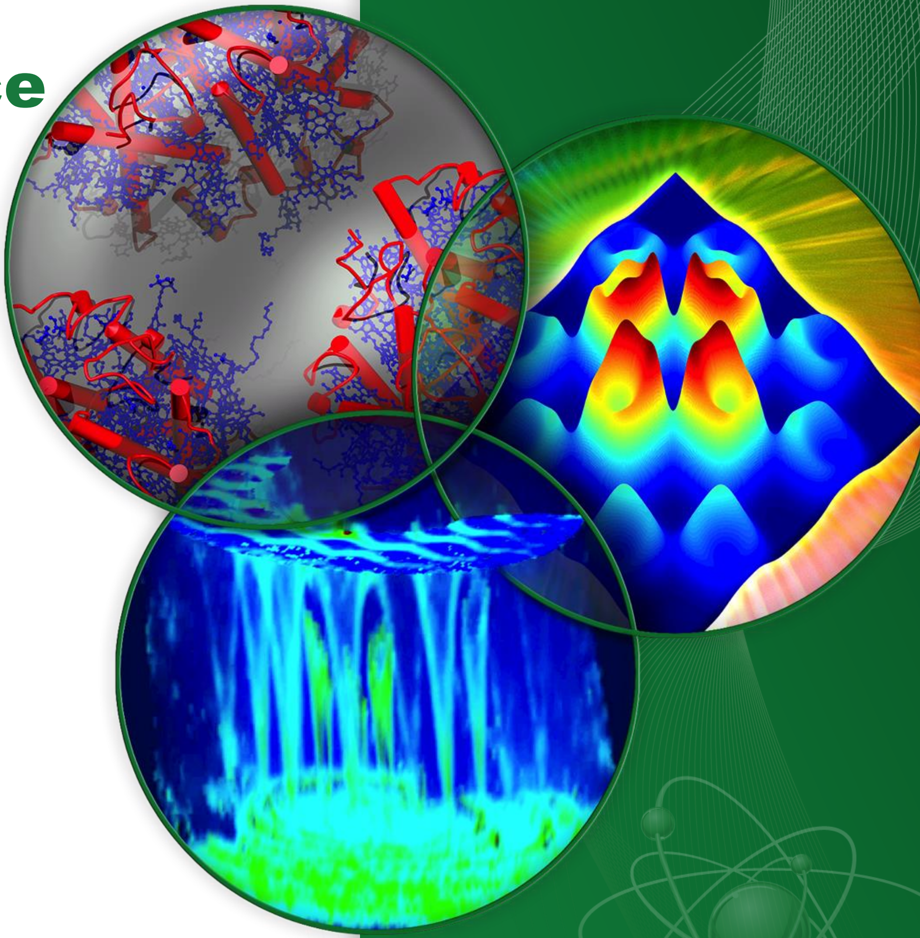
# SNS Superconducting Linac: Operational experiences and plans for performance improvement



Presented at Jefferson Lab

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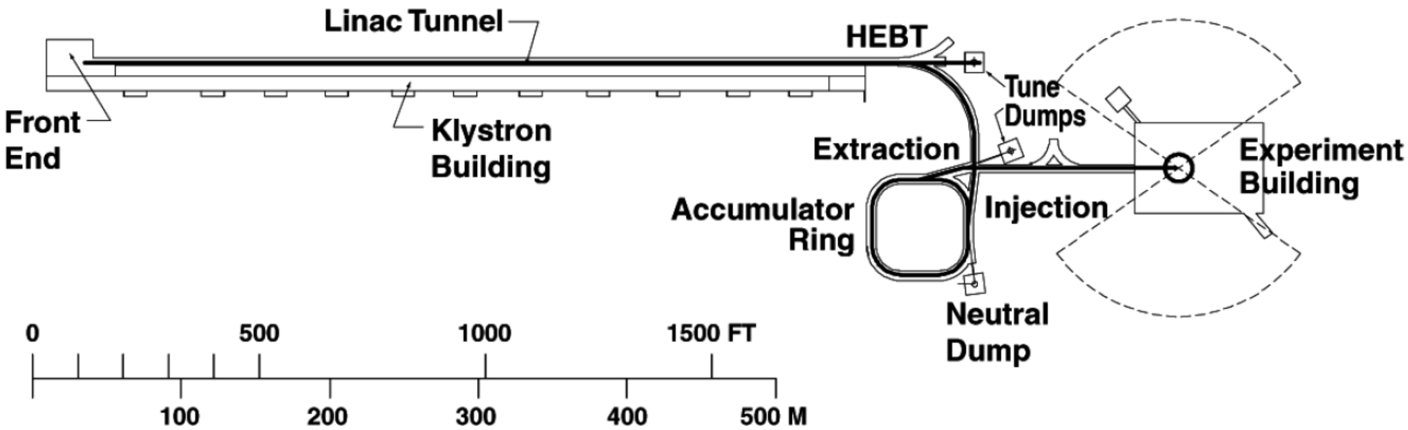
OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR | SPALLATION NEUTRON SOURCE

# Overview

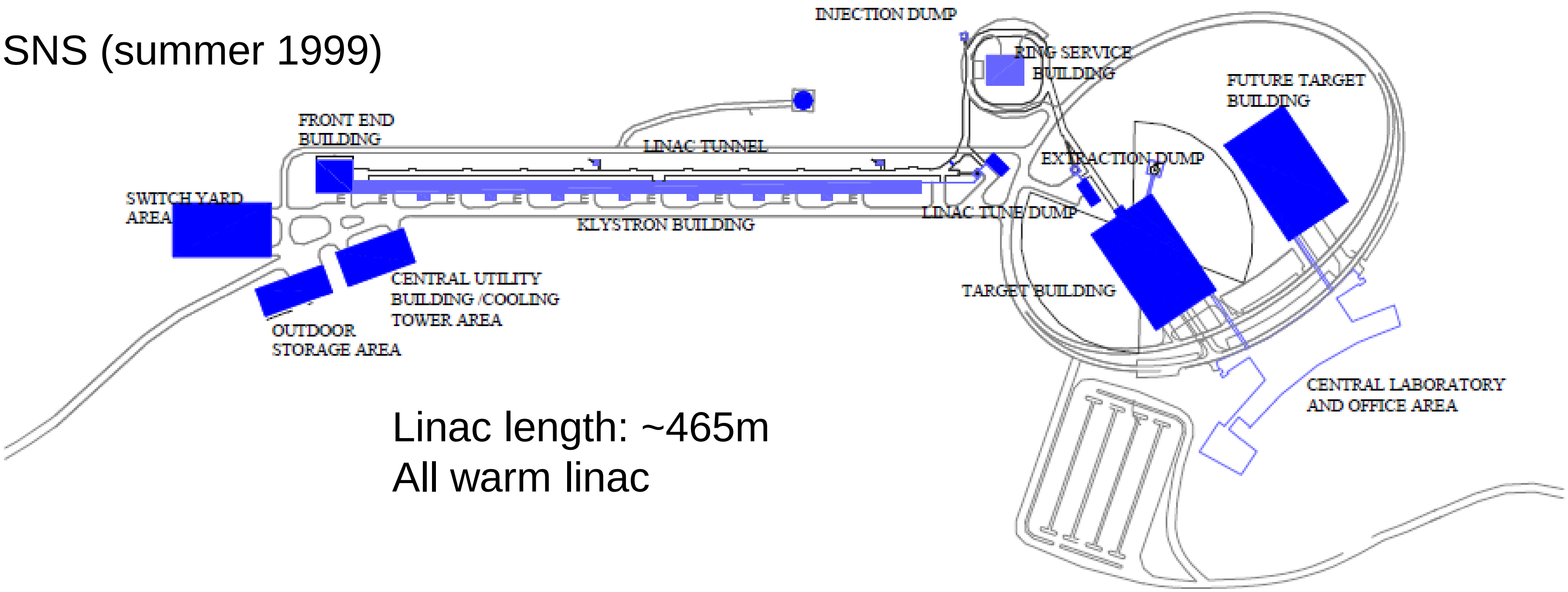
- SNS SCL brief history
- SNS SRF caivty characterization and operational status
- Performance degradation & recovery
- Performance improvement plan
- Summary

# Design evolution of SNS Complex

Concept for NSNS (1997)



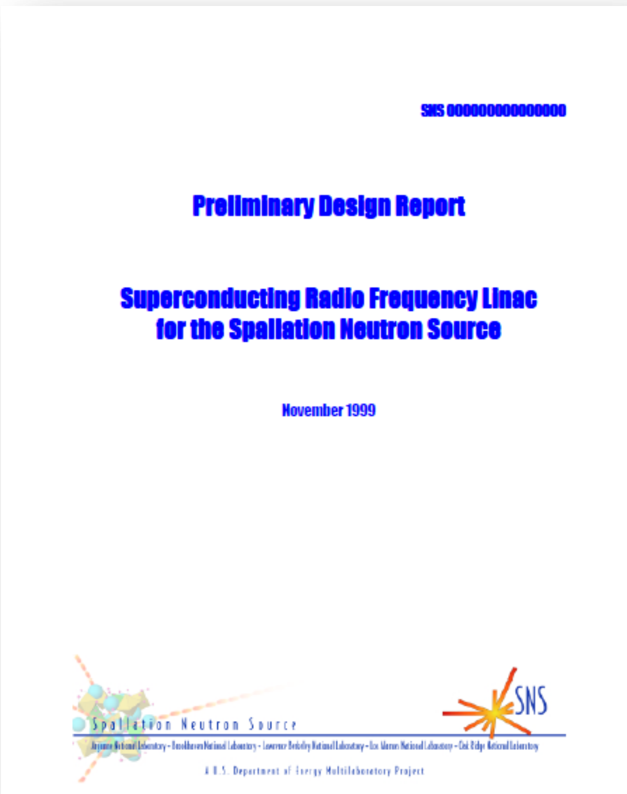

SNS (summer 1999)




Linac length: ~465m
All warm linac

# SNS superconducting linac (SCL)

Preliminary Design Report for SCL option (Nov. 1999):
Y. Cho lead a task force to investigate the feasibility to change to a SCL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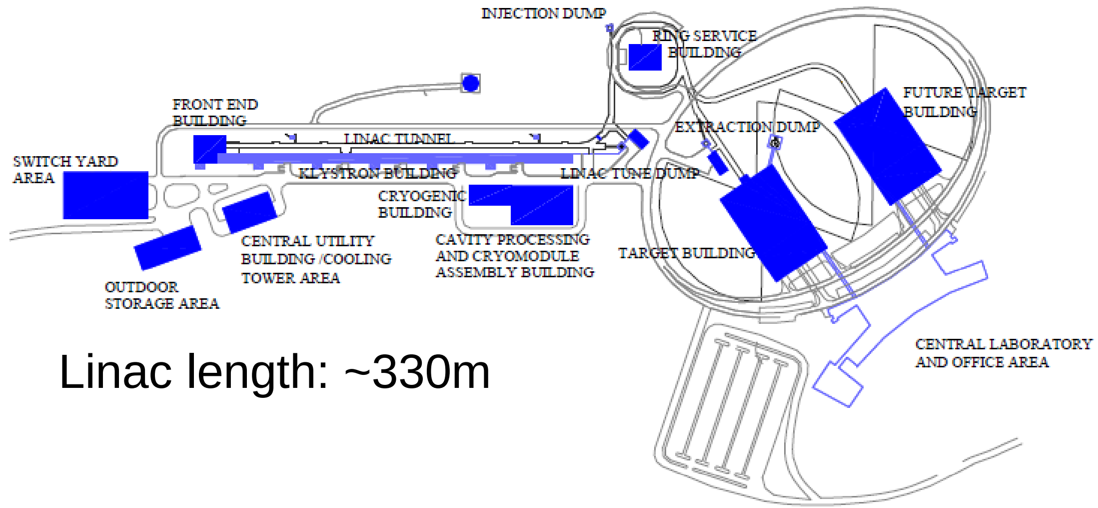
Preliminary Design Report

Superconducting Radio Frequency Linac
for the Spallation Neutron Source

November 1999

Spallation Neutron Source




Linac length: ~330m

**Figure 9.2** Site layout as modified for the SC linac.

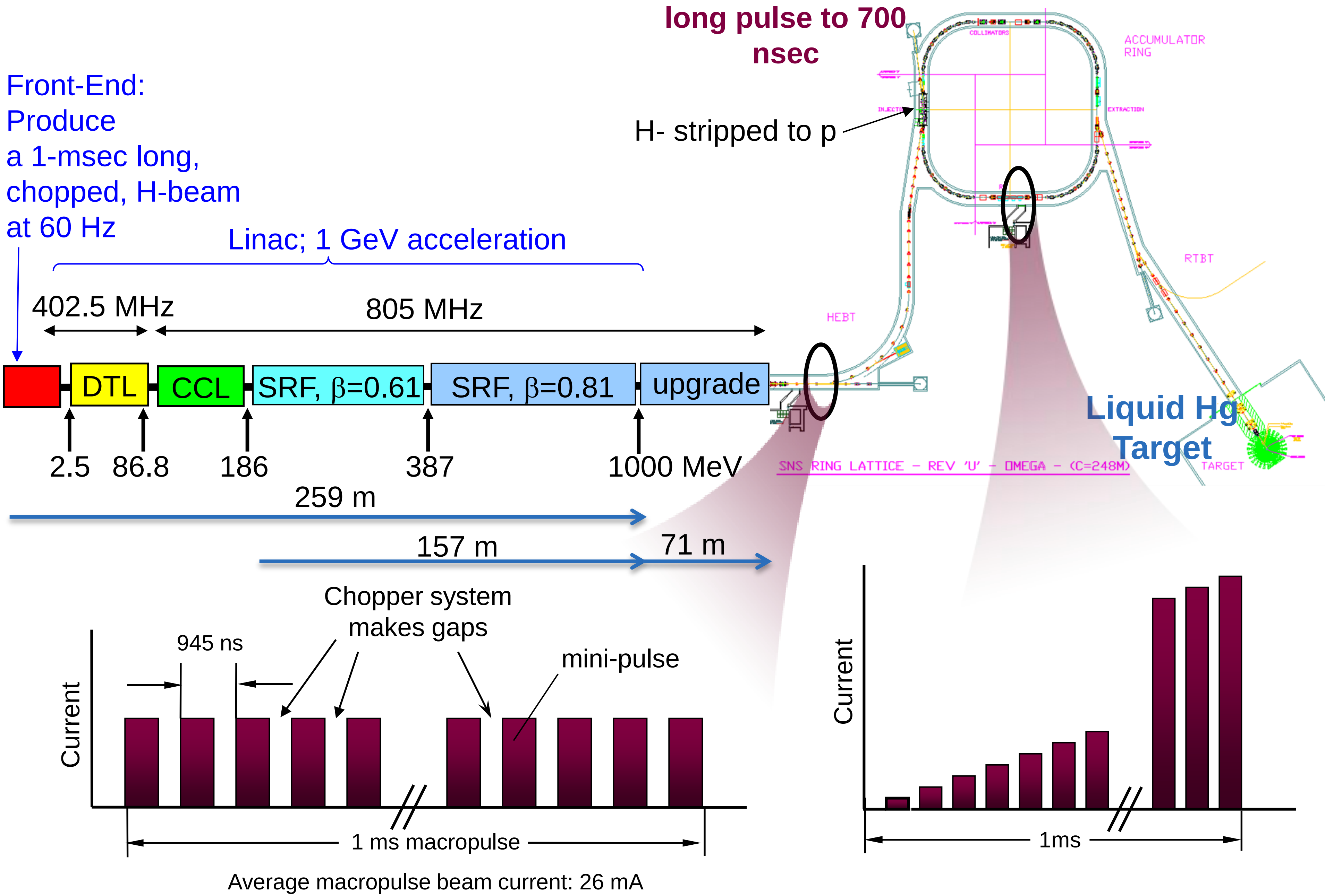
- Dec. 1999 – Jan. 2000: SNS advisory panel and DOE review panel approved the change, Jefferson Lab joined the SNS collaboration
- June 2003 - First cryo-module delivered to Oak Ridge
- August 2004– First cryo-module cool-down
- March 2005 – July 2005: High power RF tests
- August 2005: Beam commissioning
- Jan.- Feb. 2006: Support Ring Commissioning
- Oct. 2006 – present: Support neutron production runs

# SNS Superconducting Linac

- Cryomodules and CHL are designed and built by JLAB
- The first SRF technology for large scale pulsed proton machine (relatively high duty factor and high beam current)
- Designed for H- beam acceleration from 186 MeV to 1000 MeV
- 157-m long, 81 independently powered 805-MHz SRF cavities in 23 cryomodules
- Two types of cavity geometries to cover board range of particle velocities
- 71-m long space is reserved for energy upgrade




# SNS Machine layout



# SNS SRF cavity characterization and operational status

# Cavity characterization

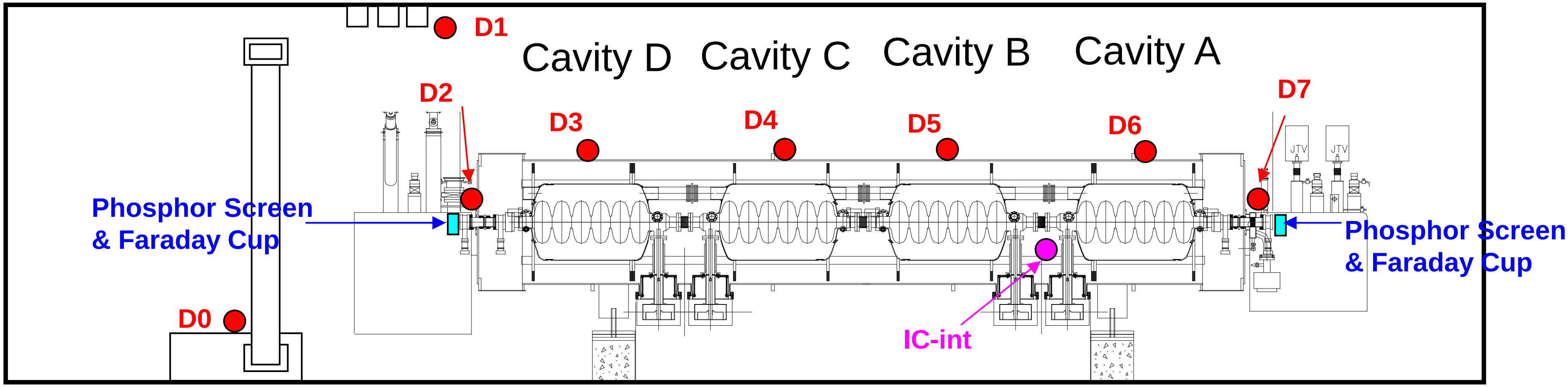
- Major limiting factor: electron loading (FE, MP)
  - Heating RF surfaces & beam line components: resulting in ‘end-group quench’
  - Following slides will show a few examples taken during qualifying tests in the test cave
- Other limiting factors
  - HOM coupler: many HOM feedthroughs were taken out
    - One cavity is not operable. Eacc of a few cavities are limited due to large coupling
  - Lorentz force detuning: a few cavities show larger LFD
  - Hot spots
  - RF/controls related issues in early days

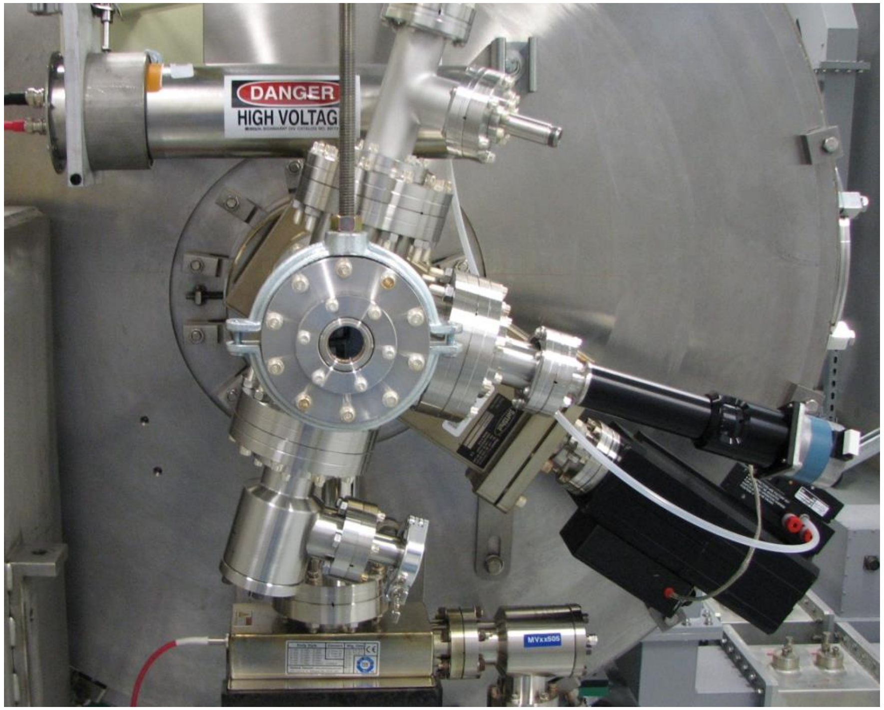
# Turning on cavities

- First turn on must be closely watched and controlled (possible irreversible damage)
  - Initial (the first) powering-up, pushing limits, increasing rep. rate (extreme care, close attention)
    - Aggressive MP, burst of FE → possibly damage weak components or RF surfaces

- Similar situation after thermal cycle and after long shut down
  - Also careful conditioning process is required to keep the same cavity condition since behavior of the same cavity can be considerably different from one run to another (gas redistribution)

# Radiation/electron activity diagnostics during qualifying tests in the test cave



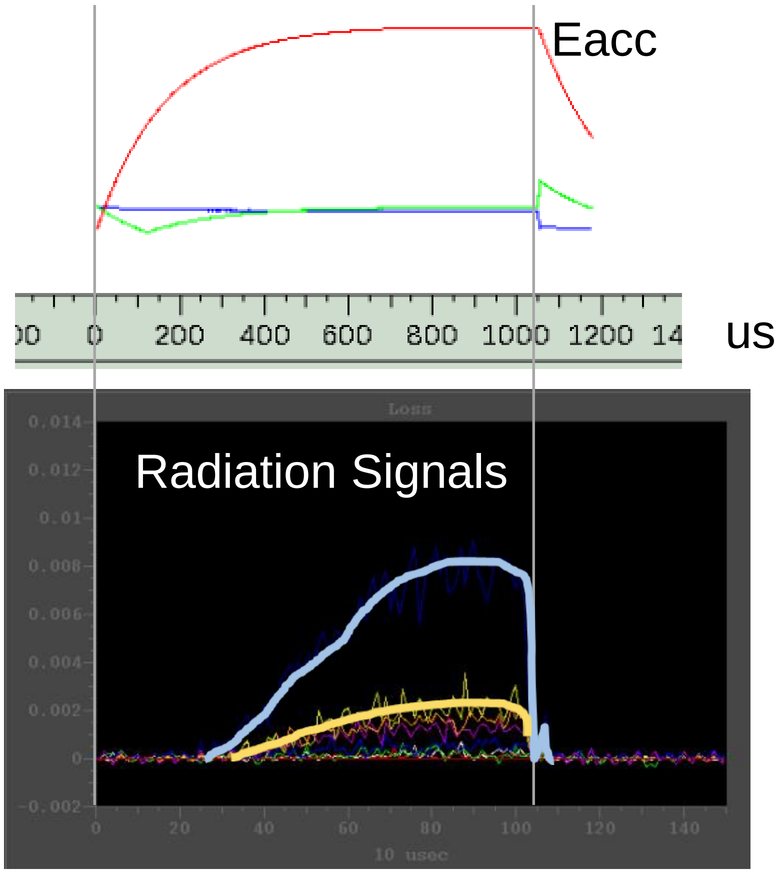




- PMT
- Internal Ionization Chamber
- Phosphor Screen, Camera, Faraday Cup

After removal of HOM feedthrus, Installed two diodes/HOM can

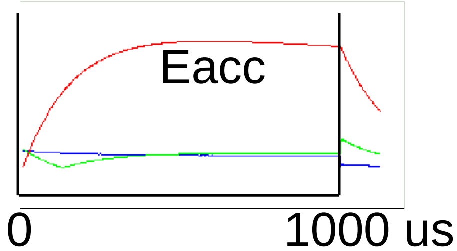
# Radiation patterns (I)

- Field emission dominant case example
  - HPRF test in open loop in the test cave
  - Typical field emission response

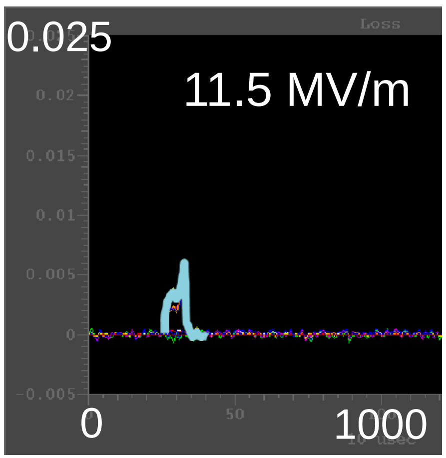


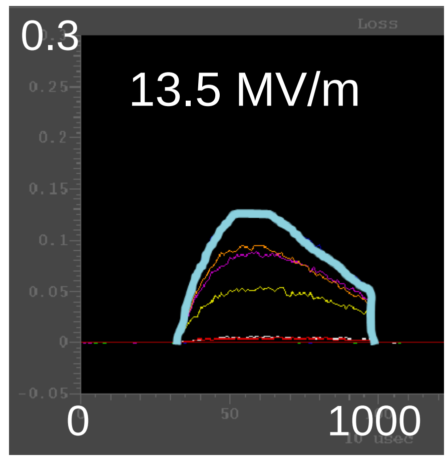

In this example, measureable radiation started from 15 MV/m and the cavity was tested up to 20 MV/m.

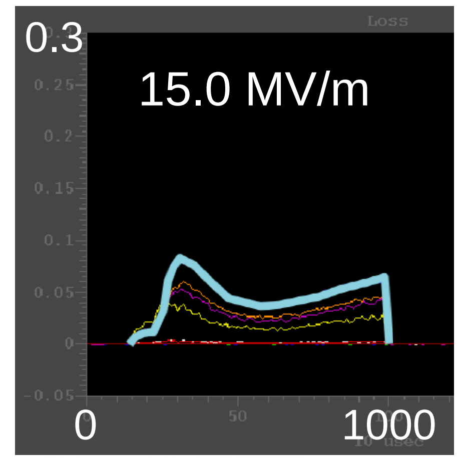
# Radiation pattern (II)

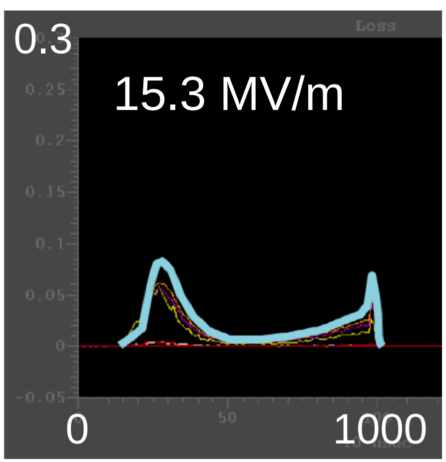


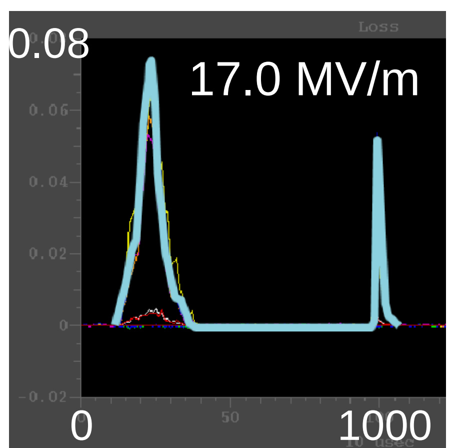

- Multipacting (MP) dominant case
  - Typical MP: from ~3MV/m up to ~15 MV/m (HOM cans, End groups, FPC, etc.)
  - The waveforms below are taken after 5-hrs long conditioning

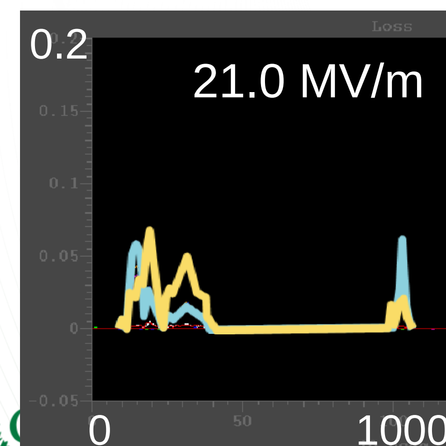


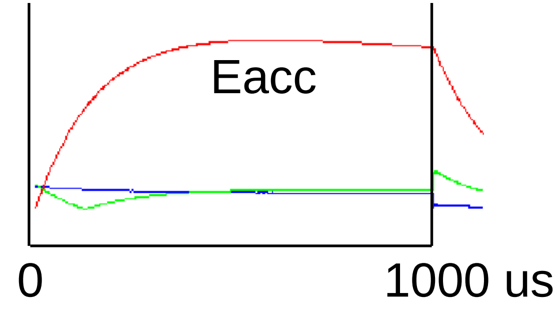



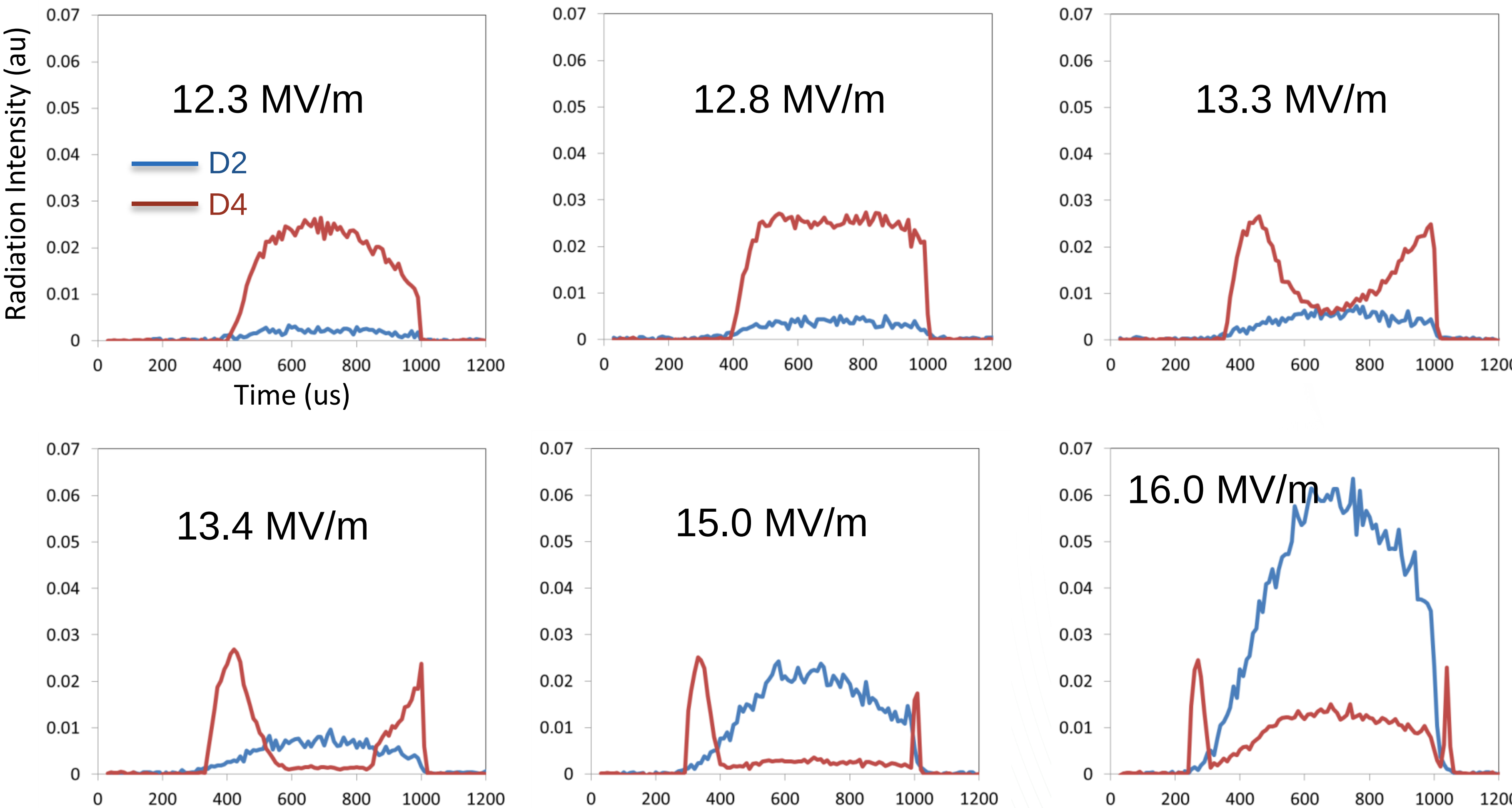



# Radiation pattern (III)

- Multipacting and field emission
  - In this example, a cavity right below D4



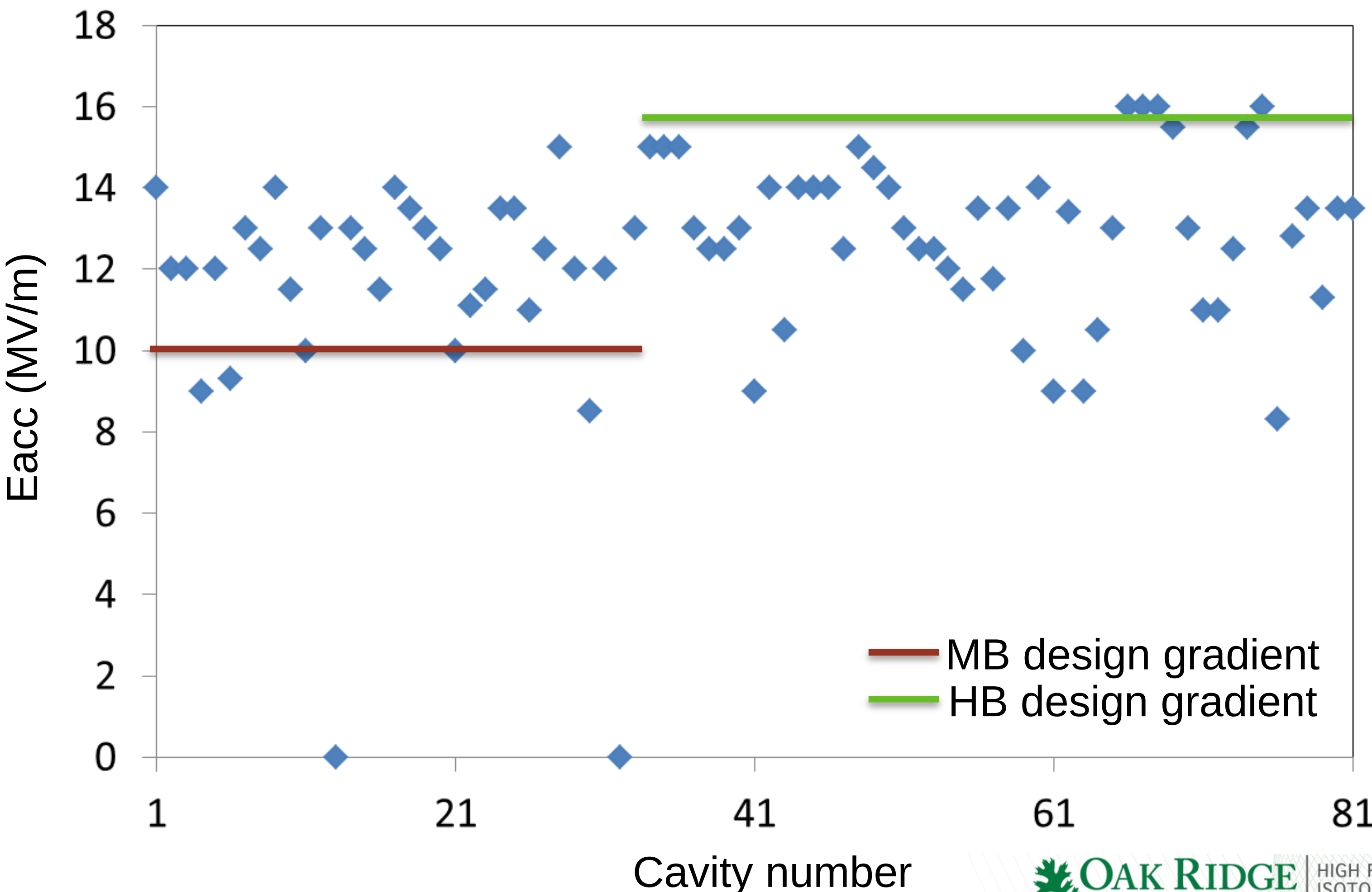



# Electron activities

- Same radiation patterns (MP, FE) from both MB and HB cavities
  – MB cavities show less thermal loading from electron activities since electron acceleration in MB structure is less efficient
- In general, x-ray levels are quite stable in the tunnel over time
  – SNS beam repetition rate is actually 59.9 Hz → Measure background radiation every 10 sec. during operation
  – A few cavities show slightly elevated x-ray levels resulting in reduction of Eacc by ~1MV/m
  – Some MP has not been processed away after 10 yrs operation
- Collective behaviors at high duty factor
  – Electrons from one cavity hit other cavities in a cryomodule
    - Not only depends on Eacc but also relative RF phases
  – Operating gradients are lower at 60 Hz than those at low repetition rate
    - Linac output energy: 940 MeV at 60 Hz vs. 1070 MeV at 10 Hz

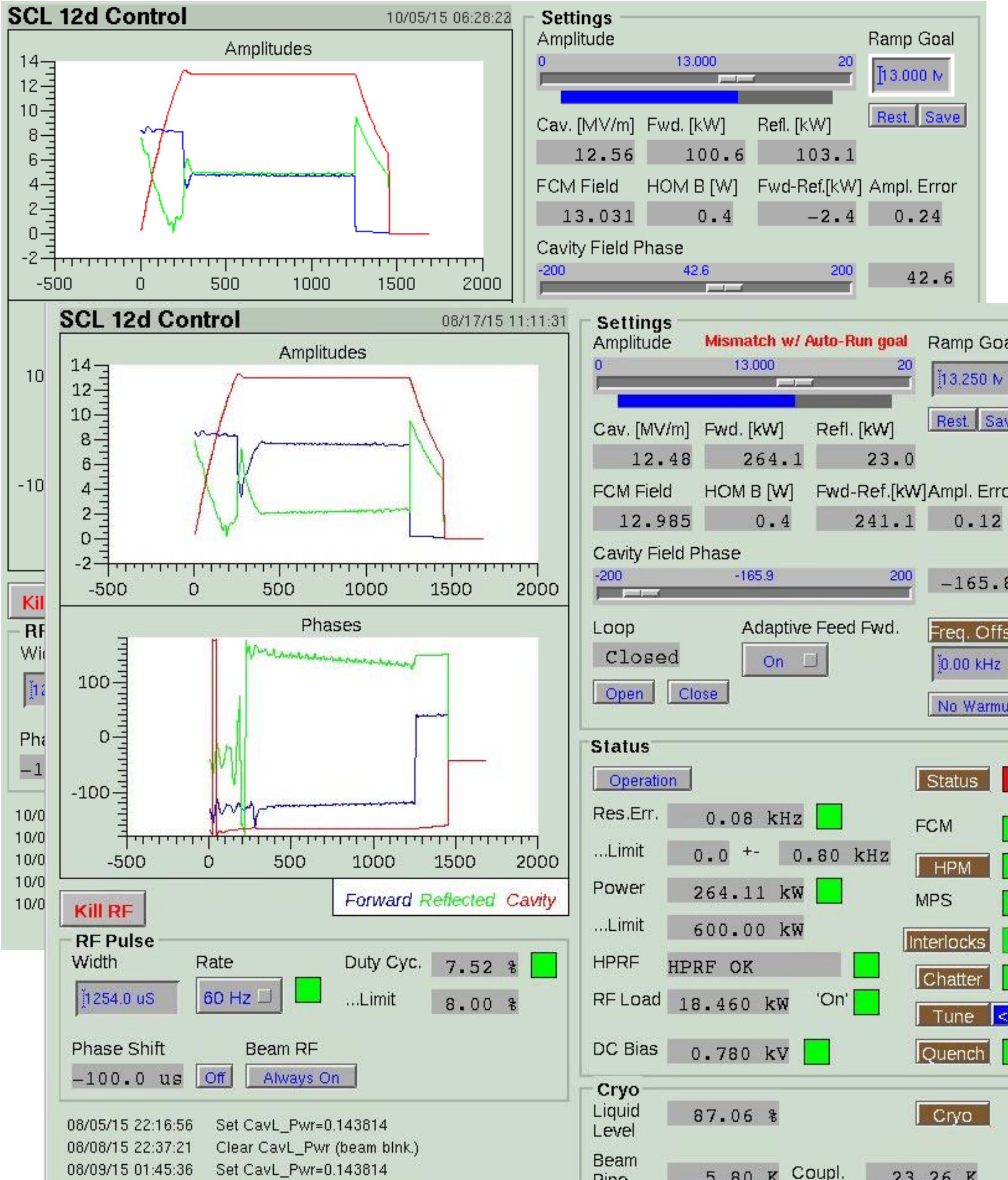
# SRF cavity operating gradients today

- Average Eacc of medium and high beta cavities: 12 MV/m and 13 MV/m respectively
  - Based on 60 Hz collective limits



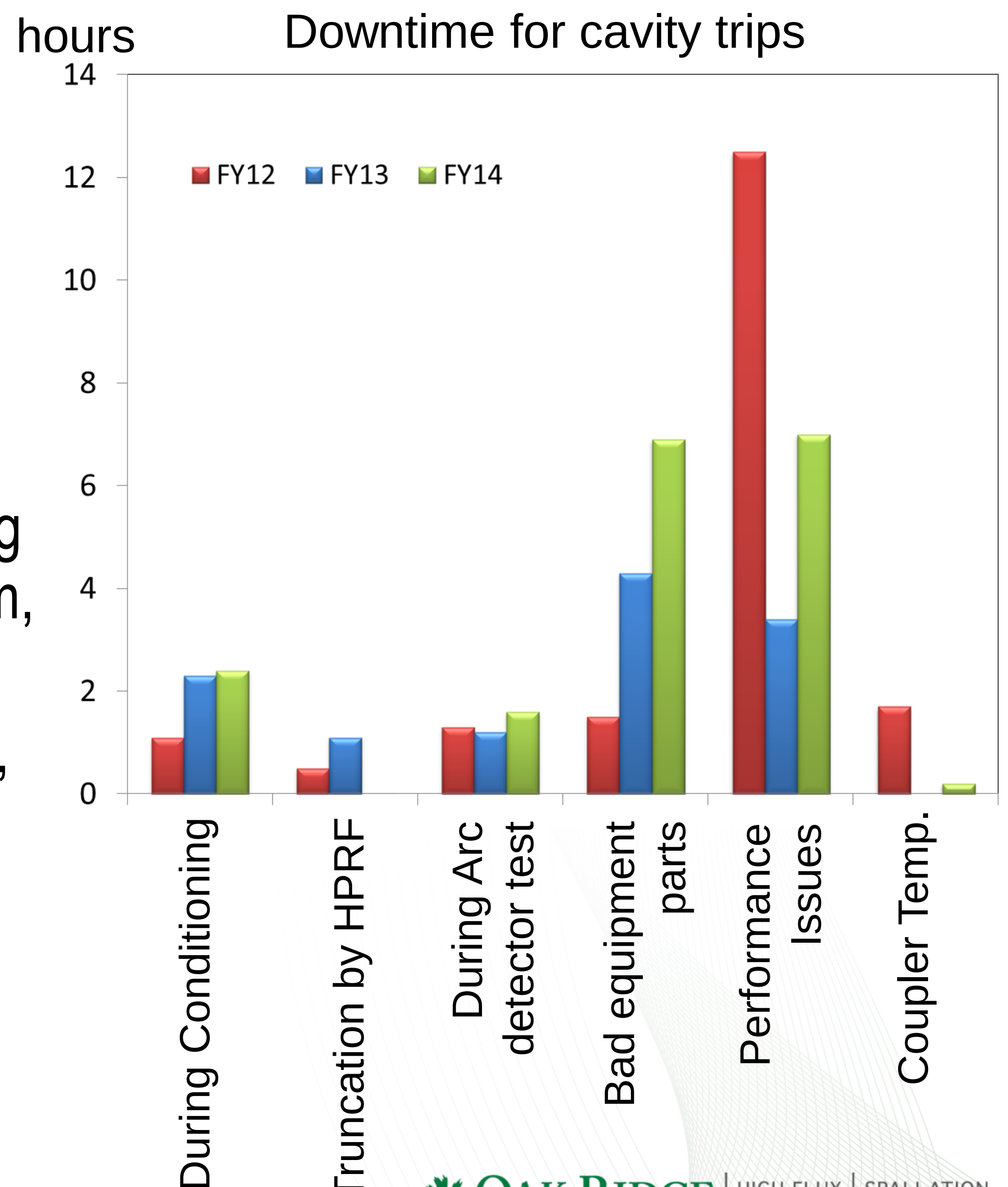
# SNS SRF cavity RF operation

- 60 Hz: 5.2 M pulses/day
- Filling: 250 us, feed forward
  - Forward power: ~3 times higher than power during the flattop without beam loading
- Flattop: 1 ms, feedback
  - With beam: + adaptive feed forward
  - Forward power at full beam loading (26mA): 2.5-3.5 times higher than power for RF only



# SNS SCL Operation Status

- Stable and reliable operation
  - Average trip (downtime):
    < 1 trip/day (<5 min./day)
  - Availability last 4 years:
    - Whole SCL system including RF, HVCM, Control, Vacuum, etc.: 98 %
    - **SRF cavities**, cryomodules, and CHL: 99.5 %



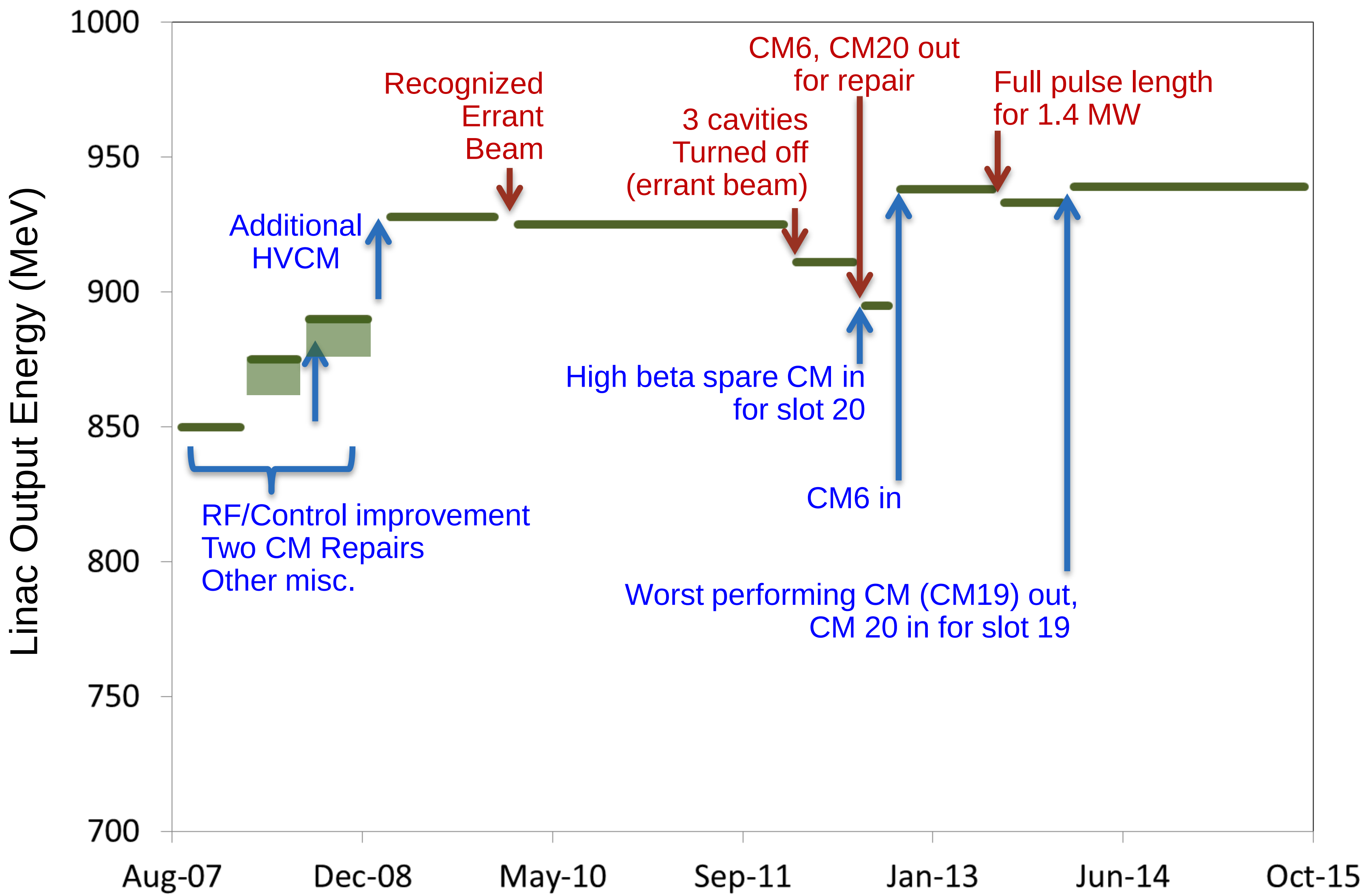
# High availability while keeping high power beam operation

- Understand machine & reliable machine setup as a whole
- Make systems as simple as possible
- Develop adequate diagnostics/protection
- Have energy margin to take advantage of operational flexibility
  - to circumvent problems that can't be addressed during operation and to minimize a down time
- Conduct proactive/preventative maintenance
- Keep good communication between machine experts and machine operators

# Performance Degradation and Recovery

# Linac Output Energy History at 60Hz

Changes of output energies are the result from specific activities and events



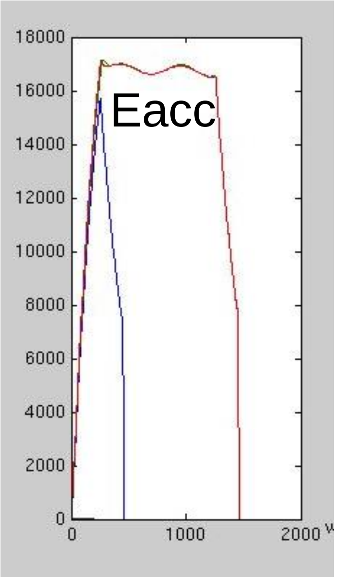
# Performance degradation during operation

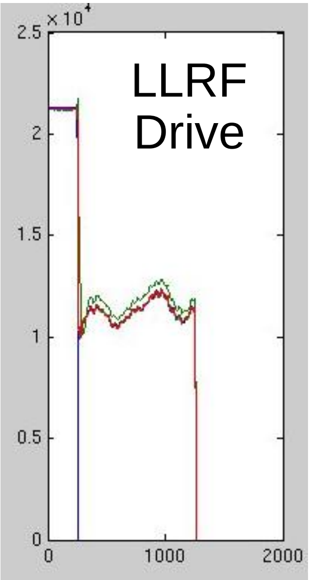
- Degradation related to vacuum activity
  - Observed performance degradations from ten cavities
  - Beam halo, errant beam, e- activity and ion pump pressure spike
    - Desorption and redistribution of gas → could create conditions for vacuum breakdown or hot spots
    - Main event: Interaction with RF (one of the worst case is surface damage and particulate contamination)
    - Not every event makes a cavity trip. But the probability for degradation increases with frequency and intensity of events
- Other potential degradation related to particulate contamination
  - Gate valve operation
- When a cavity shows a symptom of performance degradation, the gradient is lowered slightly (typically lowered by 1 MV/m or less) to avoid further degradation and to minimize downtime
  - Early diagnostics and prompt involvement from system experts are the key to minimize additional degradation

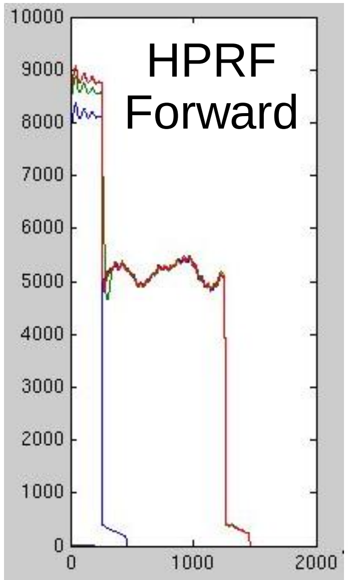
# RF waveforms at cavity trip

- Very useful to understand the trip event

**Trip 1**



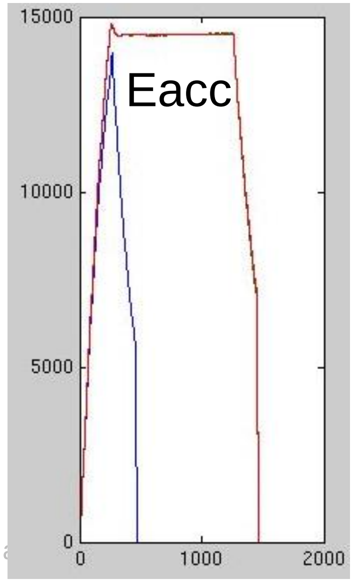



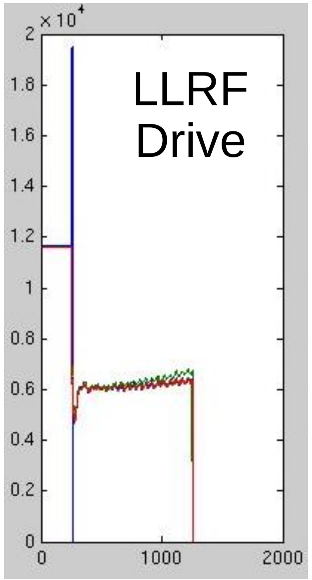



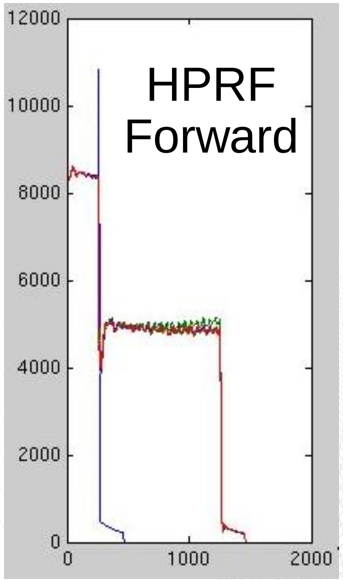

HVCM Voltage Fluctuation or Instability of HPRF

In both cases, cavities tripped because cavity field did not reach set-point during filling time

**Trip 2**



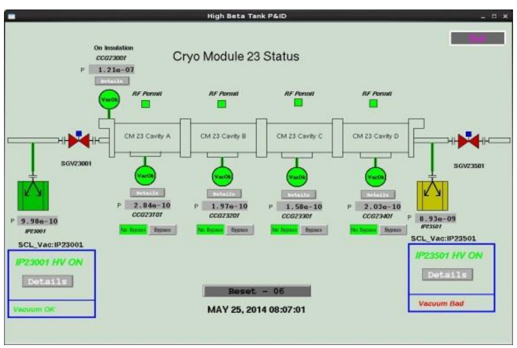



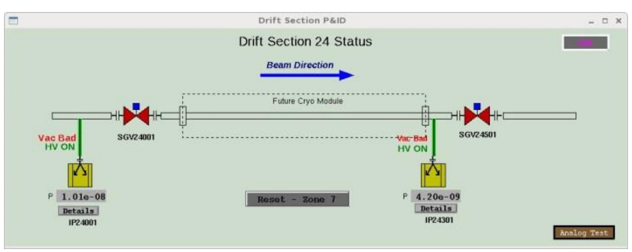



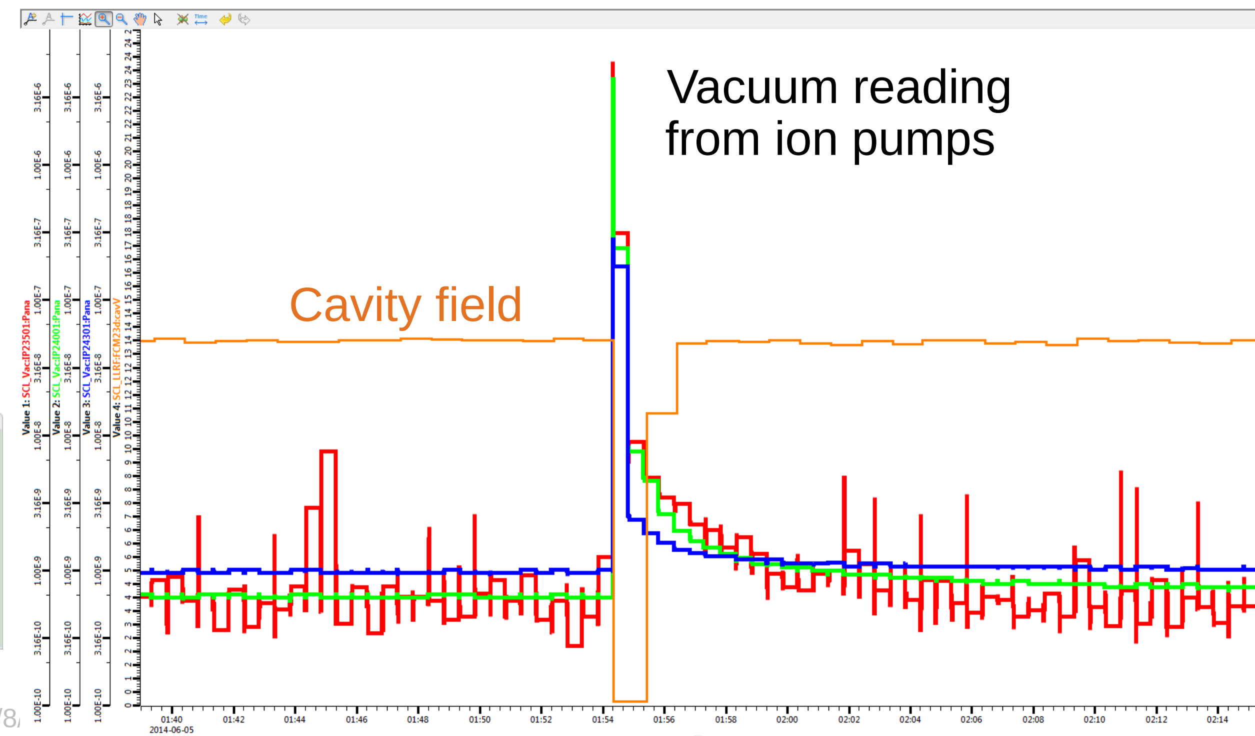

Cavity partial quench

# Ion pump pressure spike example

- A cavity was tripping with ion pump pressure spikes. Slight performance degradation (~1 MV/m) was observed.
- The cavity trips and pressure spikes became more frequent
  - What is the root cause?
- To verify the cause we turned off one ion pump after interlock logic changes
  - No trip since summer 2014

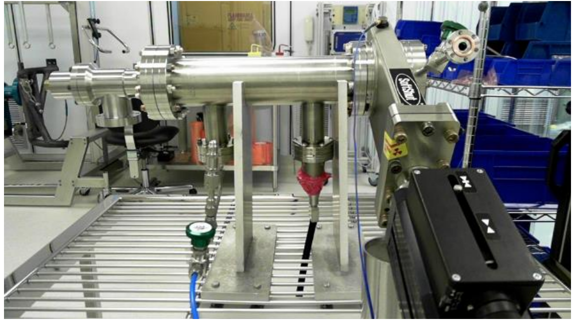


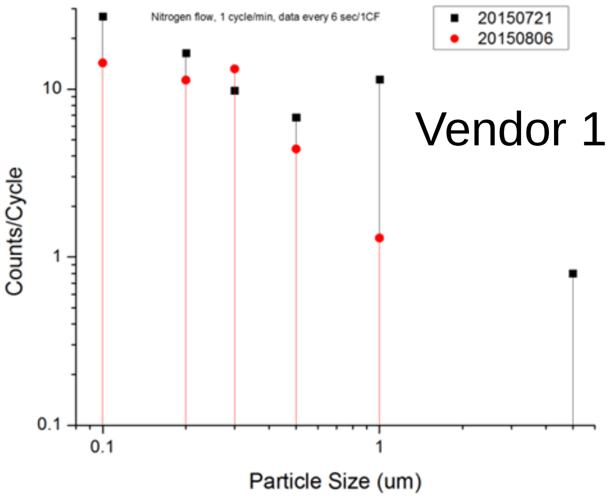



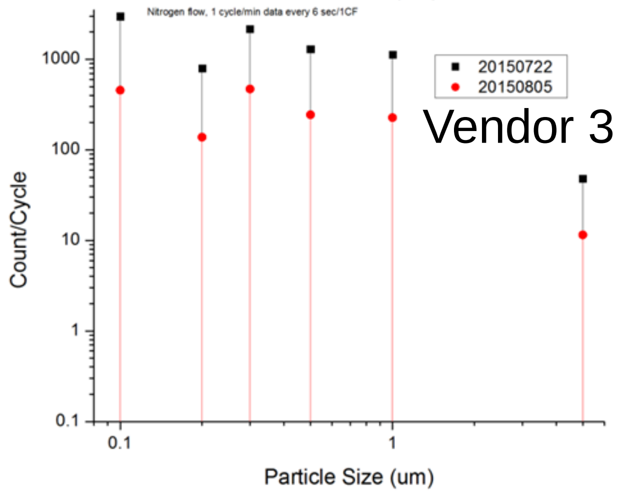



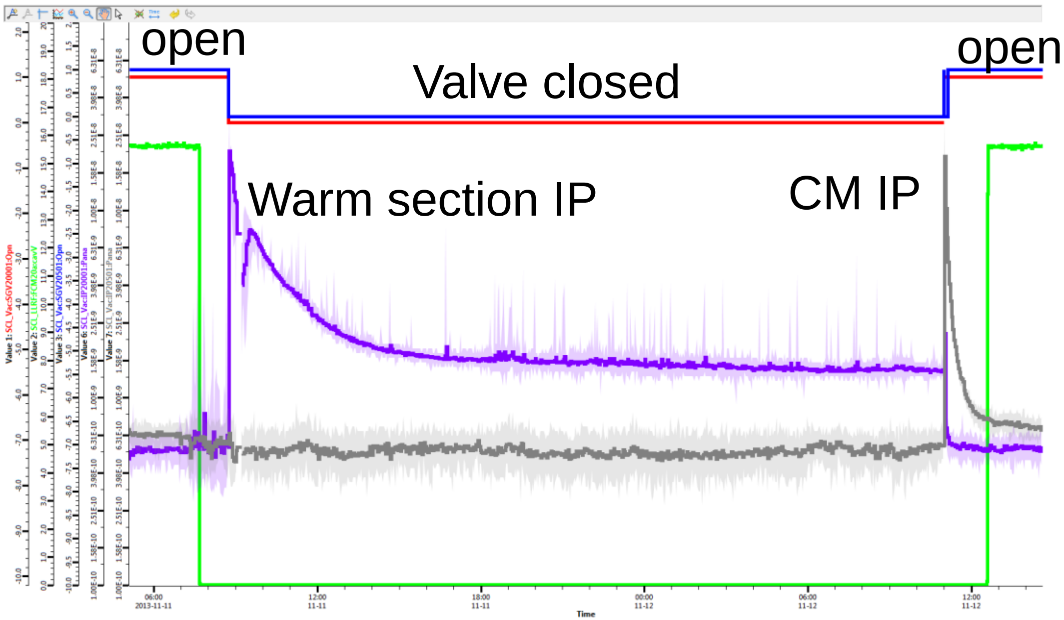
# Gate valve

- Valve actuations causing pressure spikes: observed from a few valves in the tunnel
- Particulate generation are measured on the test bench
  - Tested gate valves from three vendors
- Valve verification before installation
- During operation: Minimize valve actuation



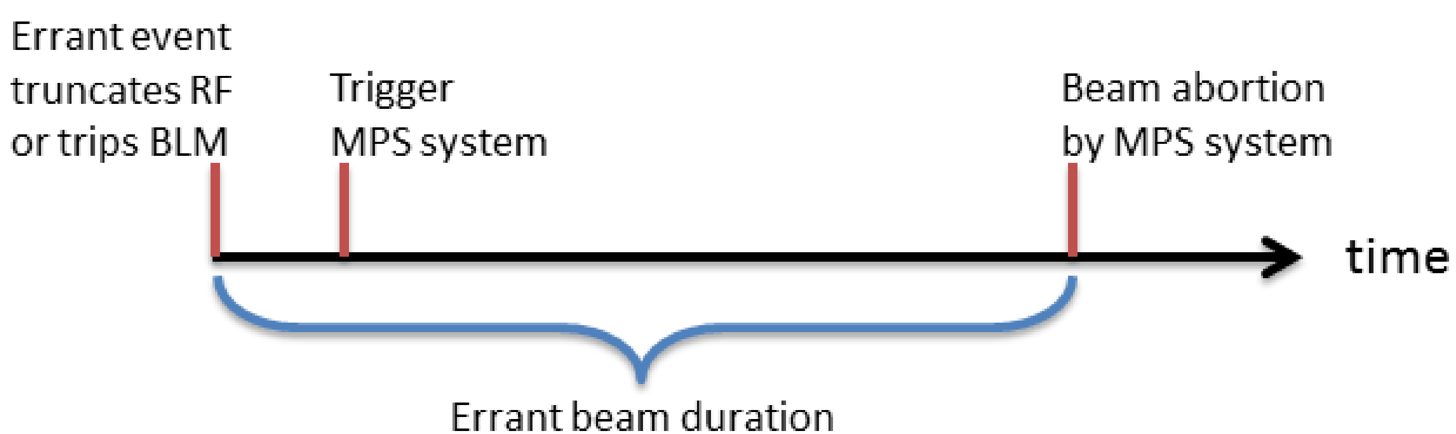


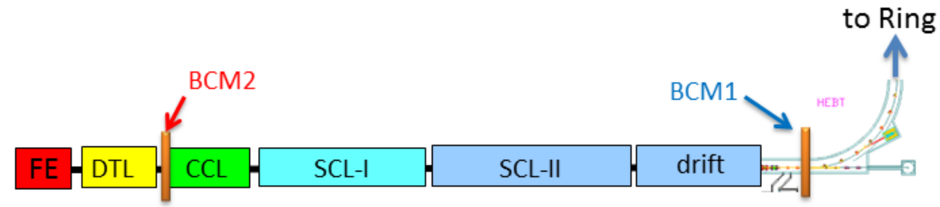
# Errant beam (I)

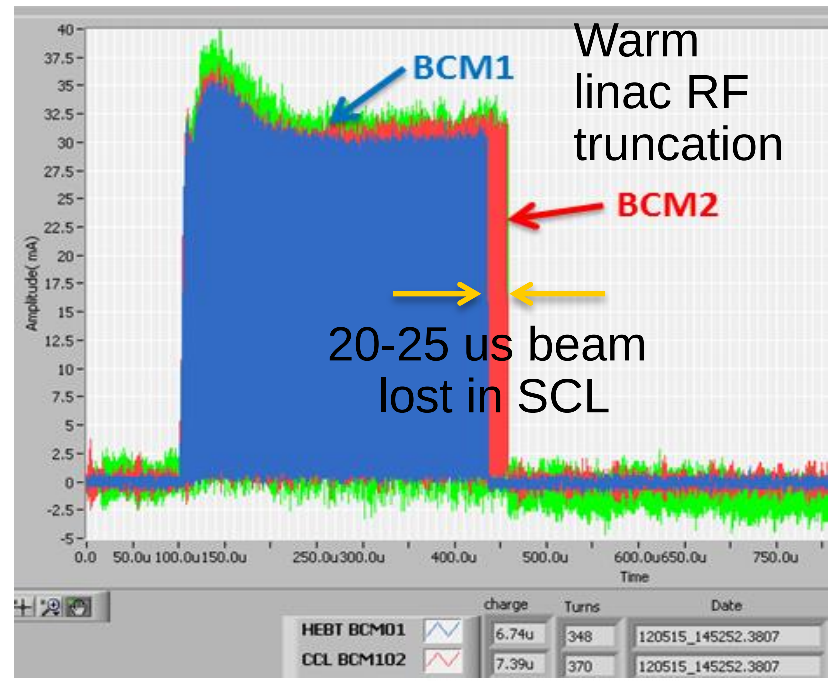
- Our definition:
  - Off-energy beam generated from a fault condition
  - Beam transported downstream and lost until beam abortion by MPS system
- Mani sources of errant beam
  - Warm linac RF truncation: arc, pressure burst, etc.
  - Ion source/LEBT: arc, unstable plasma, etc.
- SCL beam loss monitors (BLM) are the primary indication of errant beam event
- MPS delay: time between RF truncation/BLM trips and beam abortion
  - It was recognized that MPS delay was too long in 2009 :~300 us
  - MPS circuit was fixed in 2010 → MPS delay: 25 us

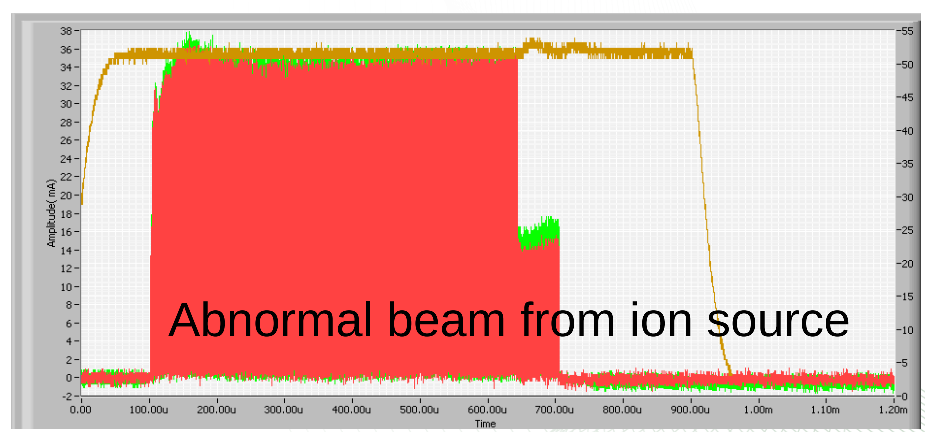


# Errant beam (II)

- Errant beam hitting a cavity surface desorbs gas and could create vacuum breakdown environment
- Errant beam events before 2012: 35 per day
  - Performance degradations by errant beam were observed
  - More diagnostics were added to detect errant beam event
  - Due to this, more careful operation/conditioning of all warm linac structures and front end
- Errant beam events after 2012: 15 per day
  - Dedicated MPS circuit for errant beam event is recently installed: MPS delay 12 us
- Errant beam events since 08/2015: 5 per day
  - Warm linac vacuum system was improved last summer



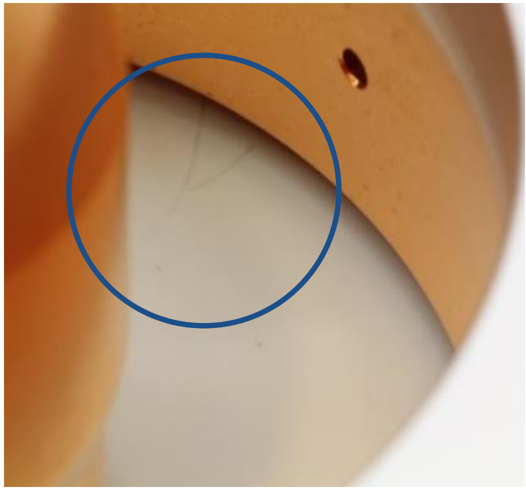



# Beam halo

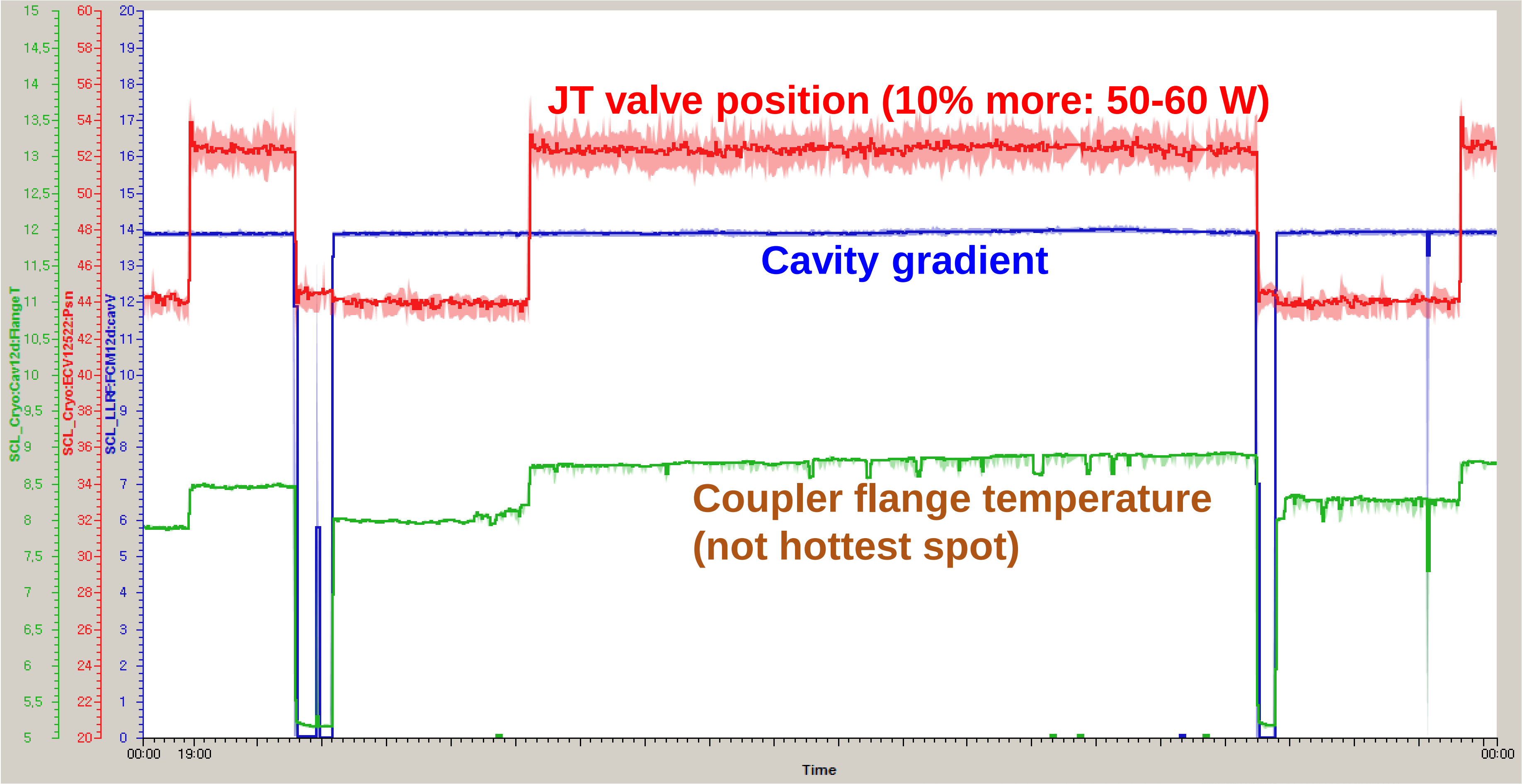
- Performance degradation from beam halo is observed in the first few cryomodules of the SC linac
- It is difficult to diagnose since the process is very slow
  - BLM is less sensitive at low energy region
  - Temperature diodes sometimes indicate slight temperature increment before quench
  - Degradation seems to develop over a long time
  - Cavity becomes very sensitive to small changes of operating conditions
- Beam scraping in the front-end helps
- More sensitive BLMs for low energy region are being prepared

# Performance degradation, component damages and recovery



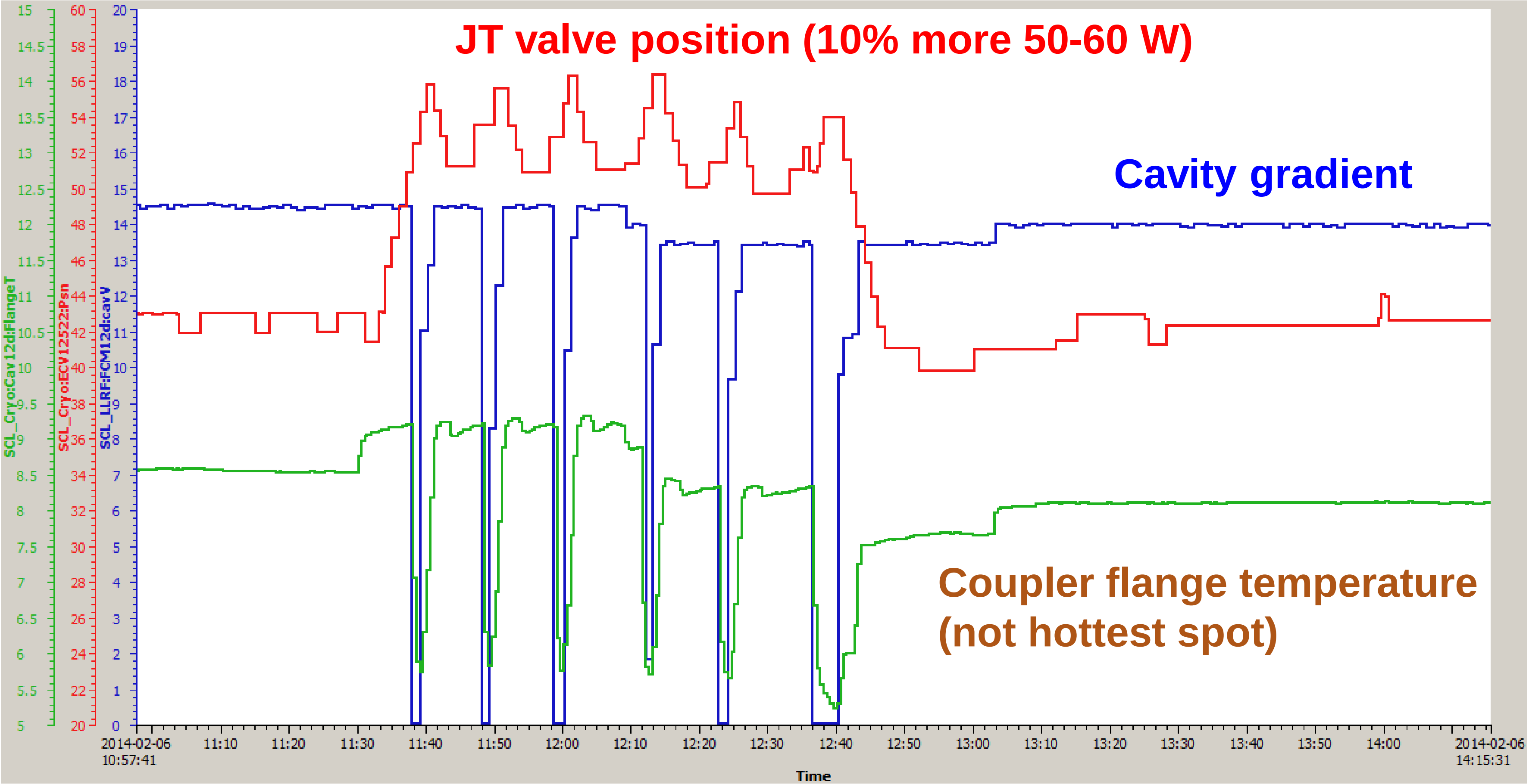
- Most frequent symptom is hot spot creation in the end group
  - Dynamic load changes 10 times higher
    - Some cavities run in this condition
    - Some others need lower Eacc by <1MV/m
  - No changes of x-rays
  - Once hot spot is developed, no correlation with beam
  - Recovery
    - RF conditioning starting from low repetition rate
    - Thermal cycling
- Other degradation/component damage
  - Two FPC windows showed leak after errant beam events
    - ~$10^{-6}$ torr l/s leaks, both were replaced with new FPCs at the SNS test facility and reinstalled in the tunnel
  - Another cavity is arcing around FPC/end group: turned off for now.

# Hot spot example 1: meta-stable condition at the same gradient




- Some part in the end group (must be very low field region) must be normal conducting but still operable
- Additional cryogenic load at 2K is about 50W more from one cavity (would be 800W in CW)

# Hot spot example 2: unstable condition




- Reduce gradient during operation by 0.5-1MV/m due to end group quench
- Cavity still unstable → have to wait 10-15 min. for cool-down
- Performance recovered by thermal cycle during long-maintenance period

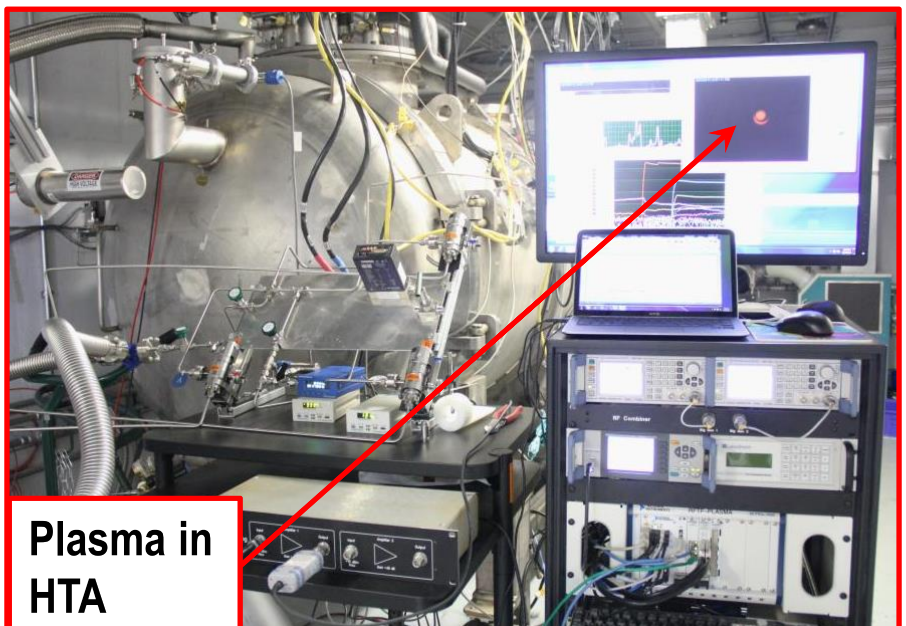
# Plan for performance Improvement

# In-situ processing in the tunnel

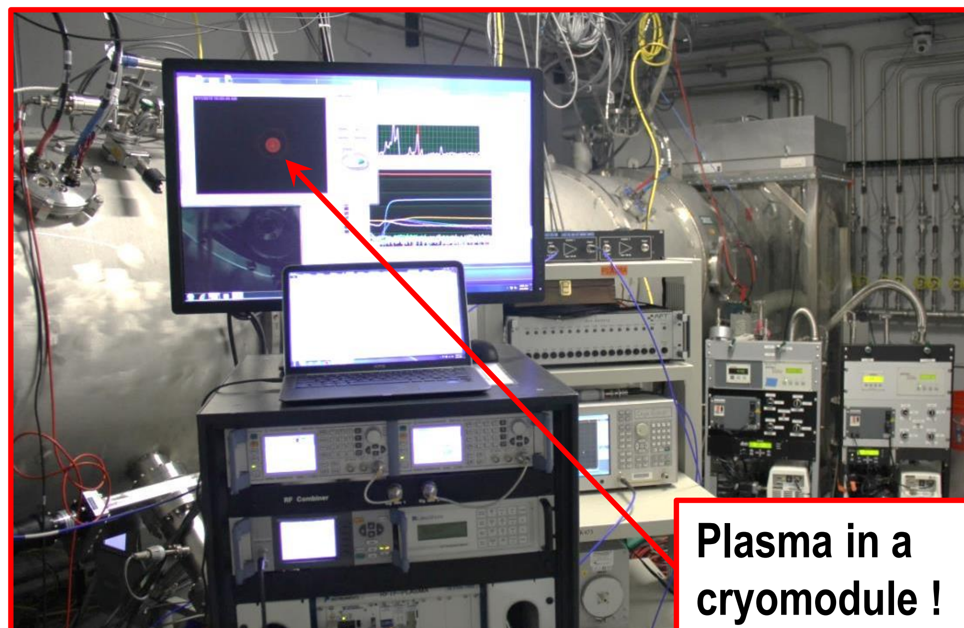
- Develop a cost effective processing method with minimal impact on machine operation
  - Goal is 15-20% improvement on average
  - In-situ plasma processing R&D
    - Preliminary attempts in 2009
    - Focused on removing of residual hydro-carbons
- Medium term goal
  - Reach 1GeV + energy reserve (Increase high beta cavity gradients by about 2 MV/m in average)
- Long term goal
  - 38-mA beam loading with 2$^{nd}$ target station: Need narrower performance scattering → Efficient utilization of RF power (ideally constant RF power/cavity is preferred)
  - Pertains mostly to medium beta cavities

# In-situ Plasma processing

- Low density reactive plasma at room temperature to clean residual hydrocarbons on RF surfaces
  - Demonstration of performance improvement with single cavities in Horizontal Test Apparatus and in offline cryomodule
  - Increase of Eacc at 60 Hz after processing: >25 %
  - Observed reduced FE, MP, vacuum activities, thermal load in the end group
- Deployment in SNS tunnel planned during shutdown periods starting FY16



Plasma in HTA



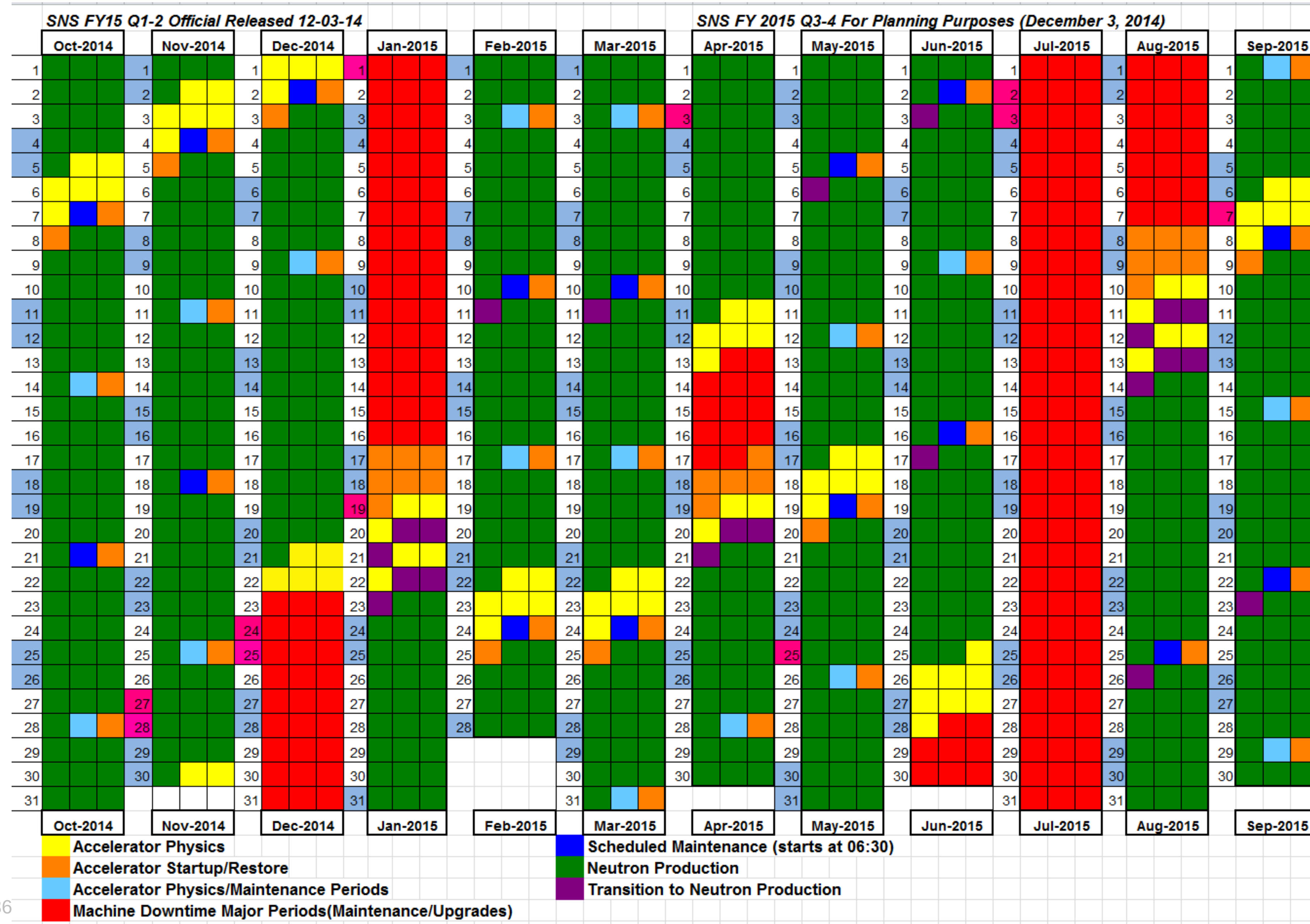
Plasma in a cryomodule !

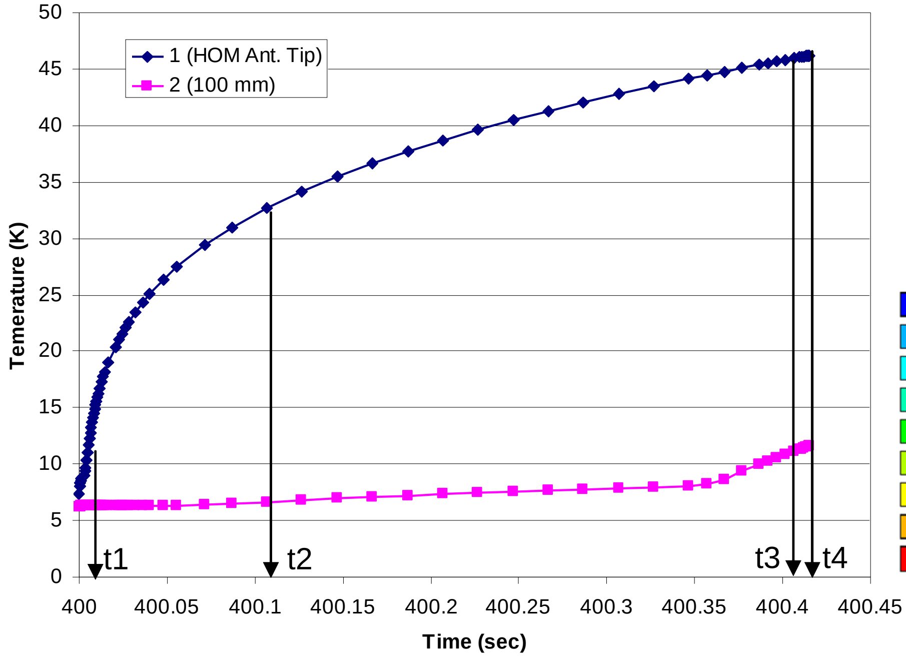
# Summary

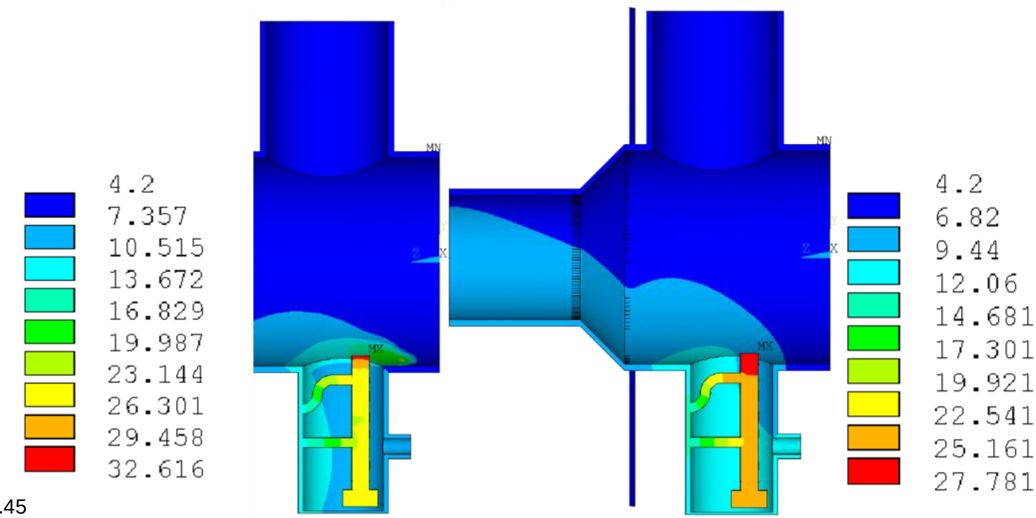
- The SNS SCL is providing stable operation for the neutron production up to 1.4 MW beam power on target
  - Understanding of system as a whole leads to the most efficient and reliable operation
- Causes for performance degradation during operation at SNS are identified
  - Continuous development of dedicated diagnostics and protection systems
  - Recovery actions including thermal cycling and offline repair are ongoing
- R&D is ongoing to improve the current SRF cavities performance
  - Plasma cleaning technique was demonstrated with performance improvement of offline cavities in HTA and cavities in offline cryomodule
  - Plan on deploying plasma processing in the linac tunnel in FY16 and FY17

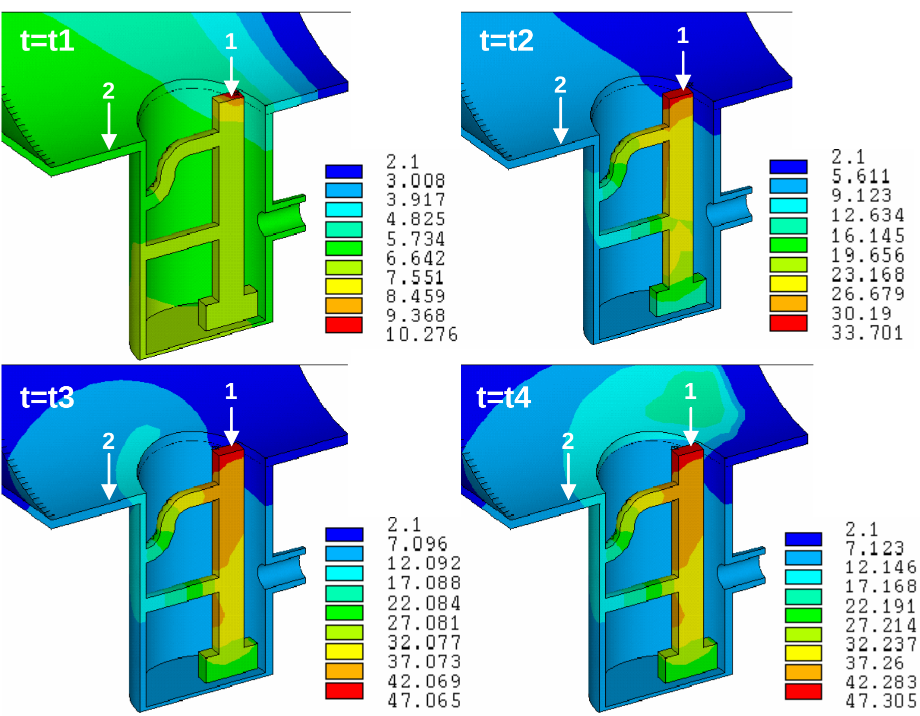
# Backup Slides

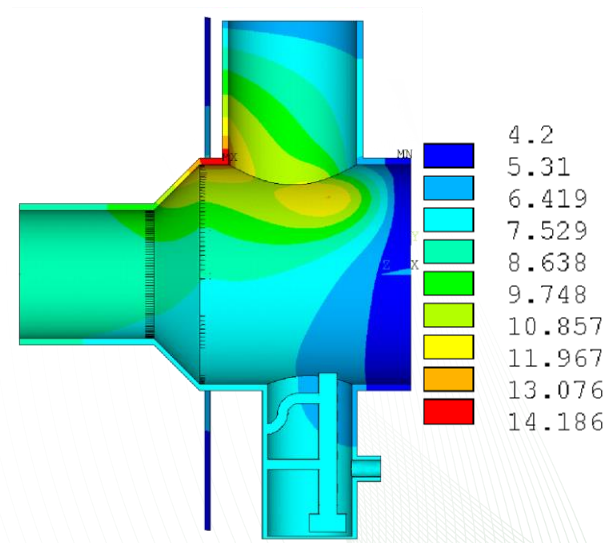
# FY15 Operation



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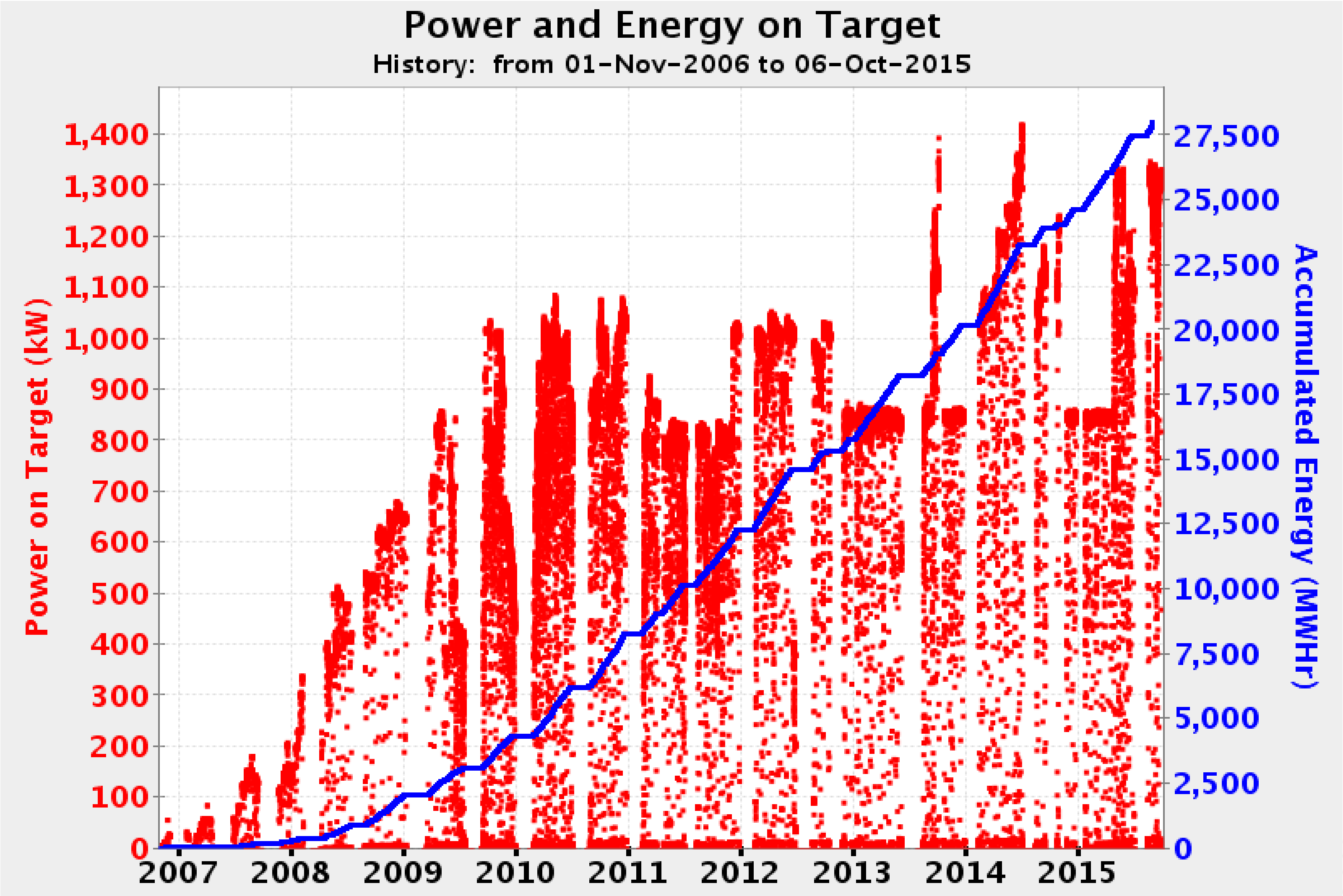
# SNS Beam Power History

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