SNS PPU Cavity Fabrication and Test Results

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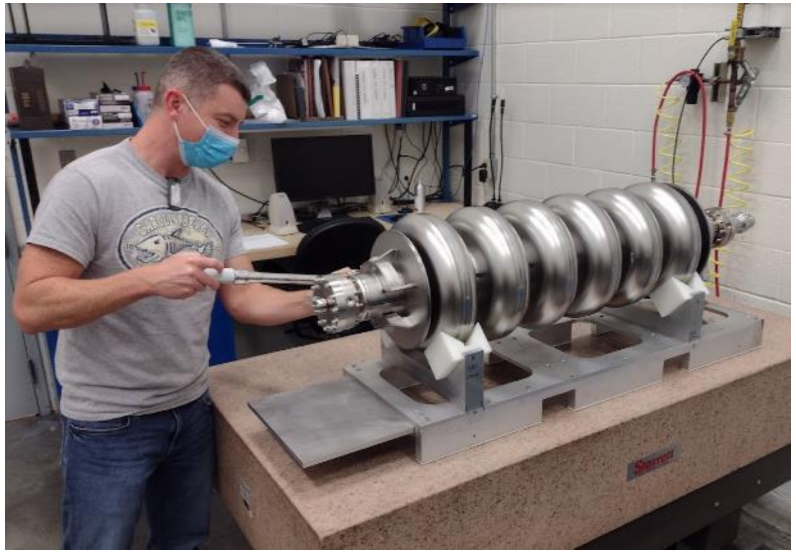
On the behalf of PPU Cavity Team

January 27, 2022

Outline

- Background
- Preparation of cavity qualification and Helium vessel welding prior to production run
- Cavity qualification steps
- RF performance
- Lessons learned and challenges
- Summary



SNS PPU Upgrade

- Upgrade will double the proton beam power from 1.4 to 2.8 MW by adding 7 additional cryomodules each contains four six cell high beta (β= 0.81) SRF cavities.

- This will be accomplished by ~50% increase in beam current, from 25 to 38 mA and an increase in the final beam energy from 1.0 to 1.3 GeV

Parameters	Original SNS high-beta cryomodule	PPU high-beta cryomodule
E_{acc} (=$E_o T_g$, T_g: Transit time factor at β=0.81) (MV/m)	15.8 $Q_0>5\times10^9$	16.0 $Q_0>8\times10^9$
Fundamental power coupler (FPC) rating, peak and average (kW)	550, 50	700, 65
External Q of FPC, Q_{ex}	7×10^5 (±20%), fixed type	8×10^5 (±20%), fixed type
Material of cavity	High RRR niobium (RRR>250) for cells, reactor-grade niobium for end groups	High RRR niobium (RRR>250) for both cells and end groups
Higher-order mode couplers per cavity	Two (one at each end group)	None

PPU Upgrade (Original Vs Upgrade)

Cavities

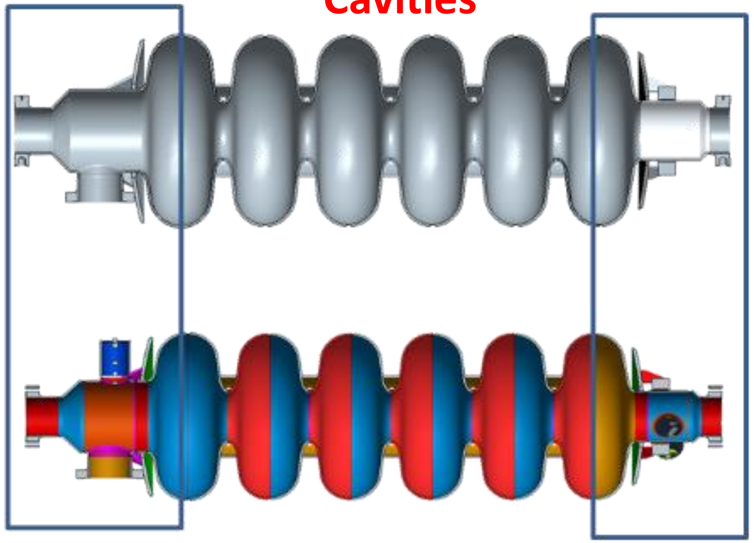


Figure 3.3. End group modification. (Top: cavity with modified end group for the PPU. Bottom: Original SNS high-beta cavity).

Vacuum vessel

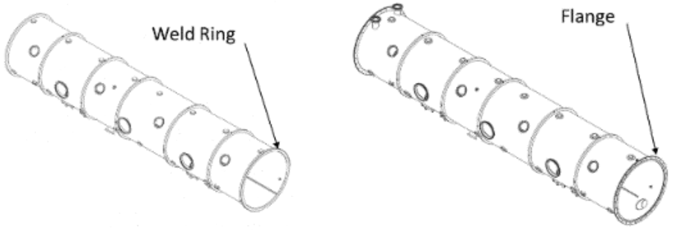


Figure 3.15. Original (left) versus new (right) vacuum vessel.

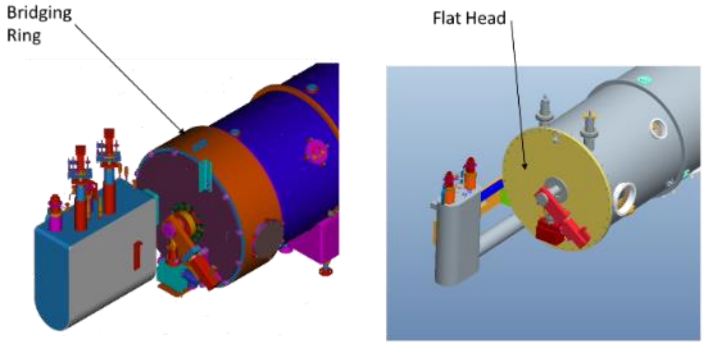


Figure 3.16. Original (left) versus new (right) vacuum jacket design.

JT valves

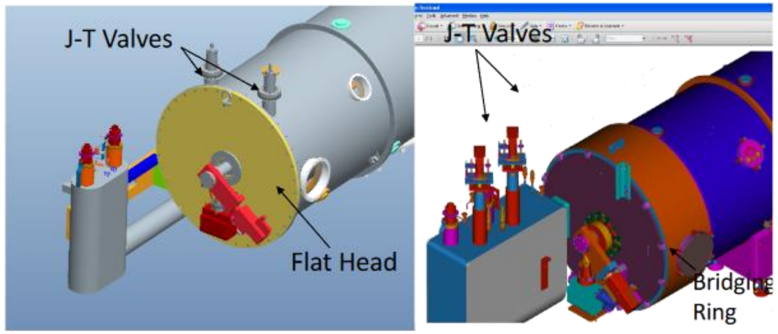
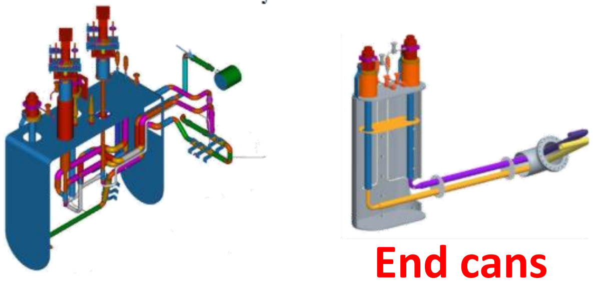


Figure 3.17. JT valve positions for the PPU cryomodule (left) and the original (right) cryomodule.



End cans

Figure 3.18. Original (left) versus new (right) supply end can.

He vessel

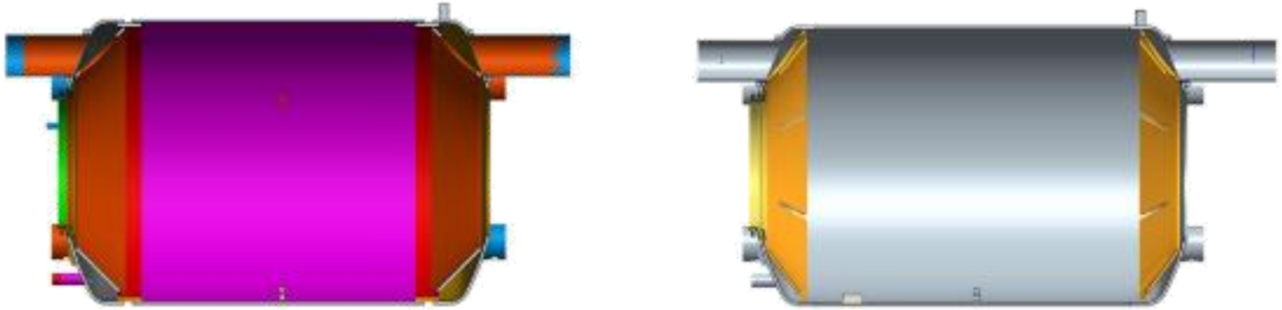


Figure 3.5. Original (left) versus new (right) helium vessel designs.

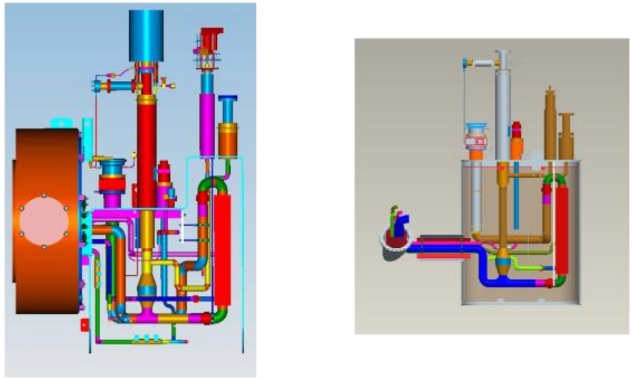
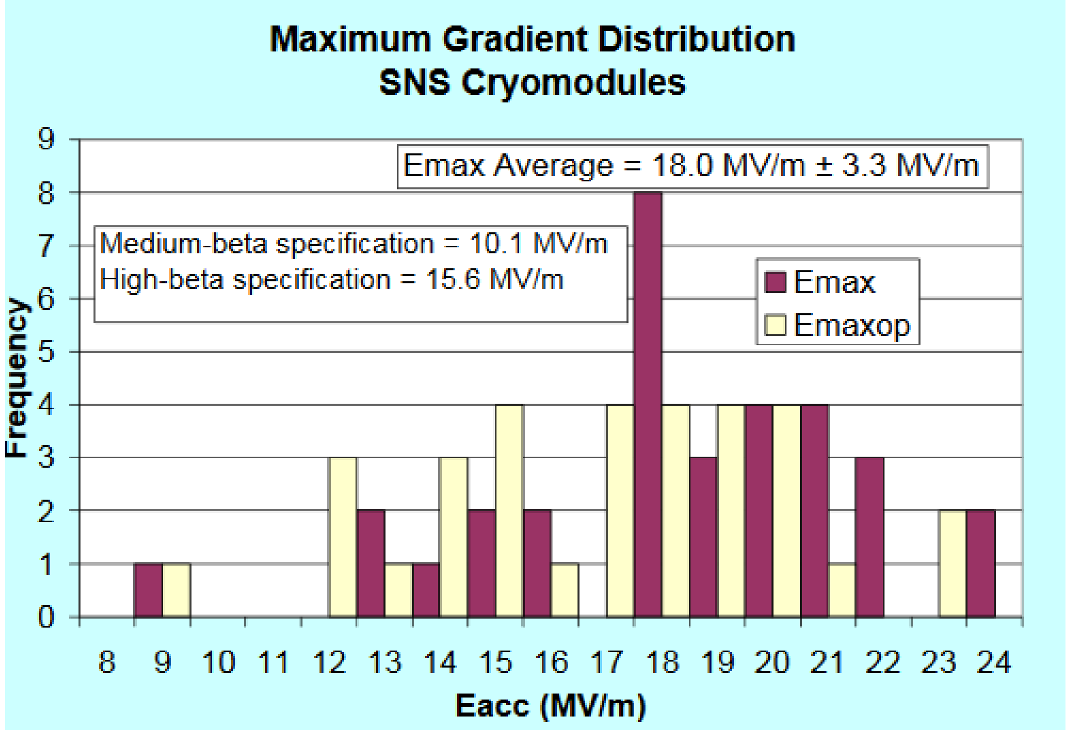


Figure 3.19. Original (left) versus new (right) return end can.

SNS HB cavities (Original)

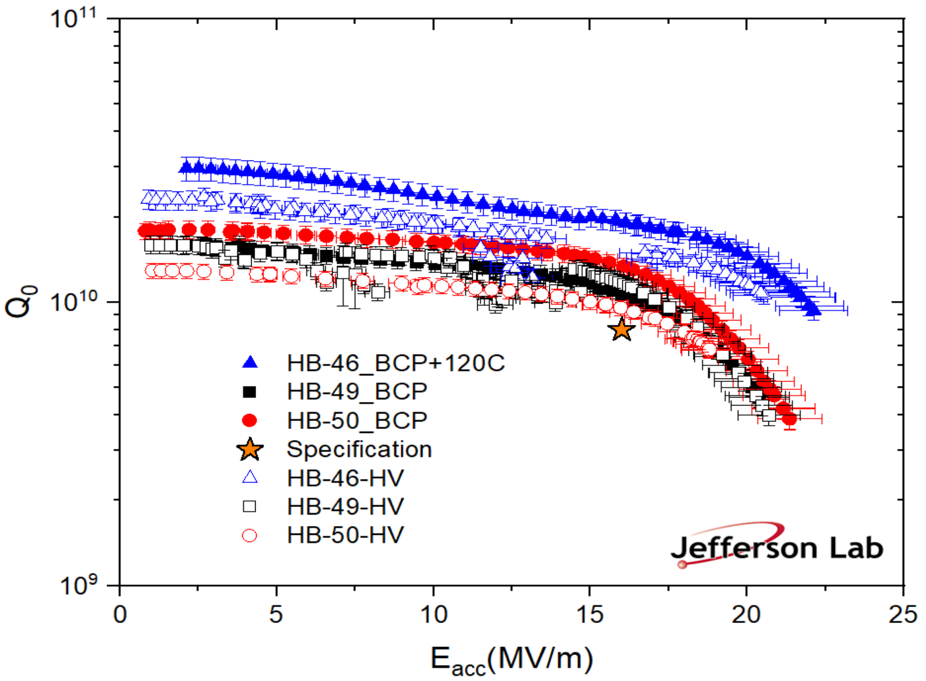
$\beta = 0.81$,
f = 805 MHz
$E_{pk}/E_{acc} = 2.19$,
$B_{pk}/E_{acc} = 4.72$ mT/(MV/m)
R/Q = 483 ohms

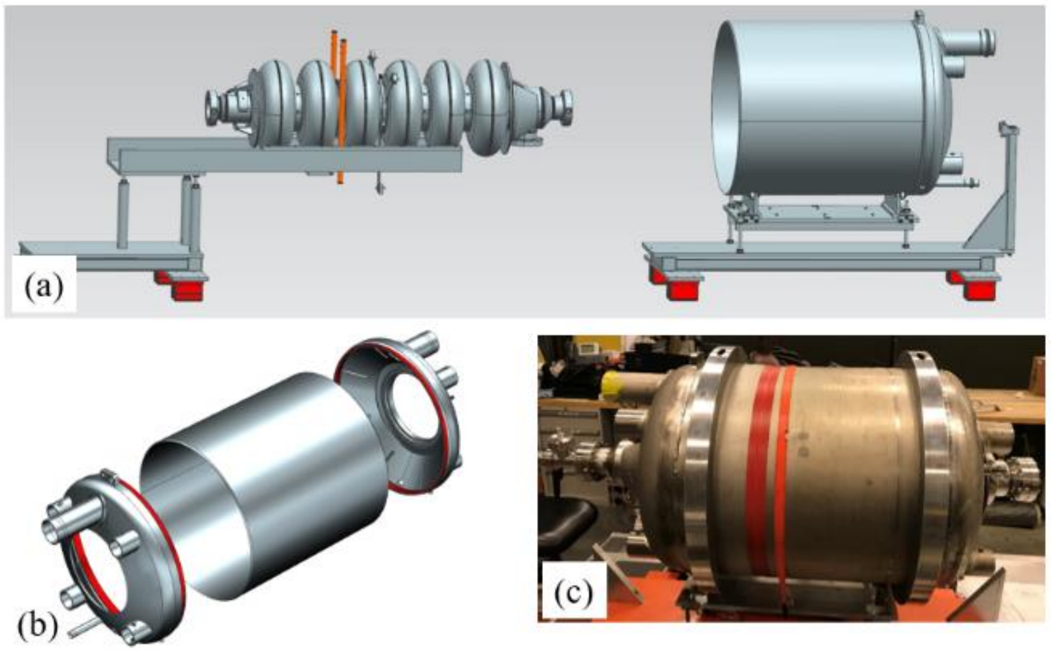


- The performance of the original SNS cavities in the linac is mainly limited by field emission and multipacting, resulting in lower operating gradients at 13.5 MV/m on average.
- A high-beta spare cryomodule was developed in-house at SNS and has been installed in the tunnel for operation since summer 2012 with average gradient greater than 16 MV/m
- A major change on spare module was the cavity being treated by electropolishing over BCP used in original HB cavities.

Helium Vessel Welding Development Work

- Production cavities were delivered to JLab, under vacuum, ready to be tested. After the VTRF qualifications, HVs are added before qualifying for the string assembly.
- Prior to production cavities Jefferson Lab received 3 (old design) cavities to develop the HV welding process (horizontal under vacuum) as original HV was done in vertical.
- HV welding processes was developed. The frequencies and field flatness were measured before and after the welding. The field flatness was within ±2% and in an average ~ -100 KHz frequency shift was observed.



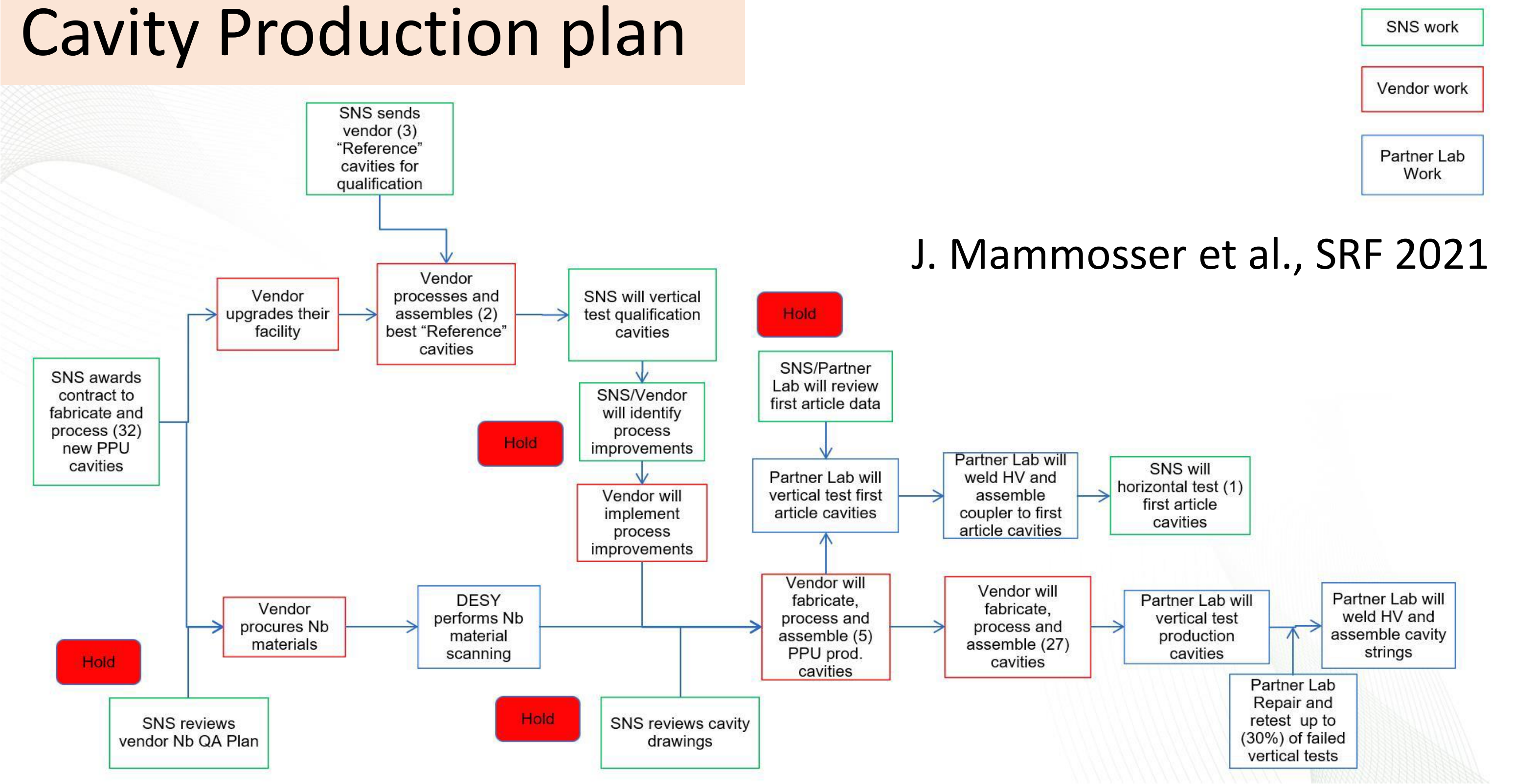


P. Dhakal et al., IPAC2021

PPU Upgrade Cavities

- SNS was responsible to contract production cavities. The cavities contract was awarded to RI, initially for 30 cavities
  - 7 cryomodules plus 2 spares
- Additional two cavities were ordered with an additional 8th cryomodule to be built.
- The vendor was responsible for procurement of material, material inspection, fabrication and processing.
- Cavities send to JLab under vacuum ready to be tested.

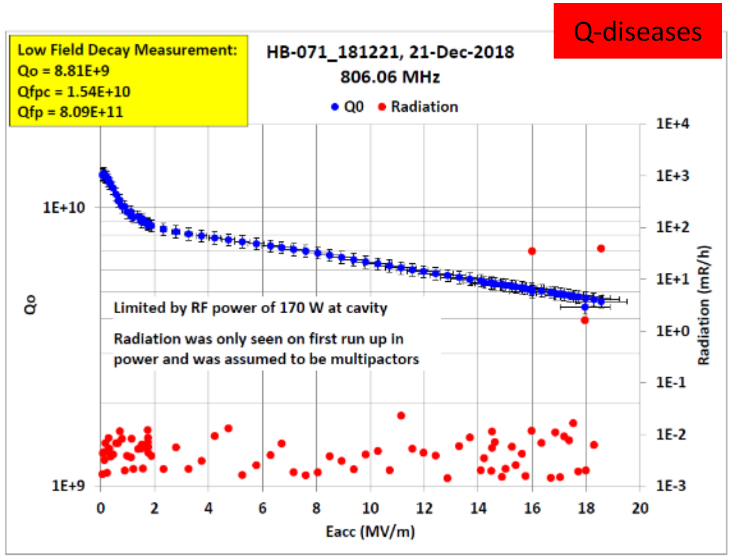
Cavity Production plan

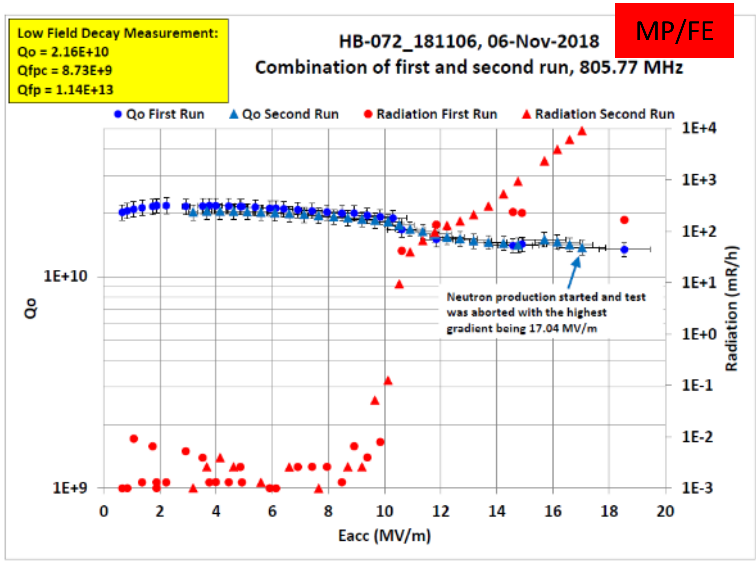


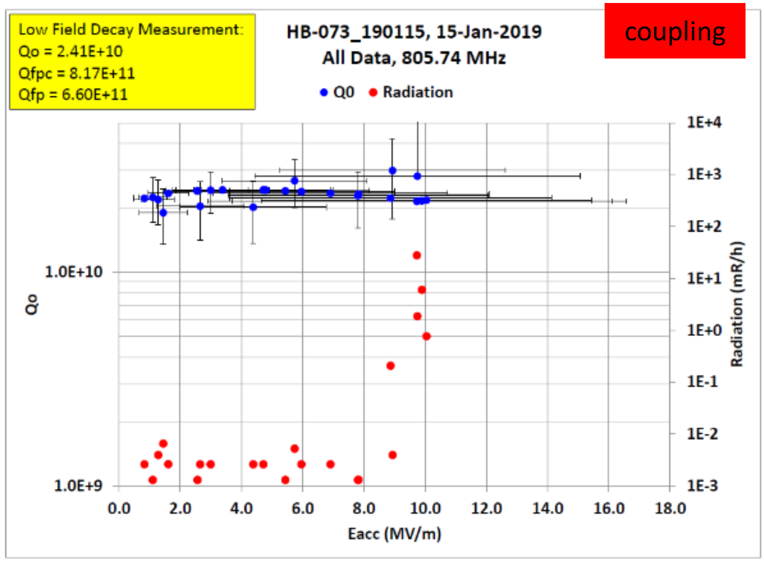
J. Mammosser et al., SRF 2021

EP Process Development (Original)

- During 2018, JLab received 3 cavities to investigate the EP process on cavities
  - The cavities were EP'd at JLab and RF tests were performed.
- RF tests were not so encouraging due to issues with EP, Q-disease, MP and FE.
- Re-processing wasn't done due to schedule constraints.





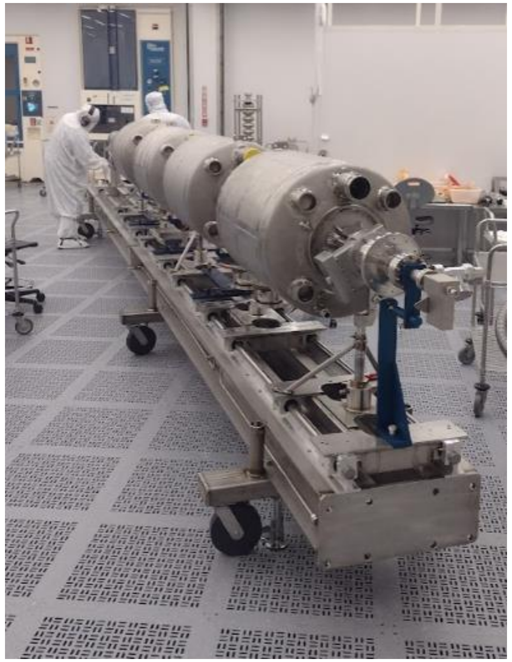


- EP process was developed with the vendor. Both JLab and SNS scientists visited the vendor several times during the start up of EP process.
- Two cavities that were EP'ed at vendor site and RF tested at SNS met RF performance
  - EP parameters were fixed for production cavities.

For more see: J. Mammosser et al., SRF 2021

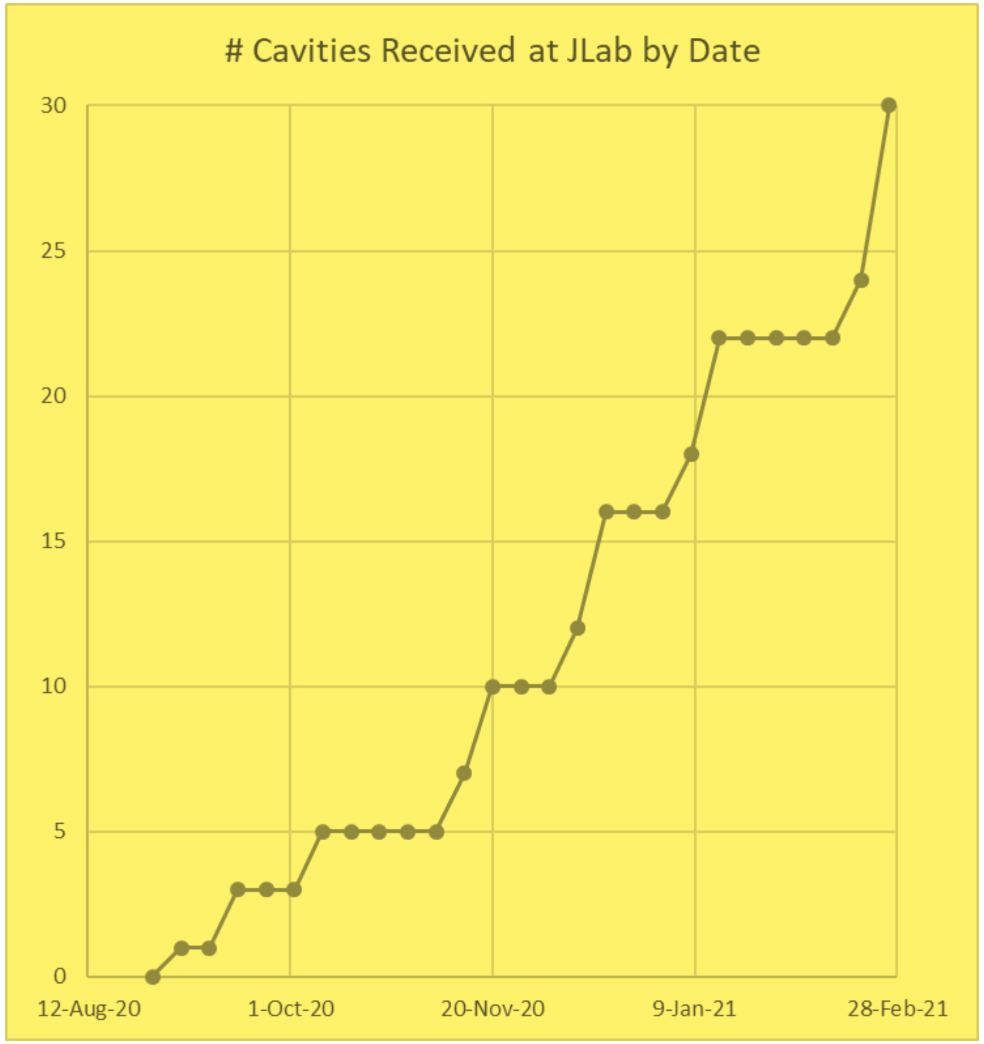
Vertical Test Qualification of PPU Cavities at JLab

- Incoming Visual and CMM
- Incoming RF Inspection
- Wipe down
- Attached to test stand (VAA)
- Pumpdown/leak check
- 120C/24hrs bake
- Load to Dewar/ Cooldown to 2.1K
- RF Test Q(E)
  - Pass → Helium Vessel Weld
  - Fail → HPR Assembly Evacuation Leak Test RF Test
    - Pass → Helium Vessel Weld
    - Fail → TBD
- Helium Vessel Weld
- Post HV RF test
- Final HPR String Assembly



VTA Qualification of PPU Cavities (01/01/2022)

- Jefferson Lab received all 32 cavities from vendor under vacuum, ready for testing. First cavity received on 09/04/2021
- 29 cavities were VTA RF tested to date as received from vendor. Total 80 RF test were done including bare and tanked cavities.
- 24 cavities completed HV welding.
- 4 string assembly was completed.
- About 75% of cavity related work is completed.

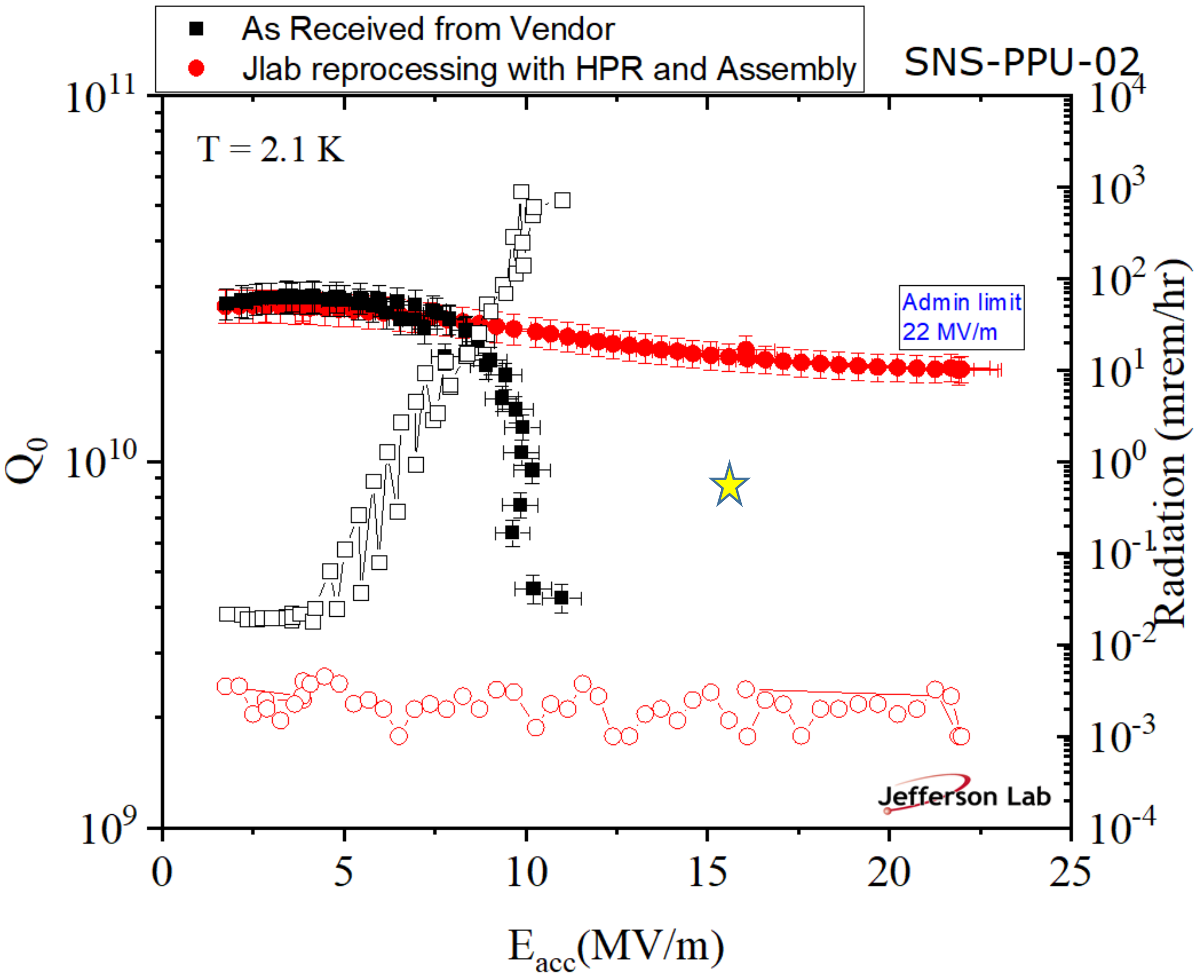


Acceptance Criteria for Vertical RF Testing

Final Run Vertical Test Acceptance Criteria	Test to be Conducted	Nominal Value for Acceptance for PPU String Assembly
1. Field Emission at 16 MV/m	Measure Eacc vs Rad with admin limit at no greater than 22 MV/m	Integrated dose of ≤ 20mR/hr At 16MV/m
2. Gradient Limit	Measure the Eacc vs Qo with admin limit at no greater than 22 MV/m	≥18 MV/m
3. Unloaded Q	As part of the Eacc vs Qo measurement	Qo ≥ 8e9 up to 16MV/m
4. Field Probe Coupling	Calculated from decay measurement and power balance	Range: 7e11 to 2e12
5. Pi Mode Frequency	Measured with calibrated frequency counter in closed loop at 2.1K	805.6 ± 0.250 MHz
6. Residual Magnetic field	Measured in dewar during cold test	≤ 20mG

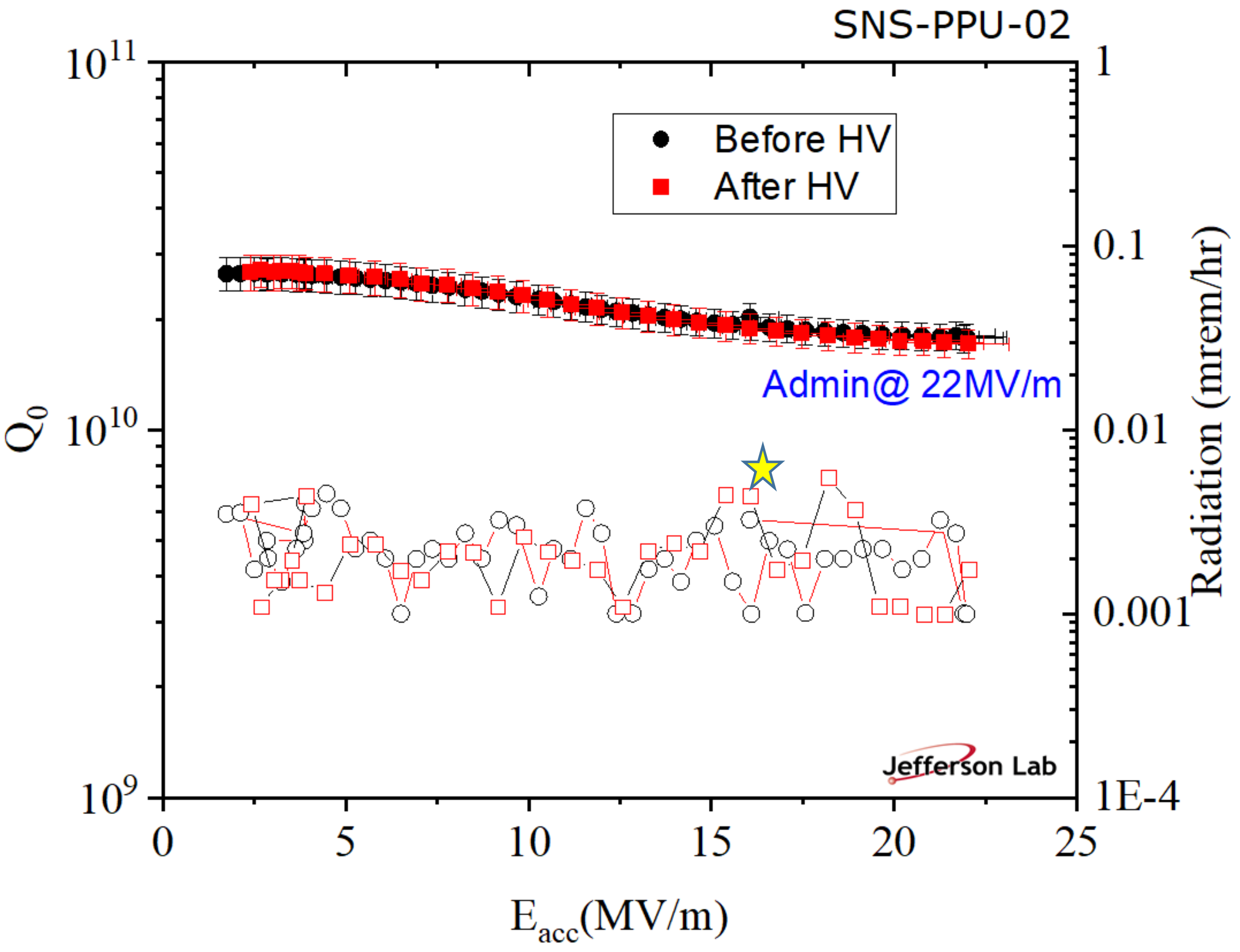
Cavity RF Performance (Bare Cavities – VTA test)

- First few cavities received from vendor were limited by early field emission.
- The FE on cavities were eliminated after JLab reprocessing with high pressure rinse and clean assembly.
- In some occasion multipacting was observed ~ 10-15 MV/m, but it was processed with high power processing.
- After the cavity qualifies from VTA test, the cavity sent to helium vessel welding work station and HV welding was conducted under vacuum in horizontal positon.
- After the completion of HV welding, with appropriate external cleaning (most cavities received additional HPR), the cavity retested in VTA.

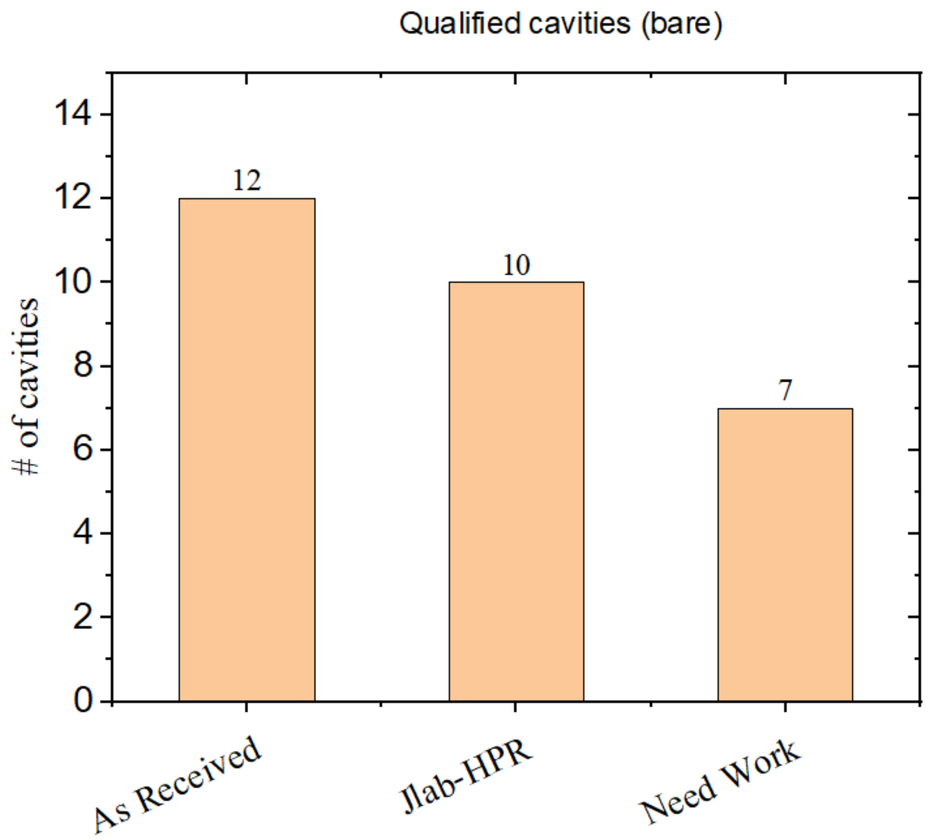


Cavity RF Performance (Bare vs Tanked cavities – VTA test)

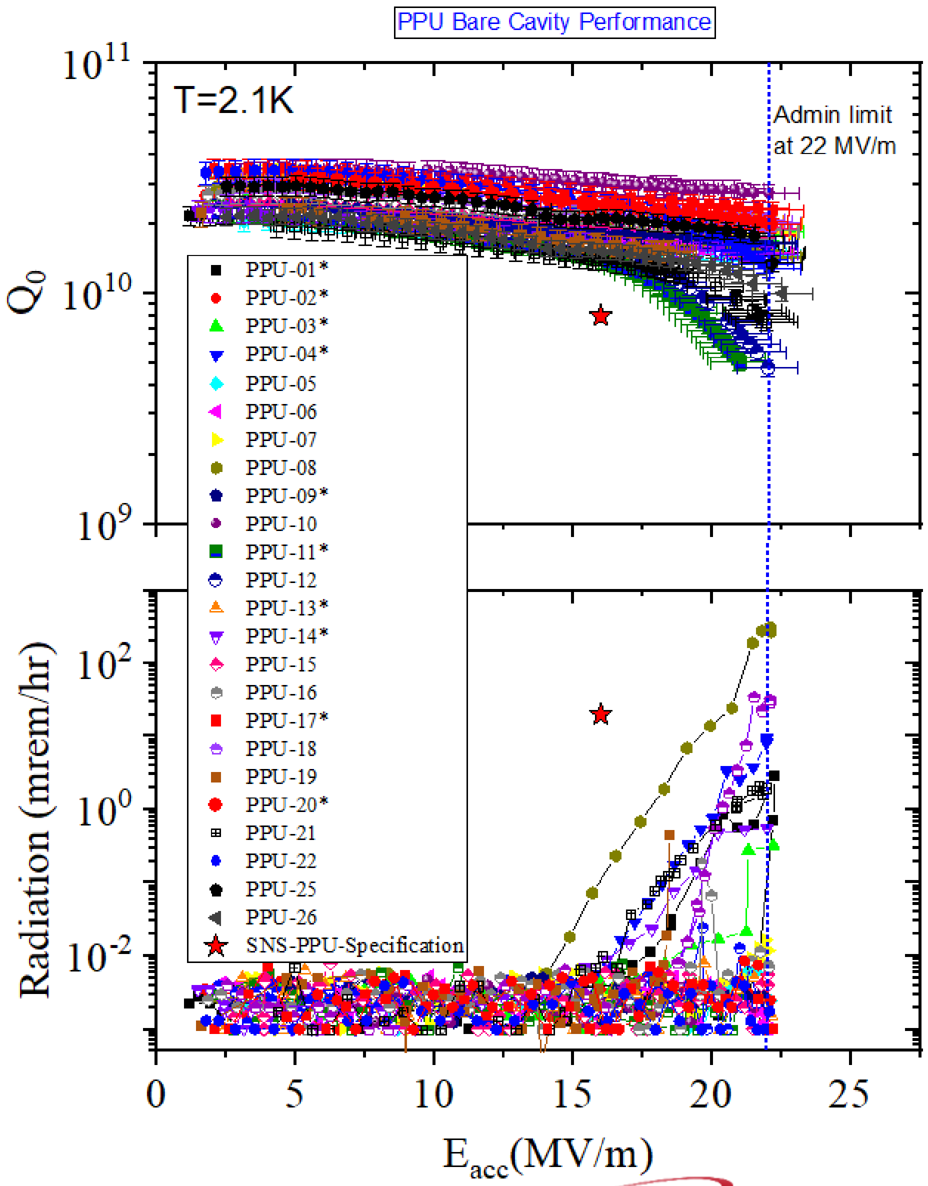
- The re-test of the tanked cavities reproduced the performance of bare cavity.
- We suspected the burst disk was collecting rinse water and re-contaminating the cavity during processing steps. So, the burst disc was remove from assembly at vendor site after the first 4 cavities.
- We started to see the performance improve on PPU05 which had no field emission as delivered from vendor.
- Additional change was made to replace the ethanol rinsing after EP to detergent degreasing and DI water rinsing before HPR, following JLab's successful procedure. All second HPR rinsed cavities at JLab showed little or no field emission up to 22 MV/m



Cavity RF Performance (Bare cavities – VTA test)



Qualification Spec:
E_{acc} > 18 MV/m
Q_0 > 8 x 10^9
FE
@16 MV/m < 20 mrem/hr



- 42% (12/29) of cavities were qualified as received from vendor.
- 100% (10/10) cavities met PPU spec after reprocessing with HPR at JLab.
- 7 cavities still need reprocessing with HPR to meet specification. Based on 10 cavities work at JLab, project is going forward with HV welding and re-test (requalify) after tanking.

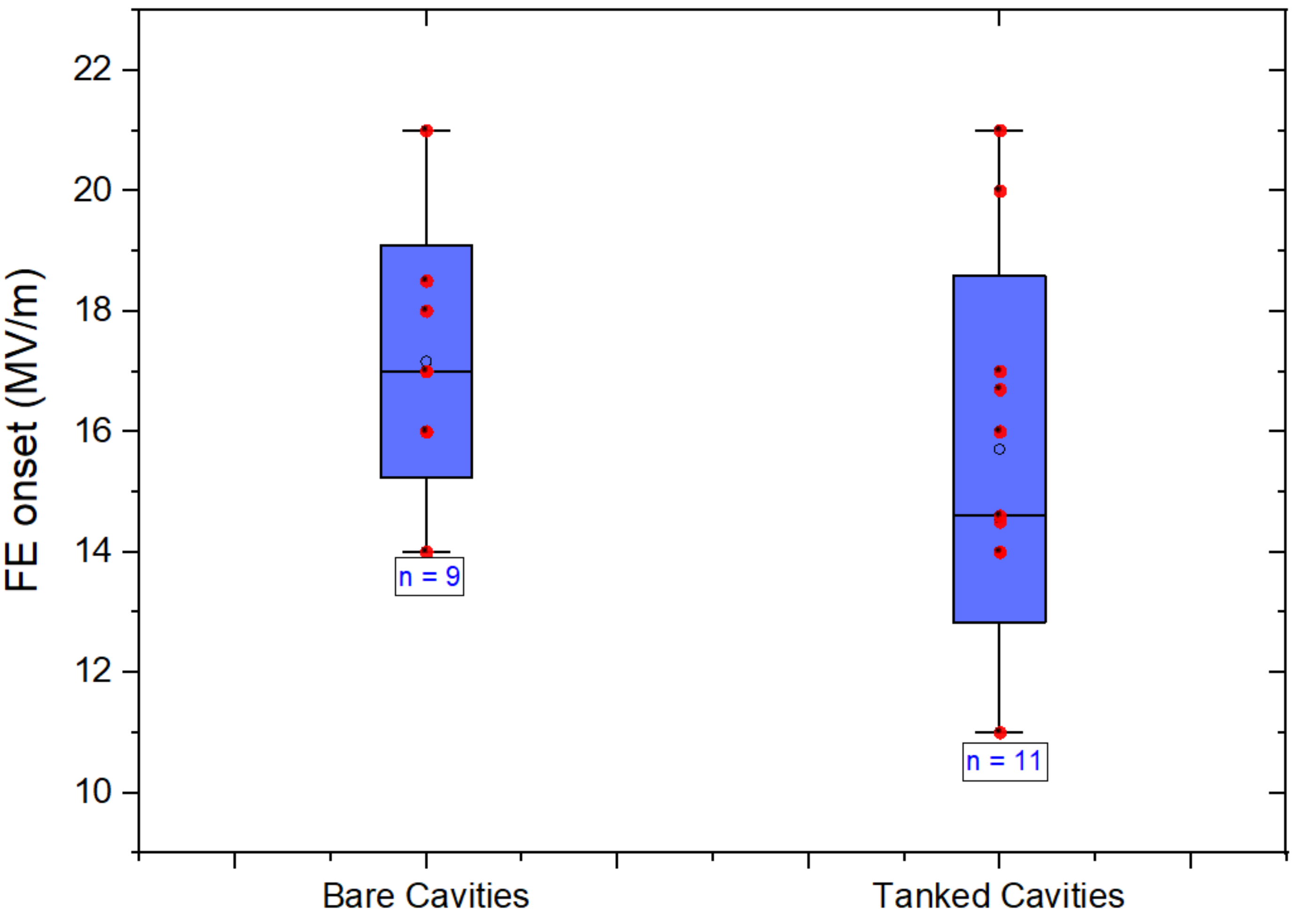
Challenge : Minimizing FE on Tanked Cavities

- The main challenge we encountered was the cross-contamination of the tanked cavities during the disassembly process.

- Periodically the exterior cleaning process needed to be changed to mitigate the early FE of tanked cavities, which resulted in multiple RF tests of tanked cavities.

- Current process includes the exterior pressure wash of tanked cavity, DI water rinse, long high pressure rinse and final clean assembly.

- Process change minimized the number of cycle the cavities needed for reprocessing.



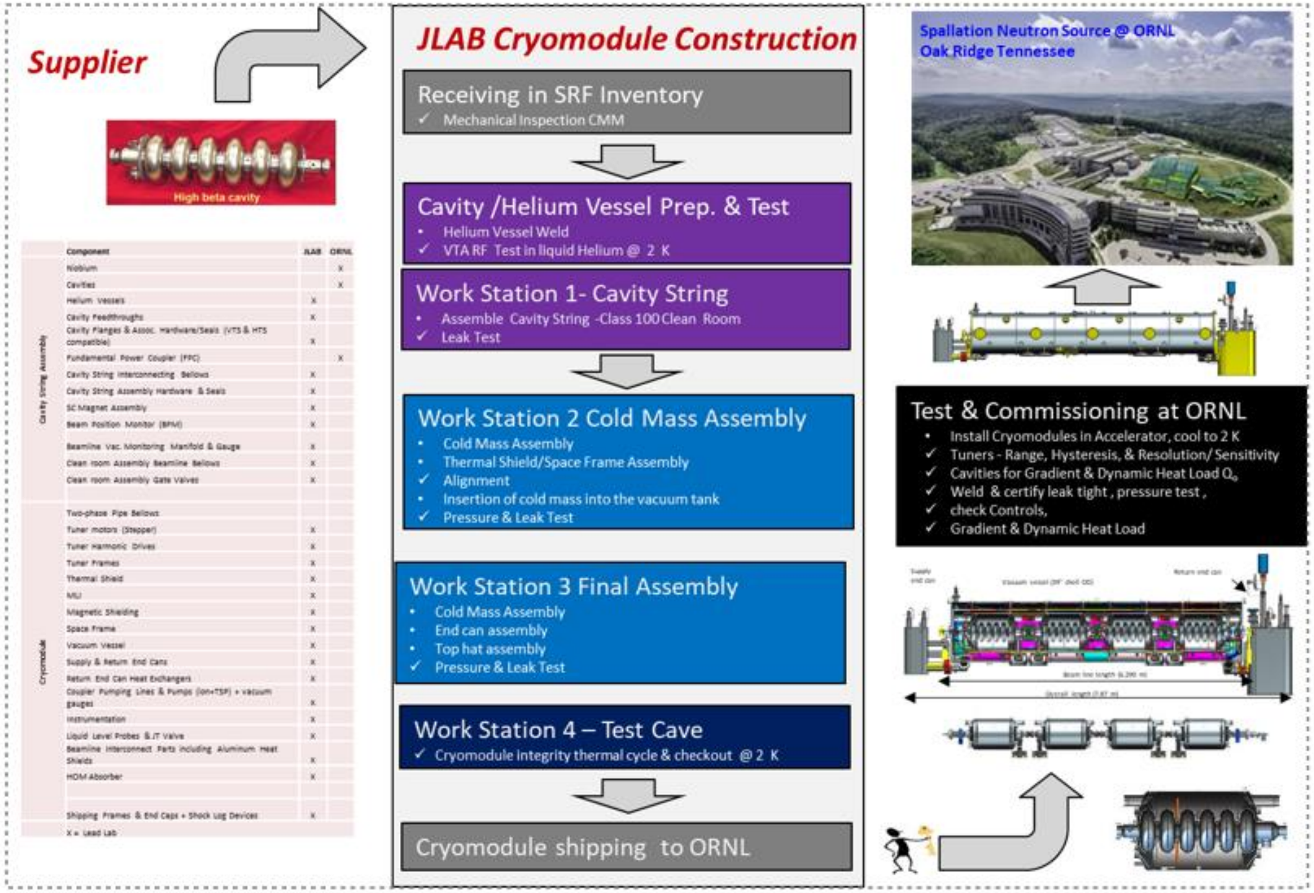
Cryomodule Production

- CM1 nearly completed
  - Will go into CMTF next week
  - Expect to ship to SNS in time for high-power testing in March
- CM2 is currently in early stage of Final Assembly
- CM3 & CM 4 are in Cold Mass Assembly work station

Summary & Highlight

- All 32 cavities were delivered to JLab required for 8 cryomodules (No spares).
- 42% of cavities passed initial RF test as received from vendor.
- 100% of bare cavities met specification after reprocessing with HPR at Jlab with all cavities reaching 22 MV/m limited by admin limit.
- 4 cryomodule string assemblies are complete.
- First cryomodule is scheduled to be delivered to SNS in March.

Production – Well-Defined Process Flow: On Track



Acknowledgements

To all Jefferson Lab Cavity Production Staff

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PPU Cavity Team at SNS