OAK RIDGE National Laboratory

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Post-Mortem Insights into the SNS RFQ01: Implications and Paths Forward for High Beam Power Operation

Haitao Ren

Spallation Neutron Source, ORNL

On behalf of the SNS RF Structures team:

S. Lee, J. Moss, G. Toby, S. Kim

U.S. DEPARTMENT of ENERGY

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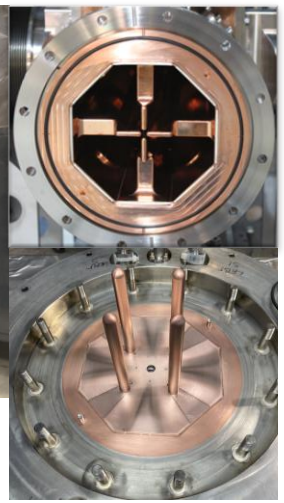
Outline

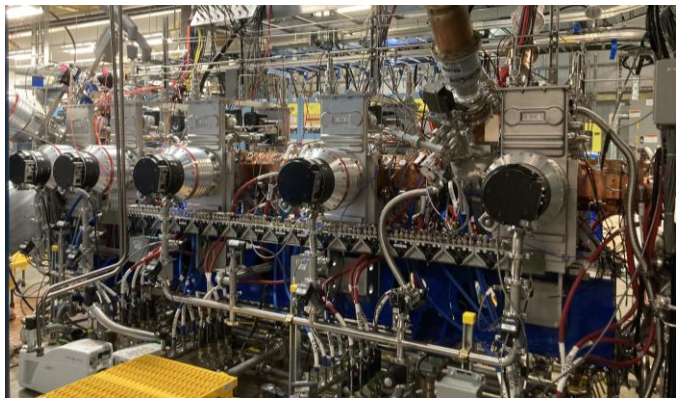
- SNS RFQs
- Experience with the original RFQ (RFQ01)
- Precise erosion measurements
- CST modeling and PIC simulation
- Borescope inspection
- Implications for high-power RFQ operation
- Summary

SNS RFQs

For post-mortem analysis

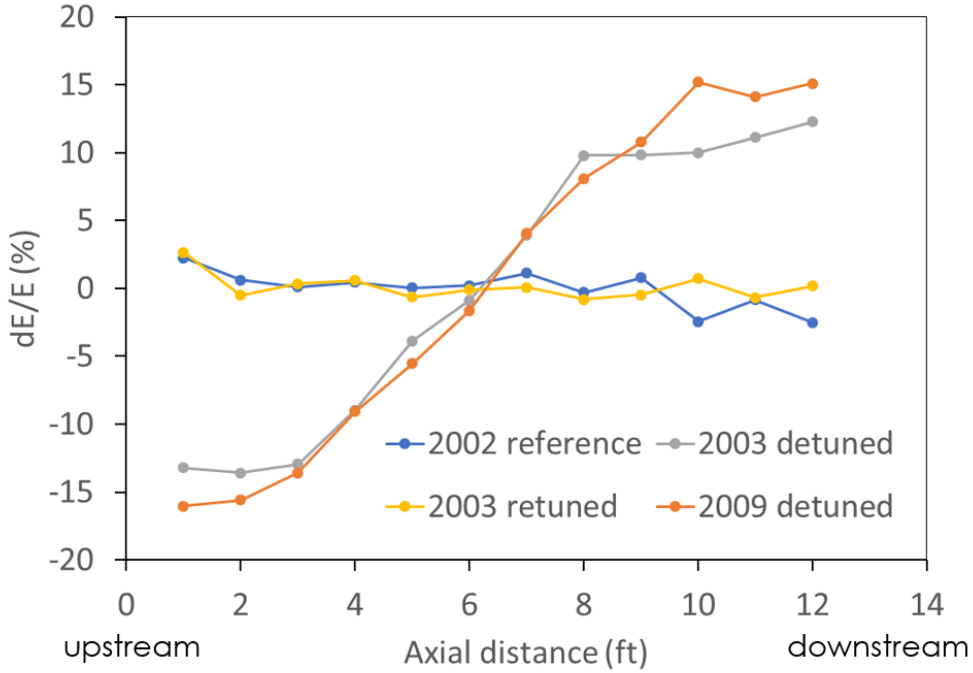
	RFQ01	RFQ02	RFQ03
Operation begins	2006	2018	2023
RF Frequency	402.5 MHz	402.5 MHz	402.5 MHz
Length	3.7 m 4 segments	3.7 m 4 segments	3.7 m 4 segments
Material	Glidcop + Copper	Copper	Copper
Design transmission	90%	90%	90%
Beam dynamic design	Original design	Same as RFQ01	Same as RFQ01
Vane-vane volt	83 kV	83 kV	83 kV
Kilpatrick	1.85	1.85	1.85
Dipole mode suppression	π-mode stabilizers	4-rod stabilizers	4-rod stabilizers
Coupler	8 coaxial couplers (later 2 coaxial couplers)	2 coaxial couplers	2 coaxial couplers
Tuners	80 fixed slug tuners	64 fixed slug tuners	64 fixed slug tuners
Vacuum pumping	6 cryo-pumps	6 cryo-pumps + 4 turbo pumps ⇨ **10 turbo pumps**	10 turbo pumps

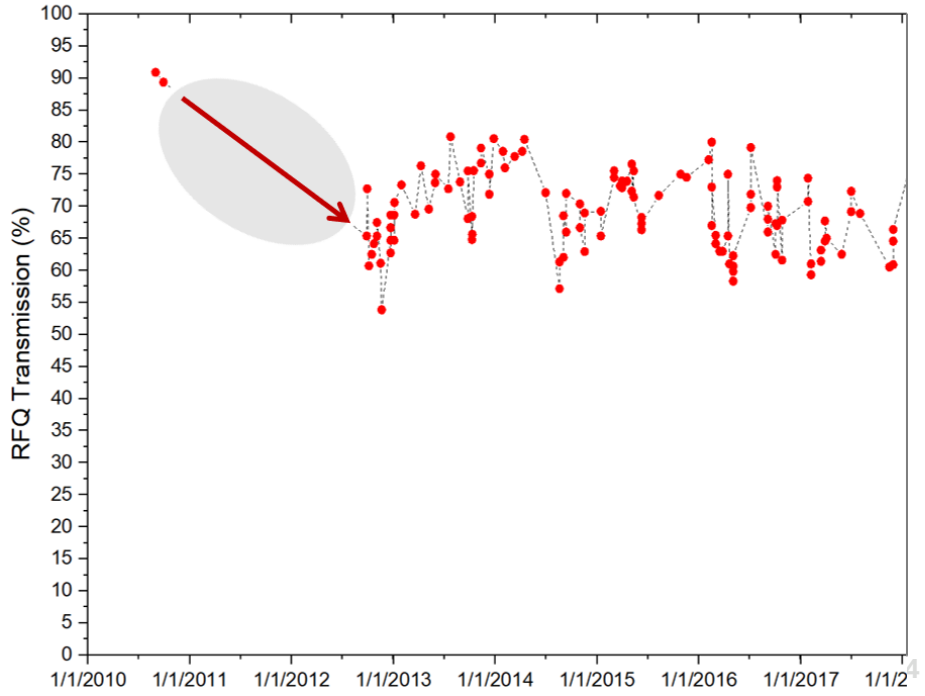




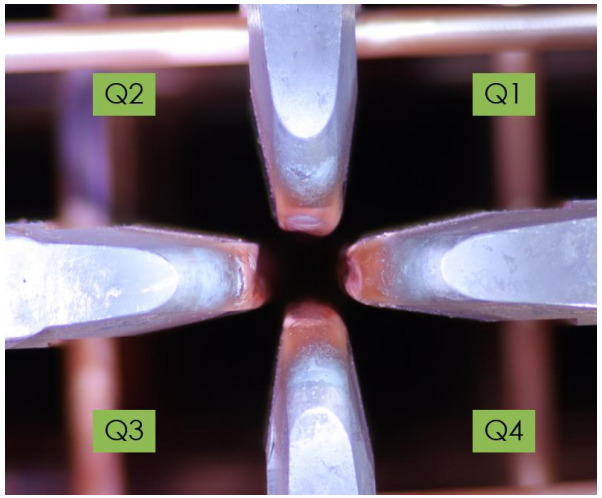
SNS RFQ01 history

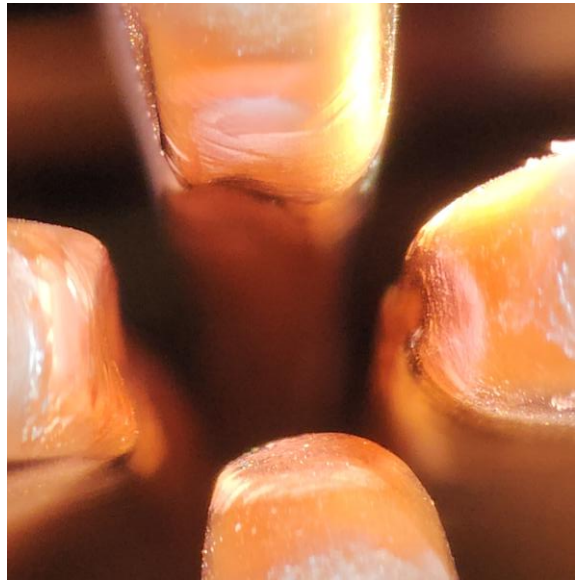
- ~20 years service
  - 2002 – 2006: Beam commissioning
  - 2006 – 2017: SNS operation
  - 2017 – 2022: Beam Test Facility (BTF)
- Issues experienced
  - Resonance detuning events in 2003 and 2009
    - Coincident with cooling system upsets
    - Field was tilted by -15%/+15% (upstream/down stream)
    - Retuned and back to service
  - Reduction of beam transmission by 20-30%
    - No significant detuning
    - Field tilted by about -15%/+5%
    - Beam transmission did not recover after retuning in 2013
  - Additional ~20% beam transmission loss on BTF
  - Root cause was inconclusive

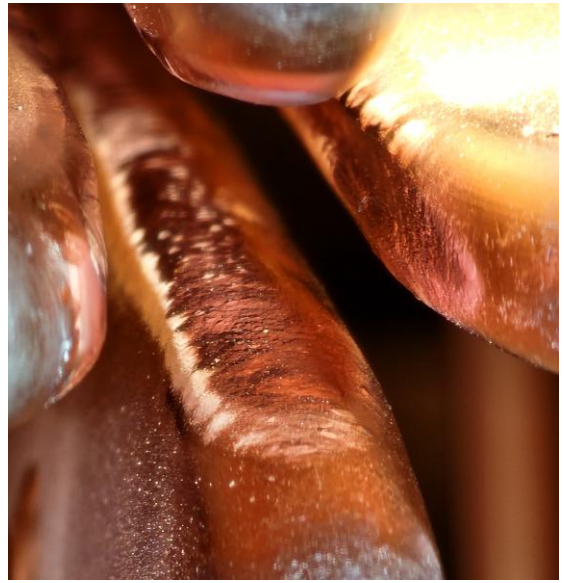


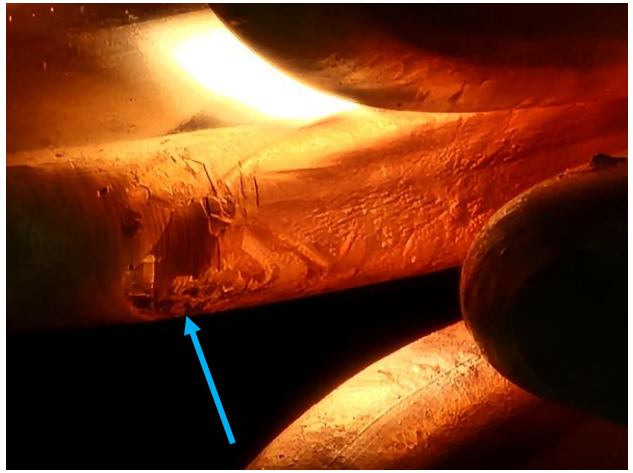


Visual inspection – Substantial erosion at entrance



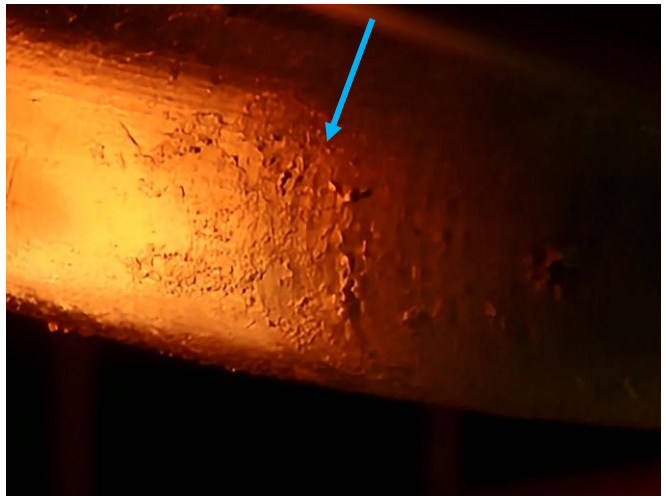




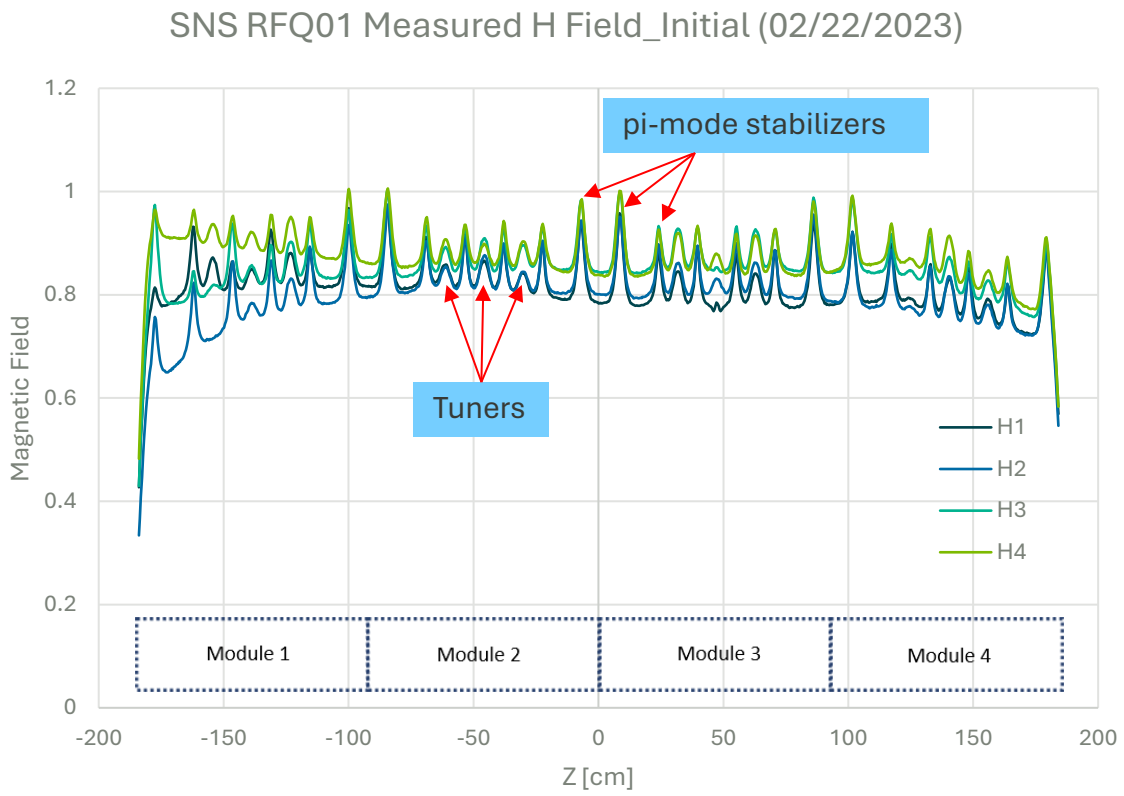


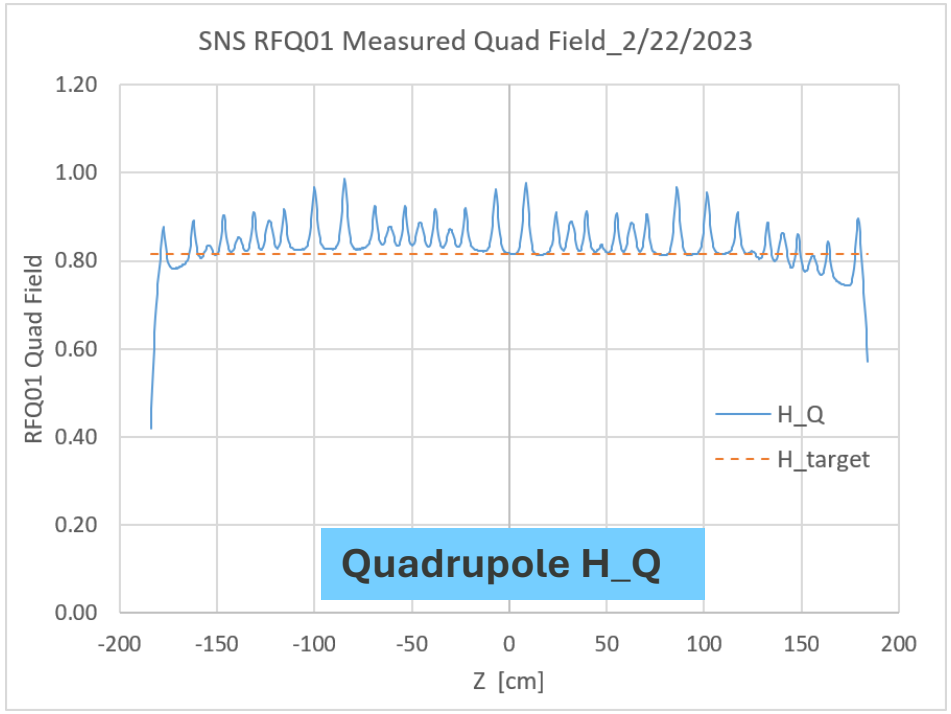
Suspected copper blistering

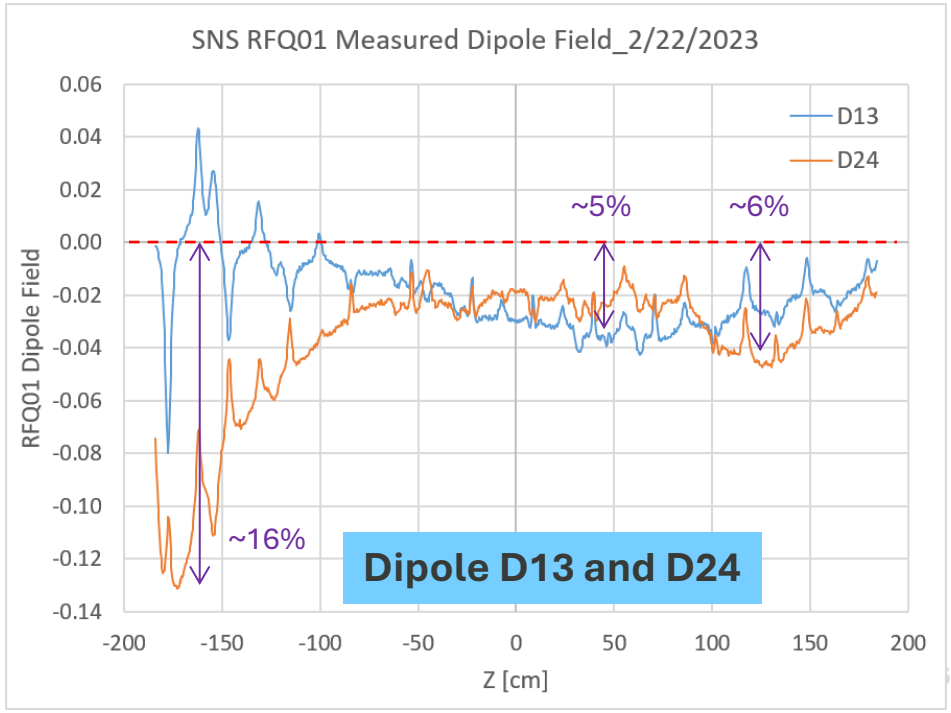
- Substantial erosion damage observed on the first a few inches of vane tips
- Copper sputtering (with 65 keV H- ions) is suspected a cause of the erosion
- Copper blistering can result in modification of physical properties of the copper surface and in the increased erosion rate



Bead-pull measurement

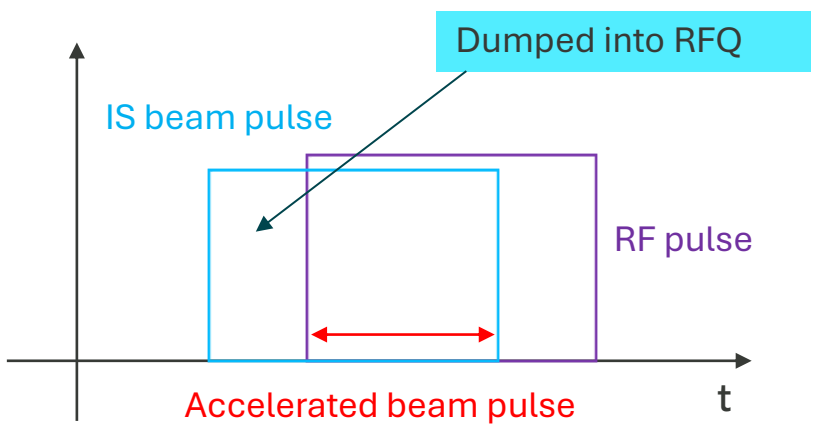




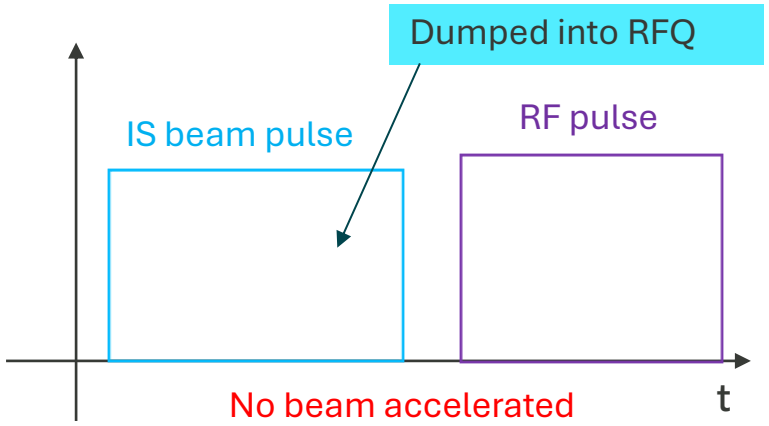


- Quadrupole field flatness: **H_Q** = (H1 + H2 + H3 + H4)/4
- Dipole component asymmetry: **D13** = (H1 - H3)/2
  D24 = (H2 – H4)/2
- Field error is typically +/- 1% ~2%

Why erosion happens at entrance – SNS beam time gating



SNS Beam Mode



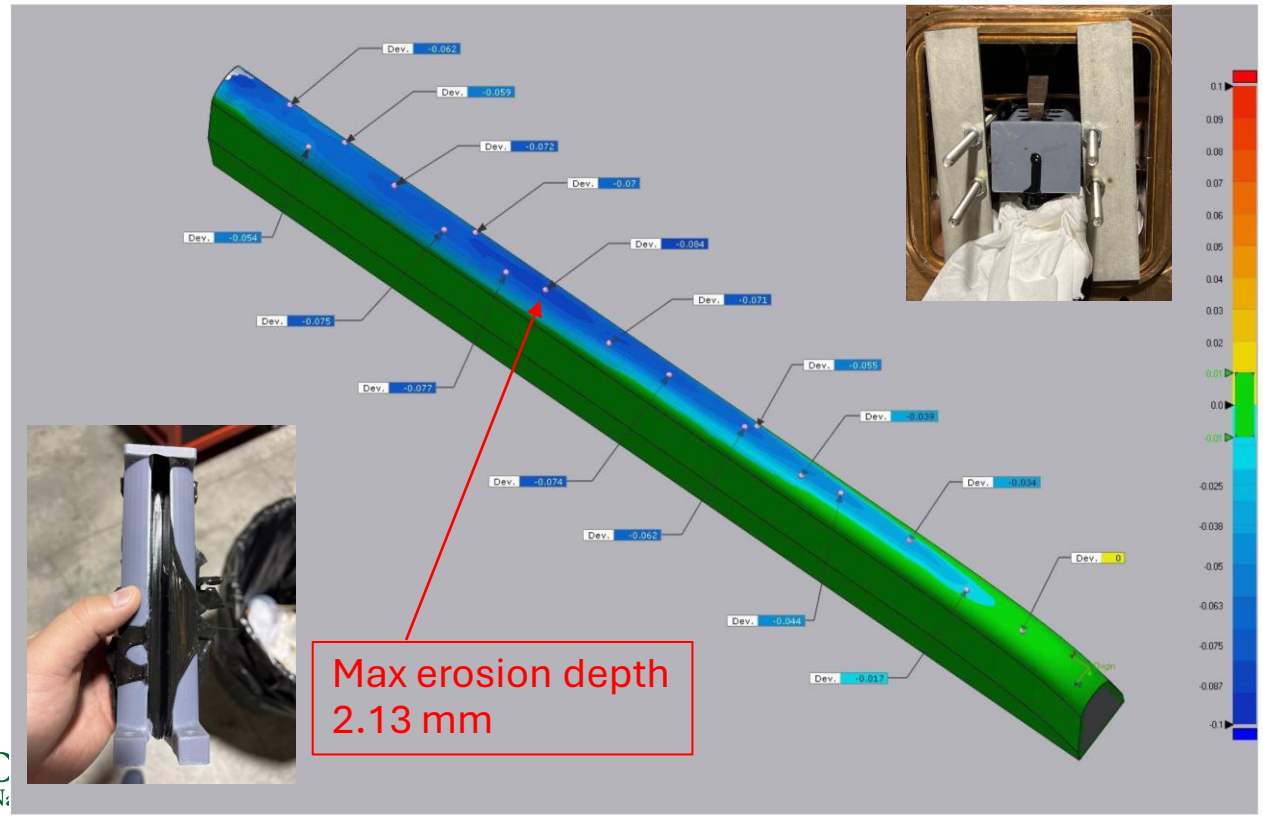
SNS Beam-off Mode

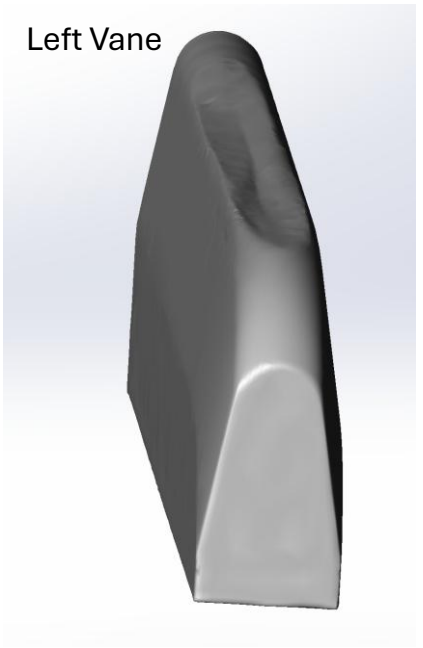
- SNS ion source (IS) produces 1000 μs beam pulses at 60 Hz
- IS pulse to be synchronized with RFQ RF pulse
- Accelerated beam pulse is the overlap between IS pulse and RF pulse
- Beam-off mode (during troubleshooting, or short maintenance) dumps all unsynchronized pulses to the RFQ entrance

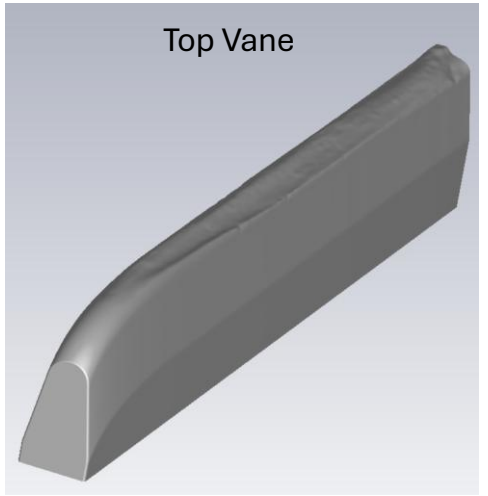
3D measurement of vane erosion at entrance

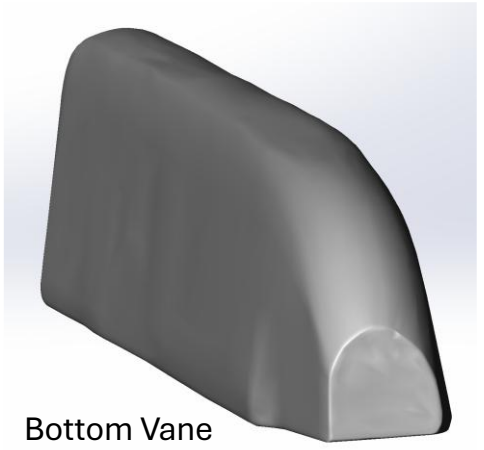
- RepliSet is a specialized, fast-curing two-part silicone rubber replication system
  - Special mold designed to fit RFQ structure
- The cured replica was digitized on a precision tabletop laser scanner
- Only cover the first 6 inch of vane tips
- The scan shows a maximum erosion depth of 0.084 in (2.13 mm)

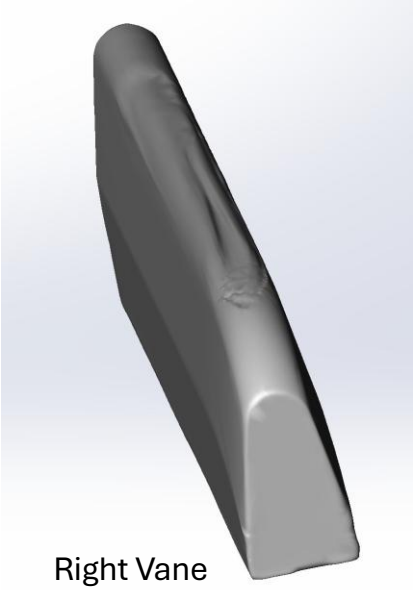
RFQ 1 – Top Vane (View 1)



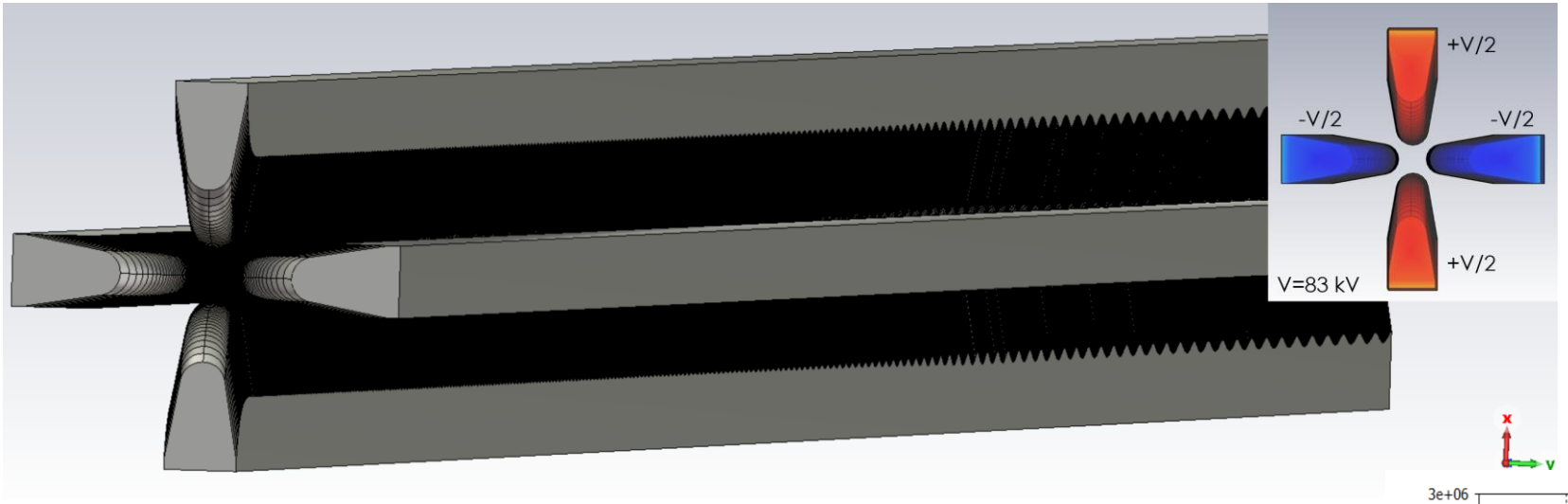




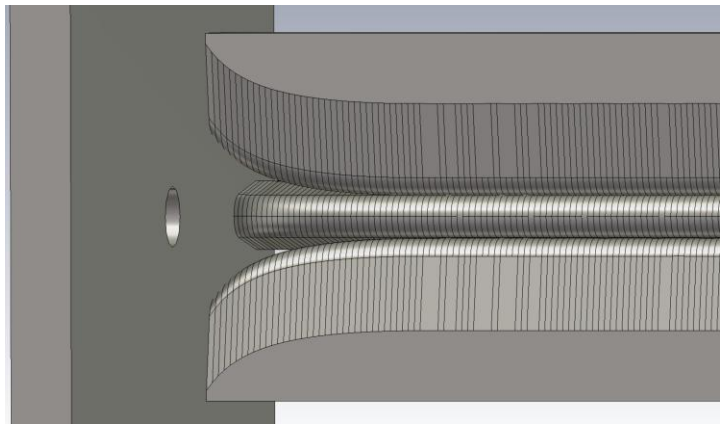




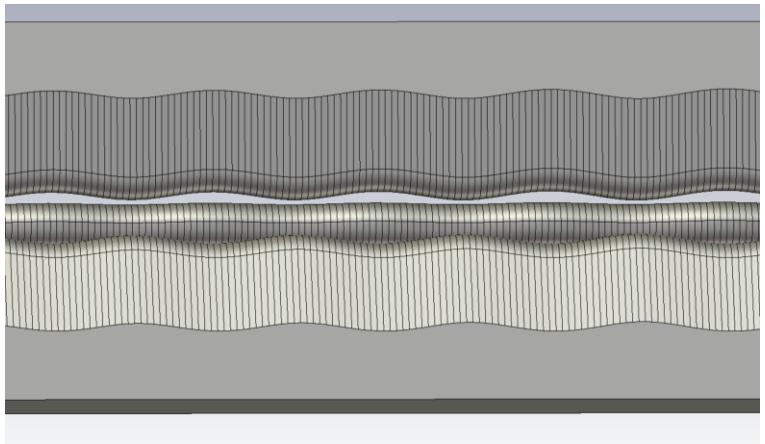
RFQ 3D model with modulation developed at SNS



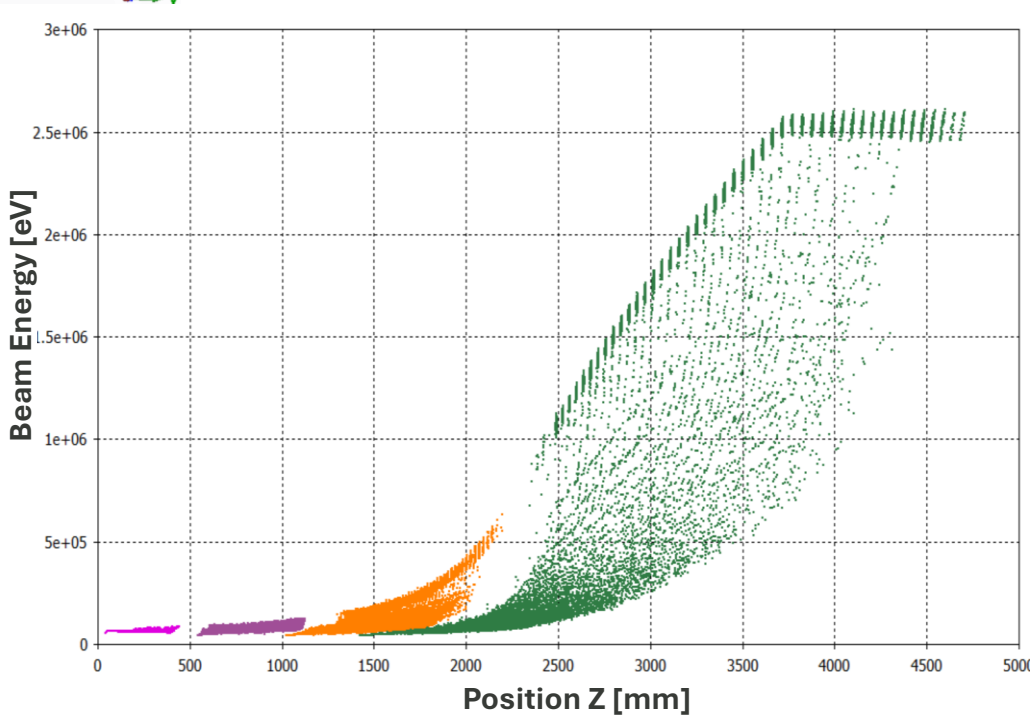
- 3D modulation model built with CST VBA macro script
- Vane-tip electric field distribution calculated with CST electrostatic solver
- CST Particle-in-cell (PIC) simulation then applied with the electric field model



RFQ entrance



RFQ modulation



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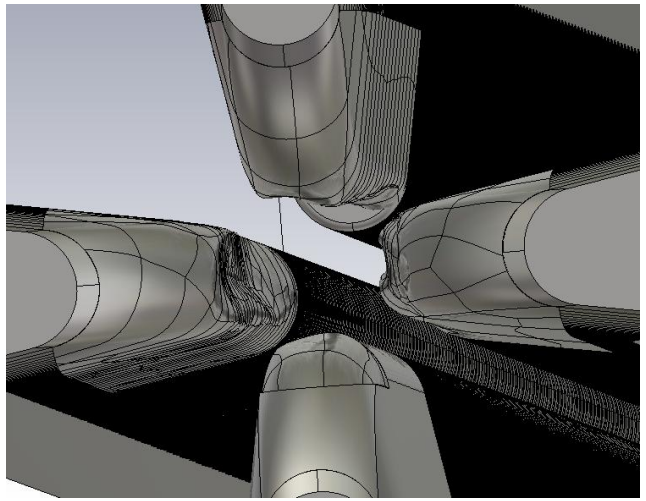
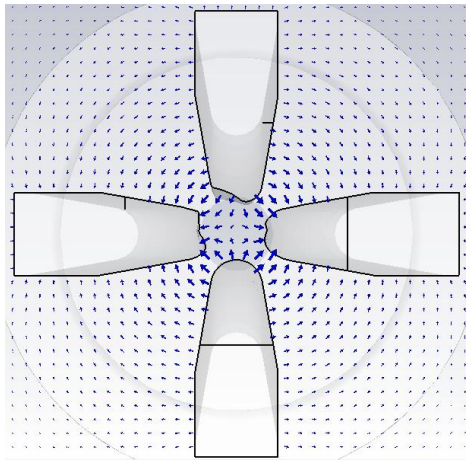
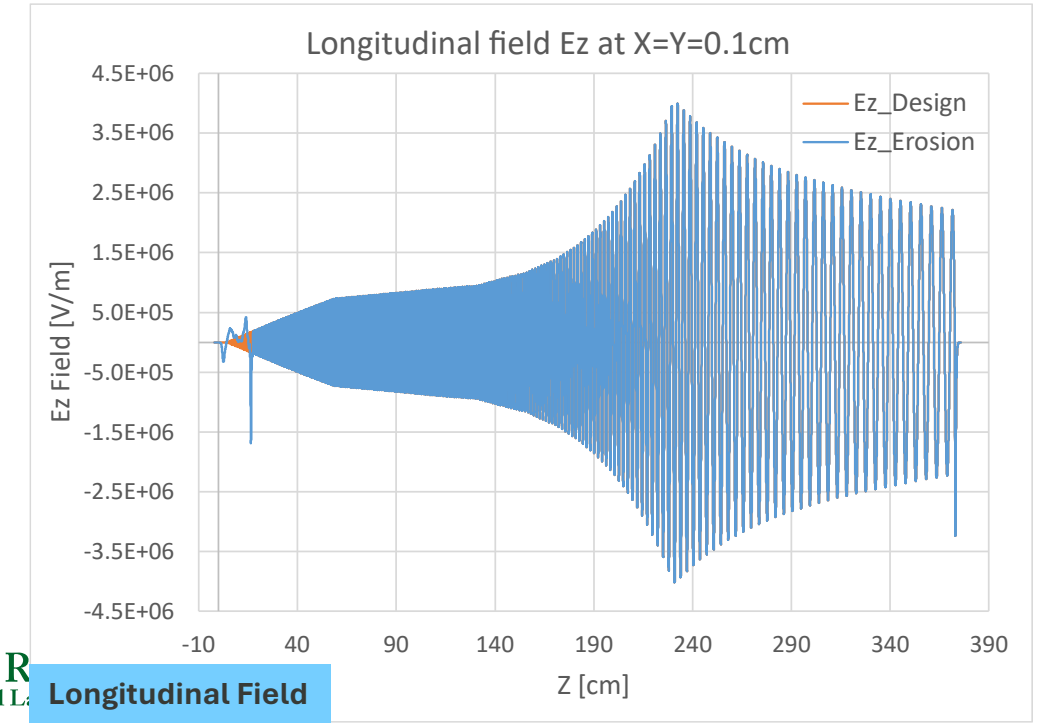
3D erosion profile applied to RFQ 3D model



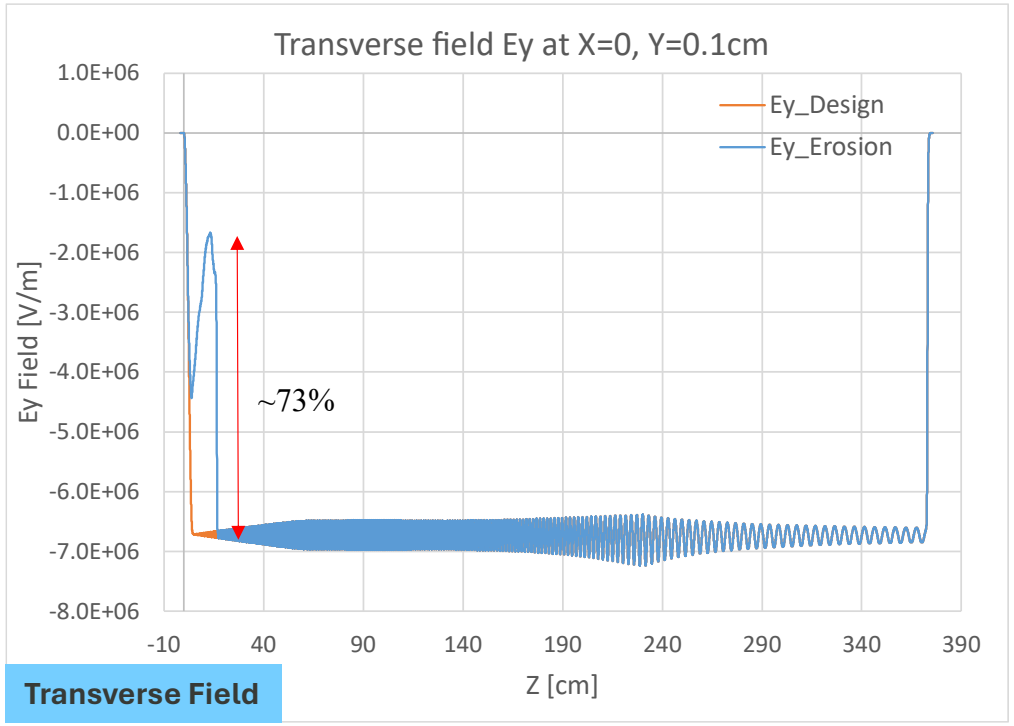


E-field distribution at Z=8 cm

- The laser-scanned erosion model was applied to the RFQ 3D model
- Vane field distribution was re-calculated
- Both longitudinal and transverse field patterns have been compromised at erosion area

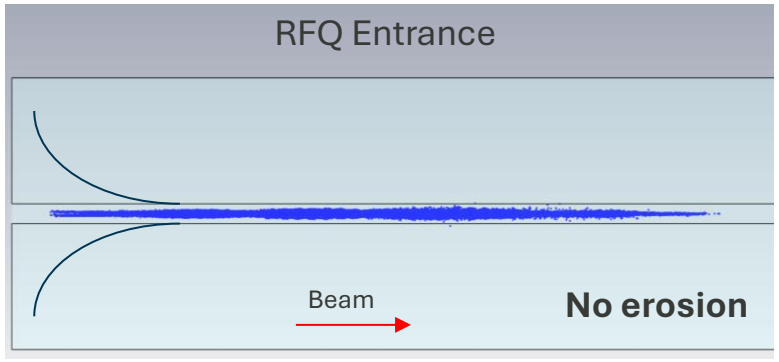


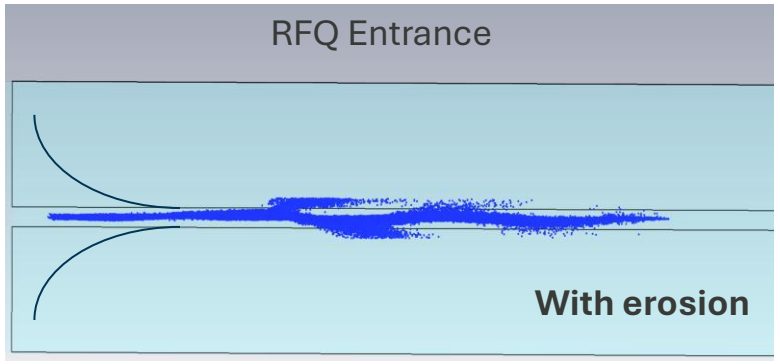
Longitudinal Field



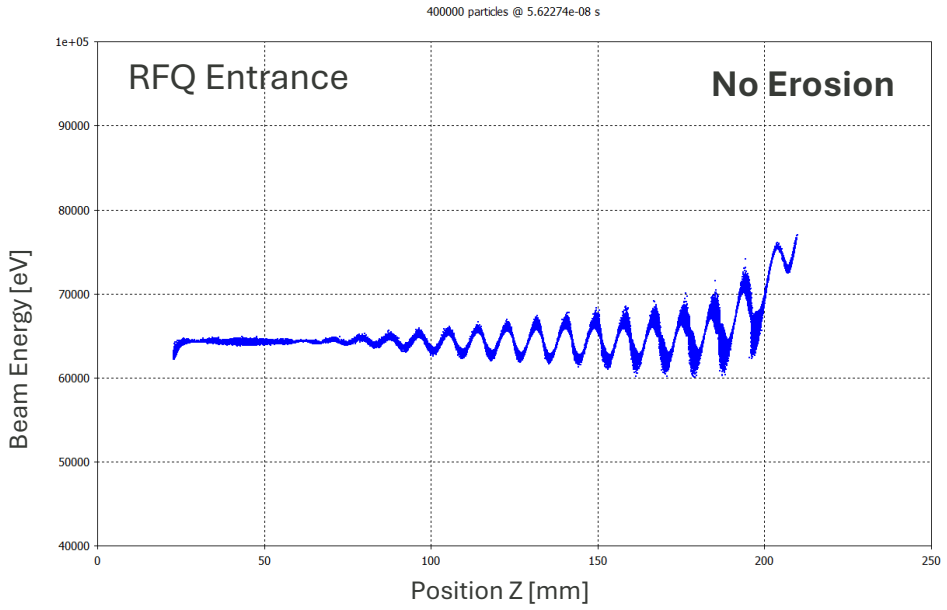
Transverse Field

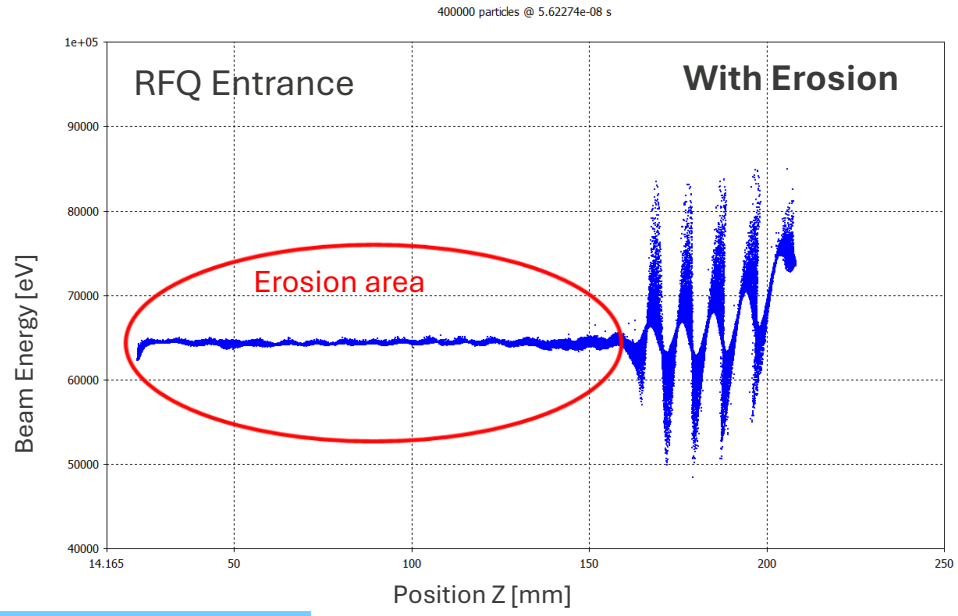
CST PIC Simulation – Erosion impact at entrance





Particle view at RFQ entrance

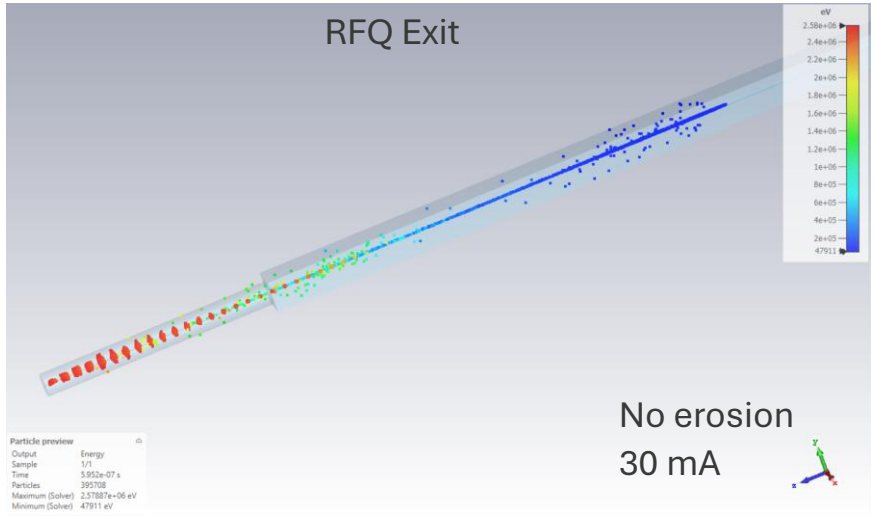


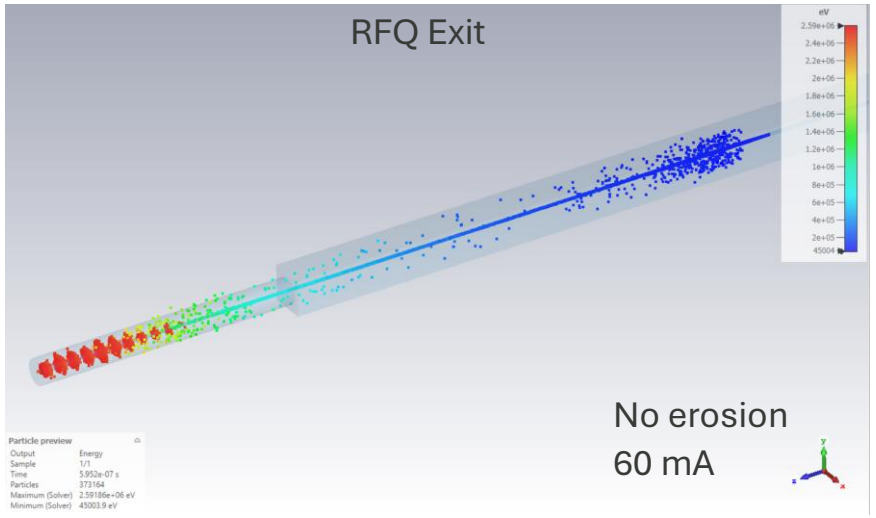


Beam Energy vs. Z (0 – 200mm)

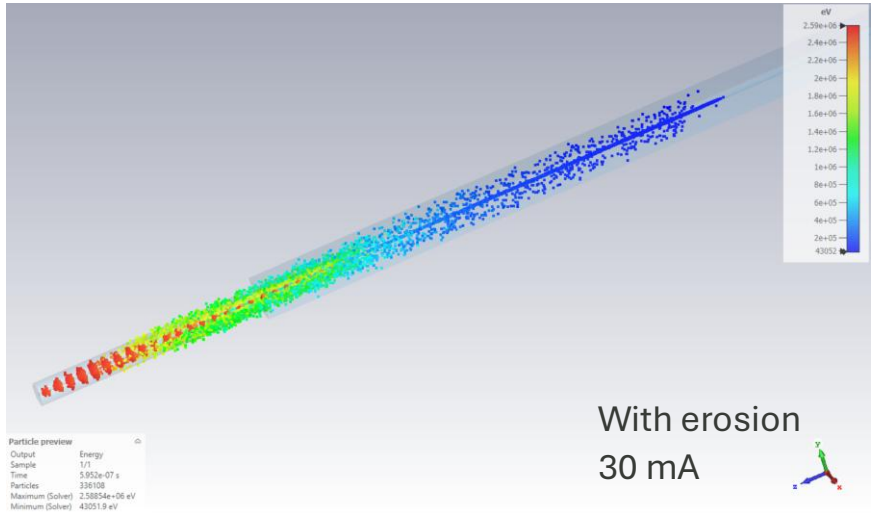
CST PIC Simulation – Particle distribution at RFQ exit

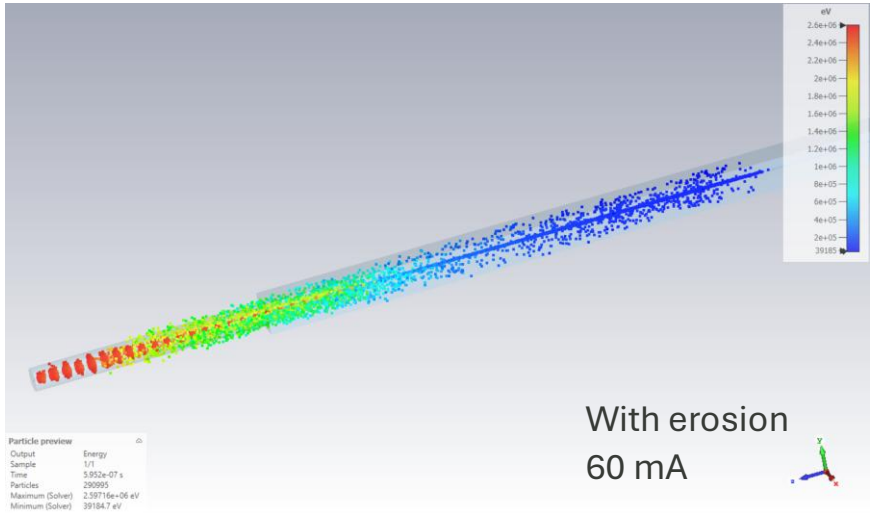
No Erosion



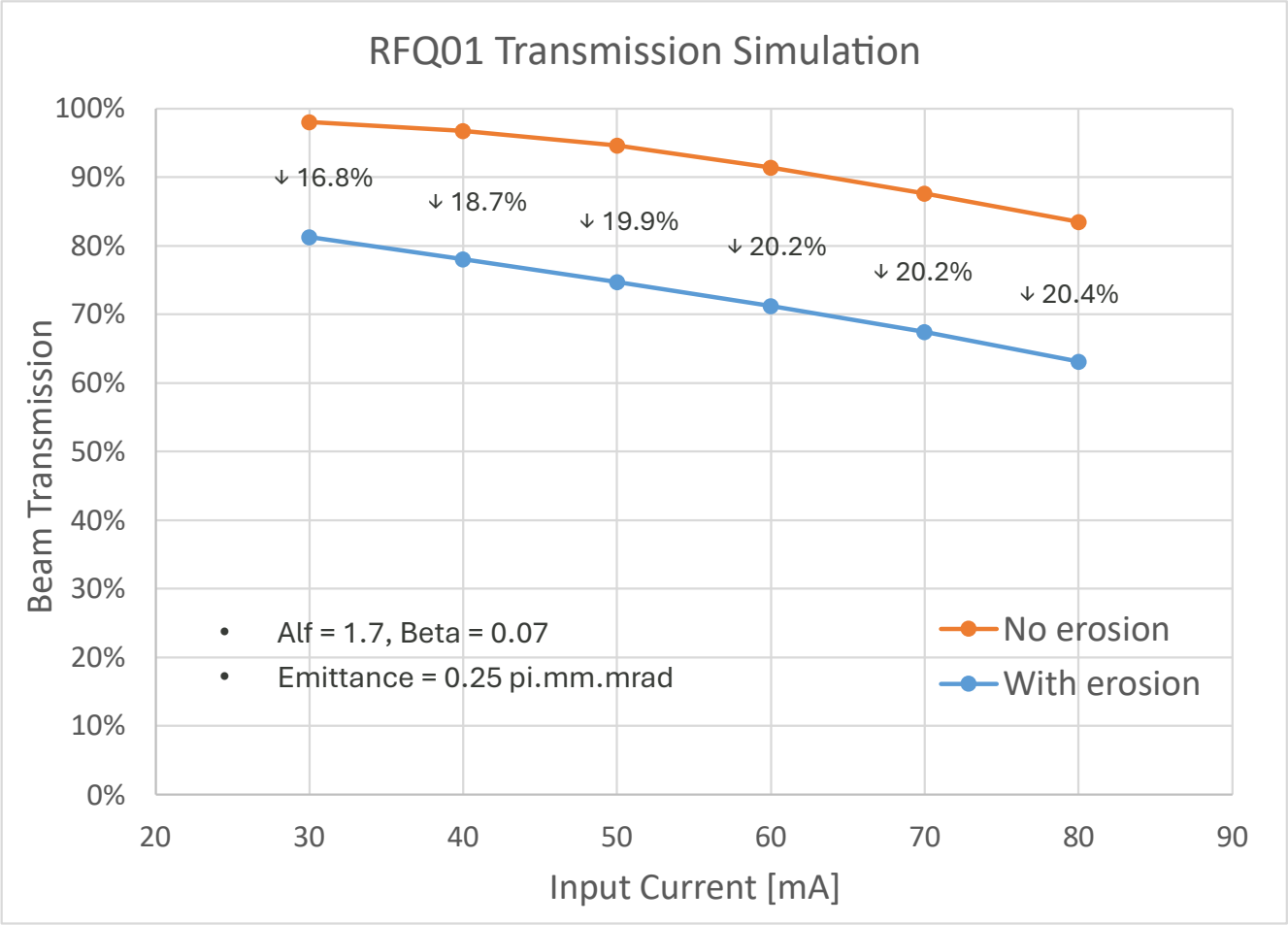


With Erosion



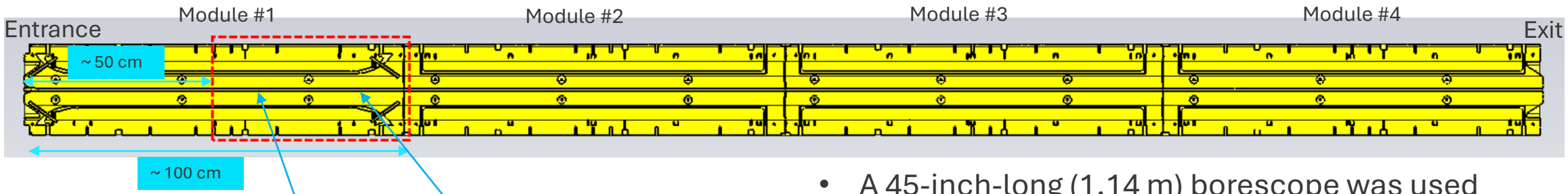


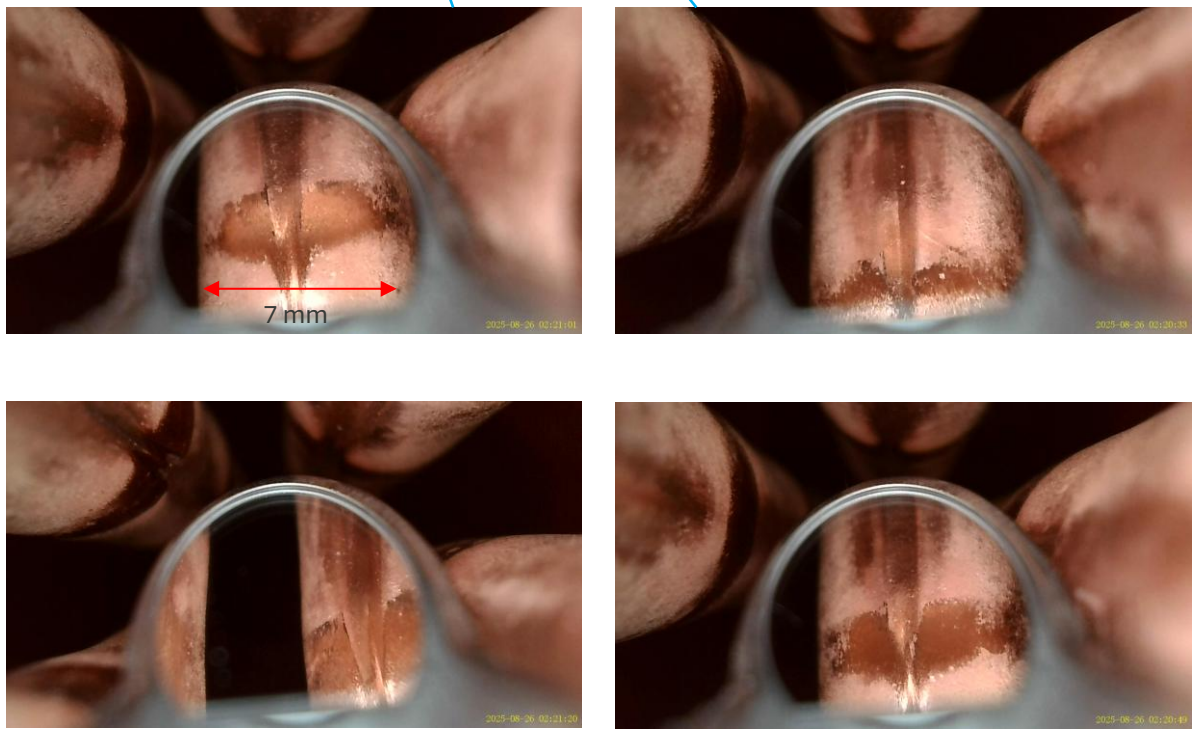
Entrance erosion impact for different input currents



Considering the entrance erosion only, RFQ beam transmission drops by about 20%

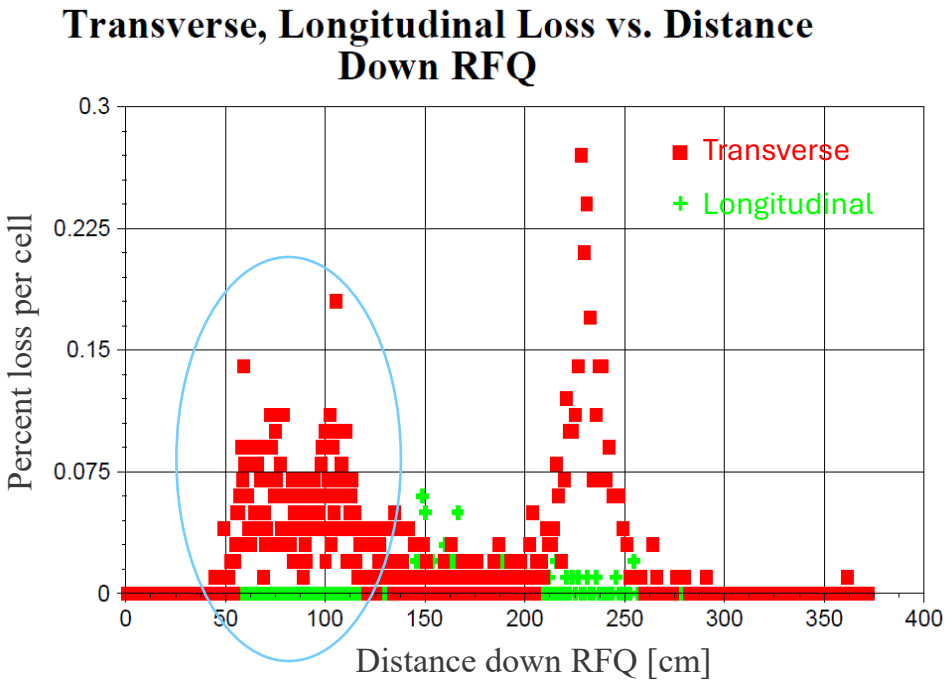
RFQ01 Borescope Inspection – More erosion observed





More erosion damage observed on vane tips in the second half of Module #1

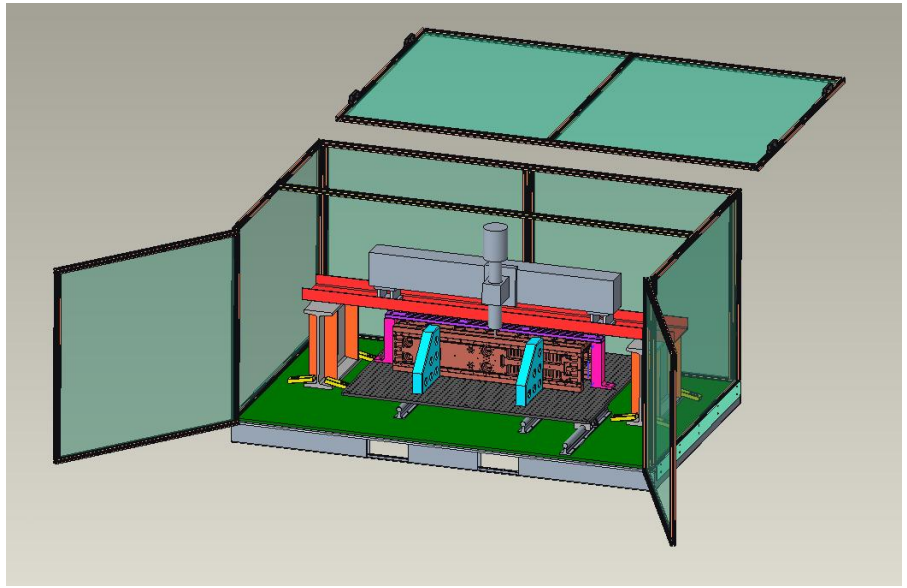
- A 45-inch-long (1.14 m) borescope was used
  - Not long enough to cover the full cavity

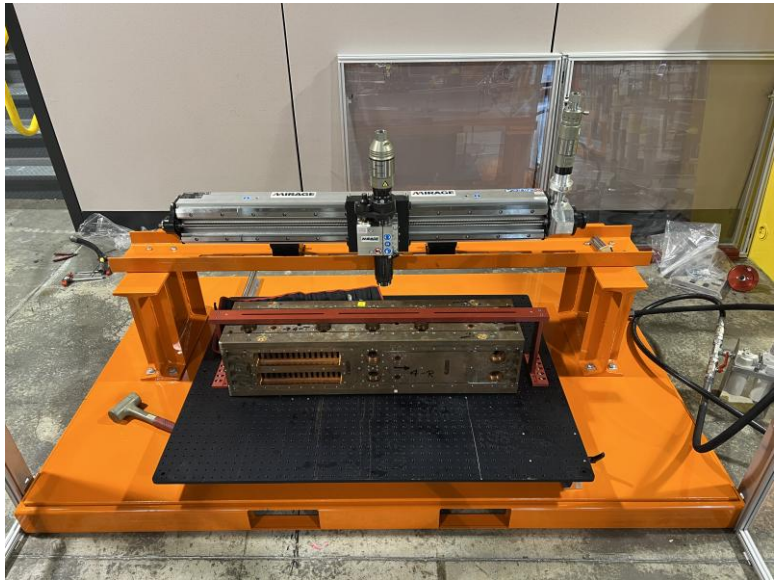


RFQ01 beam loss tracking (PARMTEQ)

RFQ01 cavity cutting is underway

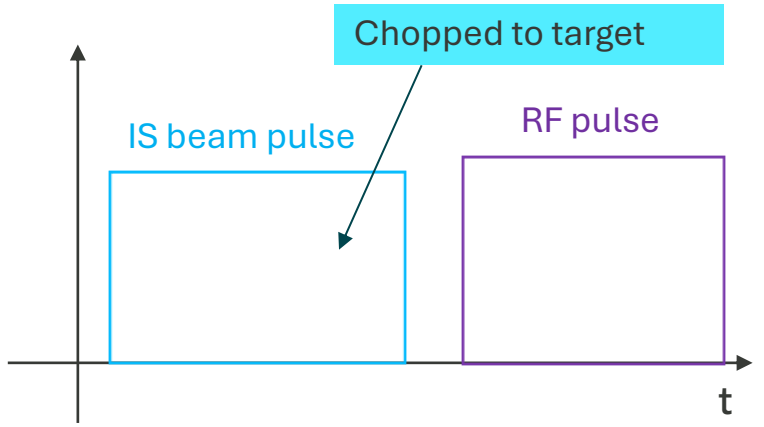
- RFQ01 is planned to be cut for a full-length scan
- Cutting fixture has been fabricated and is currently under assembly testing





Implications for High-Power RFQ Operation

- Entrance erosion correlates with the 65 keV input beam
- Localized erosion in downstream section of Module 1 needs better understanding
- Routine borescope inspection now applied to other SNS RFQs
- Mitigations at SNS:
  - Chopper upgraded to blank RFQ beam off-cycle – implemented
    - IS beam fully chopped now, won't enter RFQ
  - Under study:
    - Magnetic LEBT option
    - Additional collimation before RFQ
    - New RFQ design study for higher transmission



Summary

- The issues experienced with the original SNS RFQ were not fully understood, however
  - Post-mortem studies are now connecting those issues to physical mechanisms
  - Post-mortem studies are expected to tell the path forward for RFQ reliable high-power operation

THANK YOU