

Understanding the Source and Impact of Errant Beam Loss in the SNS Superconducting Linac

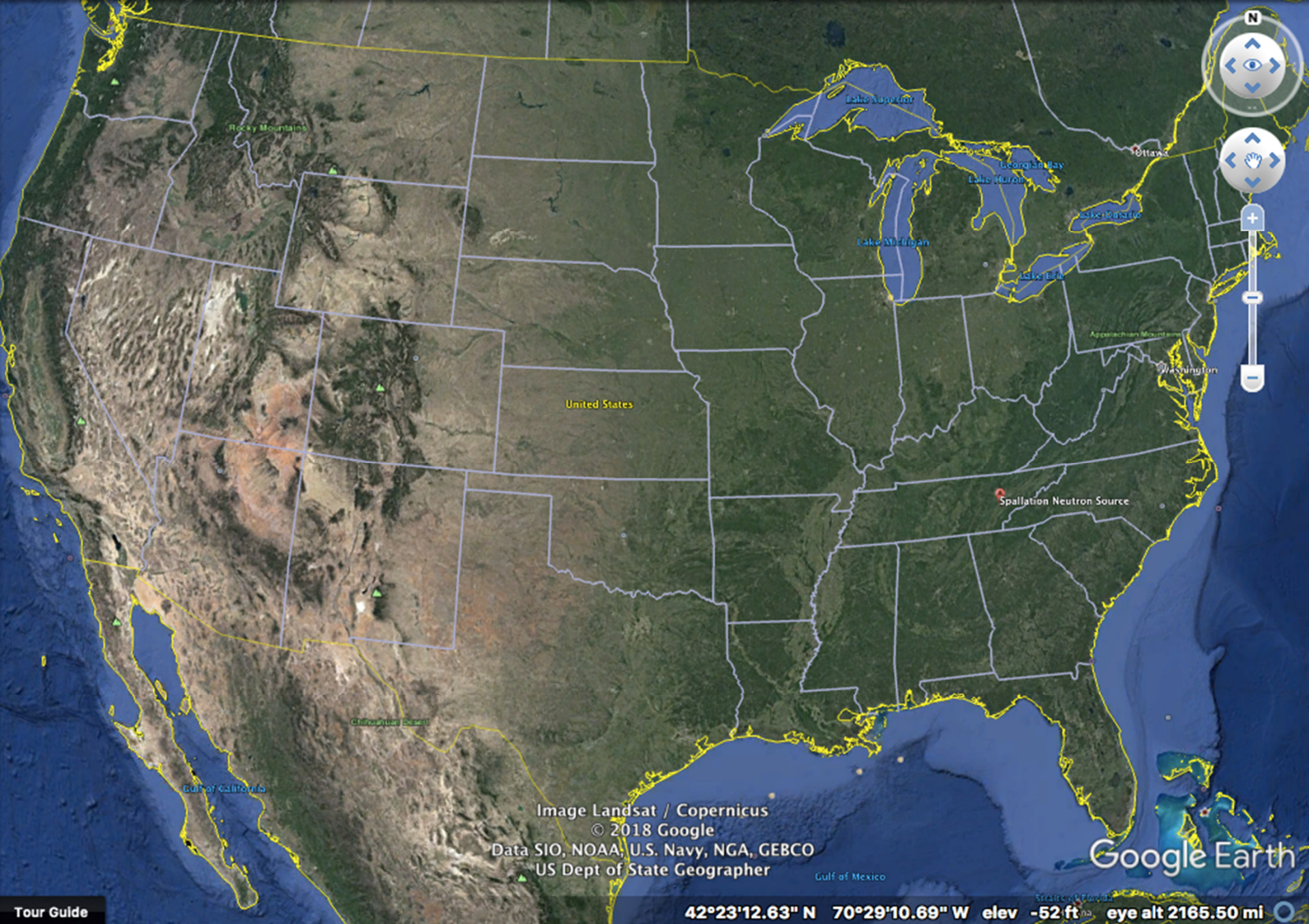
C. Peters

18 June 2018



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Spallation Neutron Source

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Tour Guide



1992

35°57'07.65" N 84°18'15.67" W elev 1134 ft eye alt 2035 ft

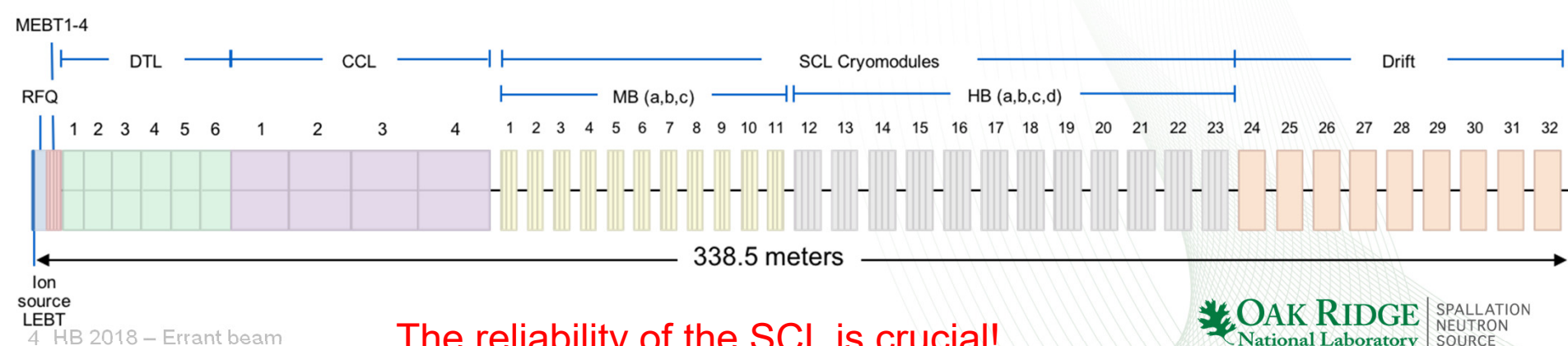
3 HB 2018 – Errant beam

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The Superconducting Linac (SCL) provides the majority of beam energy acceleration

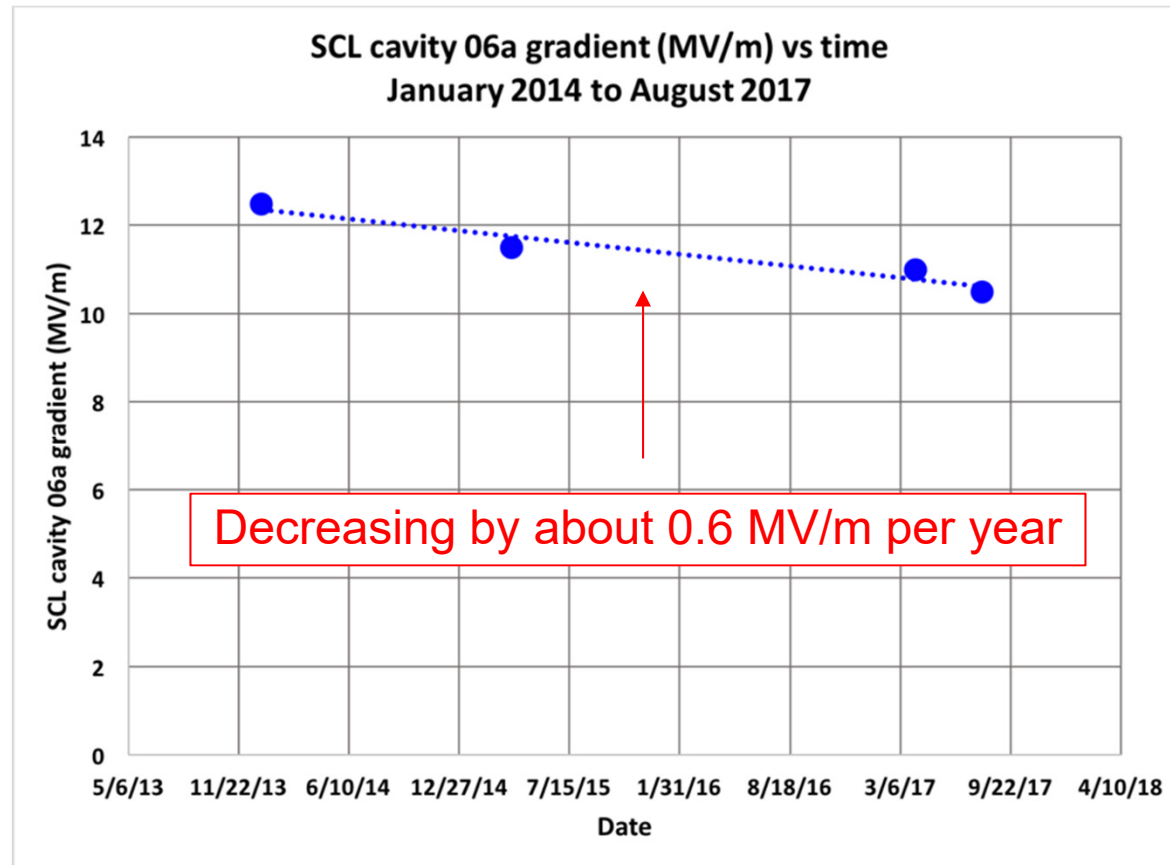
- The linac is broken up into segments with different types of RF cavities
- Front end
 - 1 RFQ bunch beam at 402.5 MHz and accelerate 65 keV→2.5 MeV
 - 4 MEBT RF buncher cavities match into the DTL, no acceleration
- Warm linac
 - 6 DTL cavities, 2.5 MeV to 87 MeV
 - 4 CCL cavities, 87 MeV to 186 MeV
- Cold linac
 - 81 SCL cavities (33 medium beta and 48 high beta), 186 MeV to 1.01 GeV



The reliability of the SCL is crucial!

SCL cavity gradients must be reduced in order to maintain high reliability

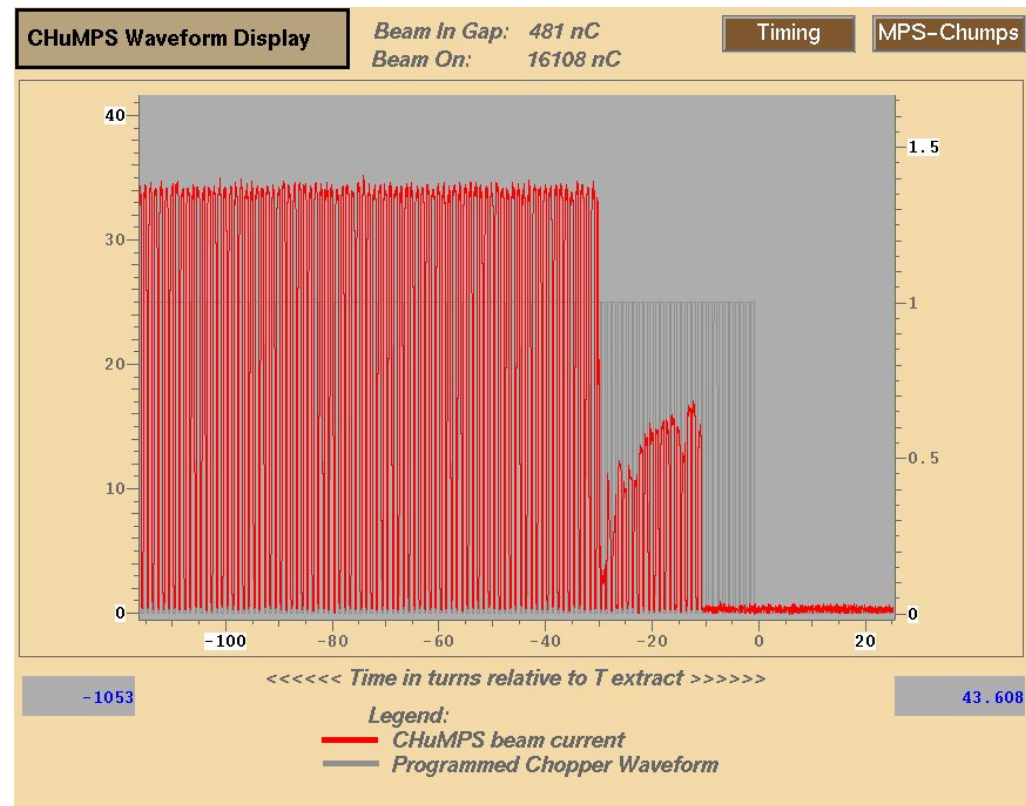
- In 2009 SCL cavity damage occurred from beam loss due to a malfunctioning Machine Protection System (MPS)
- The MPS issue was resolved but SCL cavity degradation due to errant beam has continued
- Luckily not all of the SCL has been affected by errant beam
- Luckily not every errant beam event causes an SCL RF cavity to trip off
- Luckily the degradation process is slow, and almost always can be undone with thermal cycling or plasma processing



In 2012 the errant beam task force established to understand errant beam

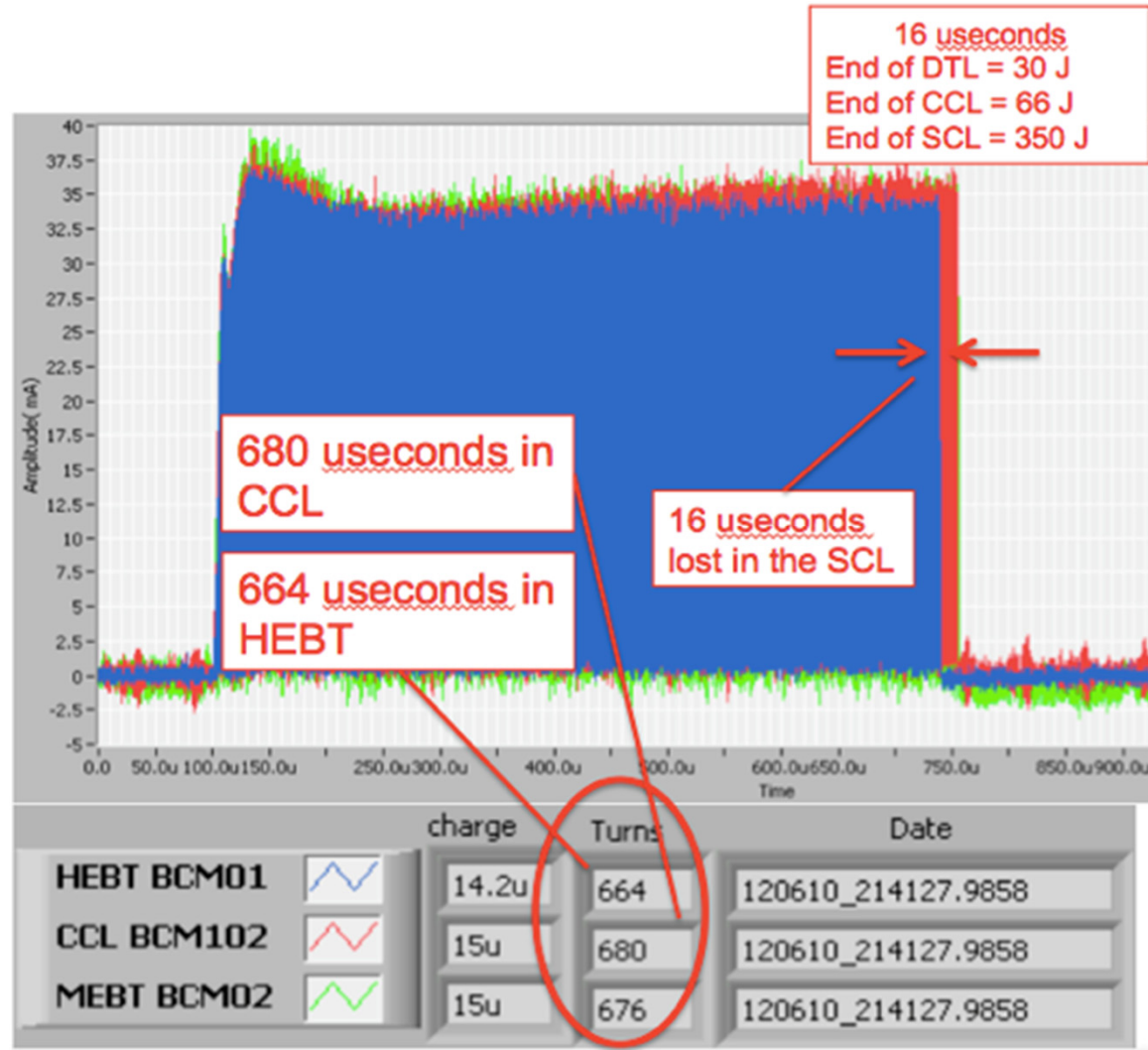
- The task force came up with the following plan:

- Measure the amount of beam lost during an errant beam event (verify the MPS was working correctly)
- Gather errant beam trip statistics and find causes
- Reduce errant beam frequency and the amount lost during each event



The MPS does turn off the beam in about 15 μ s

- BCM measurements verified the MPS works properly
- In most cases the beam is completely lost between CCL1 and the HEBT
- The MPS was and is currently working as designed
- The next step was to find causes for the errant beam



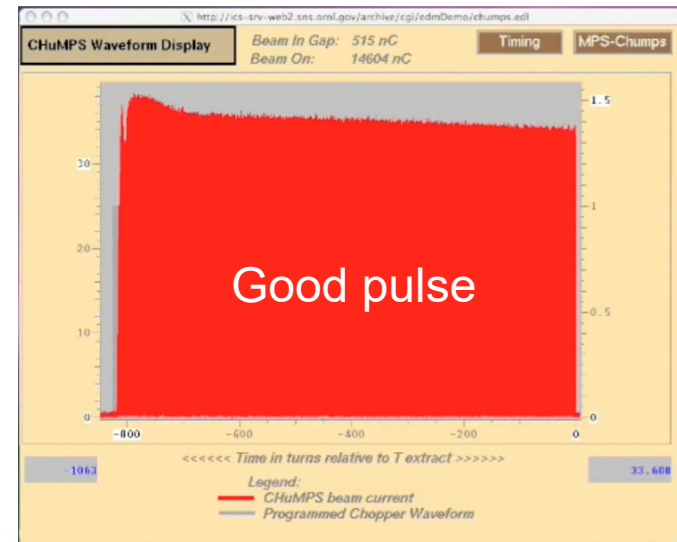
Data mining identified two major causes for errant beam

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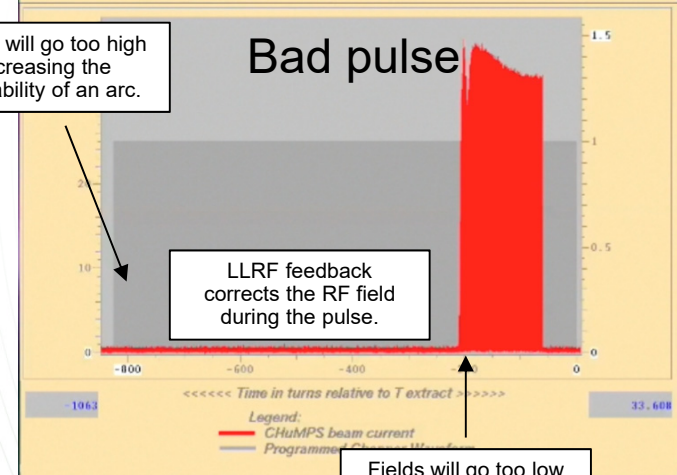
- Ion source/LEBT
 - Two major ion source issues
 - High voltage arcing
 - Beam halo

Ion source turn on instability and high voltage arcing have a two-fold effect

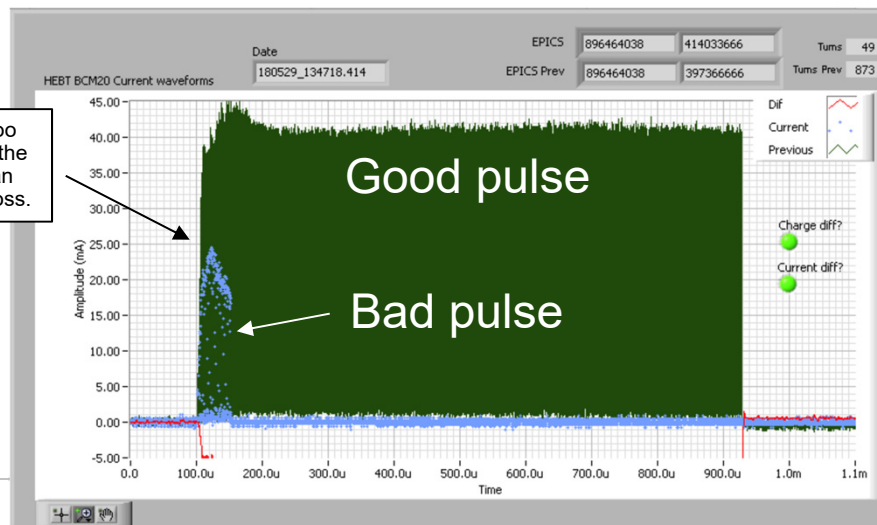
- AFF increases RF power to compensate for beam loading
- Delayed ion source turn on or a high voltage arc in the ion source will cause a drop in beam current
- RF power will be too high, which will transition to the cavity field being too high
 - Cavities are more likely to arc
 - Beam loss will occur due to incorrect fields and phases



Fields will go too high increasing the probability of an arc.



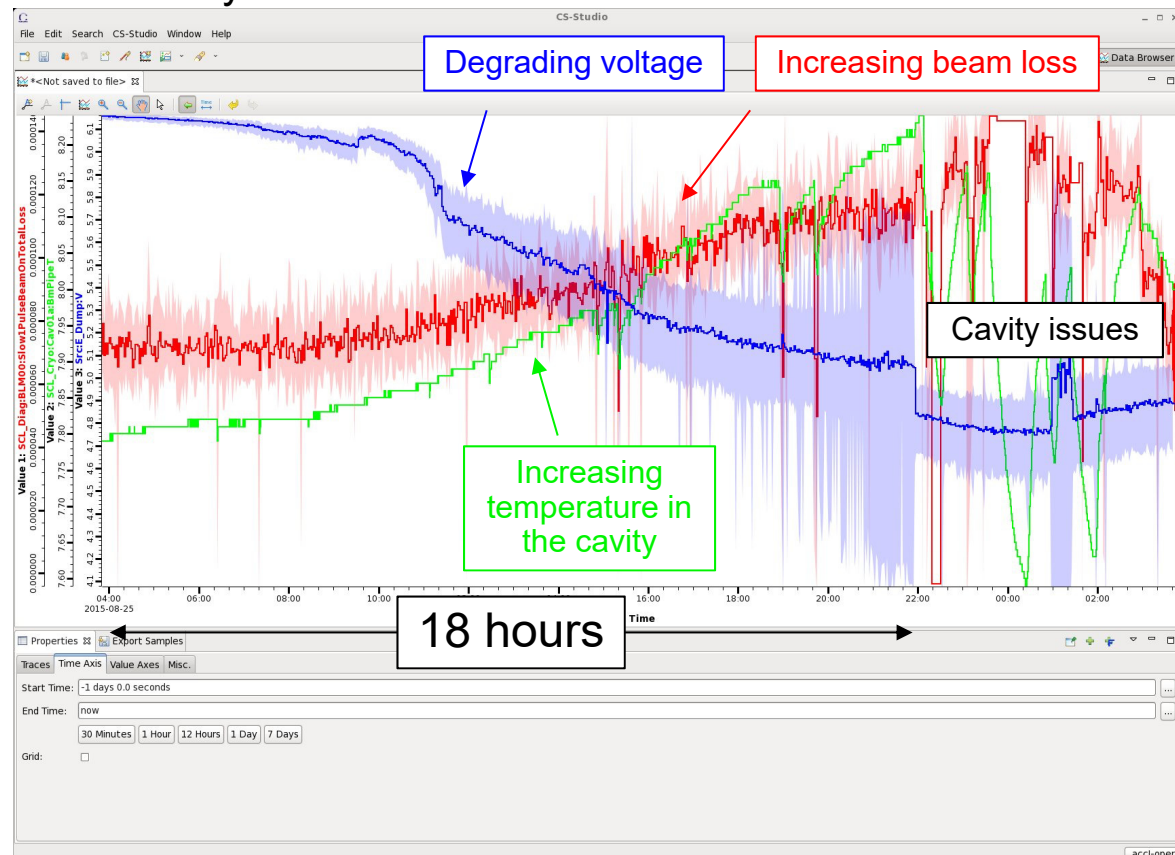
Fields will go too low increasing the probability of beam loss.



Fields will go too high increasing the probability of an arc, and beam loss.

Beam halo can degrade cavity performance

- An ion source extraction electrode was unable to maintain the appropriate voltage
- As the voltage decayed beam loss began to occur in the first SCL cavity
 - An upstream Beam Loss Monitor (BLM) increased by about 30% over 18 hours
 - Beam pipe temperature within the cavity increased from 7.8 K to 8.25 K
- Eventually the cavity could not run reliably and the gradient had to be reduced
 - Adjustments were made in the ion source, but the cavity gradient needed to remain reduced



Data mining identified two major causes for errant beam

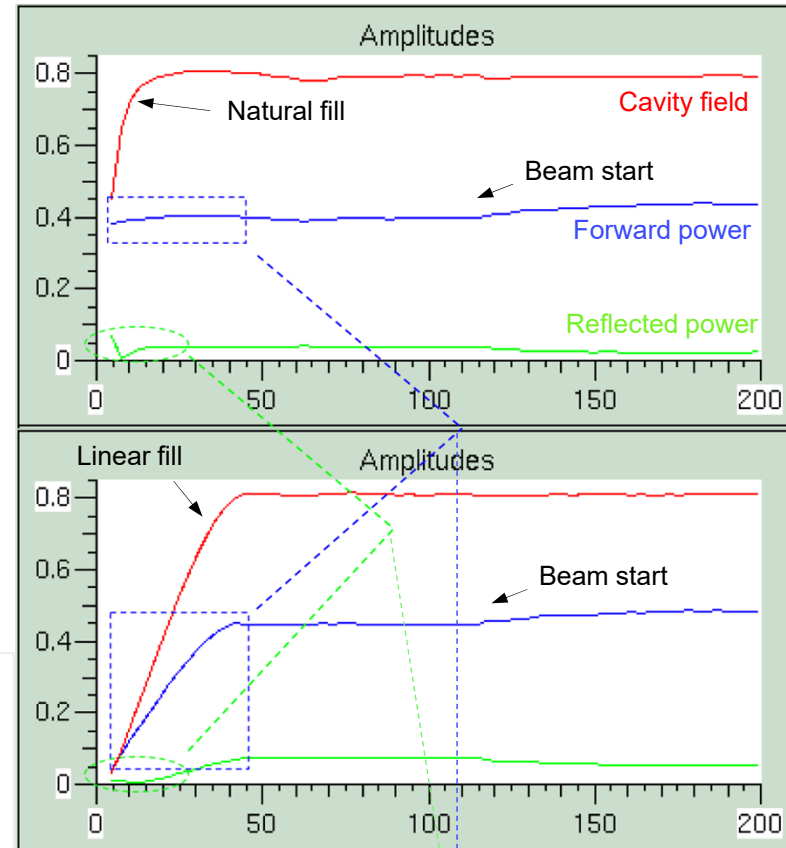
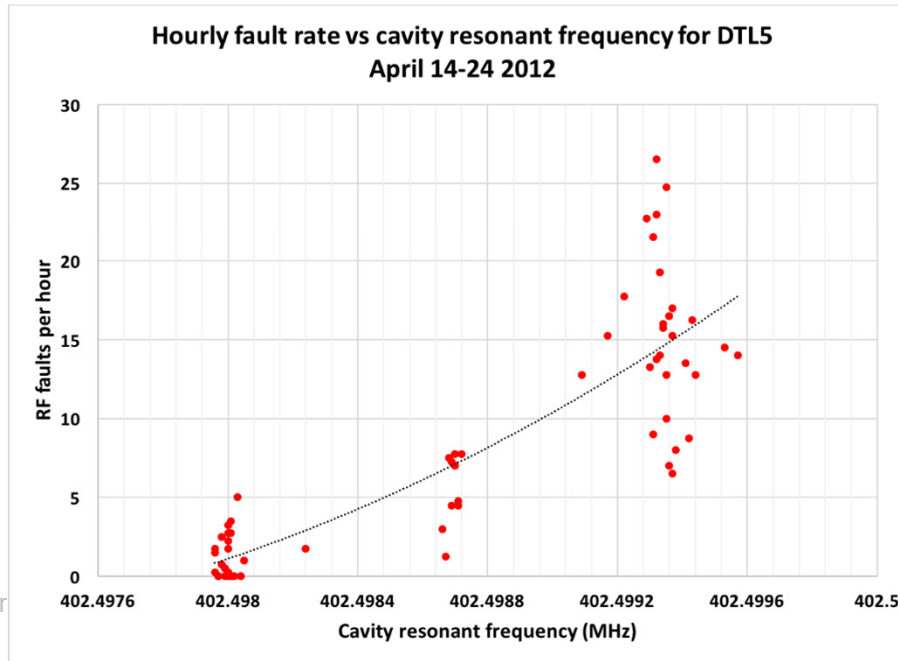
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Data mining identified two major causes for errant beam

- Ion source/LEBT
 - Two major ion source issues
 - High voltage arcing
 - Beam halo
- Warm Linac RF
 - RF faults caused by a range of different issues
 - Arcing/Multipacting
 - Vacuum
 - Operating practices
 - Other contributors

Reducing cavity fill faults reduced errant beam frequency

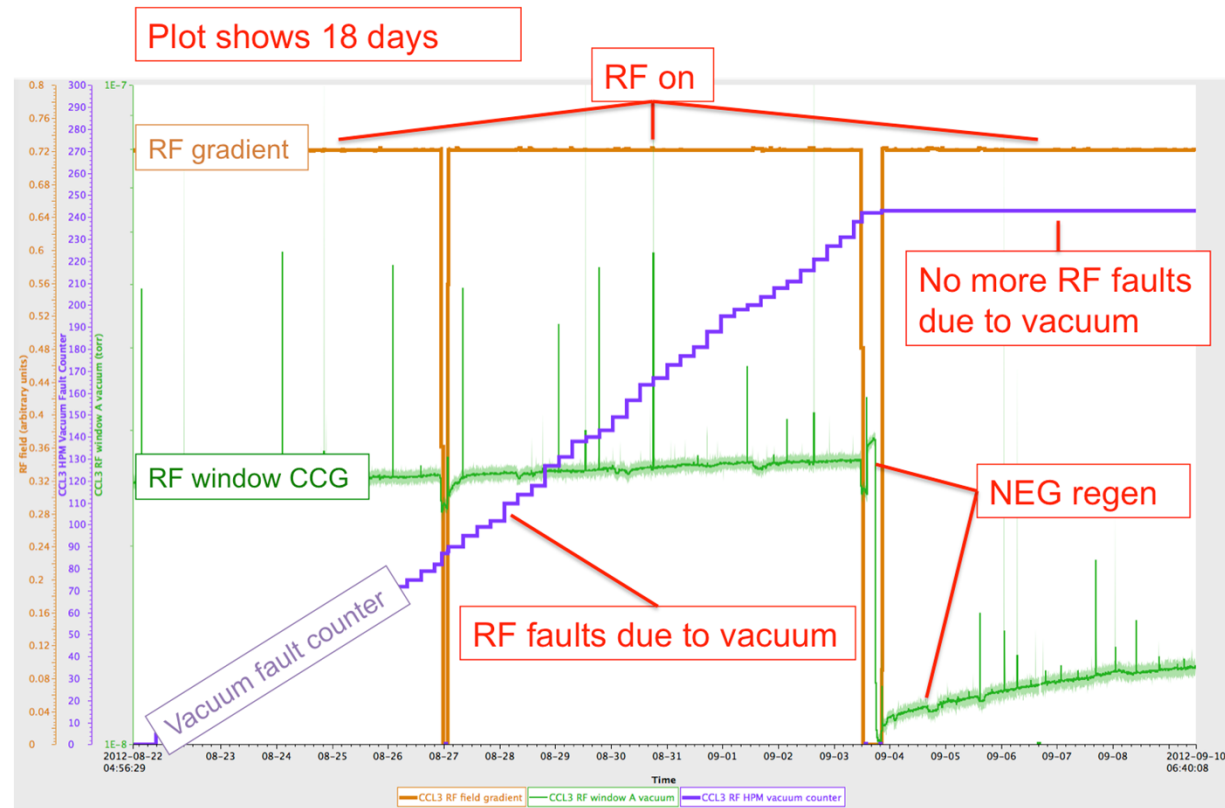
- Most of the warm linac RF cavities were faulting during the fill time of the RF pulse
- Two methods were used to affect the fill time faults
 - Linear RF power fill
 - Change the cavity resonant frequency
- The combination reduced errant beam faults in half



Note change in
shape of waveform

Vacuum upgrade decreased downtime and errant beam

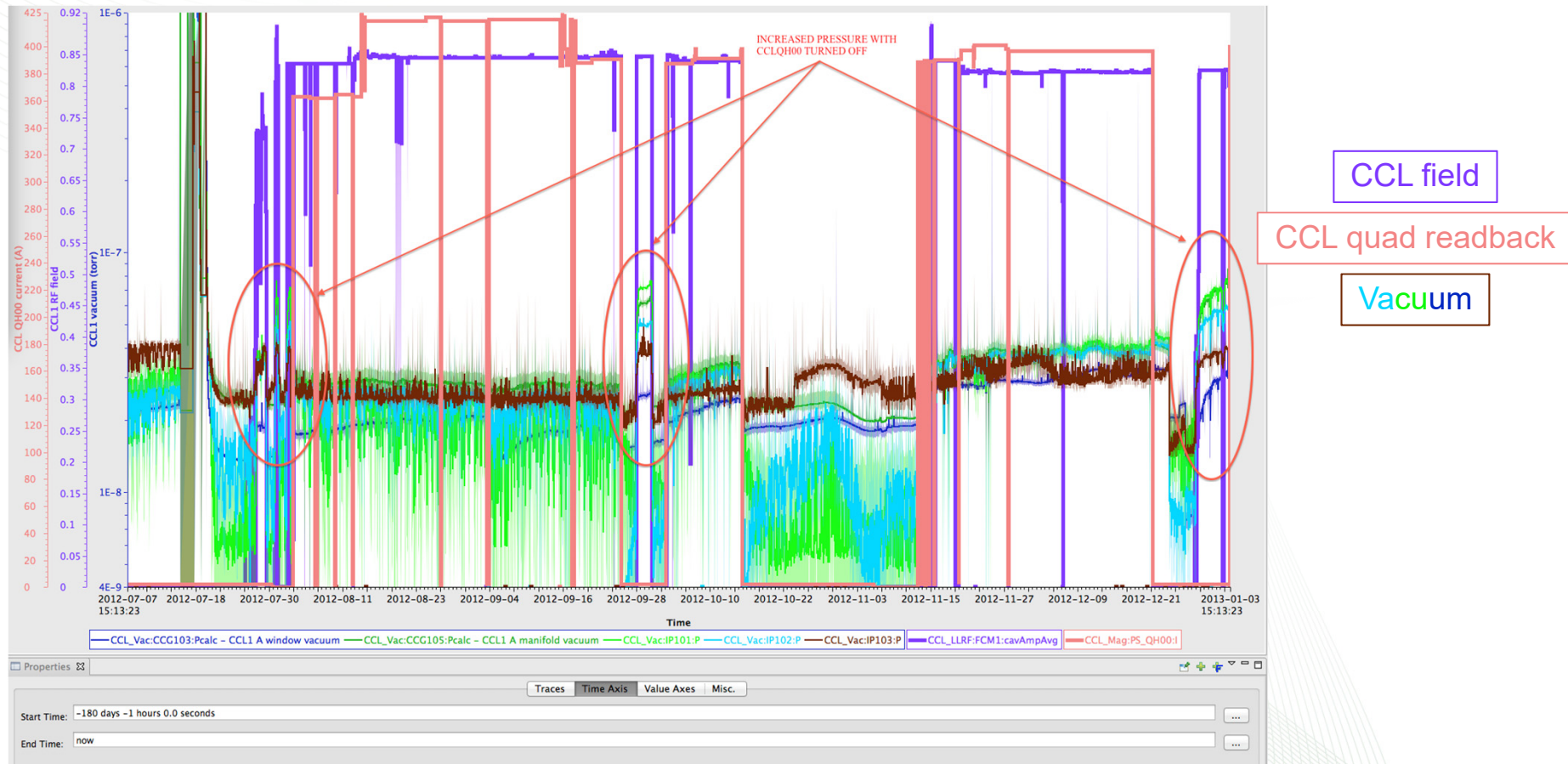
- Vacuum capture pumps have not worked well in the RF cavity environment
 - Cryopumps in the RFQ, ion pumps in the MEFT, DTL, CCL, and SCL, and Non-Evaporable Getter (NEG) pumps in the DTL and CCL
- Switching all warm linac ion and NEG pumps to turbopumps decreased overall beam downtime by 1%
- Eliminated possible cause of RF faults and errant beam



Timeframe	Total downtime (hours)	Number of events	% of total beam downtime	Beam hours requested
January 2014 to July 2015	51.3	92	2.16	10210
July 2015 to January 2017	12.6	23	1.04	9717

Quadrupole magnets need to be on in order to disburse field emitted electrons

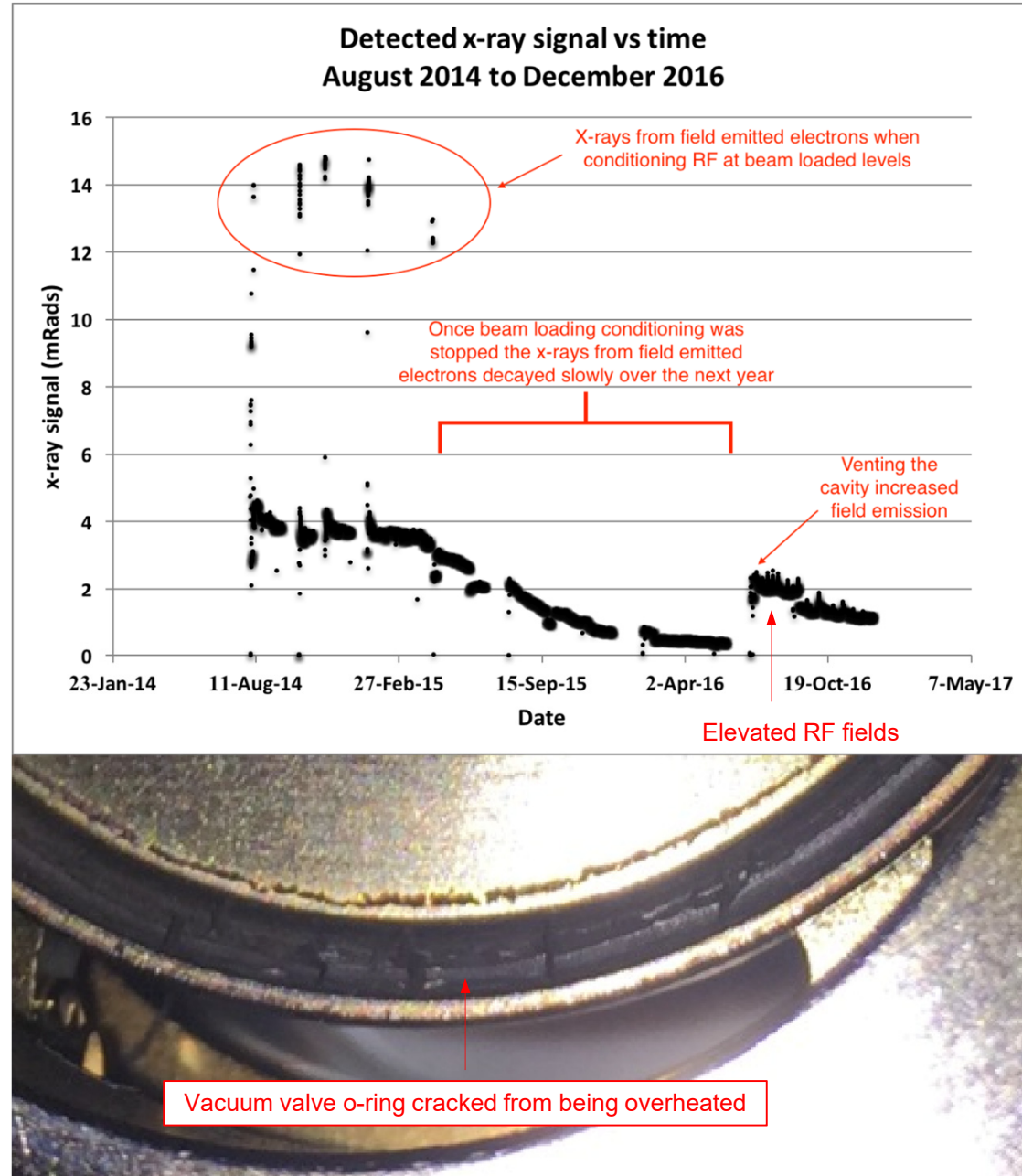
- CCL vacuum levels degrade when RF is on without quadrupole magnets energized



- Without quads on the field emitted electrons heat up secondary equipment and cause contamination

RF conditioning caused contamination

- RF conditioning of the warm linac is done after every extended maintenance period
- Previously the conditioning procedure had steps for RF conditioning to non-beam loaded levels (for cavity) and to beam loaded levels (for coupler)
- How to condition the coupler is the issue
 - Choice was to increase the cavity power to the beam loaded levels (about 10% in field)
- It's the secondary equipment within or just outside of the cavity that cause contamination



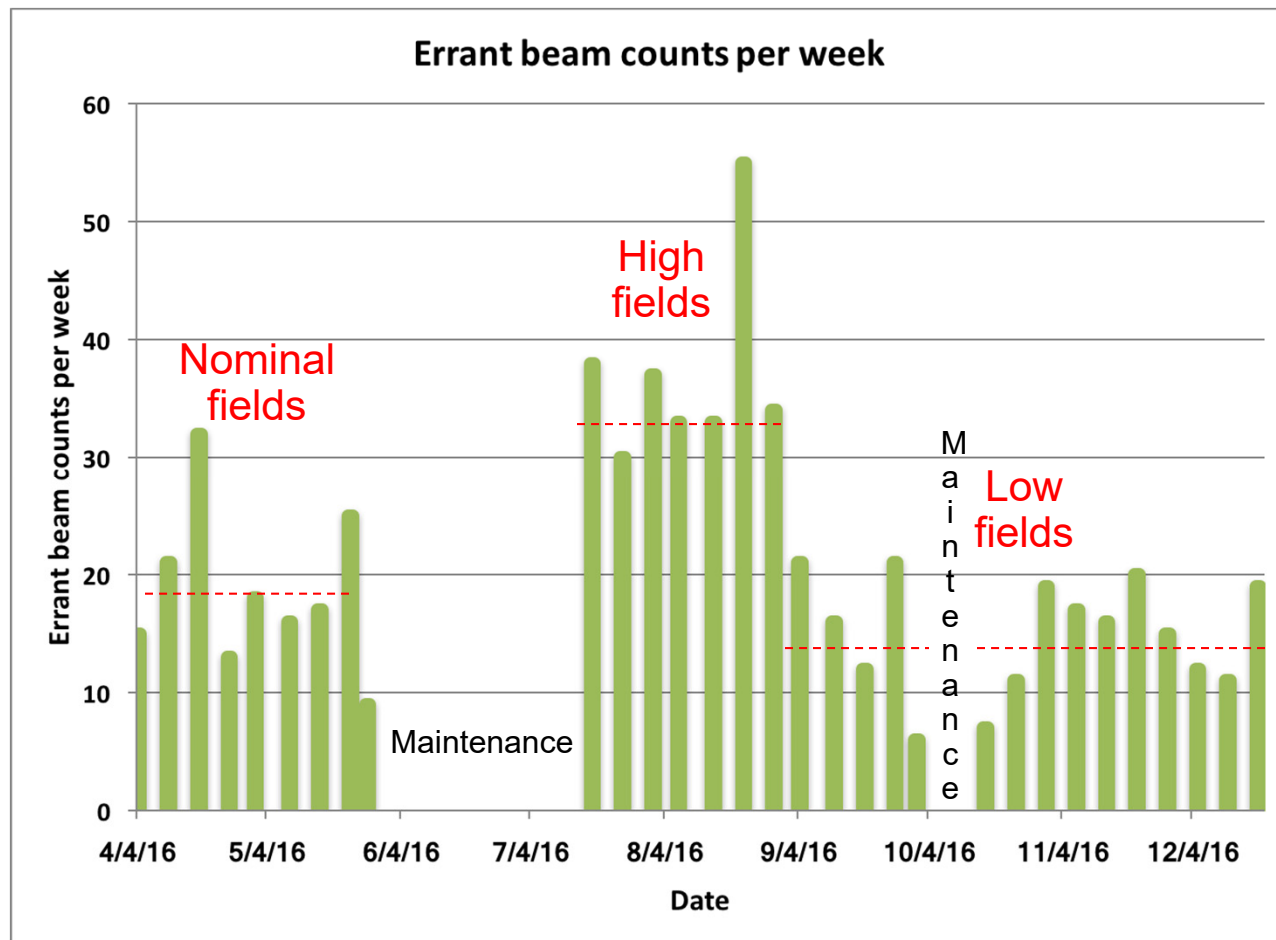
Elevated RF fields increase RF faults and errant beam

- Fields should be fixed in warm linac, but every tune-up gave different results (5% changes in field run to run)
 - Decided to fix net RF power (forward – reflected) and just set RF phase during beam tune-up
 - Use powers because they are calibrated (cavity Field Control Module (FCM) field setting is not)
- The calibration for forward and reflected power changed
 - It was noticed when setting up the beam, but just noted

ALWAYS BELIEVE THE BEAM

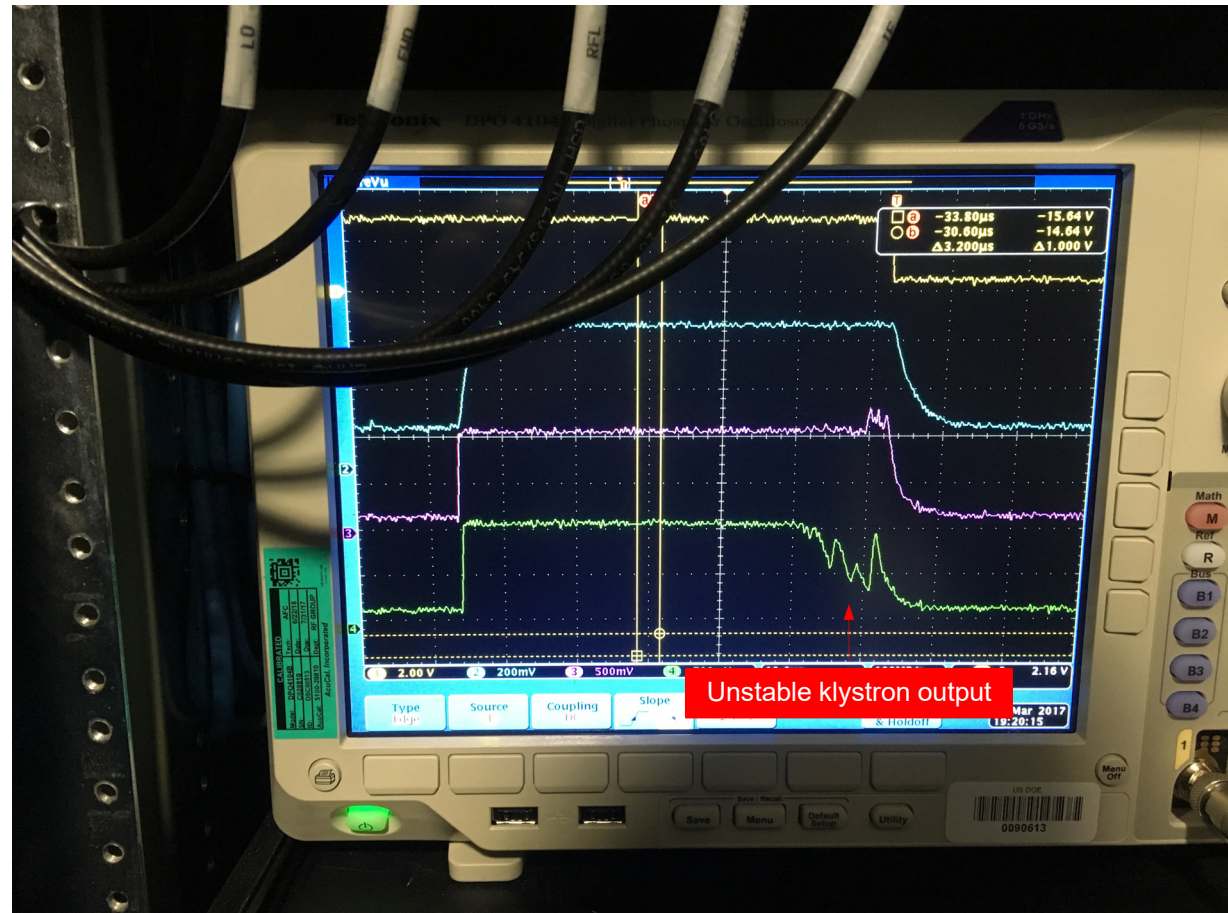
Lowering warm linac RF field decreased errant beam

- If higher fields cause more RF faults then reduce RF fields until beam losses go up
- Lowering warm linac fields decreased RF faults, and errant beam
- Run the warm linac at the minimum field necessary to transport the beam cleanly



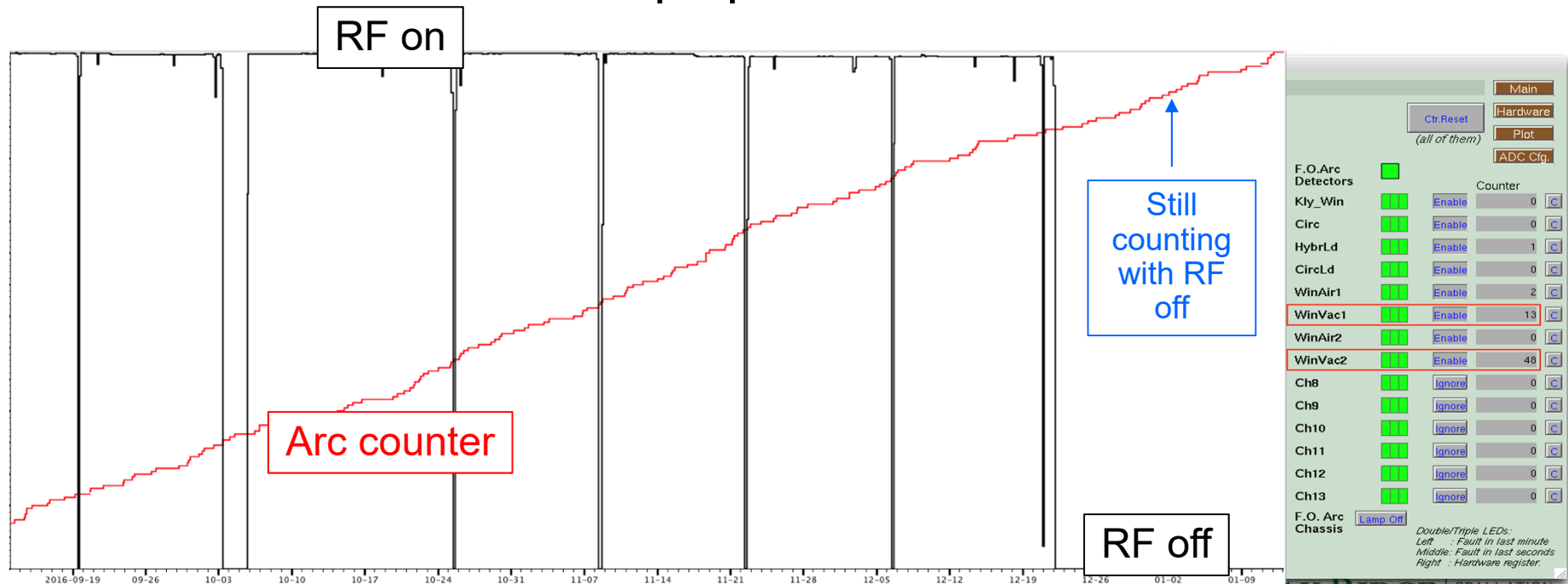
Klystron instability reminds of problems that can exist with the High-Power RF system

- In general the HPRF is very stable, but at any time a new problem can develop increasing errant beam frequency
- Difficult to convince management to change a \$750K klystron without complete failure
- Trip statistics can be used as a diagnostic to see that a problem is developing



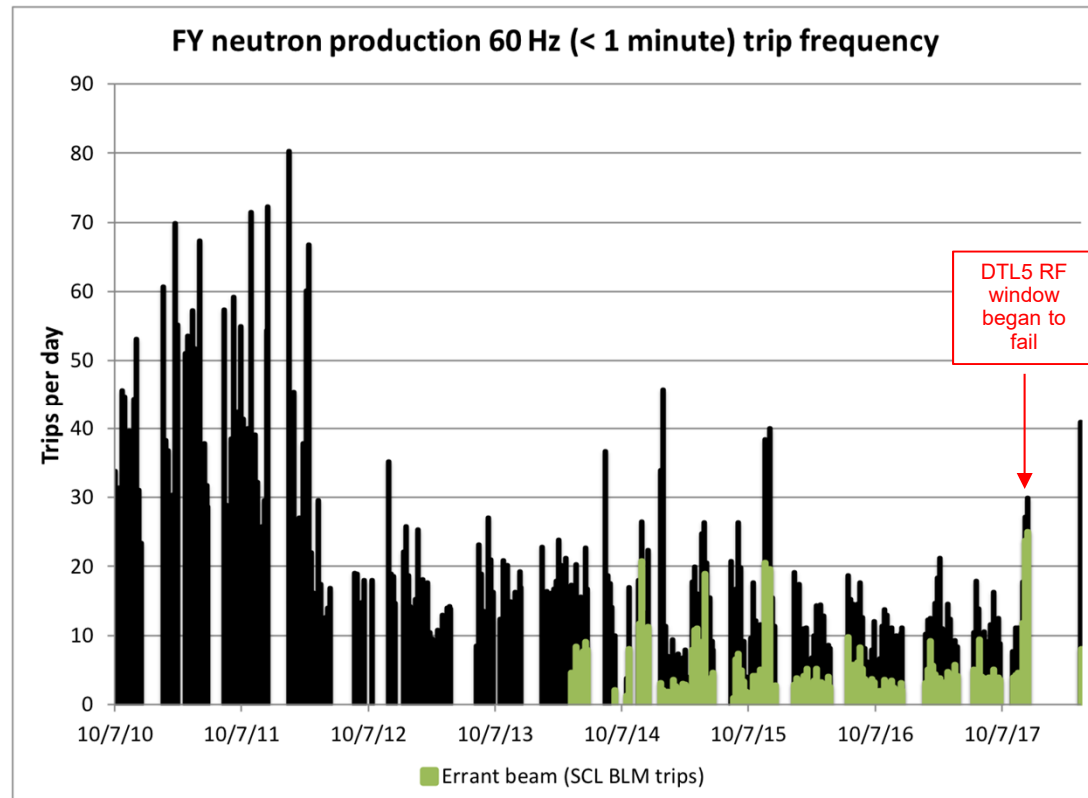
CCL false arc detection is important too

- 4 CCL cavities with 2-4 false arcs were detected per cavity per day
 - 8-16 false arcs detected per day
 - The arcs were detected at all times, but only a 6% (duty factor) probability of occurring during a beam pulse
- About 3-7 errant beam trips per week



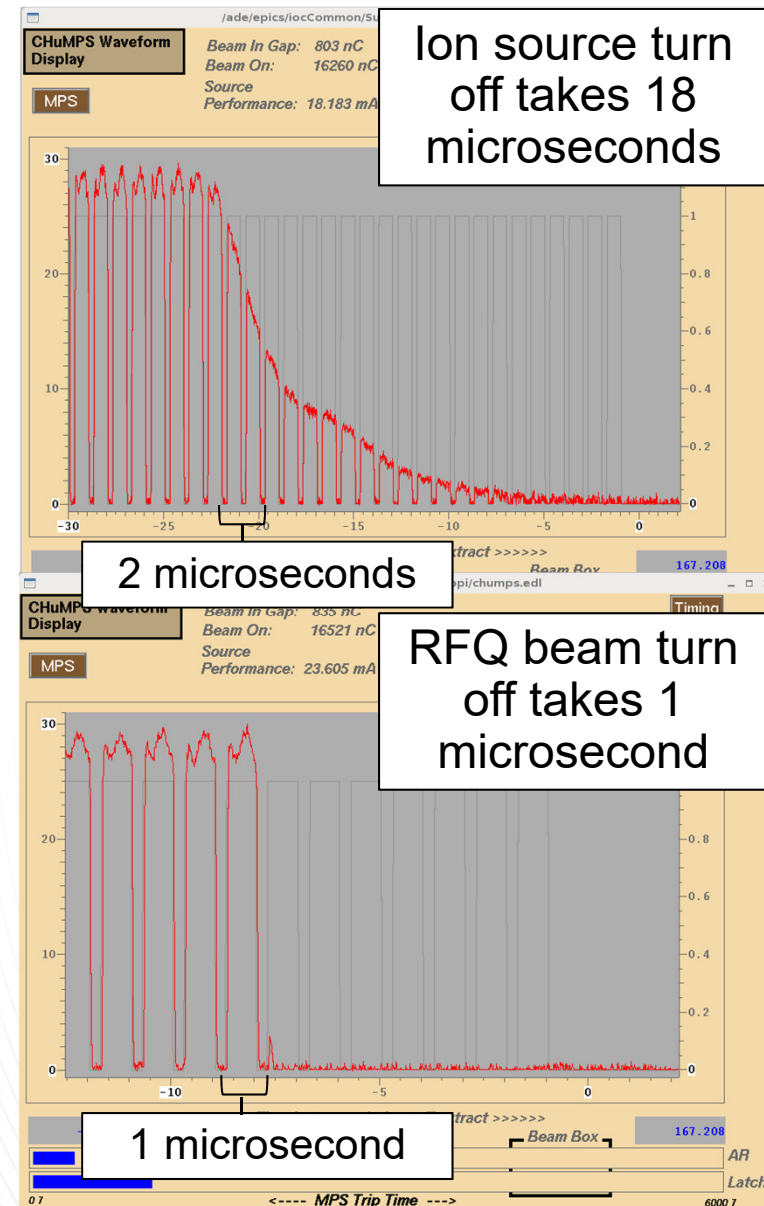
Errant beam event frequency is significantly reduced

- Errant beam event frequency has been reduced by almost an order of magnitude
- Ion source development and warm linac optimization have significantly reduced errant beam
- The frequency will never be reduced to zero and can only be minimized
- The next goal was to reduce the amount of beam lost per event



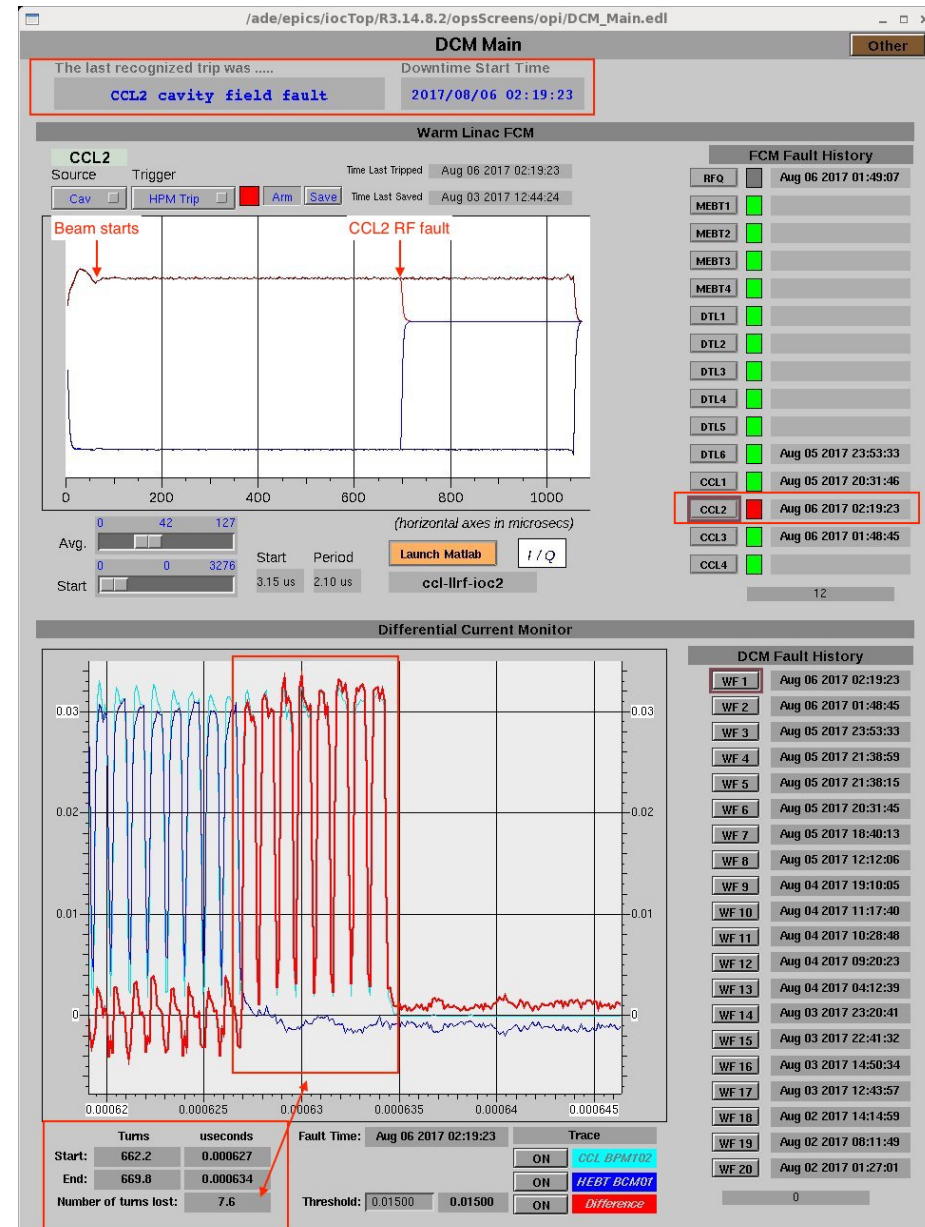
The MPS is designed to turn off the beam in about 20 μ S

- A system detects a fault condition and tells the MPS to turn off the beam
- The MPS turns off the timing gate to the ion source and the RFQ, and turns on a beam chopper to chop all of the beam before it is injected into the RFQ
- The whole process from detection to beam off should take on average 15-20 microseconds



SCL Differential Beam Current Monitor (DBCM) has reduced beam loss

- Goal was to turn off the beam faster than the MPS
- Fastest way to turn off the beam is the RFQ or LEBT chopper
 - Chose LEBT chopper because worried about RFQ stability
- Uses a BPM upstream and a BCM downstream of the SCL
- Detects a charge difference and sends one signal directly to the LEBT chopper and one to the MPS
 - LEBT chopper chops until the MPS can turn off the ion source and RFQ
- Reduced beam turn off time from 15 to 8 microseconds



Faster beam turn off is still not fast enough to prevent SCL cavity downtime

- Even with reduced beam turn off time SCL cavities do occasionally trip when struck with errant beam during a warm linac cavity fault
 - Usually at the beginning of a run or after a 4 K to 2 K transition

95. Fri, May 18, 2018 06:12

Geoffrey Milanovich

[CCL 4 fault tripped SCL 04b](#)

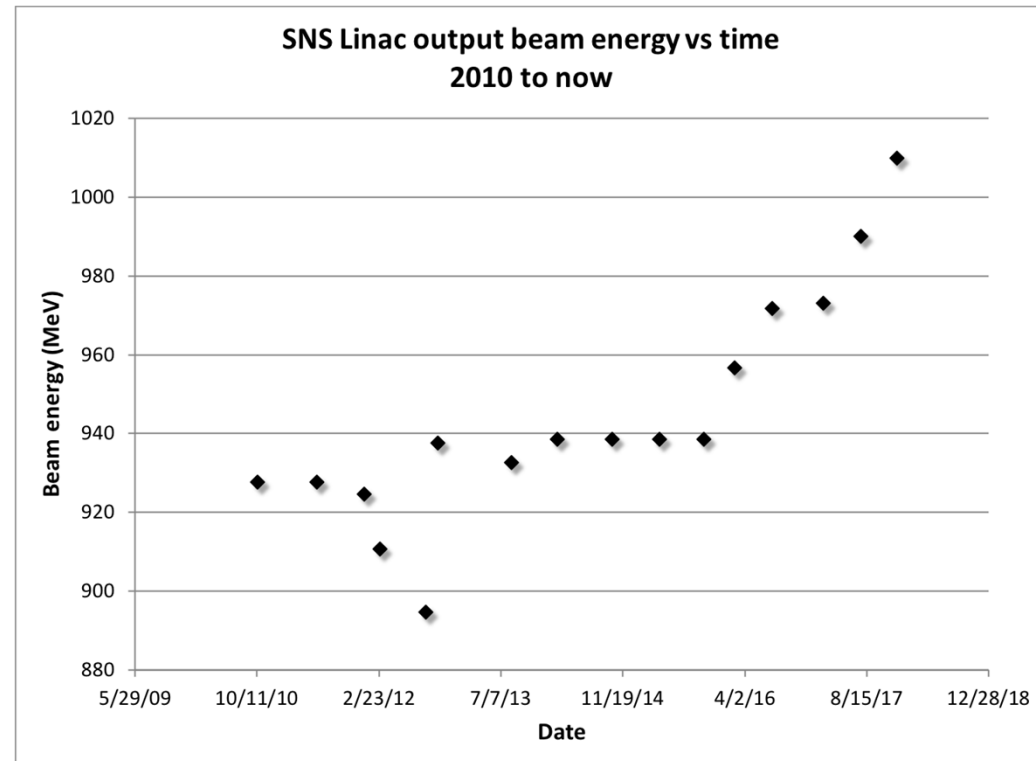
{Operations} () 20

CCL HPM fault sent errant beam into SCL 04b.

- It's not clear how fast the beam needs to be turned off to avoid all SCL cavity trips due to errant beam
- Planned beam power upgrades will nearly double the beam charge per microsecond which means more beam loss during an errant beam event
 - Further reducing the beam lost during each event remains a priority

Path forward

- Plasma processing has increased the beam output energy by ~8% since 2016
- Don't want to lose plasma processing gains
 - Continue to monitor and minimize frequency
 - Beam turn off time is minimized with currently installed hardware but upgrades are being worked on
 - Building a MEBT DBCM system for pulse to pulse checks that will limit damage from the ion source
 - Testing a machine learning algorithm that uses SCL DBCM waveforms to predict warm linac errant beam events before they happen



Thank you for your attention!

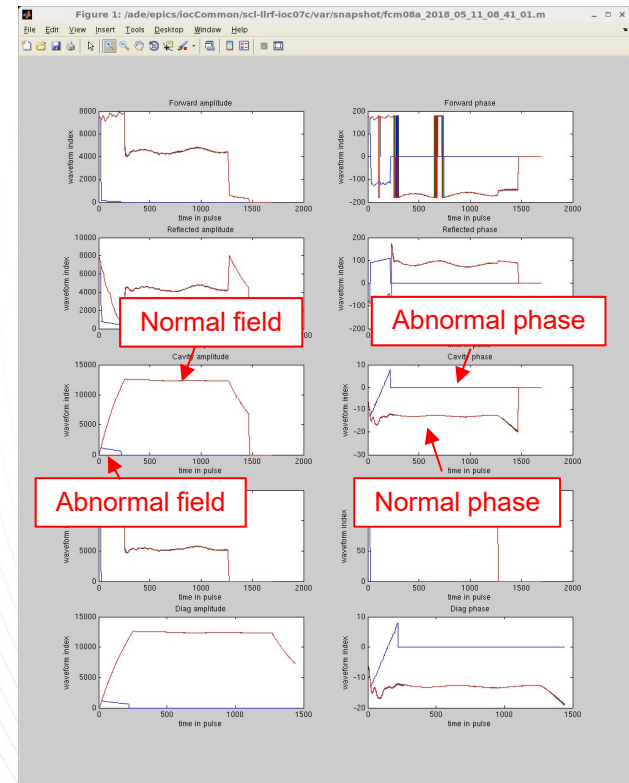
Additional slides

SCL DBCM still doesn't turn off the beam fast enough

- Central Helium Liquefier (CHL) system fault caused transition of SCL from 2 to 4 K.
 - After SCL recovery to 2 K:
 - First DTL4 RF fault caused SCL BLMs to trip, but not enough beam loss in SCL to trip cavities.
 - First DTL5 RF fault caused SCL BLMs to trip, but not enough beam loss in SCL to trip cavities.
 - First DTL6 RF fault caused SCL cavity 02b to trip.
 - First CCL1 RF fault caused SCL cavities 03b and 03c to trip.
 - First CCL2 RF fault caused SCL cavities 03c and 04b to trip.
- Need faster beam turn off time to eliminate SCL cavity trips (not clear how much faster).

SCL cavity downtime is typically a response to another malfunctioning system

- In general SCL cavity trips are a reaction to another problem.
 - HPRF and errant beam.
- Every cavity fault is investigated whether or not downtime occurs.
 - Not every fault causes the cavity to trip off.
 - LLRF waveform 20 Hz history buffers are used for fault diagnosis.
- Multiple SCL RF cavity trips in a day is not the norm now, but it has taken time to reach this point.
 - SCL cavity trip rate is ~1 every 1.5 to 2 days.

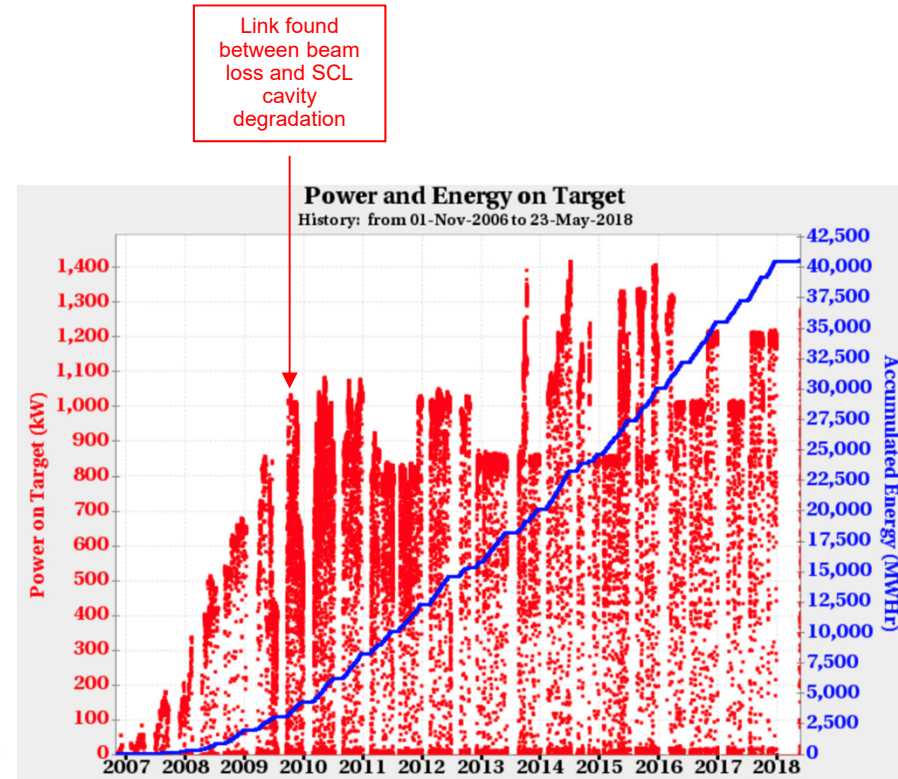


A simple understanding of Low-Level RF Adaptive Feed Forward is important

- The Low-Level RF (LLRF) feedback system maintains cavity field and phase during the RF pulse.
- Adaptive Feed Forward (AFF) learns the shape of the beam pulse (beam loading) and adjusts LLRF parameters in advance of the next beam pulse.
 - The goal is to maintain the proper cavity field and phase when beam is present.
- If the beam shape changes then the LLRF parameters will be incorrect.
 - RF fields and phases for all cavities will be wrong, and beam loss will occur.

Beam loss induced SCL cavity degradation was recognized in 2009

- SCL RF cavity gradients had to be reduced in order to maintain high reliability.
- Sang-Ho Kim linked beam loss events to SCL RF cavity downtime events.
- He suspected the Machine Protection System (MPS) was not properly terminating beam during an upstream equipment malfunction.

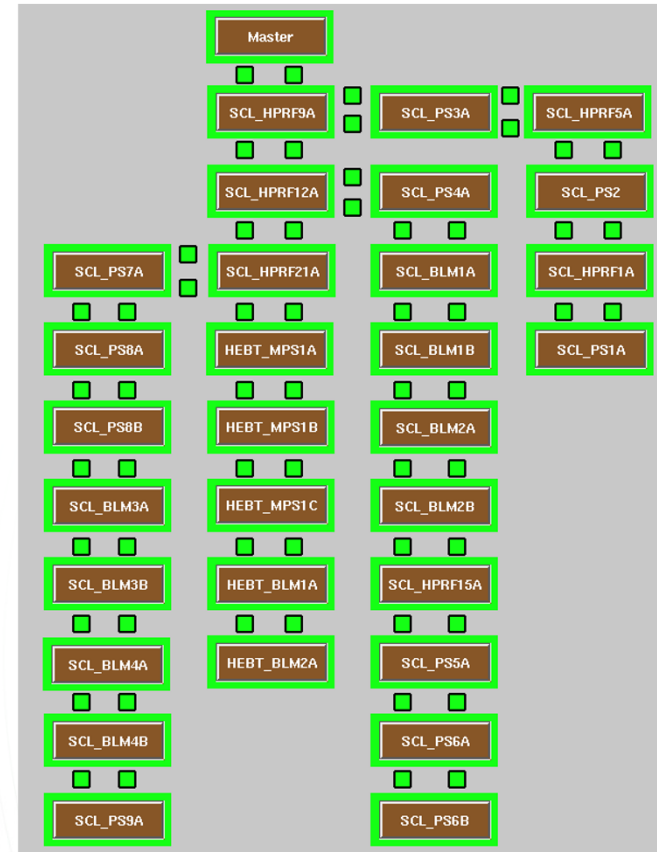


The term “errant beam” was born!

MPS beam turn off time was 200 μ S

- MPS experts induced a fault, and measured the response time to turn off the beam.

MPS chassis arrangement for the SCL

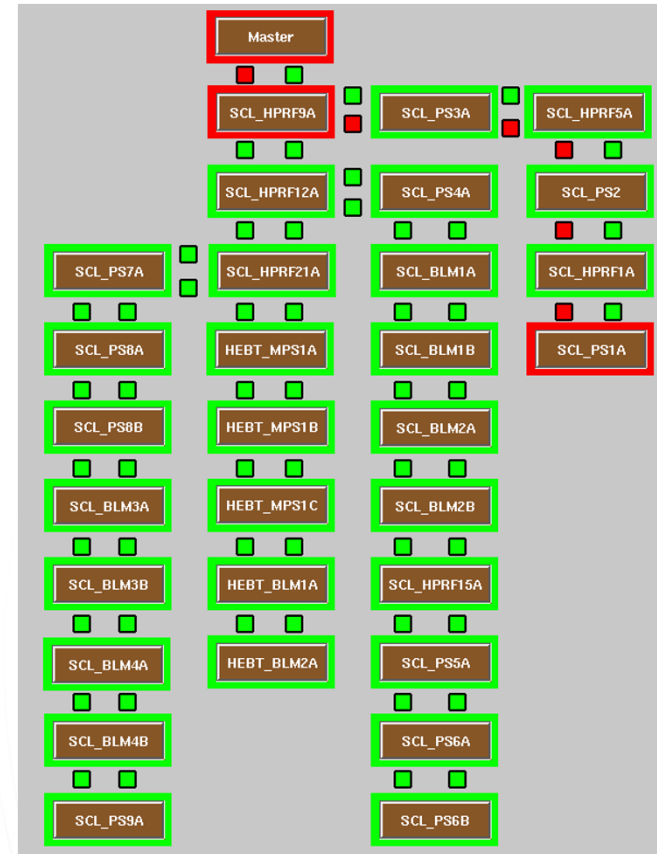


- Results showed the MPS was not turning off the beam at the designed 20 microsecond goal.
- Clear issues were found and corrected, but degradation continued.

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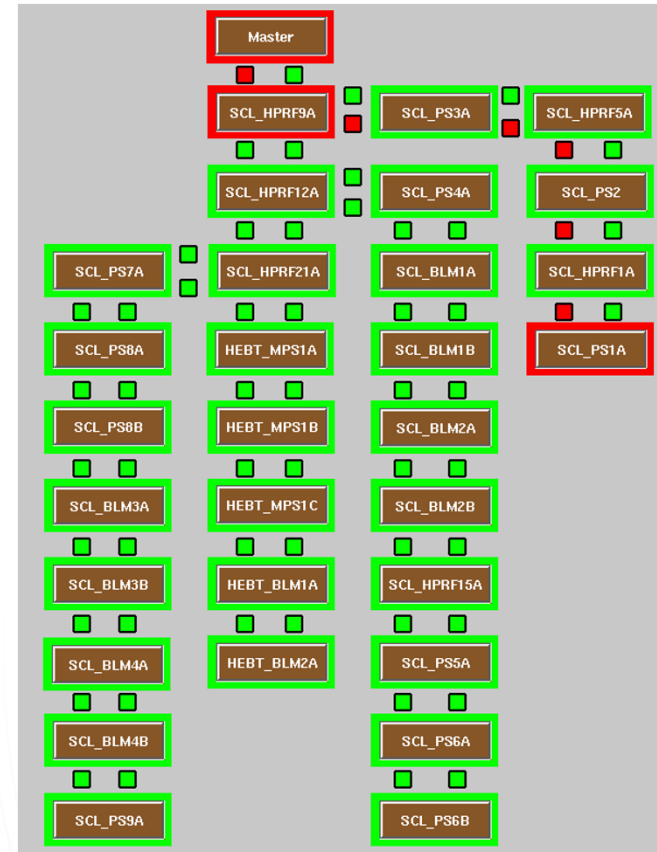
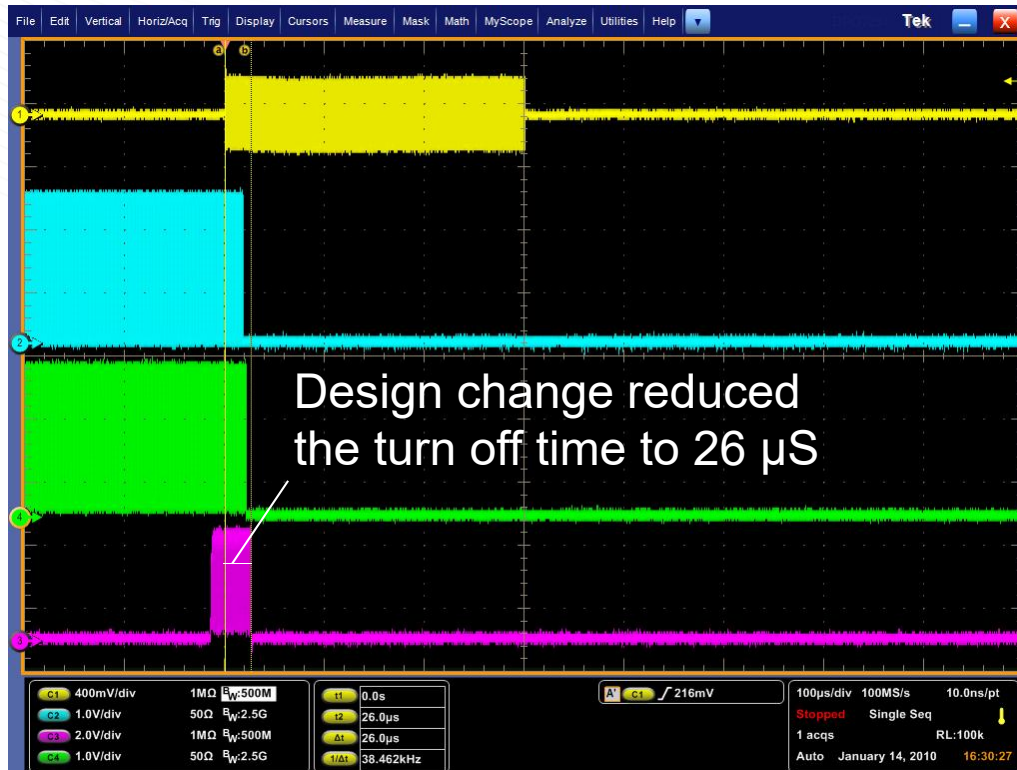


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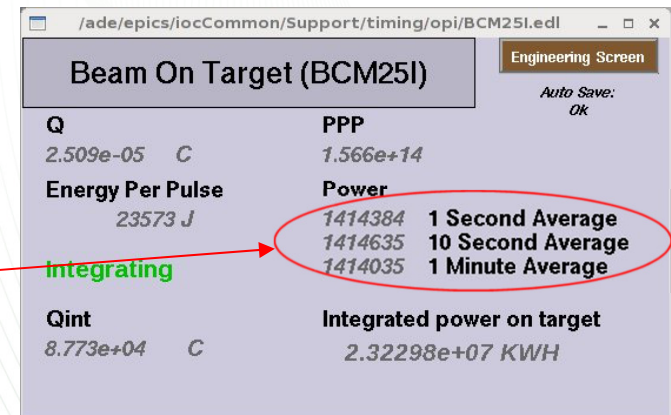
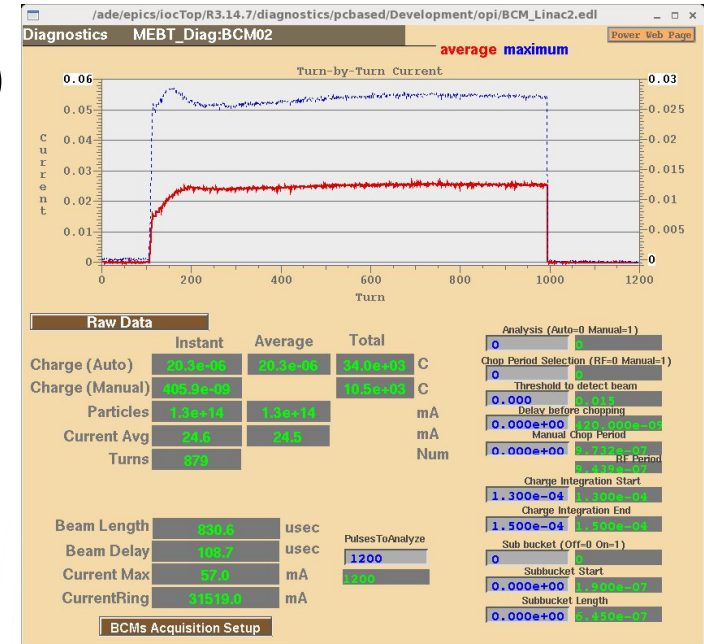


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Currently the highest power pulsed proton linac in the world

52 mA average peak and 900 μ S!

- The Spallation Neutron Source (SNS) is a pulsed neutron source used for materials research.
- Linac accelerates a 1 millisecond long H- beam to 1.01 GeV 60 times per second.
- The linac is able to produce >1.4 MW of beam power at >90% beam availability.



Sustained operation at 1.4 MW on target is the current goal

Diagnostics

- How did we figure it out?
- Statistics
- MPS
- How do our BLMs work. Single pulse loss and 1 second loss. Monitoring all of the time.
 - Every few meters we have BLMs
 - RCTs survey during maintenance days
- BPMs 1 second update (being upgraded)
- BCMs 60 Hz possible
- LLRF 20 Hz (PPU upgrades planned)