Operation Experience with SNS RFQs

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On behalf of the SNS team

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Acknowledgement

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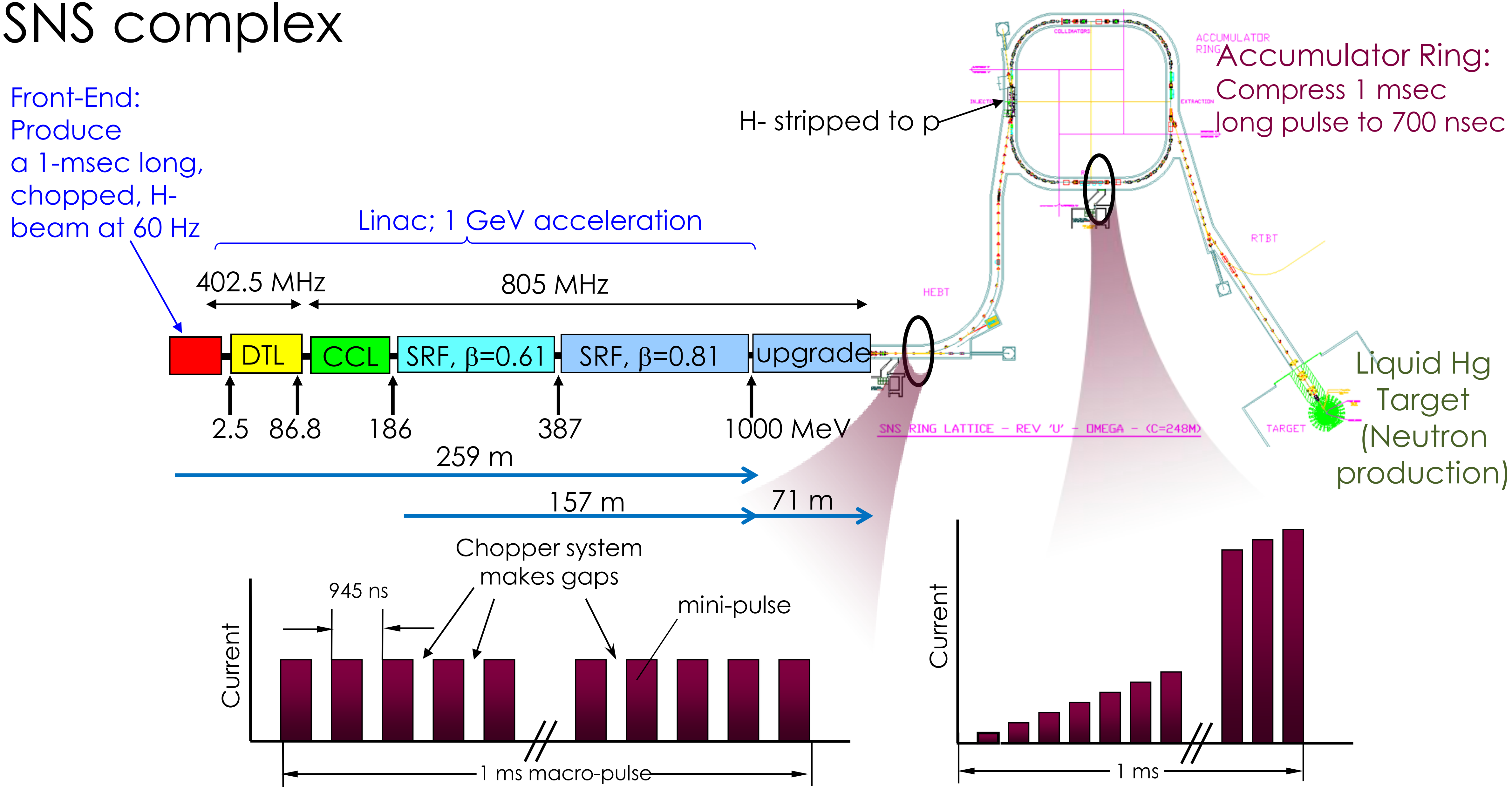
- The people at SNS who contributed to SNS RFQ efforts include A. Aleksandrov, W. Barnett, M. Champion, S. Cousineau, M. Crofford, G. Dodson, J. Galambos, N. Gerber, S. Henderson, G. Johns, Y. Kang, A. Menshov, R. Morton, S. Murray, S-W. Lee, C. Luck, R. Peglow, J. Pelfrey, C. Peters, F. Pilat, J. Price, T. Roseberry, A. Shishlo, M. Stockli, R. Welton, D. Williams, and many others

Outline

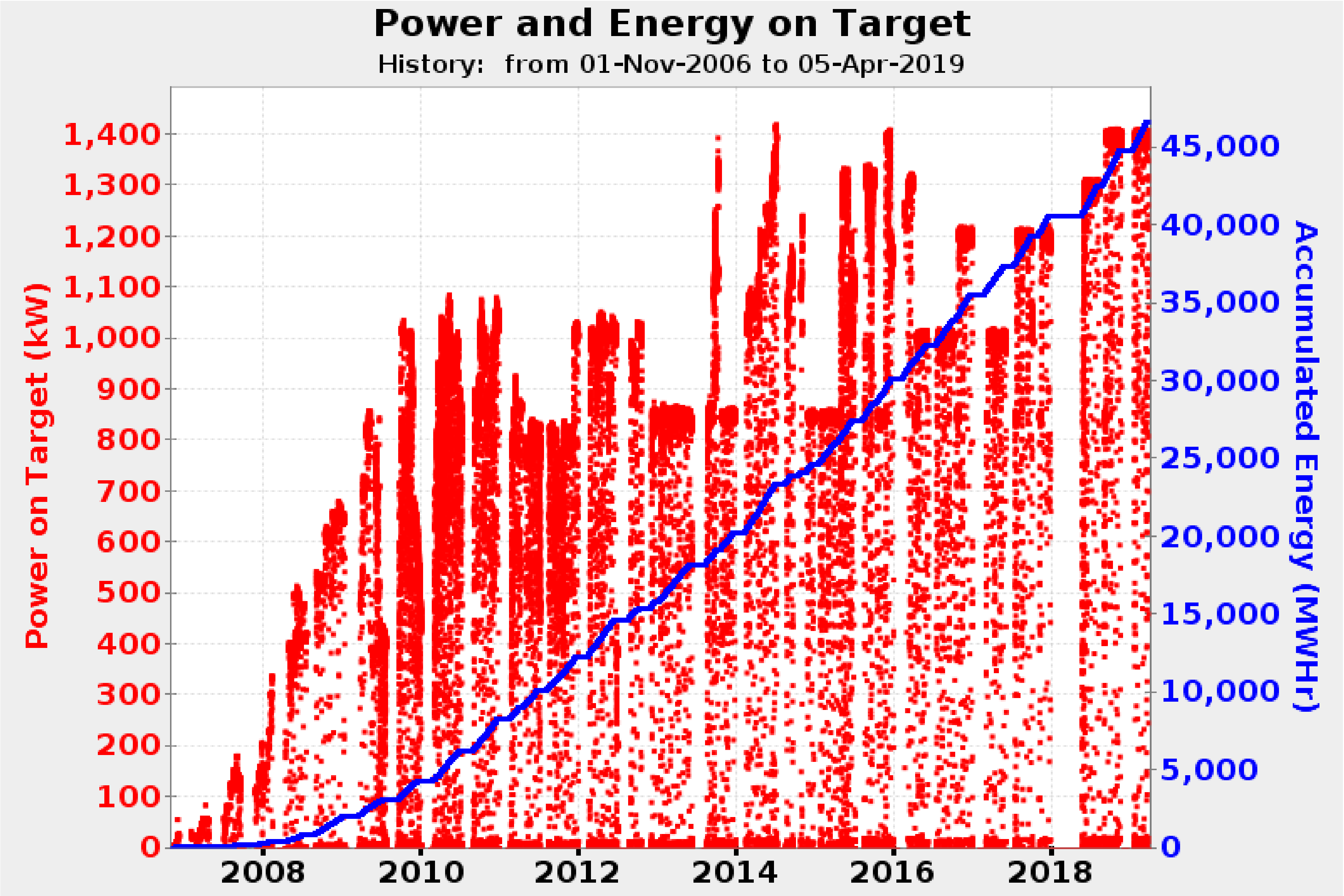
- SNS accelerator complex
- SNS operation history and status
- Experience with the original RFQ
- Experience with the new RFQ
- Summary

SNS complex

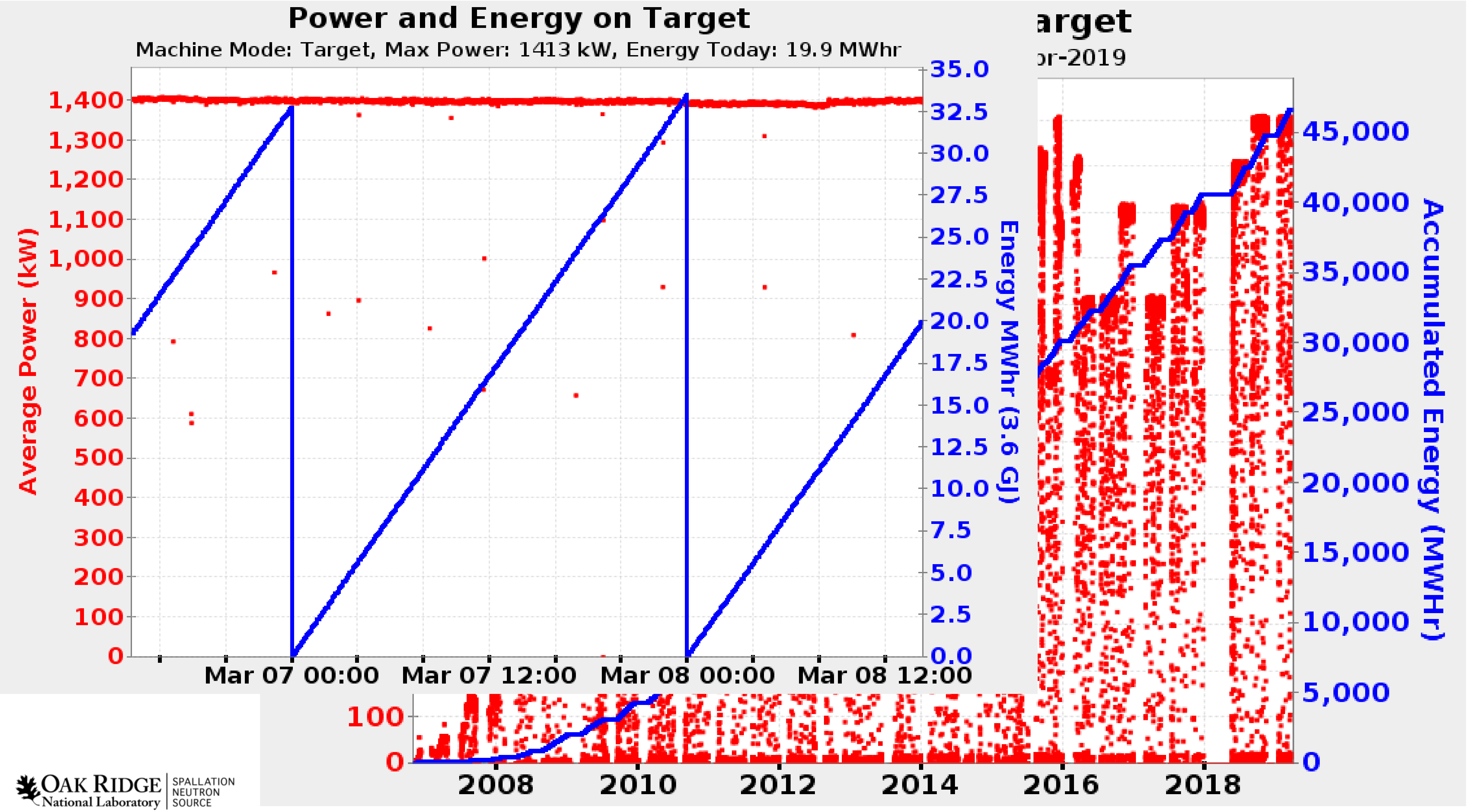


Average macro-pulse beam current:
26 mA

SNS operation history and status



SNS operation history and status



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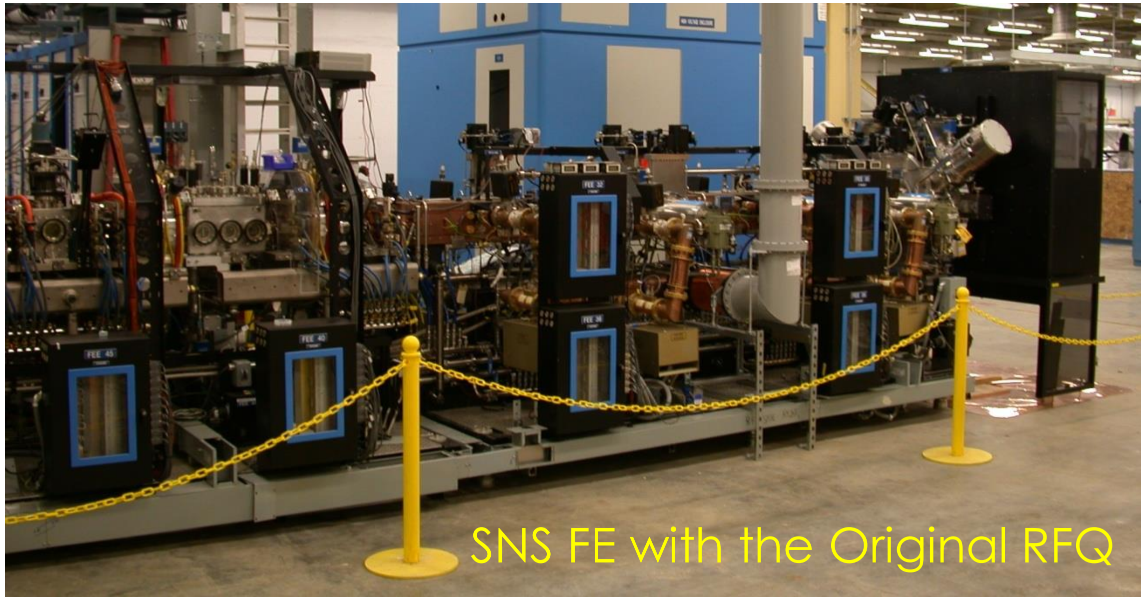
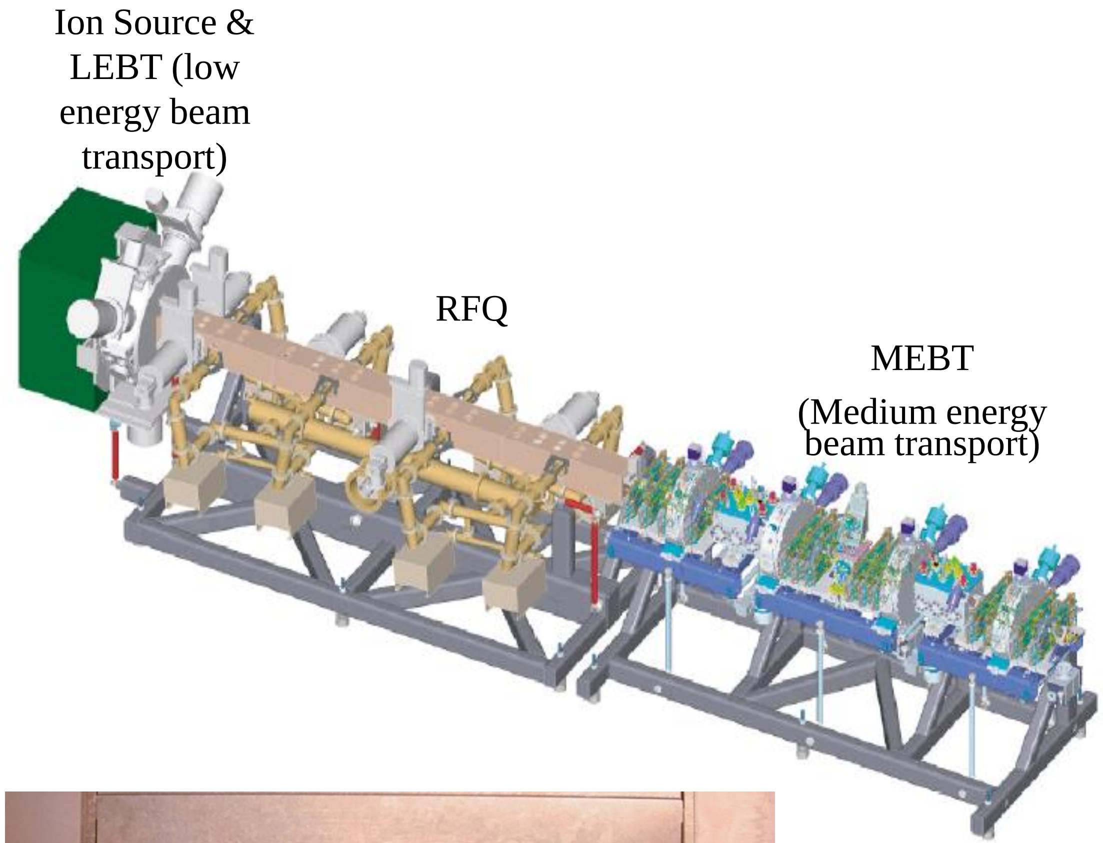
SNS Front-End (FE)

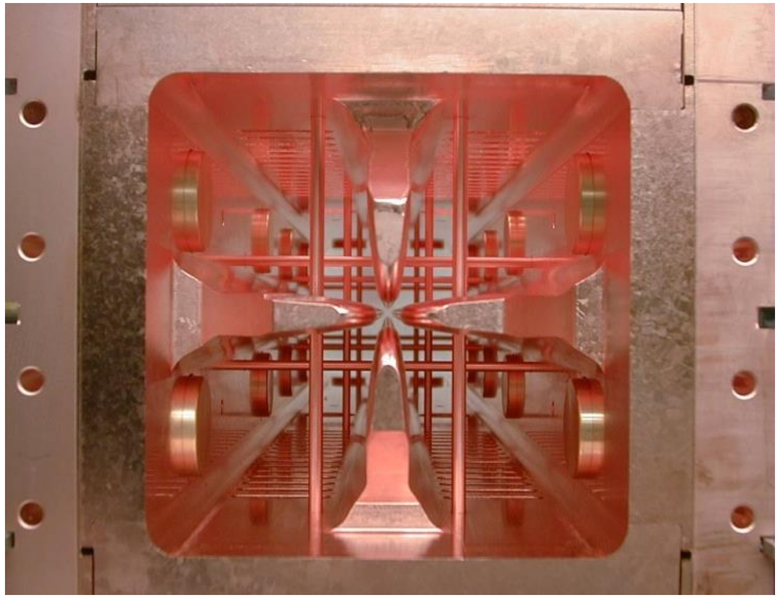
- FE System
  - 7.5-m long
  - H- ion source: 65 kV
  - Low energy beam transport system (LEBT)
  - 4-vane 402.5-MHz RFQ: 2.5 MeV
  - Medium energy beam transport system (MEBT)
- FE beam parameters
  - 26-mA macro-pulse average
    - 38-mA peak current
    - 70% beam-on chopping
  - 6% duty factor: 1 ms at 60 Hz



The original SNS RFQ (I)

- RF frequency: 402.5 MHz
- Design beam transmission: 90%
- Peak surface field: 83 kV (1.85 Kilpatrick)
- Dipole mode suppression: π-mode stabilizers
- Four segments: 3.7-m long
- RF power couplers: 8 coaxial couplers (later 2 coaxial couplers)
- Field profile tuning: 80 fixed slug tuners
- Vacuum pumping: Six cryopumps





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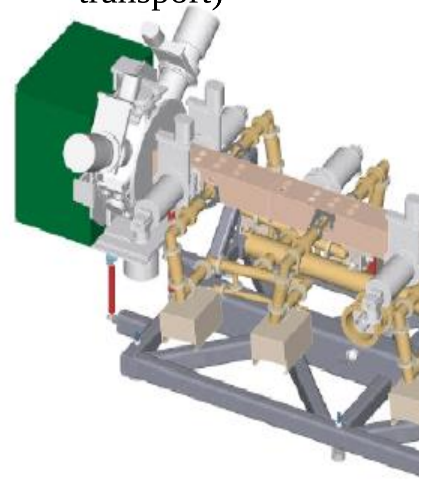
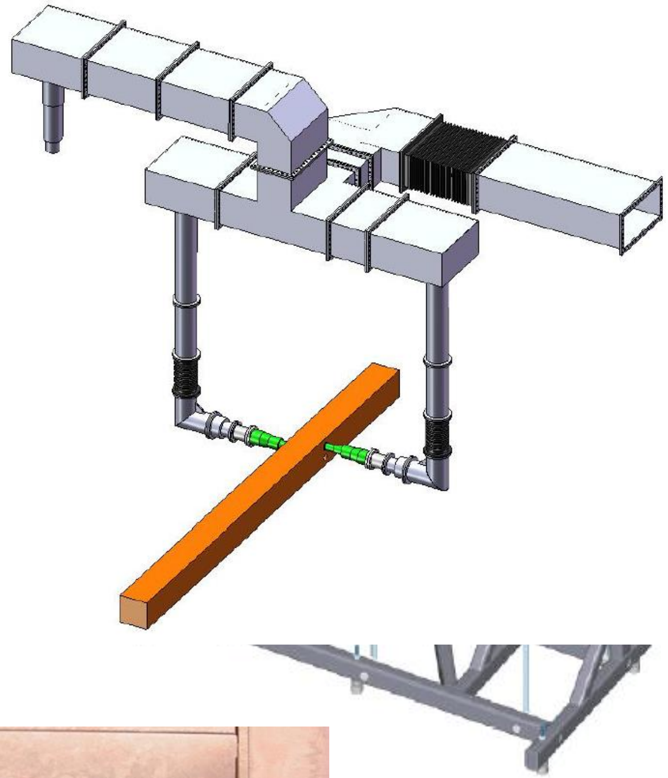
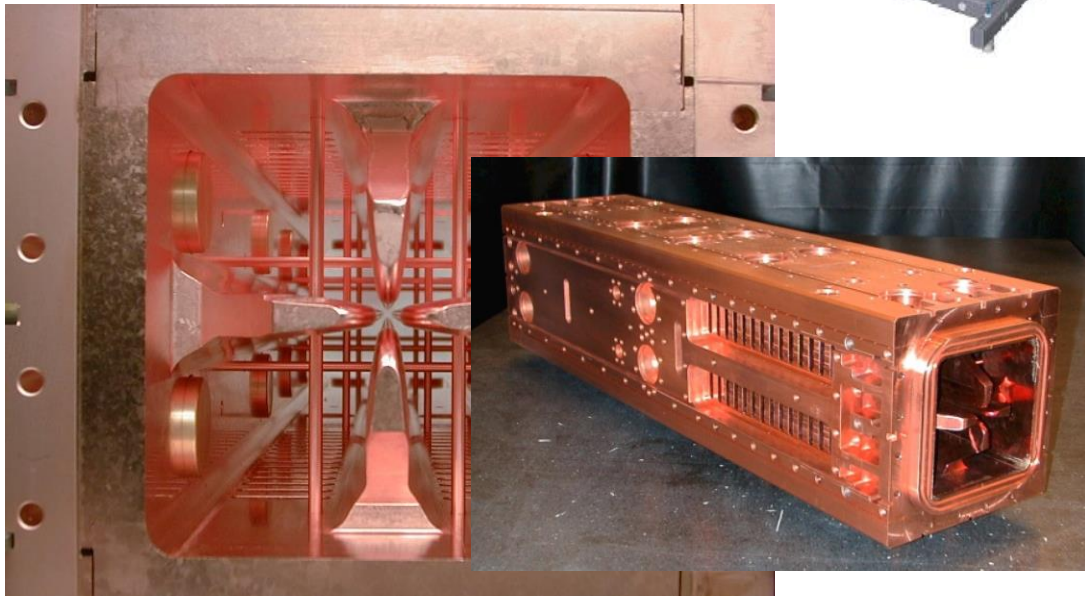
Ion Source & LEBT (low energy beam transport)

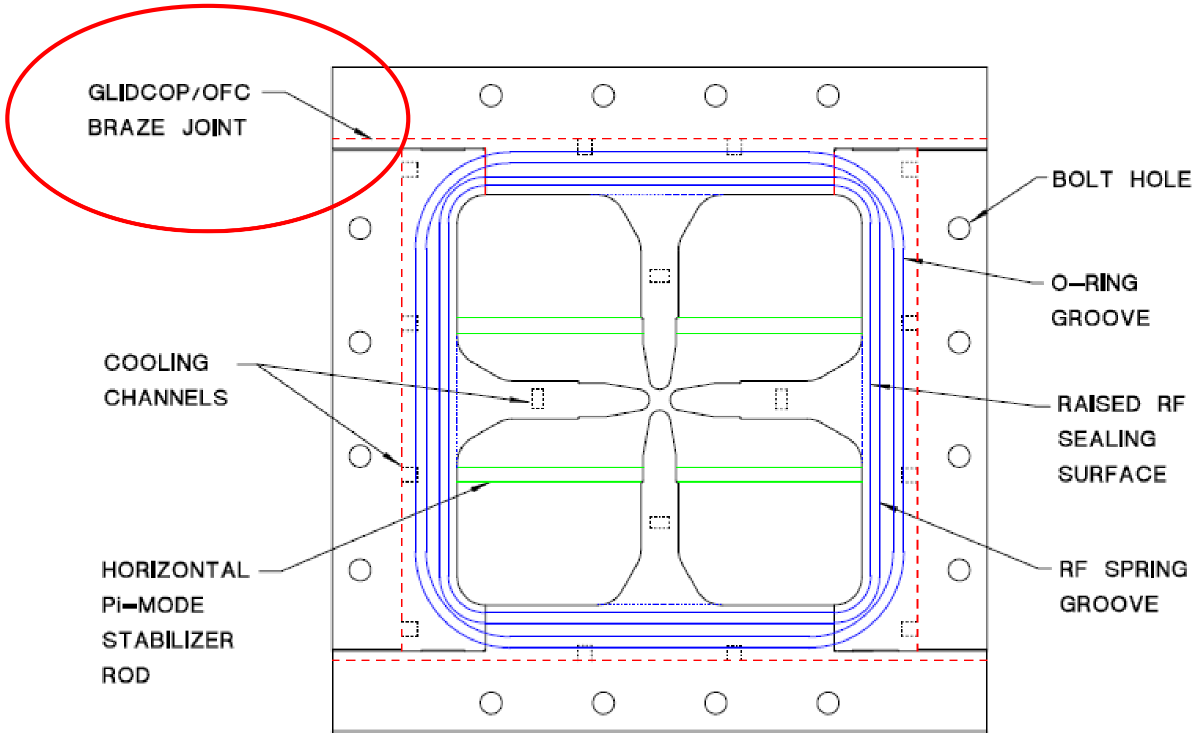


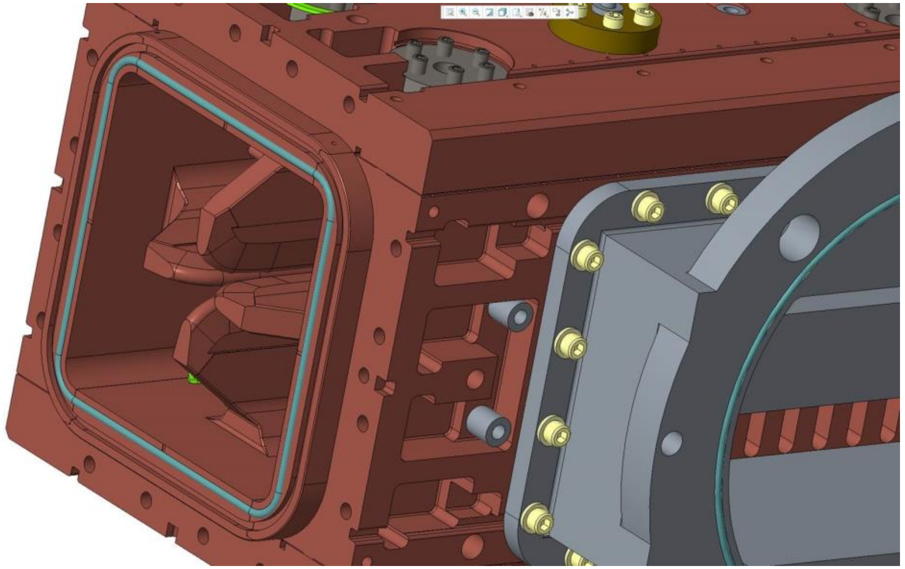




The original SNS RFQ (II)

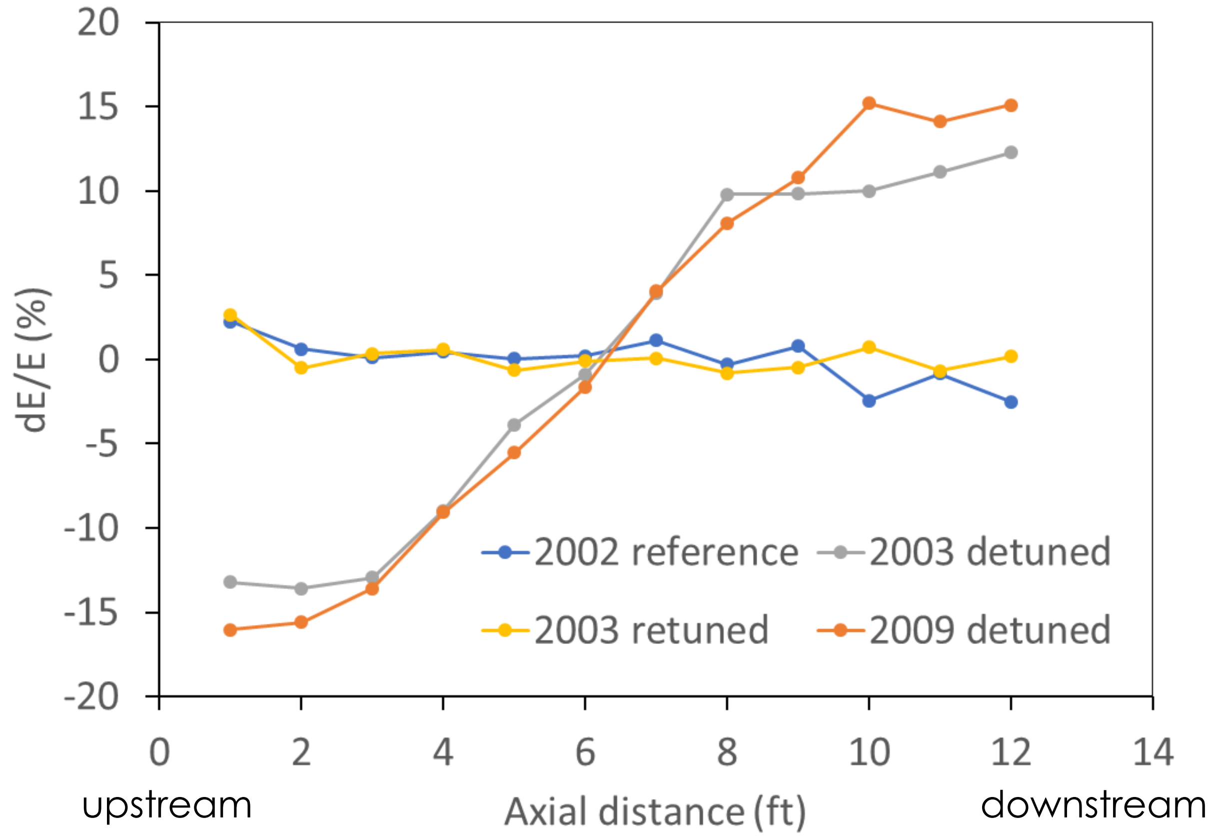
- Resonance control: water temperature (two chillers: one for vanes and one for walls)
- Vane tip sensitivity: 40 MHz/mm
- -33 kHz/°C vane cooling water temperature
- +27 kHz/ °C wall cooling water temperature
- Glidcop/OFC braze joints





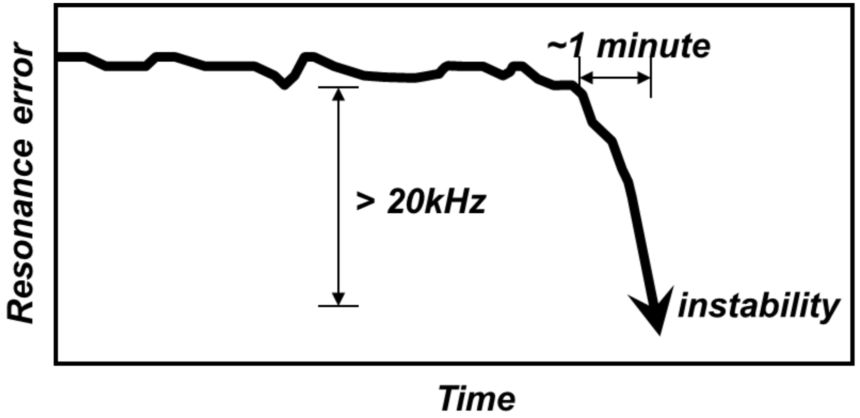
Issue (1) with the original SNS RFQ – Sudden detuning

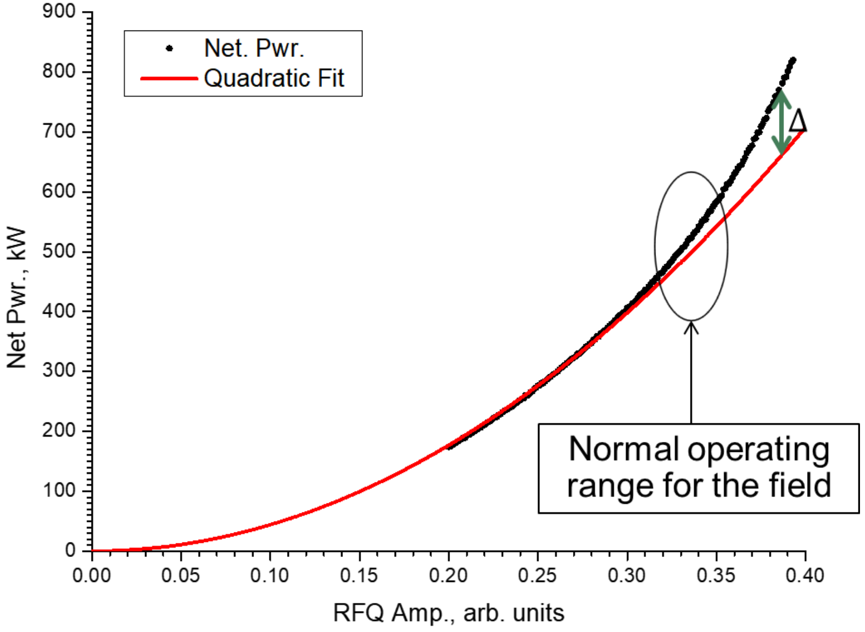
- First detuning event in 2003
  - About -450 kHz detuning
  - Suspect Glidcop/OFC brazing joint but **inconclusive**
    - Happened when cooling water system control was down
  - Retuned and back to service
- Second detuning event in 2009
  - About -230 kHz detuning
  - Suspect Glidcop/OFC brazing joint but **inconclusive**
    - Happened when cooling channel was over-pressurized by accident
  - Retuned and back to service



Issue (2) with the original SNS RFQ – Operational instability

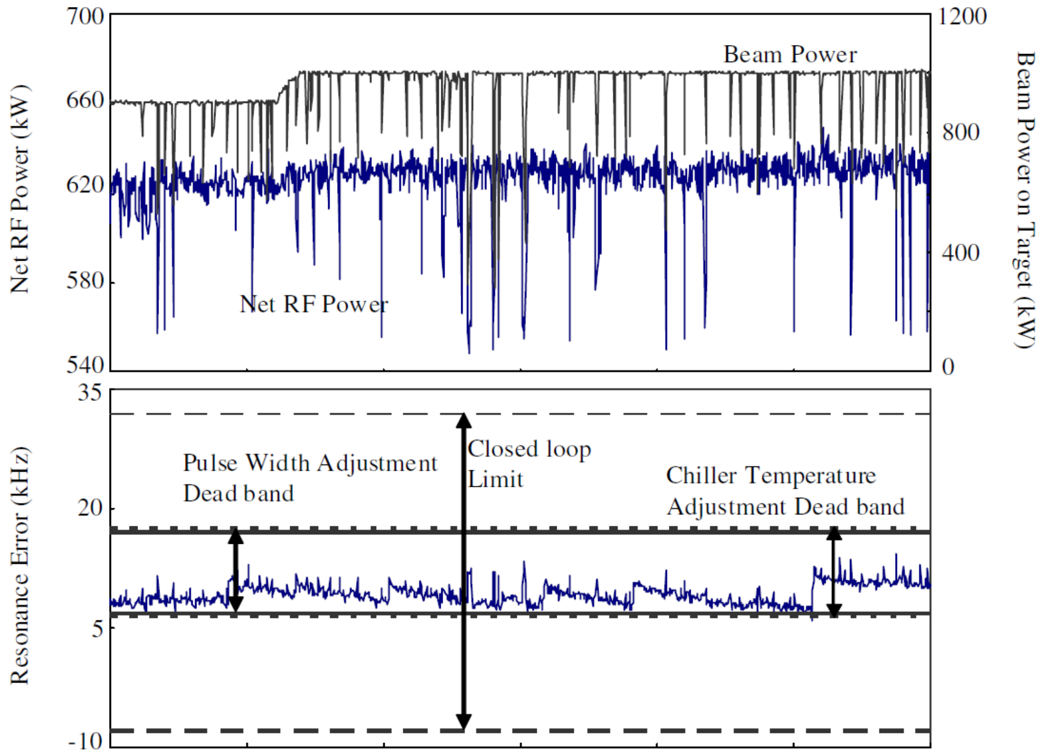
- Difficult to keep RFQ in closed-loop as we increased duty factor (2009)
- Findings
  - Changes in net RF power while running at constant setpoints (field setpoint, cooling, etc.)
    - Net RF power=Forward pwr – reflected pwr
  - Non-quadratic relation between net RF power and RFQ field amplitude
  - Correlation with Ion source/beam
- The root cause is not fully understood
  - Additional load (discharge somewhere in the structure?)





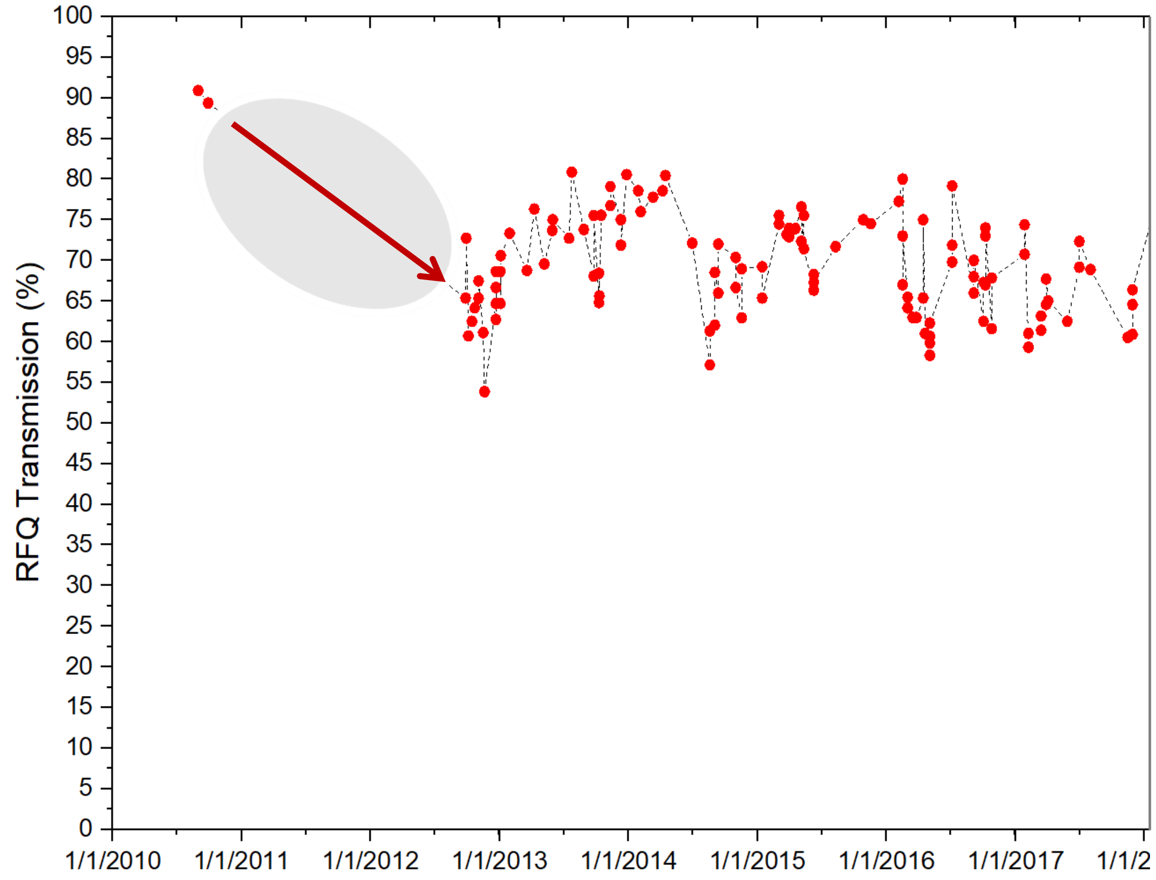
Operational improvement with the original SNS RFQ for > 1-MW operation (2009-2010)

- Reduced field setpoint
  - Kept 85%~90% beam transmission
- Reduced hydrogen flow in ion source
- Upgraded Chillers for cooling
- Improved vacuum pumping for ion source
- Implemented RF pulse length adjustment in LLRF control
  - About +/- 50 us RF pulse length



Issue (3) with the original SNS RFQ – Beam transmission

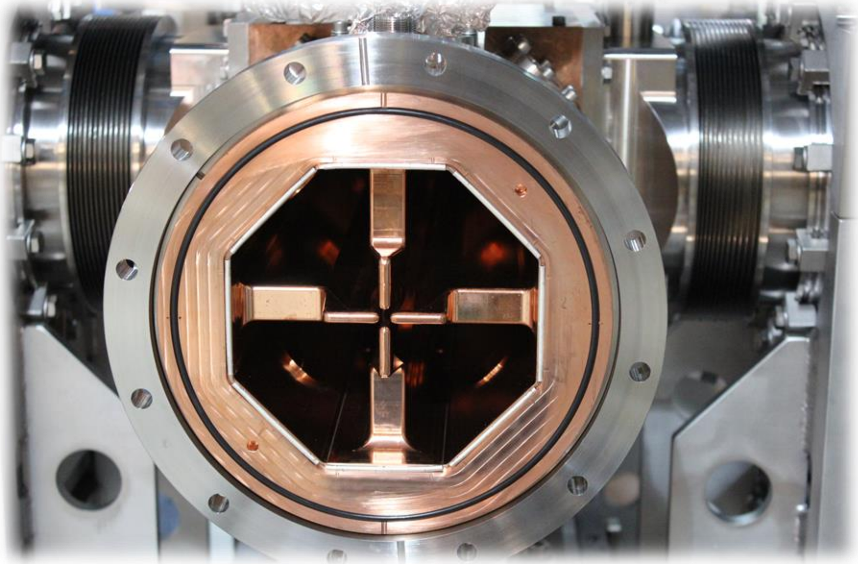
- Gradual field profile changes
  - Happened over 2 years
  - Gradual (?) reduction of beam transmission by 20-30%
- No significant detuning
- Measured field flatness in 2013: -15/+5% (upstream/downstream)
  - Retuned in 2013
  - But beam transmission did not recover. **Root cause unknown**
    - Retuning is only for overall field balancing
    - If damages are around vanes, irreversible

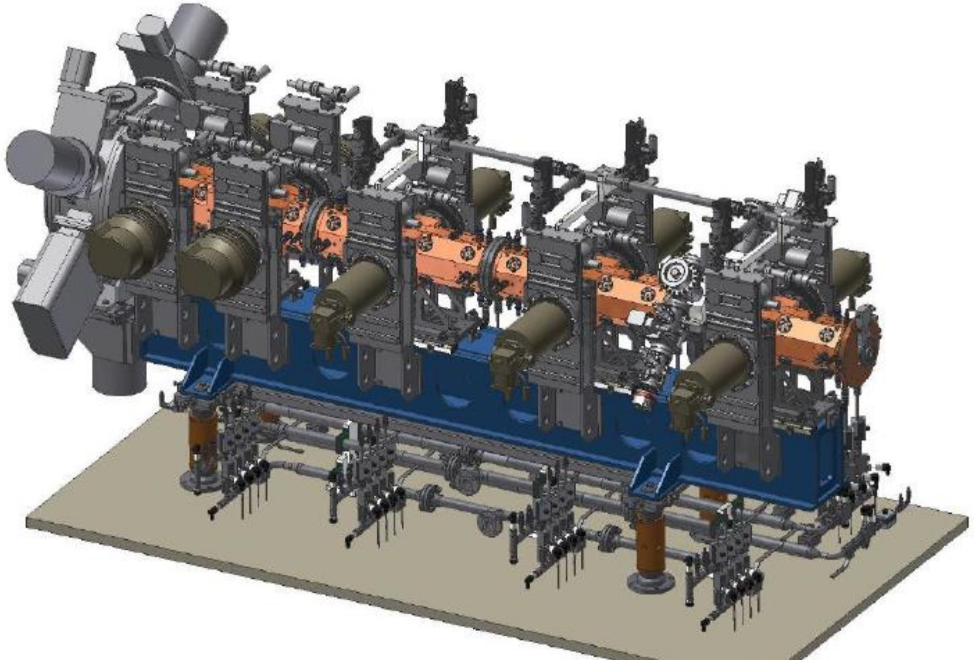


The original SNS RFQ is marginally operable for1.4-MW beam power

New SNS RFQ (I)

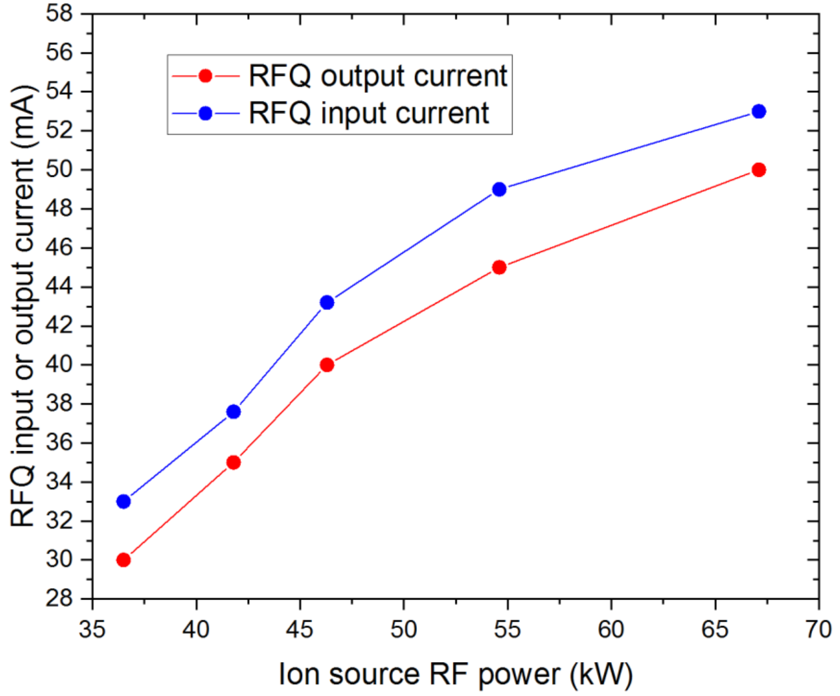
- Same beam dynamics design
- Same RF input (2 coaxial couplers)
- Same resonance control scheme
- Design changes
  - Solid copper RF structure
    (vs. Glidcop/OFC brazing)
  - Improved vacuum pumping
    4 cryo-pumps and 4 turbo pumps
  - Improved water cooling
  - 4 rods for dipole stabilizer
    (vs. π-mode stabilizers)
  - RF seal scheme

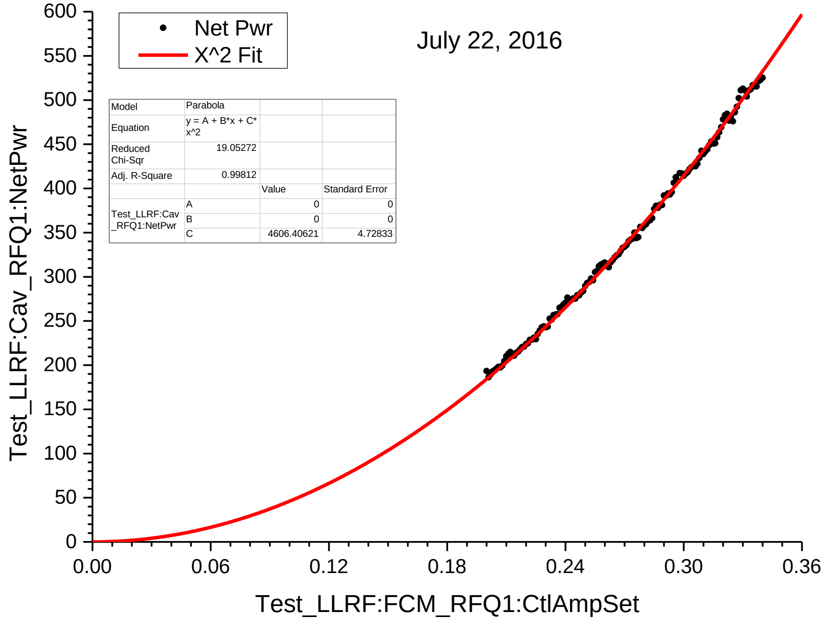




New SNS RFQ (II)

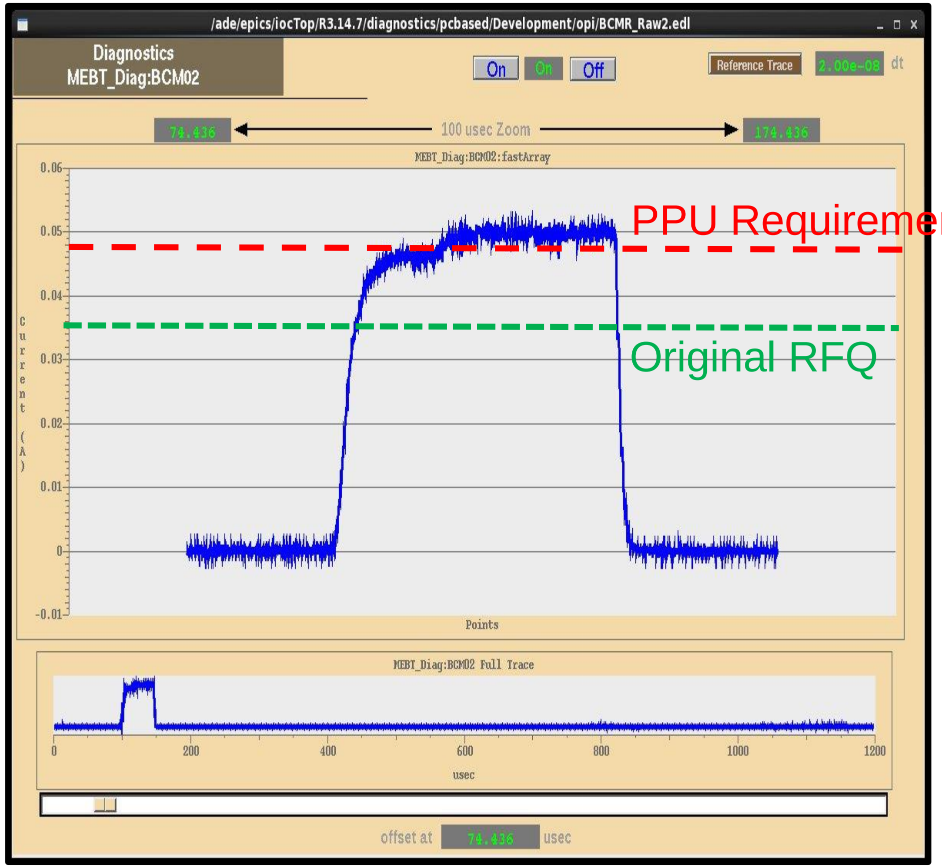
- The new SNS RFQ was commissioned with beam at SNS beam test facility in 2017
- Installed for operation in 2018
- Performance
  - Transmission: ~90% or higher
    - **Provided a very stable beam for 1.4-MW operation** with **enough margin**
  - Beam emittances are satisfactory
  - No non-quadratic growth of RF power with field





SNS front-end with the new RFQ demonstrated beam current required for PPU

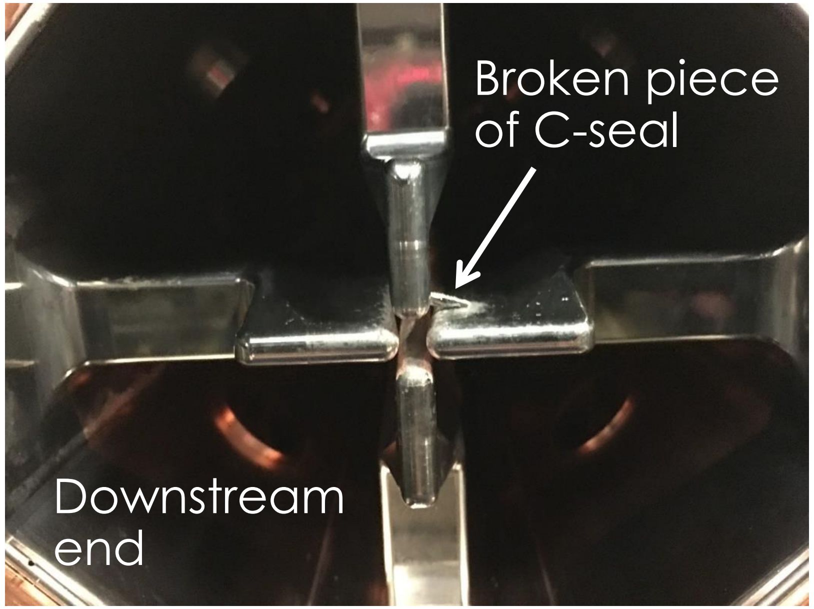
- SNS Proton Power Upgrade (PPU) project: 2.8-MW capable accelerator
  - Increase beam energy: 1 GeV → 1.3 GeV
  - Increase beam current (macro-pulse average): 26 mA → 38 mA
- Beam current out of new RFQ
  - > 40 mA macro-pulse average (>50 mA peak current)

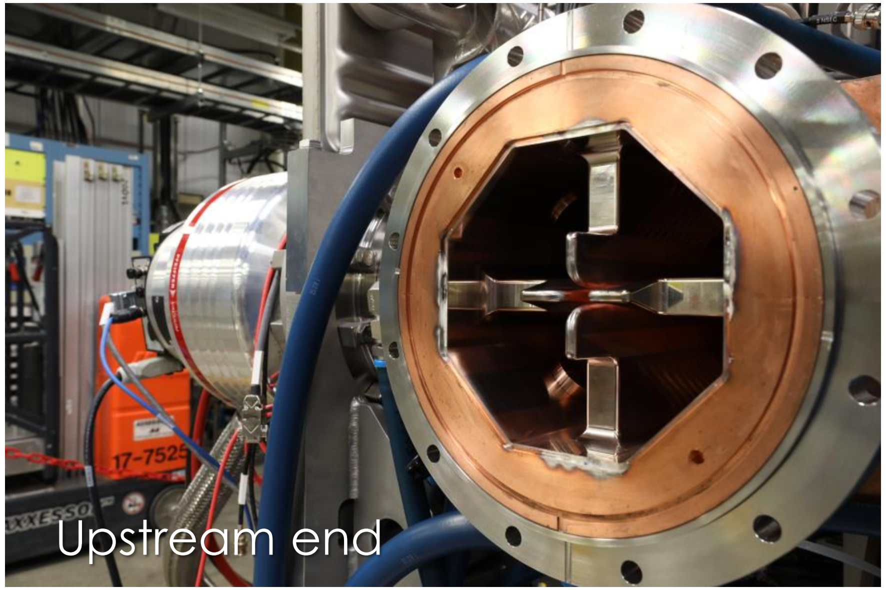


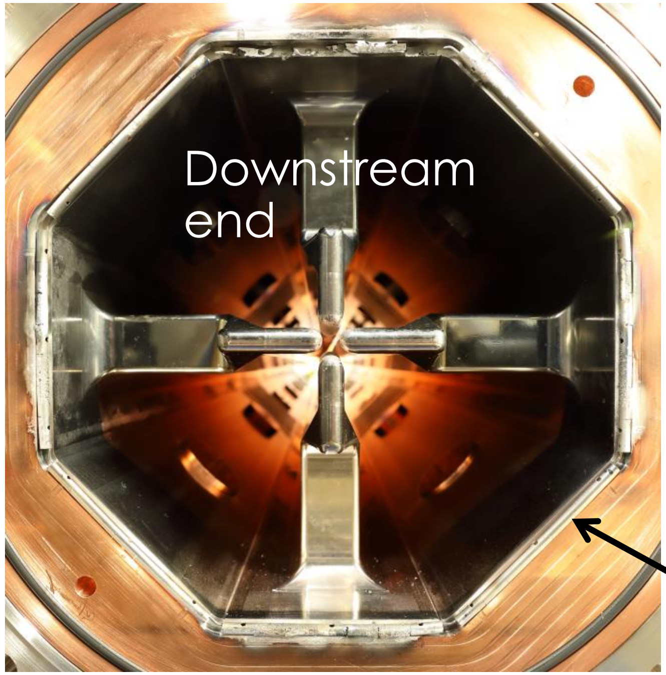
Issue with the new SNS RFQ – RF seal (C-seal)

- RFQ tripped and required investigating
  - Happened at the end of the first period of FY19 machine run (Nov. 2018)
  - The new SNS RFQ had been operated at high power and high duty factor (>5%) for 4900 hours until this trip
- Findings
  - No quadrupole mode near the operating frequency, 402.5 MHz
    - A broken piece of the C-seal shorten two vanes at the downstream side
  - Damage of C-seal at both ends (more severe damage at the down stream side)

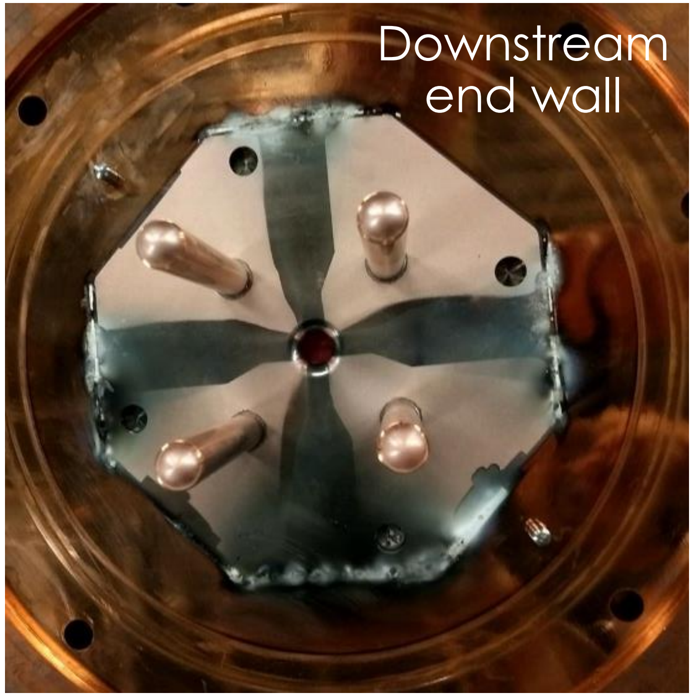
Damages





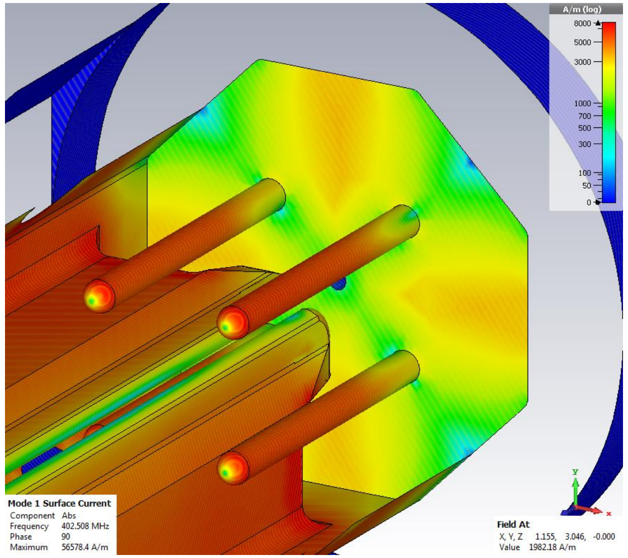


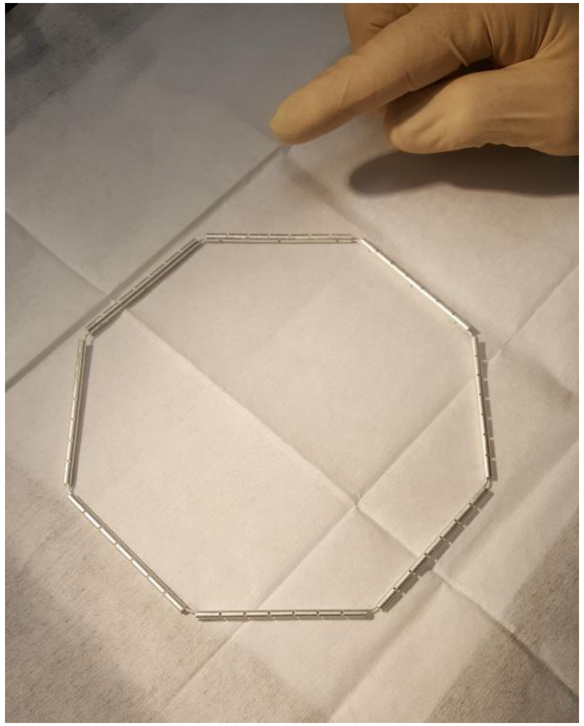
Octagonal-shape C-seal

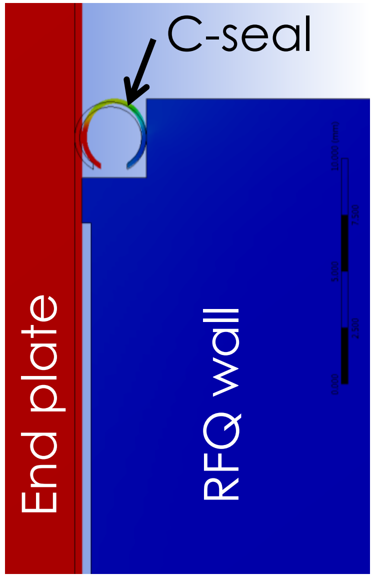


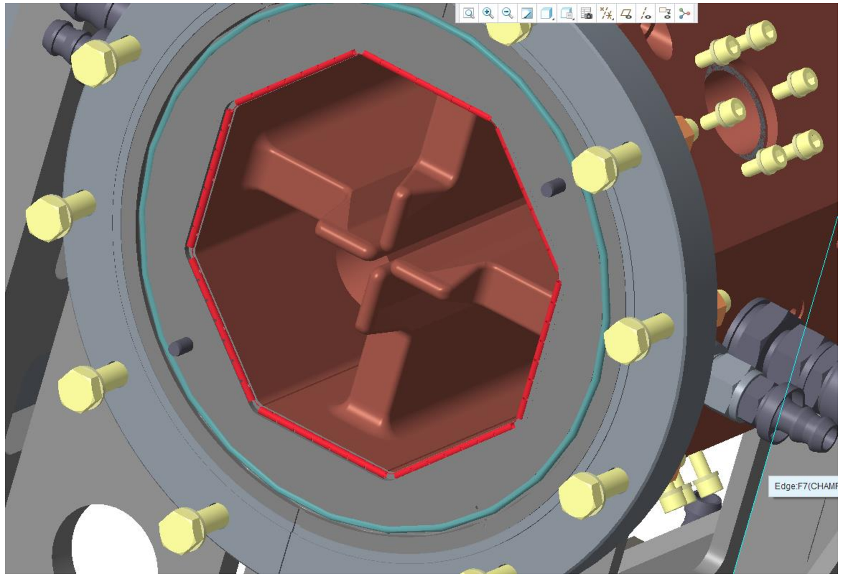
C-seal failure

- Pure thermal load from surface RF field can not explain the RF seal failure
  - Total RF power loss on C-seal < 0.2 W (silver, copper)
- Investigation is ongoing for root cause
  - Bad contact?
  - Discharge? Multipacting?



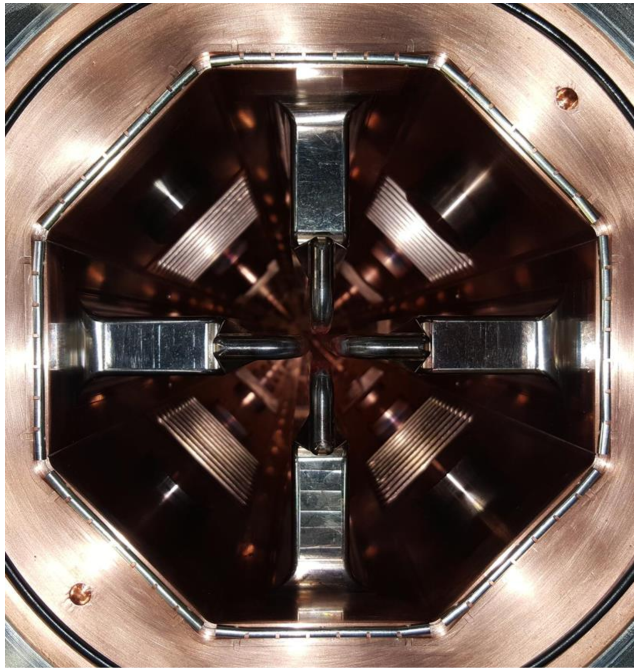


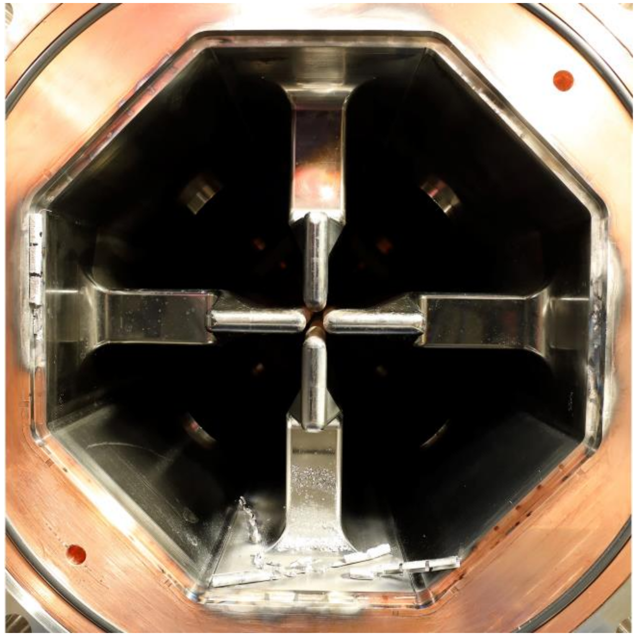




Temporary repair and back to operation

- No fundamental fix yet
  - Removed the broken C-seal piece
  - Cleaned damaged areas
    - Chemical cleaning for Ag and mild mechanical polishing
- RFQ back to service in Jan. 2019 and supported 1.4-MW operation for 2.5 months until planned machine outage
- Opened both ends of RFQ for inspection and repair
  - Severe damages of C-seal at the downstream end

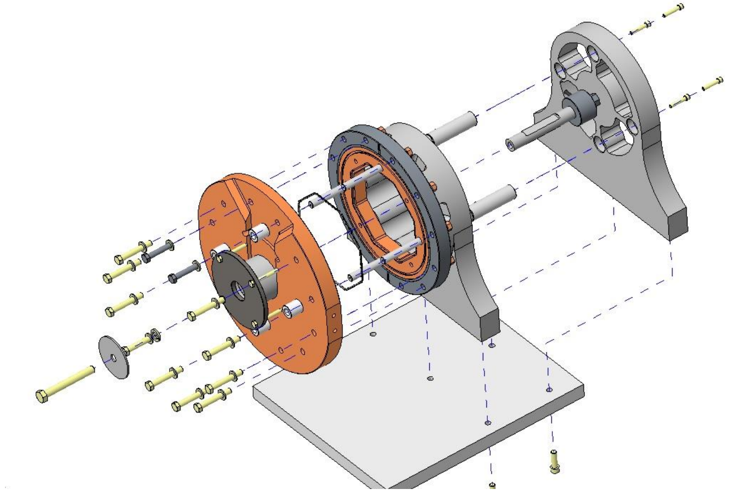


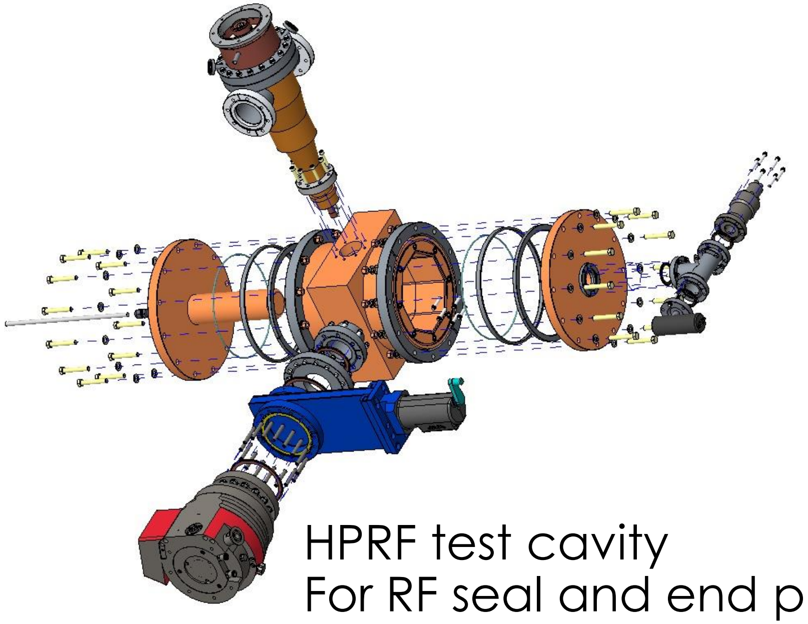


Plans

- Task force has been formed for RFQ recovery
- Short/medium term
  - Replace RF-seal during planned outage period
  - Run RFQ at minimum field required for 1.4 MW
  - Design new RF seal and/or modify design for end plate
  - Test of new RF seal and/or modified design of end plate
- Long term - Another new RFQ
  - No design changes except end wall/RF contact

RF seal mechanical test





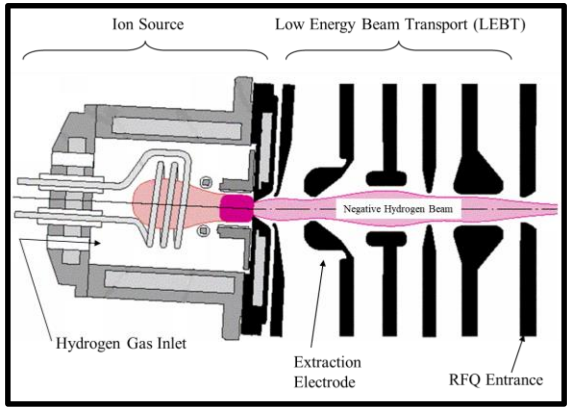
HPRF test cavity
For RF seal and end plate

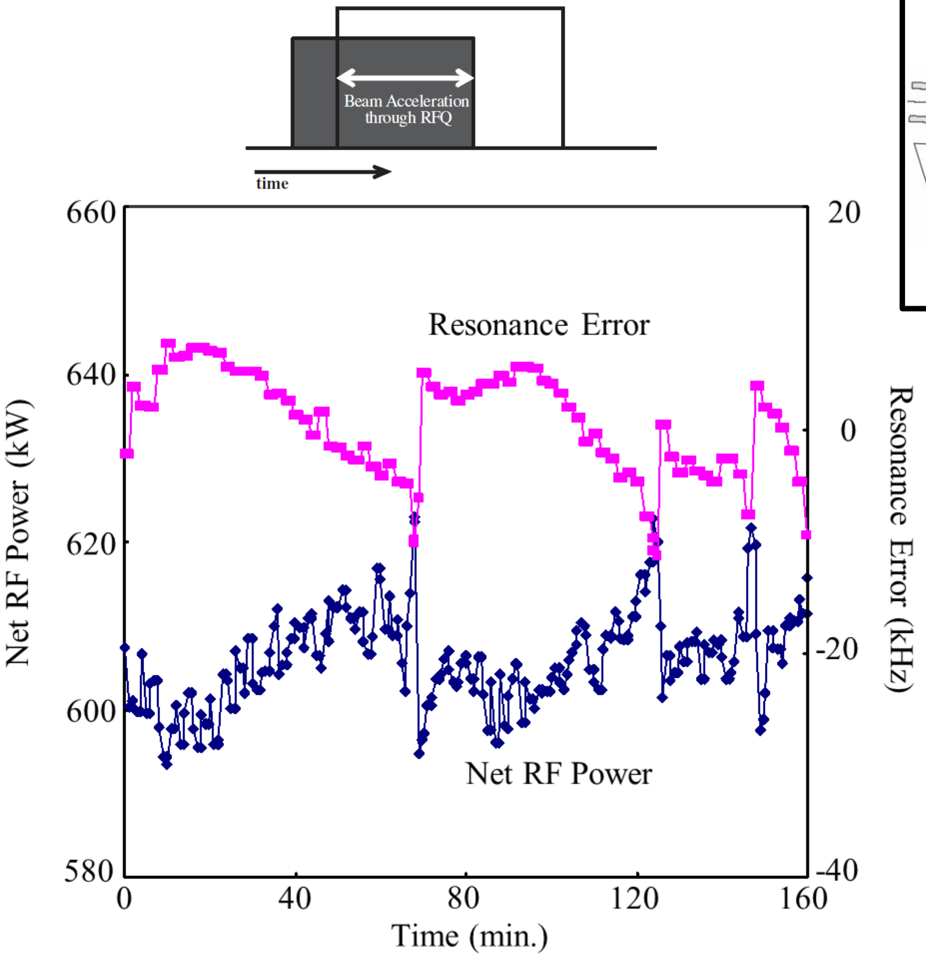
Summary

- The issues experienced with the original SNS RFQ were not fully understood, however
  - RF truncations (faults)/trip rate increases with beam at higher duty factor
  - Sufficient (not marginal) cooling and vacuum pumping are essential
  - Non quadratic relation between net RF power and RFQ field is not understood. Suspect discharge
- The new SNS RFQ showed very good performances (high transmission, provided enough margin for 1.4-MW operation)
  - One critical design flaw is identified so far related to RF seal
    - It seems very problematic when RF seal is directly facing RF field
    - RF seal compression for good RF contact may not be enough
- Nuisances are design dependent
  - Unexpected issues can arise from innocuous design choices

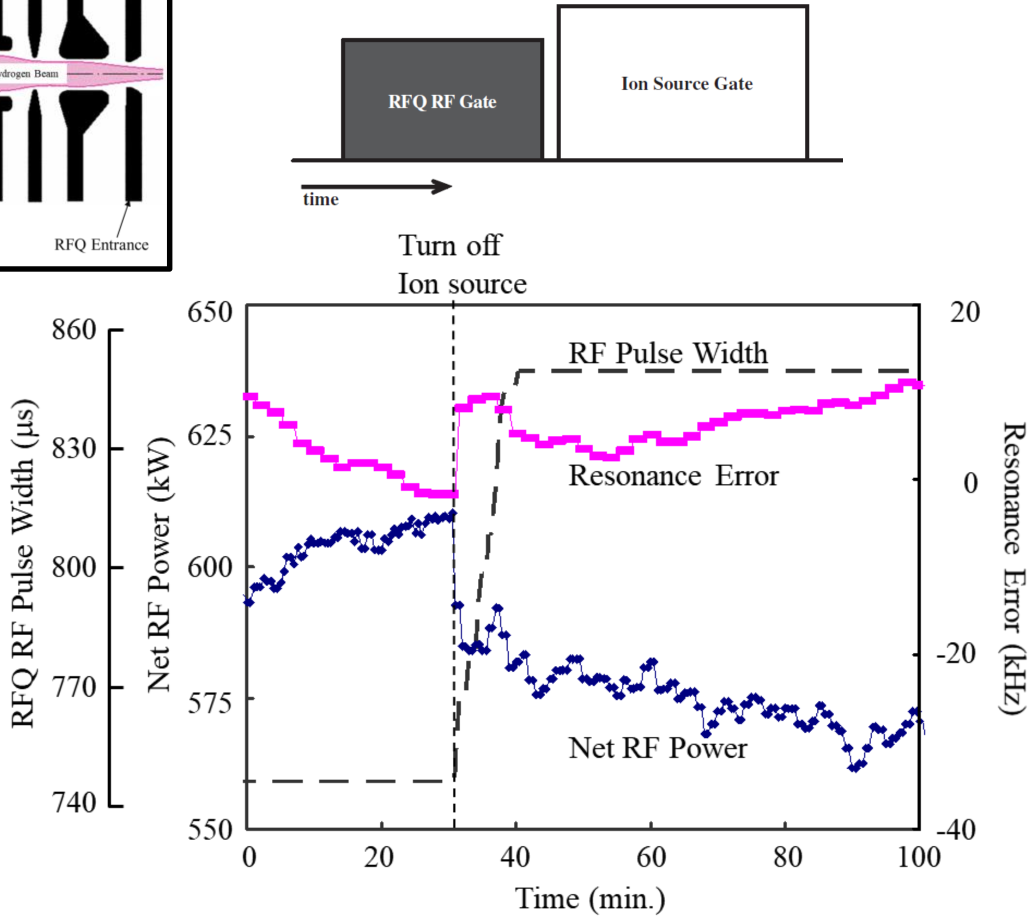
Backup slide

Examples of the original SNS RFQ: Net RF power vs. Resonance error





Beam accelerated through RFQ



No beam accelerated through RFQ

FY19 SNS Operating Schedule