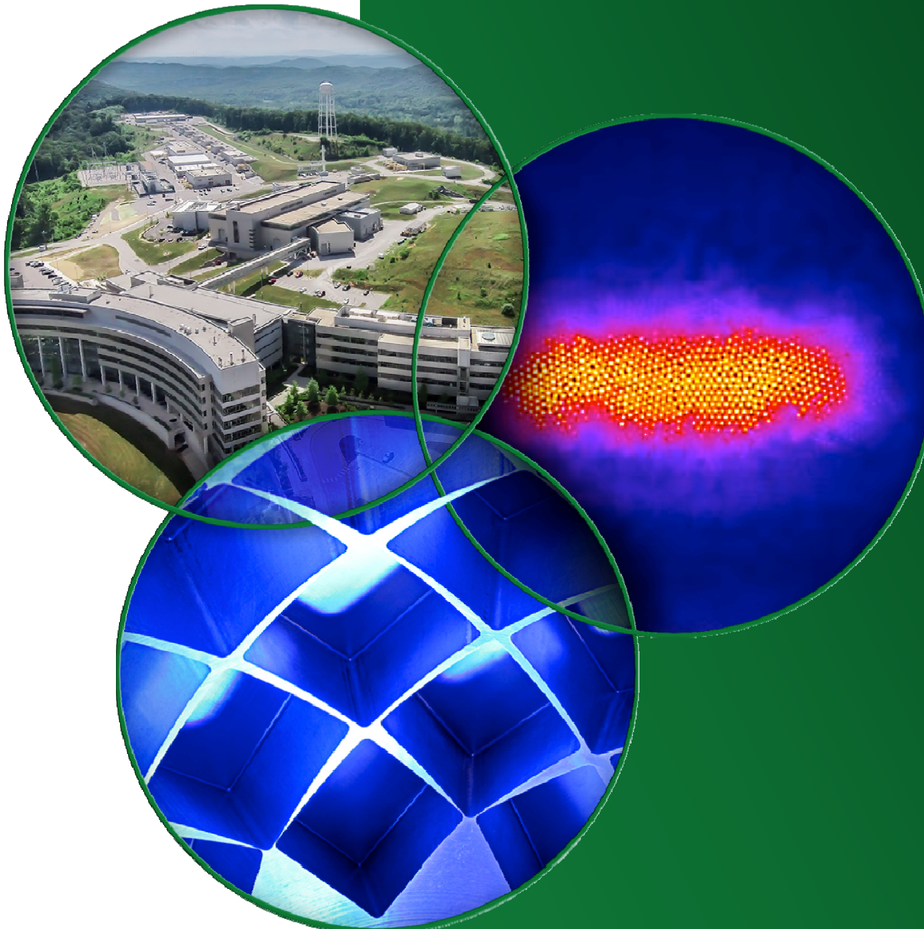
Minimizing Errant Beam at the Spallation Neutron Source (SNS)



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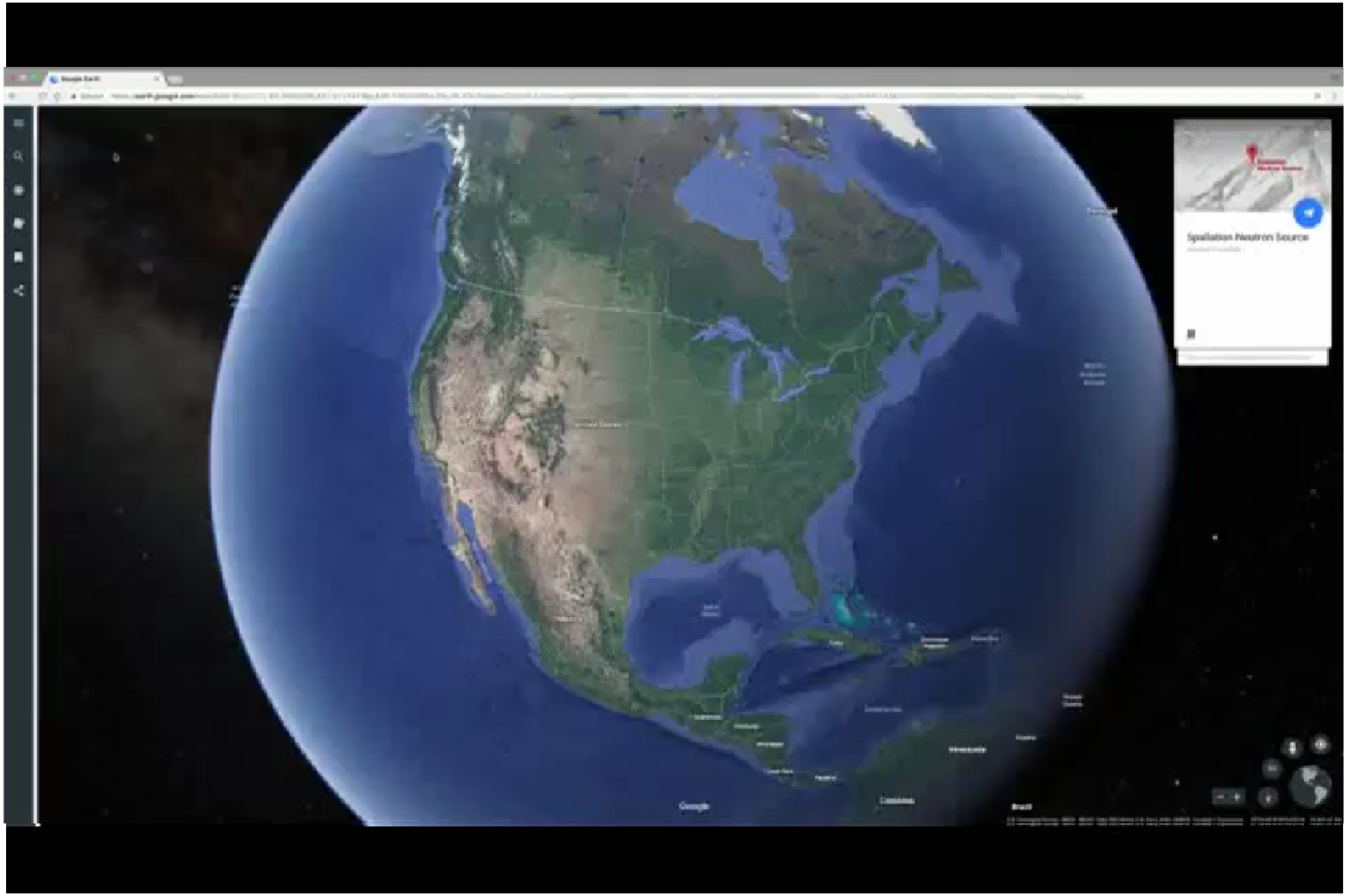
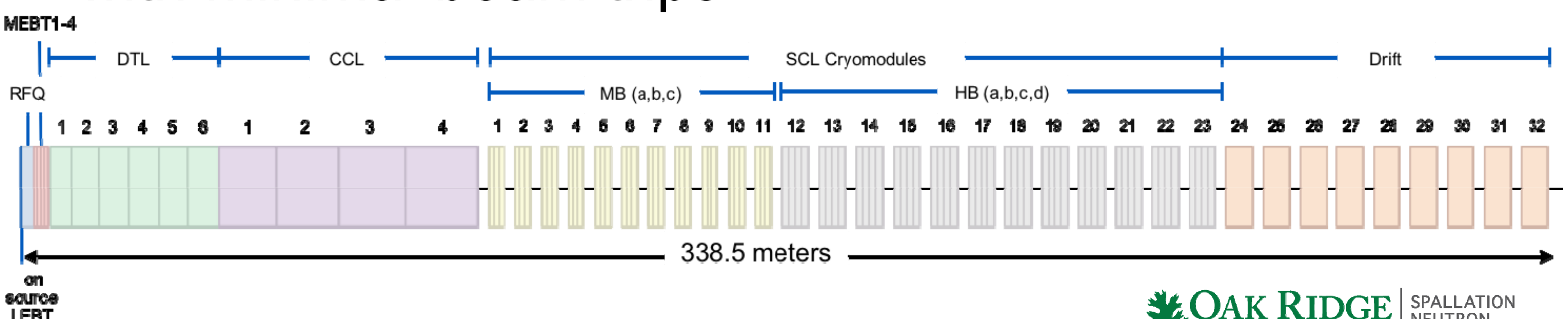
The Spallation Neutron Source

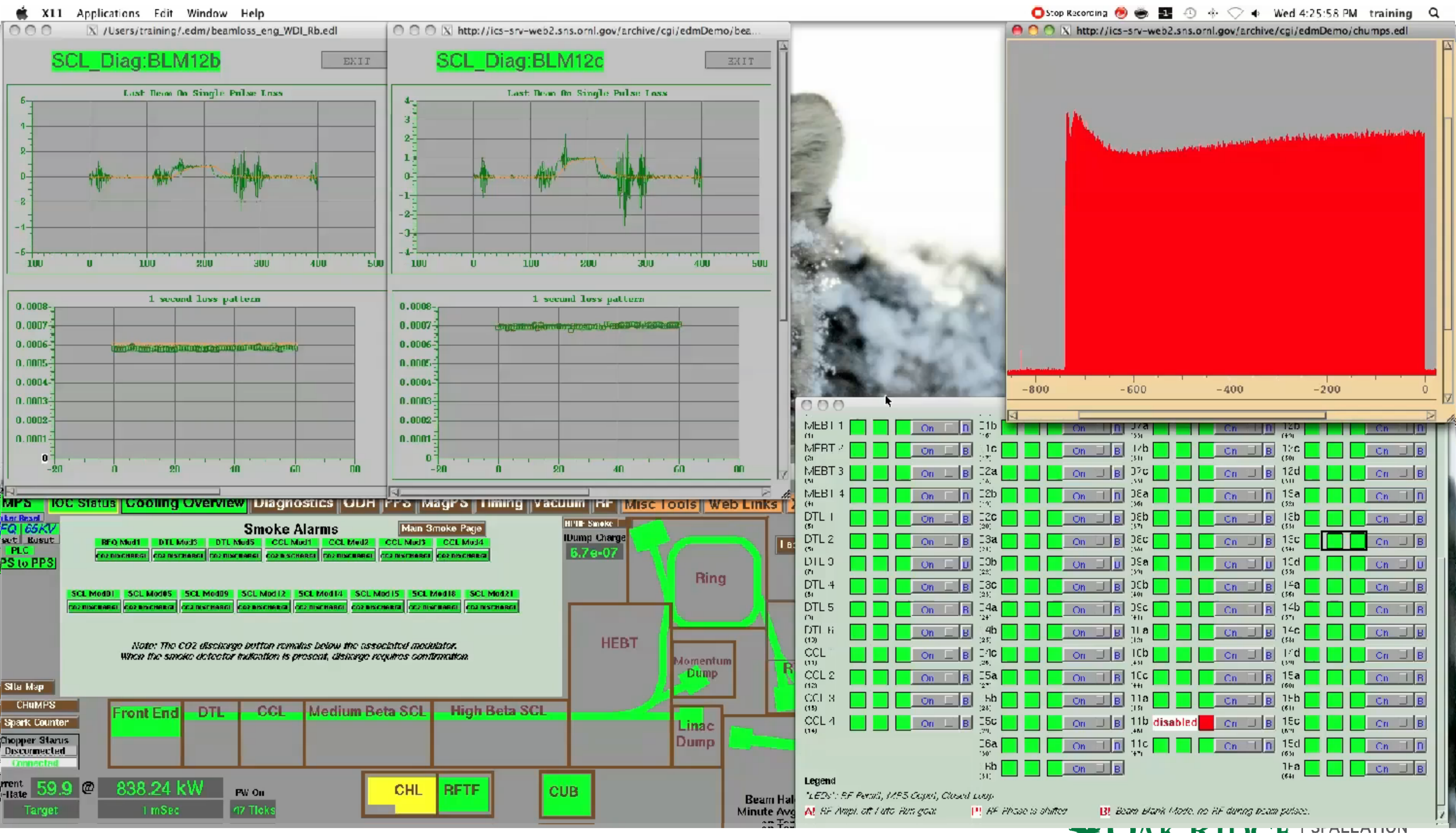


Linear accelerator information

- Highest intensity pulsed proton linac in the world.
- Accelerate 1 millisecond of H- beam to 1 GeV in about 340 meters 60 times per second.
  - 96 RF cavities
    - 15 normal conducting cavities (the “warm linac” or NCL)
      - RFQ, MEBT1-4, DTL1-6, CCL1-4
    - 81 superconducting cavities (the “cold linac” or SCL)
- Goal for the facility is greater than 90% availability with minimal beam trips.

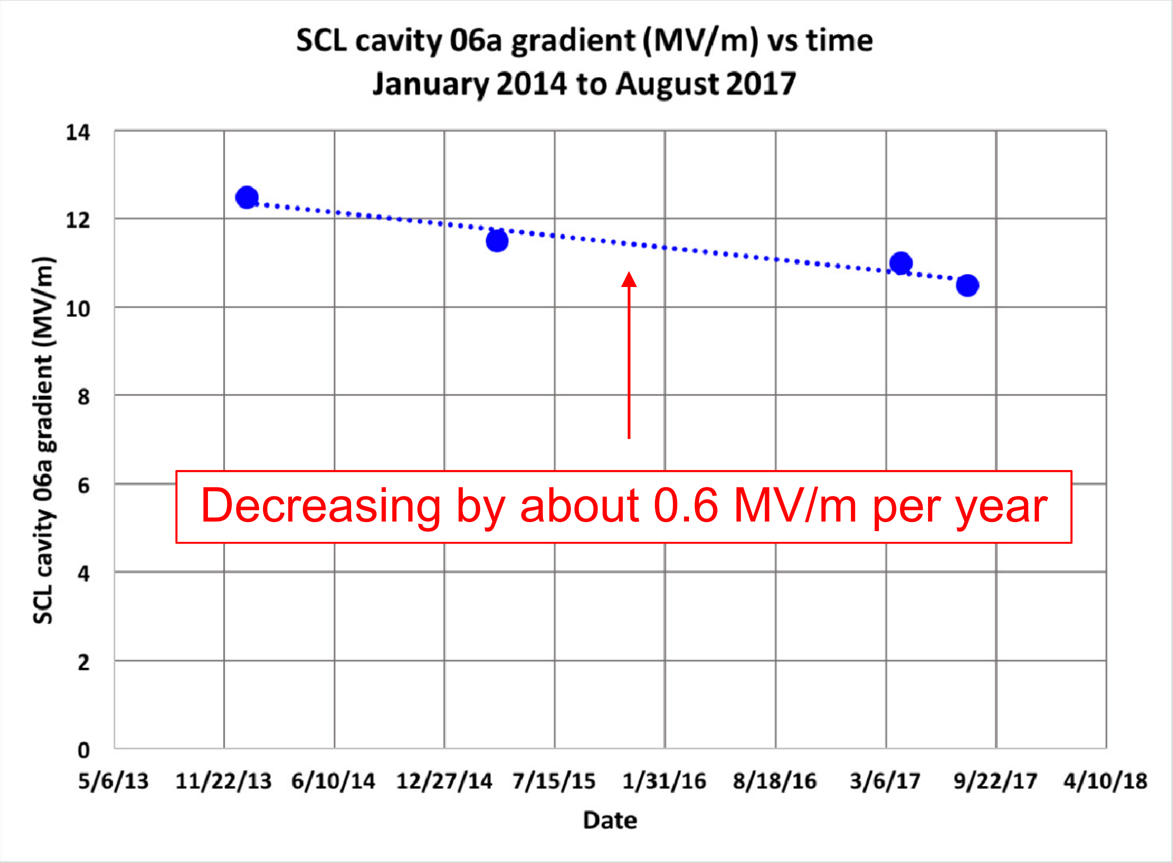


Errant beam is beam lost in the SCL (multiple systems cause beam loss)



Errant beam degrades SCL cavity performance

- Degradation means having to lower the cavity gradient in order for the cavity to run reliably.
- Not all of the SCL is affected by errant beam.
- Not every errant beam event causes an SCL RF cavity to fault off.
- The degradation process is slow, and almost always can be undone with thermal cycling or plasma processing.

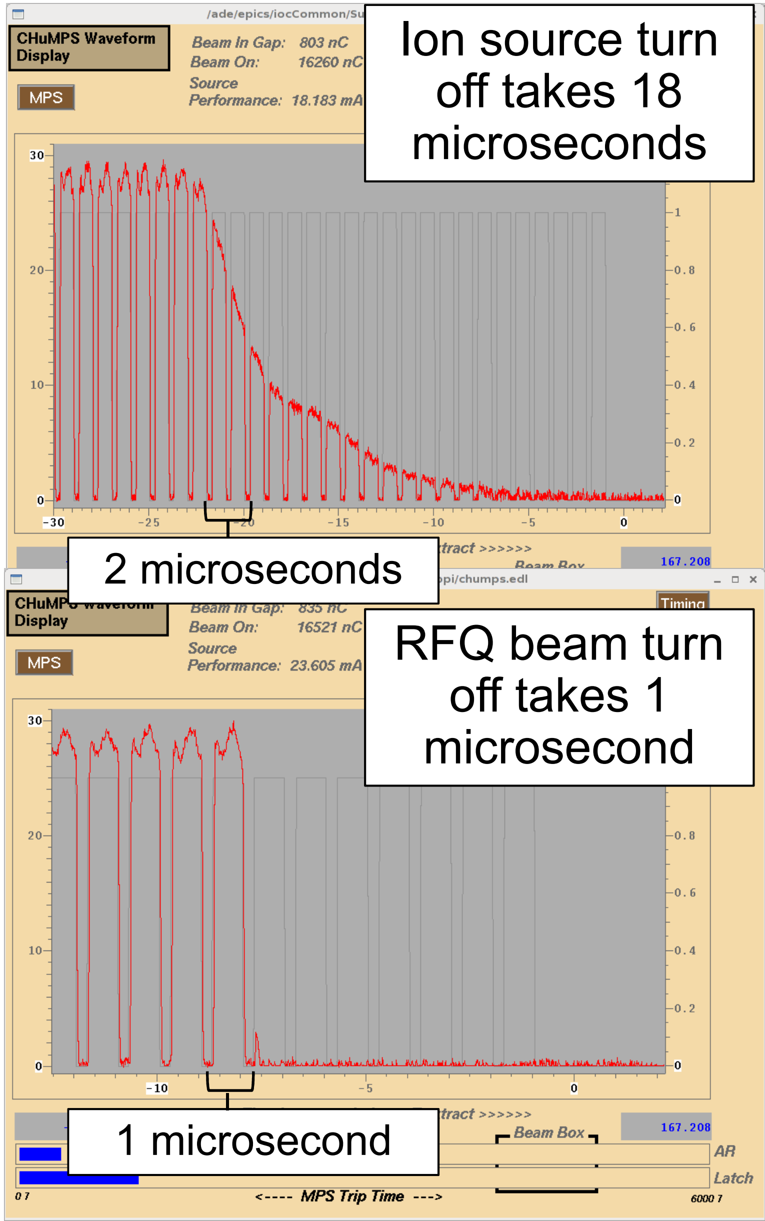


Reducing errant beam was a two step process

- Reduce the amount of beam lost during an errant beam event.
  - Measure the amount of errant beam being lost using Beam Current Monitors (BCMs).
  - Decrease the beam turn off time compared with the normal Machine Protection System (MPS) turn off time.
- Reduce the frequency of errant beam events.
  - Record fault statistics, find causes, and attempt to reduce fault rates.

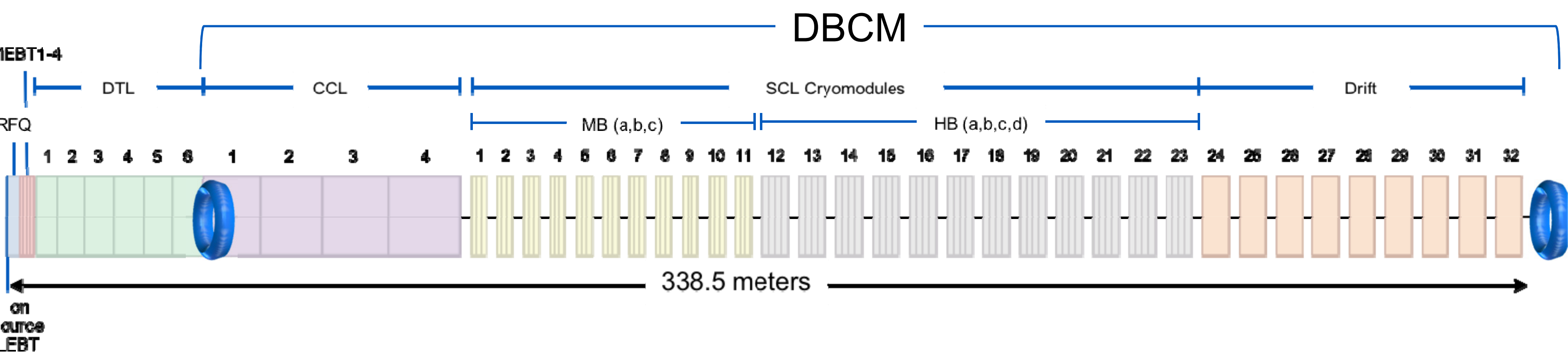
The MPS is designed to turn off the beam in about 15 uS

- 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 the LEBT chopper to chop all of the beam before it is injected into the RFQ.
- The whole process from detection to beam off takes on average 15-20 microseconds.



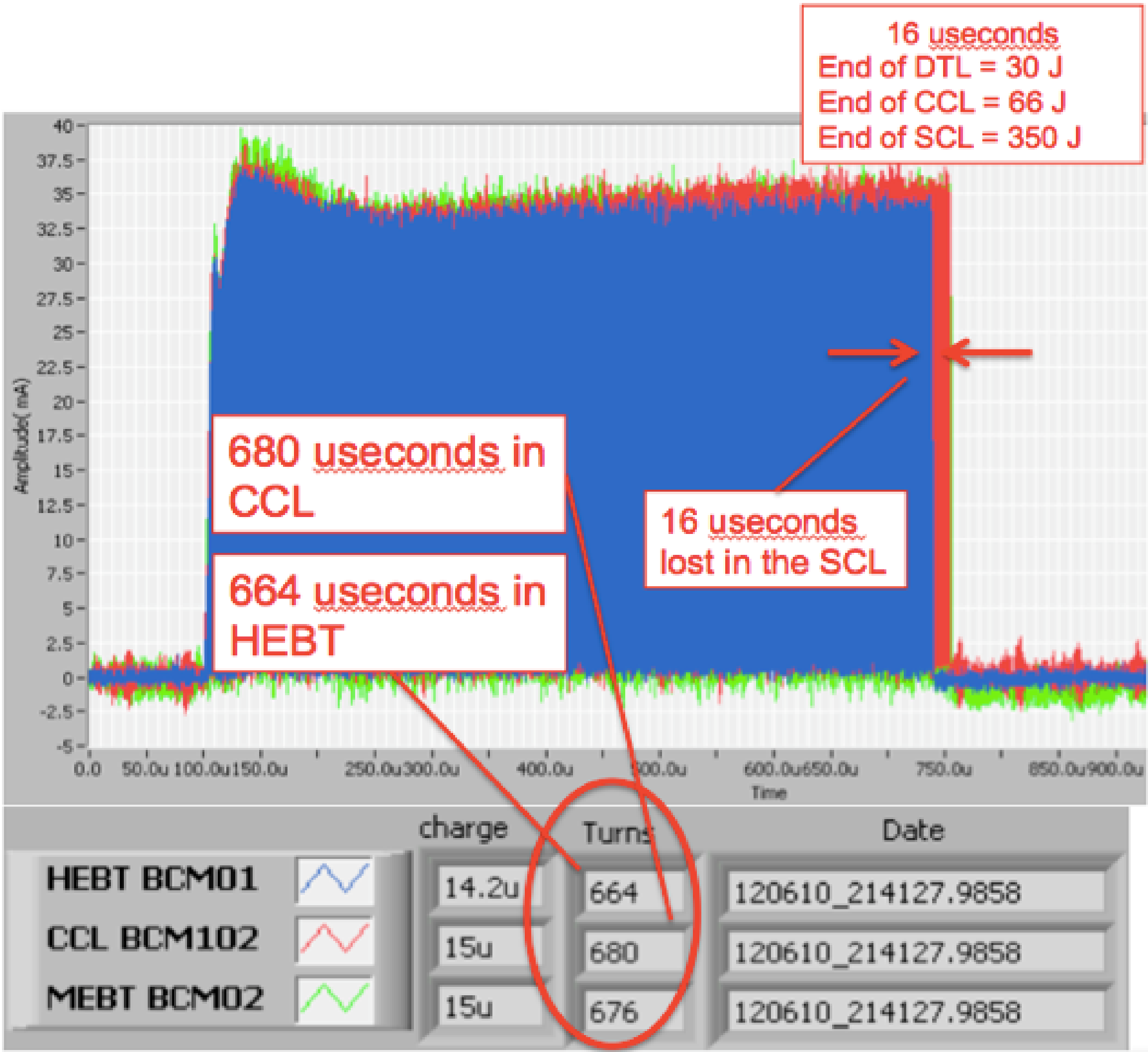
BCMs were quickly optimized for errant beam detection

- A new Differential Beam Current Monitor (DBCM) system was created using existing hardware.
  - Used a BCM in the CCL and one in the High Energy Beam Transport (HEBT) downstream of the SCL.
  - Optimized monitoring for differential charge at 60 Hz.
  - Differential charge triggered waveform saves to a web server for easy viewing.
  - No connection to the MPS.



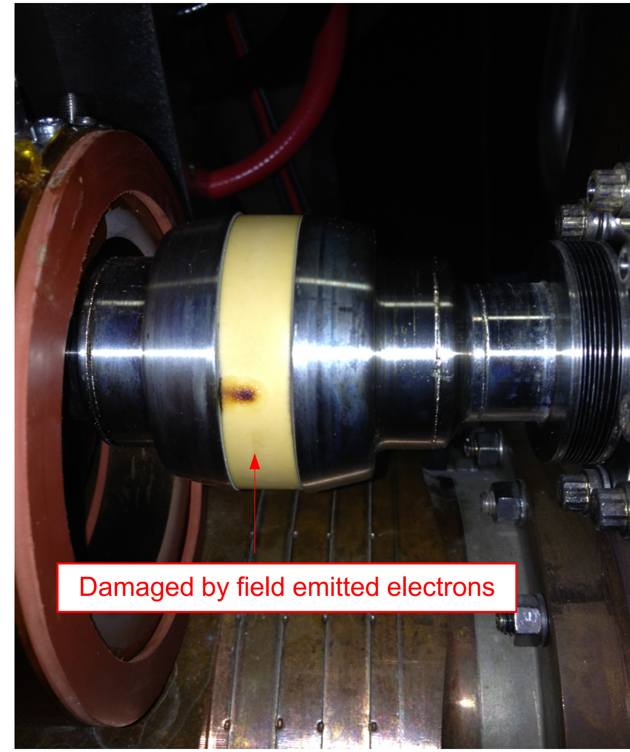
The MPS does turn off the beam in about 15 uS

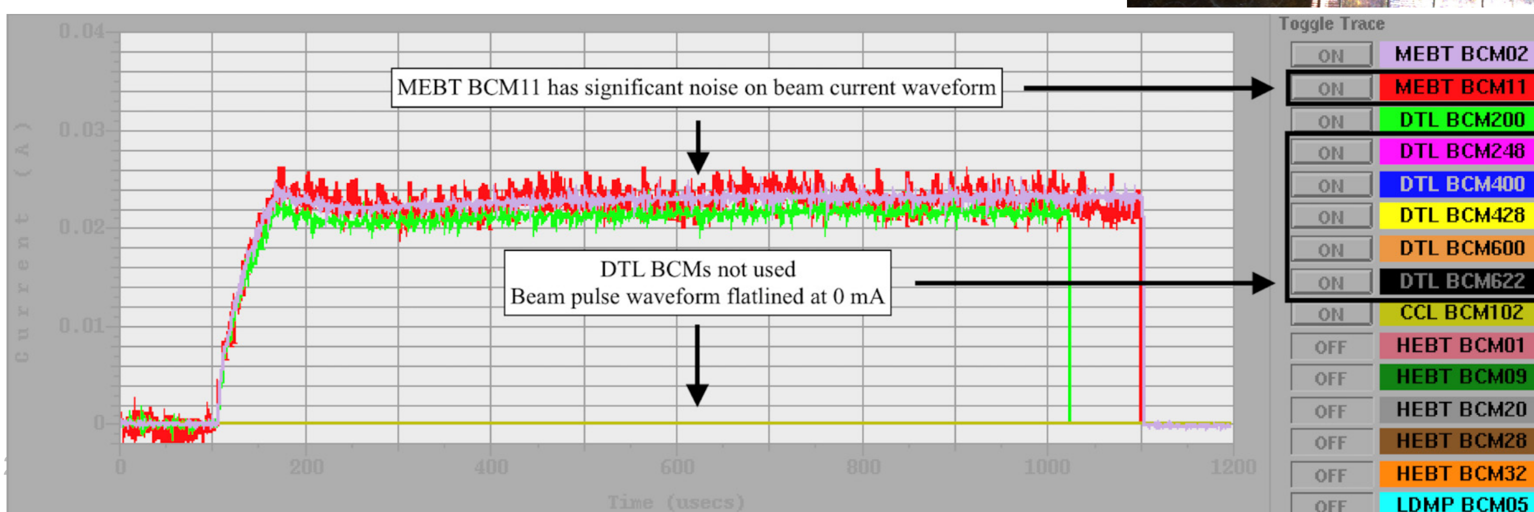
- BCM measurements verified the MPS works properly.
- Beam is completely lost between CCL1 and the HEBT.
- Able to match waveform signatures to specific errant beam cause (most look exactly the same).



BCMs near RF cavities have had issues

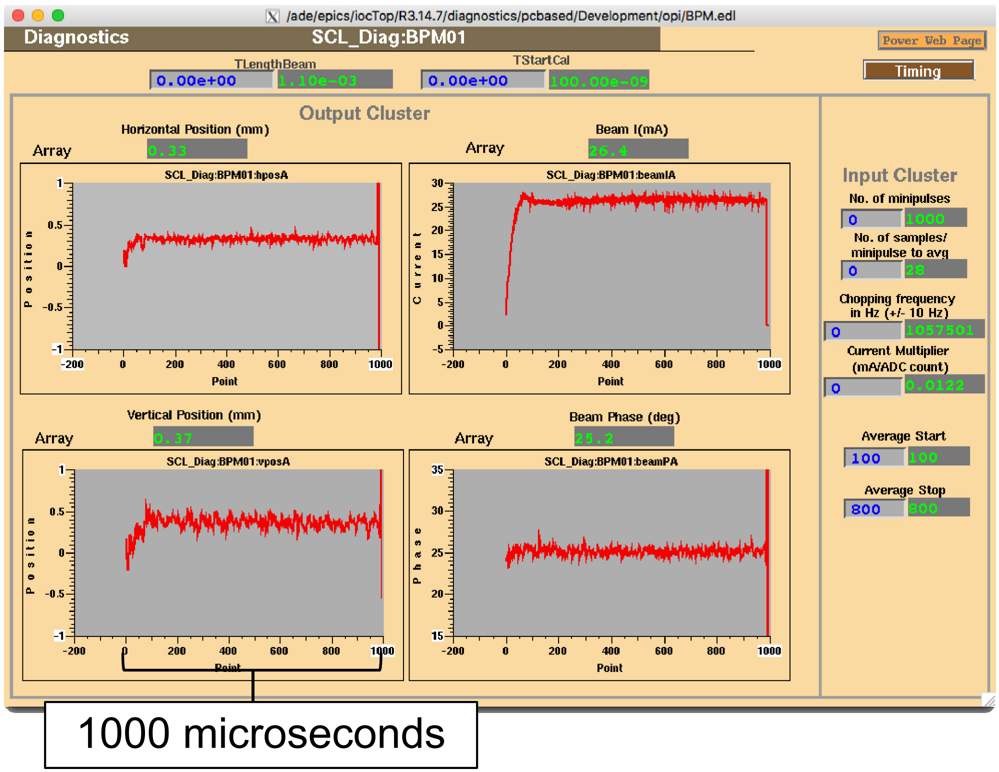
- The ceramic in the CCL BCM developed a vacuum leak.
  - Same thing happened to a BCM between the CCL and SCL.
- MEBT and DTL BCMs are noisy.
- Only need one calibrated charge measurement for measuring a differential charge.





BPMs are the most versatile beam detector

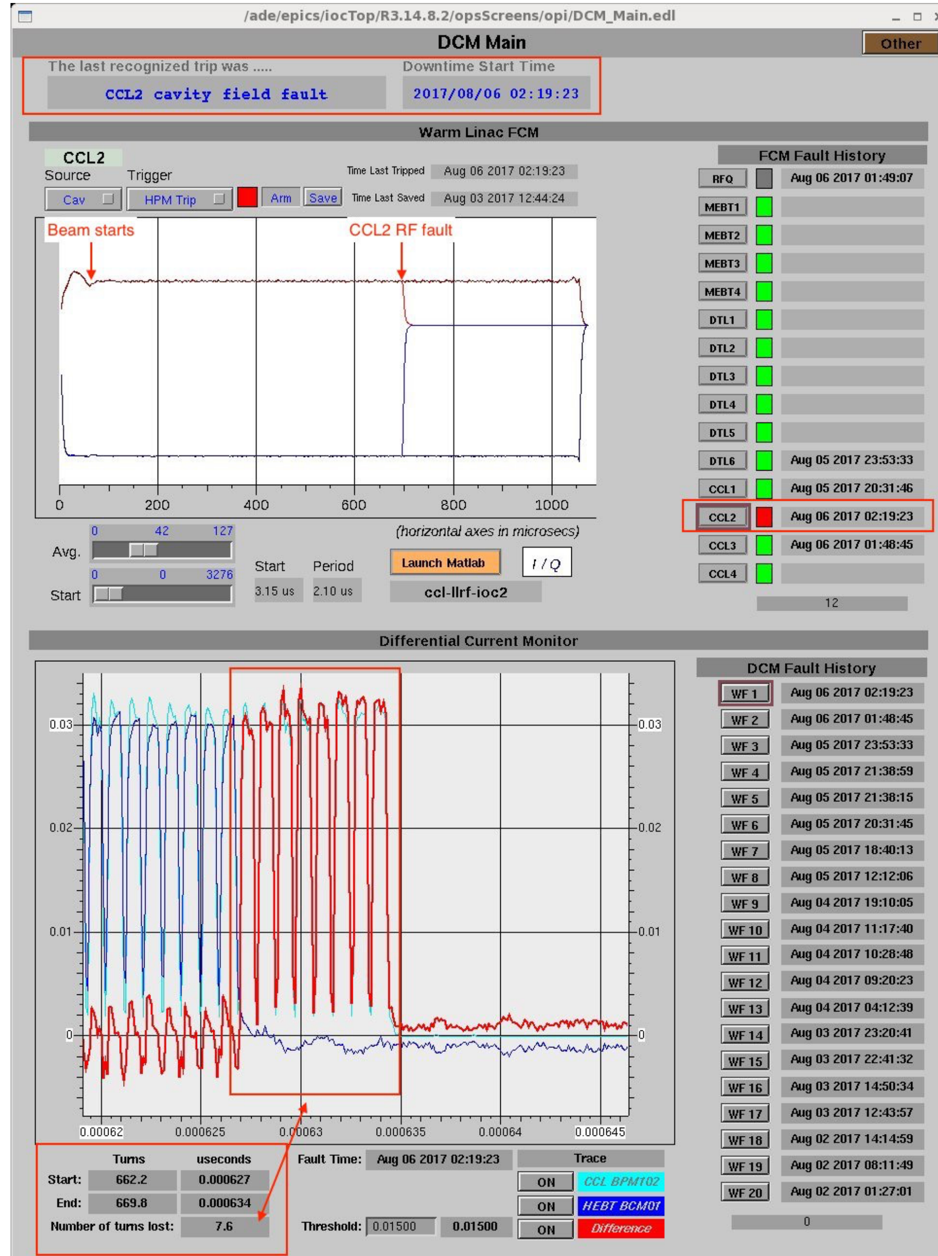
- The BPMs show horizontal and vertical beam positions, beam phase, and an <u>uncalibrated</u> beam current measurement.
- There are a lot of BPMs.
  - MEBT (6)
  - DTL (10)
  - CCL (10)
  - SCL (34)



- BPMs can be used in a differential current measurement if calibrated with a BCM.
  - Calibration dependent on longitudinal shape, beam position, and in our case log-amp electronics.

SCL 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 due to concerns with 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.



SCL DBCM still doesn't turn off the beam fast enough to eliminate SCL cavity trips

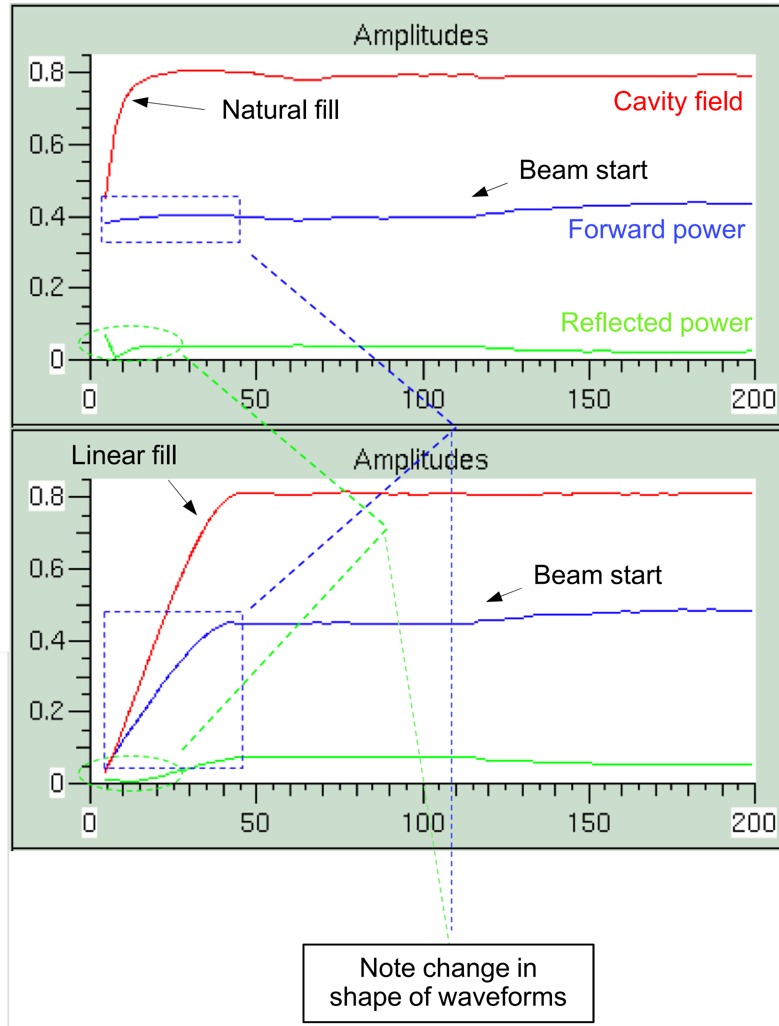
- Central Helium Liquefier (CHL) system fault caused transition of SCL from 2 to 4 K.
  - After SCL recovery to 2 K:
    - First DTL4 RF fault caused SCL BLMs to trip, but not enough beam loss in SCL to trip cavities.
    - First DTL5 RF fault caused SCL BLMs to trip, but not enough beam loss in SCL 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).
- The next goal was to minimize the frequency of trips.

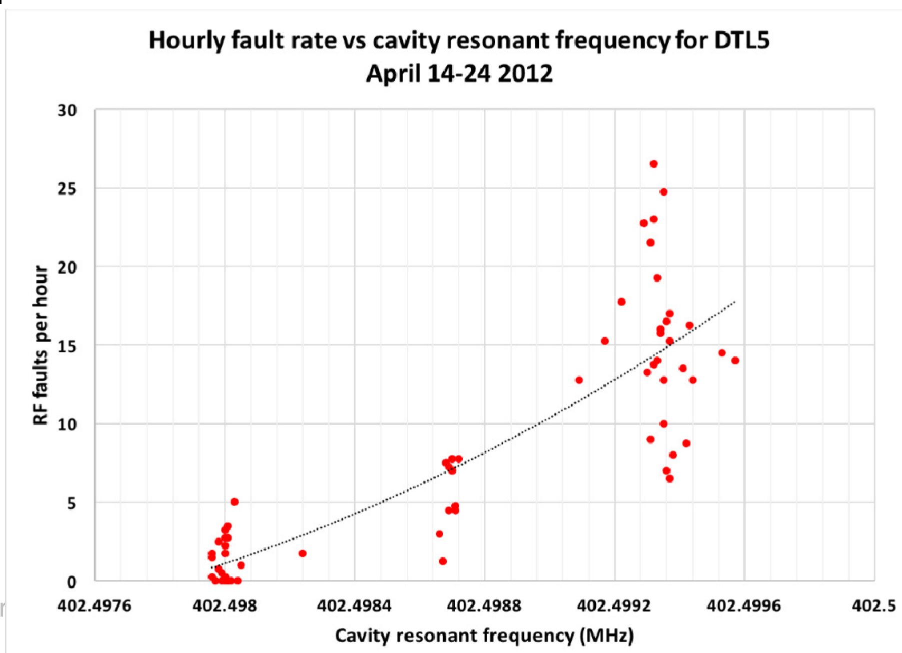
Warm linac is the major cause for errant beam

- < 10% of BLM trips were due to the Ion source/LEBT
  - Most ion source induced BLM trips occur during the first week of a new source installation
    - High voltage arcing
- > 90% of BLM trips were due to Warm Linac RF faults
  - RF faults occur at different times during the pulse
    - Faults during the RF fill had reproducible times
    - Faults during the RF flattop were random
  - Focused on improving warm linac operation

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.





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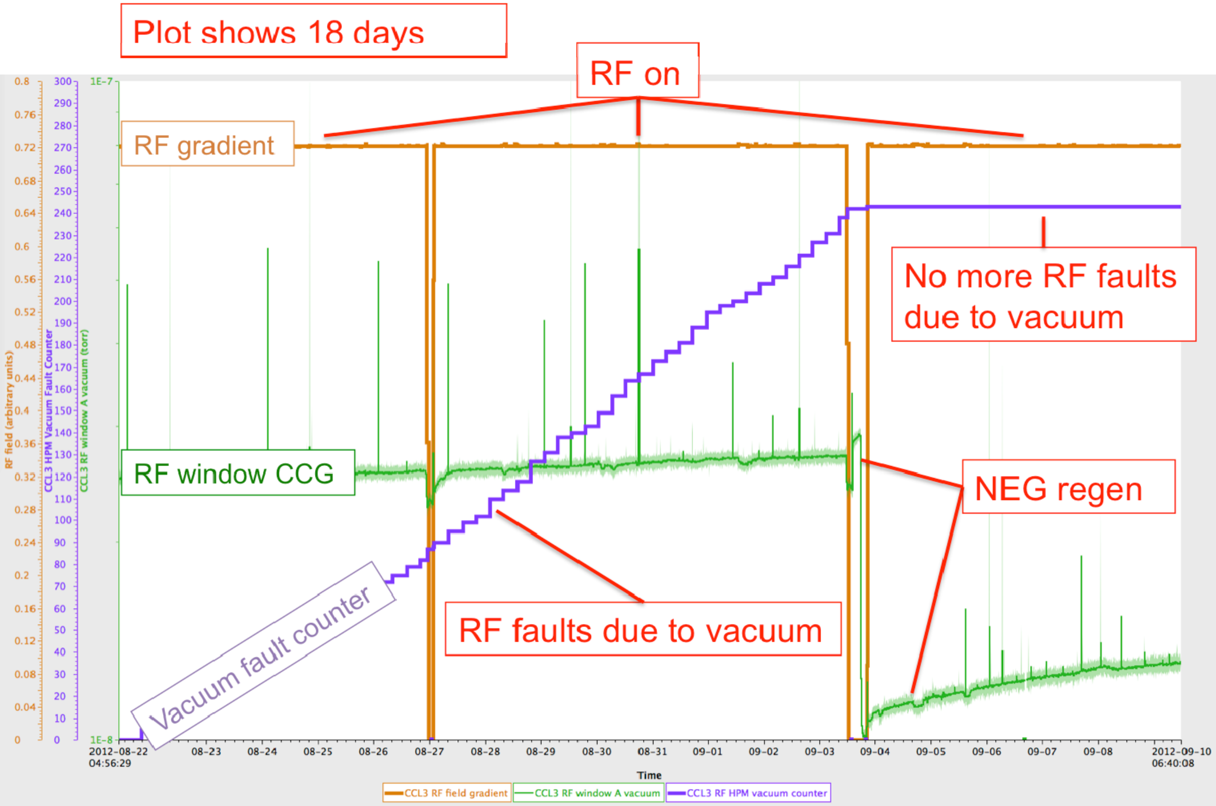
Vacuum upgrade decreased downtime and errant beam

- Vacuum capture pumps have not worked well in the RF cavity environment.
  - Cryopumps in the RFQ, ion pumps in the MEBT, 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%.

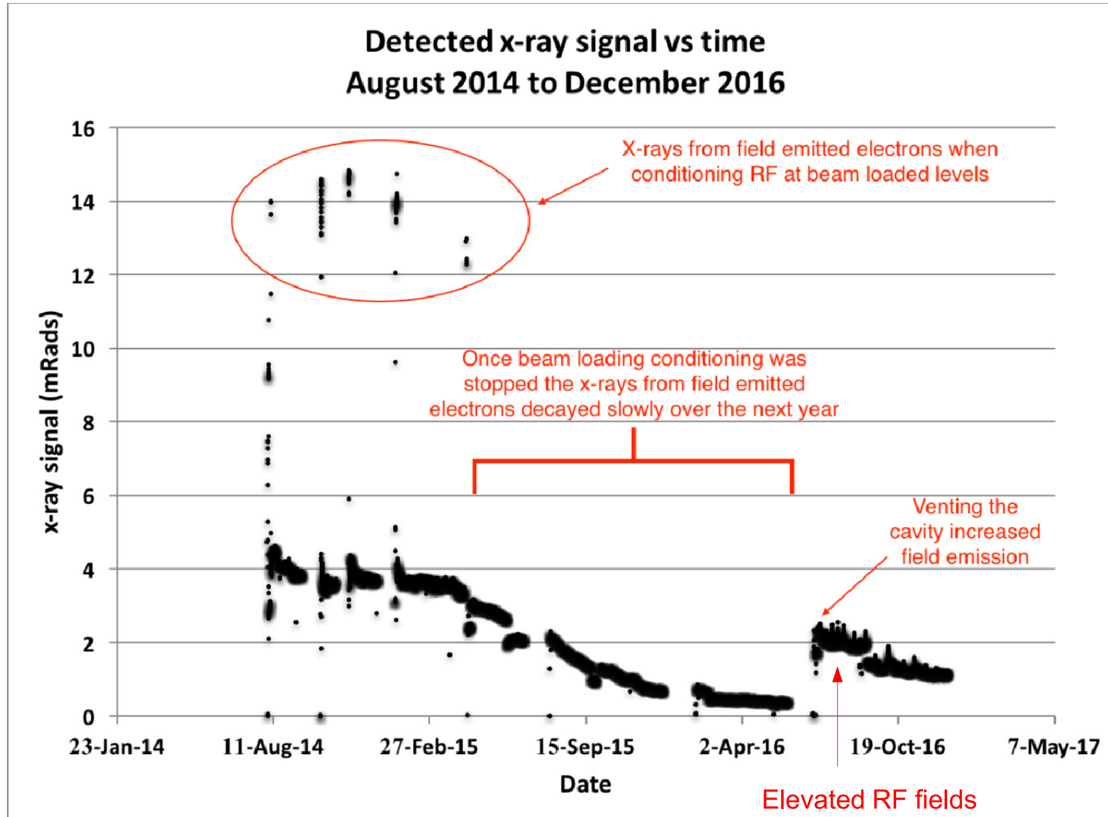


- Eliminated possible cause of RF faults and errant beam.

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

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.



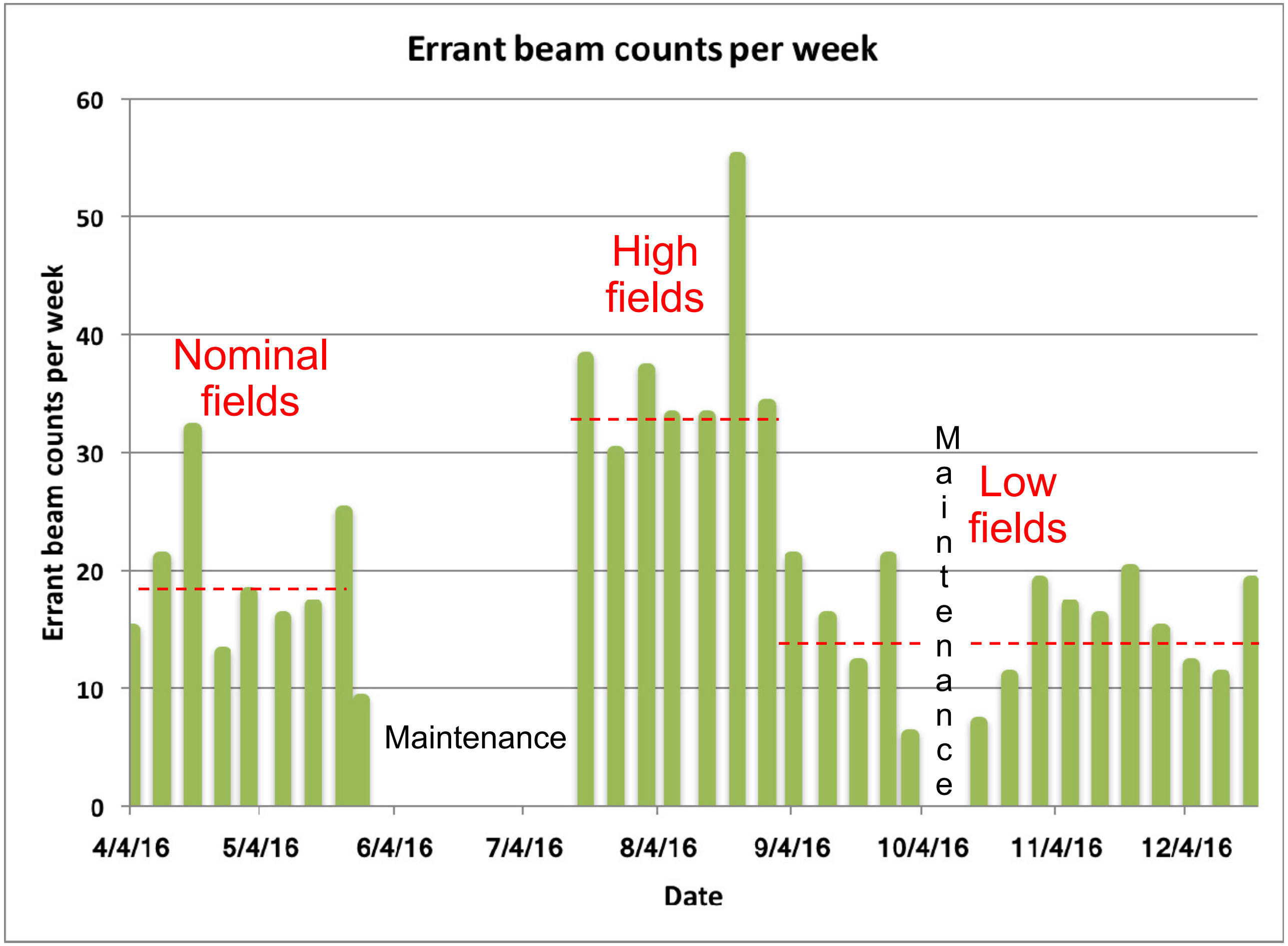
Elevated RF fields increases RF faults and errant beam

- 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

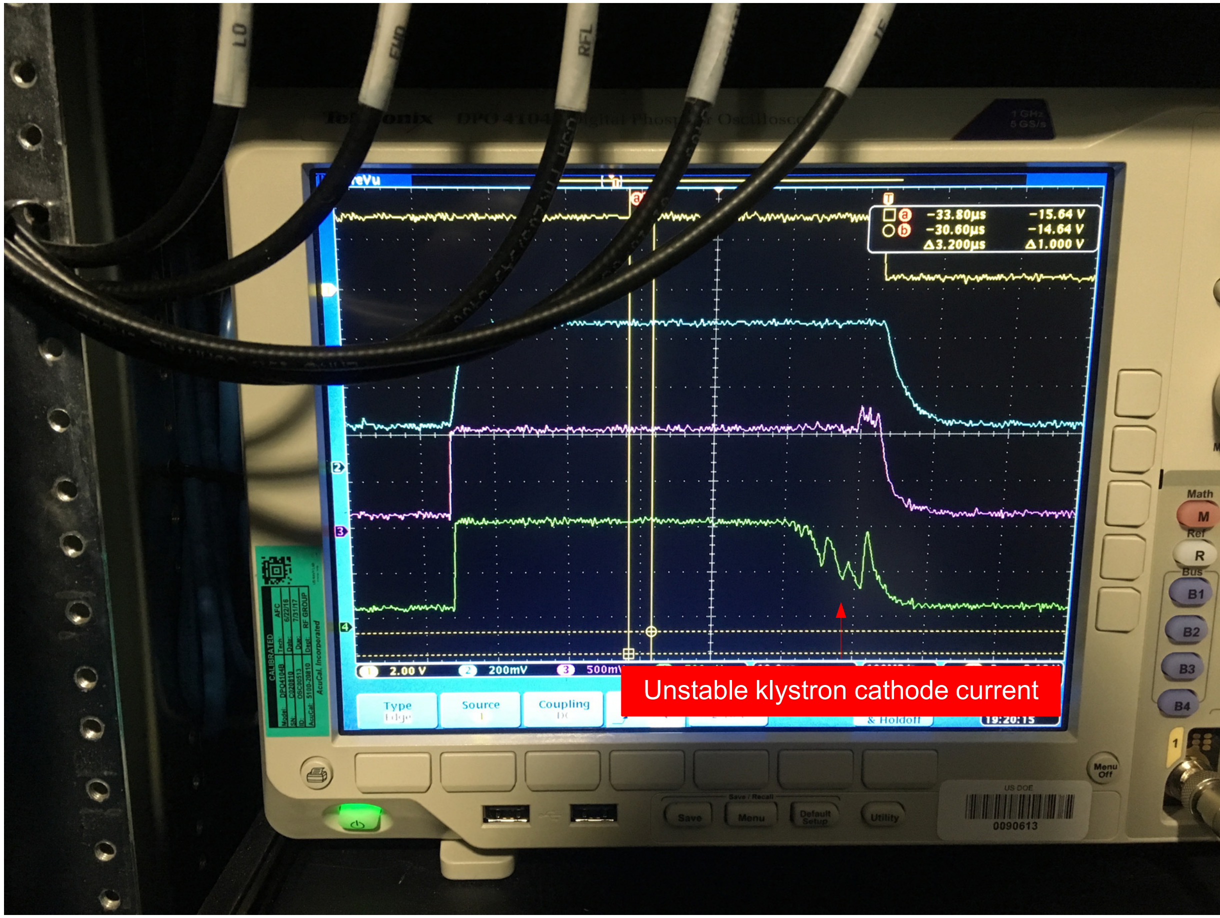
Lowering warm linac RF field decreased errant beam

- If higher field cause more RF faults then reduce RF fields until beam losses go up.
- Lowering warm linac fields decreased RF faults, and errant beam.



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.



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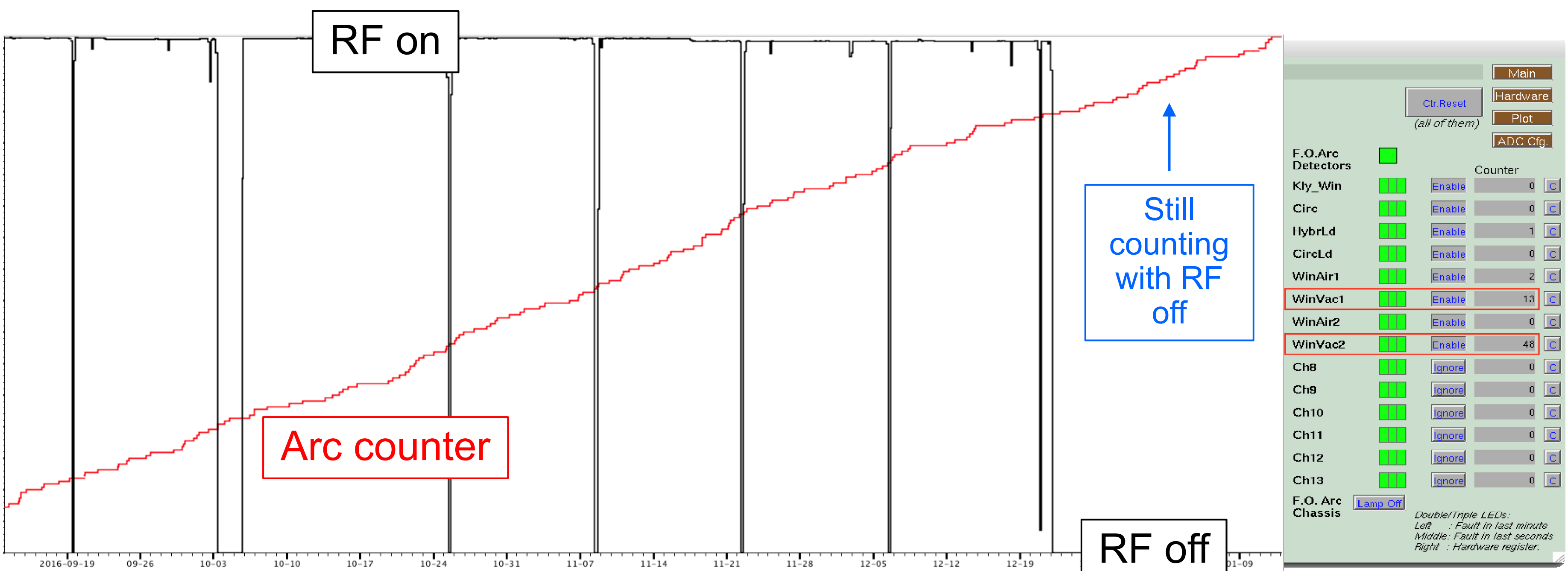
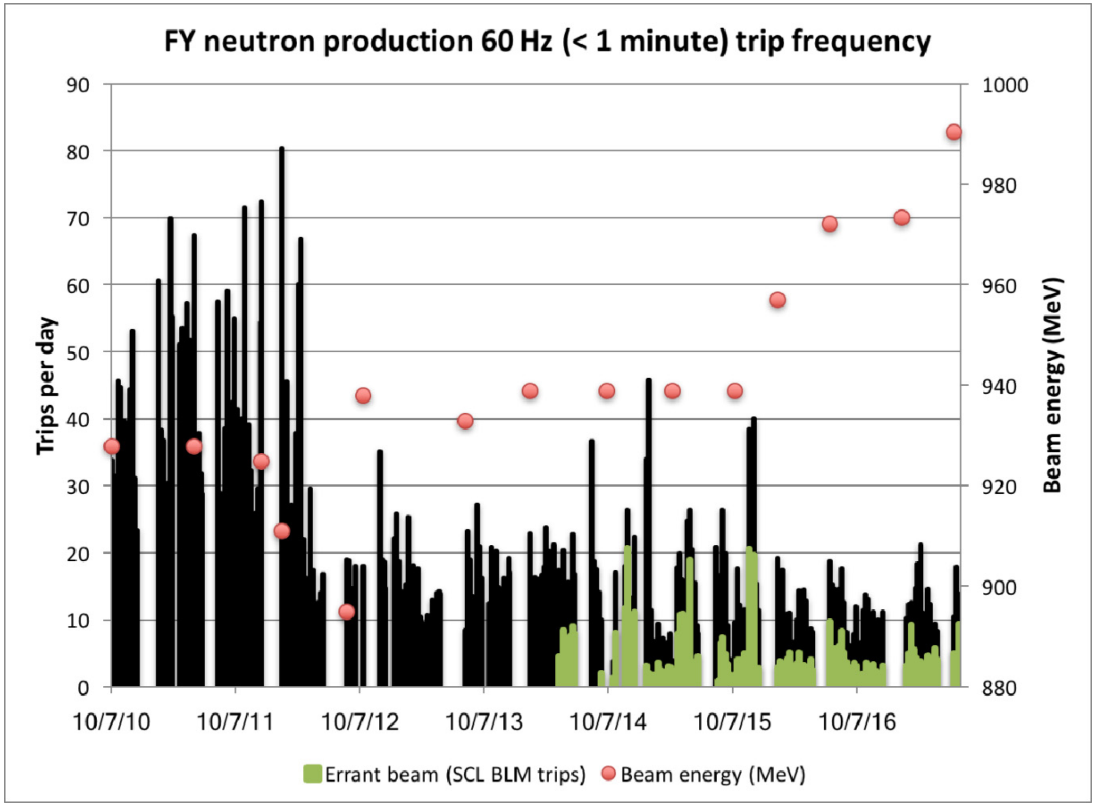
CCL false arc detection is important too

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



Results

- Errant beam loss has been significantly reduced since 2010.
  - Amount of beam loss per event is reduced by the SCL DBCM.
  - Frequency is reduced by improving performance of the warm linac.
- SCL cavity degradation has slowed, but continues.
- With the combination of errant beam reduction, thermal cycling, and plasma processing SCL gradients are increasing.



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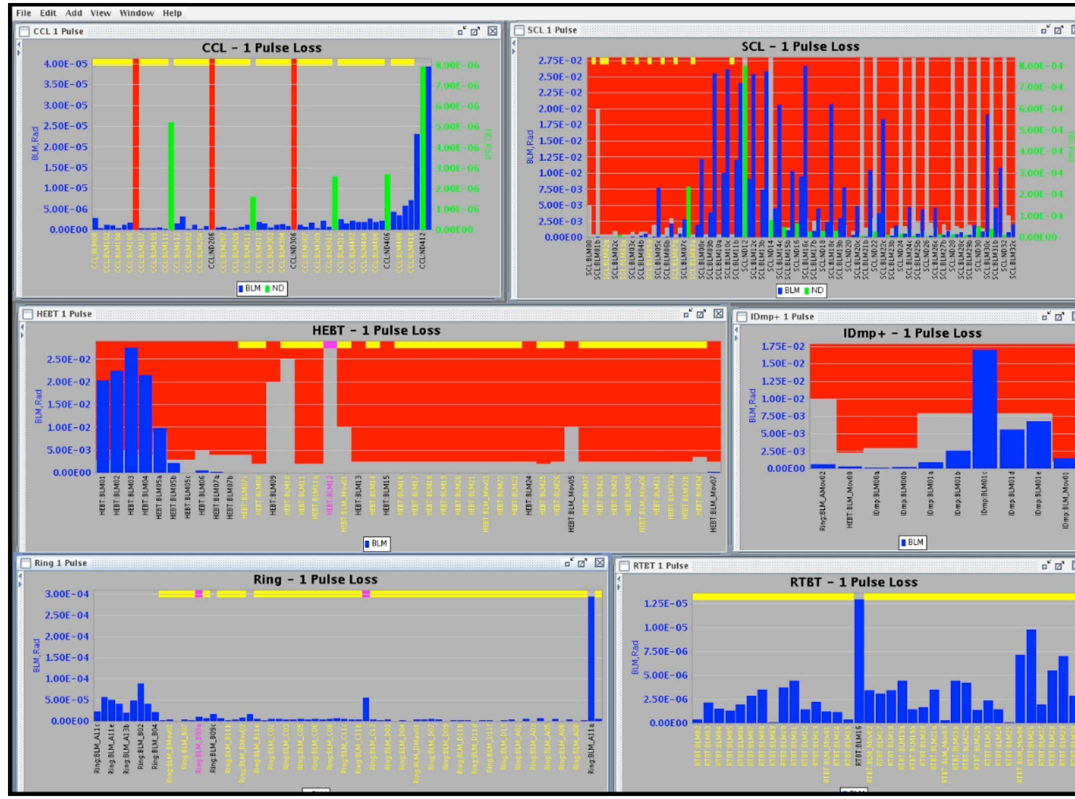
Thank you for your attention!

Additional slides

BLMs are the most sensitive errant beam detector

- Argon filled ion chamber is very sensitive for localized losses in the CCL and SCL.
  - Picks up beam loss as well as x-rays from RF.
    - Initially the x-rays were a negative because a complex subtraction technique is needed to properly abort based on real beam loss.
    - It's actually become a positive to be able see trends of health of RF cavities.
  - Not sensitive at energies below about 90 MeV.
    - A scintillator detector (Neutron Detectors (NDs)) are used in the DTL for beam loss detection.



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