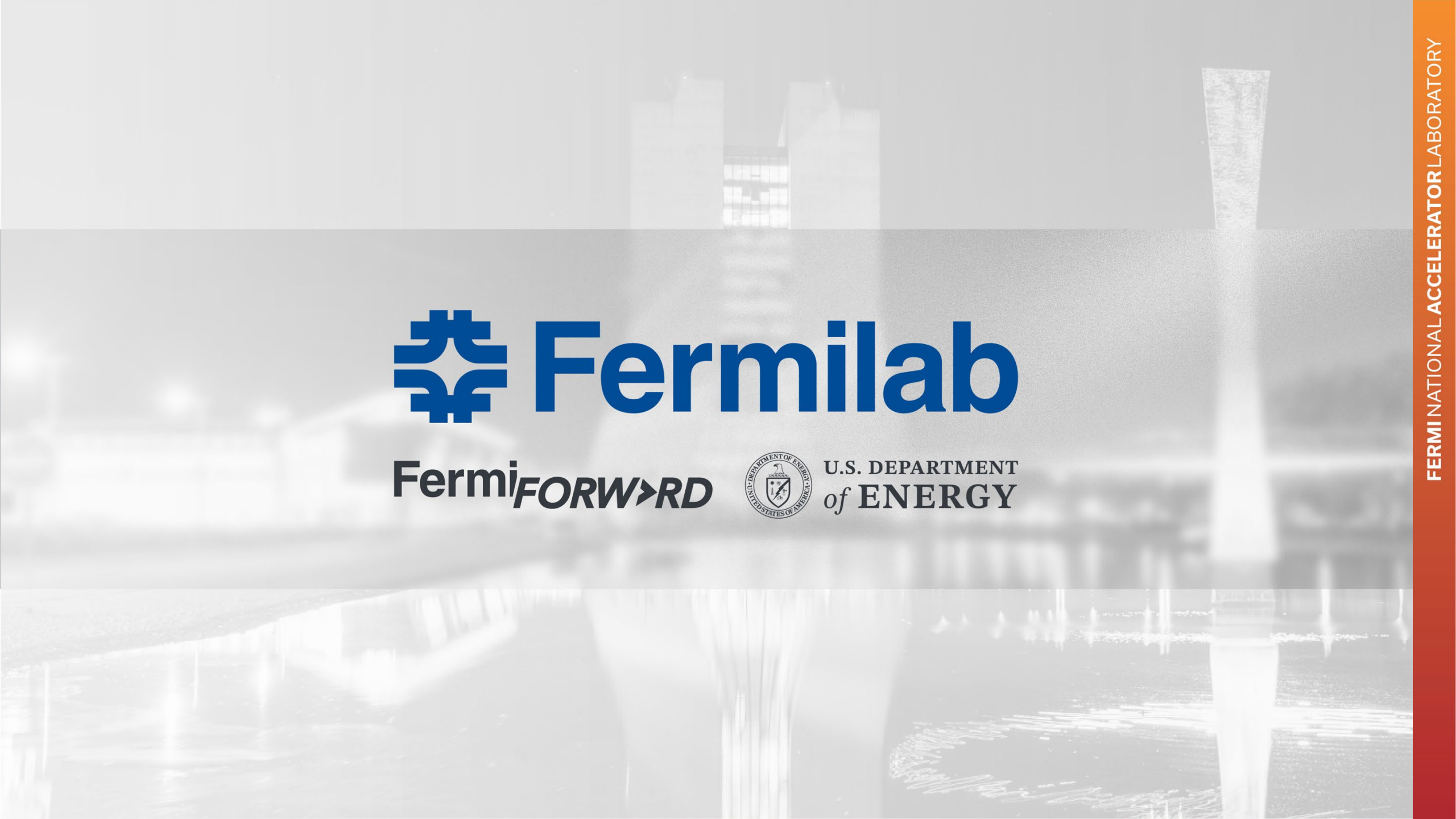
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