SLIDES-25-0071-TD

This manuscript has been authored by FermiForward Discovery Group, LLC under Contract No. 89243024CSC000002 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Mitigating field emission in SSR2 cryomodules for PIP-II

Mattia Parise

TTC 2025

April 9th, 2025

PIP-II is a partnership of:

- US-DOE
- India-DAE
- Italy-INFN
- UK-STFC-UKRI
- France-CEA, CNRS/IN2P3
- Poland-WUST, WUT, TUL

Outline

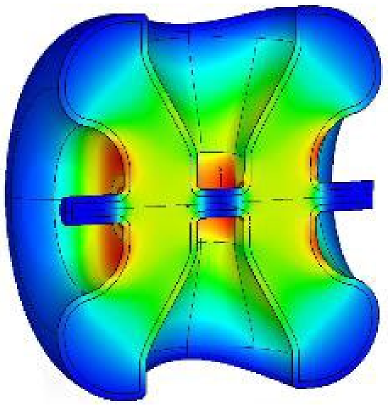
- Introduction
- Towards a FE free cavity
- Initial recipe for a FE free cavity
- The updated recipe
- Conclusions and path forward

I want to acknowledge IJCLab and MSU and the Fermilab team for the invaluable support and contribution

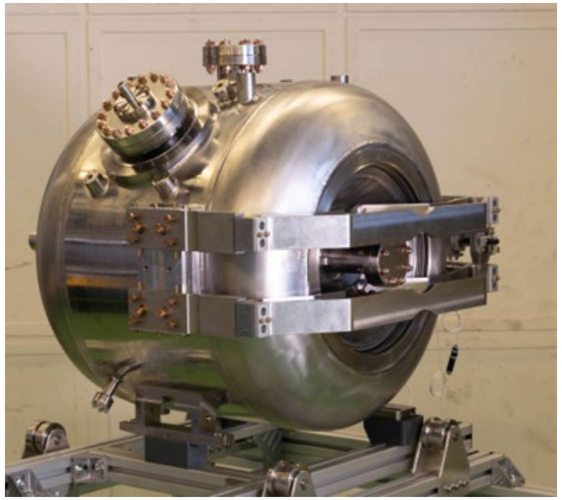
Introduction

- A total of **8 pre-production SSR2 jacketed cavities** are fabricated to date
- 7 went through cold testing, initially all of them were affected by field emission at different intensities and onsets
- The initial plan envisioned the processing entirely conducted at the vendors (apart from 1 cavity selected for processing by a partner lab - IJCLab)
- Extensive studies were conducted on the FE causes and mitigation strategies

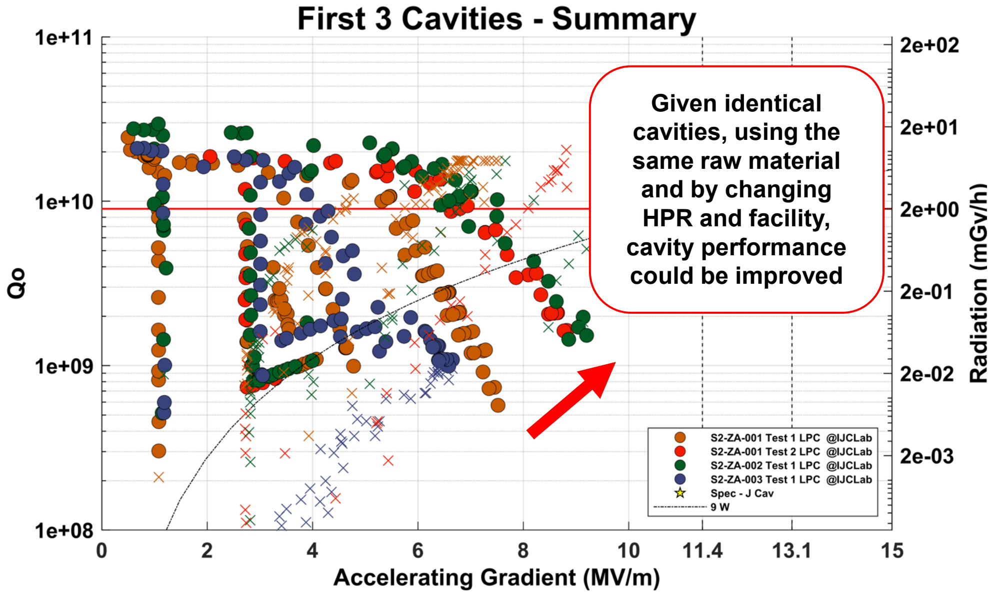
SSR2	
β	0.47
Frequency	325 MHz
Processing	Rotational BCP
LINAC quantity	35 (5xCM)
Pre-production quantity	9 (6+3) by 2 vendors



E field distribution of the fundamental accelerating mode



S2-ZA-001: first jacketed cavity entirely fabricated and processed in industry equipped with the tuner @IJCLab



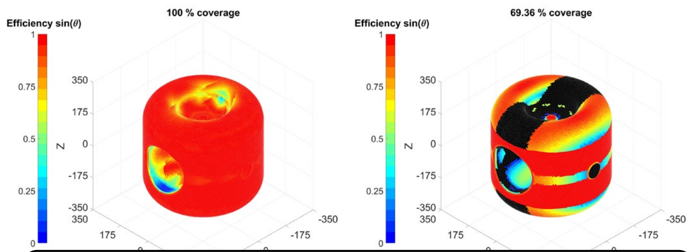
Initial cold test results on the first 3 jacketed cavities shows FE onset. Q0 degradation due to additional dissipation limits the achievable gradient

Towards a FE free cavity

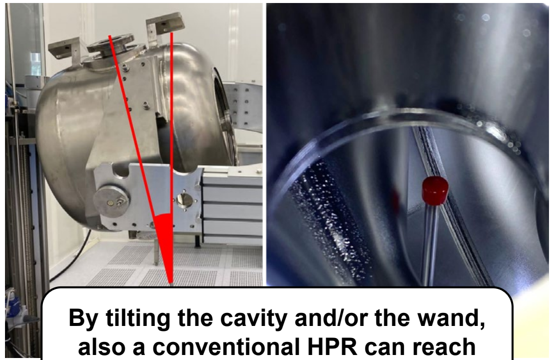
† M.Parise et al., High pressure rinse simulations for PIP-II SRF cavities, LINAC 2024

† B.Gower et al., Simulation of High Pressure Rinse in Superconducting Radio Frequency Cavities, SRF2023

- **Nozzle optimization** for enhanced **HPR coverage** and improved efficacy: by properly selecting the directions, number and fan angle(s) of the water jets is possible to achieve ~100% coverage with **good rinsing** of the **high electric field areas**.
- **Tilted HPR**: by manually adjusting the relative position between the cavity and the HPR wand is possible have a **better rinse** of those **hard-to-reach areas**.
- **Robotic HPR**: the ultimate tool in terms of flexibility and efficacy. It allows the most efficient cavity rinsed without having to rotate the cavity to change the port orientation while the process is ongoing.
- **HPR simulation tool**†: a code capable of providing the **coverage, efficiency and local rinsing time** allowing to select the optimal nozzle and wand trajectory.
- **Optimized assembly process** and cavity support frame in the cleanroom: by supporting the cavity far from the open ports and by setting the cavity above the cleanroom operators, risk of contamination is minimized. Engineered step-by-step procedure is as important as the HPR itself.
- Always enforce the **basic principle** of a **particle-free** cleanroom procedure.



Simulation tool and nozzle optimization are the base upon which a good rinse is achieved



By tilting the cavity and/or the wand, also a conventional HPR can reach the usually hidden surfaces

Cavity tooling in the cleanroom minimize the risk of contamination

Robotic HPR Courtesy of MSU

† C. Narug et al., Successful cleanroom installation of PIP-II SSR2 coupler using robotic arm, LINAC 2024

Towards a FE free cavity

- **Cobotic High Power Coupler (HPC) assembly**†: cavities are qualified with unity coupler, requiring the installation of the vacuum end HPC after cold test. By implementing a cobotic assembly, **chances of contamination are reduced**, and the process becomes **highly repeatable**. *see talk by C. Narug
- **High purging rate**: HPC cavity port requires high purging rates to avoid the air current going into the cavity while performing the assembly.
- **No nitrogen blowing** while disassembling the unity coupler: due to the cavity geometry, by blowing the bolt holes on the cavity ports after removing the studs could potentially heavily contaminate the nearby surrounding area increasing the risk of particle contamination during the assembly phases.
- **Active pumping** during cold testing is an **additional step** that can be **removed** if the cavity is tested shortly thereafter, and it is equipped with a burst disk.

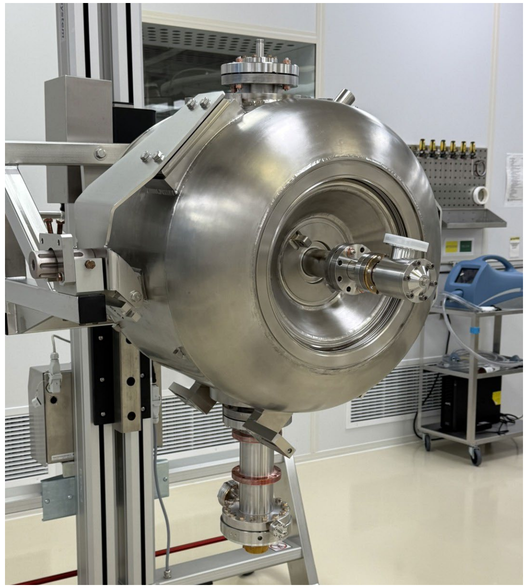
Purging of the cavity during HPC installation is performed through a filter installed on the cavity RAV

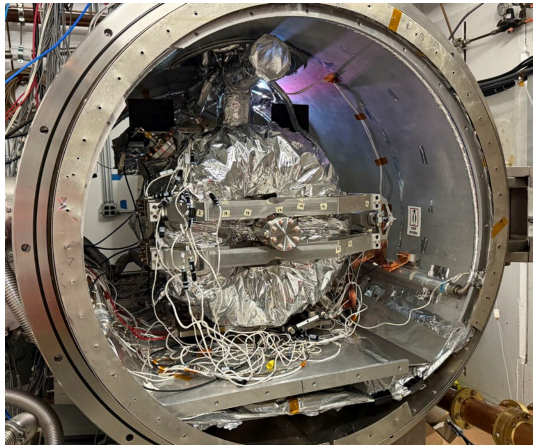
Cobotic HPC assembly allow the operator(s) to sit back while the cavity beamline volume is exposed to the cleanroom atmosphere

Avoiding active pumping is not necessary to achieve a FE free cavity but further reduce the risk of contamination when performing the cold testing

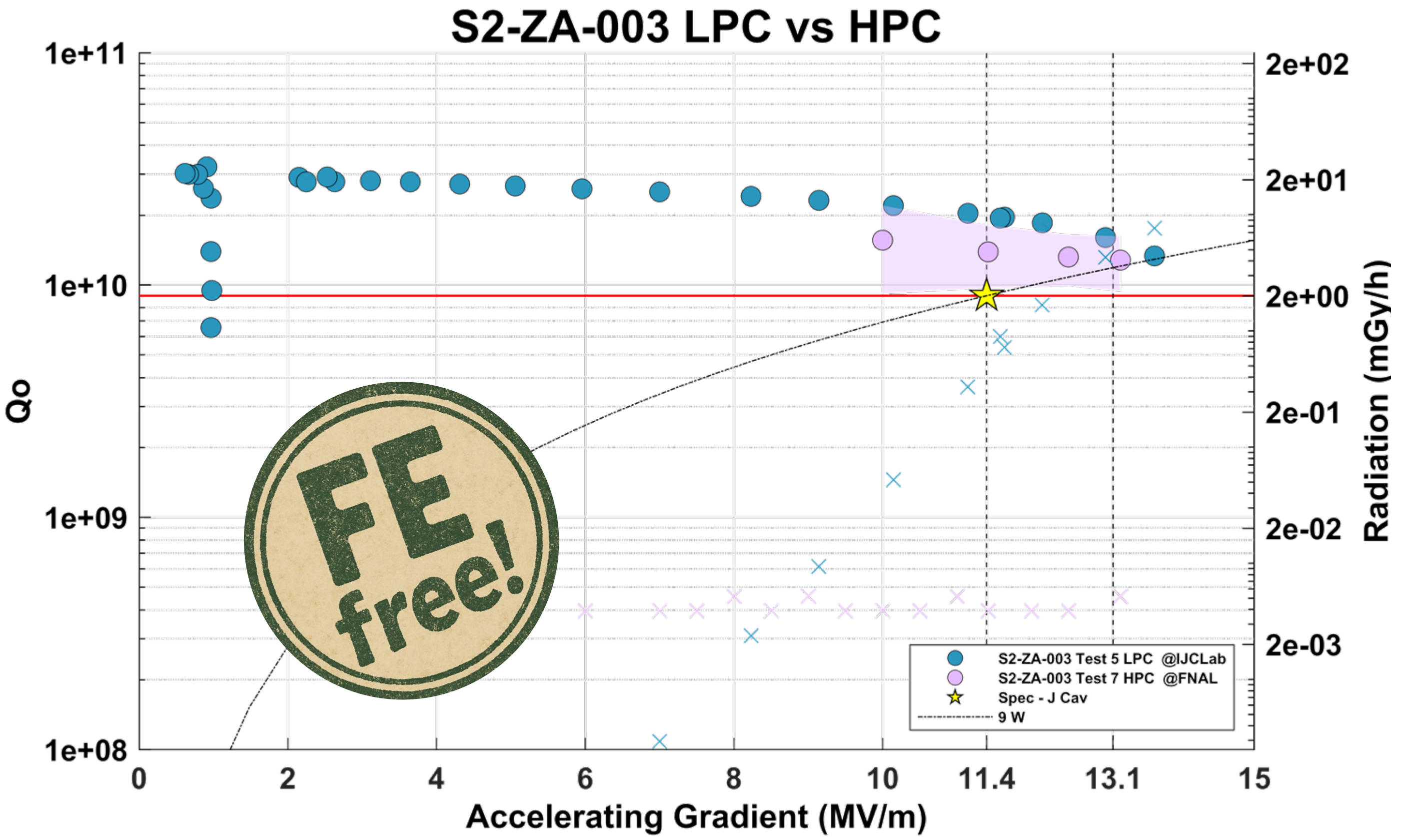
Initial recipe for a FE free cavity

- Robotic HPR @MSU
- Manual cleanroom assembly + slow pump down and leak check @MSU
- Assembly of HPC performed manually from the bottom @MSU
- Slow Pump down and leak check
- 120 C bake to mitigate multipacting
- Active pumping during cold testing @FNAL



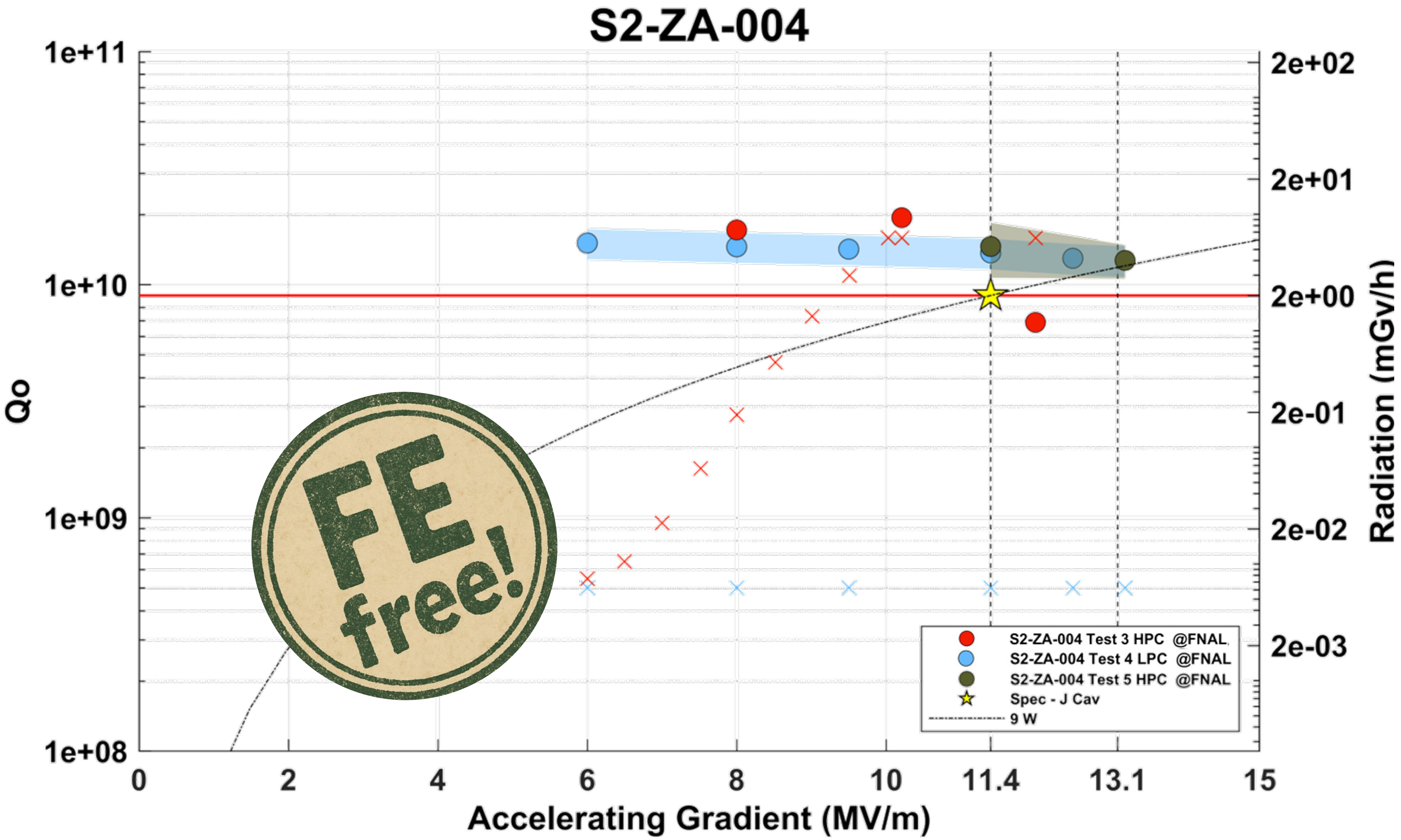


S2-ZA-003 @MSU after cleanroom assembly ready for cold testing (performed @FNAL)

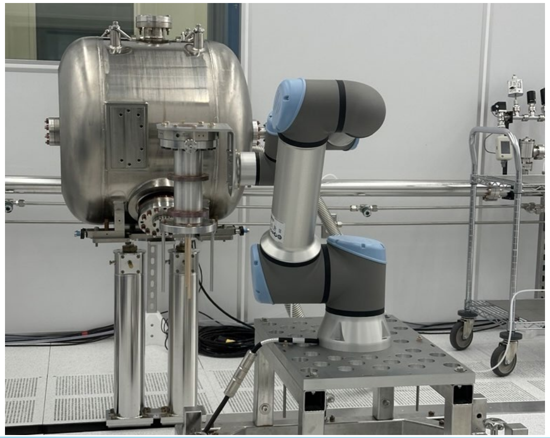


The updated recipe

- 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



S2-ZA-004 @FNAL during the HPC vacuum end assembly



Conclusions and path forward

- Spoke resonators, particularly the SSR2 cavity for PIP-II, represent a challenge when comes to effectively cleaning the RF volume after fabrication and processing.
- Years long effort, involving several institutions, key collaborators, PIP-II partners, vendors and SMEs succeeded in obtaining 2 pre-production SSR2 Field Emission free cavities that are going to be integrated in the pre-production cryomodule.
- Currently 4 out of 5 cavities satisfy the project requirement in terms of Q0, accelerating field and FE. However, 2 of them have FE onset around 9 MV/m.
- In parallel, plasma studies and application are being conducted showing promising results. *see talk by M. Parise at 5pm.

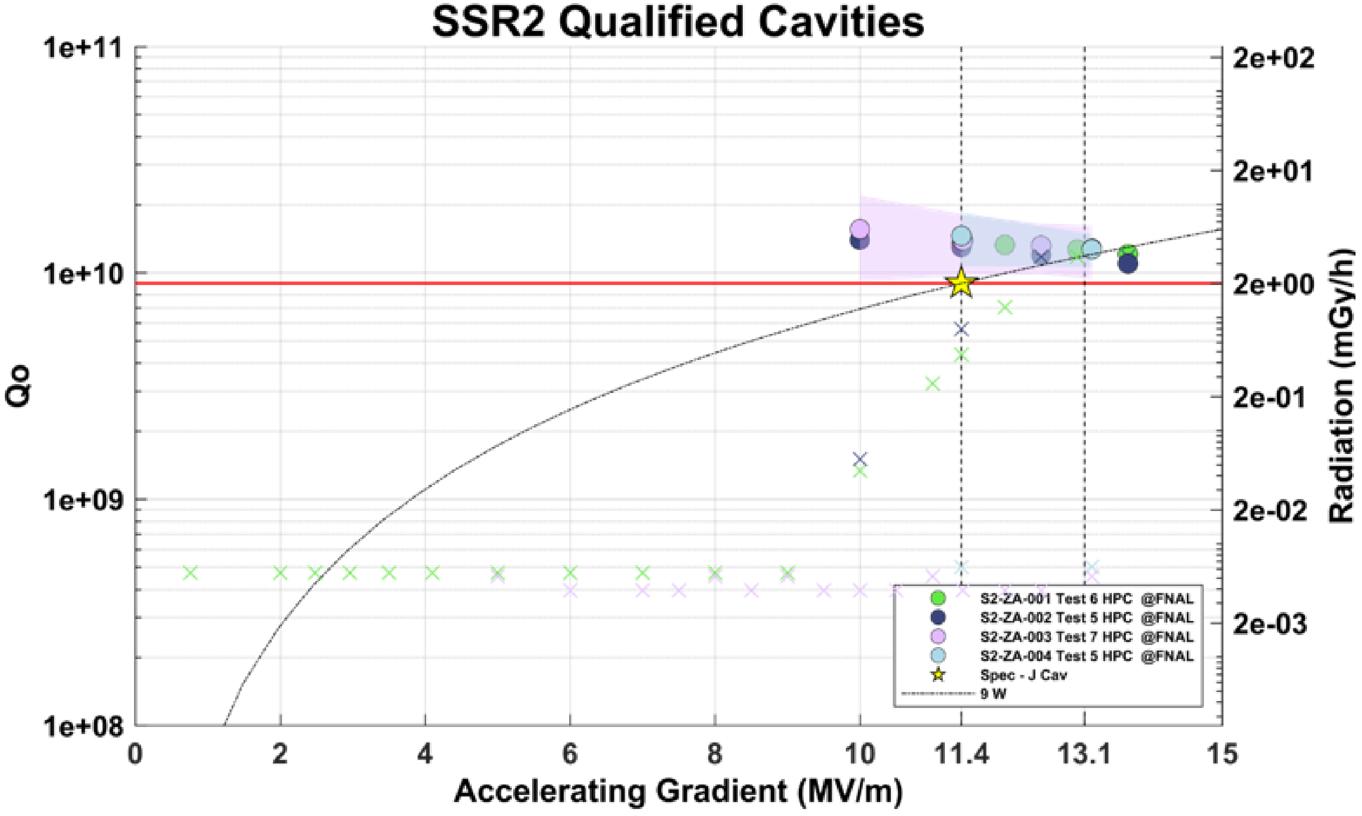


Photo credit: Tom Nicol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